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Reliability modeling and analysis for a novel design of modular converter system of wind turbines

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Abstract

Converters play a vital role in wind turbines. The concept of modularity is gaining in popularity in converter design for modern wind turbines in order to achieve high reliability as well as cost-effectiveness. In this study, we are concerned with a novel topology of modular converter invented by Hjort, Modular converter system with interchangeable converter modules. World Intellectual Property Organization, Pub. No. WO29027520 A2; 5 March 2009, in this architecture, the converter comprises a number of identical and interchangeable basic modules. Each module can operate in either AC/DC or DC/AC mode, depending on whether it functions on the generator or the grid side. Moreover, each module can be reconfigured from one side to the other, depending on the system's operational requirements. This is a shining example of full-modular design. This paper aims to model and analyze the reliability of such a modular converter. A Markov modeling approach is applied to the system reliability analysis. In particular, six feasible converter system models based on Hjort's architecture are investigated. Through numerical analyses and comparison, we provide insights and guidance for converter designers in their decision-making.

Keywords

modeling, analysis, novel, reliability, design, turbines, modular, converter, system, wind

Disciplines

Engineering | Science and Technology Studies

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Reliability Modeling and Analysis for a Novel Design of Modular Converter System of Wind Turbines

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Abstract

Converters play a vital role in wind turbines. The concept of modularity is gaining in popularity in converter design for modern wind turbines in order to achieve high reliability as well as cost-effectiveness. In this study, we are concerned with a novel topology of modular converter system invented by Hjort (2009). In this architecture, the converter system comprises a number of identical and interchangeable inverter modules. Each module can operate in either AC/DC or DC/AC mode, depending on whether it functions on the generator or the grid side. Moreover, each inverter module can be reconfigured from one side to the other, depending on the system's operational requirements. This is a shining example of full-modular design. This paper aims to model and analyze the reliability of such a modular converter system. A Markov modeling approach is applied to the system reliability analysis. In particular, six feasible converter system models based on Hjort's architecture are investigated. Through numerical analyses and comparison, we provide insights and guidance for converter designers in their decision-making.

Key words: Markov model; Modular converter; System reliability; Wind turbine; Fault- tolerant

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1. Introduction

Wind power promises a clean and renewable source of energy that can reduce greenhouse gases emissions as well as our dependence on fossil fuels. The US Department of Energy aims to achieve 20% of wind energy penetration in the utility market by the end of 2030 (US DoE 2010). At present, wind energy only represents a less than 3% share of the US utility market. For the European Wind Energy Association, the goal is to generate 26-34% of the electricity from wind by 2030 (E.W.E. Association 2011). The global market of wind energy is steadily growing.

Wind turbines are complex electromechanical systems usually having a design lifetime of 20-30 years. A comprehensive study by Tavner *et al.* (2007) showed that a failure rate of 1-3 failures per turbine per year is common onshore. Wind turbine system reliability is a critical factor in the success of a wind energy project (Walford 2006). Studies have shown that the spending on wind turbine maintenance and repair accounts for 25-30% of the life cycle cost (e.g. Yang *et al.* 2009). This has provided strong impetus for improvement on the reliability of wind turbines.

A vital subassembly in a wind turbine is the power converter, which is an electronic device that modifies electrical signals from one kind or level to another. Depending on the relations between the types of current input and output, power converters can be classified into four categories (Iglesias *et al.* 2011): (1) rectifier (input AC/output DC); (2) inverter (input DC/output AC); (3) chopper (input DC/output DC); and (4) frequency converter (input AC/output AC). A modern wind turbine converter, usually a voltage-source converter using IGBTs, as shown in Figure 1, consists of: (1) a grid-side inverter; (2) a DC link that may contain a chopper; (3) a generator-side inverter, which is rarely a rectifier. The power converter is among the subassemblies that have the highest failure rates and thus deserves reliability attention from manufacturers and operators if higher wind turbine reliability is to be achieved (Spinato *et al.* 2009).

Modular design is used in many complex products, such as electronic systems and aero-engines, to ensure that a failure can be corrected by a relatively easy replacement of the defective module, rather than by replacement of the complete unit (O'Connor 2002). Modular design offers several advantages, including: (1) increased system flexibility and scalability; (2) higher system availability achieved via modular redundancy; and (3) reduced life cycle cost owing to the use of standard or off-the-shelf components.

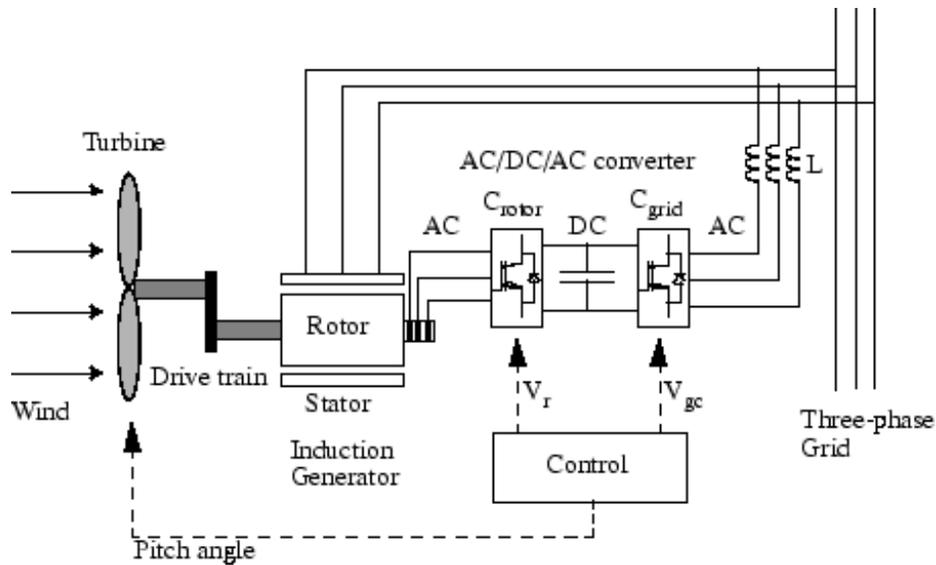


Figure 1. Schematic of a typical converter in a wind turbine

In this study, we are interested in a novel design of modular converter system invented by Hjort (2009), in which a converter system consists of a number of identical and interchangeable inverter modules being able to operate in either AC/DC or DC/AC mode. Moreover, each inverter module can be reconfigured from the generator to the grid side and vice versa, depending on the operating conditions of the system. A compelling feature of this architecture is the interchangeability of the inverter modules, which provides for a flexible, redundant and reliable converter system. This is a shining example of full-modular converter design. In light of the trade-offs between reliability, cost and space consumption we consider six feasible converter system models based on this architecture in particular. A statistical reliability model of the major turbine components would be a useful planning tool for wind energy projects (Walford 2006). In this study, a Markov modeling approach is employed to analyze the reliability performance of these six converter system models. Through performance comparison, we provide insights and guidance for designers in their decision-making.

The remainder of the paper is organized as follows. Section 2 introduces the design of modular converter systems. Section 3 describes the six feasible converter system models considered in this study. Section 4 concentrates on the reliability modeling and analysis of these system models. In Section 5, numerical examples are presented to demonstrate the analysis of the system reliability and to compare the performance of the six converter system models. Section 6 concludes the paper.

