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Operation of a wind-diesel-battery based hybrid remote area power supply system

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The operational behaviour of a Remote Area Power Supply (RAPS) system consisting of a Doubly Fed Induction Generator (DFIG) as the wind turbine generator, diesel generator system, battery storage, dump load and mains loads is investigated in this paper. The diesel generator operates during low wind penetration or high load demand periods. Otherwise, the DFIG and battery storage are able to satisfy the load demand of the system. The battery storage can be used as a source or load depending on the wind and loading conditions of the system. A control coordination among the system components is established with a view to regulate the system voltage and frequency while extracting maximum power from wind. The entire RAPS system has been modelled using SimPowerSystem toolbox in MATLAB.

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Operation of a Wind-Diesel-Battery based Hybrid Remote Area Power Supply System

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***Abstract*—The operational behaviour of a Remote Area Power Supply (RAPS) system consisting of a Doubly Fed Induction Generator (DFIG) as the wind turbine generator, diesel generator system, battery storage, dump load and mains loads is investigated in this paper. The diesel generator operates during low wind penetration or high load demand periods. Otherwise, the DFIG and battery storage are able to satisfy the load demand of the system. The battery storage can be used as a source or load depending on the wind and loading conditions of the system. A control coordination among the system components is established with a view to regulate the system voltage and frequency while extracting maximum power from wind. The entire RAPS system has been modelled using SimPowerSystem toolbox in MATLAB.**

***Index Terms*—Doubly Fed Induction Generator, Diesel Generator, Battery Storage System, Dump load and Maximum Power Extraction**

I. INTRODUCTION

MOST of rural and remote are power supply systems are supplied by diesel generator systems [1]. However, this option is becoming obsolete due to high operating cost, fuel transportation problems and environmental concerns. With the penetration of renewable energy technologies into the power market, hybrid Remote Area Power Supply (RAPS) schemes are identified as viable schemes to supply remote and regional areas [2]. Usually, hybrid RAPS systems consist of one or more renewable energy technologies with conventional generation schemes such as diesel. The integration of conventional generating technologies to a hybrid RAPS system is essential due to uncertainties associated with renewable sources, low inertial support and less reactive power support from renewable power generating units. However, to enhance the autonomy of the system, the rating of the conventional power supply scheme (ie. diesel generator) should be kept at a minimum.

Depending on the availability of resources, a suitable generation mix can be utilised to form a hybrid RAPS system. The selection of renewable energy resources for such a power system is entirely dependent on the availability of the resources such as wind, water or sun. Among all these renewable energy options, wind is identified as the fastest growing renewable energy technology in the energy industry. However, the variable and erratic nature of wind creates a lot of problems when a wind generating system operates in its standalone mode of operation that may lead to voltage and frequency fluctuations. Therefore, it is essential to incorporate an Energy Storage System (ESS) to enhance the performance of such a power system [3]. The power mismatch between generation and demand can be stored or delivered using an ESS system. When selecting an ESS system for a standalone power system, the ESS technology, cost and rating of the ESS are the most important factors to be considered. Among the various energy storage technologies available, battery can be identified as the most suitable energy storage option for an autonomous power system due to its high energy density capacity [4]. A dump load also plays a vital role in a RAPS system. In a practical RAPS system, a dump load can be a water heater or a space heater that absorbs the additional energy which cannot be utilised by an ESS.

The hybrid RAPS system considered in this paper which consists of a Doubly Fed Induction generator (DFIG) (main generator), diesel generator system, dump load and its controller, battery storage system and main loads is shown in Fig. 1. The active power control of the system has been coordinated with a view to minimise the active power imbalance of the system while extracting maximum power from wind. In this regard, individual controllers are developed for each system component including the DFIG system, diesel generator, battery storage system and dump load.

The paper is organised as follows. Section II discusses the individual control strategies applied for each system component. The Maximum Power Extraction (MPE) from wind of the proposed RAPS system is illustrated in Section III. The simulated results demonstrating the behaviour of the proposed RAPS system (ie. small signal model and detailed model) for variable load and wind conditions are discussed in Section IV. Conclusions are given in Section V.

