Management of hybrid remote area power supply systems

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MANAGEMENT OF HYBRID REMOTE AREA
POWER SUPPLY SYSTEMS

A Thesis Submitted in Partial Fulfilment of the
Requirements for the Award of the Degree

Doctor of Philosophy

from

University of Wollongong

by

Yingjie Tan, BSc.Eng (Hons)

School of Electrical, Computer and Telecommunications Engineering
Faculty of Engineering and Information Sciences
University of Wollongong, Australia

August, 2016
Declaration of Authorship

I, YINGJIE TAN, hereby declare that this thesis, submitted in partial fulfilment of the requirements for the award of Doctor of Philosophy in the University of Wollongong, is entirely my own original work except where clearly acknowledged. I certify that this thesis contains no material that has been or will be submitted for the award of any degree in my name in any other university.

Yingjie Tan

August 31st, 2016
Declaration of Publications

This thesis includes chapters that have been written as the following articles:

**Chapter 2**


**Chapter 3**


**Chapter 4**


**Chapter 5**


**Chapter 6**


Yingjie Tan, Kashem M. Muttaqi, Phil Ciufio, and Lasantha Meegahapola, "Enhanced Frequency Response Strategy for PMSG-based Wind Energy Conversion System Using Ultracapacitor in
Chapter 7


Chapter 8


As the primary supervisor, I, Prof. Kashem M. Muttaqi, declare that the greater part of the work in each article listed above is attributed to the candidate, Yingjie Tan. In each of the above manuscripts, the candidate contributed to development of the main idea or concept, which has been extended, refined and tuned for improvement with advice from myself and his cosupervisors A/Prof. Philip Ciufo and Dr. Lasantha Meegahapola, who contributing as coauthors. The candidate has prepared the first draft of each of the manuscripts and revised those according to the suggestions provided by the supervisors. The candidate has been responsible for submitting each of the manuscripts for publication to relevant publishers, and he has been in charge of responding to the reviewers’ comments, with assistance from his coauthors.

Prof. Kashem M. Muttaqi
Principal Supervisor
August 24th, 2016
Acknowledgements

The four-year research study was an enjoyable journey for me. I would like to express my sincere gratitude to those who made this happen: the **supervisor board** Prof. Kashem M. Muttaqi, A/Prof. Phil Ciufio, and Dr. Lasantha Meegahapola who provided guidance and support on completing the research work presented in this thesis; my **parents and brother** who were always around to show their encouragement and gave me a sense of belonging; my **girlfriend** TANG Lu who has been with me for five years and lightened the research journey; the staff of **Australian Power Quality and Reliability Centre (APQRC)** who helped my laboratory testing. I would also like to thank the **China Scholarship Council** for their sponsorship for my four-year study…
Abstract

Remote area power supply (RAPS) systems play a vital role in the electrification of rural and remote communities. Fossil fuels conventionally power RAPS systems. Attributing to the public consensus in renewable energy such as the wind and solar energy, renewable power generation is increasingly integrated into RAPS systems along with various energy storage technologies, thus resulting in hybrid RAPS systems.

In order to code with the challenges raised by the utilisation of renewable energy resources, this research proposes innovative techniques to enhance the reliability of the power supply in RAPS systems.

The intermittency of renewable energy resources and the adequacy of hybrid RAPS system in fulfilling the system loads were analysed. The capacity value technique is applied to evaluate the capability of the renewable energy resources in satisfying the system load demand. The impact of energy storage systems on security of the power supply reliability was also explored. The reliability study of the system provides the practical tool for the optimal sizing of the components in the hybrid RAPS systems investigated in this research.

Strategies were proposed to actively engage renewable generators in the provision of auxiliary services (e.g., frequency regulation), thus improving the stability of the RAPS system. The kinetic energy stored in the rotating mass of the doubly-fed induction generator (DFIG) based wind energy conversion system (WECS) is utilised to supply primary frequency response to the RAPS system. A droop-based controller accomplishes the control without the conventionally used high-pass-filter, which prevents the response from being activated under slow frequency disturbances. A supplementary controller is introduced to the system to enhance the primary frequency response. The proposed suboptimal power point tracking (SOPPT) strategy establishes mechanical power reserve and further improves the frequency regulation capability of the DFIG. The proposed SOPPT strategy is also applied to photovoltaic (PV) based solar energy conversion system for frequency and voltage support in a hybrid RAPS system consisting of a parallel operating diesel generator. A multimode control strategy manipulates the operating
modes of the diesel generator and solar-PV. Depending on the loading and irradiance level, the solar-PV alters its operating mode aiming to achieve: (1) energy harvesting maximization, (2) frequency support, and (3) voltage support. Ultracapacitors (UCs), generally of high power density, are used as another means of frequency response. The UC is capable of being charged/discharged rapidly, thus providing a fast frequency response. This research also suggests a multilevel energy storage strategy for a permanent magnet synchronous generator (PMSG) based WECS to supply both short and long-term frequency responses. Moreover, an adaptive virtual inertial control is proposed to enhance the primary frequency response provided by the WECS.

In regard to improving the reliability of the system components, the following approaches were suggested: (1) The involvement of renewable power generators in frequency regulation relieves synchronous generator from the burden caused by frequent frequency fluctuations. (2) The introduction of the UC into the frequency control reduces the mechanical and electromagnetic stress on the WECS. (3) The hybridisation of energy storage system optimises the advantages of each energy storage technology and avoids their weaknesses. Furthermore, the thermal problem in regard to operating a DFIG around synchronous speed was also investigated. The excessive fluctuation in junction temperature of the semiconductor devices of the rotor side (RSC) converter can significantly shorten the life expectancy of the RSC, and thus reduces the reliability of RAPS system. A deadband control approach was suggested to avoid the synchronous operation.

Comprehensive simulations were carried out on detailed RAPS system models to validate the proposed control strategies. Laboratory DFIG and PMSG test beds were also established to verify the control algorithms further. The test results validate the effectiveness of the control strategies and the applicability in practical situations. This thesis establishes solid theoretical and practical contributions to reliability improvement of RAPS systems, and provides factual insights into the planning and operation of RAPS systems. The improvement in system reliability will stimulate financial benefits and improves end-user satisfaction. The innovations established in this thesis will contribute to the initiative of eco-friendly rural and remote electrification, and thus provide economic and social benefits to rural and remote communities.
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### Variables

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<th>Description</th>
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<tbody>
<tr>
<td>$A$</td>
<td>area</td>
</tr>
<tr>
<td>$c$</td>
<td>Weibull scale parameter</td>
</tr>
<tr>
<td>$C$</td>
<td>capacitance</td>
</tr>
<tr>
<td>$E$</td>
<td>energy</td>
</tr>
<tr>
<td>$f$</td>
<td>frequency</td>
</tr>
<tr>
<td>$H$</td>
<td>inertia constant</td>
</tr>
<tr>
<td>$I, i$</td>
<td>current</td>
</tr>
<tr>
<td>$J$</td>
<td>moment of inertia</td>
</tr>
<tr>
<td>$p$</td>
<td>probability function</td>
</tr>
<tr>
<td>$P$</td>
<td>active power</td>
</tr>
<tr>
<td>$Q$</td>
<td>reactive power</td>
</tr>
<tr>
<td>$R$</td>
<td>resistance</td>
</tr>
<tr>
<td>$s$</td>
<td>slip</td>
</tr>
<tr>
<td>$S$</td>
<td>generator capacity</td>
</tr>
<tr>
<td>$t$</td>
<td>time</td>
</tr>
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<td>temperature</td>
</tr>
<tr>
<td>$U, u$</td>
<td>voltage</td>
</tr>
<tr>
<td>$V_w$</td>
<td>wind speed</td>
</tr>
<tr>
<td>$\gamma$</td>
<td>load</td>
</tr>
<tr>
<td>$\omega$</td>
<td>angular frequency</td>
</tr>
<tr>
<td>$\delta$</td>
<td>self-discharging coefficient</td>
</tr>
<tr>
<td>$\eta$</td>
<td>efficiency</td>
</tr>
<tr>
<td>$\phi$</td>
<td>wind turbine pitch angle</td>
</tr>
<tr>
<td>$\lambda$</td>
<td>wind turbine tip-speed ratio</td>
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\( \tau \)  

Torque

Superscripts, subscripts

- **a, b, c**: Phase-A, Phase-B, Phase-C
- **C**: capacitor
- **d, q**: \( d-, q \)-axis component in direct-quadrant reference frame
- **D**: droop
- **DG**: diesel generator
- **e**: electrical
- **g, gsc**: grid side converter
- **H**: inertial
- **j**: semiconductor junction
- **L**: inductor
- **m**: mechanical
- **max**: maximum
- **min**: minimum
- **nom**: nominal
- **PV**: solar-PV generator
- **r**: rotor
- **ref**: reference
- **s**: stator
- **t**: wind turbine
- **w**: wind turbine generator
### List of Abbreviations

<table>
<thead>
<tr>
<th>Abbreviation</th>
<th>Full Form</th>
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<tbody>
<tr>
<td>AC</td>
<td>Alternating Current</td>
</tr>
<tr>
<td>AGC</td>
<td>Automatic Generation Control</td>
</tr>
<tr>
<td>AI</td>
<td>Artificial Intelligence</td>
</tr>
<tr>
<td>DC</td>
<td>Direct Current</td>
</tr>
<tr>
<td>DER</td>
<td>Distributed Energy Resource</td>
</tr>
<tr>
<td>DFIG</td>
<td>Doubly-Fed Induction Generator</td>
</tr>
<tr>
<td>DG</td>
<td>Diesel Generator</td>
</tr>
<tr>
<td>ELCC</td>
<td>Effective Load Carrying Capability</td>
</tr>
<tr>
<td>FOR</td>
<td>Forced Outage Rate</td>
</tr>
<tr>
<td>FSIG</td>
<td>Fixed-Speed Induction Generator</td>
</tr>
<tr>
<td>GA</td>
<td>Genetic Algorithm</td>
</tr>
<tr>
<td>GSC</td>
<td>Grid Side Converter</td>
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<tr>
<td>HOMER</td>
<td>Hybrid Optimisation Model for Electric Renewables</td>
</tr>
<tr>
<td>IC</td>
<td>Incremental Conductance</td>
</tr>
<tr>
<td>IG</td>
<td>Induction Generator</td>
</tr>
<tr>
<td>IGBT</td>
<td>Insulated Gate Bipolar Transistor</td>
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<tr>
<td>LAB</td>
<td>Lead Acid Battery</td>
</tr>
<tr>
<td>LOLE</td>
<td>Loss of Load Expectation</td>
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<tr>
<td>LOLP</td>
<td>Loss of Load Probability</td>
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<tr>
<td>LPSP</td>
<td>Loss of Power Supply Probability</td>
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<tr>
<td>LVRT</td>
<td>Low Voltage Ride Through</td>
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<tr>
<td>MPP</td>
<td>Maximum Power Point</td>
</tr>
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<td>MPPT</td>
<td>Maximum Power Point Tracking</td>
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<tr>
<td>MSC</td>
<td>Machine Side Converter</td>
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<tr>
<td>PI</td>
<td>Proportional Integral</td>
</tr>
<tr>
<td>PLL</td>
<td>Phase-Locked Loop</td>
</tr>
<tr>
<td>Abbreviation</td>
<td>Description</td>
</tr>
<tr>
<td>--------------</td>
<td>----------------------------------</td>
</tr>
<tr>
<td>PMSG</td>
<td>Permanent Magnet Synchronous Generator</td>
</tr>
<tr>
<td>PV</td>
<td>Photovoltaic</td>
</tr>
<tr>
<td>PWM</td>
<td>Pulse Width Modulation</td>
</tr>
<tr>
<td>P&amp;O</td>
<td>Perturbation and Observation</td>
</tr>
<tr>
<td>RAPS</td>
<td>Remote Area Power Supply System</td>
</tr>
<tr>
<td>ROCOF</td>
<td>Rate of Change of Frequency</td>
</tr>
<tr>
<td>ROCOP</td>
<td>Rate of Change of Power</td>
</tr>
<tr>
<td>RSC</td>
<td>Rotor Side Converter</td>
</tr>
<tr>
<td>SEIG</td>
<td>Self-Excited Induction Generator</td>
</tr>
<tr>
<td>SFO</td>
<td>Stator-Flux-Oriented</td>
</tr>
<tr>
<td>SM</td>
<td>Synchronous Machine</td>
</tr>
<tr>
<td>SOC</td>
<td>State Of Charge</td>
</tr>
<tr>
<td>SOPPT</td>
<td>Suboptimal Power Point Tracking</td>
</tr>
<tr>
<td>STATCOM</td>
<td>Static-Synchronous Compensator</td>
</tr>
<tr>
<td>UC</td>
<td>Ultracapacitor</td>
</tr>
<tr>
<td>VSD</td>
<td>Variable Speed Drive</td>
</tr>
<tr>
<td>WECS</td>
<td>Wind Energy Conversion System</td>
</tr>
<tr>
<td>WRIM</td>
<td>Wound Rotor Induction Machine</td>
</tr>
</tbody>
</table>
Chapter 1

Introduction

1.1 Motivation and Problem Statement

The remote area power supply (RAPS) system is a standalone power system that usually supplies power to small rural or remote communities. These communities do not have access to a large utility grid, and it is technically and economically infeasible to extend the utility grid to these remote regions. According to the International Energy Agency report in 2015, 1.2 billion people worldwide, which is 17% of the global population, do not have access to electricity [1]. RAPS system is considered to be a feasible option for electrification and is highly promoted by the Energy Access Practitioner Network launched by the United Nations Foundation to ensure universal access to modern energy services [2].

Conventional generators, such as diesel generators (DGs), are being used widely in RAPS systems. As the RAPS systems are significantly smaller in comparison to general utility grids, sophisticated system control facilities and advanced control strategies may not be included in RAPS systems due to the cost-effective design and operation. Consequently, high sensitivity to system disturbances can be a common characteristic of RAPS systems.

Due to the decreasing fossil fuel reserves, increasing fuel prices, as well as environmental issues, renewable energy resources are gaining popularity in power systems. The problems caused by renewable power generators in large utility grids have drawn considerable attention in both academic and industrial communities. In reality, the situation in RAPS systems is more urgent due to a much higher renewable power penetration level. Renewable power generators are traditionally controlled to maximise their power generation for financial incentives, which further worsens the power supply quality of the RAPS system due to the existing basic control hierarchies and non-stiff nature of RAPS systems. Although the grid standards for RAPS systems may not be as stringent as a large utility grid, the security of the power supply reliability cannot be over emphasised. Maintaining safe
and economic operation of the system and improving the electricity end-user satisfaction could be the paramount task for the system operator.

The power supply reliability is mainly determined by 1) the ability of the generation sources to fulfil the load demand, 2) the system stability maintenance, and 3) the service status of the system components.

Due to the volatility of renewable energy resources and the unscheduled tripping of generators, the power generated may not be able to meet the power consumed by the load in a RAPS system. When a power deficit occurs in the RAPS system, load shedding should be carried out to maintain the stability of the system and some electricity users are forced to be offline. As a consequence, the power supply reliability is reduced. Hence, the probability that the generation can meet the load demand should be evaluated at the system planning stage. However, unlike conventional generators whose power output can be controlled by the consumption of fossil fuels, the renewable energy production depends on the availability of renewable energy resources and is not dispatchable. Hence, conventional reliability estimation techniques could not be used. In particular, hybrid RAPS systems consist of conventional generators, renewable power generators and energy storage systems. The diversified energy resources complicate the reliability assessment while cost-effective approaches are expected in RAPS system. Therefore, a straightforward and reliable algorithm is required for a RAPS system.

Stability of a RAPS system should be maintained to secure the reliable power supply and safety of the system components. Frequency regulation could be the first and foremost task to maintain the system frequency stability. However, the hybridisation of the RAPS system by combining renewable power generators and non-renewable power generators, or specifically inertial and non-inertial generators, frequency management becomes an ever-challenging mission. The reasons are as follows:

- Synchronous generators conventionally establish the system frequency and contribute to frequency responses. Nevertheless, without the presence of generators of predominant capacity in a RAPS system, synchronous generators have comparatively small capacity compared to the total load in the system. Under large frequency disturbances, it can be beyond the capability of synchronous generators to supply the required frequency response. Moreover, the response speed of conventional generators may not be adequate to arrest the fast changing frequency in RAPS systems due to the slow
fuel combustion and mechanical power conversion processes. Therefore, the traditional frequency regulation mechanism that solely relies on synchronous generators can no longer dominate the frequency control process in hybrid RAPS systems. Otherwise, reserve capacity in synchronous generators has to be increased along with the investment.

- Renewable power generators are operated in a way to maximise the renewable energy harvesting, which ignores the operating condition of the system. Renewable power generators traditionally do not provide frequency support to the network. The power delivered to the network is solely relying on the availability of the renewable energy resources. The power output from renewable power generators usually fluctuates with the variation in renewable energy (especially wind and solar energy). Moreover, renewable power generators are commonly connected to the RAPS network through power converters made up of semiconductor devices. Unlike synchronous generators which possess a direct electromagnetic interaction with the network, the system dynamics do not interfere with the operation of renewable power generators significantly. Thus renewable power generators cannot react to system frequency disturbances naturally. In particular, the inertial response inherently provided by synchronous generators is not available in power electronics based renewable power generators. Hence, the total system inertia will be significantly reduced in a RAPS system with a high renewable power penetration. The reduction in system inertia results in higher sensitivity to the imbalance between the generation and load demand.

Reliability of system components also has a direct impact on the operation and maintenance (O&M) cost of the system as well as the financial loss due to the offline maintenance. In order to extend the service life of system components, generators should be protected from detrimental stress. For example, abrupt torque variations will increase wear and tear on mechanical components of the rotating machines. In the case when renewable power generators do not participate in frequency regulation, the interconnected synchronous generators will be highly stressed by frequent frequency fluctuations, which will ultimately reduce their operational lifetime. Similarly, if renewable power generators are involved in frequency regulation, the control mechanism may also give rise to significant stress on the renewable power generators. A case in point is that the gearboxes and pitching system of the wind turbine generators are susceptible to failures under frequent mechanical shock. Apart from the mechanical torque stress, electrical stress may burden
or cause damage to system components as well. For example, when energy storage system is implemented in RAPS systems to mitigate the imbalance between power generation and the load demand, energy storage devices are prone to violent charging/discharging demand. Such frequent charging/discharging cycles and fast energy transfer can speed up the degrading of lead-acid batteries (LABs).

1.2 Research Objectives and Contributions

The main objective of this thesis is focused on the frequency regulation in RAPS systems. Frequency response control strategies are adopted in renewable power generators. In order to provide frequency support, power reserve is a fundamental requirement. Hence, various strategies were proposed to establish power reserve and suitable control algorithms are developed to utilise the power reserve for frequency responses and regulations.

(1) Kinetic Energy: In regard to the rotating-machine based renewable power generators such as doubly-fed induction generator (DFIG) based wind energy conversion system (WECS) and permanent magnet synchronous generator (PMSG) based WECS, considerable amount of kinetic energy is stored in the rotating mass of the turbine blades, drivetrain and generator. The kinetic energy can be a favourable means of power reserve. By utilising kinetic energy in frequency response under contingencies, renewable power generators can contribute to the frequency regulation in RAPS systems. This thesis proposed a primary frequency response control strategy for DFIG to inject a predesigned amount of kinetic energy into the network. The control is based on droop mechanism, which is only activated for short-term frequency response without the implementation of commonly used high-pass filters. The motivation is to prevent the response to be active for permanent frequency deviation as excessive draining of kinetic energy can cause a stall for the DFIG. The elimination of high-pass filter enables the DFIG to respond to slower frequency change and improve the dynamic performance. The proposed primary frequency controller successfully utilises kinetic energy to provide frequency response and a supplementary control is also added to the controller to enhance the frequency response by extracting extra kinetic energy.

(2) De-loading Operation: As in conventional generators, primary and secondary frequency response reserve is maintained as a standby reserve, and when frequency response control is activated, the power reserve will be utilised. This thesis also aims to establish
another means of power reserve in the renewable power generators by de-loading the renewable power generators. Traditionally, WECS and solar-PV are operated at their maximum power point (MPP). In this thesis, an alternative approach was proposed to de-rate the energy production of renewable power generators, which is referred as suboptimal power point tracking (SOPPT) strategy. The SOPPT control is achieved by intentionally shifting the operating point of the renewable power generators off their MPP and thus a fraction of the mechanical power (in the case of WECS) or irradiation (in the case of solar-PV) is reserved. This thesis explored the approaches to utilise the power reserve as primary frequency reserve or secondary frequency reserve. The impact of the power reserve on the enhancement of frequency responses was also investigated. In the scenario when energy storage systems are implemented, the power reserve takes the role of maintaining the state-of-charge (SOC) of the energy storage device.

(3) Energy Storage Systems: Energy storage system can be used as a promising source of frequency response reserve, which is gaining popularity in utility grids to mitigate the fluctuation of renewable power generation. Peak shaving of load demand can also be achieved by storing surplus energy in the system for use when a power deficiency occurs. Various energy storage technologies are available in the market as well as in the research stage. Characteristics of the energy storage devices are diversified, and their cost is also varied. Hence, proper selection of energy storage technologies in a RAPS system directly affects the effectiveness of the obtained frequency response. Undoubtedly, the cost-effectiveness of the system is also largely determined by selection of energy storage technologies. Specifically, a particular type of frequency response technique (i.e., inertial response, primary frequency response, secondary frequency response, etc.) covers a predefined timeframe. The response speed and power requirement of different frequency response techniques are also not the same. Therefore, it is necessary to match a particular type of frequency response with an appropriate energy storage technology. In this research, energy storage systems are integrated into renewable power generators as single units or as hybrid units (comprising of multiple energy storage technologies) depending on the control objectives of the RAPS system. The hybridisation of the energy storage technologies enables improved frequency response. This is achieved by optimising the advantages of each energy storage technology in the system and their individual disadvantage is avoided by the compensation effect from the other energy storage technology. 
The supportive frequency response from renewable generators maintains the frequency stability thus reliability of RAPS systems. With regard to the reliability of system components, objectives are also formulated to extend the service life of generators. In this thesis, a series of stress-relieving strategies were proposed for generators. a) The involvement of renewable power generators in frequency regulation relieves synchronous generators from frequent mechanical shock caused by frequency disturbances. b) The integration of energy storage systems into renewable power generators replaces the mechanical power reserve used for frequency regulation, and thereby the electrical/mechanical torque stress on the WECS can be eliminated. c) The hybridisation of the energy storage technologies avoids destructive impact on energy storage devices, thus preventing the energy storage device from fast degradation. For example, the combination of ultracapacitors (UCs) and LABs can be controlled to minimise charging/discharging cycles for LABs while achieving the control target, consequently extending the life expectancy of the LABs. d) Failures on power converters are common in power electronics based renewable power generators, which are mainly due to excessive junction temperature as well as temperature variations of the semiconductor devices. For example, large junction temperature swings present at the semiconductor devices of the rotor side converter (RSC) in DFIGs, when the generator is operating around synchronous speed. The temperature variation accelerates the failure of the semiconductor devices and thus the DFIGs. Hence, a deadband control strategy was introduced to WECS to avoid the synchronous operation and effectively improve the reliability of the electrical components.

Furthermore, for the purpose of adequately determining the capacity ratings of components (especially generators) in a RAPS system, another objective is set to evaluate the capability that the energy resources satisfy the energy requirement of the load in RAPS systems. The metric, capacity value, was introduced to renewable energy resources to indicate the amount of load that the renewable power generator can supply at a specified reliability level. An iterative approach was applied to estimate the reliability of power supply in the overall RAPS system. This theoretically straightforward iterative technique is suitable for the renewable energy resources with stochastic nature. The computation burden caused by iterations is also generally low due to the limited number of generators in RAPS systems. Hence, the introduction of iteration based reliability estimation technique and the capacity value in RAPS system provides a cost-effective solution for system planning. Moreover, in order to improve the power supply reliability in RAPS systems,
energy storage systems are commonly used to improve the time coordination between generation and load demand. In this research, the impact of energy storage system on improving the system reliability was also studied using an iterative approach, and the contribution to the capacity value of renewable energy resources is also investigated. A summary of the objectives and contributions of this thesis is presented in Figure 1-1.

Figure 1-1 Objectives and contributions of the thesis.

1.3 Thesis Layout

The remainder of this thesis is organised as follows.

Chapter 2 – A comprehensive literature review was carried out to summarise the research work conducted on RAPS systems. The review mainly discusses on the research progress of planning and operation of RAPS systems. The corresponding technical challenges were also highlighted in the chapter. This chapter formulated research objectives and methodologies for the following chapters.

Chapter 3 – The capacity value of the renewable energy resources in a RAPS system was evaluated. Iterative method assesses the balance between the generation and load demand, and thus reliability level of power supply. Ultimately, the capacity value of the
generation resources can be determined. The implementation of the energy storage system significantly improves the system reliability. The study provides a meaningful approach for the sizing of the generator and energy storage devices in RAPS systems.

Chapter 4 – Kinetic energy stored in the rotating mass of WECS is investigated in this chapter as a primary source to provide primary frequency response for the RAPS system. The strategy is based on droop mechanism and adapts to the WECS by taking the characteristics of the WECS into consideration. A supplementary control was added to the controller to enhance the frequency response provided by the WECS. Mechanical power reserving strategy, SOPPT, was also elaborated in this chapter. The control strategy was validated on a DFIG using simulations.

Chapter 5 – A hybrid RAPS system including solar-PV and DG was investigated in this chapter. The multimode control strategies realise the autonomy of the RAPS system. Solar-PV system and DG swap their role in frequency regulation and voltage regulation depending on the availability of solar energy in the RAPS system. The SOPPT strategy plays a significant role in frequency regulation provided by the solar-PV.

Chapter 6 – UCs are integrated into a PMSG for the purpose of frequency response. The energy stored in the UCs serves as the energy source for the short-term frequency responses. Hence, the PMSG is freed from fast power change and electrical/mechanical torque stresses. The power reserve established by SOPPT is utilised for maintaining the SOC of the UCs in this application. Simulation study and laboratory tests are carried out to verify the effectiveness of the control strategy.

Chapter 7 – A hybrid energy storage system consisting of UCs and LABs improves the frequency regulation performance of a PMSG. The hybrid energy storage system is capable of providing both short-term and long-term frequency response. Moreover, the mechanical power reserve obtained using the SOPPT strategy provides another energy source for long-term frequency response. Hence, a multilevel energy storage system is established to manipulate RAPS system frequency. The UCs and LABs are responsible for fast changing and slow changing power demand respectively in order to extend the lifetime of the LABs. Enhanced primary frequency response control is also achieved by the hybrid energy storage system. Simulations and practical results supported the analysis.
Chapter 8 – The thermal heating problem of the RSC was demonstrated when a DFIG is operating around synchronous speed. A deadband control strategy was recommended to avoid the high fluctuations in junction temperature of the RSC. The strategy operates the DFIG as an induction generator (IG) around synchronous speed using the existing crowbar system of the DFIG. The approach can extend the service life of the RSC and improve the reliability of the WECS. Based on simulation studies, practical test rig was also setup to observe the transitions between IG mode and DFIG mode.

Chapter 9 – Conclusions of this thesis and some recommendations for future research are presented.
Chapter 2

A Review of Technical Challenges in Planning and Operation of Remote Area Power Supply Systems

2.1 Foreword

RAPS systems are becoming increasingly popular as a rural electrification scheme; hence it is a timely requirement to review the planning and operation techniques feasible for RAPS systems. Therefore, the main emphasis of this chapter is to present a review on various planning and operational techniques, such as system architecture, renewable generator sizing and control techniques associated with RAPS systems. Ultimately, this will enable RAPS system designers to choose appropriate techniques to design an economically feasible and reliable RAPS system.

2.2 Overview

RAPS systems are being used for many years to supply power to rural or remote communities where the utility grid is not accessible. In order to avoid the high operating cost and environmental impact caused by conventional generators, renewable energy resources are currently being utilised in RAPS systems. However, the intermittency of such renewable energy resources greatly impacts on planning and operation of RAPS systems. This chapter aims to present a comprehensive review considering the RAPS system planning and operation techniques published in the literature. This chapter summarised different modelling approaches associated with the RAPS system architectures, pre-feasibility studies for energy potential analysis, component modelling, unit size optimisation approaches, and system control aspects. In addition, technical challenges associated with RAPS systems, such as system sizing, voltage and frequency control and coordination of
different system components were also highlighted in this chapter. Moreover, further research avenues with regard to various aspects of RAPS systems were also delineated in the chapter.

The review methodology of the chapter is shown in Figure 2-1. Section 2.3 clarifies common misinterpretations related to RAPS systems considering the characteristics of microgrid systems. Section 2.4 presents a review of different RAPS system architectures and energy resources utilised in the RAPS system as well as RAPS system topologies. The pre-feasibility studies and component modelling techniques for energy management together with associated challenges are presented in Section 2.5 and Section 2.6 respectively. The unit size optimisation techniques and associated technical challenges are summarised in Section 2.7. Section 2.8 outlines the control strategies used in RAPS systems. Conclusions of the review are summarised in Section 2.9.

Figure 2-1 The review methodology for RAPS system planning and operation techniques.
2.3 Background

The RAPS system can be defined as a small electricity network which serves a single property owner with very simple loads or several communities with complex and interconnected power stations [3]. The architecture of a typical RAPS system is presented in Figure 2-2. The system was constructed under the King Island Renewable Energy Integration Project (KIREIP) in Australia [4]. King Island is located in the halfway of the Bass Strait between Victoria and Tasmania and the power system on the island is isolated from the main network of the National Electricity Market (NEM) in Australia. The KIREIP aims provide reliable and stable electricity supply on the island.

Different terminologies have been used in the literature to define RAPS systems, such as ‘standalone power systems’ [5], ‘off-grid power systems’ [6], ‘isolated power systems’
‘electrification power systems’ [8], ‘household power system’ [9], ‘mini-grids’ [10], ‘autonomous power systems’ [11], and in certain cases it is defined as a ‘microgrid’ [6, 12]. The typical feature of a RAPS system is being isolated from the main utility grid. The generators in a RAPS system supply power to a cluster of loads, and the system balances generation and demand autonomously. From this perspective, the terms like ‘standalone power systems’, ‘off-grid power systems’, and ‘isolated power systems’ are used due to the fact that RAPS systems are isolated from the main grid, whereas the term ‘electrification power system’ is used due to the fact that RAPS system is used for the rural electrification schemes. As defined by [13], mini-grids are centralised generation systems to provide electricity to small towns or large villages. Therefore, mini-grid is also another form of a RAPS system with a higher capacity. Similarly, ‘household power system’ is a kind of RAPS system with smaller capacity serving a single residential user. The ‘autonomous power systems’ are also designed for electrification of regions without large transmission networks. Their capacity can be ranging from a few hundred Watts to tens or hundreds of mega-Watts [14]. It can be seen that the definition of autonomous power systems is also similar to that of the RAPS system.

The Consortium for Electric Reliability Technology Solutions (CERTS) explored the potential of generation by locally available smaller distributed energy resources (DER) to meet customers’ needs with the emphasis on reliability and power quality, and developed the concept of ‘microgrid’, i.e., an aggregation of load and micro-sources operating as a single system providing both power and heat and presenting itself to the bulk power system as a single controlled unit [15]. Microgrids can operate in two modes: grid-connected mode, and islanded mode. Contrarily, RAPS systems always operate in standalone mode and do not inject or absorb any energy from the utility grid. Additionally, energy storage devices are commonly used in both microgrid and the RAPS system to mitigate the impact of fluctuation of non-dispatchable energy resources and improve system reliability, and utility grid can also be regarded as a storage system with an infinite capacity. Hence, storage devices may have relatively smaller capacity compared to the RAPS system of comparable size [16]. In microgrids, advanced communication infrastructures are usually applied to realise centralised control schemes [17, 18], which can be costly and impractical for RAPS systems considering the budget limitation as well as geographical constraints. As the microgrids are connected to the utility grid, certain power quality requirements such as voltage, frequency and harmonic emission must be maintained according
to the utility grid codes at the point of common coupling (PCC). However, RAPS systems are not obliged to maintain such rigorous grid-codes [16, 19]. Moreover, voltage and frequency at the PCC are commonly used as the reference for the microgrid, whereas a RAPS system has to establish its own voltage and frequency references. Therefore, it is inappropriate to use the same terminology to represent both the RAPS system and the microgrid. The aforementioned differences between microgrids and RAPS systems are summarised in Table 2-1.

Table 2-1 Comparison between RAPS systems and microgrids

<table>
<thead>
<tr>
<th>Items</th>
<th>Microgrids</th>
<th>RAPS Systems</th>
</tr>
</thead>
<tbody>
<tr>
<td>Utility Grid Availability</td>
<td>Yes</td>
<td>No</td>
</tr>
<tr>
<td>Energy Storage Devices</td>
<td>Storage systems and grid</td>
<td>Storage systems</td>
</tr>
<tr>
<td>Communication Infrastructure</td>
<td>Costly advanced techniques</td>
<td>No or normal tech-</td>
</tr>
<tr>
<td></td>
<td></td>
<td>niques</td>
</tr>
<tr>
<td>Performance Requirement</td>
<td>Specific utility grid standards</td>
<td>Flexible</td>
</tr>
<tr>
<td>Voltage and Frequency Reference</td>
<td>Yield from PCC</td>
<td>Self-established</td>
</tr>
</tbody>
</table>

Nevertheless, microgrids and RAPS systems share some similarities. For example, in microgrids and RAPS systems, both conventional energy resources and renewable energy resources with smaller capacity are utilised. Energy resources are located in close proximity to the end-user and system voltages are at the low voltage level, so tie-lines are usually resistive rather than inductive as in the high voltage systems [20]. Therefore, some control strategies used in islanded microgrids can be readily applicable to RAPS systems and vice versa.
2.4 Technical Challenges on RAPS System Architectures

2.4.1 Energy Resource Utilisation

The RAPS systems can be mainly classified into three groups based on energy resource utilisation: single energy resource based RAPS system (e.g., diesel-only, wind-only, solar-only), hybrid RAPS system (e.g., diesel/wind, wind/hydro, diesel/wind/solar, etc.), and RAPS system with storage system. The main advantage of the DGs based RAPS system is that it is highly reliable compared to renewable only based RAPS system. However, the following disadvantages defy its further expansion.

- Operating cost is very high due to the high fuel cost. The transportation cost of diesel also increases the generation cost.
- The operating efficiency of DGs can be very low. A DG indicates the highest efficiency when the engine is loaded at around 70-80% of its rated capacity, and if the load is less than the half the rated capacity, then the generator will operate in an inefficient manner [21, 22]. Therefore, if the DGs are lightly loaded it will result in a very poor efficiency. Usually, the load in a RAPS system fluctuates frequently and the power factor can be very low. Installing generators of different rated capacities to operate under different load conditions increases loading level, but the generation costs will be high.
- DGs cause environmental problems, for example, noise, greenhouse gas emission, etc.

Therefore, diesel-only RAPS system is not considered to be a favourable choice and renewable energy resources, like wind, solar, hydro, etc. are currently being used in RAPS systems. However, a RAPS system with single renewable energy resource is not reliable due to the intermittency and variability of the renewable energy source. By combining renewable energy resources with diesel, the fuel consumption can be decreased due to the peak-shaving capability of renewable energy resources, and hence power output can also be smoothened. Nevertheless, the renewable energy resources are usually interfaced to the grid through inverters, which challenges the coordination with the conventional generator with inherent inertia [23]. This challenge is also discussed in Section 2.8. Hybrid system with the wind and solar energy can make use of the complimentary characteristics of the wind and solar energy to improve energy supply continuity and overall system
efficiency, but the integration of two non-dispatchable energy resources further complicates the coordination process. Storage system acts as an energy buffer, storing surplus energy when generation is more than the load demand and releasing energy when load demand exceeds generation. The imbalance between generation and load demand can be significantly mitigated and system reliability can be improved dramatically [24]. Popular storage devices are LABs, UCs, flywheels, hydrogen, compressed air storage systems, etc. Storage devices add to RAPS system capital investment, and O&M cost. Furthermore, complicated control strategy should be developed to protect the storage devices from damage and extend the life time of storage [25].

2.4.2 RAPS System Topology

AC generator like DG and WECS can either serve AC loads directly or convert AC power to DC power. Similarly, DC generator like solar-PV and fuel cells can either supply power to DC loads or invert DC power to AC power. Storage devices can be charged by DC generator directly or through converters. Hence, different RAPS system topology patterns can be developed: common AC-bus RAPS system, common DC-bus RAPS system, and hybrid-bus (i.e., combination of AC-bus and DC-bus) RAPS system. The different RAPS system topologies are illustrated in Figure 2-3.

In a common AC-bus RAPS system [26] as shown in Figure 2-3(a), both the AC generator and DC generator are connected to the common AC bus. Therefore, inverters are used at the DC generator. The AC load absorbs energy from the AC bus and the DC load absorbs energy from the AC bus through converters. If the storage system is installed in the system, it absorbs or injects power to achieve power balance between generation and load demand through bidirectional converters. Common DC-bus configuration is also widely being used in RAPS systems [5]. This RAPS system scheme is also referred as a
series system in [21]. As shown in Figure 2-3(b), all the generated AC power is converted to the DC and subsequently converted to the AC to supply power to AC load. DC load and storage are connected to the DC bus. A Hybrid-bus RAPS system is shown in Figure 2-3(c), which is a combination of common AC-bus scheme and common DC-bus scheme. A comparison between three RAPS system topologies schemes considering the power conversion processing details is presented in Table 2-2. Table 2-2 is formed based on the power conversion procedures that a type of generator (i.e., AC generator or DC generator) should go through to serve a particular type of load (i.e., AC load or DC load). An exception is an energy storage system which can be regarded as either generator or load since storage systems can absorb or release energy.

<table>
<thead>
<tr>
<th>Load Generator</th>
<th>AC Load</th>
<th>DC Load</th>
<th>Storage</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>A</td>
<td>B</td>
<td>C</td>
</tr>
<tr>
<td>AC Generator</td>
<td>-</td>
<td>Δ◊</td>
<td>-</td>
</tr>
<tr>
<td>DC Generator</td>
<td>Δ</td>
<td>○Δ</td>
<td>○Δ</td>
</tr>
<tr>
<td>Storage</td>
<td>Δ</td>
<td>Δ</td>
<td>Δ</td>
</tr>
</tbody>
</table>

A, B, and C refers to common AC-bus scheme, common DC-bus scheme, and hybrid-bus scheme respectively.

“○” - DC to DC conversion; “Δ” - DC to AC conversion; “◊” - AC to DC conversion; “-” - No conversion process; “\” - Not applicable.

From Table 2-2, it can be seen that power produced by the AC generator is supplied to AC directly in both common AC-bus scheme and hybrid-bus scheme whereas two conversion stages should be practised in common DC-bus scheme. The AC/DC conversion is required in three schemes for providing energy to DC load and storage system from the AC generator. Hence, it can be concluded that, as far as efficiency is concerned, the AC generator has better performance in serving the AC load in common AC-bus scheme than the AC generator in common DC-bus scheme [27]. Hybrid-bus scheme has similar performance with common AC-bus scheme with regard to the AC generator. However, the storage system efficiency in powering the DC load is the lowest among the three schemes as two power conversion processes are required, whereas there is no need to convert power in other two schemes. This also applies to the DC generator in serving the DC load.
and storage, since an extra conversion stage should exist in common AC-bus scheme. Nevertheless, the DC to DC conversion stage can be eliminated for common AC-bus scheme as compared to the other two schemes in providing power to the AC load. Therefore, there is no easy way to draw the conclusion about a single scheme which is the best. The energy resources availability, load variability and storage system capacity are considered to maximise the system efficiency. Furthermore, system operating reliability also affects the decision and complicates the planning procedure. For example, the reliability of serving the DC load largely depends on the converter connecting the AC bus to the DC load in common AC-bus scheme. Such single point of failure also exists where AC load is connected to the DC bus in common DC-bus scheme. Although the hybrid-bus scheme has higher overall operating efficiency as discussed in this section, it eliminates the single point of failure by the application of two buses. Moreover, the interconnecting bidirectional converter between the two buses is heavily burdened, and control of the converter becomes more complex.