2. Design of Modular Converter Systems

The power drive train system of a typical wind turbine consists of a gearbox, a generator, a converter, and a transformer. The converter connects the generator rotor and a three-phase power grid in between. A schematic diagram of a typical converter system is depicted in Figure 1. When the wind speed is low, the converter gets power from the grid and adjusts the magnetization of the stator in order to keep the power output compliant with the grid. As a matter of fact, the power output of a wind turbine is highly random due to the stochastic nature of the wind speed. Under variable speed operations, the use of power converters incorporating IGBT (Insulated Gate Bipolar Transistor) switches and pulse-width modulation (PWM) in wind turbines offers many advantages, including improved power production and reduced structural loads.

However, there are also problems associated with the use of power converters in wind turbines. These problems include (Birk and Andresen 2007):

- Converters are subject to failure, resulting in loss of power production.
- The efficiency of a converter drops at low power levels.
- Power converters cause harmonic voltages on the grid due to the PWM.

A converter system designed with fault-tolerant architecture of converter modules can mitigate these problems significantly (Andresen and Birk 2007). Figure 2 shows a schematic diagram of a power converter system consisting of plural parallel-connected converter modules. These converter modules are identical, each of which is a channel comprised of several IGBT switches and brake chopper in the DC-link, i.e. AC/DC/AC module. If one of the modules fails, the total current output can be maintained constant by increasing the individual output from the other modules. This is a fault-tolerant form of N -modular redundancy. When designing such a converter system, one needs to determine how many modules are required in order to meet the reliability target. The converter system shown in Figure 2 can be treated as a k -out-of- n : G warm or hot standby system. If the reliability distributions of the individual modules are available, the system reliability can be appropriately derived. Then, the number of modules required can be determined based on the design specifications.

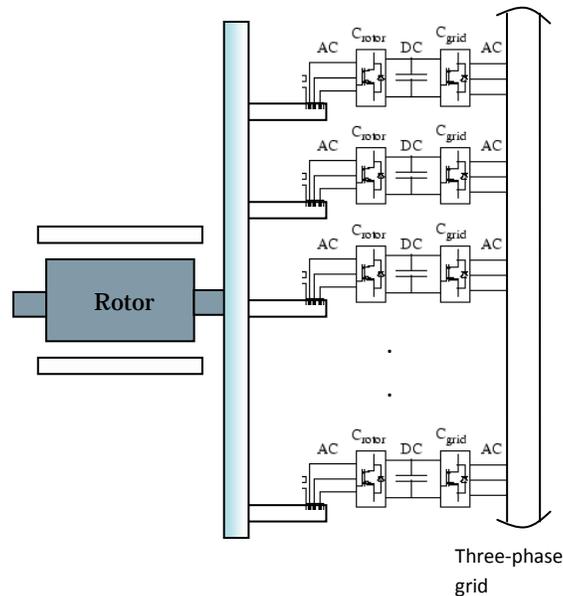


Figure 2. Schematic of a fault-tolerant modular converter system

Over the years, various architectures of power converters have been developed by researchers in academia and industry alike. These include multilevel, matrix, and modular converters (Iglesias *et al.* 2011).

Multilevel converters offer various topologies using diode-bridges, bidirectional switches, cascade H-bridges, etc. (Glinka and Marquardt 2005; Rodriguez *et al.* 2007; Ng *et al.* 2008; Colak *et al.* 2011; Iglesias *et al.* 2011). They have gained great interests in wind power conversion applications in recent years owing to their advantages including better waveform of voltage outputs, reduced harmonic content compared to standard two-level converters, higher power rating, and lower stress across the switches (Ghennam and Berkouk 2010). An instance of three-level converter can be found in Backlund and Ebner (2011). Nonetheless, a multilevel topology has not been favored in wind industry applications so far due to the increased complexity and part count which will have a negative effect on reliability (Backlund and Ebner 2011). Furthermore, redundant multilevel converters will be more expensive.

Another category is matrix converters (e.g. Erickson and Al-Naseem 2001; Angkititrakul and Erickson 2004; Kwak 2007, Lee *et al.* 2010). A matrix converter is capable of converting the variable AC from the generator into constant AC to the grid in one stage (Baroudi *et al.* 2007). An excellent review of matrix converters can be found in Wheeler *et al.* (2002). Matrix converters offer several advantages, such as all-silicon based converter, no DC-link requirement, low volume, and compact design. However, the absence of a DC link also entails a more complex modulation strategy (Iglesias *et al.* 2011). Another disadvantage of matrix converters is the high cost associated with the use of a number of switched (Baroudi *et al.* 2007).

Modular converters typically comprise a number of converter modules connected in parallel (Figure 2). Despite variation in the topology of modular converters, the basic module is either an integrated AC/DC/AC module or an AC/DC (or DC/AC) module that is connected on the generator (or the grid) side. Recently, Hjort (2009) developed an innovative design of modular converter system made up of identical and interchangeable inverter modules, for which a schematic is shown in Figure 3. Each of the inverter modules can operate in either AC/DC or DC/AC mode. Furthermore, each inverter module can be reconfigured from the generator to the grid side and vice versa, depending on the operating requirements of the system. A prominent advantage of this architecture is that the basic inverter modules are interchangeable and reconfigurable, thereby providing for a flexible, redundant and reliable converter system.

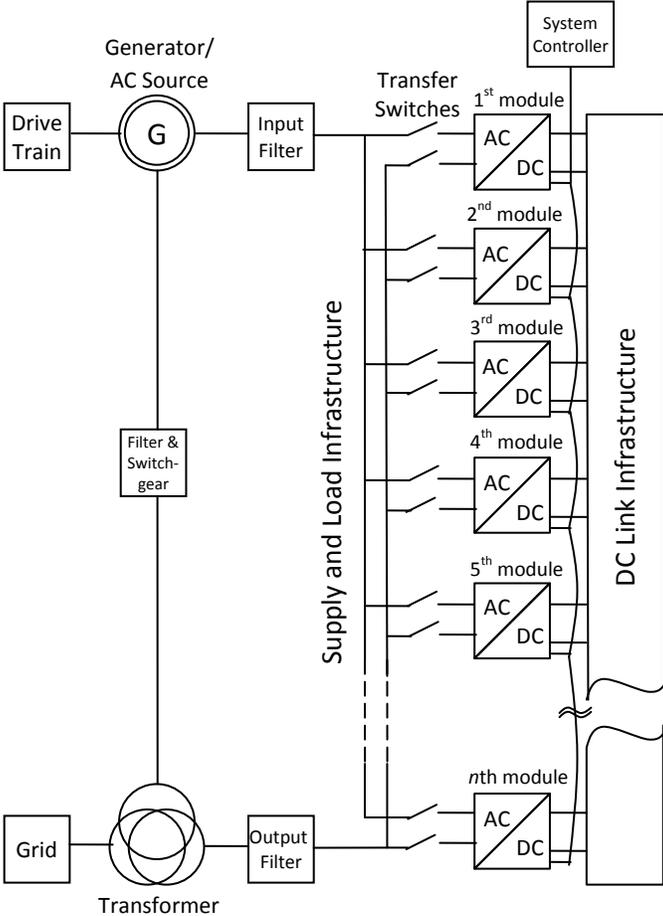


Figure 3. Schematic of a converter system with interchangeable modules (Hjort 2009)

3. Description of Modular Converter System Models

In the converter system architecture invented by Hjort (2009), each inverter module can operate in either AC/DC or DC/AC mode, depending on whether it functions on the generator or the grid side. From our experience, normally 6 inverter modules are required on each side to ensure the converter system can operate at the rated capacity. Under this requirement, at the same time considering the tradeoffs between reliability, cost and space consumption, in this study we only consider six feasible converter system models based on Hjort's architecture, which are listed in Table 1.