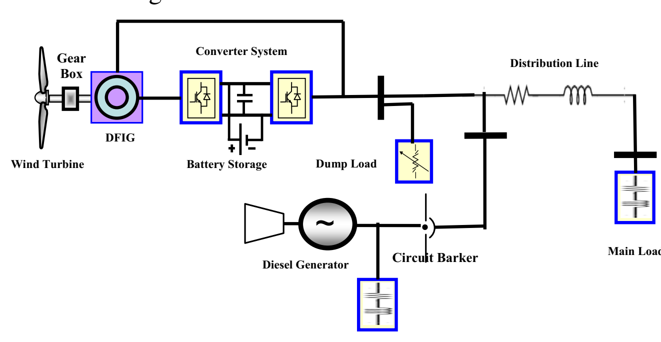

Fig. 1. Proposed hybrid RAPS system

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II. Control Strategies Associated with Individual System Components

From customer's perspective, voltage and frequency are the most important aspects to be controlled in a RAPS system. In the RAPS system shown in Fig. 1, the DFIG acts as the main source of energy. In this regard the highest contribution towards the voltage and frequency regulation of the system should be achieved by implementing the control for the back-to-back converter system of the DFIG. The diesel generator of the system is connected via a circuit breaker and the transition from Wind-Only (WO) to Wind-Diesel (WD) mode and vice versa is handled through the control logic associated with the circuit breaker. The battery storage unit is connected to the DC link of the back-to-back converter using a bi-directional buck boost converter. The dump load is connected to the AC side of the system.

A. DFIG control strategy

The voltage and frequency control of the RAPS system was achieved by implementing the vector control for the Rotor Side Converter (RSC). The Line Side Converter (LSC) is used to control the DC link voltage of the back-to-back converter system.

The voltage is controlled by controlling the magnestising current of the DFIG as given in (1). The frequency of the system is controlled by satisfying the condition given by (2). This condition is the necessary and sufficient to enure indirect stator flux oriented mode of operation of the RSC. With this control strategy, the frequency control of the system is made independent from the resistive loading condition and rotational speed of the wind turbine [5].

$$\frac{L_s}{R_s}\frac{di_{ms}}{dt} + i_{ms} = i_{rd} + \frac{v_{sd}L_s}{R_s L_m} \tag{1}$$

where,
R_s- stator resistance, i_{ms}- stator magnetising current, v_{sd}- stator d-axis voltage, i_{rd}- rotor d-axis current.

$$i_{rq} = -\frac{L_s}{L_m} i_{sq} \tag{2}$$

where,
i_{rq}, i_{sq} - rotor and stator q-axis current respectively, L_s, L_m - stator inductance and magnetising inductance respectively.

B. Diesel Generator System

The diesel generator is connected to the system via a circuit breaker. It is connected to the main system only when the generation-demand mismatch satisfies the minimum loading condition of the diesel generator (ie. 20% of diesel generator rating). The size of the diesel generator has been selected such that it will meet the minimum loading condition by supplying power to the local loads to avoid low load factor operation. A simplified block diagram of the diesel generator system used in this paper is shown in Fig . 2. When the diesel generator serve the local loads, the input to the PI controller remains zero otherwise it is set to Δp, which is generated from the demand generation mismatch. IEEE type 1 voltage regulator and exciter system is used for the diesel generator.