2.5 Technical Challenges on Pre-feasibility Study

The pre-feasibility study is typically conducted to assess the potential of the generation to meet the load demand, and to assist in determining the component size. The pre-feasibility study is considered to be the first step for implementing an energy project [28]. Energy resources have different characteristics and their coordination in a RAPS system determines the performance and operating cost of a RAPS system. With conventional generators it is easy to estimate their power output which generally depends on the fuel consumption. However, some renewable energy resources, such as solar and wind energy, are weather dependent and their power output varies with the meteorological condition. Therefore, it is a challenging task to estimate power output from renewable energy resources. Generally, meteorological profiles are obtained to estimate the power production along with power characteristic of generators. As with weather dependent renewable energy generation, load demand profiles are also of high uncertainty. Usually, meteorological profiles and load profiles are generated in two approaches: chronological approach and stochastic approach, which are discussed below.
2.5.1 Chronological Approach

In chronological approach, the meteorological profiles and load demand profiles are considered to be deterministic quantities and their variation with respect to time is determined with either historical data or synthesised data. In order to achieve high estimation accuracy, data sources like local meteorological stations or experimental measurements are typically being used. In [7, 8, 29-31], the hourly solar radiation data for the whole year was measured at the site. Wind speed data in [7, 30-32] was also obtained with the anemometers installed at the site. In order to yield a more accurate estimation of the power output from a solar-PV system, ambient temperature may also be taken into consideration; so temperature profile is also obtained during the measurement campaign [31].

There are some sites where complete records of meteorological data or load data are not available, the generation of profiles becomes a challenge. Three methods are commonly seen in literature to address this problem. Firstly, the authors in [22] use the wind profile of a neighbouring community as the wind profile at the site, which is also an acceptable option as recommended in [7]. Secondly, obtaining global meteorological data from the internet might be another option [7]. Thirdly, incomplete data sets can be used to synthesise profiles using statistical algorithms and the selection of synthesising algorithms is also variable. Some optimisation tools have synthesising algorithms to generate profiles, such as HOMER (Hybrid Optimisation Model for Electric Renewables). The HOMER was developed by the US National Renewable Energy Laboratory which can synthesise solar radiation values for each of the 8760 hours of a year by using the Graham algorithm [9]. In [29] the hourly load data was measured in a whole week and then average load profiles were obtained. In [9, 32], load profiles were generated by synthesising the load data in a typical day and then adding some randomness. For load profile studied in [31], it is produced by down-scaling an actual annual load profile of a larger RAPS system. In [9, 33], HOMER has been used to synthesise annual hourly solar radiation and wind speed profiles based on the monthly solar data and wind speed data obtained from National Aeronautics and Space Administration (NASA). In [34], a load profile in a village was studied by interpolating and averaging a 24-hour summer load profile and a 24-hour winter load profile over a one-year period; then a second-order polynomial function is fitted to the daily profile. Similarly, solar insolation data for a village is fitted by a third-order polynomial function to obtain daily profiles.
A chronological approach is theoretically straightforward and simple to implement for reliability or cost analysis in the feasibility study. However, the representation of future climate condition and load demand with historical data may inherently cause an error in planning since climatic conditions and load profiles vary from year to year. Accurate estimation of the error is beneficial but difficult to achieve and the compromise in estimating accuracy raises another topic, i.e., the determination of sizing margin in planning.

2.5.2 Stochastic Approach

Using a stochastic approach, the availability of primary energy resources and load demand are considered as random variables; however, certain theories can estimate the probability of specific energy potential and load demand at a particular time instance. For example, the wind speed probability density functions (PDF) describe the frequency of occurrence of wind speeds at a particular site, that is, the likelihood that certain wind speed will occur at a particular time instance. Some characteristic parameters have to be assigned to those functions to match with the actual site conditions. Weibull PDF has been widely applied in WECSs with the following form [35-37]:

\[
p(V_w) = \frac{k}{c} \left( \frac{V_w}{c} \right)^{k-1} \exp \left[ - \left( \frac{V_w}{c} \right)^k \right]
\]

where \(p(V_w)\) is the probability for a particular wind speed \(V_w\) at the site. \(k\) is called the shape parameter, and \(c\) is referred to as the scale parameter. A special case of Weibull PDF is named as Rayleigh PDF when the shape parameter is equal to two. It must be noted that the Weibull PDF is unable to represent all the wind structures encountered in nature. One main limitation of the conventional Weibull PDF is that it does not accurately model calm winds and those with bimodal or even multimodal distributions resulting from special climatic conditions [38]. Other PDFs are developed to accommodate more situations, such as truncated normal distribution[38], Gamma PDF[39], etc. Some mixture functions are also built to meet special cases where the single function is not suitable for simulating the actual wind speed [38, 40]. Similarly, PDF is also used to model solar irradiance distribution. Beta distribution is popular in literature [35-37, 41].

\[
f(r) = \frac{\Gamma(\alpha + \beta)}{\Gamma(\alpha) \cdot \Gamma(\beta)} \cdot \left( \frac{R}{R_{\text{max}}} \right)^{\alpha-1} \cdot \left( 1 - \frac{R}{R_{\text{max}}} \right)^{\beta-1}
\]
where $R$ and $R_{\text{max}}$ (W/m$^2$) are the actual and maximum solar radiance respectively, $\alpha$ and $\beta$ are the shape parameters of the distribution, and $\Gamma$ is the Gamma function shown in (2-3).

$$\Gamma(x) = \int_0^\infty t^{x-1} \cdot \exp(-t) \, dt.$$  \hspace{1cm} (2-3)

In [7], the normal distribution is used to estimate the availability of solar irradiance. Solar irradiance distribution can also be approximated by superposition of two distribution functions. For example, it can be derived choosing two functions from normal, beta or Weibull distributions [42]. As for the load distribution, the simplest method assumes the load to be uniformly distributed between lowest load demand and highest load demand [41]. In [43, 44], the peak load demand is assumed to follow a probabilistic normal distribution. The approach suggested in [37, 44] arranges loads during a timeframe in descending order to form a cumulative load model which is known as load duration curve. The probability of load level $\gamma$ during the time frame is given by (2-4) [35].

$$f(\gamma) = \frac{\text{number of occurrences of load level } \gamma}{\text{total number of load points during the time frame}}$$  \hspace{1cm} (2-4)

The challenges embedded in stochastic approach are multi folds:

- The PDFs of energy resources and load forecasting are varied from site to site, and these PDFs are determined based on the historical data. These data may not be available for the particular site, and the fitting of the data to a PDF may not be perfect which necessitates the error control.

- With the stochastic approach, the correlation between energy resource profiles as well as load profiles is usually ignored. The approach treats these profiles separately. In fact, wind speed and solar irradiance may have complementary characteristics and load can also be highly correlated with energy resources. Therefore, by considering the correlation among these profiles improves the calculation; however it is a challenging task.

- In a realistic model, wind speed, solar irradiance or load in a particular moment should not be independent of the values in previous moment. Taking the independence between adjacent time intervals into consideration significantly complicates the profile generation.
Deterministic and probabilistic approaches are two common strategies for feasibility study [7]. A deterministic approach is usually based on the profiles generated by the chronological approach, which is implemented in an iterative way and intensifies computational burden. Additionally, the study with the chronological approach is not transparent, since the impact of characteristics of energy resources and the load is not easy to be observed. On the contrast, the probabilistic strategy is based on profiles determined by the stochastic approach, which provides more transparency. However, in a RAPS system with climate dependent energy resources and variable loads, the number of possible generation-demand scenarios can be enormous, which deteriorates the effectiveness of this strategy. When the energy storage system is mounted, or system device failure is considered, the probabilistic strategy is even harder to implement. Therefore, development of a proper method which simplifies the analysis while ensuring reasonable accuracy remains a challenging task.

2.6 Energy Conversion Modelling

A RAPS system mainly consists of generators, loads, storage systems, and power conditioning units. Component models used for feasibility study represent the simple energy conversion processes from energy resources to electrical power. Solar generation, wind generation, diesel generation, and battery storage models are briefly discussed as follows.

2.6.1 Modelling Solar Generation

The available solar power on a PV array can be determined using [28]

\[ P_{PV} = P_{PVr} \cdot D_{PV} \cdot R_T \]  

(2-5)

where \( P_{PV} \) is the power output of a PV array, \( P_{PVr} \) is the rated capacity of a PV array, \( D_{PV} \) is the de-rating factor, and \( R_T \) is the total solar radiation on the surface of the PV array. The rated capacity of a PV array is the power produced when the solar radiation is 1 kW/m\(^2\) and cell temperature is 25 °C. The de-rating factor is a factor which is used to scale down the ideal output of the PV array due to any other causes such as dust, wire losses and an elevated temperature.
2.6.2 Modelling Wind Generation

In a RAPS system, only a few WECSs are used in comparison to a wind farm. Therefore, power output from wind generation can be estimated considering only one single generator and the impact of other WECSs can be ignored. The specification provided by the wind turbine manufacturer describes the relationship between wind speed and power output of wind generator and the relationship is commonly presented as a power curve [45]. A WECS has a cut-in wind speed at which the generator starts to generate power and a cut-off wind speed beyond which the generator is shut down for safety. Between the cut-in wind speed and the cut-off wind speed, the wind generator power output varies and spline interpolation functions are used to fit those discrete wind speeds and corresponding power output of the generator as specified by the wind turbine manufactures. Hence, the power output of the generator at any wind speed can be determined. The simplest model is a linear model [45]. However, quadratic equations can be used to fit each section of the power curve for high fitting accuracy [46]. A model based on the Weibull parameters can be found in [47] where Weibull shape parameter is incorporated to the fitting function. The quadratic model is a special case of the Weibull model, in which the shape parameter is two [48].

2.6.3 Modelling Diesel Generation

For a single DG, the fuel consumption can be determined by [49]

\[ F_{DG} = a \cdot P_{DGr} + b \cdot P_{DG} \] (2-6)

where \( P_{DGr} \) is the rated power, \( P_{DG} \) is the actual power output. \( a \) and \( b \) are the coefficient of the fuel curve defined by the user. When biodiesel is used instead of diesel, fuel consumption is increased [31]. If only two operating modes are considered: rated operation and offline, then power output of the generator is \( P_{DGr} \) and zero respectively. The forced outage rate (FOR) is used to estimate the failure and repair frequency (offline probability) of the DG [50].

2.6.4 Modelling Energy Storage System

Storage system is an essential component in RAPS systems to ensure continuous power supply. Although many storage devices are available, such as supercapacitors, flywheels, and compressed hydrogen storage systems, batteries are still very popular due to their low
cost and high energy density. SOC is the key index to indicate the battery capacity, and the SOC at the time $t$ is given as [51]

$$SOC(t) = SOC(t - \Delta t) \cdot (1 - \delta) \pm \frac{I_c(t) \cdot \Delta t \cdot \eta_c}{E}$$

(2-7)

where $\delta$ is the self-discharging coefficient, $I_c$ is the charging or discharging current, $E$ is the nominal battery capacity and $\eta_c$ is the battery charging efficiency which is taken as one during the discharging process. A positive sign in the equation represents battery charging process while negative sign represents the discharging process. Capacity curve and lifetime curve are another two characteristics curves used for batteries. The capacity curve demonstrates the battery capacity in ampere-hours as a function of the constant current discharging rate in amperes, whereas lifetime curve represents the number of cycles a battery can stand as a function of depth of discharge in each cycle [52].

In fact, all previously discussed models are approximate models. When accuracy is of priority, it is a great challenge to model the generator as well as storage system; hence more sophisticated models should be developed to accommodate that task. For example, when taking the impact of cell temperature into consideration, the power produced by the PV array is determined by [31]:

$$P_{pv} = P_{pvr} \cdot D_{pv} \cdot R_T \cdot \left[1 + (T_{pv} - 25) \cdot k_T\right]$$

(2-8)

where $k_T$ is the PV temperature coefficient and $T_{pv}$ is the temperature of PV cells. $T_{pv}$ can be estimated using (2-9).

$$T_{pv} = T_a + \frac{NOCT - 20}{0.8} \cdot R_T$$

(2-9)

where $NOCT$ is the normal operating cell temperature usually valued at 48 °C and $T_a$ is the ambient temperature. If other factors such as shading and ventilation effects are non-negligible, the PV modelling complicates the process significantly.

Although the power output of WECSs can be estimated based on models mentioned in Section 2.6.2, the power curve can only provide the power output as a function of average wind speed. Thus the instantaneous wind speed variations are ignored, which will affect the accuracy of the estimation. In [53] the power curve is modified to address this problem by considering both wind dynamics and the capability of capturing extra energy from a WECS. Other challenges like temperature and pressure corrections, unevenly distributed
wind speed across the blade sweeping area, and tower spacing effect in the wind farm are also required to be considered when improving the modelling accuracy.

2.7 Technical Challenges on Unit Size Optimisation

Under certain energy resources profiles and load demand profiles, the size of the system components can be determined with proper modelling of the system components.

The objective is to ensure power supply continuity while minimising generation cost.

2.7.1 Criteria for Unit Size Optimisation

Through the aforementioned pre-feasibility and system component modelling studies, the energy generation and load demand can be estimated. The capacity of the system components affects the power supply continuity directly. The particular standard should be set to choose proper capacity for the components and meet end user’s requirement. Power supply reliability and generation cost are two basic criteria used for RAPS system unit sizing. Reliability denotes the probability of generation to satisfy the load demand whereas the generation cost relates to capital investment, O&M cost, and environmental cost. In practice, unit sizing is subjected to some technical constraints as well.

2.7.1.1 Reliability Estimation Techniques

Different metrics are being used to determine the RAPS system reliability. The loss of load expectation (LOLE) and loss of energy expectation (LOEE) are two commonly used parameters to estimate reliability in power systems [54]. The LOLE is the average number of hours for which the load is expected to exceed the available capacity while the LOEE is defined as the expected energy that will not be supplied when the load exceeds the available generation. Capacity value can be denoted as effective load carrying capability (ELCC). The LOLE and LOEE are calculated by evaluating reliability with regard to the ELCC, which is demonstrated in [35, 55]. Contrarily, loss of load frequency (LOLF) may provide unmatched values even the same generation and load profiles are analysed. As suggested in [55], LOLF can be affected by the hour-to-hour variations in wind speed.

2.7.1.2 Cost Estimation Techniques

Various economic indicators are proposed in the literature to study the economic feasibility of RAPS systems. The cost of energy is the ratio of summation of annualised capital cost and O&M cost to the amount of energy delivered [7]. The levelised cost of energy is
defined as the total cost of the whole hybrid system divided by the energy supplied from the hybrid system [51]. The life cycle cost is used in [6] which is comprised of capital cost, O&M cost, replacement cost, and fuel cost. The simple payback time is used in [34] to study the economic feasibility of integrating PV arrays into a diesel-battery RAPS system, and it is defined as the ratio of extra cost of the PV system and fuel savings made in a year. Unlike most of the literature related to the RAPS system economic analysis, a dynamic method is introduced in [56] taking into account the time component in evaluating the investment. Environmental cost can also be taken into consideration. The avoided cost, which is defined as the ratio of cost of energy savings and reduced emissions, is used to denote environmental cost [34] while external costs representing estimations of the effects on both health and the degradation of the environment due to polluting emissions [6].

2.7.1.3 Constraints for Unit Size Optimisation

A number of constraints must be considered for unit size optimisation aiming for a technically feasible and cost-effective RAPS system. The available energy is limited due to the energy resource potential of a given site. In order to have a prolong battery life, charging and discharging current should be below its upper limit. DGs are expected to be operating under proper loading level in order to avoid low efficiency. Budget limit is another crucial consideration. Assuming a battery with an initial zero state, the final stored energy level should not be negative at the end of the time horizon [7]. In [57], with the aim of minimising the system total cost, the balance between the generation and the load demand, the battery SOC limits, as well as the nominal capacities of PV arrays, are considered as constraints in the optimisation algorithm. Some constraints are presented in [31], which include initial cost, the unmet load, capacity shortage, fuel consumption, renewable fraction and components' size. The operating reserve, which is defined as the operating capacity minus the electrical load, is used as the safety margin for a RAPS system in unit size optimisation algorithm presented in [28]. In [58], carbon dioxide emission is also regarded as one of the constraints.

2.7.2 Unit Size Optimisation Strategies

RAPS system unit sizing combines all the methodologies discussed in previous sections. Determining the optimal configuration for a RAPS system from a large number of feasible options can be a very challenging task for following reasons:
Unit size optimisation is a multi-objective topic. Various factors as discussed in previous sections should be taken into consideration and the presentation of each factor can be a quite complicated task.

Reliability and cost criteria usually contradict each other, since a RAPS system of high reliability requires extra investment and vice versa. Therefore, trade-offs between the two criterions are inevitable in unit sizing depending on end-user requirements. The optimal configuration in [6] is selected based on the lowest cost of energy with a specified reliability level. The cost increases dramatically if a high reliability level is expected from the system. The solar-wind optimisation model developed in [50], which determines system configurations that meet the target reliability level, and subsequently the configuration with the lowest levelised cost of energy is considered to be the optimal configuration. In [67], priority is given to offered service rather than production cost, so reliability is highly emphasised.

The design of an optimal RAPS system is heavily site dependent. At the site studied in [29], the wind and solar-PV based RAPS system reduces system cost significantly compared to diesel-only, wind-only, and PV-only configurations due to the complimentary nature of the multiple renewable energy resources. Similarly, among the scenarios studied in [67], hybrid RAPS system with wind, solar-PV and DG is also the best option although the cost of energy is largely dependent on renewable energy potential and quality of supply. Nevertheless, renewable energy of high potential energy output is not necessarily the best option as analysed in [21]. Although wind capacity factor is higher than solar CF due to low cut-in wind speed for small wind turbines, PV system is chosen for its installation simplicity, lower capital and O&M cost. Moreover, RAPS systems are not always the best option for electrification when extending utility grid is feasible considering the distance between the remote area and the main grid, peak electrical load and load factor [68].

Therefore, various optimisation algorithms are proposed in the published literature to optimise the unit size [11, 27, 50, 59]. The optimisation techniques presented in the literature can be classified into two groups: enumeration technique and artificial intelligence techniques.
2.7.2.1 Enumeration Techniques

Enumeration technique searches the optimum solution among different RAPS system configurations. The options are formed by changing the capacities of energy resources and storage systems in an iterative way. The configuration that best satisfies the optimisation criterion is chosen as the optimised configuration. In [51], the optimising procedure for a solar-wind system follows two steps. Firstly, with a particular storage size and reliability target, subsequently configuration with the lowest levelised cost of energy can be determined by changing the number and the orientations of PV modules, and the rated capacity and tower height of the wind turbine. Secondly, a global optimum solution can be obtained by repeating step one with different storage sizes. Similarly, WECS, solar-PV, and battery sizes are determined in an iterative way on the condition of zero-load rejection with the minimum cost in [30], but only several sizes for solar-PV are explored. The optimum RAPS system configuration with minimum initial investment cost is explored from the possible instances by considering load density, load location, generator size and generator location [12]. The authors compare two mathematical formulations which use either integer or binary variables to define the location and size of the equipment while revealing the superiority of integer model [11]. The technique proposed in [46] can narrow the searching space. The minimum size for the solar-PV and wind turbine to meet predesigned reliability level by assuming infinite capacity for batteries is determined first and subsequently maximum battery capacity can be found with the predetermined size of the solar-PV and WECS. Within the narrowed searching space for component sizes, the optimum configuration with the lowest cost of energy is determined using the widely used enumeration technique. The sizing curves and design space introduced by [7] are formed to show all those feasible configurations that satisfy the load reliably, which benefits analysis of the impact of a specific system parameter on unit size optimisation.

Complete enumeration technique is the method applied by HOMER which is widely used for feasibility studies. Enumeration technique is a straightforward. However, the enumeration technique is challenged technically in two ways. One is that it is very computationally intensive as it explores solution iteratively through series of variable parameters and large amount of weather and load data. Actually, it is in fact a kind of trial and error process. To meet the intensive computational burden, costly computing devices are
necessary and computation time can be quite long. The other challenge is that this technique may provide suboptimal solutions or local optimum [31, 58].

2.7.2.2 Artificial Intelligence Technique

Due to those aforementioned demerits related to enumeration techniques, various artificial intelligence (AI) techniques are proposed and become alternatives for unit sizing. AI techniques have the ability to learn from examples, handle noisy and incomplete data, deal with non-linear problems, and perform prediction and generalisation at high speed [59]. Common AI techniques in the literature include genetic algorithms, simulated annealing technique, and artificial neural networks.

*Genetic Algorithms (GA):* GA imitates the process of evolution of a population by selecting only the fittest individuals for reproduction [59]. GA is applied in [58] to determine optimal sizes for WECSs, PV, and DG. Fuzzy-c-mean is employed to identify states from chronological data to establish Markov models, which can greatly reduce the computational time when GA algorithm is used. The GA optimisation tool in MATLAB is used in [60] to size a hybrid PV–wind-diesel-battery RAPS system with the objective of cost minimisation and the condition that load is supplied at all times. Multiple objectives are managed in [61] using GA. A weighting factor is set for each objective in the fitness function to show design priority.

*Simulate Annealing Technique (SA):* SA is based on an analogy to the cooling of heated metals. In physics, annealing refers to the process of heating up a solid to a high temperature followed by slow cooling achieved by decreasing the temperature of the environment in steps [31]. SA is introduced by [62] to a PV–wind hybrid system. The system total cost is minimised through choosing proper PV size, wind turbine rotor swept area and battery capacity using SA, and it is claimed that SA provides a better result than the response surface methodology. An optimisation of a RAPS model consisting of a PV, diesel and battery is solved using SA [63] with the objective of maintaining an optimum trade-off between energy cost and CO₂ emission. SA is capable of escaping from being trapped into a local optimum [31, 62, 63].

*Artificial Neural Network (ANN):* ANN is a mathematical model based on the biological neural network [64]. ANN can be trained by data sets and new data sets can be presented to it for the process without being programmed to perform the task. Hence it is cost effective and convenient. The greatest advantage of the ANN is the capability to model
complex, non-linear processes without having to assume the form of relationship between input and output variables. ANN can address the issues like pattern matching, combinatorial optimisation, data compression, and function optimisation [59]. As for the RAPS system unit sizing optimisation, the ANN is usually combined with other AI to accomplish the task jointly.

AI techniques are also subjected to some technical challenges. For example,

- **AI techniques are much more theoretically complex than enumeration technique.**
- **Limitations also exist for AI techniques.** Although SA excels at gravitating towards the global optimum, it is not especially fast in finding the optimum in a given solution region [31]. In regard to GA, it is not effective when the problem is too large [59]. Similarly, as suggested in there is no guarantee that the ANN model can perform well for a particular problem. To mitigate the disadvantages of an individual AI technique, several AI techniques can be combined to solve an optimisation problem. The hybrid algorithm has the advantage of making use of the merits of each technique. A hybrid heuristic algorithm SA-Tabu search (TS) is introduced. SA provides an initial solution for optimum and TS searches the given neighbourhood to find the optimum. In [61], a linear optimisation method, which converges very fast starting from a precise point, is used to re-optimise the solution obtained by GA. This hybrid approach converges to the global optimum faster than by using only GA. In [65], SA is used as a local search algorithm to prevent GA from converging to a local optimum in determining the minimum COE. The ANN-GA algorithm developed by [66] is verified to be able to generate the sizing curve for a RAPS system, and GA determines weights and/or architecture of the ANN when measured data are not available.

### 2.8 Technical Challenges on RAPS System Control Strategies

RAPS systems are generally expected to supply power continuously to end-users cost-effectively and efficiently. Designing such a RAPS system is far more than the planning process as mentioned in previous sections, and RAPS system control is of paramount importance. Several facts, as discussed below, may account for the RAPS system control difficulties.
• Unlike utility grid to which upper limit of renewable energy resources penetration is usually assigned, the penetration of renewable energy resources in a RAPS system can be as high as hundred percent. The intermittency of the climate dependent energy resources results in fluctuations in power generation. Load can also be highly variable [10]. RAPS systems are more prone to be disturbed by generation fluctuations and sudden load changes. The variation in generation and load requires more robust voltage and frequency regulation, and energy management.

• Various energy resources and energy storage systems are utilised in RAPS systems, such as conventional and non-conventional, rotational and static, renewable and non-renewable sources, etc. The characteristics of different energy resources can be very distinct from each other. Therefore, coordinating all those energy resources in a single RAPS system is not an easy task.

• Nonlinear and single-phase loads occupy a significant portion of the total load and deteriorate the voltage waveforms [67].

• It is impractical to implement high bandwidth communication due to the sparse distribution of DER as well as geographical constraints.

• In low voltage level network such as RAPS systems, large mechanical inertia usually does not present, especially when electronically interfaced generation dominates the system. Moreover, the power line is resistive rather than inductive generally, which may make some control theory widely used in utility grid invalid in RAPS system.

Nevertheless, as mentioned in Section 2.3, RAPS system shares similar control strategies with islanded microgrids, the control strategies be roughly classified into two layers: component-level control and the system-level control [68].

2.8.1 Component-Level Control Strategies

A RAPS system is mainly composed of generators, storage devices, load and converters as can be seen from RAPS architectures shown in Section 2.4. Nonconventional generators like microturbine, solar-PV and fuel cells, and energy storage devices like battery and flywheel are interconnected to the system through converters. The converters play a major role in interfacing various energy resources to the RAPS system. Hence, component-level control strategies are mainly implemented at the converter. According to [69], the control objectives of converters can be grid-forming, grid-feeding, or grid-supporting.
2.8.1.1 Grid-Forming Control

When a generator is connected to the utility grid, the utility grid can be regarded as an infinite bus, and voltage and frequency reference can be obtained from the PCC. However, in a RAPS system, no such bus exists. Hence, voltage and frequency reference must be generated internally. If a DG is installed, it can provide the voltage and frequency reference [10]. Otherwise, the converter is responsible for establishing voltage and frequency references for the system and holds system voltage and frequency constant. The master/slave control technique for inverters operating in parallel is such an example [70]. The master converter maintains a constant sinusoidal wave output voltage and generates proper current commands for the slave converters. PMSG is the only generator in the RAPS system introduced in [71]; so the interface inverter controls the system voltage and frequency under varying wind speed and load condition, and the maximum power point tracking (MPPT) strategy is implemented by the generator side DC to DC switch-mode converter. A control strategy is presented in [72], for a RAPS system with a DFIG. In order to maintain the system frequency and voltage under contingencies, the grid-forming generators should have sufficient capacity in case of disturbances. However, the challenge is, in RAPS systems, the generators have comparable capacities and there is usually no generator of dominant capacity.

2.8.1.2 Grid-Feeding Control

Grid-feeding control is also referring to grid-following control as defined in [68]. Grid-feeding converters are typically controlled as current sources to export predefined active and reactive power. Nevertheless, the output of the renewable energy resources in a RAPS system can be intermittent, and these energy resources are not dispatchable, which makes grid-feeding control difficult unless storage devices are connected with such energy resources or accurate power estimation technique is implemented. Although grid-feeding converters do not participate in the frequency and voltage control directly as grid-forming converters, they are capable to control voltage magnitude and frequency through active/reactive power control. Grid-feeding converters obtain voltage and frequency reference from the system and act as a current source. Current regulation is mainly based on either the $d$-$q$ synchronous reference frame or stationary reference frame [69]. The $d$-$q$ synchronous reference frame current regulation approach transforms AC signals to DC quantities, which makes it simple to control using proportional-integral (PI) controller. In
The $d$-$q$ synchronous frame was adopted to control a single-phase inverter by constructing the second phase by shifting 90 degrees with respect to the single-phase signal. A stationary reference frame current regulator is proposed in [74]. The regulator overcomes the normal stationary frame regulator’s steady-state error which occurs as a result of the PI controller.

2.8.1.3 Grid-Supporting Control

Grid-supporting converters can regulate the system frequency and voltage by adjusting the active and reactive power delivered to the system. Other auxiliary functions may also include balancing unbalanced load condition and mitigating of harmonics. A static synchronous compensator (STATCOM) is installed at the terminal of a self-excited induction generator (SEIG) to meet reactive load demand [75] in a petroleum extraction application. The STATCOM not only maintains the SEIG terminal voltage constant, but it will also balance the generating system under unbalanced loading conditions and filter the harmonics emitted by system loads.

2.8.2 System-Level Control Strategies

In the utility grid, system-level control accounts for load and generation forecasting, unit commitment, economic dispatch, and security constraints [68]. In a RAPS system, system-level control performs similarly and has its own features as well. It is impossible for a RAPS system to ensure proper operation without the global knowledge of the system due to following reasons:

- Energy resources have different characteristics.
- Power output fluctuates due to weather dependent nature of the renewable energy generator.
- Minimum fuel cost and maximum renewable energy penetration are targeted.
- Energy storage devices are adopted and lay some constraints for control.
- Environmental impact is also considered.

Therefore, coordinated control strategies are required for the RAPS system components to operate in a cooperative and efficient manner. Furthermore, system level control strategies in the published literature can be classified into centralised and decentralised control strategies [55, 73-75].
2.8.2.1 Centralised Control Strategies

Centralised control strategies operate based on communication facilities to enable the communication between the control centre and local controllers. Local controllers send information on operating conditions, such as the power output from the generators, voltage and frequency deviations, load demand estimations and charging status of storage systems, to the control centre. Control centre collects the information and makes optimising decisions on system power flow, and then it assigns set points for the components in the system. The optimal objectives of centralised control can be system stability, minimisation of operating cost, life extension for system equipment, and the impact on the environment.

The supervisory predictive control strategy developed in [25] for a wind/solar RAPS system computes the power references for the wind and solar subsystems while minimising the operating cost. Local controllers control generators to deliver active and reactive power as specified by the central controller. Practical issues like extending equipment lifetime by reducing inrush or surge currents are considered for the optimal control. The optimal operation method suggested in [76] diverts short-term charging/discharging events induced by PV and load fluctuations to the upper band of the battery SOC regime along with the operation of fuel cells and electrolyser. Hence, the impact on battery life can be reduced while reducing the operating cost.

In a RAPS system, demand side management is also an important part of centralised control, and the control strategy can be implemented at the customer load, dump load, and storage devices. A load shedding strategy is introduced by [77] to maintain the stability of the wind-diesel RAPS system. The strategy determines the load to be shed at each stage using the under frequency relay, and the load shedding is minimised using GA. Penalty functions and chromosomes with varying lengths are utilised in the GA to determine the optimal number of loads to be shed at all stages. In [78], the load is divided into steps according to their priorities, and wind speed is also divided into different levels; subsequently each load step can be supplied by the WECS when wind speed varies between two predefined wind speed levels. With this load control strategy, energy storage devices are not necessary for the RAPS system. If energy storage device is installed, then the surplus energy is usually absorbed by the energy storage system when the generation is more than the load demand. However, if the storage devices are full, then the extra energy should be consumed by other means, since overcharging of storage devices like
LABs will harm the storage devices. Dump load such as space heating is commonly used in RAPS systems for energy balancing purposes [72]. A dump load power control strategy is introduced by [5] in order to eliminate the actual dump load and to prevent battery overcharging, hence, the lifetime of the batteries can be extended and system cost can be reduced.

Notable challenges for centralised control lay in the single point of failure and communication. The entire system is controlled by the central controller. On the one hand, if the controller fails, the whole system collapse and system reliability level decreases. On the contrary, effective centralised control demands high-speed communication among components. The high bandwidth communication links require extra investment and adversely impact on the RAPS system budget. Additionally, complex communication techniques may be infeasible in some occasions when severe natural situations deteriorate its effectiveness.

2.8.2.2 Decentralised Control Strategies

On the contrast with a centralised control strategy, decentralised control strategy does not need a control centre to determine an optimising decision. The components in a RAPS system with decentralised control make their own intelligent decision by communicating with each other using inherent communication channels. Following discusses the technical challenges on droop control strategy and multi-agent control strategy.

Droop Control Strategy

The most widely adopted strategy to ensure real and reactive power sharing among generators without communication infrastructure is the droop control strategy. The system frequency and voltage magnitude are maintained in accordance with the active and reactive power deviation from the pre-specified requirement. For conventional generators, the active power \( P \) output mainly depends on the power angle or the frequency whereas the reactive power \( Q \) is mainly determined by the voltage magnitude. Therefore, the conventional frequency droop and voltage droop have the following form [79].

\[
\begin{align*}
    f &= f_n - k_p \cdot (P - P_r) \quad (2-10) \\
    U &= U_n - k_q \cdot (Q - Q_r) \quad (2-11)
\end{align*}
\]
where $f_n$ and $U_n$ are the nominal frequency and voltage respectively, $f$ and $U$ are the actual frequency and voltage respectively. $S = \sqrt{P_r^2 + Q_r^2}$ is the rated capacity of the generator, and $k_p$ and $k_q$ are the frequency droop and voltage droop constants respectively. Several technical challenges are common for droop control strategy.

- **Frequency and Voltage Deviation:** With droop control, system frequency and voltage magnitude will generally vary with the fluctuation of load demand. However, the deviations of frequency and voltage are expected to be within acceptable limits. Regulating techniques are required to satisfy the requirement. In [80], frequency droop is applied for real power management in an islanded microgrid. The system frequency deviation can be minimised by adjusting frequency droop characteristic, and frequency restoration technique is also integrated into the real power controller. A recent work presented in [81] proposes the arctan droop control which ensures the operational frequency is always within preset bounds.

- **Impact of Line Impedance:** Line impedance unbalance may degrade the load sharing accuracy, although the authors in [79] claim that the impact is not necessarily a disadvantage since the generators that are located electrically far from the load centres automatically deliver a lower share of power with $P/V$ droop control, and thus line losses can be reduced in a resistive RAPS system. Due to the resistive nature of the line impedance in low voltage network, another form of droop controllers may be used in such system [69].

$$f = f_n + k_q \cdot (Q - Q_r) \quad (2-12)$$

$$U = U_n - k_p \cdot (P - P_r) \quad (2-13)$$

The reactive power sharing accuracy is enhanced using the improved droop control strategy developed in [82] for a low voltage RAPS system where the real power and reactive power are inherently coupled. This strategy estimates the reactive power control error though injecting small real power disturbances and an integration term for reactive power sharing error elimination is added to the conventional voltage droop. In contrast to the conventional droop control, the output impedance of the inverters in [83] is enforced to be virtually resistive rather than inductive considering the resistive characteristic of the RAPS system.
network. Such a resistive droop method has good power sharing performance with low sensitivity to the line impedance unbalance.

- **Nonlinear Loads**: the droop control strategy presented in the literature is generally verified to operate well with a linear load. In fact, nonlinear loads can present a high portion of the total load and have a strong impact on voltage waveforms in a weak power system such as RAPS system [67]. The voltage at the load side can be highly distorted. In order to address the harmonic current sharing problem, several control strategies appear in the literature [80, 82-83]. The harmonic current sharing strategy for each order of harmonics developed by [84] is based on the conventional droop control for fundamental voltage and frequency. This strategy enables to equally share nonlinear loads among converters connected in parallel. An instantaneous current control loop can be implemented to program the output impedance to be resistive, and then the harmonic current can be shared without increasing the voltage distortion too much [85]. The same authors apply similar resistive output impedance for harmonic current sharing in [83], but the output impedance presented to the fundamental and harmonic components are fixed independently, to avoid the excessive increase of output voltage total harmonic distortion. In [86], droop control and average power control are combined to share both linear and nonlinear load, and a harmonic control loop is proposed to guarantee harmonic power sharing using low-bandwidth communication to enable the power information exchange among generators.

- **Inertia Coordination**: A high droop gain improves power sharing accuracy, but it worsens the stability. Virtual inertia is applied to the DFIG in [87] with either rotating mass or super-capacitor, and the droop dynamic behaviour improves. When both conventional generators and inverter-based generators present in a RAPS system, the control performance is affected by the different characteristics of conventional generators and inverter-based generators. For example, the rotational speed of the conventional generator cannot change instantaneously due to the inertia of the rotating mass whereas the inverter-based generator has little inertia responds to disturbances very fast. Additionally, the reactive power supplied by the conventional generator is naturally related to the frequency and voltage respectively whereas control strategies have to be used to establish such relationship for inverter-based generators. The performance of different combinations of conventional generators and inverter-based generators in a RAPS system is compared in [23].
**Multi-Agent Strategy**

The multi-agent system is an evolved form of the classical decentralised control system with the feature of imbedded local intelligence in each agent. Each agent uses its intelligence to determine future actions and independently influences its environment [68]. In [88] a decentralised control system is designed based on multi-agent system to coordinate. All the system components collaborate to reach a global coordination and the whole system can continue to work when the system configuration is changed, since the agents can adapt their behaviour to new conditions. Authors of [89] propose a dynamic demand response approach using the multi-agent system to optimise the energy management by controlling load and shifting loads to off peak hours. The approach reduces the energy consumption cost of the residential customers.

Centralised and decentralised control strategies can operate separately, and they can also be applied in a coordinated manner in a RAPS system. In [18], two main control strategies are investigated. 1) The single master operation strategy uses one voltage-source inverter acting as master to provide voltage reference for the islanded microgrid and the others operating in PQ mode (slave). 2) The multi master operation strategy uses several voltage-source inverters to operate under droop control strategy and the other inverters operating in PQ mode. Additionally, the control centre has the control over two operation strategies and it can modify generation profile by sending control information to generators. Droop control has formed the basic load sharing in [90], and wireless network plays the role of acquiring the information of the total real and reactive power generation of all generators. Using the collected information, the traditional droop control strategy is modified considering the difference between the desired and actual power generation and thus system stability can be improved.

### 2.9 Summary

A RAPS system based on renewable energy resources is considered to be an ideal electrification method for those areas where utility grid is not accessible. An up-to-date review of different planning and operation techniques was presented in this chapter. In this review, it was revealed that the most important task in RAPS system planning is the study of the energy potential of a proposed site either using chronological data series or stochastic information. In particular, it is essential to model the system components along
with the renewable energy resources to accurately estimate the available energy at the site. In order to design a reliable, cost-effective, and environmentally friendly RAPS system, unit size should be optimised to meet particular cost and reliability target under certain design constraints, and they are exemplified in this chapter. The unit sizing is a multi-objective problem. Hence, appropriate optimisation techniques are required and they are generally classified into conventional enumeration techniques and AI techniques. In terms of RAPS system operation, two levels of control techniques, namely, component-level-control and system-level-control, are discussed. Component-level-control mainly refers to converters’ roles in a RAPS system (i.e., grid-forming, grid-feeding, or grid-supporting) while centralised control and decentralised control including droop control and multi-agent system technique are reviewed for system-level-control. In addition, a clarification of the terminology used for RAPS system and different RAPS system architectures were also presented in this chapter. From this review, it can be concluded that both planning and operation techniques are essential to counteract the technical challenges associated with system sizing, unit cost of generation, voltage and frequency control and coordination of different system components in RAPS systems.
Chapter 3

Impact of Energy Storage System on Capacity Value of Renewable Energy Resources in RAPS Systems

3.1 Foreword

Appropriate sizing of the system components is the core requirement for improving the security of power supply in a RAPS system. In this chapter, the capacity value of renewable energy resources (wind and solar energy) in a RAPS system was evaluated. The reliability of the power supply is also assessed. This chapter provides a practical approach for the sizing of the generators in hybrid RAPS systems. The RAPS architecture studied in this chapter established a benchmark system used for validating the proposed control strategies in other chapters.