Table 1. Six feasible converter system models

Index	Converter system model	No. of inverter modules	
		Generator side	Grid side
1	Model 6-6	6	6
2	Model 6-7	6	7
3	Model 7-6	7	6
4	Model 7-7	7	7
5	Model 8-6	8	6
6	Model 6-8	6	8

Nomenclature

Gen. Grid $\begin{matrix} \text{---} & \text{---} \\ \circ & \circ \\ i & j \end{matrix}$	An operating state of the converter system, where i, j denote the numbers of operating inverter modules on the generator and the grid sides, respectively
Gen. Grid $\begin{matrix} \text{---} & \text{---} \\ \circ & \circ \\ i & j \end{matrix}$	An intermittent failure state, defined as $\{i + j > 9, \min(i, j) \leq 4\}$, which can be restored to an operating state through reconfiguration
Failure $\begin{matrix} \text{---} & \text{---} \\ \circ & \circ \\ i & j \end{matrix}$	A failure state which is reached when $\{i + j \leq 9\}$
$\lambda_{i,j}$	Failure rate of an inverter module working on the generator side, when there are i and j modules operating on the generator and the grid sides, respectively
$\delta_{i,j}$	Failure rate of an inverter module working on the grid side, when there are i and j modules operating on the generator and the grid sides, respectively
μ	Reconfiguration rate of an inverter module from the generator to the grid side or vice versa
$R(t)$	Reliability of the converter system at time t
$P_D(t)$	Probability of the converter system operating in a degraded state at time t

Reliability analysis of power converters can be conducted based on physical models (e.g. Chen *et al.* 2004, Aten *et al.* 2006) or probabilistic models. Markov models have been widely and usefully applied to system reliability, safety and availability studies (e.g. Zhang *et al.* 2003, Rausand and Høyland 2004, Dominguez-Garcia *et al.* 2006, Guo and Yang 2008, Liu *et al.* 2011, Lisnianski *et al.* 2012). Markov modeling has also been used to analyze the reliability of power converters (e.g. Dominguez-Garcia and Krein 2008). Despite the constraint of constant failure rate assumption, Markov modeling is still considered instrumental in reliability studies, especially at design stages. In order to model the system reliability and assess its performance using Markov approach, we make the following assumptions:

1. All inverter modules are independent and identical.
2. Failure rate of each inverter module in a given configuration is constant. Specifically, if there are i and j modules working on the generator and the grid sides, respectively, then each module on the generator side (i.e. in AC/DC mode) has a constant failure rate $\lambda_{i,j}$, and each module on the grid side (i.e. in DC/AC mode) has a constant failure rate $\delta_{i,j}$.
3. All available modules on both sides are put into operation. The work load is evenly allocated to the modules on either side.
4. When there are 6 inverter modules working on each side, the converter system works at the rated capacity. Allowing for reconfiguration, if the number of operating modules on either side falls below 6 (i.e. ≤ 5), the converter system is considered to have entered a *degraded state*, meaning it cannot work at the rated capacity. When the numbers of operating modules are not equal on the two sides, we call the side having fewer modules the *low side* and the side having more modules the *high side*. In such cases, the maximum capacity of the converter system is determined by the low side and the modules on the high side will work at partial capacity. When the number of operating modules on each side is greater than 6, the converter system will work at the rated capacity but each individual module will work only at partial capacity.
5. Because of the physics of failure, an inverter module working at partial capacity has a smaller failure rate than one working at full capacity has. The failure rate is non-decreasing as the capacity utilization rate increases.
6. An inverter module's functionality can be reconfigured from one side (the generator or the grid) to the other, whenever needed. The reconfiguration time is exponentially distributed with rate $\mu = 1/20 \text{ sec.} = 180/\text{hour}$. The reconfigurations are independent.
7. Allowing for reconfiguration, if the number of operating inverter modules on either side falls below 5 (i.e. ≤ 4), the system is considered to have failed. In other words, if the total number of modules on both sides falls below 10 (i.e. ≤ 9), the system fails.

- 8. No reconfigurations will be initiated from one side to the other as long as both sides have sufficient number of modules (i.e. 6) to ensure the converter system can operate at the rated capacity. In particular, if the number of operating modules on each side is greater than 6, then no reconfigurations will take place.

4. System Reliability Analysis

In this section, the reliability performances of the six feasible converter system models are derived following a Markovian approach.

4.1 Converter system Model 6-6

In this model a converter system consists of 12 inverter modules with 6 on each side. An illustration of the converter system Model 6-6 is displayed in Figure 4. A Markov state transition diagram for it is shown in Figure 5. Each inverter module on either side works at full capacity when the system starts in state (6 6). When any inverter module fails, the converter system enters a degraded state, meaning it cannot work at the rated capacity.

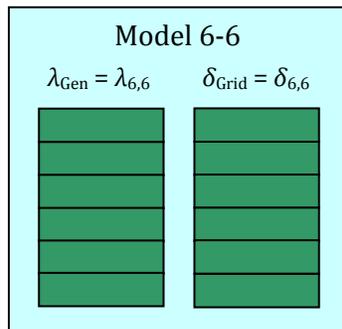


Figure 4. Illustration of converter system Model 6-6

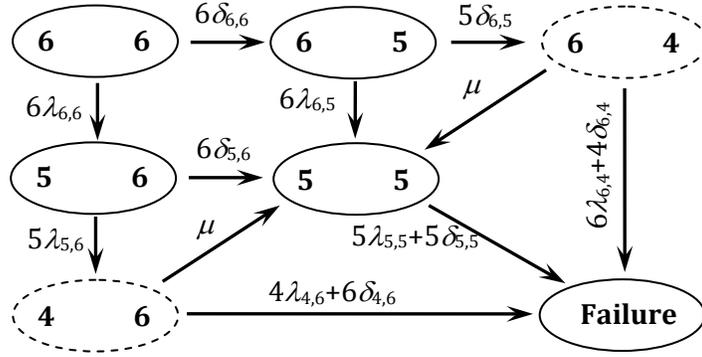


Figure 5. Markov state transition diagram for Model 6-6

Without performance degradation, the system reliability is

$$R(t) = \exp[-6(\lambda_{6,6} + \delta_{6,6})t]. \quad (1)$$

Based on Figure 5, Equations (2) can be derived to describe the system's operating behavior.