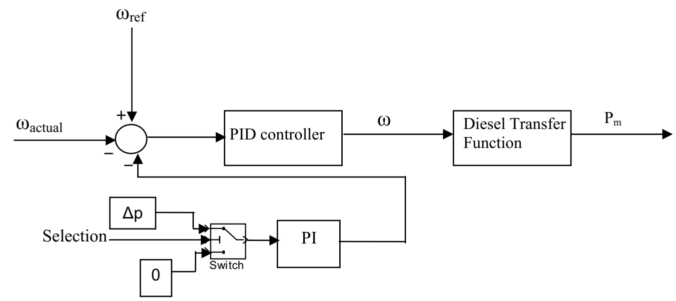

Fig. 2. Simplified model a diesel engine model

C. Battery Storage System

As mentioned earlier, in this paper, the battery storage unit is connected to the DC link of the DFIG using a two stage bi-directional DC/DC buck-boost converter. The prime objective of having a battery energy storage system is to minimise the demand-generation mismatch in the absence of the diesel generation system. The other objective is to operate the DFIG in its MPE mode of operation. The adopted control strategy of the battery storage system is shown in Fig. 3. The reference battery current is compared with the actual battery current (ie. i_b) and the error is compensated through a PI controller. The output of the PI controller is compared with a triangular carrier wave to generate the switching signals (ie. Q_1 and Q_2) for the buck-boost converter. The capacity of the battery is limited to 0.2 pu on the base of 1000 kW system.

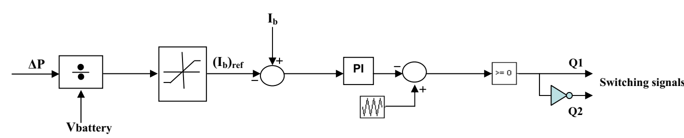

Fig. 3. Battery control strategy

D. Dump load

The dump load of the system is coordinated with the battery energy storage system to maintain the power balance of the system. In this paper, the dump load consists of a series of resistors which are connected across switches. The condition under which the dump load is operated is given in (3). A simple control block diagram of the dump load is shown in Fig. 4.

$$P_w + (P_b)_{max} - P_L > 0 \tag{3}$$

III. Maximum Power Extraction from Wind

Since the Rotor Side Converter (RSC) control is used to control the voltage and frequency of the system, MPE cannot be implemented within the inverter controls of the DFIG. In

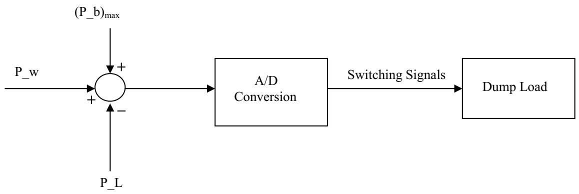

Fig. 4. Dump load control strategy

this paper, the maximum power extraction from wind has been achieved with the aid of the battery storage and dump load. The MPE from wind can be described using (4) [6]. With the DFIG frequency control discussed in Section II-A, i_{qs} represents the active power of the main load and hence, any change in the main load is reflected as a change in i_{qs} which causes a change in i_{qr} and T_e as evident from (2) and (6) respectively. By controlling the power flow into the battery storage and dump load according to the MPE algorithm, it is possible to impose appropriate torque on the DFIG shaft to extract the maximum power from the wind. The turbine power characteristics with MPE curve described by (4) is shown in Fig. 5.

$$(P_m)_{\text{opt}} = k_{opt}[(\omega_r)_{opt}]^3 \quad (4)$$

$$k_{opt} = \frac{1}{2}(C_p)_{opt}\rho A(\frac{R}{\lambda_{opt}})^3 \quad (5)$$

where,
P_m - power output from the turbine, C_p - power coefficient of turbine, A - area swept by the rotor blades, ρ - air density, R - radius of blade and $(P_m)_{opt}$ - maximum power output from the wind.

$$T_e = \frac{L_m}{L_s + L_m}\frac{V_s}{\omega_s}i_{qr} \quad (6)$$

where,
T_e - electromagnetic torque of the DFIG, i_{qr} - rotor, L_s, L_m - stator inductance and magnetising inductance respectively.