3.2 Overview

Renewable energy resources are being utilised widely in RAPS systems. The capacity value of renewable energy resources in a RAPS system indicates the ability of renewable energy resources to serve the load demand in the RAPS systems. In this chapter, the impact of the capacity value of renewable resources on energy management of a RAPS system, while maintaining system reliability, was investigated. It was revealed that capacity value of renewable energy resources has a direct influence on RAPS system energy management. By utilising storage in conjunction with renewable energy resources, the RAPS system can cater load demand while achieving a higher reliability. A case study based on a remote village has shown that presence of a renewable energy resource with a high capacity value can meet the load demand with a relatively small storage system for energy balance while maintaining the level of reliability target. Therefore, it is imperative to consider the capacity value of renewable energy resources to design a reliable RAPS system. The structure of the rest of Chapter 3 is shown in Figure 3-1.
3.3 Background

Wind and solar energy are becoming popular for the use in RAPS systems. However, their intermittent nature has resulted in design and operational challenges. In particular, energy management is a challenging issue that directly affects the reliability of the RAPS system.

Energy management aims to balance the power generation and demand in a power system. Reliability is an important objective of energy management in a power system, and a reliability target is usually set depending on the load requirements. The loss of load probability (LOLP) is defined as the probability of not meeting the load demand by the generation. The loss of load expectation (LOLE) indicates the total time when demand is more than generation in a given time period, generally described by hours/year or days/10 years. The LOLP and the LOLE are two main reliability indicators used for power supply systems. The loss of power supply probability (LPSP) is extensively used as a criterion to indicate reliability in a RAPS system. In [91], unit size is optimised based on the LPSP requirement. In [92], by setting the LPSP target to zero, system cost is analysed to develop an optimal sizing of the components in a RAPS system. This will enable to develop a sustainable and cost-effective RAPS system.

Capacity value is defined as the additional load that a system can serve by adding a new generator while maintaining the same system reliability level [93]. Effective load carrying capability (ELCC) is a metric to denote the capacity value [94], which is usually determined based on the reliability criteria – LOLP. Different methods for the calculation of capacity value are presented in the literature. The Garver method introduces a system
character parameter to determine the ELCC with graphical aids [95]. The Z-method defines a Z factor, and keeps the Z-factor constant when additional generation and load are added to the system [96]. The chronological method described in [43] estimates the capacity value by computing capacity factor over an appropriate time-period.

Due to the intermittent nature of the climate dependent renewable energy resources like wind and solar energy, the penetration of renewable energy resources in power systems is constrained to a low level. Storage systems are being used widely in RAPS systems [46, 91, 92], and they play a major role in energy management by mitigating the impact of intermittency of renewable energy resources while enhancing the reliability. In a RAPS system, energy storage gains more importance due to its high renewable energy penetration level [97]. The energy storage system supplies extra energy during energy deficits, in order to balance the generation and load demand, thus improving power supply reliability. The energy storage system cannot generate any energy itself, but it can reduce the need for a conventional generation by mitigating energy imbalance between generation and demand through charging/discharging procedure. The authors of [98] applied the concept of capacity value on energy storage for the first time and propose a dynamic programming approach to estimate the capacity value of energy storage.

### 3.4 Capacity Value

#### 3.4.1 Definition

The power supply reliability of a power system can be described as a function of system peak load which is presented by the curves as shown in Figure 3-2.

![Figure 3-2 Definition of capacity value.](image)
From the Figure 3-2, it can be seen that the system with an additional generator, whose rated capacity is $S$, can serve an additional load of $\Delta \gamma$ compared with the original system at a predesigned reliability level. Capacity value is usually denoted as a percentage of the rated capacity of the generator in the form of (3-1)

$$Capacity\ Value = \frac{\Delta \gamma}{S} \times 100\%$$  \hspace{1cm} (3-1)

3.4.2 Estimation Techniques

Methods used for reliability estimation can be classified into iterative techniques and non-iterative techniques based on whether iteration is required [44].

3.4.2.1 Iterative Technique

In order to obtain the reliability-load curves shown in Figure 3-2, an iterative method examines the power supply reliability in each time interval (which is chosen either using a random approach or sequential approach as explained below) during a study period with chronological generation and load profiles. The procedure is then repeated at different load levels; hence, reliability under different loads is determined. Consequently, the capacity value can then be found after both the reliability-load curves for the original system and the system with the additional generator are formulated.

Random Approach: For example, Monte-Carlo method is used to conduct reliability study in [99]. This approach chooses time intervals randomly neglecting the impact of the previous time interval on the present time interval. This approach may bring significant errors in some cases such as when energy storage is utilised in the system.

Sequential Approach: The energy deficit between generation and load demand is assessed interval by interval sequentially in the whole study time period, which is recommended in [94].

The iterative method is theoretically straightforward and preferred in [94] to estimate capacity value of wind plant. The disadvantages are: 1) simulation process is computationally intensive, and 2) it is lack of transparency (it is not easy to determine the impact of system characteristics on capacity value).
3.4.2.2 Non-iterative Technique

The non-iterative technique determines capacity value directly from sample data (i.e., approximation approach) or a formula characterising system features (i.e., analytical approach). This technique provides some transparency since the factors affecting capacity value can be determined.

**Approximation Approach:** The capacity factor during a peak time period can be approximated as the capacity value of a generator. The capacity factor is the ratio of a generator’s actual energy production over a given time period and the energy it can produce if it runs at full capacity during the same period of time [99]. Hence, the capacity value determined by this approximation method depends on the selection of peak time period. It can be either the time period when peak load occurs or the time period when there is a high risk of energy deficit. In addition, as claimed in [94], the capacity factor approximation method does not capture the short-term or annual variability of wind power, or the correlation of wind availability with load demand.

**Analytical Method:** Analytical method presents the capacity value of a generator as a function of several parameters denoting the characteristics of both the additional generator and the existing system, which enables the capacity value to be estimated directly and the impact of factors on capacity value to be determined. Garver proposed an analytical formula to determine the capacity value of an additional conventional generator [96]. Garver assumes the annual risk expressed in terms of the installed reserve, and it can be expressed as (3-2).

\[ R(x) = a \times e^{-\frac{x}{m}} \] (3-2)

where \( R(x) \) is the annual risk with the installed reserve of \( x \), \( a \) is a constant, and \( m \) is the system characteristic. The value \( m \) can be found graphically on the curve representing the relationship between the annual risk and the installed reserve of the original system. Based on the assumption (3-2), the ELCC of the additional conventional generator with the capacity of \( S \) and FOR of \( p \) can be estimated using (3-3).

\[ ELCC = S - m \times \ln \left( (1 - p) + p \times e^{\frac{S}{m}} \right) \] (3-3)
Based on Garver’s concept, a similar noniterative method to approximate the ELCC of a wind plant is proposed in [100]. The approach computes the ELCC from a single function using the multistate probabilistic representation of the wind plant, but the characteristic parameter of the original system is determined by an iterative method. Similar to Garver’s method, Claudine and Surya [100] developed a capacity value estimation method for wind plant based on the multistate model for wind plant and the assumption expressed as (3-4).

$$LOLE(x) = a \times e^{mx}$$

(3-4)

where $LOLE(x)$ is the loss of load expectation of the original system under the peak load of $x$, $a$ is constant, and $m$ is determined by exponential curve fitting method. The ELCC can then be estimated using (3-5).

$$ELCC = -\ln\left\{ \sum_{i=1}^{n} \left[ p_i \times e^{m(S_i-S)} \right] \times \frac{1}{m \times S} \times 100\% \right\}$$

(3-5)

where $n$ is the number of outage states for the wind plant, $S_i$ and $p_i$ are the $i$th outage capacity state and the corresponding probability, and $S$ is the capacity of the wind plant.

The iterative method is recommended in [94], which calculates the ELCC using generation and load time series in an iterative manner. This chapter also employs the iterative method to compute the capacity value of renewable energy resources and investigates the impact of the capacity value of renewable energy resources on RAPS system energy management. The energy storage system is also utilised and the minimum nominal capacity for the storage system is determined using an iterative method.

### 3.5 Component Modelling for the RAPS System

A schematic diagram of a RAPS system is shown in Figure 3-3. An AC/DC converter interfaces the PMSG driven by a wind turbine to the DC bus. A DC/DC converter connects PV system to the DC bus. The wind generator and PV system are controlled to operate at their MPP. Dump load, which could be a space heating or water-heating system [100], and load are illustrated by a single load block shown in Figure 3-3. A RAPS system consisted of DGs has been considered as the base-model for this chapter. In order to determine the capacity value of renewable energy resources and the impact of capacity value on energy management, different RAPS system configurations are considered with various combinations of renewable energy generators and DGs.
The LAB has been used as the main storage element to manage energy balance in the RAPS system. Since the purpose of this chapter is to investigate the impact of capacity value, only simple mathematical models have been used for the system components which are described in following subsections.

![Schematic diagram of the target RAPS system.](image)

**Figure 3-3 Schematic diagram of the target RAPS system.**

### 3.5.1 Diesel Generator

Rated capacity and FOR are two key parameters of a conventional generator. Several generators usually work in combination to improve stability. The capacity outage probability table (COPT) \[97\] lists possibly unavailable capacity along with the probability that the corresponding outage capacity may occur. Each generator has two states: online and offline. In general, for \(n\) generators, \(S_i (i=1, 2, \ldots, n)\) and \(p_i\) are the rated capacity and FOR of the \(i^{th}\) generator respectively, \(2^n\) combinations of operating states may occur and \(2^n\) outage capacities can be determined by (3-6).

\[
\left(S_{o1}, S_{o2}, \ldots, S_{o2^n}\right)^T = A \cdot (S_1, S_2, \ldots, S_n)^T \tag{3-6}
\]

where \(S_{oj}\) refers to \(j^{th}\) \((j=1, 2, \ldots, 2^n)\) outage capacity. Identical outage capacities may exist, they can be regarded as a single outage capacity and addition of their probabilities is the total probability for this outage capacity \([97]\). \(A\) is an array with the dimension of \(2^n \times n\) and each row of the array represents one of the \(2^n\) possible operating states. The value of the \(i^{th}\) element in a row depends on the \(i^{th}\) generator’s operating state. If the \(i^{th}\) generator is offline, the \(i^{th}\) element in the row is considered to be one. Otherwise, the element is zero.

The probability \(P_{oj}\) for outage capacity \(S_{oj}\) is determined by (3-7).
\[ P_{ij} = \prod P_i \] (3-7)

where \( P_i \) equals \( p_i \) if the \( i^{th} \) generator is offline (or the \( i^{th} \) element in a row in \( A \) is one). Otherwise \( P_i \) equals to \((1 - p_i)\). As an example, for two DGs operating in combination, and each rated at 10 kW with FOR being 0.02, the COPT for these two generators is given in Table 3-1.

Table 3-1 COPT for generators (10 × 2 kW, FOR = 0.02)

<table>
<thead>
<tr>
<th>Outage Capacity (kW)</th>
<th>20</th>
<th>10</th>
<th>0</th>
</tr>
</thead>
<tbody>
<tr>
<td>Probability (%)</td>
<td>0.04</td>
<td>3.92</td>
<td>96.04</td>
</tr>
</tbody>
</table>

3.5.2 Wind Generator

Manufacturers usually provide a power curve for WECS to represent the actual relationship between power output and wind speed at hub height. The available specification for WECS generally lists discrete wind speeds and corresponding power output. In order to find out the power output for any wind speed, cubic spline interpolation functions are used to fit the curve [46, 96]. A piecewise fitting technique is applied by separating the curve into \( n \) subsections and each subsection fits a cubic polynomial equation. The equation for \( k^{th} \) (where \( k=1, 2, \ldots, n \)) subsection can be (3-8).

\[
P_{wk}(V_w) = a_k \cdot V_w^3 + b_k \cdot V_w^2 + c_k \cdot V_w + d_k, V_{w(k-1)} < V_w < V_{wk}\] (3-8)

where \( P_{wk}(V_w) \) is the power output of the wind turbine at a wind speed of \( V_w \). \( V_{wk} \) is the wind speed at which the curve is separated. \( a_k, b_k, c_k, d_k \) are the polynomial coefficients. \( V_{wci} = V_{w0} \) is called the cut-in wind speed and \( V_{wco} = V_{wa} \) is the cut-out wind speed. When wind speed is beyond the range \([V_{wci}, V_{wco}]\), the wind turbine power output is zero.

3.5.3 PV and Battery Modules

Power output of PV modules can be expressed as (3-9) [46].

\[
P_{PV} = \eta \cdot A_t \cdot R\] (3-9)

where \( \eta \) is the module conversion efficiency which is assumed to be 15% in this chapter. \( A_t \) is the total area of PV modules. \( R \) is the solar insolation on the surface of the PV module.
The battery model given in [96] is used in this chapter. During charging process, the following two cases can be considered.

1) For generation from diesel $P_{DG}(t)$ is higher than load $P_{LD}(t)$, the SOC at time $t$ is determined by (3-10).

$$SOC(t) = SOC(t-1) \cdot (1-\sigma) + [P_{WS}(t) + P_{DG}(t) - P_{LD}(t)] \cdot \eta_{bat}$$  \hspace{1cm} (3-10)$$

2) For generation from diesel $P_{DG}(t)$ is less than load $P_{LD}(t)$, the SOC at time $t$ is determined by (3-11).

$$SOC(t) = SOC(t-1) \cdot (1-\sigma) + [P_{WS}(t) - [P_{LD}(t) - P_{d}(t)]/ \eta_{inv}] \cdot \eta_{bat}$$ \hspace{1cm} (3-11)$$

During discharging process,

$$SOC(t) = SOC(t-1) \cdot (1-\sigma) + [(P_{LD}(t) - P_{DG}(t))/ \eta_{inv} - P_{WS}(t)] \cdot \eta_{bat}$$  \hspace{1cm} (3-12)$$

where $P_{WS}(t)$ is either WECS and/or solar-PV output. $\sigma$ is the self-discharge rate of batteries and is assumed to be 0.14% per day in this chapter. Battery efficiency $\eta_{bat}$ is set to 1 during the discharging process and 0.8 during the charging process. Inverter efficiency $\eta_{inv}$ is used as 80%. Battery capacity is determined using (3-13), thus the two constraints: nominal capacity $E$ and maximum permissible depth of discharging (DOD) are satisfied.

$$DOD \cdot E \leq SOC(t) \leq E$$  \hspace{1cm} (3-13)$$

### 3.6 Energy Management Strategy

The real power balance of the RAPS system can be represented as:

$$P_{DG}(t) + P_{WS}(t) \pm P_{bat}(t) - P_{LD}(t) = 0$$  \hspace{1cm} (3-14)$$

The balance between generation and load must be maintained instantaneously in a reliable RAPS system. Due to the intermittency of the wind and solar energy resources, battery plays a key role in power balancing. The surplus energy during low load period will be stored for peak load period. Therefore, if power surplus exists, batteries act as a load to absorb surplus power $P_{bat}(t)$ and store the power until a power deficit occurs in the RAPS system. The capacity of the batteries is finite, so if it is full, then surplus power can be consumed by a dump load. Contrarily, if power generation is insufficient to meet load
demand, then batteries will be discharged to mitigate the power deficit. These two operating conditions for batteries are represented by negative and positive signs in (3-14). If batteries cannot meet the demand, load shedding is implemented, resulting in a ‘loss of load’ case which will ultimately increase the LOLE, hence reduce the system reliability.

With the presence of a renewable energy resource of higher capacity value, the renewable resource can supply power when load demand increases, or generation and load are highly correlated. Therefore, (3-14) can be satisfied during most of the time even without battery element \( P_{\text{bat}}(t) \), while exhibiting a higher reliability level. However, if a renewable energy resource of lower capacity value exists in the RAPS system, the generation is poorly correlated to the load. Although surplus energy exists in certain situations, power deficit may also occur quite often and hence storage systems must be used for energy management. Therefore, under such situations, the energy stored in batteries during the time periods of surplus energy should be discharged to mitigate the power deficit. The nominal capacity of batteries should be large enough so that surplus energy can be stored and this may be sufficient to provide the energy requirement in order to eliminate the possibility of “loss of load” case while improving reliability. Larger nominal capacity may be required for batteries to enhance reliability with renewable energy resources of lower capacity value. The minimum nominal capacity for batteries can be determined to achieve the level of reliability target.

### 3.7 Case Study

A case study has been carried out considering the wind and solar insolation data for a remote village. A sample of the annual hourly wind generator power output, PV power output and load profiles at the site are shown in Figure 3-4.

As shown in Figure 3-4, neither the wind generator nor the PV can meet the load demand alone. Thus, DGs are utilised. The system configurations investigated for the RAPS system are listed below.

1) Only DGs (10 kW × 3)

2) DGs (10 kW × 3) and wind turbine (10 kW)

3) DGs (10 kW × 3) and PV (10 kW)
4) DGs (10 kW × 2), wind turbine (10 kW), and batteries

5) DGs (10 kW × 2), PV (10kW) and batteries.

Figure 3-4 Hourly wind generator power output, PV power output, and load profiles in a day.

The system is designed with LOLE of 1 day per 10 years, which is 2.4 hours per year. The first three scenarios determine the capacity value of the wind and solar energy by using following procedure: Firstly, considering scenario 1, the system supplies power to the load at high reliability level (LOLE is less than 2.4 hours). Constant load Δγ is added to load time series across each hour iteratively until the annual peak load increases by 20%. During this process, the LOLEs for each load time series are computed. The relationship between peak load and corresponding LOLEs is shown by the solid curve in Figure 3-5. Secondly, renewable generation time series is added to load time series as negative load for scenarios 2 and 3. The LOLEs for each new load time series are then determined. The impact of additional generation on the LOLE is shown by the other two curves in Figure 3-5.

Due to the addition of renewable generation, the system becomes more reliable at each load level and extra load can be served while maintaining the same reliability level. The amount of the extra load (i.e., capacity value), can be determined by the distance between the curve representing a system with renewable energy and the curve representing original system at the required reliability level (i.e., LOLE of 2.4 hours per year). In this case the capacity value of the wind system is larger than the capacity value of the PV system. The
curves indicate that system with wind generation is more reliable than a system with PV at each load level. Scenarios 1 to 3 operate at high reliability level under the load profile at the remote village.

Figure 3-5 Impact of additional generation on reliability.

Figure 3-6 Impact of the nominal capacity of batteries on reliability considering wind and solar energy.

In scenarios 4 and 5, one DG was eliminated, and subsequently system reliability has substantially decreased below the level of reliability target. As an example, LOLEs have
increased more than 40 hours per year (see Figure 3-6 for zero battery capacity). If batteries are installed, reliability can be improved as demonstrated in Figure 3-6. When the nominal capacity of batteries increases, LOLE decreases. Particularly, the batteries of 7.5 kWh can reduce the LOLE for a system with wind energy to 1.9 hours per year. If the same batteries are applied to the system with solar energy, the LOLE is only reduced to 3.4 hours per year, and fail to meet the level of reliability target. The increase in capacity of batteries brings down the LOLE to predesigned level. In this case, batteries of 8.5 kWh fulfil the reliability requirement, and LOLE becomes 2 hours per year. As shown in scenarios 2 and 3 by utilising another DG (i.e., all 3 DGs are now in operation), it can eliminate the battery requirement while maintaining reliability target. Therefore, for different energy resources, lower capacity value contributes to less reliable energy balancing performance, requiring a larger nominal capacity for batteries to achieve the reliability target.

Furthermore, the impact of different capacity values for a single renewable energy resource was also investigated. The wind speed at the site is scaled to yield variable capacity values. The corresponding LOLEs for different nominal battery capacities are found under scaled wind speed profiles. According to Figure 3-7, a system with wind energy of larger capacity value is more reliable at each battery size and tends to require less nominal capacity for batteries to meet the reliability target.

Figure 3-7 Impact of the nominal capacity of batteries on reliability considering wind energy of different capacity values.
3.8 Summary

This chapter investigated the impact of the capacity value of renewable energy resources on RAPS system energy management. The iterative method has been utilised to compute the capacity value of renewable energy resources. The case study carried out based on a RAPS system in a remote village has shown that capacity value has a direct influence on energy management as the size of the storage system depends on the capacity value of the renewable energy resource used in the RAPS system. A renewable energy resource with high capacity value tends to balance generation and load at higher reliability level, and smaller nominal capacity is required for storage to improve reliability to a target level. Therefore, it is essential to consider the capacity value of renewable energy resources while planning for a highly reliable RAPS system.
Chapter 4

A Suboptimal Power Point Tracking based Primary Frequency Response Strategy for DFIGs in Hybrid Remote Area Power Supply Systems

4.1 Foreword

In an optimally sized hybrid RAPS system, the energy balance between the generation and load demand can be maintained over a long timeframe and the power supply reliability is generally high as discussed in Chapter 3. Nevertheless, the active power generated at a particular time instant may not be equal to the power consumed. For example, a sudden load increase or the tripping of a generator in the network can cause significant transient energy imbalance. This energy imbalance will be reflected by a frequency deviation in the network. Hence, in order to achieve satisfactory frequency regulation, generators should actively manipulate their power output under contingencies in a short timeframe. Therefore, this chapter investigated DFIG’s potential in transient power management or frequency response provision in a hybrid RAPS system.

4.2 Overview

Due to the presence of a power electronic converter, the DFIGs are isolated from grid frequency variations, which will impose a significant burden on conventional generators to regulate frequency in a hybrid RAPS system. Thus, the participation of wind generators in frequency control is increasingly demanded. In this chapter, a primary frequency response strategy was proposed for the DFIGs to regulate the RAPS system frequency. A droop control loop without conventionally used high-pass filter was integrated to generate the torque reference for the DFIGs to provide primary frequency response, and a supplementary control loop was proposed to enhance the primary frequency response with
torque feedback control. Furthermore, the suggested SOPPT strategy is capable of reserving wind power to improve the frequency response. The proposed strategy enables DFIGs to participate in RAPS system frequency regulation while alleviating high rate of change of power (ROCOP) and thus stress on the DGs under highly variable load demand. The effectiveness of the proposed strategy was validated through simulations. The structure of the rest of Chapter 4 is shown in Figure 4-1.

Figure 4-1 Structure of Chapter 4.

4.3 Background

4.3.1 Problem of Frequency Fluctuation

Traditionally, RAPS systems utilise DGs, and subsequently due to increased interest in renewable power generation, it has paved the way to adopt various renewable power generators in RAPS systems to supply power to electrically ‘isolated’ communities.

The frequent load fluctuations in RAPS systems may result in large frequency excursions and high rate of change of frequency (ROCOF), which will trip the renewable power generators and/or loads [101]. Moreover, as the RAPS systems are comprised of small number of generators and renewable energy penetration can be significant, it is difficult to handle the frequency fluctuations by a single generating source with no dominant capacity [102]. The DGs will be heavily stressed during the process of balancing the generation and highly variable load due to the high rate of change of power (ROCOP) [103]. Therefore, it is a necessity for renewable generating sources such as wind WECSs to participate in frequency regulation.
4.3.2 Limitations of Existing Techniques

Frequency regulation methods are generally classified into inertial response, primary response, secondary response, and high-frequency response [104], among which the inertial response and primary response can be categorized as short-term frequency response. Upon frequency disturbance, conventional generators provide natural inertial response to support system frequency as they have a direct coupling between the system frequency and the generator electromagnetic torque. The governor with droop control activates primary frequency response by varying the valve or gate position for steam turbine and hydro turbine respectively. Contrarily, without the presence of rotating mass, no kinetic energy exists in generating source like solar-PV generating system. With regard to WECSs equipped with conventional control, the availability of the inherent inertial response depends on the type of the generators. The DFIG has limited inertial response, whereas the fixed-speed induction generator (FSIG) based WECSs provides substantial inertial response [105]. The PMSGs is totally decoupled from the grid frequency by the converter and kinetic energy cannot be released during system disturbances. The frequency regulation capabilities of various generators are summarised in Table 4-1.

Table 4-1 Comparison of frequency regulation capability of various generators

<table>
<thead>
<tr>
<th>Generator Category</th>
<th>Inertia Constant</th>
<th>Speed Range</th>
<th>Natural Inertial Response</th>
<th>Inertial Response Speed</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Conventional Generator</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Hydro Turbine</td>
<td>2s to 9s [106]</td>
<td>Minimum 0.95 p.u. [107]</td>
<td>Available [108]</td>
<td>Slower than steam turbine [109]</td>
</tr>
<tr>
<td>Steam Turbine</td>
<td></td>
<td></td>
<td></td>
<td>Reference for comparison</td>
</tr>
<tr>
<td><strong>Renewable Generator</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>DFIG</td>
<td>2s to 6s [106]</td>
<td>0.7 p.u. to 1.3 p.u. [110]</td>
<td>Limited [105]</td>
<td>Instant artificial response</td>
</tr>
<tr>
<td>PMSG</td>
<td>2s to 6s [106]</td>
<td>Full range</td>
<td>Negligible [111]</td>
<td></td>
</tr>
<tr>
<td>Solar-PV</td>
<td>Not applicable</td>
<td>Not applicable</td>
<td>Not available</td>
<td>Not applicable</td>
</tr>
</tbody>
</table>
As it can be seen from Table 4-1, the inertia constant of WECS is comparable with conventional generators, and WECS such as DFIG and PMSG have a wider speed range. As claimed in [107, 108], the kinetic energy extraction in WECS can exceed that of conventional generators, which enables them to participate in frequency regulation with the support of fast responding electronic converters. In [102], authors utilise the kinetic energy in WECSs to provide short-term frequency support in coordination with conventional generators. The artificial inertial response is investigated by the authors in [40] using the kinetic energy stored in the rotating mass, and impact factors on the inertial response are explored. The frequency support from variable-speed wind turbines can effectively mitigate the frequency variations when a hydro turbine fails to respond promptly due to the initial opposite power surge [109]. A droop based supplementary controller is proposed in [106] to exploit the kinetic energy to increase the inertia contributed by wind generators. However, using the kinetic energy to provide frequency response, it will create a power dip following the release of the stored kinetic energy, which may cause another frequency event [112, 113]. Two reasons can explain the cause of the power dip: 1) Due to the release of kinetic energy, a part of mechanical energy will be absorbed after the disturbance by turbine itself to recover the optimum speed under the MPPT strategy. 2) The turbine operates away from the MPP due to the speed reduction under frequency disturbance, which further attenuates the power output.

To enhance the frequency support supplied by kinetic energy, power reserve is usually recommended. The power reserve is achieved by deliberately operating WECSs away from their MPP. In the published literature, this strategy is commonly referred as ‘de-load’ control [104, 114-116], power reserve control [117, 118], generating margin control [119] or SOPPT control as referred in this thesis. With the power reserve, wind generators may handle the secondary frequency response [104, 116, 120] or even load sharing [117, 118] with droop control. However, the abrupt wind speed may result in an insufficient power reserve at the wind generator for long-term frequency response [112]. Consequently, the excessive energy demand may cause system instability, and frequency response is deteriorated due to the unreliable power reserve. Therefore, some research studies suggest to use WECS for short-term frequency response, and a high-pass filter can be used in the droop control loop to prevent frequency controller from being activated by permanent frequency deviation [102, 121, 122]. The demerit is that the controller with
high-pass filter may not be able to respond to slow frequency fluctuations for which droop control is more effective [117].

The main contribution of this chapter is the development of an enhanced primary frequency response strategy for DFIGs in RAPS systems. A droop based primary frequency controller is proposed which only acts on transient frequency variation without the implementation of a high-pass filter. The primary frequency is enhanced by the addition of a supplementary control loop. Furthermore, the proposed SOPPT strategy combines two conventional algorithms, and the primary frequency response from DFIG is improved by the power reserve. Due to the rapid response of power electronic interfaced DFIGs, the torque stress on the DG shaft can be relieved by reducing its ROCOP in a wind-diesel hybrid RAPS system.

### 4.4 Suboptimal Power Point Tracking (SOPPT) Strategy for the DFIG

#### 4.4.1 Basics of the SOPPT Strategy

There are two types of control strategies for power reserve: delta control and balance control [117]. The delta control approach reserves constant value or constant percentage of the available power, whereas with the balance control an upper limit is imposed on the power output of the generator under normal operation. The main disadvantage of the constant power reserve control is WECSs only have power reserve when wind speed reaches a predesigned level. With regard to the constant percentage control of power reserve, the excessive power reserve at high winds may not be needed in the system and it reduces economic benefits. In [119], a moving average method is introduced to determine the optimal power reserve, but the power reserve quantity is uncertain under any wind conditions, which complicates the control. With the balance control, the reserved power is not known to the generator either.

The rotor speed control and pitch angle control are two techniques used for SOPPT control [120, 123, 124]. Pitch angle control varies the pitch angle to adjust the wind power output, and is more widely used due to its ease of control. In [125], an algorithm is proposed to vary the DFIG pitch angle continuously and share the load according to the available power. Similar pitch control approaches are used in [115, 116] with the purpose
of engaging DFIGs in system frequency regulation. The slow response speed of pitch angle control is of concern, and other techniques (such as structure design of the wind turbine [123]) or external mechanism [123, 125] may be required. Moreover, the wear and tear on pitch control system increases the O&M cost significantly.

Figure 4-2 SOPPT strategy for wind turbine: (a) power-speed characteristic; (b) torque-speed characteristic.
4.4.2 Proposed SOPPT Strategy

The mechanical characteristics of a wind turbine are shown in Figure 4-2 with the red solid line indicating the typical MPPT curve. The SOPPT curve for the WECS can be established either on the left side or right side of the typical MPPT curve. If the wind turbine is regulated by the left side SOPPT curve, a part of the energy is absorbed by the rotating mass to increase its speed when wind turbine tends to increase the power output. Hence frequency response is attenuated. By operating the DFIGs at the right side of their MPPs, an additional kinetic energy reserve can be achieved in addition to the power reserve obtained through the SOPPT strategy. The estimation of the extractable kinetic energy under frequency disturbance is discussed in detail in [110].

In order to effectively utilise the energy reserve for frequency regulation, the right side SOPPT curve is chosen in this chapter. The blue dotted line presents the SOPPT curve with 0.05 p.u. power reserve, and the green dash-dot line presents the SOPPT curve with 20% power reserve. To overcome the disadvantages of constant power reserve strategy and constant percentage reserve strategy as mentioned in Section 4.4.1, these two strategies are combined. At lower wind speed, constant percentage power reserve control is applied, whereas constant power reserve control is active during high wind speeds. The wind speed boundary is set at which constant power reserve strategy and constant percentage power reserve strategy can reserve the same amount of power. Hence, the transients caused by the transition between these two strategies can be avoided. The transition point is indicated by point Y’ and point Y in Figure 4-2(a) and Figure 4-2(b) respectively. The corresponding wind speed is 7.7 m/s for the WECS used in this chapter. The combined SOPPT curve is shown as the orange bold solid line in Figure 4-2.

As discussed in Section 4.4.1, pitch control can be disadvantageous if the pitch angle needs to be adjusted continuously. In this chapter, only rotor speed control based SOPPT strategy is active and pitch angle is kept at zero before the rotor speed reaches its rated value. When rotor speed approaches the turbine speed upper limit, pitch angle controller is activated to manipulate the constant power reserve and prevent the rotor from over speeding. Pitch angle controller is also responsible for ensuring the DFIG to operate within its rated power output. Details of the pitch controller can be found in [120]. Mechanical power output of wind turbines can be determined by [126].
\[ P_w = \frac{1}{2} \rho \cdot A \cdot V_w^3 \cdot C_p(\lambda, \phi) \]  

(4-1)

where \( \rho \) is the air density usually taken as 1.225 kg/m\(^3\), \( A \) is blade sweeping area, \( V_w \) is the wind speed at the hub height, and \( C_p(\lambda, \phi) \) is the power efficiency of the wind turbine, which is a function of tip-speed-ratio \( \lambda \) and pitch angle \( \phi \). Wind turbines are usually operated under MPPT to maximise their power production by controlling \( \lambda \) and \( \phi \) at their optimal value.

In order to maintain the power reserve \( \Delta P \) as given by (4-2), the rotor speed and/or pitch angle are different from their optimal values.

\[ \Delta P = \frac{1}{2} \rho \cdot A \cdot V_w^3 \cdot \left[ C_p(\lambda_1, \phi_1) - C_p(\lambda_2, \phi_2) \right] \]  

(4-2)

where \( C_p(\lambda_1, \phi_1) \) and \( C_p(\lambda_2, \phi_2) \) are the wind turbine power efficiency under typical MPPT and SOPPT respectively. By looking at an internal lookup table, the power efficiency referring to the typical MPPT can be determined. With a designated \( \Delta P \), the power efficiency under the SOPPT is found with (4-2). Hence, the \( \lambda_2 \) and \( \phi_2 \) reference values under SOPPT control are determined to maintain \( \Delta P \).

### 4.5 Wind-Diesel Hybrid RAPS System Model

In this section, a wind-diesel hybrid RAPS system is introduced for investigations of the proposed strategy. As shown in Figure 4-3(a), an 11 kV RAPS system is comprised of two DFIG and a DG unit. Such an isolated system is commonly used for investigating the frequency controllers of WECS [116, 120, 127, 128]. Frequency fluctuations are more frequent in isolated power systems due to small generating capacities of energy resources. In such an integrated hypothetical system shown in Figure 4-3(a), the frequency dynamics can be easily observed and the contribution of a controller to the frequency regulation can be easily determined. The network parameters marked in Figure 4-3(a) are obtained from [80]. The DG regulates system voltage within the stipulated limits (e.g., 1±5% p.u.) while fulfilling the reactive power requirement of the RAPS system. The DG is also operated with droop control to support system frequency. Droop settings for generators in power systems are in the range of 3% - 6% [115]. In this RAPS model, the droop coefficient for the DG is set at 3.125% (which is estimated based on the droop assumption that for the
increase of 1 Hz in frequency, 2 MW of power will be decreased in the generator output and vice versa). The dynamic models and parameters for the diesel engine governor, synchronous machine (SM) and its exciter are obtained from [129].

\[ S_{base} = 10 \text{ MVA}, \quad V_{base} = 11 \text{ kV} \]
\[ k_p: \text{frequency droop constant} \]

Figure 4-3 System modelling: (a) RAPS system architecture; (b) DFIG control block diagram.
A detailed model is used for DFIGs as shown in Figure 4-3(b) and it is operated at unity power factor. The stator power output is controlled by the RSC in the stator-flux-oriented (SFO) reference frame. The grid side converter (GSC) is controlled in the stator-voltage-oriented (SVO) reference frame and it is responsible for maintaining DC-link voltage constant. The details of the RSC and GSC controllers can be found in [130], and the phase-locked loop (PLL) in [131]. The frequency response controller in shadowed box in Figure 4-3(b) is mainly investigated in this chapter. Main parameters of generators are listed in Table 4-2 and Table 4-3. The RAPS system given in Figure 4-3 has been modelled in MATLAB/SimPowerSystems, and is used as a benchmark system for evaluating the proposed primary frequency response strategy through simulation studies.

Table 4-2 DG parameters

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Value</th>
<th>Parameters</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rated Capacity</td>
<td>3.125 MVA</td>
<td>T1</td>
<td>0.01</td>
</tr>
<tr>
<td>Rated frequency</td>
<td>50 RPM</td>
<td>T2</td>
<td>0.02</td>
</tr>
<tr>
<td>Rated Voltage</td>
<td>2400 V</td>
<td>T3</td>
<td>0.2</td>
</tr>
<tr>
<td>Pole Pairs</td>
<td>2</td>
<td>T4</td>
<td>0.25</td>
</tr>
<tr>
<td>$H_d(s)$</td>
<td>0.75 s</td>
<td>T5</td>
<td>0.009</td>
</tr>
<tr>
<td>$T_D(s)$</td>
<td>0.024 s</td>
<td>T6</td>
<td>0.0384</td>
</tr>
<tr>
<td>$H_s(s)$</td>
<td>1.07 s</td>
<td>K</td>
<td>40</td>
</tr>
</tbody>
</table>

Table 4-3 DFIG parameters

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Value</th>
<th>Parameters</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rated Power</td>
<td>1.5 MW</td>
<td>$X_m$</td>
<td>2.3 p.u.</td>
</tr>
<tr>
<td>Turbine Inertia Contant</td>
<td>4.32 s</td>
<td>$R_s$</td>
<td>0.023 p.u.</td>
</tr>
<tr>
<td>Rated wind speed</td>
<td>11 m/s</td>
<td>$X_r$</td>
<td>0.18 p.u.</td>
</tr>
<tr>
<td>Rated Stator Voltage</td>
<td>400 V</td>
<td>$R_r$</td>
<td>0.016 p.u.</td>
</tr>
<tr>
<td>DC bus voltage</td>
<td>800 V</td>
<td>$X_r$</td>
<td>0.16 p.u.</td>
</tr>
</tbody>
</table>
4.6 Primary Frequency Controller for the DFIG in RAPS System

As discussed in Section 4.3, DFIGs have the potential for frequency support, and it can be realised artificially by the fast responding power electronic interfaces. It is plausible to further enhance the frequency support from wind generators using the substantial kinetic energy stored in the rotating mass and the energy reserve maintained by the SOPPT strategy. In this section, a discussion on the frequency control principles is presented. Furthermore, the advantages of the proposed primary frequency response strategy for DFIGs are highlighted by comparing with existing controller. The proposed supplementary control loop is also presented in this section.

4.6.1 Emulated Inertial Response Strategy

During a frequency dip, the conventional synchronous generator decelerates and the stored kinetic energy is released to the grid based on the ROCOF. The decelerating torque of the synchronous generator is given by [104]:

$$\tau_{md} = J \frac{d\omega_m}{dt}.$$  \hfill (4-3)

where $J$ is the inertia of the generator and $\omega_m$ is the rotational speed. Since the rotational speed of the conventional generator is directly coupled with the system frequency $f_{sys}$, the decelerating torque is also proportional to the ROCOF $df_{sys}/dt$. If the inertial response is demanded from DFIGs, an additional torque term [127] given in (4-4) should be added to the electromagnetic torque reference to emulate the inertial response so that it behaves similarly to the conventional generator, which is called virtual inertial response.

$$\Delta \tau_H = k_H \cdot \frac{df_{sys}}{dt}$$  \hfill (4-4)

where $k_H$ is a weighting constant which should be set to manipulate ROCOF within designated level while system stability is maintained. As suggested in [102, 120], $k_H$ is traditionally regarded as twice the total inertia constant ($H$) of wind generator, and $H$, on the system base, can be determined with the following equation [122].
\[ H = \sum_{i=1}^{n} \left( H_i \cdot \frac{S_i}{S_{sys}} \right) \]  

where \( i \) refers to \( i \)th wind turbine whereas \( n \) is the total number of wind turbines in a wind farm, \( H_i \) and \( S_i \) are the inertia constant and MVA rating of the \( i \)th generator respectively, and \( S_{sys} \) is the system MVA base. According to (4-4), the inertial response is effective only when the frequency is varying at a higher rate. Therefore, this strategy becomes ineffective when ROCOF is low, and system frequency settles at a different value from the nominal frequency (such situation will arise when the conventional synchronous generator is operating without secondary governor control to bring frequency back to nominal value).