$$\begin{pmatrix} \dot{P}_{6,6} \\ \dot{P}_{6,5} \\ \dot{P}_{5,6} \\ \dot{P}_{5,5} \\ \dot{P}_{6,4} \\ \dot{P}_{4,6} \end{pmatrix} = \begin{pmatrix} -6(\lambda_{6,6} + \delta_{6,6}) & 0 & 0 & 0 & 0 & 0 \\ 6\delta_{6,6} & -(6\lambda_{6,5} + 5\delta_{6,5}) & 0 & 0 & 0 & 0 \\ 6\lambda_{6,6} & 6\lambda_{6,5} & -(5\lambda_{5,6} + 6\delta_{5,6}) & 0 & 0 & 0 \\ 0 & 6\delta_{5,6} & 6\delta_{5,6} & -5(\lambda_{5,5} + \delta_{5,5}) & \mu & \mu \\ 0 & 5\delta_{6,5} & 0 & 0 & -(\mu + 6\lambda_{6,4} + 4\delta_{6,4}) & 0 \\ 0 & 0 & 5\lambda_{5,6} & 0 & 0 & -(\mu + 4\lambda_{4,6} + 6\delta_{4,6}) \end{pmatrix} \begin{pmatrix} P_{6,6} \\ P_{6,5} \\ P_{5,6} \\ P_{5,5} \\ P_{6,4} \\ P_{4,6} \end{pmatrix} \quad (2)$$

In Equations (2), $P_{i,j}$ is the probability of the system being in state (i, j) and $\dot{P}_{i,j}$ is the first derivative of $P_{i,j}$.

The probability of the system operating in a degraded state, denoted by P_D , is

$$P_D(t) = P_{6,5}(t) + P_{5,6}(t) + P_{5,5}(t). \quad (3)$$

4.2 Converter system Models 6-7 and 7-6

In either of these two models a converter system comprises 13 inverter modules with 6 on one and 7 on the other side. Illustrations of Models 7-6 and 6-7 are shown in Figure 6. In Model 7-6, each inverter module on the grid side works at full capacity while each on the generator side works at partial capacity when the system starts in state (7, 6). Likewise, in Model 6-7, each inverter module on the generator side works at full capacity while each on the grid side works at partial capacity when the system starts in state (6, 7).

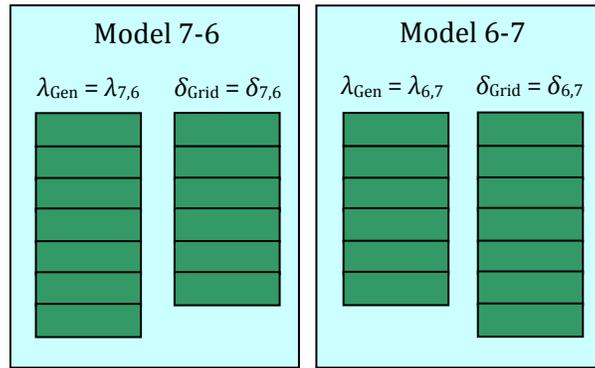


Figure 6. Illustrations of converter system Models 6-7 and 7-6

A Markov state transition diagram for converter system Model 6-7 is shown in Figure 7, where states (6 7) and (6 6) represent the system being in the healthy state without performance degradation. A Markov diagram for converter system Model 7-6 can be easily obtained by transposing that for Model 6-7 (i.e. Figure 7), swapping i and j for each state except the failure one, and exchanging the transition rates accordingly (i.e. exchanging λ and δ). The detailed diagram is therefore omitted.

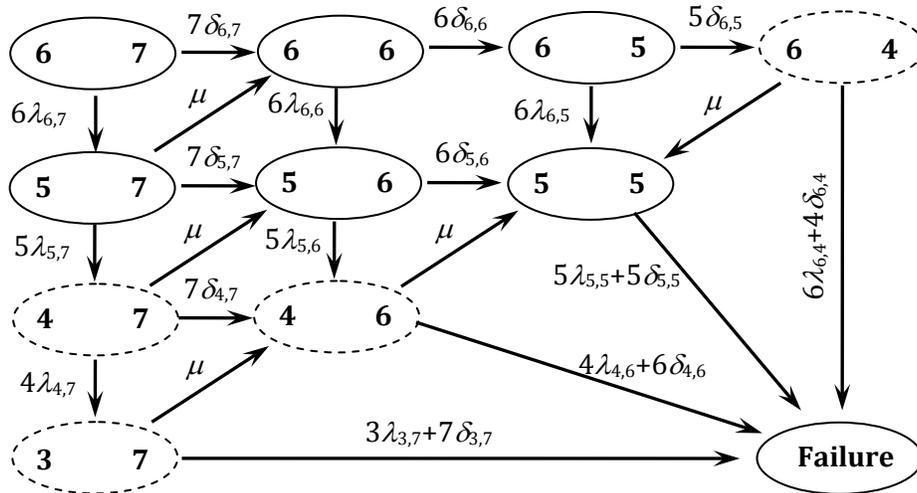


Figure 7. Markov state transition diagram for Model 6-7

Based on the Markov diagrams, a set of state equations that describes the system's dynamic behavior for Models 6-7 and 7-6 can be derived in the same way as for Model 6-6. For conciseness, the detailed equations are omitted here. By solving the system of ordinary differential equations, we can obtain the reliability of the models. Particularly, without performance degradation, the system reliability of Model 6-7 is

$$\begin{aligned}
R(t) &= P_{6,7}(t) + P_{6,6}(t) \\
&= \frac{6\lambda_{6,6}\mu}{(\mu - 6\lambda_{6,6} - 6\delta_{6,6} + 5\lambda_{5,7} + 7\delta_{5,7})[\mu - 6\lambda_{6,6} + 5\lambda_{5,7} + 7\delta_{5,7} - 7\delta_{6,7}]} e^{-(5\lambda_{5,7} + 7\delta_{5,7} + \mu)t} \\
&+ \frac{6\lambda_{6,6}(\mu - 7\delta_{6,7}) + 7\delta_{6,7}(\mu - 6\delta_{6,6} + 7\delta_{5,7} + 5\lambda_{5,7})}{(6\delta_{6,6} - 7\delta_{6,7})[6(\lambda_{6,6} + \delta_{6,6}) - 5\lambda_{5,7} - 7\delta_{5,7} - \mu]} e^{-6(\lambda_{6,6} + \delta_{6,6})t} \\
&+ \frac{6[\mu(\lambda_{6,6} + \delta_{6,6}) - 6\lambda_{6,6}\delta_{6,6} + 5\lambda_{5,7}\delta_{6,6} + 7\delta_{5,7}\delta_{6,6} - 7\delta_{6,7}\delta_{6,6}]}{(7\delta_{6,7} - 6\delta_{6,6})[6\lambda_{6,6} + 7\delta_{6,7} - 5\lambda_{5,7} - 7\delta_{5,7} - \mu]} e^{-(6\lambda_{6,6} + 7\delta_{6,7})t}
\end{aligned} \tag{4}$$

The probability of the system operating in a degraded state is

$$P_D(t) = P_{6,5}(t) + P_{5,7}(t) + P_{5,6}(t) + P_{5,5}(t). \tag{5}$$

Without performance degradation, the system reliability of Model 7-6 is

$$R(t) = P_{7,6}(t) + P_{6,6}(t) \tag{6}$$

The probability of the system operating in a degraded state is

$$P_D(t) = P_{5,6}(t) + P_{7,5}(t) + P_{6,5}(t) + P_{5,5}(t). \tag{7}$$

4.3 Converter system Model 7-7

In this model a converter system is made up of 14 inverter modules with 7 on either side. When the system starts in state (7 7), each inverter module on either side works at partial capacity. Figure 8 displays an illustration of this converter system model.