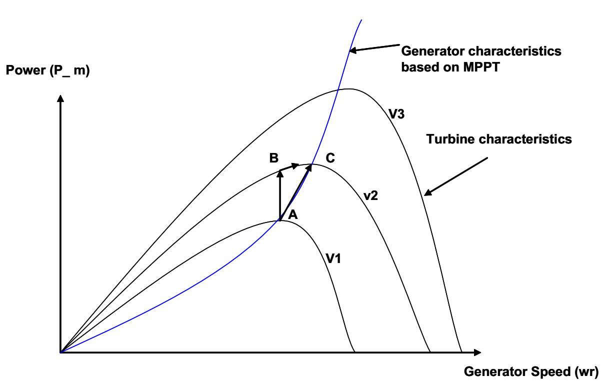

Fig. 5. Wind turbine power characteristics and maximum power extraction curve

IV. Simulation Results

The proposed hybrid RAPS system was simulated under changing wind and variable load conditions. Fig. 6 shows the system response whereas Fig. 7 shows the power sharing among different system components.

The wind condition under which the system has been simulated is shown in Fig. 6-(a). The wind velocity is set initially at 12 m/s. After t = 3 s, the wind velocity drops to 9 m/s, then it is increased to 11 m/s at t = 6 s. The load demand is initially set at 0.6 pu. At time t = 2 s, the load is increased to a value of 0.85 pu and the same load (ie. 0.25 pu) is disconnected from the system at t = 5 s as shown in Fig. 7-(d). The AC voltage at PCC is shown in Fig. 6-(b). It can be seen that there is a 10% increase of the AC load voltage at t = 5 s which corresponds to the disconnection of the diesel generator as evident from Fig. 7-(b). The load side voltage of the system stays within $\pm 2\%$ of its rated value during normal operation. Fig. 6-(c) shows the frequency of the system voltage. As expected, it is closely regulated about the rated value of 1.0 pu and is not seen to be influenced by the wind speed change and load step change. The frequency of the system is maintained within 0.3% of its rated value during normal operation. The proposed frequency control methodology of DFIG is independent from the shaft speed and resistive load condition of the system. Hence, as anticipated, the system frequency is not seen to be affected with the above mentioned transient conditions (ie. load step changes and wind variations). The DC link voltage of the DFIG is depicted in Fig. 6-(d). The simulated behaviour of the DC link voltage shows that it is regulated at its rated value throughout the operation except during load and wind step changes. However, the highest DC link voltage variations are seen to occur at t = 2 s and t = 5 s from Fig. 7-(b) which corresponds to the ON and FF operation of the circuit breaker respectively.

The wind power variation of the system is shown in Fig. 7-(a). According to the wind turbine characteristics, the corresponding maximum power output of the wind generator is 0.73 pu at a shaft speed of 1.2 pu for a wind speed of 11 m/s. From Fig. 7-(a), the power output of the DFIG is seen to rise to a value of 0.65 pu at t = 3 s. At this time, the load demand is set to 0.6 pu. The additional power is absorbed by the battery storage unit. During this time period, the diesel generator provides power to its local loads as shown in Fig. 7- (b). At time t = 2 s, the load of the system is increased to 0.825 pu and the diesel generator is then connected to the main system to provide the required power deficit demanded by the load as shown in Fig. 7-(b). The diesel generator keeps providing power until the load step down at t = 5 s. During this time period (ie. t = 2 to 5 s), the battery storage operates as a buffer to ensure maximum power extraction from wind as shown in Fig. 7-(c). After t = 5 s, the diesel generator is disconnected from the main system and supplies power only to its local loads. After diesel generator is disconnected from the system, the required power is entirely supplied using the DFIG and battery storage.

The maximum power extracted from wind is shown in

Fig. 8. It can be seen that the DFIG runs on its maximum power extraction mode of operation except during transient conditions which is unavoidable.