### 4.6.2 Primary Frequency Response Controller

The power/frequency droop control strategy is widely being adopted to share the load and provide primary frequency response under frequency variations. However, as highlighted in [127], droop control approach may cause DFIGs to stall when there is a large frequency deviation in the RAPS system as the droop control strategy demands significant additional power from the turbine, based on the severity of the frequency deviation. Alternatively, the frequency droop control strategy can be modified by demanding an additional torque from the turbine instead of requesting additional power. The additional torque for primary frequency response is obtained by

\[ \Delta \tau_D = k_D \cdot (f_{sys} - f_{nom}) \]  

where \( k_D \) is the droop control coefficient, and \( f_{nom} \) is the nominal system frequency. The droop control coefficient \( k_D \) can be determined using (4-7) [106].

\[ k_D = \frac{1}{\Delta f_{max}} \cdot \sum_{i=1}^{n} \frac{S_i}{S_{sys}} \]  

where \( \Delta f_{max} \) is the maximum deviation in the system frequency, and \( S_i \) and \( S_{sys} \) have been defined earlier. The droop setting for the case studies in this chapter, if not indicated particularly, is given in the Table 4-4.
Table 4-4 Simulation parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>PI proportional gain</td>
<td>3</td>
<td>Wind speed</td>
<td>8.8 m/s</td>
</tr>
<tr>
<td>PI integral gain</td>
<td>0.6</td>
<td>MAXG</td>
<td>-3 m/s</td>
</tr>
<tr>
<td>$k_s$</td>
<td>0.2</td>
<td>MAXR</td>
<td>-3 m/s</td>
</tr>
<tr>
<td>$k_H$</td>
<td>7.1</td>
<td>$t_{IG}$</td>
<td>95 s</td>
</tr>
<tr>
<td>$k_D$</td>
<td>2.4%</td>
<td>$t_G$</td>
<td>6 s</td>
</tr>
<tr>
<td>$\tau_{max}$</td>
<td>1 p.u.</td>
<td>$t_{Ir}$</td>
<td>95 s</td>
</tr>
<tr>
<td>$\tau_{min}$</td>
<td>0</td>
<td>$t_{2r}$</td>
<td>98 s</td>
</tr>
</tbody>
</table>

The droop control can be active for both primary and secondary frequency response control and it is referred as the Type 1 Controller. To overcome the shortcomings of Type 1 Controller, a droop based controller participating in primary frequency response only is proposed, which is named as Type 2 Controller. For the case when a supplementary loop is added to the proposed Type 2 Controller to further improve its control performance, the enhanced controller is named as Type 3 Controller. The performance of these three types of controller are critically evaluated and compared below.

4.6.2.1 Type 1 Controller

With Type 1 controller, droop control participates in both primary and secondary frequency response. The schematic diagram of the Type 1 frequency controller is shown in Figure 4-4, which is used in [104]. The electromagnetic torque reference ($\tau_{ref}$) is given in (4-8).

$$
\tau_{ref} = \tau^* - \Delta\tau_H - \Delta\tau_D
$$

where $\tau^*(\omega_r)$ is the mechanical torque at a rotor speed of $\omega_r$ determined by the pre-designed torque tracking curve (see Figure 4-2(b)). $\Delta\tau_H$ and $\Delta\tau_D$ are given in (4-4) and (4-6) respectively.

Originally, the DFIG operates at the suboptimal power point (SOPP) as indicated by point A’ and A in Figure 4-2(a) and Figure 4-2(b) respectively. During a system frequency
dip, electromagnetic torque reference $\tau_{\text{ref}}$ increases, and hence the speed of the generator is decreased. The DFIG torque set-point $\tau^*$ governed by SOPPT control shifts from point A to point C in Figure 4-2(b) while turbine mechanical torque moves from point A to point B. Hence, an accelerating torque tends to drive the rotor back to its original speed. As inertial control and droop control schemes increase the $\tau_{\text{ref}}$, the accelerating torque is reduced, and thus rotor speed deviation increases and more kinetic energy is released to improve frequency response. Furthermore, the mechanical power output from wind turbine also increases with the reduction in the rotor speed (power output increases from A' to B' in Figure 4-2(a)) and it further enhances the frequency support.

If there is no secondary governor control to bring the frequency back to nominal value, DFIGs can supply both primary frequency response and secondary frequency response using the Type 1 controller. This can be explained as follows.

**Primary Response:** During the transient period, primary frequency response is provided under frequency disturbances as discussed above.

**Secondary Response:** With the permanent frequency deviation $\Delta f'$, generator speed is not able to recover to its original value after providing primary frequency response. The rotor speed stabilises at a value of $\omega_r'$ and it satisfies the following condition,

$$
\tau_m'(\omega_r') = \tau^*(\omega_r) + k_D \cdot \Delta f'
$$

where $\tau_m'(\omega_r')$ is the mechanical torque at the rotor speed $\omega_r'$ under a corresponding wind speed. If the increase in load demand is less than the power reserve in DFIGs, the DFIG stabilises at a point between the original SOPP and the MPP at steady state. Hence, the
secondary frequency response is provided. In particular, the DFIGs switches to MPPT control if the load demand is larger than the power available at the MPP of DFIGs. The DFIGs with Type 1 controller is tested in the RAPS system given in Figure 4-3(a) and the results are depicted in Figure 4-5. Some of the simulation parameters are given in Table 4-4. Inertial response is deactivated to show the contribution of DFIGs in primary and secondary frequency response. Therefore, the virtual inertial response control in the frequency controller is disabled (which is shadowed in Figure 4-4). As seen in Figure 4-5(a), the SOPPT operation of DFIGs is carried out from $t = 45$ s, consequently, a frequency event at $t = 45$ s is generated by the DFIGs themselves. The power output from DFIGs decreases from around 1.15 MW at the MPP to 1 MW at the SOPP, and thus a fraction of the power available at the WECS is reserved as seen in Figure 4-5(b). The RAPS system takes around 40 s to stabilise. It is worth to be noted that this process will not be encountered in real systems if SOPPT is enabled during the DFIG start-up.

![Figure 4-5 RAPS system operation: (a) system frequency; (b) DFIG power output; (c) DFIG rotor speed; (d) DG power output.](image_url)
The frequency event at $t = 90\ s$ is intentionally generated by a sudden load increase of 0.2 MW and the frequency response of the DFIG is tested. The rotor speed of the DFIGs with droop control decreases (see Figure 4-5(c)) and the electromagnetic torque increases as shown in Figure 4-6. Although mechanical torque from wind turbine also increases with decreasing speed, it is a slow process in comparison to the rapid response of power electronic converters. With the droop control and energy reserve, the DFIGs can share the load with the DG in accordance with their droop settings as shown in Figure 4-5(d); however without droop control, DFIGs maintain their power output as a constant value after the transient period as shown in Figure 4-5(b). The frequency deviation during this transient period is mitigated owing to the primary response provided by DFIGs with droop control as shown in the zoomed plot in Figure 4-5(a). The frequency after the transient period is different from the nominal frequency (i.e., 50 Hz) as presented in Figure 4-5(a). In order to recover frequency back to the nominal system frequency, a secondary controller can be implemented in the diesel engine governing the system.

![Figure 4-6](image)

Figure 4-6 Turbine mechanical torque and generator electromagnetic torque under droop control.

It is advantageous that DFIGs can share load with DG using the droop controller in a ratio set by their droop settings. However, wind energy resource is not dispatchable. At an instance when power demand exceeds the maximum power available from DFIGs, DFIGs cannot provide secondary frequency response effectively. Autonomous frequency control can be assured as long as sufficient energy resources are available, which is not always guaranteed for WECSs. Hence, secondary frequency response may only be ena-
bled when wind speed is favourable to maintain a sufficient reserve with the SOPPT control, for example, when wind speed is above the wind speed boundary (as mentioned in Section 4.4.2) to maintain constant value power reserve in DFIGs.

4.6.2.2 Type 2 Controller

With Type 2 controller, the droop control participates in primary frequency response only: Droop control is effective in supporting primary frequency response, whereas it is not desirable to demand secondary frequency response by DFIGs in low wind condition as explained above. As proposed in this chapter, a droop control based frequency controller (i.e., Type 2) only provides primary frequency response even when permanent frequency deviation exists as seen in Figure 4-7. All inputs and outputs variables of Figure 4-7 are given in per unit based on the generator ratings.

The droop and inertial control schemes also exist in this controller for frequency response purposes. Alternatively, the $\tau^*$ is generated by a PI controller. The PI controller acts based on the error between actual rotor speed ($\omega_r$) and the rotor speed reference ($\omega^*$) corresponding with the power output $P_{w0}$ on the pre-specified power tracking curve. Hence, the reference torque can be determined by the following equation:

$$
\tau_{ref} = k_p \cdot (\omega_r - \omega^*) + k_i \cdot \int (\omega_r - \omega^*) dt - \Delta \tau_H - \Delta \tau_P
$$

(4-10)

where $K_p$ and $K_i$ are parameters of the PI controller. These parameters can be designed through stability analysis to achieve desired dynamic performance of the system without interference to the system stability. If a frequency dip occurs in the system, electromagnetic torque reference $\tau_{ref}$ increases and rotor speed $\omega_r$ deceases. Consequently, the DFIG power output $P_{w0}$ increases to provide frequency response, which leads to the increase in rotor speed reference $\omega^*$ according to the predesigned SOPPT curve as it can be seen in Figure 4-2(a). Therefore, the $\tau^*$ shifts to a lower value with a negative $e_{\omega_r}$ counteracting the increase in $\tau_{ref}$, which drives the DFIG to return to its original operating condition. DFIG will not be stabilised until it reaches to its original operating point since any positive deviation in $P_{w0}$ brings $\omega^*$ and $\omega_r$ further apart and thus resulting in reduction of $\tau_{ref}$ and $P_{w0}$. Therefore, the frequency response is only provided during the frequency fluctuation, and the permanent frequency deviation cannot activate the frequency response. The high-pass filter is omitted to avoid the sensitivity problem as explained in Section 4.3, but its functionality is preserved through the proposed controller.
For the purpose of comparing with Type 1 controller, the Type 2 controller is operated under the same loading scenario as mentioned earlier and inertial control is also disabled. The SOPPT control is also activated at \( t = 45 \text{ s} \) for being consistent with the test of Type 1 controller, and it must be noted that this transient period caused by SOPPT activation will not be encountered when SOPPT is activated during the initialization of DFIGs. The performance of the Type 2 controller is shown in Figure 4-8 and Figure 4-9.

![Block diagram of the proposed Type 2 frequency response controllers.](image)

Figure 4-8 RAPS system operation: (a) system frequency; (b) DFIG power output; (c) DFIG rotor speed; (d) DG power output.
Under the frequency disturbance at $t = 90$ s, if the droop control is not implemented, no primary frequency response is provided as shown in Figure 4-8, which is the same as the Type 1 controller without droop control. With the droop control, the DFIG electromagnetic torque increases temporarily as shown in Figure 4-9, which results in the increase in power output of DFIGs and reduction in rotor speed as seen in Figure 4-8(b) and (c) respectively. Hence, the frequency excursion during the transient period is significantly reduced (see zoomed plot in Figure 4-8(a)). Opposite to the Type 1 controller, DFIG with the proposed Type 2 controller recovers its pre-disturbance operating condition, rather than changing its power output permanently according to the droop setting. It can be seen in Figure 4-8(b) that the power output from DFIGs after the frequency disturbance is the same as that before frequency disturbance occurs at $t = 90$ s. Hence, the load increase is totally handled by DG, but the ROCOP on DG during the transients is reduced as shown in Figure 4-8(d).

4.6.2.3 Type 3 Controller

As discussed in Section 4.6.2.2, the Type 2 primary frequency response controller is capable of providing primary frequency response with the kinetic energy stored in rotating mass and power reserve obtained through SOPPT control in DFIGs. However, there exists a drawback in Type 2 primary frequency response controller. When frequency response is provided, the negative speed error $e_\omega$ between rotor speed $\omega_r$ and its reference value $\omega^*_r$ results in the reduction of torque reference $\tau_{\text{ref}}$, and thus the reduction in power output. As discussed, this is the mechanism for Type 2 controller to provide temporary frequency response. However, this mechanism attenuates the frequency response that
DFIGs can provide. In order to enhance the primary frequency response in DFIGs provided by Type 2 controller, a supplementary control loop is added to the Type 2 controller given in Figure 4-7 to have the Type 3 controller shown in Figure 4-10.

The control loop compares the DFIG electromagnetic torque reference ($\tau_{\text{ref}}$) with the actual mechanical turbine torque ($\tau_m$), and the weighted torque error ($e_\tau$) is added to the speed error ($e_\omega$). Subsequently, the aggregated error ($e_t$) is fed to the PI controller as represented in (4-11). Please note that the variables used are in per unit.

$$
e_t = (\omega_r - \omega^*) + k_s \cdot (\tau_{\text{ref}} - \tau_m)$$

where $k_s$ is the weighting constant for the torque error. When frequency disturbance occurs in the RAPS system, system frequency decreases and electromagnetic torque $\tau_{\text{ref}}$ increases. The increase in power output and a decrease in rotor speed tends to reduce $\tau^*$, as well as $\tau_{\text{ref}}$ and thus attenuates the frequency response. The slow change in mechanical torque, compared with the rapid change of the electromagnetic torque, results in a positive torque error $e_\tau$. Hence, the reduction in $\tau^*$ can be compensated with the supplementary control loop and subsequently the frequency response can be improved. In the steady-state, the electromagnetic torque and mechanical torque are equal, so the supplementary control scheme has an insignificant effect on steady-state operation.

The performance of the RAPS system under various control schemes (i.e., inertial control only, droop control only, and droop control with supplementary control loop) are
tested with the same loading scenario to compare their performance. The simulation results are shown in Figure 4-11. Due to the mild load change at $t = 90$ s, the ROCOF is small, and droop control acts effectively to the frequency disturbance, whereas the inertial control has an insignificant contribution to frequency support as shown in Figure 4-11(a).

![Figure 4-11 Comparison between DFIGs equipped with different frequency controllers: (a) system frequency; (b) DFIG power output; (c) DFIG rotor speed; (d) DG power output.](image)

It can be seen in Figure 4-11(c) that the DFIG with Type 3 controller has the highest amount of decrease in rotor speed in comparison to other controllers, and hence more kinetic energy can be extracted to increase the power output of the DFIG (see Figure 4-11(b)). Thus, with the additional supplementary control loop, the frequency response has improved. The increase in power output with the supplementary control relieves the burden of DG as demonstrated in Figure 4-11(d). It can be seen from Figure 4-11(a) that the ROCOF has also reduced, and the instant of the frequency nadir has been delayed. At the post-disturbance period, higher frequency dip and power output reduction in DFIGs can be observed in Figure 4-11(a) and Figure 4-11(b) respectively. This is due to the
substantial extraction of the kinetic energy in DFIGs for primary frequency response during the transient period, and thus part of the generated power is utilised to recover the rotor speed and the stored kinetic energy in the rotating mass of the DFIGs after the transient.

Figure 4-12 Phase A voltage and current at the PCC of DFIG with Type-3 controller.

Figure 4-12 shows the phase A voltage and current at the PCC where the DFIG with Type 3 controller is connected to the RAPS system. It can be seen that the magnitude of the voltage is constant under disturbance. Contrarily, the current increases, thus power increases and frequency response is provided. Moreover, the voltage and current are in phase as shown by the zoomed plot in Figure 4-12, which means the power factor of the DFIG system is unity and meets the design objective as mentioned in Section 4.5. The DC-link voltage is presented in Figure 4-13 indicating that the DFIG is able to maintain the DC-link voltage constant while providing frequency response.

Figure 4-13 DC-link voltage of DFIG with Type-3 controller.
4.7 Impacts of Control Parameters and Wind Fluctuations

The proposed Type 3 frequency controller is applied to improve the frequency response by DFIGs under mild system disturbances for which inertial response from DFIGs has an insignificant effect. Hence, the main parameters which can be tuned for the Type 3 frequency controller are droop coefficient $k_D$, supplementary control constant $k_s$ and power reserve $\Delta P$. These are discussed in detail in the following subsections. The performance of the strategy has also tested with scenarios of wind gust and wind ramp.

![Graph](image)

Figure 4-14 Effect of droop coefficient: (a) system frequency; (b) DFIG power output; (c) DFIG rotor speed; (d) DG power output.

4.7.1 Effect of Droop Coefficient on DFIG Performance

DFIGs with Type 3 controller is tested under different values of droop coefficient, and the other parameters are given in Table 4-4. At $t = 90$ s, the load in the RAPS system increases by 0.2 MW. Without the droop controller (or $k_D = 0$), frequency decreases sharply and then recovers to around 49.9 Hz as shown in Figure 4-14(a). The droop control has a significant effect to reduce the ROCOF and frequency deviation by increasing the power output (see Figure 4-14(b)) from DFIGs during the transient period. The time
instant at which the frequency reaches to its nadir can be delayed by using the Type 3 controller. Hence, both the ROCOP and overshoot in power from DG can be decreased as presented in Figure 4-14(d). With the increase in droop coefficient $k_D$, the frequency response becomes more effective.

![Diagrams showing the effect of supplementary control gain on system frequency, DFIG power output, DFIG rotor speed, and DG power output.](image)

Figure 4-15 Effect of supplementary control gain: (a) system frequency; (b) DFIG power output; (c) DFIG rotor speed; (d) DG power output.

### 4.7.2 Effect of Supplementary Control Constant

The effect of supplementary control constant $k_s$ is illustrated in Figure 4-15 and Figure 4-16 with the other simulation parameters given in the Table 4-4. The load increase of 0.2 MW also happens at $t = 90$ s. As it can be seen from Figure 4-15(a) and (d), the ROCOF and the ROCOP of the DG decrease when $k_s$ increases. The time for frequency reaching to the nadir is delayed further with the increase of $k_s$, which is further illustrated in Figure 4-16(a). It can be seen that the instant that frequency nadir occurs is linearly related with $k_s$. Figure 4-16(b) shows the variation in peak power output from DFIGs as $k_s$ varies during the frequency disturbance. A strong linear relationship between the DFIG peak power and $k_s$ can also be observed when stability is maintained. However, due to the kinetic
energy extraction under frequency disturbances, the reduction in power output from DFIGs during the post-disturbance period is amplified (see Figure 4-15(b)) since more power is consumed by the rotor to recover its speed as indicated in Figure 4-15(c). Furthermore, due to the power output reduction at DFIGs, a larger frequency excursion and increase in peak power output from the DG can be seen in Figure 4-15(a) and (d) respectively.

![Graph showing relationship between ks and frequency nadir time delay, and between ks and DFIG peak power output after disturbance.]

Figure 4-16 Effect of supplementary control constant: (a) relationship between $k_s$ and frequency nadir time delay after disturbance; (b) relationship between $k_s$ and DFIG peak power output after disturbance.

### 4.7.3 Effect of Power Reserve

Owing to the kinetic energy in the rotating mass, the Type 3 controller can achieve frequency response to a certain extent even without any power reserve. The proposed SOPPT control reserves a fraction of the available wind power. This strategy is superior to using only kinetic energy in DFIG attributing to the merits of: (1) avoiding excessive power extraction; (2) releasing more energy. Thus, the presence of power reserve further may enhance the benefits of the Type 3 controller as explored below.

As with the scenario studied in section 4.7.1 and 4.7.2, the DFIGs equipped with Type 3 frequency controller are investigated under the disturbance of a sudden load increase of 0.2 MW (which is same as before). Different values of power reserves in DFIGs are investigated and the performance of the controller is tested with the other parameters listed in Table 4-4. Figure 4-17 shows the effect of power reserve on the frequency response. Due to the different power reserves, the RAPS system initial operating states before the occurrence of the disturbance at $t = 90$ s are different. In order to demonstrate the effects
of power reserve, the variations in DFIG power output, rotor speed and DG power output are presented in Figure 4-17(b), (c) and (d) respectively.

![Graphs showing effects of power reserve](image)

Figure 4-17 Effect of power reserve: (a) system frequency; (b) DFIG power output variation; (c) DFIG rotor speed variation; (d) DG power output variation.

It can be seen in Figure 4-17(a) that the ROCOF is reduced with the increase in power reserve. With the power reserve, the mechanical power from wind turbines increases when rotor speed decreases. Hence, extra power is added into the power output of the DFIGs as shown in Figure 4-17(b), which reduces the ROCOP of the DG (see Figure 4-17(d)). Moreover, the frequency dip and maximum power output from the DG have decreased during the transient period with a higher power reserve as shown in Figure 4-17(a) and (d) respectively. However, the improvement of the frequency response does not linearly vary with the increase in power reserve.

4.7.4 Effect of Wind Speed Variation

In this scenario, wind speed variation is taken into consideration to study its impact on the frequency response from DFIGs equipped with Type 3 controller. This scenario is used to evaluate the robustness of the controller under worst possible conditions. That is,
a wind gust down or wind ramp down [4] incident occurs when DFIGs are providing frequency support under a frequency event caused by a sudden load increase.

Figure 4-18 Wind profiles: (a) wind gust down; (b) wind ramp down.

1) Wind gust: The wind gust can be presented qualitatively as given by (4-12) [106, 132].

\[
V_w = \begin{cases} 
0, & t < t_{1G} \\
MAXR \cdot [2\pi \cdot \frac{t - t_{1G}}{t_G}] & t_{1G} < t < t_{1G} + t_G \\
0, & t > t_{1G} + t_G
\end{cases}
\]  

(4-12)

where MAXG is the gust peak, \( t_{1G} \) is the gust starting time, and \( t_G \) is the gust period. The gust parameters and other control parameters used in this case study are listed in the Table 4-4, and the gust down wind profile is shown in Figure 4-18(a).

The disturbance used is still the same which is the sudden load increase of 0.2 MW at \( t = 90 \) s. As shown in Figure 4-19, the results for DFIGs with or without the proposed Type 3 frequency controller are presented when a wind gust down occurs. It can be seen in Figure 4-19(a) that frequency response is available at both instants when load increases and wind speed decreases. However, due to the continuous reduction in wind speed, mechanical power from wind decreases rapidly as shown in Figure 4-19(b), and the DFIG power output decreases after providing minor frequency response. Consequently, the frequency nadir for the scenario with frequency controller is lower in comparison to the scenario without the frequency controller. Nevertheless, in the scenario with frequency controller, the instant that frequency reaches its nadir is delayed as compared with the scenario without frequency controller, and ROCOP on DG is alleviated (see Figure...
Furthermore, the system maintains its stability and rides through the worst condition when sudden load increase and wind speed decrease occurs simultaneously.

Figure 4-19 Effect of wind gust down: (a) system frequency; (b) DFIG power output; (c) DFIG rotor speed; (d) DG power output. (Note: ‘f’ refers to frequency in the figure).

2) Wind ramp: Similar with the above case, a wind ramp down, as presented by (13), is introduced in the simulated system.

\[
V_w = \begin{cases} 
0, & t < t_{1R} \\
MAXR \cdot \left[ \frac{t_{1R} - t}{t_{1R} - t_{2R}} \right], & t_{1R} < t < t_{2R} \\
MAXR, & t > t_{2R}
\end{cases}
\]  \hspace{1cm} (4-13)

where \( MAXR \) is the ramp peak, \( T_{1r} \) is the ramp starting time, and \( T_{2R} \) is the ramp ending time. The ramp parameters and other control parameters used in this case study are listed in the Table 4-4, and the ramp down wind profile is shown in Figure 4-18(b). The simulation results are shown in Figure 4-20. The DFIGs tends to provide frequency response under frequency disturbance when wind speed decreases suddenly as seen in Figure 4-20(a), but the support is not effective due to the wind power reduction. However, the
time instant at which frequency nadir occurs is also delayed in comparison to the scenario without the frequency controller, and system stability can be maintained. After the wind ramp down, DFIGs power output settles at a new value (see Figure 4-20(b)) and rotor stabilises at a lower speed as shown in Figure 4-20(c).

![Figure 4-20](image)

Figure 4-20 Effect of wind ramp down: (a) system frequency; (b) DFIG power output; (c) DFIG rotor speed; (d) DG power output. (Note: ‘f’ refers to frequency in the figure).

### 4.8 Summary

In this chapter, a droop based primary frequency controller was proposed to provide short-term frequency response without a high pass filter. An improved SOPPT strategy was proposed by combining the traditional constant power reserve strategy and constant percentage power reserve strategy. The research investigations shown that SOPPT strategy can enhance the primary frequency response. Furthermore, a supplementary control loop using electromagnetic torque reference signal as a feedback was introduced at the frequency controller to improve the frequency response. The proposed controller can significantly reduce the system ROCOF while relieving the ROCOP at the DG.
The performance of the proposed controller was further tested under different values of control parameters, such as droop coefficient \((k_D)\), supplementary loop gain \((k_S)\), and power reserve \((\Delta P)\). From the simulation studies, it was revealed that: 1) A larger \(k_D\) provides improved frequency response; 2) The time for frequency to reach its nadir and the maximum power output of DFIGs during the frequency response period have a linear relationship with the \(k_S\); and 3) Power reserve improves the primary frequency response of the DFIGs in RAPS systems when the proposed primary frequency response controller is implemented. Since high \(k_D\) and \(k_S\) may cause instability in the RAPS system, and higher power reserve attenuates the energy production from the DFIGs, trade-offs among these three parameters largely depend on the frequency regulation requirement when tuning the frequency controller to achieve desired dynamic performance. Financial benefits might be compromised under the critical scenario.

Wind gust down and ramp down scenarios were also considered to validate the robustness of the proposed strategy. It shown that the system stability can be well maintained with the proposed control strategy, even though frequency support is limited during frequency response period if large wind speed variations and sudden load increase occur simultaneously. The proposed frequency response strategy was tested in DFIGs, and it can also be readily applied in full-converter based WECS such as PMSGs with minor adjustments.
Chapter 5

A Suboptimal Power Point Tracking based Control Approach for Autonomous Operation of a Solar-PV Dominated Hybrid RAPS System

5.1 Foreword

The proposed SOPPT strategy was validated for DFIGs in a hybrid RAPS system in Chapter 4. The mechanical power reserve established using SOPPT was utilised to enhance the primary frequency response provided by the WECS. In this chapter, the proposed power reserving strategy is extended to apply for frequency regulation in solar-PV dominated RAPS system. The strategy aims to enable the non-inertial solar energy conversion system to participate actively in frequency regulation, thus improving the autonomy of the PV-diesel hybrid RAPS system.

5.2 Overview

MPPT is commonly being used in solar-PV power generators to maximise solar energy extraction. In this chapter, it was proposed to operate the solar-PV generator at the SOPPT to manage power balance in a PV-diesel hybrid RAPS system. Using the proposed SOPPT strategy, the solar-PV generator can be operated in one of the four different operating modes: (I) frequency control mode, (II) active power control mode, (III) constant power reserve mode, and (IV) voltage support mode. DG can also be operated in one of the two modes: (I) synchronous condenser mode and (II) generation mode. Simulation studies were carried out to validate the effectiveness of the SOPPT-based power management strategy for a PV-Diesel RAPS system. Results indicated that the proposed SOPPT strategy can improve the RAPS system performance even under worst operating conditions. The proposed strategy will also improve the lifetime of the DG by utilising the
auxiliary services provided by the solar-PV generator, and also it eliminates the requirement for a dummy load or energy storage system for frequency control. The structure of the rest of Chapter 5 is presented in Figure 5-1.

Figure 5-1 Structure of Chapter 5.

5.3 Background

RAPS systems operate independently from utility power systems, and it is an ideal option for electrically “isolated” areas where grid connection is financially or technically infeasible. Due to the lack of dominant energy resource and interconnection in RAPS systems, power management in a RAPS system is more challenging than the utility grid, in particular when non-schedulable renewable energy resources, like solar-PV, are utilised as main power generating source [101]. Both active and reactive power should be balanced between generation and load demand to achieve frequency and voltage regulation of the RAPS system. The energy storage system can effectively mitigate the impact of active power fluctuations in a RAPS system by absorbing surplus energy when generation is more than sufficient to supply the load demand, and injecting power when an energy deficit occurs in the system [133, 134]. Dummy load can be used to consume extra energy, preventing the storage system from overcharging [135]. Nevertheless, the capital investment for the energy storage system and dummy load is significant, and the O&M cost will add to the energy cost.

DG has been used as the dominant energy resource in conventional RAPS systems [22]. The DG has the advantage of high reliability, but environmental and economic factors prohibit its continuing expansion. Another constraint is its poor efficiency under low load condition [101]. Usually, the load in a RAPS system fluctuates frequently, and may result in very low load factor. The DG units in diesel-only RAPS systems are commonly oversized to fulfil the peak demand, and operating efficiency can be low during the off-peak
period. The utilisation of renewable energy resources in both large utility grids and RAPS systems has gained a wide attention. In particular, profiting from its low susceptibility to geographical position, and ease of installation, solar-PV is widely being used. Solar-PV generators are mainly operated under MPPT strategy to maximise the economic benefit. Due to the high penetration of solar energy in power system and the fast responding nature of the power electronic converters, solar-PV generators are increasingly demanded to provide auxiliary services, such as frequency and voltage support [136], in particular for RAPS systems where small number of generators with low capacity serve the loads [137]. In [133], the inverter based energy resources were used to regulate the voltage and frequency in a RAPS system by operating the distributed generation in different modes, but no details about distributed generation model were given and its control mechanism was not explained. A similar RAPS system and control logic are also studied in [134] with detailed solar-PV models. In both [133] and [134], energy storage system is utilised for frequency regulation. In [138], a reconfigurable controller is proposed, enabling the solar-PV generator to work at island mode without storage. However, the impact of solar energy unavailability has not been investigated. The solar-PV generator is used to regulate system frequency with droop control strategy, and a power-tracking algorithm is suggested in [137] to track the power reference rapidly. The power output from the solar-PV generator is curtailed when the system frequency is above a certain value. Nevertheless, frequency support is not available when the frequency decreases below a critical value. The operating efficiency of the DG is considered in [139, 140] by defining a minimum loading level for the DG in the hybrid diesel-PV RAPS system. However, with DG controlling the frequency and solar-PV controlling the voltage, the solar-PV inverter may experience overloading, and a large capacitor is required for the inverter to regulate system voltage [141]. Furthermore, in [141] reactive power capability of the SM is not utilised, and the fuel savings cannot be maximised with this approach as the DG continuously supplies power even when the solar-PV generation is able to fulfil the load demand. With regard to active power control, the solar-PV power output is controlled using a lookup table in [140], which depends on the parameters of the solar-PV arrays, whereas a sliding mode controller is proposed in [139].

Based on the operation of the solar-PV generator at SOPPT mode, a supervisory power management strategy is developed in a hybrid PV-diesel RAPS system. The frequency regulation and voltage regulation are achieved by coordinating solar-PV generator with
the DG through the multimode operation. The proposed strategy can eliminate the necessity of an energy storage system or a dummy load in the RAPS systems. Comprehensive analysis is carried out to study the dynamic performance of the DG and improve its transient performance, especially during mode transition. Detailed multimode operation logic and corresponding solar-PV controllers are also investigated.

5.4 System Modelling

To demonstrate the proposed SOPPT-based power management strategy, a PV-diesel RAPS system presented in Figure 5-2 is investigated. A two-stage converter converts the DC power generated by the solar-PV arrays to AC. The boost converter regulates the operating point of the solar-PV arrays whereas the inverter supplies AC voltages while maintaining constant voltage at the DC-link. The diesel engine drives the SM through a clutch. When the clutch is engaged, the SM operates as a generator. Otherwise, the SM operates as a synchronous condenser [142]. The detailed models of the solar-PV generator and the DG are discussed in following subsections.

![Figure 5-2 Architecture of the PV-diesel RAPS system.](image)

5.4.1 Solar-PV Generator Modelling

As shown in Figure 5-2, the equivalent circuit of a solar-PV module is composed of a current source, a parallel diode, a parallel resistor \(R_p\), and a series resistor \(R_s\). The mathematical representation of the equivalent circuit has the form of (5-1) [134].
where $I_m$ is the module output current, $U_m$ is the module terminal voltage, and $I_s$ is the photocurrent which is proportional to the solar irradiance. The $I_p$ is the current through the parallel resistance and $I_d$ through the diode. $I_r$ is the diode reverse saturation current, $q$ is the electrical charge ($1.6 \times 10^{-19}$ C), $\eta$ is the p-n junction quality factor, $k$ is the Boltzmann constant ($1.38 \times 10^{-23}$ J/K), and $T$ is the ambient temperature (in Kelvins).

To obtain the required power output, a multitude of solar-PV modules are connected in series and in parallel to form solar-PV arrays. The terminal voltage across the input capacitor $C_m$ of the boost converter is symbolized as $U$ in Figure 5-2, and current flowing through the inductor $L_s$ is $I$. The electrical parameters of the solar-PV module used in this chapter under standard test conditions (STC) are listed in the Table 5-1. The nonlinear current-voltage relationship of the solar-PV module, which is known as the $I$-$U$ photovoltaic characteristic curves, is presented by the dashed blue curves in Figure 5-3 for various solar irradiance levels. The relationship between power output and terminal voltage, commonly known as $P$-$U$ power characteristic curves, is also shown as solid (red) curves in Figure 5-3 for various solar irradiance levels.

![Figure 5-3 $I$-$U$ characteristic and $P$-$U$ characteristic of a solar-PV module.](image)
Table 5-1 Electrical parameters of the solar-PV module

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Open Circuit Voltage (V)</td>
<td>64.2</td>
</tr>
<tr>
<td>Short Circuit Current (A)</td>
<td>5.96</td>
</tr>
<tr>
<td>Voltage at MPP (V)</td>
<td>54.7</td>
</tr>
<tr>
<td>Current at MPP (A)</td>
<td>5.58</td>
</tr>
</tbody>
</table>

It can be seen from the power characteristic curve that the MPP marked with ‘*’, indicates for each solar irradiation level. The MPP can be tracked with a MPPT strategy to maximise the solar energy extraction. Variable MPPT techniques have been proposed in the published literature [143], and perturbation and observation (P&O) method and incremental conductance (IC) method are popular techniques used by many researchers [144, 145]. The P&O method is implemented by imposing periodic positive or negative perturbations for the terminal voltage of the solar-PV array. If the varying direction (increase or decrease) of the solar-PV output power is the same with the varying direction of the terminal voltage, then the same voltage perturbation is applied to the next step. Otherwise, a voltage perturbation of opposite polarity with the present step perturbation is imposed in the next step. The P&O has the advantage of ease of implementation, whereas sudden irradiance variation may confuse the controller, and oscillations around the MPP are inevitable [146]. The IC algorithm can overcome the drawbacks of P&O [146]. The IC algorithm is developed based on the fact that the derivative of the power with respect to the voltage at MPP is zero, hence (5-2) can be derived. By adding a simple PI controller, the performance of the IC method can be improved with fewer oscillations in the steady-state and thereby it can improve the tracking performance [143].

\[
\frac{dI}{dU} + \frac{I}{U} = 0
\]  

(5-2)

Voltage oriented vector control [141] is a common method to control the interface inverter of the solar-PV generator. If the direct-quadrant (d-q) reference frame rotates synchronously with d-axis aligned with grid voltage, then the active power and reactive
power supplied by the inverter can be controlled by the \( d \)-axis component and \( q \)-axis component of the current respectively, which are given by (5-3) and (5-4) respectively.

\[
P_{PV} = \frac{3}{2} u_{pd} \cdot i_{pd} \tag{5-3}
\]

\[
Q_{PV} = -\frac{3}{2} u_{pd} \cdot i_{pq} \tag{5-4}
\]

where \( P_{PV} \) and \( Q_{PV} \) are the active and reactive power respectively, \( i_{pd} \) and \( i_{pq} \) are \( d \)-axis and \( q \)-axis component of the current, and \( u_{pd} \) is the \( d \)-axis component of voltage at the point of connection of solar-PV generator into the grid.

### 5.4.2 Diesel Engine and Governor Modelling

The diesel engine consumes fuel and produces mechanical torque based on the governor response. As shown in, the controller is designed with a second-order transfer function, and the fuel injection actuator with a third-order transfer function [129]. A time delay \( T_D \) is added to the model in order to represent the time delay between the fuel injection and mechanical torque developed at the shaft of the diesel engine. As claimed in [114], the engine speed in per unit is approximated by (5-5).

\[
\omega = \frac{1}{2H_d} \int (\tau_d - \tau_c) dt \tag{5-5}
\]

where \( H_d \) is the diesel engine inertia constant, \( \tau_d \) is the engine mechanical torque, and \( \tau_c \) is the transmitted torque from engine to SM, which is given by (5-6).

\[
\tau_c = \begin{cases} 
0, & \text{clutch disengaged} \\
\frac{H_s \cdot \tau_d + H_d \cdot \tau_c}{H_s + H_d}, & \text{clutch engaged}
\end{cases}
\tag{5-6}
\]

where \( H_s \) and \( \tau_e \) are the inertia constant and electrical torque of the SM respectively. As claimed in [139], a second order function can be used to present the engine dead time, which is represented as (5-7).

\[
e^{-T_{pd}} = \frac{1 - k_1 \cdot s + k_2 \cdot s^2}{1 + k_1 \cdot s + k_2 \cdot s^2} \tag{5-7}
\]
where $k_1 = T_d/2$ and $k_2 = T_d^2/12$. The electric torque $\tau_e$ of SM can be considered as disturbance and therefore the open loop transfer function of the system shown in Figure 5-4 can be obtained as (5-8). The derivation process is detailed in Appendix A. The exciter of the SM given in [23] is used for this chapter, and the main parameters of the DG are given in Table 5-2.

$$TF_{ol}(s) = \frac{K}{2(H_s + H_d)} \frac{1 + sT_1 + s^2T_2}{s(1 + sT_3)(1 + sT_4)} e^{-sT_5}$$

$$\tau_e = \tau_{max} - \tau_{min}$$

$$\omega_{ref} = \frac{1}{H_s + H_d} (H(s)\omega)$$

Figure 5-4 Diesel engine and governor block diagram.

Table 5-2 DG parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
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<td>Rated Power (kVA)</td>
<td>275</td>
<td>$T_1$</td>
<td>0.12</td>
</tr>
<tr>
<td>Rated Speed (rpm)</td>
<td>1500</td>
<td>$T_2$</td>
<td>0.0002</td>
</tr>
<tr>
<td>Rated Voltage (V)</td>
<td>400</td>
<td>$T_3$</td>
<td>0.35</td>
</tr>
<tr>
<td>Pole Pairs</td>
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<td>$T_4$</td>
<td>0.25</td>
</tr>
<tr>
<td>$H_d$ (s)</td>
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<td>$T_5$</td>
<td>0.009</td>
</tr>
<tr>
<td>$T_D$ (s)</td>
<td>0.024</td>
<td>$T_6$</td>
<td>0.0389</td>
</tr>
<tr>
<td>$H_s$ (s)</td>
<td>1</td>
<td>$K$</td>
<td>40</td>
</tr>
</tbody>
</table>

5.5 Proposed Power Management Strategy

If a conventional MPPT strategy is implemented at the solar-PV generator in a PV-diesel RAPS system (without employing energy storage), a dummy load should be used
to consume the surplus energy when the generation is greater than load demand. In addition, DG may operate at a very light loading level, which deteriorates the operating efficiency of the DG. Therefore, it is beneficial for the solar-PV generator to tailor its power output deliberately in certain situations by operating at the suboptimal power point, which is defined as SOPPT in this thesis. With the SOPPT control strategy, the requirement for energy storage system or dummy load can be eliminated, and DG can be operated above the minimum loading level (usually specified by the DG manufacturers) at all the times.

In order to effectively utilise the power reserve available at the solar-PV generator (i.e., when operated at SOPPT), a multimode operation strategy is introduced in the PV-diesel RAPS system. In this approach, solar-PV generator is operated in one of the four different operating modes: (I) frequency control mode, (II) active power control mode, (III) constant power reserve mode, and (IV) voltage support mode. Based on the mismatch between the maximum available solar-PV generation and current load demand, an appropriate operating mode can be selected and implemented. The details about the different operating modes are discussed below.

5.5.1 Operation Mode I

If the load demand $P_{load}$ is less than $P_{PV}^{MPP}$ by a particular value, $\Delta P$, as shown in (5-9), no active power is requested from the DG.

$$P_{load}(t) < P_{PV}^{MPP}[i(t)] - \Delta P(t)$$  \hspace{1cm} (5-9)

where $P_{PV}^{MPP}[i(t)]$ is the maximum available power from solar-PV generator under the solar irradiance of $i$ at the time interval of $t$. As discussed in [147], if the $\Delta P$ is chosen as zero, the frequency deviation during the mode transition can be high due to the energy deficiency and slow response of the DG. $\Delta P$ can be determined with the historical load profiles. By examining the rate of change of load, nonzero values can be dynamically assigned to the $\Delta P$, which can be utilised to reduce the energy deficiency during the mode transition, and hence frequency deviation is reduced.