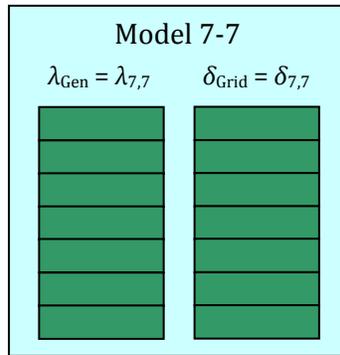


Figure 8. Illustration of converter system Model 7-7

A Markov state transition diagram for converter system Model 7-7 is shown in Figure 9. Based on this diagram, a set of state equations can be deduced to describe the system's dynamic behavior. Then, the system of equations can be solved for the reliability of the model. In particular, without performance degradation the system reliability of Model 7-7 is

$$R(t) = P_{7,7}(t) + P_{7,6}(t) + P_{6,7}(t) + P_{6,6}(t). \quad (8)$$

The probability of this system operating in a degraded state is

$$P_D(t) = P_{7,5}(t) + P_{6,5}(t) + P_{5,7}(t) + P_{5,6}(t) + P_{5,5}(t). \quad (9)$$

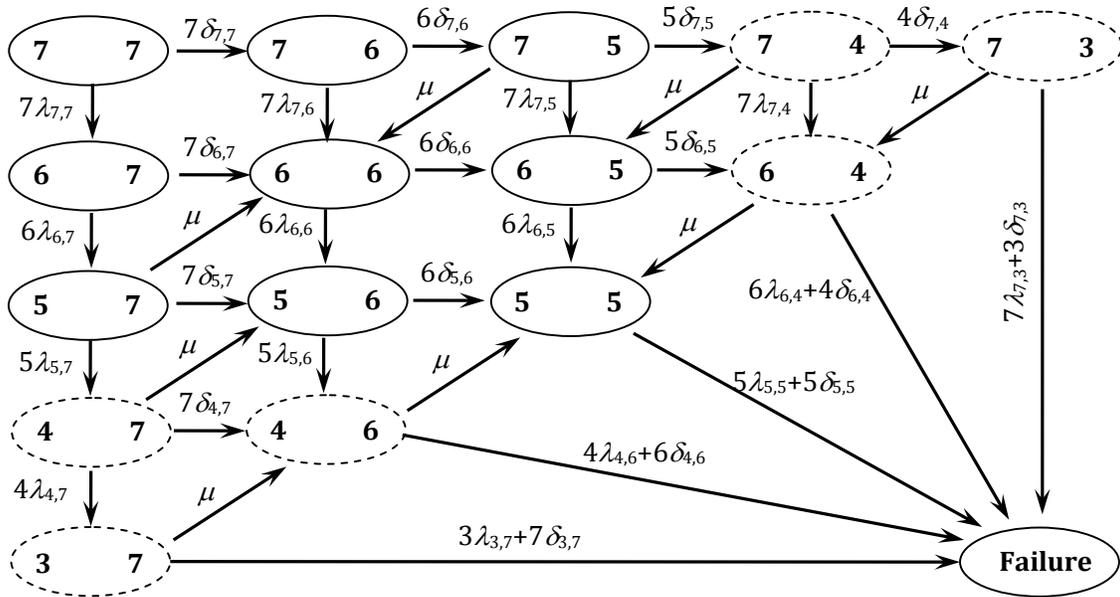


Figure 9. Markov state transition diagram for Model 7-7

4.4 Converter system Models 6-8 and 8-6

In Model 8-6 or 6-8 a converter system comprises 14 inverter modules with 8 on one and 6 on the other side. Illustrations of these two models are depicted in Figure 10. In Model 8-6 (Model 6-8), each inverter module on the generator (grid) side works at partial capacity and each on the grid (generator) side works at full capacity in the initial state (8 6) ((6 8)).

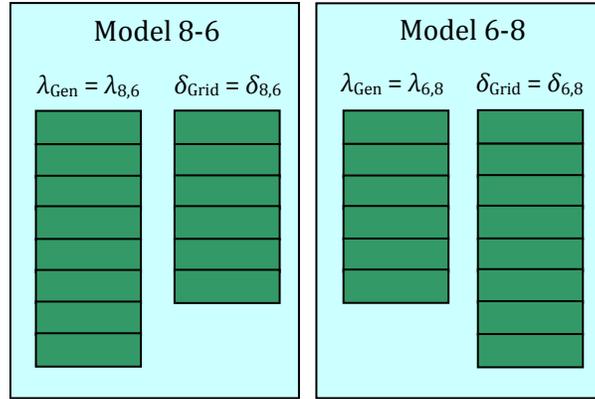


Figure 10. Illustrations of converter system Models 8-6 and 6-8

A Markov state transition diagram for Model 6-8 is plotted in Figure 11, where states (6 8), (6 7) and (6 6) represent the system being in the healthy state without performance degradation. A Markov diagram for Model 8-6 can be easily obtained by transposing that for Model 6-8 (i.e. Figure 11), swapping i and j for each state except the failure one, and exchanging the transition rates accordingly (i.e. exchanging λ and δ). The detailed diagram is omitted as well.