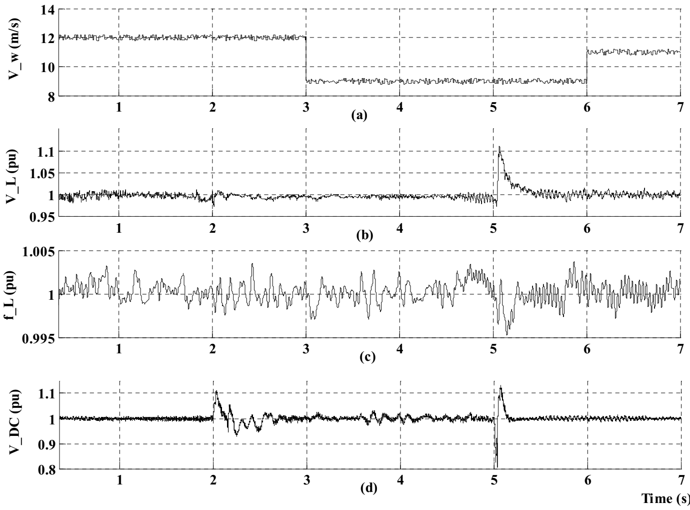

Fig. 6. Response of the RAPS system under variable wind and load conditions. (a) Wind Speed, (b) Voltage at PCC, (c) Frequency at PCC, and (d) DC link Voltage

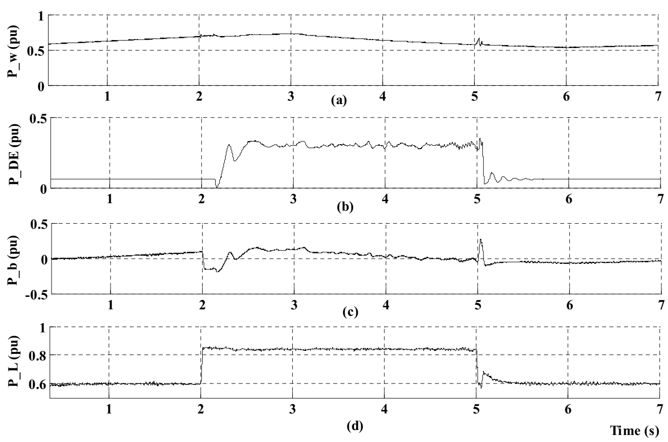

Fig. 7. Power sharing of the RAPS system under variable wind and load conditions. (a) wind power, (b) diesel power, (c) battery power and (d) load demand

V. Conclusions

This paper has investigated the hybrid operation of a novel hybrid wind-diesel-battery remote area power system. The system performance has been investigated in relation to the bandwidth of the voltage regulation capability under variable load and wind conditions. Frequency regulation is investigated using detailed model analysis. It is seen that the proposed RAPS system is capable of regulating both the voltage and frequency within acceptable limits except during some transient conditions (eg. due to load step down). The proposed control coordination for the detailed model works well as anticipated. Power sharing among the different system components together with their individual controls contribute

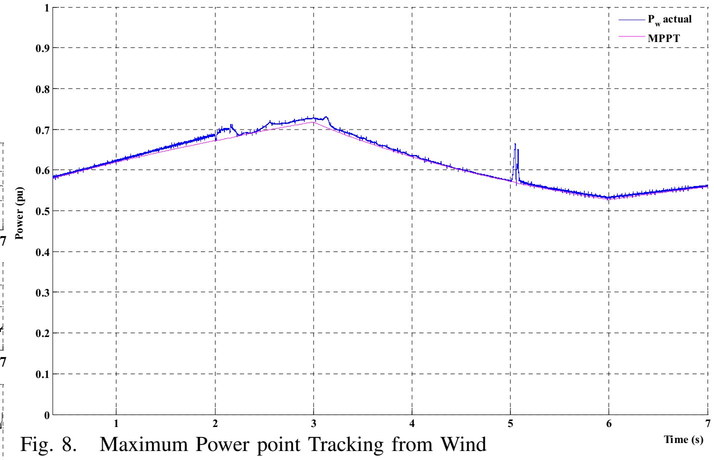

Fig. 8. Maximum Power point Tracking from Wind

to maintain the system voltage and frequency within the acceptable limits.

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