With the energy reserve, the solar-PV generator is capable of operating in frequency control mode, hence it shifts away from its MPP to match with the load. The diesel engine can be shut down after disengaging the clutch mounted on the diesel engine shaft and the SM shaft. Since the solar-PV inverter is fully engaged to supply active power, it does not
provide any reactive power in this mode, whereas the SM is operated in SC mode to regulate voltage through excitation control. The maximum generation of reactive power should be limited based on the reactive capability curve given by the manufacturer of the synchronous generator to avoid overloading the synchronous generator [148]. As shown in Figure 5-5, the generator can only safely operate in the shaded region bounded by the generator and prime mover limits. This power limitation also applies to the other operation modes.

\[
P_{\text{load}}(t) > P_{PV}^{\text{MPP}}[i(t)] - P_{PV}^{\text{res}} + P_{DG}^{\text{min}}
\]  

(5-10)

where \(P_{PV}^{\text{res}}\) is the designed constant power reserve at the solar-PV generator and \(P_{DG}^{\text{min}}\) is the designed lower loading limit of DG. The DG operates in a grid forming mode to establish system frequency and voltage reference in the system, whereas the solar-PV generator maintains constant power reserve. The clutch should be engaged to transfer mechanical torque from the engine to the machine. The active power reference for the solar-PV generator is given by (5-11).

\[
P_{PV}^*(t) = P_{PV}^{\text{MPP}}[i(t)] - P_{DG}^{\text{min}}.
\]  

(5-11)

The main reason for the solar-PV generator to compromise its maximum power output in this mode is to provide frequency support and relieve torque stress on DG under system
disturbances. In addition, the DG can always operate above its lower loading limit during this mode of operation.

5.5.3 Operation Mode III

Under the previous two operating modes, if $P_{\text{load}}$ satisfies (5-12), then the RAPS system will be either unable to maintain its stability or unable to operate the DG above its lower loading limit.

$$P_{\text{PV}}^{\text{MPP}}[i(t)] - \Delta P(t) < P_{\text{load}}(t) < P_{\text{PV}}^{\text{MPP}}[i(t)] - P_{\text{DG}}^\text{res} + P_{\text{DG}}^{\text{min}}$$

(5-12)

With the operating Mode III, the solar-PV generator is operated at power control mode, whereas the DG still operates in grid forming mode. The solar-PV generator curtails its power output to ensure the DG is loaded at its lower loading limit. Hence, the active power setting for the solar-PV generator can be determined by (5-13).

$$P_{\text{PV}}^\star(t) = P_{\text{load}}(t) - P_{\text{DG}}^{\text{min}}.$$  

(5-13)

5.5.4 Operation Mode IV

The maximum available power from the solar-PV generator depends on the climatic conditions, hence the power output can be very low or even zero at certain times of the day (e.g., during passing clouds or at night). In such situations the aforementioned operating modes are unable to maintain stability in the RAPS system; thus another mode is required to handle low solar power situations, which can be defined by (5-14).

$$P_{\text{MPP}}[i(t)] < P_{\text{PV}}^{\text{min}}.$$  

(5-14)

where $P_{\text{PV}}^{\text{min}}$ is the stipulated critical MPP to trigger Mode IV.

In this mode, solar-PV generator operates at the MPPT mode, while the DG is fully engaged in maintaining system frequency and leaves relatively lower capacity for voltage regulation, which is given as (5-15).

$$P_{\text{PV}}^\star(t) = P_{\text{PV}}^{\text{MPP}}[i(t)].$$  

(5-15)

Unlike the previous three modes, the inverter system of the solar-PV generator can participate in voltage regulation by using its available Volt-Ampere (VA) capacity under low
solar irradiation. Therefore, no additional VA capacity is required for the interfacing inverter. The inverter of the solar-PV generator will provide reactive power together with the DG. To ensure safe operation of the RAPS system without overheating the DG and solar-PV generator, both DG and solar-PV generator should be loaded within their power limits. To determine the reactive load limits in the RAPS system, the DG capability curve and solar-PV inverter capability curve are drawn in a single diagram (see Figure 5-5).

The original point of the inverter capability curve plane overlays on the point \((P_{DG}, Q_{DG})\) as indicated by D in the synchronous generator capability curve plane. Hence, the active power load, as shown as P-coordinate \(P_{load}\) of point A in the synchronous generator capability curve plane, is shared between DG and solar-PV generator, which can be denoted by (5-16).

\[
P_{load} = P_{pv} + P_{DG}.
\]

where \(P_{pv}\) is the power output from solar-PV generator and it is shown as P-coordinate of point \(A'\) in the inverter capability curve plane.

As shown in Figure 5-6, the reactive power capability of DG \((Q_{DG}^{max})\) is indicated by C on the synchronous generator capability curve when the active power output from DG is \(P_{DG}\). The point \(B'\) on the inverter capability curve gives the reactive power capability of the inverter, i.e., \(Q_{pv}^{max}\) presented in (5-17), when solar-PV provides active power \(P_{pv}\).

\[
Q_{pv}^{max}(P_{pv}) = \sqrt{S_{pv}^{2} - P_{pv}^{2}}
\]
where $S_{PV}$ is the capacity of the inverter. Therefore, the reactive load limit in the RAPS system can be determined by (5-18).

$$Q_{load}(t) < Q_{PV}^{\text{max}}(P_{PV}) + Q_{DG}^{\text{max}}(P_{DG}).$$

(5-18)

The decision-making process involved in determining the suitable operation modes can be illustrated in Figure 5-7. The details of the four operating modes are summarised in Figure 5-8. It also shows the transition logics among the four operating modes.

![Flowchart of the power management decision-making process.](image)

Figure 5-7 Flowchart of the power management decision-making process.

### 5.6 Controller Design

By operating the DG and the solar-PV generator in a coordinated manner, active and reactive power generation and demand in the RAPS system can be balanced at each time instance. The DG regulates the active and reactive power through diesel engine governor and SM exciter respectively, whereas $d$-axis and $q$-axis components of inverter current control the active and reactive power of the solar-PV generator respectively. In this section, power controllers for the DG and the solar-PV generator are designed based on the
multi-mode operation strategy explained in Section 5.5, and their responses to different operating conditions are analysed.

**Mode I**
PV: SOPPT, f control
DG: SC, v control
Clutch: Disengaged

**Mode II**
PV: SOPPT, P control
g DG: f & v control
Clutch: Engaged

**Mode III**
PV: SOPPT, f support
g DG: f & v control
Clutch: Engaged

**Mode IV**
PV: MPPT, v support
g DG: f & v control
Clutch: Engaged

Figure 5-8 RAPS system operating modes and their transition.

5.6.1 Diesel Generator Control

1) Diesel governor: The open loop transfer function of the diesel engine and governor, $T_{F_{ol}}(s)$ is presented in (5-8). The open loop frequency response of diesel engine system is shown in Figure 5-9(a) and the step response of the corresponding closed loop transfer function is shown in Figure 5-9(b).
Figure 5.9 Diesel engine system dynamic performance: (a) Open loop frequency response; (b) Closed loop step response.

As shown in Figure 5.9(a), there is a slope of -20 dB per decade (dB/dec) around the crossover frequency, which is approximately 1 Hz, which helps to stabilise the system while providing a fast dynamic response. The step response presented in Figure 5.9(b) has an overshoot of less than 20% and a rise time of around 0.25 s. The system is slightly under-damped, responds quickly and has only small oscillations. Additionally, the slope of the magnitude response plot reaches up to -80 dB/dec in the high-frequency range, contributing to less interference from high-frequency noises.

Figure 5.10 Root locus diagram of the closed loop system as a function of control parameter $T_l$. 
To study the effect of the parameters, e.g., $T_1$, of the controller on the stability of the DG, the root-locus method given in [149] is applied. That is to transform the characteristic equation as shown in (5-19) of the closed loop transfer function of the diesel system to the form given by (5-20).

$$1 + H(s) \cdot TF_{OL}(s) = 0$$  \hspace{1cm} (5-19)

$$1 + T_1 \cdot L[s, (T_2, T_3, T_4, \ldots)] = 0$$  \hspace{1cm} (5-20)

where $H(s)$ is the feedback loop which is taken as 1 in this chapter, and the transfer function $L[s, (T_1, T_2, T_3, \ldots)]$ is a rational function of $s$ with constants $T_1, T_2, T_3, \ldots$ as its parameters. The solutions of (5-20) are the roots of (5-19) and thus the poles of the closed loop system. The loci of all possible roots of (5-20) as $T_1$ varies from zero to infinity are plotted in Figure 5-10. It can be seen that when $T_1$ is less than 1.65, the real parts of all the poles of the closed loop system are negative, and hence the system is stable.

2) **Clutch Control:** Clutch transforms the RAPS system operation mode from Mode I to other three modes or from other three modes to Mode I. When the clutch is engaged, the shaft of the SM rotates at the same speed of the shaft of the diesel engine, and the engine drives the machine to operate in generating mode. When the clutch is disengaged, the two shafts rotate at their own speeds, and the machine operates at the SC mode without generating any active power. As explained in Section III, to engage the clutch, the following conditions have to be fulfilled:

1) The condition specified by (5-10), (5-12), or (5-14) to operate in Mode II, Mode III or Mode IV respectively should be satisfied;

2) The speed difference of the diesel engine shaft and SM shaft should be less than a certain value $\varepsilon$, which can be presented by (5-21).

$$|\omega_d - \omega_g| < \varepsilon$$  \hspace{1cm} (5-21)

where $\varepsilon$ is taken as $10^{-5}$ [114] in this chapter. The clutch controller is presented in Figure 5-11.
5.6.2 Solar-PV Generator Control

With the two-stage converter, the boost DC/DC converter controls the voltage across the solar-PV array array terminals and thus it controls the power output from the solar-PV array. The inverter maintains the DC link voltage while supplying power to the system at a particular power factor.

**Boost converter control**: In this chapter, the IC algorithm described in Section 5.4 is used to detect the MPPs by changing the duty ratio of the boost converter, the PV array terminal voltage can be changed. As it can be seen from the power characteristic curve shown in Figure 5-3, the power output can be adjusted by varying solar-PV array terminal voltage according to the power requirements of the RAPS system. To enable wide range of power variation and avoid excessive low voltage, the P-U characteristic curve at the
right side of the MPP is chosen for power regulation. Under each operating mode, the system is equipped with a different operating strategy to generate the duty signal for the boost converter, which is illustrated in Figure 5-12.

In *Mode I*, the solar-PV generator controls the system frequency, so that the frequency error is fed into the PI controller and the duty ratio is generated accordingly to control the solar-PV system power output to match with the load. Constant power reserve method is used for *Mode II*, and the power reserve is utilised to provide the frequency response when a frequency deviation occurs in the RAPS system. A frequency droop term is added to the power control loop and the summation with the power reference error forms the input reference for the PI controller to generate the duty ratio of the boost converter. Since the DG operates in frequency control mode, the solar-PV generator provides only frequency support during the transient period of frequency disturbance. In *Mode III*, a power control method is also used, but the power reference is determined by (5-13), and the PI controller produces the duty signal based on the error between the actual power output and reference power. Under low power output of the solar-PV generator *Mode IV* is activated, in which the solar-PV generator operates at the MPPT mode. In particular, to avoid saturation of the controller and cause large transient during the mode transition, the control output of the current mode is used to initialise the controller for the mode to which the system is transiting.

![Diagram](image)

Figure 5-13 Inverter controller: (a) Active power control; (b) Reactive power control.
Inverter control: As mentioned in Section 5.4, the active and reactive power generated by the solar-PV generator can be controlled by varying \( d \)-axis and \( q \)-axis current components respectively. The \( d \)-axis current reference is generated by a PI controller based on the error between nominal DC-link voltage and actual DC voltage (see Figure 5-13(a)). Under Mode II, the frequency droop branch is also added to the error signal to enhance the frequency response of the solar-PV generator. In regard to reactive power control, the \( q \)-axis current reference is set at zero except in Mode IV, under which inverter capacity can be utilised to supply reactive power. When reactive power support is required, i.e., system voltage drifts away from its nominal value, a voltage droop control method determines the reactive power reference. The reference value is compared with the actual value, and the error is processed at the PI controller to determine the \( q \)-axis current reference. The control diagram is shown in Figure 5-13(b).

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
<th>Parameter</th>
<th>Value</th>
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</thead>
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<tr>
<td>Rated Voltage (V)</td>
<td>400</td>
<td>( C_{in} ) (( \mu )F)</td>
<td>100</td>
</tr>
<tr>
<td>Rated Frequency (Hz)</td>
<td>50</td>
<td>( C ) (mF)</td>
<td>24</td>
</tr>
<tr>
<td>Rated DC Voltage (V)</td>
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<td>( L_{f1} ) (mH)</td>
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</tr>
<tr>
<td>Inverter Switching Frequency (Hz)</td>
<td>1650</td>
<td>( L_{f2} ) (mH)</td>
<td>0.45</td>
</tr>
<tr>
<td>Boost Switching Frequency (Hz)</td>
<td>5000</td>
<td>( C_t ) (( \mu )F)</td>
<td>200</td>
</tr>
</tbody>
</table>

5.7 Simulation Results

A RAPS system with a solar-PV generator and a DG was modelled in MATLAB/Simulink using the SimPowerSystem toolbox. The DG has a capacity of 275 kVA and the solar-PV generator is rated at 100 kW under standard test conditions (STC). Ratings of the system components can be determined using the approach developed by the authors in [150]. The component sizes are determined in an iterative manner until the system reliability level denoted by LOLE meets a designated level with the solar irradiation and load profiles as discussed in Chapter 3. The lower loading limit of the DG is set to be 10% of the capacity of the DG. Since the purpose of this chapter is to evaluate the performance of the power management of the RAPS system, the impact of ambient temperature on the
solar-PV generator has not been considered here, and the temperature of the solar-PV cells is considered to be 25 °C. The simulation parameters are listed in Table 5-3.

Figure 5-13 Active power management.

The case study demonstrates the solar-PV-generator’s capability to track maximum power at a given instance as well as the ability to adjust its power output under multimode operation. The simulation starts with a solar irradiance of 1 kW/m² and the total load of 50 kW + j 20 kVAR. The MPP is detected as 100 kW, which is greater than the sum of load active power and the margin ΔP. Hence, the RAPS system switches to Mode I at t = 0.2 s (see Figure 5-13). The solar-PV generator supplies all the active power demand of the load while maintaining the system frequency, and the active power output of the DG is zero in this case (see Figure 5-13). The load changes to 85 kW + j 35 kVAR at t = 4.5 s and the condition given by (5-9) is still satisfied. The solar-PV generator increases its power output to match with the load demand while the DG supplies no active power. It is worth to be noted that natural inertia response is provided by the SM as seen in Figure 5-13 when system load increases.

When another 12 kW load is added to the system, the condition given by (5-9) is no longer fulfilled, and the system loading level meets the condition given in (5-12). System is commanded to switch to Mode III, however, the clutch is disengaged and diesel engine has been shut down under Mode I operation. As described in Section IV, speed difference between the SM and the diesel engine should be less than ε. Due to the slow mechanical
response as well as the cranking process of the diesel engine, it takes considerable time to engage the clutch. During this transition period, the power margin $\Delta P$ comes into effect and is utilised to reduce the energy deficiency and improve the frequency regulation. The detailed SM and diesel engine operation during the transition process is illustrated in Figure 5-14.

At $t = 9$ s, the clutch engaging condition given in (5-12) is fulfilled. At this stage, the cranking system is usually switched on to raise the engine speed to firing speed. Firing speed is considered to be 0.3 p.u. in this chapter. In order to simplify the simulation of cranking process, the diesel engine is running at a firing speed rather than being shut down when it is not driving the SM, and a time delay of 0.5 s is added to represent the cranking time period as used in [114]. Hence, the diesel engine is fired at $t = 9.5$ s and the speed increases under the control of the diesel governor. Due to the stored kinetic energy release during this process, the synchronous generator speed deceases. At $t = 11.5$ s, the clutch engaging requirement given in (5-21) is also satisfied and subsequently the clutch engages. Afterwards, the diesel engine and the SM operate at the same speed and recover to its nominal speed.

![Figure 5-14 DG mode transition.](image-url)
After the clutch is engaged, the power output from the solar-PV generator is curtailed to ensure the DG is loaded above its lower loading limit. As shown in Figure 5-15, the DG is loaded with 30 kW, whereas the solar-PV generator adjusts its power output to balance the load power variation until the condition for the Mode II is satisfied at $t = 21$ s. Under Mode II, a constant 10 kW power reserve is maintained at the solar-PV generator for the frequency response. The DG controls the system frequency under this mode. A 5 kW power increase occurs in the system, and the RAPS system frequency starts to decrease and the inertial energy in the DG is rapidly released followed by the frequency response of the solar-PV generator. It can be seen from Figure 5-15 that a peak in the solar-PV generation appears after $t = 25$ s. The frequency response from the solar-PV generator relieves the torque stress on the diesel engine to manage a sharp load variation. Load decreases by 15 kW at $t = 29$ s and system returns to Mode III. At $t = 32$ s, the solar irradiance suddenly decreases to 120 W/m², the maximum available power from the solar-PV generator is rapidly detected to be less than 10 kW and the Mode IV is activated. In this mode, the solar-PV generator operates at its MPP. Due to the low active power generation, the redundant capacity of the solar-PV inverter is applied to provide VAr support and around 10 kVAr of reactive power is provided by the interfacing inverter as shown in Figure 5-15.
Figure 5-16 presents the frequency and voltage variation of the RAPS system, and it can be seen that the voltage is well regulated within an acceptable range, i.e., voltage within $(1 \pm 0.05)$ pu and frequency within $(50 \pm 0.5)$ Hz. Figure 5-17 illustrates the DC link voltage variation under the multi-mode operation. The DC link voltage is regulated at the nominal value except when the solar-PV generator provides frequency response. The reason for the DC link voltage dip is that the interfacing inverter increases power output rapidly while the solar-PV array and boost converter do not respond fast enough to recharge the DC link capacitor and maintain the voltage across the capacitor.

![Figure 5-16 Voltage and frequency regulation.](image1)

![Figure 5-17 DC-link voltage.](image2)
5.8 Summary

This chapter proposed the SOPPT control strategy for power management in a solar-PV generator based hybrid PV-diesel RAPS system. The proposed SOPPT strategy enables the RAPS system to operate in multiple operating modes based on the solar irradiance level and load demand. The optimal coordination between solar-PV generator and DG balances both active and reactive power in the RAPS system by switching between four different operation modes. The proposed strategy can also improve the life-time and efficiency of the DG by: 1) maximising fuel savings through shutting down the diesel engine when solar-PV generation is sufficient to cover the load demand; 2) ensuring DG is loaded above its lower loading limit to improve its operating efficiency by curtailing solar-PV output; 3) relieving torque stress on DG by providing frequency response through the solar-PV generator under frequency disturbances, and 4) protecting DG from overloading by providing reactive power support from solar-PV generator under low irradiance condition. The dynamic performance of the DG controller and the solar-PV generator controller have been investigated for different operation scenarios. The effectiveness of the proposed sub-optimal MPPT based power management strategy have been scrutinised through simulation studies, and results have indicated that the proposed strategy can seamlessly maintain the power balance in the RAPS system while maintaining the voltage and frequency within stipulated limits.
Chapter 6


6.1 Foreword

The frequency regulation approach proposed in Chapter 4 utilised the kinetic energy stored in the DFIG for frequency response. The strategy can effectively handle the frequency variations, but the frequent frequency fluctuations in the RAPS system will create significant electrical/mechanical torque stress on the DFIG. Consequently, the wear and tear on the DFIG worsens, which risks the power supply reliability. This chapter proposes a frequency response control strategy for PMSGs while the PMSGs are not burdened by the provision of frequency response. Hence, the service life of the PMSG can be extended, and reliability of the RAPS system can be improved.

6.2 Overview

Conventional generators in wind-diesel hybrid RAPS systems are likely to be heavily stressed during frequency disturbances due to the poor frequency response of power electronic interfaced WECSs. Hence, it is imperative for WECS to provide frequency support during frequency excursions. However, existing frequency control strategies are slow and will also impose severe mechanical/electromagnetic stress on WECSs. In this chapter, frequency response strategies for the PMSG were explored, and an enhanced frequency response strategy was investigated to regulate RAPS system frequency jointly with the integrated UCs. The proposed short-term frequency response strategy utilised virtual inertial technique along with the supplementary droop control. SOPPT was also imple-
mented at the WECS to improve the active power reserve. The enhanced frequency response strategy can regulate RAPS system frequency while alleviating high ROCOP, and thus stress on the conventional generator and WECS under frequency disturbances. Proposed control strategies were validated by simulations and laboratory experiments. Figure 6-1 shows the structure of the rest of Chapter 6.

Figure 6-1 Structure of Chapter 6.

6.3 **Background**

RAPS system operates in a similar way as an islanded ‘Microgrid’, and supplies power to the ‘isolated’ (e.g., offshore) communities where large-area power system is not accessible [101]. Due to the growing interest in renewable energy production, most of the RAPS systems now deploy renewable generators; hence it has imposed challenging operation and control issues in modern RAPS systems. For example, power electronic based renewable generators are isolated from grid dynamics. Hence, the reduction in system inertia imposes an additional burden on the existing synchronous generators, such as DGs to regulate system frequency and ultimately leads to system frequency instability [151]. Consequently, there is an urgent need for renewable generators such as WECSs to participate in frequency regulation in combination with conventional synchronous generators.
Frequency support capability of DFIG has been widely investigated in the published literature [115, 121, 127, 151]. However, the power electronic converters of the DFIGs are typically designed to be operated at only 20%–30% of the full rating of the generator; the turbine rotor speed is generally within the range of 0.67 p.u.-1.33 p.u. [115], and the design constraints (e.g., the maximum available power output) limit the frequency response capability of DFIGs. In particular, when rotor speed control is applied to ‘deload’ [123] the WECS in order to reserve part of the available wind power, the rotor speed is intentionally increased above or decreased below the optimal rotor speed at the MPP. Hence, the ‘deloaded’ control requires a wider rotor speed range. PMSG also utilises power electronic converters, which enables the wind turbine to operate in variable speed mode and maximise the energy extraction from the wind. Unlike DFIG whose stator is connected to the grid directly, PMSG is totally decoupled from the system frequency by the fully rated back-to-back converter scheme. Consequently, PMSG presents no natural frequency response under-frequency event, whereas DFIGs are capable of providing limited inertia response [105]. Furthermore, the full-scale power converter enables the PMSG to operate in a wider rotor speed range [152], which benefits the frequency response. Therefore, it is imperative to explore the frequency response capability of PMSG further.

6.4 Limitations in Existing Control Strategies and Technical Contributions

Frequency response capability of PMSG is studied in [108], and a control scheme with virtual inertia and droop control is implemented to extract the kinetic energy. It is found in [108] that the frequency support from PMSG can be comparable with conventional synchronous generators, and a novel approach is proposed to avoid the frequency event caused by the sudden ending of the frequency support from the wind farm. In [153], a PMSG exports constant power when available wind power exceeds a particular percentage of the rated power, and hence energy reserve is established. With the power reserve, the WECS changes the power output using droop control technique, when power imbalance between generation and load demand occurs. However, considering the randomness of the wind speed and the resulting unreliable energy reserve, the participation of WECS in load sharing with droop control may cause stability problems. In [117], a general frequency regulation strategy was proposed for a variable-speed WECS, which is applicable
for both the DFIG and the PMSG. This strategy is capable of supplying both transient frequency support and permanent frequency response in an islanded power system.

Above research studies [108, 117, 153] placed limited emphasis on mechanical stress in the drivetrain system of the WECS. Due to the fast responsive nature of the power electronic converters, the PMSG rapidly regulate frequency fluctuations in the RAPS system while imposing significant torque stress in the drivetrain system. The frequent abrupt torque variations in the drivetrain will increase O&M cost of the mechanical components, particularly when a gearbox presents in the drivetrain system. The long downtime due to the drivetrain-failure will cause significant economic loss to the wind farm owner [154]. In order to address this problem, a limit on the ROCOP is set for the variable speed WECS to reduce mechanical stresses on the drivetrain as suggested in [112]. However, the limits sets on ROCOP compromise the frequency response of the WECS. Hence it will adversely impact on RAPS system frequency stability. Moreover, frequency fluctuations are more common in RAPS system with significant frequency excursions. Therefore, it is imperative to design a robust frequency regulation strategy for the PMSG, when deployed in RAPS systems.

UC is featured with low energy density, high power density, and fast charge/discharge rates, which qualifies UC as an ideal storage for providing short-term frequency response [155]. In [156], UC is integrated into the DFIG to smooth the wind power fluctuations and enhance the LVRT capability. A combination of battery and UC is used for power management in a DFIG in [135]. The UC responds to a high frequency component in power fluctuations to mitigate ripple current components in the battery. UC has also been utilised in PMSG. In [157], a probabilistic method is proposed to determine the capacities of the battery energy storage system and UC to limit the wind power fluctuations within a certain value. A similar study is carried out in [158], but zinc-bromide flow battery and lithium-ion capacitors are used as a hybrid storage system to constrain the wind power output ramp rates. Few research studies explored the effects of UC on the transient performance of the WECS. Moreover, the PMSG seen in the aforementioned research work applies two full controlled converters for the back-to-back AC/DC/AC converter scheme.

In this chapter, the PMSG is interfaced to the grid through a simpler AC/DC/AC converter scheme consisted of an uncontrolled diode rectifier, a boost converter, and an inverter. This chapter utilises UC in the PMSG to provide frequency response. The short-
term frequency support is achieved using virtual inertia control while being enhanced by a supplementary droop control. The control strategy enables to relieve the mechanical torque stress on both the conventional generator and WECS while providing frequency support. Furthermore, by reserving a part of wind power in the PMSG, the frequency response supplied by WECS with UC can be further enhanced.

* $S_{\text{base}} = 10 \text{ MVA}, U_{\text{base}} = 11 \text{ kV}$
  $k_p$: frequency droop constant

**Figure 6-2 RAPS system architecture.**

### 6.5 RAPS System Modelling

#### 6.5.1 RAPS System Architecture

A RAPS system consisting of a DG and two PMSGs is used as the test system (see Figure 6-2) to investigate the performance of proposed control strategies. Similar hypothetical systems have been widely employed in the literature to test the frequency response controllers [116, 127, 128]. The motivations are two folds: firstly, frequency variations are more frequent and higher in magnitude for such isolated systems with small generating capacity. Secondly, instead of having an infinite bus to generate a frequency event passively to observe the frequency response of the WECS, the frequency dynamics and the contribution of the WECS to the system frequency regulation can be easily observed and determined using such a moderately sized RAPS system. The 11 kV network parameters marked in the diagram of Figure 6-2 are obtained from [80].

#### 6.5.2 Diesel Generator

The DG is used to improve the reliability of the RAPS system and regulate system voltage within the stipulated limits (e.g., $1\pm5\%$ p.u.) while fulfilling the reactive power re-
quirement of the RAPS system. Moreover, the DG is operated with droop control to support system frequency. Generally, droop settings for generators in power systems are in the range of 3% - 6% [115]. In this RAPS model, the droop coefficient for the DG is set at 3.125% (i.e., 2 MW/Hz). The dynamic models and parameters for the diesel engine governor, SM and its exciter are obtained from [129].

6.5.3 PMSG

A detailed model for the PMSG is used in this chapter and the main control diagram is shown in Figure 6-3. The machine side converter (MSC) of the back-to-back converter scheme is an uncontrolled diode bridge which rectifies the three-phase voltage produced by the PMSG. The output DC voltage of the MSC is coupled to the DC-link through the boost converter. The GSC consisting of a full controlled bridge inverts the DC-link voltage and interfaces with the grid through the filter. The GSC is controlled in the grid voltage oriented reference frame with the $d$-axis aligned with grid voltage. Hence, the $d$-axis component and $q$-axis component of the output current can control the active and reactive power exchange respectively with the grid. Since DG fulfils the reactive power demand in the RAPS system, the PMSG is operated at the unity power factor. The UC is utilised for frequency response and it is mounted on the DC-link through a bidirectional DC/DC converter. The advantage of this configuration is that no additional inverter is required to connect UC to the grid. Sophisticated UC model is capable of modelling both the short-term and long-term behaviour of the UC such as the three RC branches model proposed in [159]. Since this chapter focuses on the short-term frequency response which is within the time-frame of seconds, the equivalent circuit of the UC is presented as a classical model consisting of a series connection of resistor and capacitor [157]. The model is also shown in Figure 6-3. The variables used for corresponding control are in per unit.

WECS are generally operated under MPPT strategy to maximise the wind energy extraction. As shown in Figure 6-4, the solid red curve indicates the typical MPPT curve of the wind turbine used in this chapter, and the curve can be fitted to the third degree polynomial represented by (6-1).

$$P_m^* = 0.750 \times \omega_r^3 - 0.001 \times \omega_r^2 + 0.001 \times \omega_r$$  (6-1)

where $P_m^*$ is the wind turbine power output reference, and $\omega_r$ is the rotor rotational speed.
In order to enhance the frequency response provided by the WECS, a fraction of the available wind power should be reserved in the wind turbine. Therefore, instead of operating the PMSG under MPPT, the PMSG is deliberately operated below its MPP, which is referred as SOPPT in this thesis and in [151]. In this chapter, a delta control approach [117] is used to maintain a constant power reserve of 0.01 p.u. (based on the active power rating of the wind turbine). As it can be seen from Figure 6-4, the SOPPT curve with 0.01 p.u. power reserve can be on either side of the typical MPPT curve. The right side SOPPT curve, as indicated by the green dash-dot line in Figure 6-4, is chosen in this chapter. The reason is that kinetic energy is released to enhance frequency response when wind generator is providing frequency support by lowering its rotor speed and thus increasing the power output. The right side SOPPT curve can be fitted to the polynomial as given in (6-2).

\[ P_m^* = 0.772 \times \omega_r^3 - 0.141 \times \omega_r^2 - 0.063 \times \omega_r - 0.012 \]  

(6-2)

6.6 Proposed Frequency Response Strategies

As it can be seen in Figure 6-3, the MSC is not controllable, and the GSC is responsible for maintaining the DC-link voltage constant while controlling the power factor of the WECS. Hence, the frequency response control mainly relies on the control of the boost converter between MSC and GSC, and the bidirectional DC/DC converter coupling UC
to the DC-link. The frequency response strategy developed by using these two converters is discussed in following subsections.

6.6.1 Frequency Response Strategy Using the Boost Converter

By controlling the current \((I_{L0})\) flowing through the inductor \(L_0\), the power output from the wind turbine (i.e., \(P_m = U_0 \cdot I_{L0}\), where \(U_0\) is the voltage across the MSC side capacitor) can be regulated. As a result, the frequency response from the WECS can be achieved. The detailed algorithm for controlling the boost converter is presented in Figure 6-5.

Wind turbine power output reference (\(P_m^*\)) is generated by the tracking curves as shown in Figure 6-4 in accordance with the rotor speed. Wind turbine power output is controlled by the power regulator fed by the error between the wind turbine power output reference and the actual power output. The power regulator generates the inductor current reference (\(I_{L0}^*\)) for the current regulator. The duty cycle (\(D\)) of the boost converter is produced by the current regulator under the constraint of duty-cycle limits (i.e., \([D_{\text{min}}, D_{\text{max}}]\)). With the typical frequency response control mechanism using virtual inertial control and droop control, as shown by (6-3) and (6-4) respectively, additional terms (i.e., \(AX_H\) and \(AX_D\)) reflecting the frequency changes are added into the controller.

\[
AX_H = -k_H \cdot \frac{df_{\text{sys}}}{dt} \tag{6-3}
\]
where $f_{sys}$ is the RAPS network frequency, $f_{nom}$ is the nominal system frequency (i.e., 50 Hz), and $k_H$ and $k_D$ are the inertial control and droop control coefficients respectively. The techniques used for determining the coefficients are discussed in [151]. The inertial control term emulates the conventional synchronous generator response for frequency variations. A low-pass filter with a time constant of $T_f$ is added in front of the derivative process to prevent the high-frequency noise caused by frequency measurement from affecting the controller performance. A deadband is applied to the frequency deviation in droop branch, which avoids frequent activation of the droop control when the frequency is within the non-critical region. The noncritical range of frequency is chosen as [49.95, 50.05] Hz in this chapter. The frequency response control terms can be added into one of the two control variables to achieve different control purposes: 1) the error between the wind turbine power output reference and actual power output (i.e., Branch 1 in Figure 6-5), or 2) the error between inductor current reference and actual inductor current (i.e., Branch 2 in Figure 6-5). The frequency response obtained through 1) and 2) is further discussed below.

\[
\Delta X_D = -k_D \cdot (f_{sys} - f_{nom})
\] (6-4)

Figure 6-5 Boost converter controller with frequency response control.

6.6.1.1 Long-Term Frequency Response

When the inertial and droop terms are added to the error between the wind turbine power output reference and actual power output, the inductor current reference can be determined using PI controller as given by (6-5).

\[
I_{L0}^* = k_{p1} \cdot (P_m^* - P_m + \Delta X_H + \Delta X_D) + k_{i1} \cdot \int (P_m^* - P_m + \Delta X_H + \Delta X_D) dt
\] (6-5)
where $k_{PI}$ and $k_{II}$ are the proportional gain and integral gain of the power regulator respectively. Since no modification is required for the power regulator design, existing regulator parameters can be used.

An example is taken to illustrate the operating principle of the long-term frequency response. The WECS is assumed to be originally operated at point $A(\omega_{rA}, P_{mA})$ as shown in Figure 6-4. A sudden frequency dip contributes to the increase in inductor current (as given by (6-5)) and power output from the WECS, and the rotor speed decreases due to the release of kinetic energy. For instance, the wind turbine operating point shifts to point $B(\omega_{rB}, P_{mB})$ in Figure 6-4. Meanwhile, the decrease in rotor speed causes the turbine power output reference to decrease along the tracking curve to point $C(\omega_{rC}, P_{mc}^*)$. Hence, the negative active power error (i.e., $P_{mc}^* - P_{mB}$) tends to bring rotor speed back to the original point $A$ by lowering the inductor current, thus the power output. However, due to the presence of the droop based frequency response control term (i.e., $\Delta X_D$) acting on frequency deviation, the negative power error can be cancelled out, and the system stabilises at the new steady-state point $B$ where

$$\omega_{rB} = \omega_{rC}$$

$$P_{mB} = P_{mc}^* + \Delta X_D$$

(6-6)

(6-7)

If secondary frequency control is not implemented to bring the frequency back to nominal value, WECS changes its power output permanently, i.e., long-term frequency response is obtained. It is to be noted that long-term frequency response from WECS might not be desirable since the power reserve in the WECS is not a reliable resource. Insufficient power to satisfy the long-term frequency response may lead to stability problems.

6.6.1.2 Short-Term Frequency Response

the inertial and droop terms in per unit are added to the error between inductor current reference ($\dot{I}_{L0}^*$) and actual inductor current ($I_{L0}$) as shown as ‘Branch 2’ in Figure 6-5. If a PI controller is also used for the current regulator, the generated duty cycle is determined by (6-8).

$$D = k_{P2} \cdot (\dot{I}_{L0}^* - I_{L0} + \Delta X_H + \Delta X_D) + k_{I2} \cdot \int (\dot{I}_{L0}^* - I_{L0} + \Delta X_H + \Delta X_D) dt$$ (6-8)
where $k_{P2}$ and $k_{I2}$ are the proportional gain and integral gain of the current regulator respectively.

Under a frequency dip, positive frequency response control terms drive the inductor current to increase. Hence, power output from wind turbine increases and frequency support is provided. Due to the decrease in rotor speed and thus the wind turbine power reference, the negative power error fed to the power regulator reduces the inductor current reference and counteracts the increase in the frequency response control terms. Therefore, the increase in the power output from a wind turbine cannot be sustained. Any negative error between the wind turbine power reference and the actual power output forces the WECS to recover to its original operating point. Therefore, frequency response obtained through the controller with Branch 2 is only available during the transient period. The WECS with this short-term frequency response controller does not provide frequency support at steady-state even though system frequency deviation exists. Therefore, the droop term typically used for load sharing is only applied to enhance short-term frequency response.

6.6.2 Frequency Response Strategy Using the Ultracapacitor

The two frequency response strategies discussed in Section 6.6.1 utilise the mechanical power (i.e., kinetic energy or power reserve), which can be slow and cause torque/electromagnetic stress to the WECS. Moreover, the sophisticated strategy is required to restore WECS kinetic energy as well as power reserve to avoid a second frequency event. The UC is superior in power density and charging/discharging rate, which can be capable of relieving the stress on WECS by acting as a supplementary source of frequency response. The proposed strategy of utilising UC in short-term frequency response control is presented below.

6.6.2.1 Control Algorithm for Ultracapacitor

Since the UC is mainly responsible for providing the frequency response, similar frequency response control as proposed for the boost converter in Section 6.6.1 is also used for the bidirectional converter. The control block diagram is presented in Figure 6-6.

By comparing Figure 6-6 with Figure 6-5, it can be seen that a washout filter [102] with a time constant of $T_\omega$ is added in the droop branch of the frequency response controller. Due to the low energy density of the UC, the washout filter prevents the droop
branch from being activated by permanent frequency deviation, thus forcing UC to provide only short-term frequency response. The power output reference \( P^* \) set for UC is given by (6-9).

\[
P^*_c = P_{cg} + \Delta X_D + \Delta X_H
\]  

(6-9)

where \( P_{cg} \) is the UC auxiliary charging power demand. This term is activated when power reserve in the wind turbine is utilised to charge the UC. With the measured UC voltage, the current reference \( I^*_{Le} \) flowing through the inductor \( L_c \) can be determined (i.e., \( I^*_{Le} = P^*_c / U_c \)). The error between the inductor current reference and actual inductor current is fed into the current regulator to generate the duty cycle of the gate signal for the active IGBT of the bidirectional DC/DC converter while the other IGBT is blocked (anti-parallel diode is active) depending on the charging or discharging state of the UC.

![Figure 6-6 Bidirectional converter controller block diagram.](image)

### 6.6.2.2 Control Algorithm for PMSG

When the power reserve in the wind turbine is activated for charging the UC, the wind turbine is desired to increase its power output. Hence, a controller similar to the long-term frequency response controller as discussed in Section 6.6.1.1 is implemented. The boost converter controller used for coordinating with the UC controller to provide frequency response is shown in Figure 6-7.

An auxiliary control is added into the boost converter controller to increase the wind turbine power output when power reserve is used to charge the UC. To avoid excessive power extraction from the wind turbine and alleviate the stress on wind turbine when sudden charging demand is requested, two limiters are implemented to the charging power demand \( P_{cg} \). One limiter \([0, P_{res}]\) constrains the charging demand within power
reserve \( (P_{res}) \). The other limiter is used to limit the changing rate of power demand on wind turbine. Sophisticated charging algorithm can be used to generate the charging power demand to achieve multi-objective optimisation, including maximum WECS power production, minimum power output fluctuation, etc. The optimisation is not the focus in this thesis and therefore it is not discussed. Simple constant power charging approach [160] is used in this thesis. The charging procedure aims to create no interference to the output of the WECS.

**Figure 6-7 Boost converter controller with supplementary charging control.**

Certain conditions should be satisfied to enable the utilisation of power reserve for UC charging, which are illustrated in the logical diagram shown in Figure 6-8. Firstly, the stored energy of the UC reaches a lower limit, which can be set as 25% (i.e., UC voltage reduces to the half of its rated value) [161]. Secondly, the RAPS network frequency is within the noncritical range to ensure the power reserve is not utilised to charge the UC during a frequency event. Hysteresis comparator blocks are used to observe these two conditions.