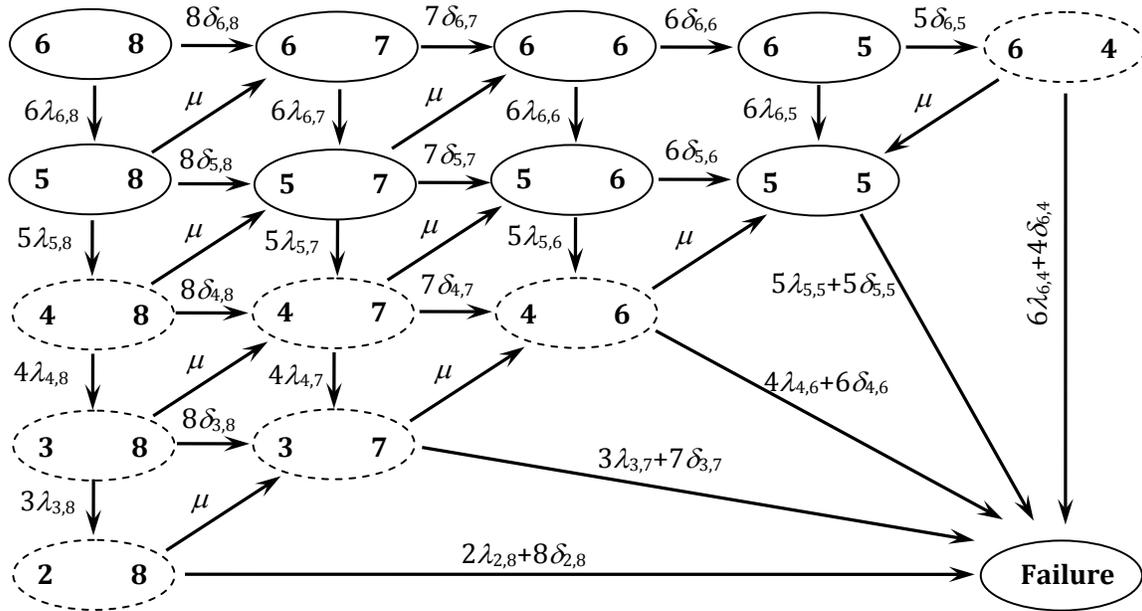


Figure 11. Markov state transition diagram for Model 6-8

Similarly, we can work out a set of state equations for Models 6-8 and 8-6 based on the Markov diagrams. Then, we can solve the system of state equations for the reliability of the models. Again, the detailed equations are omitted for conciseness. Specifically, the system reliability of Model 6-8 without performance degradation is

$$R(t) = P_{6,8}(t) + P_{6,7}(t) + P_{6,6}(t). \quad (10)$$

The probability of this system operating in a degraded state is

$$P_D(t) = P_{6,5}(t) + P_{5,8}(t) + P_{5,7}(t) + P_{5,6}(t) + P_{5,5}(t). \quad (11)$$

Without performance degradation, the system reliability of Model 8-6 is

$$R(t) = P_{8,6}(t) + P_{7,6}(t) + P_{6,6}(t). \quad (12)$$

The probability of this system operating in a degraded state is

$$P_D(t) = P_{5,6}(t) + P_{8,5}(t) + P_{7,5}(t) + P_{6,5}(t) + P_{5,5}(t). \quad (13)$$

5. Numerical Analysis and Comparison

The analytical solutions to the Markov models in the preceding section are mathematically messy and even intractable and therefore numerical solutions have to be resorted to. In this section we demonstrate the reliability analysis of the six converter system models and compare their performance using numerical examples.

5.1 System reliability

Given the parameter values, the reliability performance of a converter model can be evaluated, which will assist designers in making various choices, such as determining converter specifications, selecting suppliers and sourcing components. Nevertheless, accurate estimates of the failure rates of converters or inverter modules have been a challenge. For one thing, their failure rates depend on their architecture and configuration. For another, operating conditions and maintenance activities also influence the figures. According to Spinato *et al.* (2008), the failure rate of wind turbine converters ranges from 5.1×10^{-6} to 2.3×10^{-5} (h^{-1}). A comprehensive study by Tavner *et al.* (2007) of the maintained, onshore German and Danish wind turbines using Windstats failure data has derived converter failure rates ranging from 5.7×10^{-6} to 2.6×10^{-5} . These results are pretty consistent. However, all these are failure rates of the whole converter subassemblies. In the current study, we are concerned with the failure rate of individual inverter modules, in particular, IGBT-based. According to ABB's experience, a reasonable estimate of the failure rate of IGBT-based inverter modules is 0.9×10^{-6} (Backlund and Ebner 2011). This value appears to agree with the reliability information on photovoltaic inverters from a report of the National Renewable Energy Laboratory, U.S.A commissioned by the Navigant Consulting Inc. (Navigant Consulting 2006, p.37). Therefore, it is reasonable to assume based on these data a failure rate in the order of magnitude 10^{-6} for individual inverter modules. The set of parameter values used in the numerical analysis are summarized in

Table 2.

Table 2. System parameter values

$\lambda_{7,7} = 1.5 \times 10^{-6}$	$\delta_{7,7} = 1.5 \times 10^{-6}$	$\lambda_{7,6} = 1.5 \times 10^{-6}$	$\delta_{7,6} = 2.3 \times 10^{-6}$	$\lambda_{7,5} = 1.0 \times 10^{-6}$	$\delta_{7,5} = 2.3 \times 10^{-6}$
$\lambda_{7,4} = 1.0 \times 10^{-6}$	$\delta_{7,4} = 2.3 \times 10^{-6}$	$\lambda_{7,3} = 1.0 \times 10^{-6}$	$\delta_{7,3} = 2.3 \times 10^{-6}$	$\lambda_{6,8} = 2.3 \times 10^{-6}$	$\delta_{6,8} = 1.3 \times 10^{-6}$
$\lambda_{6,7} = 2.3 \times 10^{-6}$	$\delta_{6,7} = 1.5 \times 10^{-6}$	$\lambda_{6,6} = 2.3 \times 10^{-6}$	$\delta_{6,6} = 2.3 \times 10^{-6}$	$\lambda_{6,5} = 1.3 \times 10^{-6}$	$\delta_{6,5} = 2.3 \times 10^{-6}$
$\lambda_{6,4} = 1.0 \times 10^{-6}$	$\delta_{6,4} = 2.3 \times 10^{-6}$	$\lambda_{5,8} = 2.3 \times 10^{-6}$	$\delta_{5,8} = 1.0 \times 10^{-6}$	$\lambda_{5,7} = 2.3 \times 10^{-6}$	$\delta_{5,7} = 1.0 \times 10^{-6}$
$\lambda_{5,6} = 2.3 \times 10^{-6}$	$\delta_{5,6} = 1.3 \times 10^{-6}$	$\lambda_{5,5} = 2.3 \times 10^{-6}$	$\delta_{5,5} = 2.3 \times 10^{-6}$	$\lambda_{4,8} = 2.3 \times 10^{-6}$	$\delta_{4,8} = 1.0 \times 10^{-6}$
$\lambda_{4,7} = 2.3 \times 10^{-6}$	$\delta_{4,7} = 1.0 \times 10^{-6}$	$\lambda_{4,6} = 2.3 \times 10^{-6}$	$\delta_{4,6} = 1.0 \times 10^{-6}$	$\lambda_{3,8} = 2.3 \times 10^{-6}$	$\delta_{3,8} = 1.0 \times 10^{-6}$
$\lambda_{3,7} = 2.3 \times 10^{-6}$	$\delta_{3,7} = 1.0 \times 10^{-6}$	$\lambda_{2,8} = 2.3 \times 10^{-6}$	$\delta_{2,8} = 1.0 \times 10^{-6}$	$\mu = 180$	

In light of the primary failure mechanisms, we assume that $\lambda_{i,j} = \delta_{j,i}$ in our numerical analyses. As a result, the symmetric pairs of Models 6-7 and 7-6 as well as Models 6-8 and 8-6 will have the same reliability performance. The reliability performance of the six converter system models are assessed in terms of three metrics: reliability $R(t)$, probability of the system operating in a degraded state $P_D(t)$, and their sum $[R(t) + P_D(t)]$. The last one refers to the probability of the system being in operation. The metric $P_D(t)$ is particularly meaningful for operations where wind speeds cannot reach the rated speed most of the time in a year. In such situations, permitting a converter system to work in a degraded state may not increase the *lost production factor*, which is the share of the potential wind not harvested by the turbines.