**Figure 6-8 Logic diagram for UC charging command.**

### 6.7 Simulation and Discussions

The RAPS system shown in Figure 6-2 is used as the test system to validate the effectiveness of the proposed frequency response strategy for PMSG.
6.7.1 Ultracapacitor based and Boost Converter based Frequency Response Strategies

A frequency disturbance is created intentionally by a sudden load increase of 0.3 MW at the time of \( t = 40 \) s (which applies to all case studies in this chapter). The wind speed is assumed to be constant in this case study. Four scenarios are studied to show the effect of frequency control strategies on system frequency regulation: (1) WECS without frequency response control; (2) long-term frequency response strategy implemented in the boost converter controller of the WECS without UC; (3) short-term frequency response strategy implemented in the boost converter controller of the WECS without UC; (4) frequency response strategy implemented in the UC controller of the WECS with UC. The simulation results are shown in Figure 6-9.

By comparing scenario (2), (3) and (4) with scenario (1) in Figure 6-9(a), it can be seen that all frequency response strategies can improve the frequency regulation by reducing the frequency nadir. Figure 6-9(b) shows that the mechanical torque on the turbine shaft is not affected by the sudden load increase in the scenario (4) whereas torque increases sharply in scenario (2) and (3). Furthermore, torque oscillations are evident for scenario (2) and (3) which indicates that the drivetrain of the turbine is highly stressed when frequency response is provided by extracting mechanical power. It can also be seen from Figure 6-9(b) and (c) that the mechanical torque and rotor speed in scenario (2) stabilise at a value different from the pre-disturbance value. Contrarily, the rotor speed and mechanical torque recover in scenario (3), which verifies the difference between long-term frequency response control strategy and short-term frequency response control strategy. Although the wind turbine power output does not change during frequency dip in scenario (4), the WECS power output increases due to frequency response supplied by the UC as seen in Figure 6-9(d). With the absence of frequency response from WECS, nearly a step change in the DG power output can be observed following the sudden increase in load as shown by scenario (1) in Figure 6-9(e). The frequency response from WECS significantly reduces the ROCOP at the DG. Therefore, any of the proposed frequency response strategies can relieve the frequency regulation burden on the conventional generator. Nevertheless, frequency response extracted from mechanical power simply shifts the mechanical stress to the WECS. The frequency response provided by the UC coupled on the DC-link of the WECS can effectively provide frequency support while alleviating torque stress on both conventional generator and the WECS.
Effect of the Supplementary Droop Control on Short-Term Frequency Response

As shown by the blue dash curve in Figure 6-10(b), the limited short-term frequency response can be supplied by the UC if the controller only implements the virtual inertia...
control strategy. Consequently, lower frequency nadir presents in the RAPS network (see blue dash curve in Figure 6-10(a)). Moreover, the power absorption by the UC during the period of frequency recovery prolongs the transient period. The introduction of droop control in short-term frequency response significantly improves the frequency response as shown by the red curve in Figure 6-10. Since no secondary frequency response is considered in this scenario, the network frequency stabilises at a value different from the nominal frequency.

![Figure 6-10 Effect of the supplementary droop control.](image)

6.7.3 Ultracapacitor Charging Using Power Reserve in the Turbine

For the purpose of demonstration, the SOC level to activate the UC charging with wind power reserve is set at 98% in this case rather than the value (i.e., 25%) recommended in Section 6.6.2. The discharging and charging procedure is shown in Figure 6-11.

Upon the frequency dip at $t = 40 \text{ s}$ (see Figure 6-11(a)), it can be seen from Figure 6-11(b) that the SOC reaches the lower limit after providing frequency response during the frequency disturbance. The charging process is activated around $t = 75 \text{ s}$. The wind turbine power output starts to increase while WECS power output maintains constant, which becomes opposite when frequency response is provided (i.e., wind turbine power output is maintained constant while WECS power output increases to provide frequency response). The power difference is absorbed by the UC and the SOC of the UC increases. Since the UC is slightly discharged, it does not take too long to charge to fully charged status. After UC is charged to a certain level (e.g., SOC = 99%), wind turbine power output ramps down to SOPPT operating point (as shown in Figure 6-11(d)) to avoid a sudden power increase from WECS when the UC is fully charged and stops absorbing energy. The frequency variation is well regulated in a small range during the charging
procedure as shown in Figure 6-11(a). The permanent frequency variation exists because no secondary frequency control is implemented in the RAPS system to recover frequency back to nominal value.

![Graphs showing frequency, SOC, rotor speed, and wind power over time.](attachment:image.png)

Figure 6-11 UC charging using power reserve in the wind turbine: (a) system frequency; (b) SOC of the UC; (c) wind turbine rotor speed; (d) wind power.

### 6.7.4 Applicability of the Frequency Response Strategy under Variable Wind Speed

To further study the frequency regulation capability of the proposed frequency response strategy for the UC, WECS under variable wind speed scenario is also investigated. Simulation results are shown in Figure 6-12. A wind speed profile shown in Figure 6-12(a) is taken as a snapshot of real wind speed profile. Without the presence of the UC, the RAPS network frequency frequently exceeds the noncritical frequency zone as shown by the blue curve in Figure 6-12(c). Particularly, the frequency reaches as low as 49.8 Hz under the frequency disturbance as used for previous case studies at $t = 90$ s. The frequency response strategy implemented in UC control smooth out the frequency fluctuations and
improves the frequency regulation under frequency disturbance by providing short-term frequency response (see red curve in Figure 6-12(c)).

Moreover, the ramp rate of the power output from the WECS due to the wind speed variation is reduced to some extent as compared to its counterpart when no frequency response control is implemented as shown in Figure 6-12(b), which is another benefit of the proposed frequency response strategy. The smoothing effect attributes to the absorption or injection of power in the UC regulated by the frequency response strategy. As it can be seen from Figure 6-12(d), the SOC of the UC fluctuates, denoting continuous charging or discharging process of the UC. It can be seen that when the UC is fully charged at some time instants, which results in failure of constraining frequency within
the noncritical zone by the UC (see Figure 6-12(c)). This problem can be solved by maintaining a charging reserve in the UC or applying additional emergency resistor as used for batteries in [162].

6.8 Proof of Concept Using Experiment Tests

A small scale RAPS system (see Figure 6-13) similar to the simulation test system, as shown in Figure 6-2 and Figure 6-3, was established to verify the proposed control strategy in the laboratory environment. The three-phase system mainly consists of a PMSG and a voltage source operating at 415 V (The voltage source replicates the response of the synchronous generator and it is not installed adjacent to the PMSG test rig, hence not shown in Figure 6-13). The wind turbine is emulated by a squirrel cage induction machine (SCIM) driven by a variable speed drive (VSD). The power converter control and the torque-speed characteristic of the wind turbine are processed by the TMS320F28335 digital signal controller (DSC) along with the interfaces. Other details of the laboratory RAPS system are given in Appendix C.

Initially, the network frequency is 50 Hz, and the emulated wind speed is 5.5 m/s. The PMSG and voltage source supplies power to the load jointly and the disturbance (i.e., increase or decrease) in network frequency is generated passively by the voltage source.
In the first test, conventional virtual inertia and droop based frequency response (i.e., long-term frequency response) are implemented in the energy storage controller. The variation in frequency is presented as yellow curve (see Figure 6-14(a)). When the network frequency increases, the WECS increases its power output (see Figure 6-14(a)) by discharging the energy storage system (see Figure 6-14(b)). The droop controller maintains the power output as long as the network frequency is not within the noncritical zone. Energy storage system may not be able to constantly absorbing or injecting the required power, particularly using the UC of low energy density. Hence, the availability of long-term frequency response using UC is undesirable.

Figure 6-15 shows the performance of the proposed short-term frequency response strategy achieved by virtual inertia and the supplementary droop (as discussed in Section 6.6.2.1). It can be seen that the permanent frequency deviation does not trigger the frequency response supplied by the energy storage system. It is important to be noted that the turbine power output (as indicated by the purple curve in Figure 6-14(a) and Figure 6-15) does not change during the frequency events, hence the mechanical/electromagnetic stress is not applied to the wind turbine and PMSG while frequency response is provided. The difference between the turbine power and the WECS power mainly under normal operation attributes to the power loss in converters.
current flowing out of the energy storage system is referred as positive value

charging/discharging current

1.25 A

energy storage charge

average current

charging/discharging
energy storage discharge

Figure 6-14 Long-term frequency response: (a) frequency, turbine power, WECS power and DC-link voltage; (b) charging/discharging current.

Figure 6-15 Short-term frequency response.
6.9 Summary

In this chapter, a UC based frequency response strategy was proposed for a PMSG. In this proposed strategy, the short-term frequency response was obtained by virtual inertia control while the supplementary droop control enhances the frequency response. The UC responds to the frequency variation, hence the wind turbine mechanical power output is not affected by frequency disturbance. Thus the proposed strategy would relieve the mechanical/electromagnetic stress on both the conventional generator and the WECS. SOPPT was also applied in the WECS to reserve a part of the wind power for charging the UC, thus enhancing the effectiveness and reliability of the proposed frequency response strategy. Both simulation and experimental tests were carried out verify the proposed control strategy. The results demonstrated the significant improvement in the frequency regulation capability of the WECS.
Chapter 7

Enhanced Frequency Regulation Using Multilevel Energy Storage in Remote Area Power Supply System

7.1 Foreword

The frequency regulation strategy proposed in Chapter 6 utilised the UC in primary frequency response. The limited energy density of the UC constrains the frequency response for short time frame. In this chapter, an enhanced frequency regulation using multilevel energy storage technology (i.e., a combination of UC, LAB and mechanical power reserve in wind turbines) was developed to enable PMSGs to participate in both short-term and long-term frequency response. Moreover, a sophisticated control strategy was proposed to enhance the frequency response while minimising stress on the PMSG as well as energy storage devices for the purpose of extending RAPS system components’ lifetime.

7.2 Overview

The frequency support from renewable power generators is critical requirement to ensure frequency stability of RAPS systems with high penetration of renewable electricity generation. However, the traditional control strategies and the stochastic nature of wind resource constraint WECSs such as PMSG to participate in frequency regulation. This chapter proposes to integrate hybrid energy storage system including UCs and LABs into the PMSG to provide frequency support. The UCs acts on fast changing frequency by emulating conventional inertial response, whereas the LABs mimics the automatic governor response (i.e., primary frequency response). The power reserved in the wind turbine using SOPPT strategy is utilised to restore system frequency (i.e., secondary frequency response). Moreover, the UC and the LAB also aids the primary frequency response and secondary frequency response respectively. The strategy can effectively regulate RAPS
system frequency while avoiding abrupt and frequent charging/discharging of the LAB and significant mechanical stress on the WECS. Simulation study and experimental tests are carried out to validate the effectiveness of frequency regulation provided by the multilevel energy storage. The rest contents of Chapter 7 are organised as shown in Figure 7-1.

![Diagram of Chapter 7 organisation]

**7.3 Background**

Rural electrification and reduction in dependency on fossil-fuel rely on the concept of non-conventional renewable energy (e.g., wind, solar) based remote area power supply (RAPS) system [101]. One major problem with renewable power generation is that it is not dis-patchable as in the case of conventional energy sources such as thermal and hydro. Therefore, it becomes onerous for the conventional generators to meet the network side (or load side) requirements in RAPS systems due to increasing penetration levels of renewable energy resources.

The low inertia characteristic of small-scale RAPS system results in system’s high sensitivity to the mismatch between generation and load demand. Large frequency excursions are common in such systems [163]. The adoption of power electronics based renewable generation such as WECSs aggravates the frequency stability problem since these renewable generators are not naturally involved in frequency regulation. The capability
of frequency regulation using DFIG has been widely investigated [104, 115, 151] due to the large market share of DFIG in renewable rich power networks. The WECS is being developed to very high capacity and, is achieving popularity in remote locations like off-shore where the wind resource is abundant but the harsh environment demands a greater degree of reliability on WECS [164]. PMSG with full-scale converter can be a good option to meet this requirement. The PMSG is suitable for wind power generation due to its high torque-to-volume ratio, the elimination of the requirement for excitation windings and its capability of direct drive variable speed operation without a gearbox. The PMSG is gaining attention on its contribution to frequency regulation. In [108], a frequency controller based on virtual inertia and droop loop is introduced to the PMSG. The kinetic energy stored in rotating mechanical components of the WECS is extracted and injected into the grid according to the variation in system frequency. The main drawback of this controller is a requirement for a proper termination of the frequency support to avoid a second frequency event (as the WECS accelerates and restores the kinetic energy at the post-disturbance stage). Similar frequency regulator is also applied in [117], and the frequency support is enhanced with power reserve in WECS apart from the kinetic energy. Nevertheless, the utilisation of mechanical power in frequency regulation is a slow process. Additionally, due to the frequent frequency fluctuation and thus abrupt torque variation, the mechanical/electromagnetic stress on the WECS will deteriorate the reliability of the WECS.

As summarised in [165], energy storage system is a promising technology for 1) smoothing renewable power generation; 2) levelling load demand; 3) arbitraging energy; 4) supporting primary frequency response; and 5) shaving peak load. In particular, UC can be a decent short-term energy storage device due to its high round-trip efficiency, and fast charging/discharging rates. The high power characteristic enables UC to support the instantaneous load spikes and variation [165, 166]. UC is applied in [163, 167] for dynamic frequency support under frequency disturbance in an isolated power system. Due to the limited energy density of the UC, the capability of dynamic frequency support is limited to primary frequency response that lasts less than 30 s [104]. Batteries have high energy density and suitable for long-term frequency regulation [166]. In [168], batteries are utilised to provide primary frequency reserve in large utility grids and optimised sizing strategy is proposed taking economic benefits into consideration as well as the technical limitations of the energy storage. It is found that LABs can be the optimal energy
storage system for primary frequency reserve with its lower cost and degree of maturity. However, under variable charging current caused by fluctuating wind speed, the LAB are subjected to faster degradation rates [169], and shorter service life [166].

The complementary characteristics of LAB and UC contribute to the advantages of the hybrid energy storage system while alleviating the drawbacks associated with the single energy storage system. Hence, the hybrid energy storage may radically improve the frequency regulation in a self-reliant remote area power supply system. In [170], an optimised sizing method is proposed to determine the capacity of battery and UC to maintain the power balance in an isolated power system with wind generation. The method decomposes the mismatch between generation and demand into three components depending on the power variations which are catered by UC, battery and synchronous generation respectively. In the wind-diesel generation system studied in [171], two-level storage system (including vanadium redox flow battery and UC) makes changes to the dispatch order in order to minimise the usage of dump load and changing rate at the diesel power output. Similarly, a knowledge-based energy management strategy is used in [172] to modify the two level storage power allocation reference provided by a low pass filter. A grid connected PMSG with integrated hybrid energy storage system is studied in [173] using real-time simulator. The storage system is commissioned to smooth the wind power output by absorbing the faster and slower power fluctuations in wind power using UC and battery respectively. Moreover, these previous research studies are focused on the numerical study of the balance between generation and load demand, which provide good guidelines for sizing RAPS system components. The contribution of hybrid energy storage system for improving the RAPS system dynamic performance of the system remains to be an unexplored area.

In this chapter, a hybrid energy storage consisting of high capacity buffer storage (i.e., LAB bank) and a short-term cache storage (i.e., UC) and they are integrated on the DC link of the PMSG. The UC is mainly utilised to provide virtual inertia to the RAPS system whereas battery mainly supplies primary frequency response. Furthermore, a pre-defined power level is reserved in the WECS using SOPPT strategy. The power reserve assists the restoration of system frequency with supplementary energy supplied by the battery. A control strategy is also proposed to engage UC in enhancing the primary frequency response provided by the batteries. Hence, a multilevel energy storage system is designed to support the frequency regulation.
7.4 Modelling of Multilevel Energy Storage System

The modular hybrid energy storage system (i.e., UC and LAB), integrated into a PMSG, is shown in Figure 7-2. An MSC (i.e., diode bridge) converts the variable magnitude variable frequency power generation to DC. A second stage involves a boost converter to control the power output from the PMSG. Hence typical MPPT or the SOPPT strategy can be implemented here. The PMSG is interfaced with the RAPS network at the PCC with the GSC which maintains a constant DC link voltage. The two complementary types of energy storage devices are connected to the DC link through two separate bi-directional DC/DC converters. The structure grants more flexibility in controlling the storage system. The capacity of the GSC will be fully utilised with the storage devices sharing the GSC due to: 1) The PMSG is not always operating at its full rating under variable wind speed; 2) The SOPPT strategy is used to establish power reserve. An additional grid-connected three-phase inverter can be implemented to couple the storage devices at the PCC, which is less cost-effective.

7.4.1 Ultracapacitor Dynamic Model

Various electric dynamic models of the UC can be used for different purposes. For example, a simplified RC model [173] consists of an equivalent series resistor to represent the ohmic loss during charging or discharging and a capacitor to represent the UC’s capacitance. An equivalent parallel resistor can be added across the capacitor to include the
self-discharging effect [174]. More advanced model is also proposed in [175]. In this chapter, an RC parallel branch model as shown in Figure 7-3(a) is implemented. The characteristics of each RC branch differs in terms of their time scale of response due to the different time constant of each branch. The model has three RC branches, namely short-term branch (i.e., $R_s$, $C_s$), medium-term branch (i.e., $R_m$, $C_m$) and long-term branch (i.e., $R_l$, $C_l$). The short-term branch dominates the charging or discharging behaviour in the timeframe of seconds whereas medium-term branch is more effective in order of minutes and long-term branch has even larger time constant. These timeframes match with the timeframes of the inertial response, primary frequency response and secondary frequency response respectively. Therefore, this UC model is suitable for the study in this chapter.

$\begin{align*}
    U_b &= E_0 - K \cdot \frac{B}{B - \Delta B} \cdot \Delta B - R \cdot I_b + \text{Exp}(t) - K \cdot \frac{B}{B - \Delta B} \cdot I_b^* \\
\end{align*}$

where $E_0$ is the battery constant voltage, $K$ is the polarisation resistance, $B$ is the battery capacity, $\Delta B$ is the actual battery charge, $R$ is the internal resistance, $I_b$ is battery current.

Figure 7-3 Dynamic models of energy storage system: (a) the UC; (b) the LAB.

7.4.2 Lead-Acid Battery Dynamic Model

Battery dynamic models are well documented in [176]. The model can be represented as a current controlled voltage source connected in series with a resistor ($R_b$) as shown in Figure 7-3(b). The mathematical models of the charge and discharge of a LAB are as below.

Charge model: the battery voltage can be determined using (7-1).
and $I_b^*$ is the filtered current using low pass filter. $Exp(t)$ is the exponential zone voltage which can be determined using (2).

$$\frac{dExp(t)}{dt} = -M \cdot |I_b^*| \cdot Exp(t) \quad (7-2)$$

where $M$ is the exponential capacity.

**Discharge model:** similar to (7-1), the battery voltage is given by (7-3):

$$U_b = E_0 - K \cdot \frac{B}{B - \Delta B} \cdot \Delta B - R \cdot I_b + Exp(t) - K \cdot \frac{B}{\Delta B - 0.1 \times B} \cdot I_b^* \quad (7-3)$$

The exponential zone voltage $Exp(t)$ has the form as (7-4):

$$\frac{dExp(t)}{dt} = M \cdot |I_b^*| \cdot [U_e - Exp(t)] \quad (7-4)$$

where $U_e$ is the exponential voltage.

The parameters of LAB model in (7-1) to (7-4) can be easily extracted using the data sheet provided by the battery manufacturer, and experimental measurements are not necessary for parameter identification. The sizing strategy of the energy storage system is dependent on the requirements on system reliability and dynamic performance. A frequency-based approach is proposed in [170], which provides a good example where the power balance between generation and load is satisfied and high and low fluctuations in power demand are allocated to UC and LAB respectively.

### 7.5 Multilevel Storage based Frequency Regulation

Conventionally, upon the occurring of a frequency disturbance in the power system, the synchronous generators release its stored kinetic energy inherently to provide inertial response and limit the ROCOF. Primary frequency response reserve is activated in a few seconds when the frequency exceeds the noncritical frequency deviation band. This process is generally achieved by increasing/decreasing mechanical power output from the prime mover using a droop-based governor. Secondary frequency response restores the
active power balance between generation and load demand, thus recovers the system frequency to the nominal value and the secondary frequency response lasts up to 15 mins until the tertiary frequency control is online to free up the secondary frequency response reserve [177].

In this chapter, the hybrid energy storage system and power reserve available in the de-loaded PMSG provide frequency response in different time scale. The control structure is sketched in Figure 7-3. Three levels of energy storage (i.e., UC, LAB, and mechanical power reserve in wind turbine) and three levels of frequency response (i.e., inertial response, primary frequency response, and secondary frequency response) are presented. The tertiary frequency control is usually implemented manually [168] and not considered in this chapter. Details of the multilevel frequency regulation scheme are discussed in the following subsections.

Figure 7-4 Multilevel energy storage based frequency regulation strategy.

7.5.1 Enhanced Virtual Inertial Response

UC is featured as having high power density and fast charging/discharging capability, which enables UC to handle fast power response under frequency disturbances. The UC is also capable of covering frequent power absorption/injection due to its high number of cycling time of UC. Therefore, it is advantageous to apply UC for providing power surge and emulating the inertial response of conventional synchronous generator. Hence, the ROCOF can be reduced to a level where other generators in the system stay online without tripping.

The inertial response of conventional generator can be represented by (7-5) [178].

\[
P_m = 2H \cdot \omega_m \cdot \frac{d\omega_m}{dt}
\]  

(7-5)
where \( P_m \) is the mechanical power which is represented as the variation in kinetic energy, \( H \) is the inertia constant, and \( \omega_m \) is the rotor rotating speed. Hence, the virtual inertia term has the form as (7-6) to emulate the inertial response.

\[
P_H = k_c \cdot \frac{df_{sys}}{dt}
\]

(7-6)

where \( f_{sys} \) is the system frequency and \( k_c \) is the inertia coefficient. Since \( \omega_m \) is close to rated value (i.e., 1 p.u.), \( k_c \) can be set as \((2H)\) by comparing (7-5) and (7-6).

In order to enhance the primary frequency response, which to be explained in Section 7.5.2, the virtual inertial response term is directly or inversely assigned the power reference (\( P_c^* \)) for the UC depending on ROCOF during a frequency event. An example is shown in the control diagram of the UC in Figure 7-5. The frequency dip event is divided into three sections: frequency deviation section, frequency recovery section, and quasi-steady section.

**Frequency Deviation Section:** When frequency decreases, the inertial term is assigned to the UC power reference directly to increase its power output and thus inertial response is supplied.

**Frequency Recovery Section:** Due to the activation of primary frequency response, the system frequency reaches the frequency nadir and starts to recover. A fraction of the electric power will be absorbed by synchronous generators to restore their kinetic energy. Similarly, if the traditional virtual inertia control strategy is used, the UC starts to absorb energy after the frequency nadir since the ROCOF becomes positive. Consequently, the primary frequency response is attenuated, and the recovery of system frequency will be slowed down. The stabilisation and recovery of the disturbed frequency period should be as short as possible, and this period is limited to 5 minutes in an islanded system as stated in Australian National Electricity Market (NEM) mainland frequency operating standards [179]. Hence, the attenuation effect on the primary frequency response caused by UC is better to be avoided. It is important to note that the power absorption is natural performance for a synchronous generator during the frequency recovery period whereas the power consumed by the UC is controllable. Therefore, it is not necessary for the UC to emulate this inertial response during the frequency recovery period. Contrarily, the inertial term in (7-6) can be inversely assigned to the UC power reference to enhance the
primary frequency response. Hence, rather than absorbing power from the network, the UC maintains its power injection after the frequency deviation period.

**Quasi-Steady Section:** When frequency reaches lower limit of the noncritical operating frequency range, the inertial term is assigned to the UC power reference directly, then it will be ready for next frequency disturbance.

As shown in Figure 7-5, a low-pass filter with a time constant of \( T_f \) is applied in front of the derivative term to alleviate the impact of high-frequency noise on the controller. \( P_{cc} \) is the ancillary UC charging set point. The error between the inductor current reference \( (i_{Lc}) \) and the actual current \( (i_{Lc}) \) is fed to the current regulator to generate the duty ratio of gate signals for the bidirectional DC/DC converter as shown in Figure 7-2.

![Figure 7-5 Virtual inertia controller for UC.](image)

### 7.5.2 Primary Frequency Response

Primary frequency response aims to raise the frequency nadir above a particular level (ruled by local frequency operating standards). Otherwise, load shedding is expected to be carried out. For example, in Australian energy market (mainland), automatic load shedding will be triggered when frequency reduces below 49 Hz as specified in [179]. Considering the small size of the RAPS system studied in this chapter, a lower frequency (i.e., 48.5 Hz [163]) is chosen.

Primary frequency response is generally obtained using \( P-f \) droop mechanism. LAB is applied to provide long-term frequency response due to the higher energy density. Since the droop control is relatively slow [180], the surging current would not stress the energy storage system. Furthermore, a normal operating frequency band is usually set around the
nominal frequency to avoid unnecessary activation of the primary frequency response. Hence, frequent charging/discharging of the LAB can also be avoided. In mainland Australia, the band is set to be 49.5 to 50.5 Hz for an islanded system [179]. Therefore, the aging of the LAB can be delayed by engaging the combination of the UC and the LAB in frequency regulation. The power reference of the LAB is given by (7-7).

\[ P^*_b = P_{bc} + P_{bs} - k_b \cdot (f_{sys} - f_{nom}) \]  

(7-7)

where \( f_{nom} \) is the nominal system frequency (e.g., 50 Hz in this chapter), \( k_b \) is the droop coefficient, and \( P_{bc} \) and \( P_{bs} \) are LAB charging and secondary frequency response set point respectively. The control diagram of the LAB is presented in Figure 7-6. A dead band is introduced for the frequency error (\( \Delta f \)) corresponding to the normal operating frequency band.

![Figure 7-6 Droop based primary frequency controller for the LAB.](image)

### 7.5.3 Secondary Frequency Response

Secondary control usually implements centralised automatic generation control (AGC) to modify the active power set points of interconnected generators and restore the frequency to the nominal value. The integration of LAB enables the PMSG to participate in secondary frequency response. Apart from the secondary energy reserve in LAB, the wind turbine is operated away from its typical MPP intentionally. The mechanical power reserve in the wind turbine serves as another form of secondary frequency energy reserve or charging energy source for the UC and LAB. The strategy to deload the WECS is referred as SOPPT in this thesis and [151]. A constant amount of mechanical power (0.01 p.u. in this chapter) is reserved by manipulating the wind turbine to follow the SOPPT curve.

As explored in [123], WECS is capable of participating in AGC using set point control. With two secondary frequency response reservoirs (i.e., LAB and mechanical power...
reserve), a coordination strategy is required to accomplish power sharing between the wind turbine and LAB to meet the AGC set point assigned on the WECS. Equation (7-8) presents the strategy which prioritises the mechanical power reserve in secondary frequency response. When the power set point for the WECS ($P_s$) is less than the available maximum turbine power ($P_t^{\text{max}}(V_w)$), secondary frequency response set points for the LAB and the turbine are set to be zero and ($P_s - P_{w0}$) respectively. If $P_s$ is larger than the total power available in LAB and wind turbine, the LAB power set-point and turbine power set-point are assigned to their maximum. For the other scenarios, the turbine power set point is set at its maximum value whereas LAB fills the power gap between the maximum turbine power and the WECS power set point.

$$P_{bs} = \begin{cases} 0, & P_{ts} = P_s - P_0(V_w) \\ P_s - P_t^{\max}(V_w), & P_{ts} = P_{res} \\ P_{b}^{\max}, & P_{ts} = P_{res} \end{cases} \quad P_s < P_t^{\max}(V_w) \quad P_t^{\max}(V_w) < P_s < P_t^{\max}(V_w) + P_{b}^{\max} \quad P_s > P_t^{\max}(V_w) + P_{b}^{\max}$$ (7-8)

where $P_{ts}$ is the secondary frequency response set point of the turbine, $P_{w0}$ is the actual wind turbine power output, $P_{res}$ is the mechanical power reserve in the turbine, and $P_{b}^{\max}$ is LAB rated power. The control diagram of the boost converter on the DC link is shown in Figure 7-7. Ramp rate limiter is applied to the turbine power set-point to reduce the mechanical stress on the drive train.

![Figure 7-7 Control diagram of the boost converter.](Image)

### 7.6 Performance of the Multilevel Storage System

The proposed multilevel energy storage based frequency regulation strategy is validated in the SimPowerSystem platform. The simulation model (see Figure 7-8) is established
based on a practical laboratory scale RAPS system with all the parameters of the system components extracted from components’ datasheets.

\[ S_{base} = 10 \text{kVA}, \quad U_{base} = 415 \text{ V} \]

\[ (0.682+j0.241)\% \quad (1.364+j0.967)\% \]

11 kVA
415 V
6 kW
294 V
294 V/415 V
12 kVA

\[ 0.415+j0.02 \]

0.341%

\[ 0.70+j0.035 \]

\[ \text{variable} \]

\[ \text{Load} \]

DG
11 kVA
415 V

Figure 7-8 Architecture of the RAPS system.

7.6.1 Transient Frequency Regulation Using Multilevel Storage

The transient dynamics of the RAPS system under a frequency disturbance generated by a sudden load increase (10%) are shown in Figure 8. Four scenarios are investigated: 1) WECS without frequency regulation; 2) WECS equipped with UC providing inertial response; 3) WECS with LAB participating in primary frequency response; 4) WECS integrating both UC and LAB. Upon the increase in load demand, frequency drops in all scenarios as shown in Figure 7-9(a). Without the presence of frequency regulation, scenario (1) has the lowest frequency nadir which is below 49 Hz and load shedding will be activated, the high ROCOF may also trigger the disconnection of interconnected generators. With the implementation of UC, the ROCOF is reduced, but the frequency nadir is only raised slightly. The inclusion of LAB significantly reduces the frequency deviation and the frequency nadir. This is achieved by injecting a significant amount of LAB power into the RAPS network as seen in Figure 7-9(b). In scenario (4), both the frequency nadir and ROCOF are improved, and optimal frequency regulation is obtained. Due to the application of droop based frequency response, the WECS power output increases compared with the pre-disturbance value. This attributes to the permanent frequency deviation after the addition of load (secondary frequency regulation is not activated to restore the system frequency yet). Meanwhile, the power output from parallel connected DG also increases as shown in Figure 7-9(c). It is important to note that the wind turbine power output does
not change in all scenarios. Hence, the mechanical/electromagnetic stress on the WECS is eliminated compared to the case when frequency regulation is implemented in turbine control as studied in [108, 117].

Figure 7-9 Comparison of various frequency regulation strategies.

Figure 7-10 presents the power output from UC and LAB in scenario (4). It can be seen from the figure that UC covers all the fast changing power profile whereas LAB supplies low fluctuation power. The elimination of frequent charging/discharging behaviour on the battery extends the lifetime of the LAB.

### 7.6.2 Effects of Virtual Inertial and Droop Coefficients

The effects of the virtual inertial coefficient in (7-6) and droop coefficient in (7-7) on the performance of the frequency regulation using multilevel energy storage system are investigated by varying $k_c$ and $k_d$, and results are shown in Figure 7-11 and Figure 7-12 respectively. By increasing the virtual inertial coefficient of the UC, the reduction in ROCOF and increase in frequency nadir can be observed as shown in Figure 7-11(a). The zoomed figure in Figure 7-11(b) exhibits that the increase in virtual inertial coefficient augments the initial power output from WECS when the frequency disturbance occurs.
Nevertheless, the improvement in frequency nadir is limited and further increase in $k_c$ will cause large swings in WECS power output and deteriorate the stability of the system.

Figure 7-10 Charging/discharging of the energy storage system.

Figure 7-11 Effect of the virtual inertial coefficient: (a) frequency; (b) WECS power output.

Figure 7-12 Effect of droop coefficient: (a) frequency; (b) LAB power output.
In regard to the primary frequency response provided by the LAB, the effect on the ROCOF is negligible whereas frequency nadir is significantly improved with larger droop coefficient as shown in Figure 7-12(a). Particularly, the frequency nadir is raised above 48.5 Hz when $k_b$ is set at 0.04. Consequently, the load shedding will not be activated during the frequency disturbance. Since the interconnected generators share loads in proportion to their droop coefficients, the permanent change in WECS power output at post-disturbance stage increases with larger $k_b$ (the DG is governed by droop control strategy).

### 7.6.3 Effect of Enhanced Primary Frequency Response

As discussed in Section 7.5.1, a strategy is proposed to enhance the primary frequency response by involving the virtual inertial term of UC in aiding the primary frequency response provided by the LAB. The performance of the enhanced primary frequency response is compared with original strategy and the results are shown in Figure 7-13. Higher climbing rate of the frequency during the frequency recovery period and flattened overshoot can be observed in Figure 7-13(a) in the case of the enhanced controller. The faster frequency restoration is due to the increased power output from WECS as shown in Figure 7-13(b) during the frequency recovery period. Moreover, the enhanced controller has no impact on the frequency nadir.

![Figure 7-13 Enhanced primary frequency response: (a) frequency; (b) WECS power output.](image)

**Figure 7-13 Enhanced primary frequency response: (a) frequency; (b) WECS power output.**

### 7.7 Experimental Tests

Experimental tests are carried out on a laboratory RAPS system to validate the proposed frequency regulation strategy further. The RAPS system has the same configuration as the simulated model shown in Figure 7-8 and operates at a lower loading level. The architecture of the laboratory RAPS system is shown in Appendix C. The PMSG is coupled
to an induction motor, which is controlled by a VSD to emulate the torque-speed characteristics of a wind turbine. The DG is emulated by a synchronous generator coupled to another VSD controlled induction motor. A LAB bank and an UC bank are connected to the DC-link of the WECS using two independent bidirectional DC/DC converters.

(a)

(b)
Performance of the Transient Frequency Regulator

In this scenario, the synchronous generator is regulated in speed control mode to maintain the system frequency around 50 Hz (for this test, a noncritical operating frequency range of [49.95 Hz, 50.05 Hz] is chosen). A sudden load change (i.e., 600W) occurs (which is carried out intentionally) to generate a frequency disturbance. If the WECS does not provide any frequency support, as shown in Figure 7-14(a), a frequency dip of 0.71 Hz is resulted. Due to the frequency regulation of the synchronous generator, the frequency returns to the noncritical operating frequency range, and the recovery takes 1.06s while an overshoot exceeding the noncritical range can also be observed. Figure 7-14(b) presents the result with WECS providing virtual inertial response and primary frequency response ($k_b=0.1$, $k_c=0.01$). The frequency dip is reduced to 0.47 Hz and the recovery time is also reduced to 0.74s. As discussed in Section 7.5.1, the traditional virtual inertia control slows down the frequency recovery due to the UC’s power absorption at the frequency recovery section, which is indicated by the negative part of the UC power curve in Figure 7-14(b). The performance of the proposed enhanced primary frequency...
response control strategy is presented in Figure 7-14(c). By comparing Figure 7-14(b) and Figure 7-14(c), it can be seen that the main difference is the frequency recovery section of the UC power curve. When the frequency reaches the frequency nadir, the UC injects power (see the zoomed figure in Figure 7-14(c)) instead of absorbing power as in the case of traditional virtual inertia control. Hence, supplementary primary frequency response is provided by the UC to assist the frequency recovery. Consequently, the frequency recovery time is further reduced to 0.61s.

7.7.2 Performance of the Secondary Frequency Regulator

The secondary frequency response strategy discussed in Section 7.5.3 is tested in this scenario. The synchronous generator is operated at droop control mode, which means the speed setpoint of the VSD is proportionally reduced with the increase in load torque. The scaling factor is chosen to be 0.1. Hence, an initial frequency deviation of 0.35 Hz can be observed in Figure 7-15(a) when the synchronous generator is supplying a fraction of the load. Therefore, an extended noncritical operating critical frequency of [49.5 Hz, 50.5 Hz] is set to avoid the activation of primary frequency response from the WECS at the initial condition (zero LAB current can be observed in Figure 7-15(b)). The sudden load increase causes a sharp decrease in frequency and triggers the virtual inertial response and the enhanced primary frequency response. After the transient period, the frequency stabilises at a value (with a deviation of 0.65 Hz) outside the noncritical operating range. The secondary frequency response from mechanical power reserve in the wind turbine is activated first. The wind turbine shifts from suboptimal position to typical MPP and an increase (around 100 W) in turbine power thus WECS power output can be seen in Figure 7-15(a). Meanwhile, the LAB power decrease on the slight increase in frequency, but the frequency is still lower than the lower limit of the noncritical operating frequency range. Subsequently, the secondary frequency response from LAB is also activated in order to restore the frequency. The LAB power increases at a ramp rate of 100 W/S. At the moment when the frequency reaches the noncritical operating range, the primary frequency response is deactivated and a minor turning point can be observed on the WECS power curve.

There is also another nonzero section on the UC current curve in Figure 7-15(b), which is due to the active enhanced primary frequency response from the UC. It is also important to note that current of high-frequency variation is handled by the UC whereas the LAB only manages slow changing current, which protects the LAB from inrush currents and
unnecessary charging/discharging cycles. The release of the secondary frequency response reserve can be achieved by tertiary frequency control [177].

![Graph showing frequency deviation, WECS status, DC link voltage, and current responses](image)

**Figure 7-15** Performance of the longer-term frequency regulator: (a) frequency deviation and WECS status; (b) UC and LAB currents.
7.8 Summary

A multilevel energy storage system comprising LABs, UCs and mechanical power reserve in a wind turbine was developed and investigated to assess their contribution towards RAPS system frequency regulation. The matching nature between the energy density of the three energy storage techniques and the response time-frame associated with three types of frequency response schemes enables multilevel energy storage system as a favourable option for frequency regulation. Control strategy for each energy storage technique was developed to realise the frequency regulation capability for each component. Moreover, a novel strategy was also proposed involving the UC to provide supplementary primary frequency response and enhance the frequency regulation performance provided by the WECS. Simulation studies and laboratory tests were carried out to validate the proposed strategy. The strategy can effectively regulate the RAPS system frequency while eliminating the abrupt charging/discharging for the batteries and relieve electrical/mechanical stress on the WECS when the wind turbine is engaged in frequency regulation. Therefore, the overall strategy can improve the service life of WECS and LABs. Meanwhile, the service life of the UCs is not significantly shortened due to their capability of large number of charging/discharging cycles.
Chapter 8

Deadband Control of Doubly-Fed Induction Generator around Synchronous Speed

8.1 Foreword

Appropriate sizing techniques and the active participation of renewable power generators in frequency regulation can improve the power supply reliability. Nevertheless, the reliability of electrical components of a generator system also directly affects the reliability of the generator and thus the power supply in a RAPS system. The utilisation of semiconductor based power converters in renewable power generators enables flexibility to the generator control, but extra electrical components can deteriorate the reliability of the renewable power generator. In particular, the involvement of DFIG in frequency regulation in RAPS system (as discussed in Chapter 4) causes the DFIG to operate in wide rotor speed, the power converters can be subjected to high thermal stress and service life of the power converters can be severely shortened. Therefore, this chapter explored a strategy to improve the reliability of the electrical components, particularly the semiconductor devices, of a DFIG.

8.2 Overview

Semiconductor devices in power electronic converters of the DFIG are susceptible to significant junction temperature variations when operating around synchronous speed, thereby reducing the lifetime of the converters. This is due to the fact that the frequency of the rotor current in a DFIG is determined by the stator flux frequency and rotor speed, and hence will lead to low rotor current frequency when operating closer to the synchronous speed, and ultimately result in significant thermal stress on semiconductor devices. In this chapter, a multimode operation control strategy was proposed for the DFIG to prevent operating around the synchronous speed (within a predefined deadband), thus the
The proposed control strategy can avoid the thermal stress problem. The proposed strategy engages the existing crowbar scheme for DFIG to intentionally alter the operating mode of the generator between DFIG and induction generator (IG). Smooth transition between the two operating modes can be achieved with the supplementary control strategies. Unity power factor can also be maintained in both operating modes by using the GSC as a STATCOM to fulfil the reactive power requirement of the DFIG in IG mode. The structure of the rest of Chapter 8 is presented in Figure 8-1.

**Figure 8-1 Structure of Chapter 8.**

### 8.3 Background

DFIGs are widely used around the world for the wind energy harvesting. The reliability of the WECS is an important consideration which ensures a high return on the investment. Surveys carried out in [154, 181] showed that the semiconductor devices are the most vulnerable components in WECSs.

Power converters of the WECS are designed to be in service for 20-25 years, and thermal performance is closely related to the reliability of semiconductor devices in the converters [164]. Packaging-related failure mechanisms of semiconductor devices, such as bond wire lift-off and solder fatigue, are affected by junction temperature as well as temperature fluctuations in power cycling of the semiconductor devices [182]. The lifetime (or the number of cycles to failure) of switching devices is proportionally decreased with an increase in the amplitude of junction temperature fluctuation [183]. As stated in [183], the minimum operating frequency is a critical parameter of a power semiconductor device apart from overcurrent, and the designer has to take the pulsing of junction temperature into consideration when the converter operating frequency is low, since the junction temperature has a higher variation at a lower operating frequency and the maximum junction temperature is likely to be exceeded.
Conventionally, power electronic devices in the utility power industry have low temperature swings [181], but the application of wind power brings large transients and thermal cycling issues. For example, when the rotor speed approaches synchronous speed in a DFIG, the rotor current frequency becomes low as the rotor current frequency equals to the slip frequency. Hence, higher temperature swing and shorter life span of power switches in the RSC are resulted. In [184], the variation of the semiconductor junction temperature was shown to be reaching its maximum around the synchronous speed when the slip is low and the period of thermal cycle is long. The authors in [185] also suggested that the maximum junction temperature in the insulated gate bipolar transistors (IGBT) of the RSC are likely to be exceeded around synchronous speed. A power cycling capability estimation method was proposed for the DFIG in [186] and the negative effect of low slip frequency operation on power cycle capability of a DFIG power converter was studied. Authors in [187] concluded that the thermal performance of semiconductors in an RSC becomes crucial around the synchronous operating point. Therefore, semiconductor devices in the RSC are significantly stressed around synchronous speed, and it is important to investigate and propose strategies to overcome the thermal stress issue.

8.4 Limitations in Existing Control Strategies and Technical Contributions

Limiting the junction temperature of the semiconductor devices within rated limits is strictly required for maintaining the longevity of the converter. By limiting the power transfer of the converter can regulate the junction temperature [188], for example, rotor current is limited to avoid further temperature increases when the rotor winding temperature increases by 86% around synchronous speed [189], but the effectiveness of intended control strategy will be affected. A converter of higher rating and a heat sink of lower maximum temperature can be a solution, but additional investment and larger space are required. Authors in [190] proposed a different converter topology to decrease the power loss and thus reduce the risk of overheating, which may not be the preferable solution for WECS manufacturers due to high cost and space constraints [185]. The authors of [185] suggested the use of a discontinuous PWM technique to reduce power loss of the DFIG and thus the maximum junction temperature, enabling the generator to operate within the entire speed range. In [191], the authors found that the mean time to failure (MTTF) of the IGBTs in a variable speed drive(VSD) system reduces dramatically at higher junction
temperature variation, and a switching frequency reduction strategy was proposed in order to reduce the power loss under low output frequency operation, thus improving MTTF. With these sophisticated PWM techniques, the thermal problem of synchronous operation can be reduced, but the resulting harmonics problem can be difficult to address. For example, the variation in switching frequency may introduce difficulty in harmonics filtering, and advanced harmonics filtering techniques and devices are required [10]. Furthermore, there is a common limitation in existing control strategies, since the solutions are mainly capable of reducing the mean junction temperature but have limited impact on reducing the temperature swings which are mainly affected by the fundamental output frequency. As mentioned in [185, 189], another solution is to avoid synchronous operation in practical applications. In [192], an unstable section replaces the typical MPPT curve around synchronous speed. Consequently, the rotor speed slides through the unstable region when the rotor speed approaches the predefined speed range. However, mechanical torque stress caused by the fast torque change around synchronous speed brings a burden on the drivetrain and increases wear and tear of the drivetrain. The gearbox and drivetrain have the longest downtime per failure, and energy production can be significantly affected by drivetrain failure [154].

In this chapter, a multimode operation strategy is proposed to prevent the DFIG operating within a predesigned range around the synchronous speed. Hence, the large junction temperature variation can be avoided. The strategy utilises the existing crowbar protection scheme of a DFIG in order to operate it as an IG when it approaches a predefined speed range close to synchronous speed. Supplementary control strategies are proposed to achieve a smooth transition between the DFIG mode and the IG mode. The back-to-back converter scheme of the DFIG is used as an STATCOM to satisfy the reactive power requirement of the generator in IG mode. With the proposed strategy, neither additional facilities nor modifications to the current system configuration are required. Therefore, the thermal issue can be solved without derating the current performance of the DFIG and violating the grid-code standards. Power loss model and thermal network for the RSC are established to verify the effectiveness of the proposed strategy.

8.5 Operation of Wind Energy Conversion System
8.5.1 Low Slip Frequency Problem of DFIG

A DFIG is mainly composed of a wind turbine, drivetrain, wound rotor induction machine (WRIM) and back-to-back voltage source converter scheme as illustrated in Figure 8-2. The voltages and currents of variable frequencies supplied by the RSC enable the wind turbine to operate at variable speeds while keeping WECS synchronised with the grid. The control mechanisms for RSC and the GSC are well described in the published literature [130] and also included in the Appendix B, for brevity, will not be described in this chapter.

![Control diagram of the DFIG.](image)

Figure 8-2 Control diagram of the DFIG.

The angular frequency of rotor voltages and currents ($\omega$) in a doubly-fed induction machine is determined by the angular frequency of stator flux or the angular frequency of stator voltages and currents ($\omega_s$) and the rotor rotational speed ($\omega_r$) [193] (i.e., $\omega = s\omega_s$ with the $s$ being the slip). Therefore, the angular frequency of the rotor current becomes very small when the slip approaches zero (i.e., the rotor speed approaches the synchronous speed). For the DFIG used in this chapter, the performance of the generator around synchronous speed is presented in Figure 8-3. Since lower frequency causes much longer
temperature rises and falls, larger peak to peak swings will occur. For example, an enhanced air cooling system (with an air-flow of 120 m$^3$/h and a heat sink to ambient thermal resistance, $R_{th-h-a}$, of 0.093 K/W [183]) is applied to the DFIG power converter in this chapter, the resulting variation in IGBT junction temperature is shown by the orange curve in Figure 8-3(c). The variation reaches its maximum value (around 100 °C) when the rotor speed is exactly at synchronous speed and stays at the synchronous speed (which is unlikely to happen) because RSC supplies direct current and IGBTs are constantly turned on or off. The lifetime of power semiconductors decreases with an increase in the amplitude of junction temperature fluctuation. With a more sophisticated liquid cooling system (e.g., flow rate=8 L/min, water/glycol ratio 50%:50% [194]), the heat sink to ambient thermal resistance reduces to 0.0092 K/W. The mean junction temperature is reduced, and the variation in junction temperature is narrowed as shown by the blue curve in Figure 8-3(c). However, the sophisticated cooling system demands higher investment and, O&M costs also increase. Therefore, the authors propose a deadband control for the DFIG around synchronous speed to reduce junction temperature swings without upgrading the cooling system.

Figure 8-3 Operation of a DFIG around synchronous speed: (a) rotor speed; (b) rotor three-phase currents; (c) junction temperature of an IGBT in RSC.
8.5.2 Proposed Multimode Operation Strategy

Sudden grid voltage disturbances, such as voltage dips, can induce a large inrush current in rotor windings and could potentially damage the DFIG rotor windings and semiconductor devices of the RSC. A crowbar system, as shown in Figure 8-4, is widely being used to protect the DFIG during grid faults and to improve the low-voltage-ride-through (LVRT) capability. The crowbar consists of resistors and semiconductor switches. When the switches are turned on, the resistors are connected in series with the rotor windings and the IGBTs of the RSC are blocked. Consequently, the generator operates similar to an IG.

![Schematic diagram of a crowbar for a DFIG.](image)

In this chapter, the crowbar protection scheme is used to facilitate the proposed multimode operation (i.e., DFIG mode and IG mode as explained below). The multi-mode operation prevents the rotor speed of the DFIG from being within a particular range around synchronous speed. That is, a predesigned deadband \([\omega_s - \varepsilon, \omega_s + \varepsilon]\) is set for DFIG operation. The tolerance \(\varepsilon\) is set according to the thermal limits of the semiconductor devices to ensure the semiconductors operating within safe junction temperature. As suggested in [183], when frequencies are lower than 5 Hz (corresponding to a rotor speed of 0.1 p.u. in a system with a normal frequency of 50 Hz), the junction temperature follows power dissipation, which results in high temperature fluctuation. It is also recommended in [188] that derating of the converter is necessary when rotor frequencies are lower than 0.1 p.u. Otherwise, the relationship between the junction temperature and rotor current frequencies should be determined through an experiment as outlined in [185, 195] to set
the value for \( \epsilon \). In this chapter, since the DFIG is operating at unity power factor, the rotor current is less than its rated value (as used in the case where \( \epsilon \) is set at 0.1 p.u.) when DFIG operates around synchronous speed. Therefore, the deadband can be smaller and \( \epsilon \) is adjusted to be at 0.02 p.u., which corresponds to a slip frequency of 1 Hz.

1) **DFIG Mode:** when the rotor speed is outside the deadband, the WECS operates as a typical DFIG. The equivalent circuit of the generator is shown in Figure 8-5(a).

2) **IG Mode:** when the rotor speed is less than \((\omega_s + \epsilon)\) or larger than \((\omega_s - \epsilon)\), the crowbar circuit is activated by connecting an external resistance to the rotor windings while RSC is disabled. As a consequence, the DFIG becomes an induction generator. The equivalent circuit of the generator at IG mode is shown in Figure 8-5(b).

Another strategy to rectify this excessive heating issue around synchronous speed is the SOPPT approach proposed in [151]. In the SOPPT approach, it simply shifts the rotor speed to a certain value outside the deadband to avoid the synchronous operation. However, the constant speed operation can cause significant torque stress on the drivetrain. Furthermore, an anemometer is required to monitor the wind speed to determine the suitable time to shift back to MPPT operation mode. The wind speed measurement accuracy directly affects the effectiveness of the strategy based on the SOPPT. These two drawbacks can be avoided with the multimode operation strategy.

It is also important to be noted that the LVRT has higher priority over the deadband control of the synchronous operation and the system will sacrifice its component lifetime to maintain the stability of the system under contingency. With the proposed control strategy, the multimode operation mechanism is only active under normal grid voltage condition, and the mode transition is not activated under grid faults. The deadband control will not be enabled until grid fault is cleared and the LVRT operation is reset. Hence, the conflict between deadband control and LVRT control can be avoided.

### 8.6 Supplementary Control for Multimode Operation

From the equivalent circuit of the DFIG in Figure 8-5(a), the electromagnetic torque of the generator under DFIG mode can be determined by:

\[
\tau_{DFIG} = \frac{3p}{\omega_r} \cdot \frac{R_r}{s} \cdot \left| I_r \right|^2 - \frac{3p}{\omega_r} \cdot \left( \frac{1-s}{s} \right) \Re\left( U_r \cdot I_r^* \right)
\]  

(8-1)
where \( p \) is the number of pole pairs, \( R_t \) is the rotor resistance referred to the stator side, and \( \text{Re}(U_r \cdot I_r^\ast) \) indicates the real part of the multiplication of the rotor voltage phasor and current phasor conjugate. As explained in [193], (8-1) can be further extended as (8-2) and the terms of (8-2) are given in [193].

\[
\tau_{DFIG} = 3 \frac{L_m}{\sigma \cdot L_s \cdot L_r} \cdot p \cdot F^2 \{ C_r \cdot C_r \cdot |U_r| \cdot |U_s| \cdot \sin \varphi + A_r \cdot C_r \cdot |U_s|^2 \cdot \sin B_r \\
- A_s \cdot C_r \cdot |U_s|^2 \cdot \sin B_s - A_s \cdot A_r \cdot |U_s| \cdot |U_s| \cdot \sin(\varphi + B_s - B_r) \}
\]

Similarly, the electromagnetic torque of the generator under the IG mode is given by:

\[
\tau_{IG} = \frac{3p \cdot (R_s + R_{cb})}{\omega_r} \cdot \left( \frac{1-s}{s} \right) \cdot |I_r|^2
\]

(8-3)

where \( R_{cb} \) is the crowbar resistance referred to the stator side. Using Thévenin's Theorem, (8-3) can be extended as (8-4).

\[
\tau_{IG} = \frac{3p \cdot (R_s + R_{cb})}{\omega_r} \cdot \left( \frac{1-s}{s} \right) \cdot \frac{U_{TH}^2}{[R_{TH} + (R_s + R_{cb})/s]^2 + (\omega_s \cdot L_{TH} + \omega_s \cdot L_r)^2}
\]

(8-4)

The Thévenin voltage and impedance are given by (8-5) and (8-6) respectively.

\[
V_{TH} = \frac{j(\omega_s \cdot L_m)}{[R_s + j(\omega_s \cdot L_s)] + j(\omega_s \cdot L_m)} \cdot U_s \angle 0
\]

(8-5)

\[
R_{TH} + j(\omega_s \cdot L_{TH}) = \frac{[R_s + j(\omega_s \cdot L_s)] \cdot j(\omega_s \cdot L_m)}{[R_s + j(\omega_s \cdot L_s)] + j(\omega_s \cdot L_m)}
\]

(8-6)

where \( L_m \) is the magnetizing inductance, \( L_s \) is the stator leakage inductance, and \( R_s \) is the stator resistance.
In DFIG mode, the machine is controllable through the RSC. As (8-2) shows, the electromagnetic torque is controlled by adjusting the phase angle ($\phi$) and magnitude of the rotor voltage ($U_r$). Contrarily, the controllability is lost when the crowbar short-circuits the rotor. As indicated by (8-4), with a fixed stator terminal voltage and crowbar resistance, the electromagnetic torque cannot be controlled externally in IG mode. In order to achieve a smooth transition between these two operating modes, the electromagnetic torque in both operating modes is expected to be more or less the same when the transition is taking place. Hence, the torque transient on the drivetrain of the DFIG can be alleviated. Therefore, supplementary control strategies should be implemented in the torque controller as shown in Figure 8-2, in order to provide a torque reference to the RSC controller and modify the electromagnetic torque to match with the mechanical torque.

![Figure 8-5 Equivalent circuits of the generator: (a) DFIG mode; (b) IG mode.](image)

![Figure 8-6 Torque speed curve of a wind turbine at variable wind speed.](image)
8.6.1 Transition from DFIG Mode to IG Mode

Figure 8-6 shows the torque-speed curves of a wind turbine at variable wind speeds. Typically, the wind turbine is controlled to operate at the speed where wind energy extraction is maximised. The tracking curve is indicated by the thick dashed line in Figure 8-6, and there is one section within the range \([\omega_s-\epsilon, \omega_s+\epsilon]\) which should be avoided as explained in Section 8.4. Thus, this section is set as the deadband for the DFIG mode operation, and the operating mode of the WECS should be altered to IG mode when rotor speed reaches the deadband. Under the steady-state condition in IG mode, the equilibrium point (which is the intersection of the torque speed curve of the WRIM and the torque-speed characteristic curve of the wind turbine at a particular wind speed) under IG mode operation is dependent on the crowbar resistance. For example, the green dash-dot line in Figure 8-6 is the torque-speed curve with the rotor windings short-circuited (i.e., \(R=R_r\)). By connecting an external crowbar resistance into the rotor circuit, the equivalent rotor resistance is increased (i.e., \(R=R_r+R_{cb}\)). The modified torque-speed curve of the WRIM has the shape indicated by the blue dash-dot line in Figure 8-6. Although the direct short-circuit of the rotor has better operating efficiency, the additional hardware configuration is required for the DFIG to enable this operation, and the narrower operating speed range due to lower total rotor resistance significantly stresses the drivetrain. Hence, existing crowbar is applied to alter the DFIG operation modes in this chapter. With the characteristic curves of the wind turbine and WRIM, the wind speeds which drive the DFIG operation within the deadband \([\omega_s-\epsilon, \omega_s+\epsilon]\) can be determined. Then the intersections of the torque-speed curve (i.e., the blue curve) of the WRIM and the torque-speed characteristic curves of the wind turbine can be obtained under the corresponding wind speeds. Thus, the speed range \([\omega_i, \omega_h]\) for IG mode operation can be determined.

To achieve a smooth transition from the DFIG mode to the IG mode, the electromagnetic torque should be adjusted to be equal in the two different modes at the time of transition. Therefore, when the DFIG rotor speed is within the deadband, the operating point is shifted intentionally away from the optimal point (e.g., point A) to the operating point in IG mode (e.g., point B) before activating the transition. The control logic is illustrated in the flowchart shown in Figure 8-7. The DFIG is controlled by the torque regulator to change the rotor speed to the IG mode operating speed range. To avoid frequent mode transitions, hysteresis control is used to detect the rotor speed and a moving average method is used to measure the rotor speed.
8.6.2 Transition from IG Mode to DFIG Mode

In IG mode, the generator consumes reactive power from other reactive power sources for excitation. Hence, additional reactive power support should be provided to improve the power factor of the DFIG during the IG mode operation. Capacitors are commonly used for standard IG based WECS, but similar capacitors may not be installed for DFIGs. As suggested in [196], the GSC in combination with the DC-link can be used as a reactive power source. In this chapter, the GSC is used to supply reactive power for the excitation of the generator itself, thus acting as a STATCOM in IG mode to correct the power factor seen by the grid. The reactive power capability of the GSC can be fully utilised with no active power transfer and it is not compromised by grid faults, since the transition is carried out under normal operation. Power factor control is implemented in the GSC controller. With the power factor (PF) set by the wind farm system level control, and the actual active power \(P_{w0}\) generated from the generator, the reactive power reference \(Q_{ref}\) for the GSC controller can be obtained using (8-7).

\[
Q_{ref} = \left(\frac{1}{PF^2} - 1\right) \cdot P_{w0}
\]  

(8-7)
For example, $Q_{\text{ref}}$ is set to be zero if the generator is expected to be operated at unity power factor. The reactive power control logic is shown in Figure 8-8. The input to the VAr regulator is the error between the reactive power reference and actual DFIG system reactive power output ($Q_0$). The GSC $q$-axis current reference (which controls the reactive power in grid voltage oriented reference frame with $d$-axis aligned with the voltage) is supplied. The transition signal ensures the supplementary reactive power control is only activated under IG mode.

Moreover, grid codes generally have power factor limitations (e.g., 0.95 lagging to 0.95 leading under normal grid condition) for grid-connected WECSs to support voltage regulation; and extra reactive power support can also be required under fault conditions (e.g., voltage dips) [197]. If the grid demands the generator to absorb reactive power from the grid within the permissible power factor range (i.e., lagging power factor), the reactive power supplied from the GSC can be reduced and the burden on the GSC is reduced while the grid code can be satisfied. However, if the generator is expected to supply reactive power to the grid (i.e., leading power factor) in IG mode, the GSC should supply reactive power to the generator as well as the grid and it will be highly stressed or may not have enough reactive power capability to support voltage regulation. Hence, higher capacity might be required for the GSC. Nevertheless, it is important to note that the grid codes are normally by the voltage support requirements at the PCC where the wind farm is interfaced to the grid. The coordinated control among WECSs in the wind farm could be able to satisfy the reactive power requirement, since it is unlikely that all WECSs in the wind farm will operate in IG mode simultaneously. Furthermore, extra reactive power resources like STATCOM, SVC, etc. are generally equipped for wind farms at the PCC to support voltage regulation [198].

![Diagram of Reactive power control using GSC.](image)

In IG mode, when the rotor speed exceeds the IG operation range [$\omega_i, \omega_h$], the generator shifts back to the DFIG mode. Since the RSC loses the control of the generator in IG
mode, the torque of the IG cannot be actively controlled. Nevertheless, due to the fast response of electromagnetic torque control, the generator is able to track to the electromagnetic torque reference rapidly after switching back to the DFIG mode. If improper torque reference is provided, large torque transient is expected due to the mismatch between the mechanical torque and electromagnetic torque. Therefore, the torque reference provided by the torque controller should be able to closely follow the mechanical torque during the IG mode operation, and an anti-windup control loop is added into the torque controller as shown in Figure 8-9. Without the anti-windup control, an error presented between the actual rotor speed and rotor speed reference provided by the MPPT control will drive the torque reference to its limit, causing a sudden shock on the drivetrain and large oscillations in the rotor speed during transition. When the anti-windup control is applied, the electromagnetic torque reference can closely follow the mechanical torque by feeding back the error between torque reference and mechanical torque to the speed regulator. Hence, the high torque stress on the drivetrain can be alleviated. A similar supplementary controller is used in [151] to provide enhanced primary frequency response from the DFIG. The implementation of the supplementary control in this chapter further extends the benefits of the supplementary control of the frequency regulation proposed in Chapter 4.

![Figure 8-9 Torque controller with anti-windup control.](image)

### 8.7 Thermal Analysis of DFIG Components

#### 8.7.1 Thermal Analysis of Semiconductor Devices

The procedure of thermal analysis for semiconductor devices in this chapter is presented in Figure 8-10. The electrical loading signals from the DFIG electrical model as shown in Figure 8-2, such as DC-link voltage \(U_{DC}\), RSC switching frequency \(f_{sw}\) and RSC currents, are fed into an energy loss calculation function, from which power loss \(P_{loss}\) of
the semiconductors can be calculated, and then the semiconductor junction temperature \( (T_j) \) can be estimated with the thermal network of the semiconductor devices. The temperature is feedback to the loss calculation function to reflect the temperature dependency of the losses.

![Figure 8-10 Thermal analysis model.](image)

The energy loss of semiconductor devices are mainly composed of two parts: conduction loss and switching losses. The conduction loss of the IGBT and the freewheeling diode can be determined by (8-8) and (8-9) respectively [185].

\[
E_{\text{con,IGBT}}(i_T, T_j) = \int_0^T i_T(t) \cdot [u_{ce0}(T_j) + r_{ce}(T_j) \cdot i_T(t)] dt
\]

(8-8)

\[
E_{\text{con,diode}}(i_D, T_j) = \int_0^T i_D(t) \cdot [u_{f0}(T_j) + r_J(T_j) \cdot i_D(t)] dt
\]

(8-9)

where \( u_{ce0} \) and \( u_{f0} \) are the threshold voltage of the IGBT and diode respectively, \( r_{ce} \) and \( r_f \) are the bulk resistance of IGBT and diode respectively, and \( i_T \) and \( i_D \) are the current flowing through IGBT and diode respectively.

In regard to the switching losses of an IGBT and diode, it depends on the load current, DC link voltage and junction temperature as given by (8-10) and (8-11) [183, 192].

\[
E_{\text{sw,IGBT}}(i, U_{DC}, T_j) = (E_{on} + E_{off}) \cdot \frac{i}{I_{ref}} \cdot \left( \frac{U_{DC}}{U_{ref}} \right)^{K_u} \cdot \left[ 1 + C_{sw} \cdot (T_j - T_{ref}) \right]
\]

(8-10)

\[
E_{\text{sw,diode}}(i, U_{DC}, T_j) = E_{\text{sw,diode}} \cdot \left( \frac{i}{I_{ref}} \right)^{K_i} \cdot \left( \frac{U_{DC}}{U_{ref}} \right)^{K_u} \cdot \left[ 1 + C_{sw} \cdot (T_j - T_{ref}) \right]
\]

(8-11)

where \( I_{ref}, U_{ref}, \) and \( T_{ref} \) are the current, voltage, and temperature respectively. \( K_u \) and \( K_i \) are the exponents for voltage and current dependency of the switching loss respectively. \( C_{sw} \) and \( C_{rr} \) are the temperature coefficients of switching loss for IGBT and diode respectively. In this chapter, the SEMIKRON IGBT module SKiiP 2013 GB172-4DW V3 [194]
is used for thermal analysis. The values for these parameters can be found in [183, 194].

The Foster network [183] is used as the model for the thermal network used in this chapter to estimate the junction temperature which is determined by (8-12):

\[
T_{j/T/D} = \left( P_{\text{con}T/D} + P_{\text{sw}T/D} \right) \cdot R_{\text{th}_{j-h}T/D} + T_h
\]

where \( P_{\text{con}} \) and \( P_{\text{sw}} \) are the conduction power loss and switching power loss respectively for an IGBT or diode, \( R_{\text{th}_{j-h}} \) is the thermal resistance between the junction and heat sink, and \( T_h \) is the temperature of heat sink which is given by (8-13).

\[
T_h = P_{\text{tot}} \cdot R_{\text{th}_{h-a}} + T_a
\]

where \( P_{\text{tot}} \) is the total power loss of the semiconductors, \( R_{\text{th}_{h-a}} \) is the thermal resistance between heat sink and ambient which is taken as 0.093 K/W in the case studies below. \( T_a \) is the ambient temperature chosen as 50 °C [187] in this chapter.

### 8.7.2 Thermal Energy Capacity of Crowbar

According to current grid codes, the crowbar operation during LVRT is limited to 3 s [197]. In this chapter, the multimode operation intends to operate the crowbar for a longer time, so it is imperative to investigate the thermal performance of the crowbar during multimode operation. The rotor overcurrent under grid faults can be up to three times the nominal current [154]. Contrarily, when the DFIG operates in IG mode around the synchronous speed as proposed in this chapter, the rotor current is much smaller than the nominal current. For example, the 1.5 MW DFIG considered in this chapter has a rated rotor current of 880 A, and the rotor current under IG mode is approximately 350 A. Hence, the power consumed by the crowbar under IG mode is substantially less than under fault conditions. The thermal time constant of the crowbar is generally high enough to handle the rotor fault currents. A commercial crowbar resistor (model: FLWR-2040 KJ/0.17R) [199], which has an energy rating of 2040 kJ, resistance of 0.17 Ω, and operating time of 3 s, has been used as the LVRT crowbar for the DFIG in this chapter. Using (14), the rated crowbar current (by assuming 3 s operation of the crowbar during LVRT) is calculated to be 2000 A, and thus it can be shown that the crowbar is capable of operating around 100 s (\( t = 2040 \times 103/(3502 \times 0.17) \)) under IG mode without overheating the crowbar. Also, it must be noted that the improvement in self-cooling effect due to low
Crowbar current is not considered in this calculation, hence the crowbar can be actually operated much longer than 100 s under IG mode.

\[ I = \frac{E}{\sqrt{1 - R^2}} \]  

(8-14)

Therefore, no hardware modifications are required for existing DFIG, such as cooling systems etc. to implement the deadband control strategy proposed in this chapter. It is also important to acknowledge that IG mode is just a temporary operating mode considering the continuous variation in wind speed. Fast cyclic IG mode operation can be avoided as exemplified in Section 8.8.4.

\[
\begin{align*}
S_{base} &= 10 \text{ MVA}, \hspace{0.5cm} V_{base} = 11 \text{ kV} \\
11 \text{ kV/0.4 kV} &\quad 3.5 \text{ MVA} \\
11 \text{ kV/2.4 kV} &\quad 3.5 \text{ MVA} \\
DFIG &\quad 1.5 \text{ MW} \\
\text{diesel generator} &\quad 3.125 \text{ MVA} \\
\text{Load} &\quad 0.17+j0.015 \\
\text{Load} &\quad 0.090+j0.010 \\
\text{Load} &\quad 0.040+j0.001 \\
\end{align*}
\]

Figure 8-11 Architecture of the test system.

8.8 Performance of the Multimode Operation

The proposed control strategy can be used in both grid-connected WECS and RAPS systems which are ‘islanded’ power system. In this chapter, a hypothetical RAPS system is established in the SimPowerSystems platform to investigate the performance of the
multimode controller, and the details of the system are given in Figure 8-11. RAPS systems are constituted of a small number of generators, and the total capacity is usually small. Power management is more challenging, and stability is more critical to manage in comparison to a grid-connected system. By validating new control strategies through such system can show the effectiveness of the control strategy even under the worst case scenario. The loads in the system are mainly powered by a DG and a DFIG. The DG establishes the system by providing frequency and voltage reference. The DFIG is expected to support the system while operating at unity power factor, and the main parameters of the DFIG are provided in Table 8-1. A similar system has also been explored in [151] to verify the frequency response strategy, but the control strategies and loads are adjusted to test the proposed control strategy.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rated power</td>
<td>1.5 MW</td>
<td>$L_m$</td>
<td>2.9 p.u.</td>
</tr>
<tr>
<td>Turbine inertia constant</td>
<td>4.32 s</td>
<td>$R_s$</td>
<td>0.023 p.u.</td>
</tr>
<tr>
<td>Rated wind speed</td>
<td>11 m/s</td>
<td>$L_s$</td>
<td>0.18 p.u.</td>
</tr>
<tr>
<td>Rated stator voltage</td>
<td>400 V</td>
<td>$R_r$</td>
<td>0.016 p.u.</td>
</tr>
<tr>
<td>Rated DC bus voltage</td>
<td>800 V</td>
<td>$L_r$</td>
<td>0.16 p.u.</td>
</tr>
<tr>
<td>Crowbar resistance</td>
<td>0.2 Ω</td>
<td>$\omega_l$</td>
<td>1.08 p.u.</td>
</tr>
<tr>
<td>$f_{sw}$</td>
<td>1350 Hz</td>
<td>$\omega_h$</td>
<td>1.11 p.u.</td>
</tr>
</tbody>
</table>

8.8.1 Transition from DFIG Mode to IG Mode

When the rotor speed reaches the deadband under DFIG mode as detailed in Figure 8-7, the operating mode of the DFIG is altered. As shown in Figure 8-12, a step increase in wind speed causes the rotor speed to increase at $t = 75$ s.

If the speed regulation (see Section 8.6.1) is not implemented, the DFIG switches to IG mode immediately, which causes large transient in the DFIG itself as well as the RAPS system. The sudden removal of the rotor voltage causes the rotor current to decay and, the collapse of the rotor magnetic field results in the loss of electromagnetic torque (see the blue dotted curve in Figure 8-12(c)). Hence, the power output from the DFIG drops
abruptly to zero as presented by the blue dotted curve in Figure 8-12(a). Furthermore, the violent variation in electromagnetic torque will also exert additional stress on the drivetrain. As seen in Figure 8-12(d), the mechanical torque decreases sharply and oscillates before reaching new steady-state, attributing to a sudden increase and oscillation in rotor speed (see the blue dotted curve in Figure 8-12(b)). Contrarily, with the proposed control strategy, the transition from the DFIG mode to the IG mode is smoothed significantly. At around $t = 75$ s, the DFIG starts to adjust the speed (thus torque) to match with the speed under the IG mode. The DFIG switches from the DFIG mode to the IG mode around $t = 92$ s. At the moment of transition, only minor disturbances are observed in power output, system frequency, and torques.

![Graphs](image)

Figure 8-12 The DFIG switches from DFIG mode to IG mode: (a) DFIG active power output; (b) DFIG rotor speed; (c) DFIG electromagnetic torque; (d) DFIG mechanical torque.

8.8.2 Transition from IG Mode to DFIG Mode

As explained in Section 8.6.2, if the proposed anti-windup control strategy is not implemented, the error between the actual rotor speed and reference value, will increase the torque reference value to its limits. The electromagnetic torque follows the reference rapidly (see blue dotted curve in Figure 8-13(c)) and a large difference is observed between
the mechanical and electromagnetic torques, which brings enormous torque stress on the drivetrain and an almost step change in rotor speed is resulted as shown by the blue dotted curve in Figure 8-13(b). A large oscillation in mechanical torque is observed in the zoomed section in Figure 8-13(d).

Meanwhile, an active power surge can also be observed at the DFIG as indicated by the blue dotted curve in Figure 8-13(a). With the proposed anti-windup control, the electromagnetic torque reference tracks the mechanical torque during the IG mode operation. At the moment of mode transition, the torque difference between the mechanical torque and electromagnetic torque is narrowed. Consequently, large transients are avoided, and a smooth transition from the IG mode to the DFIG mode is achieved.

For the case studies presented in Sections 8.8.1 and 8.8.2, a step change in wind speed is used to investigate the dynamic performance of the WECS during the transition period.

8.8.3 Operation under Variable Wind Speed

For the case studies presented in Sections 8.8.1 and 8.8.2, a step change in wind speed is used to investigate the dynamic performance of the WECS during the transition period.
In order to validate the effectiveness of the proposed strategy under a more practical scenario, a 250-s variable wind speed profile is applied to the DFIG. The performance of the DFIG under variable wind conditions are shown in Figure 8-14.

Figure 8-14 The DFIG operation under variable speed: (a) wind speed profile; (b) DFIG active power output; (c) DFIG reactive power output; (d) GSC active power output; (e) GSC reactive power output; (f) DFIG rotor speed.
The wind speed profile is shown in Figure 8-14(a). Initially, the DFIG is operating in DFIG mode and the rotor speed ($\omega_r$) is below synchronous speed, as shown in Figure 8-14(f) and thus, the GSC is absorbing power ($P_{gsc}$) from the grid (indicated by positive values as shown in Figure 8-14(d)). Since the GSC is operating under unity power factor, the reactive power flow ($Q_{gsc}$) at the GSC is zero (see Figure 8-14(e)). Figure 8-14(b) and (c) show the active power ($P_{w0}$) and reactive power ($Q_0$) interaction respectively between the DFIG and the grid. The DFIG does not participate in reactive power support for the grid, and operates closer to the unity power factor to satisfy the power factor requirement set by the utility.

Around $t = 30$ to $40$ s, the rotor speed is detected to be within the designated deadband (i.e., $[\omega_s-\varepsilon, \omega_s+\varepsilon]$) for DFIG operation. Hence, the speed regulation is activated; the speed regulation period is shadowed in Figure 8-14. The rotor speed increases and power output from the DFIG decreases, since the operating point of the DFIG is shifting away from the point set by MPPT control. Nevertheless, the financial benefit will not be compromised significantly, because the WECS temporarily operates in IG mode considering the continuous variation in wind speed. The GSC starts to provide active power when the rotor speed exceeds the synchronous speed. At the moment when the rotor speed reaches the range $[\omega_l, \omega_h]$, the crowbar is activated to short-circuit the rotor windings and the RSC is blocked. The mode transition takes place around $t = 60$ s in this case.

From Figure 8-14, it can be seen that abrupt changes only occur at the power output from the GSC, which indicates the smooth transition from the DFIG mode to the IG mode. The active power output at the GSC suddenly decreases to zero (see Figure 8-14(d)) due to the zero active power flow from rotor windings to the DC-link when the RSC is disabled. As described in Section 8.6.2, the zero active power output from the GSC leaves the capacity of the GSC for reactive power support. Therefore, the GSC operates as an STATCOM to fulfil the reactive power requirement of the DFIG under the IG mode, and hence the reactive power output from the GSC is no longer zero, as shown in Figure 8-14(e). Consequently, the grid does not supply any reactive power to the DFIG (under IG mode) and unity power factor operation is maintained as shown in Figure 8-14(c). The DFIG operates as an induction generator until the wind speed ramps down at around $t = 150$ s.

It is worth to be noted that an additional advantage of the IG mode operation is that it can enhance the frequency support by providing a natural inertial response by using its stored kinetic energy without any control intervention [111].
On the declining in wind speed from $t = 150$ s, the rotor speed decreases and the demand for switching WECS back to the DFIG mode is activated when the rotor speed is detected to be out of the range $[\omega_l, \omega_h]$. The crowbar mechanism is deactivated, and the RSC is activated. The DFIG slowly shifts to steady-state operation under DFIG mode. The GSC stops providing reactive power and starts to deliver active power again as seen in Figure 8-14(e) and (d) respectively.

The three phase-currents in rotor windings are shown in Figure 8-15. The upper left zoomed figure in Figure 8-15 shows that the frequency of rotor currents is approximately 0.5 Hz before the DFIG switches from DFIG mode to IG mode. As explained in Section 8.5, the low frequency of the rotor currents can cause thermal problems for the semiconductor devices of the RSC. The instantaneous power loss and junction temperature are shown in Figure 8-16(a) and (b) respectively for the upper IGBT and lower diode in one leg of the RSC. Since the IGBT and the diode turn on and turn off simultaneously, the instantaneous power loss of each component is coincidental, as shown in Figure 8-16(a), and the corresponding temperature of each component is also presented in the zoomed graphic in Figure 8-16(b). Although the power loss of the IGBT is higher than the diode between 35 to 45 s, the temperature of the IGBT is roughly the same as the diode, which is due to the lower junction-to-heatsink thermal resistance of IGBT compared to the diode. An additional lower peak in the temperature waveform can be observed between two
adjacent higher peaks, which is due to the thermal coupling effect between the IGBT and its anti-parallel diode since the two chips are placed on the same base plate and close to each other. The coupling effect becomes stronger when the current frequency is low and hence further increases the junction temperature fluctuation. The heating of the antiparallel diode in the second half of the fundamental period adds to the heating of the IGBT on the same base plate.

The upper right zoomed figure in Figure 8-15 presents the rotor currents when the DFIG is operating in IG mode, and higher frequency of rotor currents can be observed. Hence, rotor currents of very low frequency are avoided. Due to the subsynchronous and supersynchronous operation in DFIG and IG mode respectively, the phase sequences of the rotor currents change with the mode transition. Since the RSC is blocked in IG mode, it can be seen from Figure 8-16(b) that semiconductor devices are cooled down in IG mode.

![Figure 8-16 Thermal performance of the IGBT and diode: (a) instantaneous power losses; (b) junction temperature.](image)

8.8.4 Riding Through Synchronous Speed

Long-term operation around synchronous speed can be avoided with the proposed control strategy for the DFIG, and the operating mode of the DFIG is not expected to be changed if the rotor speed passes the synchronous speed rapidly due to large wind speed variations. Hence, the operating mode alternation will not be activated if the DFIG can ride-through the synchronous speed within a predefined time period. For example, the
average wind speed increases from 8.5 m/s to 10 m/s with a ramp rate of 0.05 m/s² (see Figure 8-17), the operating mode is not changed. If the ramp rate of wind speed is lower than 0.05 m/s², the mode transition will be activated, since the rotor speed stays within the deadband for a longer period of time, and the junction temperature increase may damage the semiconductor devices.

The time that rotor speed takes to ride through the deadband can be approximated based on the ramp rate of wind speed and the mechanical dynamics of the wind turbine. Considering the permissible time that a semiconductor device can safely operate at maximum junction temperature, the critical ramp rate of wind speed should be set to ensure the ride-through time does not exceed the permissible operating time. Additionally, the wind speed (i.e., 11 m/s in this chapter) at the rated power output of the wind turbine is well above the wind speeds (i.e., around 9 m/s in this chapter) under which the DFIG rotor speed is within the deadband. Hence, according to the probability density function of the wind speed for a typical wind farm location, the likelihood of DFIG operating in the IG mode is low. Therefore, the temperature swing due to the RSC on and off is not frequent and the financial loss due to the non-optimal operation under IG mode is limited while the reliability of the DFIG can be improved with the extended service life of the semiconductor devices.

Figure 8-17 The DFIG operation during wind speed ramp-up scenario: (a) wind speed profile; (b) DFIG rotor speed.
8.9 Proof of Concepts Using Experimental Test Bed

The effectiveness of the proposed control strategy is verified by extensive simulation studies presented in Section 8.8. Due to the fact that the IGBT junction temperature and its power loss related to thermal analysis are not available as a direct measurement in the practical experiment, simulation is a good alternative way to validate the proposed control strategy. In this section, some experimental results are provided to prove the concept of multimode operation using the test system as shown in Figure 8-18. The setup of the test system in the laboratory is shown in Appendix D.

![Diagram of the experimental test bed](image)

Figure 8-18 Architecture of the test system.