Table 3. System reliability performance of the six converter models

Converter System	Time in operation, t (years)				
	5	10	15	20	25
Converter System	System reliability, $R(t)$ (%)				
Model 6-6	29.85	8.91	2.66	0.79	0.24
Model 6-7 (or 7-6)	68.68	33.90	14.74	5.99	2.34
Model 6-8 (or 8-6)	89.87	61.85	35.51	18.20	8.65
Model 7-7	90.91	64.73	38.88	20.98	10.54
Converter System	Probability of operating in a degraded state, $P_D(t)$ (%)				
Model 6-6	61.99	58.52	39.55	23.07	12.38
Model 6-7 (or 7-6)	29.29	51.10	48.78	36.09	23.16
Model 6-8 (or 8-6)	9.72	32.36	44.65	42.68	33.28
Model 7-7	8.72	30.02	42.76	42.17	33.91
Converter System	Probability of being in operation, $[R(t) + P_D(t)]$ (%)				
Model 6-6	91.84	67.43	42.21	23.87	12.62
Model 6-7 (or 7-6)	97.97	85.00	63.52	42.09	25.50
Model 6-8 (or 8-6)	99.59	94.21	80.16	60.88	41.93
Model 7-7	99.63	94.75	81.64	63.15	44.46

Table 3 shows some results of the reliability performance of the six models. From there it is intuitive to see that the system reliability performance improves as more inverter modules are equipped. For example, after 15 years in operation the system reliability is 2.66% for Model 6-6, 14.74% for Model 6-7 (or 7-6) and 38.88% for Model 7-7. Nonetheless, more modules installed also mean increases in cost and space requirement. Designers need to balance the various factors when making a final decision. The specific reliability metric values could provide a frame of reference. Nevertheless, bearing in mind that accurate estimates of an inverter module's failure rates under different operating conditions may not be available at the design stage, it is advisable for practitioners to vary the parameter values to perform a sensitivity analysis.

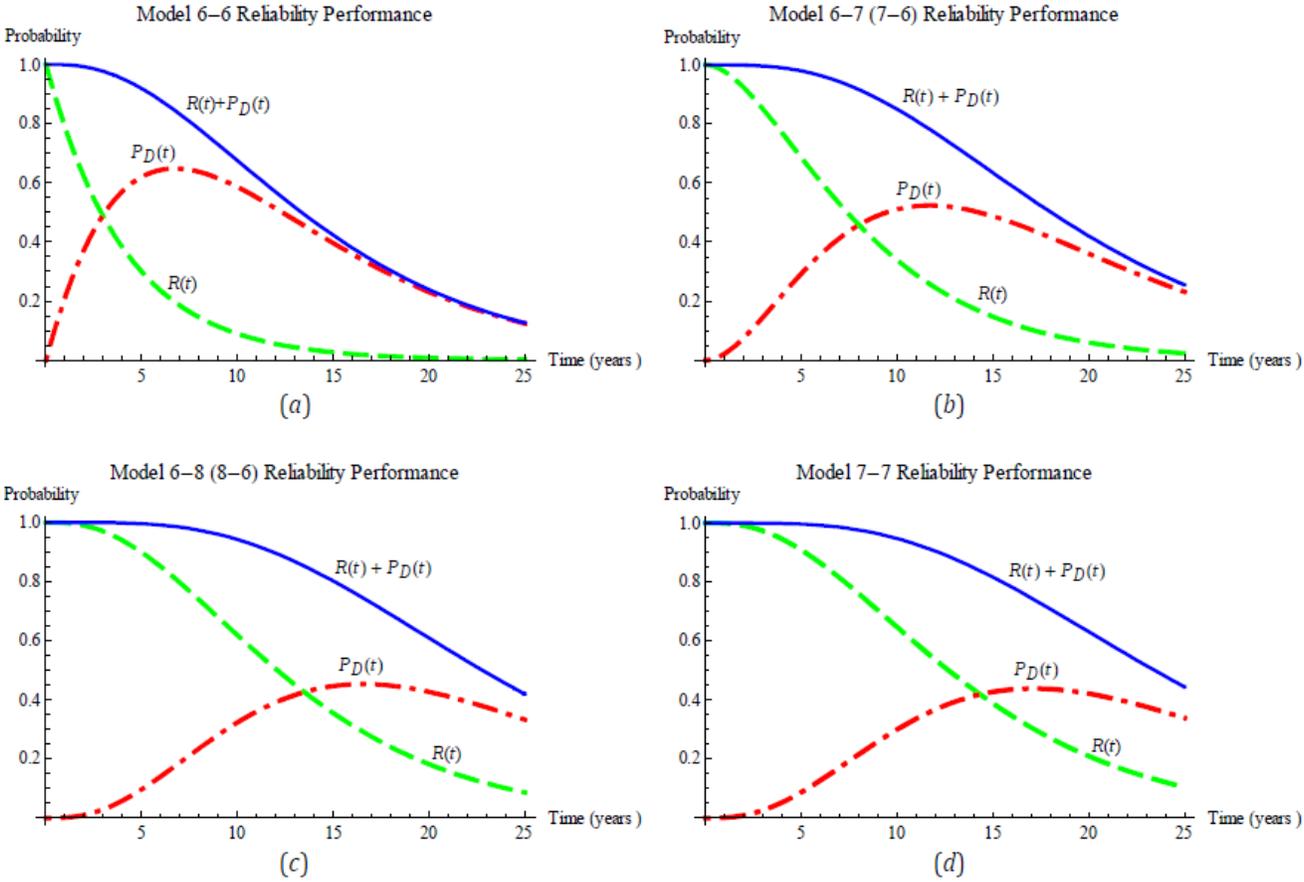


Figure 12. Reliability performance of the six converter system models

Figure 12 plots the system reliability performance including the reliability $R(t)$, probability of operating in a degraded state $P_D(t)$, and the probability of being in operation $[R(t) + P_D(t)]$, for each of the six (four, more precisely) converter system models. Figures 13 through 15 further compare the six models in terms of the metrics $R(t)$, $P_D(t)$, and $[R(t) + P_D(t)]$, respectively. From these figures it can be seen that both the reliability and the probability of being in operation increase as the total number of inverter modules equipped increases, whereas the relationship between $P_D(t)$ and the total number of modules installed shows a more complicated pattern. The curve of $P_D(t)$ tends to first increase and then decrease as time in operation increases, with its peak shifting to the right as more modules are installed. One implication is that, a converter having less modules installed may provide a more cost-effective choice for applications where the wind speeds cannot reach the rated speed most of the time in a year. It has also been revealed that Model 7-7 has slightly better reliability performance than Model 6-8 (or 8-6). This implies that given the same number of inverter modules a symmetric configuration produces the highest reliability.