The system is developed based on the LabVolt® electric power technology training system with the guidelines and parameters given in [200]. A WRIM is used as the generator, whereas a dynamometer module emulates the wind turbine with its characteristic controlled by the computer interface. Since the purpose of the test is to observe the dynamics in rotor currents, stator currents as well as rotor speed and torque during mode transitions, the back-to-back converter scheme and its control are simplified. An IGBT based inverter unit is used for the RSC, while the DC-link is connected to a variable DC voltage source. In the case of supersynchronous operation, the rotor power is absorbed by
a dump resistor across the DC-link. The RSC is manually controlled by the inverter control unit to vary its output fundamental frequency, and the variable voltage DC-link controls the rotor voltage magnitude. Besides, no external resistance is added into the crowbar because no fault study is carried out in this chapter. Consequently, the system operates on the same principle as a normal DFIG apart from the lack of physical GSC.

The generator with rotor short-circuited under a wind speed of 10 m/s is tested and the rotor speed at the equivalent operating point is determined to be 1675 rpm. Then, the inverter is enabled and the rotor voltage is manipulated to operate the DFIG at unity power factor around synchronous speed (i.e., 1500 rpm). As shown in Figure 8-19, the RSC supplies direct current to the rotor windings with the fact that one phase current is two times the current of each of the other two phase-currents, causing unbalanced heating in IGBTs. By increasing the frequency of rotor currents with the phase sequence opposite to the rotor rotating direction, the rotor speed increases. As this process is manually controlled, fluctuations in rotor and stator currents as well as mechanical torque can be observed in Figure 8-19 and Figure 8-20. The transition from DFIG mode to IG mode takes place after the rotor speed reaches the speed determined in the first step, the crowbar is enabled while RSC is disconnected. The rotor speed and torque waveforms demonstrate that smooth transition from DFIG mode to IG mode is achieved. It can be seen that the

Figure 8-19 Test results showing rotor speed and rotor currents.
rotor current decreases while stator current increases under IG mode because reactive
current is supplied by the RSC in DFIG mode whereas the grid provides reactive power
for the generator excitation under IG mode (GSC is not available to provide reactive
power support in this test.). Since the inverter control unit maintains the original control
signal (which acts similarly to the RSC controller tracing the mechanical torque reference
during IG mode as discussed in Section 8.8.2), the system transits from IG mode back to
DFIG mode by connecting RSC to the rotor and disabling the crowbar. The transition is
also smooth without any abrupt variation in rotor speed and torque as shown in Figure
8-19 and Figure 8-20 respectively. Therefore, the test results validated the basic concept
of the multimode operation.

![Diagram](image)

**Figure 8-20** Test results showing mechanical torque and stator currents.

## 8.10 Summary

In this chapter, a multimode operation control strategy was implemented to prevent the
DFIG operating around the synchronous speed. Hence, large junction temperature varia-
tion in the semiconductor devices due to low slip frequency can be avoided. Supplementary
control strategies were proposed to minimise the transients caused by the mode tran-

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sitions. Detailed simulations were carried out to investigate the performance of the proposed control strategy in a RAPS system. Power loss and thermal network for the RSC was established to verify the effectiveness of the proposed strategy. The results validated that the deadband set for synchronous operation can reduce high temperature variations. Sensitivity analysis shown that the DFIG can ride-through the deadband to avoid unnecessary mode transitions if DFIG is confronted with highly variable wind speed and passes through synchronous speed. The proposed strategy does not require any additional hardware and modifications to the current system configuration while the grid codes can be satisfied. The concept of multimode operation has also been verified using an experimental setup. Furthermore, when the DFIG operating in induction generator mode, it can also enhance the frequency support with natural inertial response using its stored kinetic energy without any control intervention, which can be further explored.
Chapter 9

Conclusions and Future Work

9.1 Conclusions

The utilisation of renewable power generation in remote locations is backed by the abundant nature of renewable energy resources and the geographical space availability in areas with low population density. Nevertheless, the common challenges of renewable energy resources, such as the stochastic nature, erect a barrier for wide proliferation. First of all, the non-dispatchable feature of the renewable power generators, thus the indeterminacy in electricity generation, places risk at the reliability of power supply. Secondly, the characteristics of RAPS systems further complicate the management of the hybrid RAPS system because: (1) RAPS systems are susceptible to disturbances due to the fact that their sizes are relatively small in comparison to large utility grids; (2) The fact that generators of comparable capacities are aggregated in a RAPS system demands that each generator to actively participates in voltage and frequency regulation; and (3) Renewable power generators are usually coupled with the network using semiconductor devices based power converters. Hence, the absence of direct electromagnetic interaction between the network and the generators leads to lower system inertia and significantly changes the dynamic behaviour of the system. The deterioration in the stability of the RAPS system inevitably affects the power supply reliability as well. Last but not least, the reliability of the system components is another major factor which determines the reliability of power supply. The highly burdened conventional generators are prone to severe wear and tear, whereas the numerous electrical components of the renewable power generators may lead to high failure rates. Therefore, these three core issues should be addressed to improve the reliability of a RAPS system.

Based on a comprehensive review of the technical challenges within hybrid RAPS system, the research outcomes of this thesis established solid contributions in the reliability improvement of RAPS system. The reliability improvement is mainly achieved through three main aspects.
(1) **System Component Sizing Strategy**: an iterative approach was applied to RAPS system in order to evaluate the capacity value of renewable energy resources. The capacity value provides a meaningful metric for the capability that a particular renewable power generator can supply power at a designated reliability level. The impact of an energy storage system on the reliability of the RAPS system was also investigated. It was found that an energy storage system can significantly improve the reliability of the power supply in a hybrid RAPS system with DGs and high penetration of dispatchable renewable energy resources. The required capacities of the generators and energy storage devices were optimised using an iterative approach based on reliability indices.

(2) **Frequency Regulation Improving Strategies**: frequency response control strategies were proposed for DFIG based WECS, PV based solar energy conversion system, and PMSG based WECS. Various techniques were implemented in renewable power generators for power reserve maintenance.

- Kinetic energy stored in the DFIG was utilised to provide primary frequency response in the RAPS systems. A droop-based controller realised the short-term frequency response without using traditional high-pass filter, which improved the sensitivity and dynamics of the frequency response. Moreover, a supplementary controller was also proposed to further enhance the frequency response supplied by the DFIG.

- Power reserve was also established by derating the renewable power generators. A suboptimal power point tracking (SOPPT) strategy was proposed to establish power reserve in WECSs and solar-PV. Using the power reserve in active frequency regulation, the autonomous operation of a hybrid diesel-PV based RAPS system was achieved. The multimode operation strategy was used to optimise the operation characteristics of the renewable power generators and capability of the synchronous generator in reactive power support.

- Energy storage system provides another form of power reserve for frequency response. Hence, UCs were integrated into a PMSG to inaugurate the short-term frequency response. The high power density and fast response of the UCs make them suitable to use in the RAPS systems, especially for the requirement of the frequency response, but their low energy density limits their applications to short-term response only. Hence, a hybrid energy storage system consisting of UCs and LABs was introduced to the PMSG in RAPS systems. Due to the complementary characteristics of the two
types of energy storage devices, the system can cope with both short-term and long-term frequency response. Furthermore, an adapted virtual inertia control was proposed to enhance the primary frequency response and accelerate the restoration of frequency. The mechanical power reserve established using SOPPT was utilised to either charging the energy storage system or improve the frequency response. The approach proposed PMSG can be extended to apply for improving frequency response in DFIG or solar PV based RAPS systems.

(3) Stress Relieving Strategies: the thermal heating problem of the RSC, when the DFIG is operating around the synchronous rotating speed, was investigated. The deadband control strategy proposed in this thesis effectively reduces the junction temperature fluctuation of the semiconductor devices of the RSC. Consequently, smaller temperature swings relieve thermal stress on the RSC. The service life of this vulnerable electrical component will be extended due to the avoidance of synchronous operation. Hence, the reliability of the DFIG can be improved. Secondly, in the case when kinetic energy is utilised for frequency response in WECS, frequent frequency fluctuations would cause significant the mechanical/electrical torque stress on the WECS. By involving the UCs in frequency regulation, the torque stress problem is totally eliminated since the UCs cope with the frequency deviations whereas the PMSG is controlled to change its power output at an acceptable rate. Last but not least, the hybridisation of the energy storage system by combining UCs and LABs benefits the batteries. That is, by allocating fast changing power demand to UCs, whereas the batteries response to the slow changing power demand, frequent charging/discharging cycles and inrush currents are prevented for the batteries, which will extend the service life of the batteries.

Comprehensive simulations verified the proposed strategies with detailed simulation models constructed in MATLAB/Simulink. Moreover, a laboratory scale hybrid RAPS system mainly consisting of a PMSG based WECS, a synchronous generator, an UC bank, a LAB bank, and various loads were established to validate the control strategies relevant to the PMSG. Another basic DFIG based WECS test system was setup to test the deadband control strategy. The practical results demonstrated the effectiveness and applicability of the proposed strategies.


9.2 Future Work

In this thesis, the proposed control strategies are mainly tested in two-bus RAPS systems (both simulation platforms and laboratory test rig). These RAPS system topologies present basic prototypes of parallel operation of inertial and non-inertial generators, as well as renewable and non-renewable power generators, which provide meaningful insights into the challenges and solutions related to hybrid RAPS systems. Nevertheless, RAPS systems with larger number of buses should be investigated to demonstrate the general applicability of the proposed control strategies in a more practical condition. For example, IEEE-9 or IEEE-13 bus systems can be used as test system in terms of a simulation study.

The hybrid sources of energy production in RAPS systems studied in this thesis include DFIG-DG, PV-DG, PMSG-UC-DG, and PMSG-UC-LAB-DG. In a practical RAPS system, several types of renewable power generators may be integrated. These renewable power generators are of various characteristics which can be complementary to each other. Hence, exploration on the coordination control among these generators may optimise the advantages of each renewable power generator and maximise the total benefits these generators contribute to the RAPS system.

Since the energy storage system is used for frequency regulation in this thesis, the energy storage system is also a favourable energy buffer to smooth the fluctuating renewable power generation. When both frequency regulation and power smoothing are assigned to the energy storage system, the coordinated control is necessary to fulfil these two control objectives. For example, basic charging algorithm is applied to maintain the SOC of the energy storage system, and sophisticated algorithm might be developed to achieve optimisation in the effectiveness of control strategies while minimising the harmful impact on energy storage systems.

Furthermore, RAPS systems possess other characteristics as summarised in Chapter 2, which inherently differentiate the RAPS system from the large utility grids. A case in point is the resistive nature of the distribution networks in RAPS system. These characteristics may have a significant effect on the effectiveness of existing control strategies used in traditional power systems. A deep research investigating on RAPS- system-oriented control strategies remain to be discussed.
Appendix

Appendix A: Derivation of the DG Open Loop Transfer Function

As seen in Figure 5-4, the transfer function for the controller is

\[ G_1(s) = \frac{1 + s \cdot T_3}{1 + s \cdot T_1 + s^2 \cdot T_2} \]  \hspace{1cm} (A-1)

and the actuator transfer function is

\[ G_2(s) = \frac{K \cdot (1 + s \cdot T_4)}{s \cdot (1 + s \cdot T_5) \cdot (1 + s \cdot T_6)} \]. \hspace{1cm} (A-2)

The engine dead time is represented by a second order transfer function as given by (A-3)

\[ G_3(s) = \frac{1 - k_1 \cdot s + k_2 \cdot s^2}{1 + k_1 \cdot s + k_2 \cdot s^2} \]. \hspace{1cm} (A-3)

Treating electromagnetic torque \( \tau_e \) as disturbance, the open loop transfer function of the DG is given by

\[ TF_{OL}(s) = G_1(s) \cdot G_2(s) \cdot G_3(s) \cdot (1 - \frac{H_s}{H_s + H_d}) \cdot \frac{1}{2H_d \cdot s} \]  \hspace{1cm} (A-4)

By combing (A-1), (A-2), (A-3), and (A-4), the (5-8) can be determined. Therefore, the closed loop transfer function of the DG unit has the following form:

\[ TF_{CL}(s) = \frac{\omega(s)}{\omega_{ref}(s)} \]  \hspace{1cm} (A-5)

\[ TF_{CL}(s) = \frac{TF_{OL}(s)}{1 + H(s) \cdot TF_{OL}(s)} \]  \hspace{1cm} (A-6)

where \( H(s) \) is the feedback loop gain.
Appendix B: Control Theory of the DFIG

Since the DFIG includes a RSC and GSC, which are controlled in stator-flux-oriented reference frame and grid-voltage-oriented reference frame, the DFIG converter control is used as an example here for analysis. The PMSG as well as solar-PV have the same interface converters as the GSC of DFIG.

B.1 Wind Turbine

The mechanical power output from a wind turbine with rotor radius of $r$ can be determined using (B-1).

$$P_m = \frac{1}{2} \rho \cdot \pi r^2 \cdot V_w^3 \cdot C_p(\lambda, \phi)$$  \hspace{1cm} (B-1)

where $\rho$ is the air density usually taken as 1.225 kg/m$^3$, $V_w$ is the wind speed at the hub height, and $C_p(\lambda, \phi)$ is power efficiency of the wind turbine which is a function of tip-speed-ratio $\lambda$ and pitch angle $\phi$.

The tip-speed-ratio is defined in (B-2).

$$\lambda = \frac{\omega_r \cdot r}{V_w}$$  \hspace{1cm} (B-2)

where $\omega_r$ is the rotor angular speed. The power efficiency is usually provided by the manufacturer as power efficient curves. Based on the modelling turbine characteristics [201], (B-3) is used to model $C_p(\lambda, \phi)$.

$$C_p(\lambda, \phi) = 0.5176 \left( \frac{116}{\lambda} - 0.4\phi - 5 \right) \cdot e^{-\frac{21}{\lambda}} + 0.0068\lambda$$  \hspace{1cm} (B-3)

with

$$\frac{1}{\lambda'} = \frac{1}{\lambda + 0.08 \cdot \phi} - \frac{0.035}{\phi^3 + 1}$$  \hspace{1cm} (B-4)

By combining (B-1) to (B-4), the mechanical power from a wind turbine can be determined, which is depicted in Figure B-1. The relationship between mechanical power and rotor speed under different wind speeds is observed. The wind turbine has a rated power of 2.5 MW and the rotor radius is 42 m. A blade angle of zero is taken as an example. It
can be seen that the maximum power output from the turbine occurs at different rotor speeds, which corresponds to different wind speeds. Therefore, the energy capture maximisation from the wind necessitates the variable speed operation.

![Figure B-1 Mechanical power versus rotor speed at different wind speeds.](image)

### B.2 Shaft System

Unlike the conventional generation systems, which are characterised by their shafts of high stiffness, the wind turbine rotor is usually connected to the generator rotor though a shaft with relatively low stiffness in a WECS. The shaft does not twist if the stiffness of the shaft $K_s$ (which is in the range of 0.15 p.u./el.rad to 1.2 p.u./el.rad for modern WECS) is ideally large enough under system disturbances, otherwise, the shaft system can accumulate energy with the increase of shaft torsion. The shaft torsion $\theta_s$ results in the fluctuation of the generator rotor speed $\omega_r$ and the electrical parameters of induction generator. Consequently, the fluctuation affects the interaction between the generation system and the grid, and differentiates the performance of the WECS from conventional generators.

Conventional generators in grid are generally presented as multi-shaft systems and computed with the use of lumped-mass model in investigations of short-term voltage stability. That is, the turbine rotor inertia $H_t$ (which is in the range of 2.5 s to 12.5 s for modern WECS) and generator rotor inertia $H_r$ (which is in the range of 0.4 s to 1 s for modern WECS) are lumped together to form a single rotating mass. However, the lumped-mass model cannot simulate the torsion of the shaft, which may bring inaccuracy during simulation. Therefore, two-mass model is used when torsion of the shaft system should be considered. The per unit state equations of the shaft system are presented in (B-5).
where $\omega_t$ and $\omega_s$ are the turbine rotor speed and grid speed base, $\tau$, $\tau_r$, and $\tau_e$ are the mechanical torque of the turbine rotor, the mechanical torque of the generator rotor torque, and the electrical torque respectively, and $D_t$ and $D_r$ are the damping coefficient of the turbine rotor and generator rotor.

The value of shaft stiffness, $K_s = 3.0$ p.u./el.rad, defines the boundary for the validity of the two-mass model [126]. If the shaft stiffness is lower than 3.0 p.u./el.rad, the two-mass model must be applied, otherwise, the lumped-mass model can be used without significant error.

**B.3 Generator**

The convention adopted for the induction generator is shown in Figure B-2 with positive quantities indicating motor operation mode. In the figure, the subscripts $s$ and $r$ stand for stator and rotor parameter respectively such as the three-phase stator currents are $i_{sa}$, $i_{sb}$, and $i_{sc}$, whereas three-phase rotor currents are $i_{ra}$, $i_{rb}$, and $i_{rc}$. The flux, and voltage induced across the windings are denoted as $\psi$ and $u$ respectively. $\theta_r$ is the angle between the stator A-axis and the rotor a-axis.

Taking phase A of the stator as an example, the voltage at the terminal can be determined using Lenz’s Law and Kirchoff’s Voltage Law and has the form:
\[ u_{sA} = \frac{d\psi_{sA}}{dt} + R_s \cdot i_{sA} \]  \hspace{1cm} (B-6)

where quantities are in per unit, \( R_s \) is the stator winding resistance and. The flux \( \psi_{sA} \) is:

\[ \psi_{sA} = (L_{ss} + L_{mn}) \cdot i_{sA} + (i_{sb} + i_{sc}) \cdot L_{ms} \]

\[ + L_{sr} \left[ i_{ra} \cdot \cos \theta + i_{rb} \cdot \cos(\theta + \frac{2}{3} \pi) + i_{rc} \cdot \cos(\theta - \frac{2}{3} \pi) \right] \]  \hspace{1cm} (B-7)

where \( L_{ss}, L_{ms}, L_{sr} \) are the stator self-inductance, stator leakage inductance, stator mutual inductance, and peak value of mutual inductance between stator and rotor windings respectively.

Transforming the quantities in three-phase frame into \( d-q \) reference frame rotating at a speed of \( \omega \) using Park Transformation [202] with the \( d-q \) reference frame and stator three-phase reference frame shown in Figure B-3, and transformation matrix below. \( \theta \) is the angle between A-axis in stator three-phase reference frame and \( d \)-axis in \( d-q \) reference frame.

\[
T = \frac{2}{3} \begin{bmatrix}
\cos \theta & \cos(\theta - \frac{2}{3} \pi) & \cos(\theta + \frac{2}{3} \pi) \\
-\sin \theta & -\sin(\theta - \frac{2}{3} \pi) & -\sin(\theta + \frac{2}{3} \pi) \\
\frac{1}{2} & \frac{1}{2} & \frac{1}{2}
\end{bmatrix}
\]  \hspace{1cm} (B-8)

Figure B-3 \( d-q \) reference frame with respect to stator three-phase reference frame.

Therefore, the stator and rotor per unit quantities in three-phase reference frame are transformed into \( d-q \) reference frame represented in (B-9) where the subscripts \( d \) and \( q \) refer to direct-axis and quadrant-axis component respectively.
\begin{equation}
\begin{cases}
u_{sd} = \frac{d\psi_{sd}}{dt} + R_s \cdot i_{sd} - \omega \cdot \psi_{sq} \\
u_{sq} = \frac{d\psi_{sq}}{dt} + R_s \cdot i_{sq} + \omega \cdot \psi_{sd} \\
u_{rd} = \frac{d\psi_{rd}}{dt} + R_r \cdot i_{rd} - (\omega - \omega_r) \cdot \psi_{rq} \\
u_{rq} = \frac{d\psi_{rq}}{dt} + R_r \cdot i_{rq} + (\omega - \omega_r) \cdot \psi_{rd}
\end{cases}
\end{equation}

where is $\omega_r$ is the rotational speed of the rotor. If the $d-q$ reference frame rotates at the speed of synchronous speed, then $\omega$ equals to $\omega_s$ and $(\omega - \omega_r) = s \omega_s$ where $s$ is the slip.

The flux is given by

\begin{equation}
\begin{cases}
\psi_{sd} = L_s \cdot i_{sd} + L_{sr} \cdot i_{rd} \\
\psi_{sq} = L_s \cdot i_{sq} + L_{sr} \cdot i_{rq} \\
\psi_{rd} = L_r \cdot i_{rd} + L_{sr} \cdot i_{sd} \\
\psi_{rq} = L_r \cdot i_{rq} + L_{sr} \cdot i_{sq}
\end{cases}
\end{equation}

where $L_s = L_{ss} + L_{sr}$ and $L_r = L_{rs} + L_{sr}$.

The instantaneous active power $P_0$ generated by the WECS is given by

\begin{equation}
P_0 = \underbrace{u_{sd} \cdot i_{sd} + u_{sq} \cdot i_{sq}}_{\text{stator\_power}} + \underbrace{u_{rd} \cdot i_{rd} + u_{rq} \cdot i_{rq}}_{\text{rotor\_power}} = R_s \cdot \left( i_{sd}^2 + i_{sq}^2 \right) + R_r \cdot \left( i_{rd}^2 + i_{rq}^2 \right)
\end{equation}

\begin{equation}
\begin{aligned}
+ & \frac{d\psi_{sd}}{dt} \cdot i_{sd} + \frac{d\psi_{sq}}{dt} \cdot i_{sq} + \frac{d\psi_{rd}}{dt} \cdot i_{rd} + \frac{d\psi_{rq}}{dt} \cdot i_{rq} \\
& + \omega \cdot \psi_{sd} \cdot i_{sq} - \omega \cdot \psi_{sq} \cdot i_{sd} + (\omega - \omega_r) \cdot \psi_{rd} \cdot i_{rq} - (\omega - \omega_r) \cdot \psi_{rq} \cdot i_{rd}
\end{aligned}
\end{equation}

By combining the airgap power with (B-10), the electrical power output $P_0$ can be determined as

\begin{equation}
P_0 = \omega_r \cdot L_{rs} \cdot (i_{rd} \cdot i_{sq} - i_{sd} \cdot i_{rq})
\end{equation}

Rather than considering the total reactive power exchanged between grid and generator (i.e., including stator and GSC), only the reactive power exchanged at the stator terminal.
and is given in (B-13). The reason is, although both the total active power and the total reactive power exchanged with the grid are dependent on control of the generator and the control of the GSC, generator can produce both active power and reactive power while the converters can only generate reactive power.

\[ Q_s = u_{sq} \cdot i_{sd} - u_{sd} \cdot i_{sq} \]

\[
= \frac{d\psi_{sq}}{dt} \cdot i_{sd} - \frac{d\psi_{sd}}{dt} \cdot i_{sq} + \omega \cdot \psi_{sd} \cdot i_{sd} + \omega \cdot \psi_{sq} \cdot i_{sq} \tag{B-13}
\]

Combining with (B-10), the reactive power produced by the generator in steady state can be presented by

\[ Q_s = \omega \cdot \psi_{sd} \cdot i_{sd} + \omega \cdot \psi_{sq} \cdot i_{sq} \]

\[
= \omega \cdot L_s \cdot (i_{sd}^2 + i_{sq}^2) + \omega \cdot L_{sr} \cdot (i_{sd} \cdot i_{rd} + i_{sq} \cdot i_{rq}) \tag{B-14}
\]

B.4 Converters and Control

The RSC and GSC are connected back-to-back with RSC interfacing to the wound rotor of the generator and GSC interfacing to the grid through inductance. The RSC enables the generator rotor, and thus the turbine rotor, to rotate at variable speed while voltage of constant frequency can be generated. Therefore, the maximum energy from the wind can be captured.

B.4.1 Rotor-side Converter Control

The RSC is controlled to supply excitation current to the WRIM. Under the condition that the generator rotor rotates at variable speed, excitation current frequency should vary correspondingly in order to produce constant frequency voltage at the generator terminals. Vector control approach is commonly used in induction machine control. The machine is controlled in a flux-oriented and voltage-oriented rotating d-q reference frame. Flux-oriented control includes SFO control, rotor-flux oriented control, and magnetising-flux oriented control while the d-axis of the d-q reference frame is oriented along the stator voltage under the voltage-oriented control strategy. SFO strategy is used for the RSC here.

Since the d-axis of the d-q reference frame rotating at synchronous speed \( \omega_s \) is oriented along the stator flux under the SFO control mode. Thus,

\[ \psi_{sq} = 0 \tag{B-15} \]

\[ \psi_{sd} = \psi_s = L_{sr} \cdot i_{ms} \tag{B-16} \]
where \( \psi_s \) is the stator flux and \( i_{ms} \) is the stator magnetising current. Combining (B-14) and (B-15) with (B-10), the stator currents expressed in the \( d-q \) reference frame are:

\[
i_{sd} = \frac{L_{sr}}{L_s} \cdot (i_{ms} - i_{rd}) \quad (B-17)
\]

\[
i_{sq} = -\frac{L_{sr}}{L_s} \cdot i_{rq} \quad (B-18)
\]

With (B-16) and (B-17), the (B-12) can be reduced to

\[
P_0 = -\omega_r \cdot L_0 \cdot i_{ms} \cdot i_{rq} \quad (B-19)
\]

where \( L_0 = \frac{L_{sr}^2}{L_s} \).

If it is assumed that the stator resistance \( R_s \) can be neglected [203] and the frequency of the terminal voltage \( u_t \) is constant, then in the steady state

\[
u_t = \omega_s \cdot L_{sr} \cdot i_{ms} \quad (B-20)
\]

Therefore, (B-18) can be rewritten as (B-21):

\[
P_0 = -\frac{u_t \cdot \omega_r \cdot L_{sr}}{\omega_s \cdot L_s} \cdot i_{eq} \quad (B-21)
\]

The electromagnetic torque \( \tau_e \) can be determined by dividing active power by \( \omega_r \),

\[
\tau_e = -\frac{u_t \cdot L_{sr}}{\omega_s \cdot L_s} \cdot i_{eq} \quad (B-22)
\]

Similarly, with (B-17), (B-18) and (B-20), (B-14) can be rewritten as (B-24);

\[
Q_s = \frac{u_t^2}{\omega_s \cdot L_s} - \frac{u_t \cdot L_m}{L_s} \cdot i_{rd} \quad (B-23)
\]

From (B-21) and (B-23), it can be seen that the active power, or torque, and reactive power can be controlled by the direct and quadrature component of the rotor current respectively. The currents are controlled in the form of voltages as shown with (B-9). Using (B-9), (B-10), (B-17), and (B-18), the rotor voltages are determined as
\[
\begin{align*}
\begin{aligned}
\dot{i}_{rd} &= \frac{1}{L_r} \left[ u_{rd} - R_r i_{rd} - s \cdot \omega_s \cdot \sigma \cdot L_r \cdot i_{rq} \right] \\
\dot{i}_{rq} &= \frac{1}{L_r} \left[ u_{rq} - R_r i_{rq} + s \cdot \omega_s \cdot \sigma \cdot L_r \cdot i_{rd} + s \cdot \omega_s \cdot L_0 \cdot i_{ms} \right]
\end{aligned}
\end{align*}
\]  \hspace{1cm} (B-24)

where

\[
\sigma = 1 - \frac{L^2_{sr}}{L_r \cdot L_s}
\]  \hspace{1cm} (B-25)

Two PI based current controllers provide the uncompensated \( d \)-axis and \( q \)-axis voltage references (i.e., \( u_{rd}' \), \( u_{rq}' \)) respectively. In order to achieve good tracking of the currents, compensation terms are added to the voltage references \cite{130}. Hence, the compensated voltage reference become

\[
\begin{align*}
\begin{aligned}
\dot{i}_{rd}' &= \dot{i}_{rd} - s \cdot \omega_s \cdot \sigma \cdot L_r \cdot i_{rq} \\
\dot{i}_{rq}' &= \dot{i}_{rq} + s \cdot \omega_s \cdot \sigma \cdot L_r \cdot i_{rd} + s \cdot \omega_s \cdot L_0 \cdot i_{ms}
\end{aligned}
\end{align*}
\]  \hspace{1cm} (B-26)

The control block diagram of the RSC is presented in Figure B-4.

**B.4.2 Grid-Side Converter Control**

The voltage at the GSC terminal is given by (B-27):

\[
\begin{align*}
\begin{aligned}
\begin{bmatrix} u_{ga} \\ u_{gb} \\ u_{gc} \end{bmatrix} &= R_f \begin{bmatrix} i_{ga} \\ i_{gb} \\ i_{gc} \end{bmatrix} + L_d \frac{d}{dt} \begin{bmatrix} i_{ga} \\ i_{gb} \\ i_{gc} \end{bmatrix} + \begin{bmatrix} u_{sa} \\ u_{sb} \\ u_{sc} \end{bmatrix}
\end{aligned}
\end{align*}
\]  \hspace{1cm} (B-27)

where \( R_f \) and \( L_d \) are the resistance and inductance of the interface filter.

Using the Park Transformation in (B-8), the terminal voltage in \( d-q \) reference frame is provided in (B-28).

\[
\begin{align*}
\begin{aligned}
\dot{i}_{gd} &= L_f \left[ \frac{d}{dt} i_{gd} - R_f \cdot i_{gd} - \omega_s \cdot L_f \cdot i_{gq} + u_{sd} \right] \\
\dot{i}_{gq} &= L_f \left[ \frac{d}{dt} i_{gq} + R_f \cdot i_{gq} + \omega_s \cdot L_f \cdot i_{gd} + u_{sq} \right]
\end{aligned}
\end{align*}
\]  \hspace{1cm} (B-28)
Two PI based current controllers provide the uncompensated \( d \)-axis and \( q \)-axis voltage references (i.e., \( u_{gd}^* \), \( u_{gq}^* \)) respectively. Similar to (B-26), the voltage references are compensated as

\[
\begin{align*}
    u_{gd}^* &= -u_{gd}^* + \omega_s \cdot L_f \cdot i_{gq} + u_{sd} \\
    u_{rq}^* &= -u_{rq}^* - \omega_s \cdot L_f \cdot i_{gd}
\end{align*}
\]

(B-29)

The control block diagram of the GSC is presented in Figure B-5.

![Control diagram of the GSC](image)

Figure B-4 Control diagram of the RSC.
Figure B-5 Control diagram of the GSC.
Appendix C: Laboratory Hybrid RAPS System

The laboratory RAPS system mainly includes a hybrid generation system (i.e., a synchronous generator and a PMSG based WECS), a hybrid energy storage system (i.e., ultracapacitor bank and lead-acid battery bank), an AC voltage source, and loads. The architecture of the RAPS system is sketched in Figure C-1. Details of the components are described in following subsections.

C.1 Synchronous Generator

As explained in Chapter 8, a wound rotor induction machine (WRIM) can be operated as a synchronous generator by supplying DC current to the rotor windings. The WRIM is mechanically coupled with an induction machine which emulates the behaviour of the required prime mover. A variable speed drive controls the operation of the induction machine. The specifications of the synchronous generator are shown in Table C-1. The synchronous generator test rig is shown in Figure C-2.
Table C-1 Specifications of the synchronous generator test rig

<table>
<thead>
<tr>
<th>Wound Rotor Induction Machine</th>
<th>Induction Machine</th>
<th>Variable Speed Drive</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Rated capacity</strong></td>
<td>10 HP</td>
<td><strong>Rated capacity</strong></td>
</tr>
<tr>
<td><strong>Rated stator voltage</strong></td>
<td>400 V</td>
<td><strong>Rated speed</strong></td>
</tr>
<tr>
<td><strong>Rated stator current</strong></td>
<td>15 A</td>
<td><strong>Rated rotator voltage</strong></td>
</tr>
<tr>
<td><strong>Rated rotor current</strong></td>
<td>33 A</td>
<td><strong>Rated current</strong></td>
</tr>
<tr>
<td><strong>Nominal frequency</strong></td>
<td>50 Hz</td>
<td><strong>Power factor</strong></td>
</tr>
<tr>
<td><strong>Rated power</strong></td>
<td>11 kW (low overload)</td>
<td>15 kW (low overload)</td>
</tr>
<tr>
<td><strong>Rated current</strong></td>
<td>23.1 A (high overload)</td>
<td>11 kW (high overload)</td>
</tr>
<tr>
<td><strong>Rated current</strong></td>
<td>32 A (low overload)</td>
<td>26 A (high overload)</td>
</tr>
</tbody>
</table>

Figure C-2 Synchronous generator test rig.
C.2 PMSG Test Rig

A permanent magnet synchronous machine (PMSM) operates as the generator for the wind energy conversion system. The PMSM is mechanically coupled with an induction motor, which emulates the characteristics of a wind turbine. The induction machine is controlled by a variable-speed drive. The output terminals of the PMSM are connected to a back-to-back power converter scheme. The machine-side converter is a three-phase diode bridge, whereas the grid side converter is an IGBT-based inverter. The two converters are linked using a boost DC/DC converter. The control of the variable-speed drive and the power converters are implemented in a Texas Instrument TMS320F28335 microcontroller. The variable-speed drive has the same features as the one used for synchronous generator test rig. The specifications PMSM, induction machine, and power converters are shown in Table C-2. The PMSG test rig is shown in Figure C-3.

Table C-2 Specifications of the PMSG test rig

<table>
<thead>
<tr>
<th>Permanent Magnet Synchronous Machine</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Nominal voltage</td>
<td>300 V (single phase)</td>
</tr>
<tr>
<td>Nominal torque</td>
<td>61 NM</td>
</tr>
<tr>
<td>Nominal current</td>
<td>20.5 A</td>
</tr>
<tr>
<td>Nominal speed</td>
<td>1500 RPM</td>
</tr>
<tr>
<td>Overload torque</td>
<td>70 NM</td>
</tr>
<tr>
<td>Overload current</td>
<td>22.3 A</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Induction Machine</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Rated capacity</td>
<td>15 kW</td>
</tr>
<tr>
<td>Rated speed</td>
<td>2925 RPM</td>
</tr>
<tr>
<td>Rated voltage</td>
<td>415 V</td>
</tr>
<tr>
<td>Rated current</td>
<td>24.9 A</td>
</tr>
<tr>
<td>Nominal frequency</td>
<td>50 Hz</td>
</tr>
<tr>
<td>Power factor</td>
<td>0.91</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Power Converter</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Maximum capacity</td>
<td>20 kVA</td>
</tr>
<tr>
<td>Maximum current</td>
<td>30 A (per phase)</td>
</tr>
<tr>
<td>Maximum AC voltage</td>
<td>480 V</td>
</tr>
<tr>
<td>Maximum switching frequency</td>
<td>20 kHz</td>
</tr>
<tr>
<td>DC bus capacitor</td>
<td>1100 μF 800V</td>
</tr>
<tr>
<td>Maximum DC bus voltage</td>
<td>750 V</td>
</tr>
</tbody>
</table>
C.3 AC Voltage Source

A California Instruments programmable power supply can be optionally connected to the RAPS network. When connected, it behaves as a relatively stiff grid. It is possible to program voltage or frequency disturbances in the network passively. The specifications of this voltage source are listed in Table C-3.

<table>
<thead>
<tr>
<th>Input</th>
<th>Output</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Rated power</strong></td>
<td><strong>Maximum power</strong></td>
</tr>
<tr>
<td>6660 VA</td>
<td>5550 VA</td>
</tr>
<tr>
<td><strong>Voltage</strong></td>
<td><strong>Voltage</strong></td>
</tr>
<tr>
<td>380-415 V</td>
<td>0-312 V (single phase)</td>
</tr>
<tr>
<td><strong>Frequency</strong></td>
<td><strong>Frequency</strong></td>
</tr>
<tr>
<td>47-440 Hz</td>
<td>40-5000 Hz</td>
</tr>
</tbody>
</table>
C.4 Transformer

The PMSG test rig is interfaced to the RAPS network through a transformer. The specifications of the transformer are shown in Table C-4.

Table C-4 Specifications of the transformers

<table>
<thead>
<tr>
<th>Transformer at the PMSG</th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Primary side rated voltage</td>
<td>294 V</td>
<td>Secondary side rated voltage</td>
</tr>
<tr>
<td>Primary side rated current</td>
<td>23.5 A</td>
<td>Secondary side rated current</td>
</tr>
<tr>
<td>Nominal frequency</td>
<td>50 Hz</td>
<td>Configuration</td>
</tr>
</tbody>
</table>

C.5 Energy Storage Systems

Two types of energy storage devices (i.e., ultracapacitors and lead-acid batteries) are integrated into the hybrid RAPS system network. The ultracapacitor is of high power density and low energy density, which is opposite to the characteristics of the lead-acid battery. Hence, these two types of energy storage devices are complementary to each other and the combination optimises their advantages while avoids their weaknesses. The specifications of the energy storage devices are presented in Table C-5.

Table C-5 Specifications of the transformers

<table>
<thead>
<tr>
<th>Ultracapacitor Bank</th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Rated capacitance</td>
<td>130 F (each module)</td>
<td>Equivalent series resistance</td>
</tr>
<tr>
<td>Rated voltage</td>
<td>56 V (each module)</td>
<td>Maximum continuous current</td>
</tr>
<tr>
<td>Number of modules in parallel</td>
<td>1</td>
<td>Number of modules in series</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Lead-Acid Battery Bank</th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Nominal voltage</td>
<td>12 V (each module)</td>
<td>Capacity</td>
</tr>
<tr>
<td>Maximum charging current</td>
<td>9.9 A (each module)</td>
<td>Maximum discharge current</td>
</tr>
<tr>
<td>Number of modules in parallel</td>
<td>1</td>
<td>Number of modules in series</td>
</tr>
</tbody>
</table>
C.6 Other Components

Other RAPS network components include distribution line, load, PMSG interface filter. These parameters are listed in Table C-6.

Table C-6 Specifications of the distribution lines and filters

<table>
<thead>
<tr>
<th>Distribution Lines</th>
<th>Filter</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Inductance</strong></td>
<td><strong>Inductance</strong></td>
</tr>
<tr>
<td>0.265 mH (each module)</td>
<td>4.5 mH</td>
</tr>
<tr>
<td><strong>Resistance</strong></td>
<td><strong>Capacitance</strong></td>
</tr>
<tr>
<td>0.1175Ω (each module)</td>
<td>10 μF</td>
</tr>
</tbody>
</table>

The established RAPS system is very flexible and can be used for various testing purposes such as PMSG control, management of energy storage, voltage regulation, coordinated control among parallel operating generators, etc. Moreover, the RAPS system is readily applicable for grid-connected operation tests. Microgrid applications can also be tested with an extra circuit breaker at the point of common coupling.
Appendix D: Laboratory DFIG Test Rig

The DFIG test rig is established on the LabVolt Electric Power Technology Training Systems [204]. The laboratory setup is shown in Figure D-1. The block diagram of the system is shown in Figure 8-17, and main modular components used in this setup (see Figure D-2) include:

- Wound rotor induction machine: 8231-0A
- Dynamometer (simulating wind turbine in combination with computer interface): 8960-2A
- IGBT bridge module (used as RSC): 8837-AA
- IGBT control unit (manipulating fundamental frequency of the RSC voltage output): 9029-00
- Step-up three-phase transformer (connecting the DFIG to the grid): 8348-0A
- Synchronising module (emulating the crowbar): 8621-0A
- Variable DC voltage source (manipulating the magnitude of the RSC voltage output): 8821-2A.
- 400-Volts three-phase AC power supply: 8821-2A.

Since GSC is not available in this test rig and the RSC is controlled manually, it may not be used for general testing purposes of a DFIG. Nevertheless, it provides a valuable practice and solution in the scenario where smart control strategies are not the necessary. For example, the test rig is used for observing the transition dynamics of the DFIG during transitions between DFIG mode and IG mode. No fast control is required for the RSC and the GSC is not affecting the transitions. Hence, this test rig fits the testing purpose of the deadband control proposed in Chapter 8.
Figure D-1 Setup of the DFIG test rig in the laboratory.

Figure D-2 Control panel of the DFIG test rig.


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