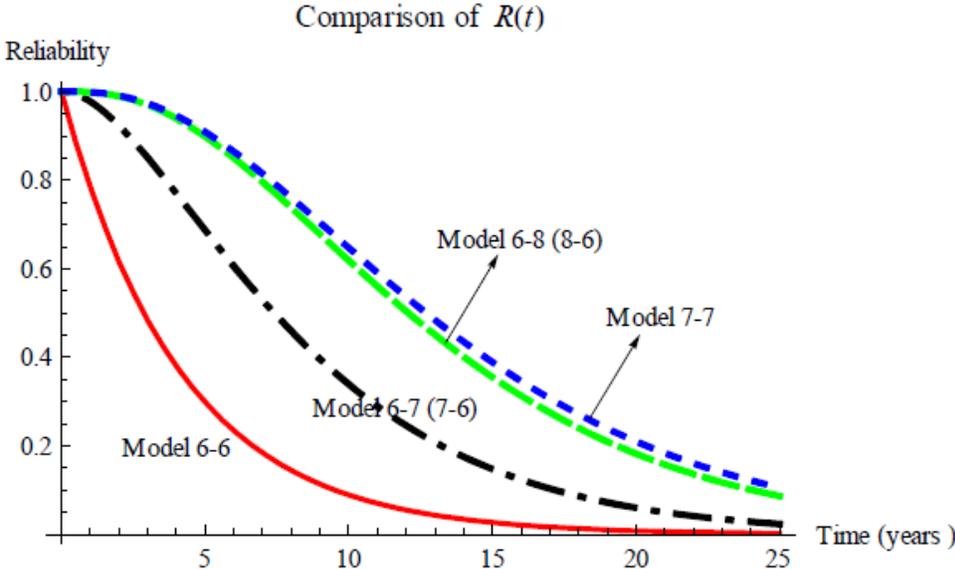


Figure 13. Comparison of system reliability performance, $R(t)$

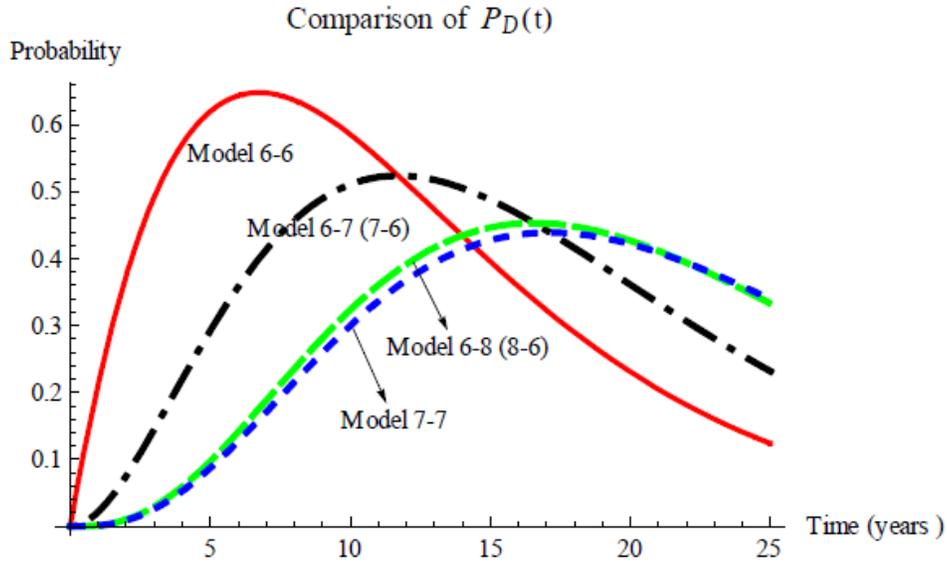


Figure 14. Comparison of probability of operating in a degraded state, $P_D(t)$

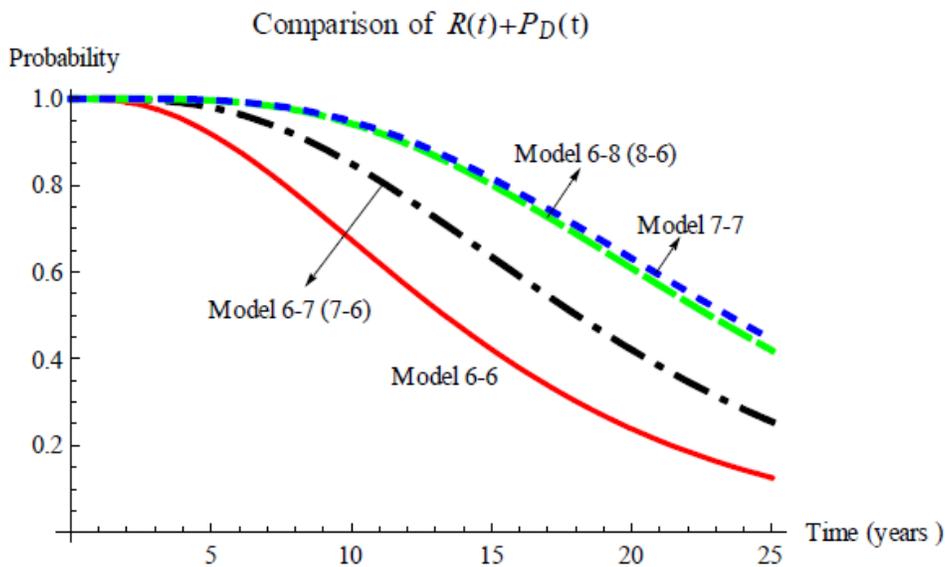


Figure 15. Comparison of probability of being in operation, $[R(t) + P_D(t)]$

5.2 System cost estimation

System cost analysis is given in the following approaches. The first approach is based on reliability obtained from Markov model. But, in fact, it should be done through Monte Carlo simulation since it involves failure and repair process, and cost of scheduled and unscheduled maintenance services. The

analytical solutions to the Markov models in the preceding section are mathematically messy and even intractable and therefore numerical solutions have to be resorted to. In this section we demonstrate the reliability analysis of the six converter system models and compare their performance using numerical examples.

6. Conclusions

In this study, we are concerned with the reliability modeling and analysis of modular converter system of wind turbines. The focus is on the novel converter architecture invented by Hjort (2009). In this architecture, a converter system consists of a number of identical and interchangeable inverter modules which can operate in either AC/DC or DC/AC mode. Moreover, each inverter module can be reconfigured from the generator side to the grid side, and vice versa. As a result, it offers prominent advantages including high flexibility, redundancy and reliability. From a development point of view, a reliability model will identify the risks associated with component types, allowing planners to steer their equipment selection process toward lower-risk configurations (Walford 2006).

In particular, six feasible converter system models based on Hjort's architecture have been examined. Markov modeling has been applied to the analysis of the system reliability. Numerical analyses have been performed to demonstrate the use of models proposed. In the numerical examples the failure rate values have been selected based on the MIL-HDBK-217F. The performance comparison of the six converter system models has shown that adding more modules to the converter system will increase its reliability, which is intuitive. It has been found out that the reliability performance largely depends on the total number of modules installed thanks to the interchangeability of the modules. For example, Model 7-7 and Model 6-8 (or 8-6) nearly have identical reliability performance. It has also been revealed that in applications where the wind speeds cannot reach the rated speed most of the time in a year it could be advisable to choose a converter system equipped with less modules and allow it to operate in a degraded state, as this may not increase the lost production factor but is more cost-effective. Furthermore, allowing the converter system to operate in a degraded state will help extend its MTBI and increase the availability of a wind turbine. The Markov models developed offer a means of reliability analysis for converter designers in their decision-making.

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