

# A Reliability Model for a Doubly Fed Induction Generator Based Wind Turbine Unit Considering Auxiliary Components

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## Abstract

Now-a-days, wind energy has gained significant attention to produce electric power because of energy and environment crisis worldwide. Due to advantages of doubly fed induction generator (DFIG), a noticeable percentage of wind turbines have been built based on DFIG. Due to the growing contribution of wind turbines in energy production, reliability of electricity produced by wind turbines is highly dependent on the reliability of each wind turbine unit (WTG). This paper presents an accurate model for calculating the DFIG based wind unit reliability based on reliability of its components. The reliability calculations of a WTGs based on conventional methods suffer shortcomings such as high computational burden and low accuracy due to their simplifying assumptions. Thus, a more accurate method has been proposed here to calculate the reliability based on Markov process by defining the absorbing states for a WTG. Also, relations for calculating Mean Time to Failure (MTTF) of the WTG are derived and formulated.

**Keywords:** Reliability, Absorbing States, Continuous Markov Process, Failure Rate, Repair Rate.

## 1. Introduction

Wind energy has gained significant attention worldwide as one of the newest and most important sources to produce electric power. Utilization of induction generators in wind energy conversion systems is growing rapidly in this field [1]. Wind units based on DFIG have grid side and rotor side convertors and consequently they benefit from high flexibility in controlling the produced energy. Some other advantages of DFIG based WTG are ability to control reactive power, ability to work in sub-synchronous and super-synchronous speeds, producing active power in constant frequency, strength and small maintenance requirements [1, 2]. Increasing the number of DFIG based WTG will obviously increase their impact on the whole power system. With high penetration of wind farms, it is clear that their interruption will lead to loss of huge

amount of energy in grid which will cause many problems. Therefore, obtaining an accurate model of reliability for a DFIG wind unit and calculation of its reliability parameters are of paramount importance. The WTG unit reliability is dependent on components used in WTG design and reliability interaction between them. In previous studies [3, 4], all components of the WTG unit are considered in series by neglecting auxiliary components thus reducing the accuracy of the reliability calculations.

In this paper, various reliability networks have been proposed for accurate modeling of the WTG system and its sub-systems. Furthermore, due to the importance of auxiliary components on reliability calculations, a WTG equipped with an auxiliary mechanical brake has been modeled and studied. The main idea is to split a WTG into its main systems and their sub-systems. In order to study the reliability of a system, it is required to have the statistical

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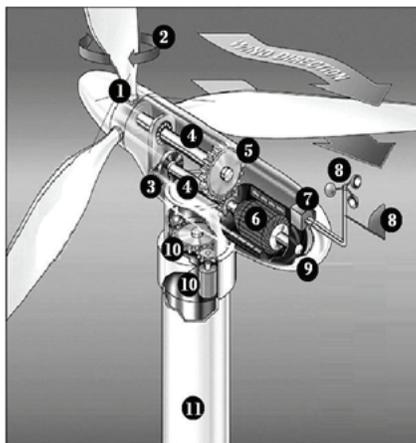
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data associated with reliability indices of each component. In this paper, the information of a Swedish research in a four year period has been used [13]. After calculating the reliability indices of each system and sub-system, Markov process is used to assess the WTG reliability based on the reliability of its components. The Markov process leads to a model of WTG reliability, which is obtained by solving the differential equations of a stochastic transitional probability matrix. Finally, the mean time to failure (MTTF) of the WTG is specified by defining absorbing states and establishing probability matrix of entrance to absorbing states.

## 2. A Background on DFIG Components

Major components of reliability network for a DFIG based WTG are explained prior to modeling them in reliability network. Figure 1 shows the typical DFIG along with its components [5, 6]:

1. Rotor: it is composed of blades and a hub. Blades absorb the wind energy and transmit it to the hub. The receiving power of turbine is directly related to the squared length of blades as pointed in [7].
2. Pitch motor: In turbines equipped with pitch control, the blades turn to the wind direction according to Maximum Power Tracking (MPT)
3. Mechanical brakes: The connection shaft between gearbox and generator is equipped with mechanical brake systems which are disc type brakes.
4. Drive train: This is an axis connecting the hub to gearbox. In a 1 MW sample, this axis turns with the speed of 19 to 30 rpm.
5. Gear box: Most DFIG units use gearbox. The purpose of gearbox which is connected to low-speed axis in one end and to electricity generator in the other end is to increase the low rate of rotor turn appropriately, so that it can be connected to the generator.
6. Generator: Generators used in DFIG turbines are of induction type. The 3-phase stator winding is connected to grid through a step up transformer. Rotor has a 3-phase winding which is fed by a slip ring from the rotor side convertor. Rotor current is controlled by this rotor side convertor which consequently controls active/reactive powers [8].
7. Controllers: They include several microprocessors and microcontrollers for controlling and coordination of different parts of the DFIG.
8. Sensors: In each DFIG based WTG, sensors of different types are used to provide information such as wind direction, wind intensity, rotor speed, voltage, current, output power, heat indicators, gearbox oil, hydraulic system gauges and so on.
9. Nacelle: Nacelle holds the main components of a wind turbine like gearbox, generator, shaft and other parts. Rotor is located at the Nacelle head while sensors for wind and speed are placed at the end.
10. Yaw motor: This system employs two or more electric motors for rotating the nacelle in the wind direction. They are controlled from a central control room which recognizes the wind direction based on data from sensors and sends the required commands to motors.
11. Tower: Nacelle with blades is mounted on a tower. In general, the higher tower is better because wind speed increases with height from ground. In a 1MW DFIG, the tower height is about 50 to 80m.
12. Convertors: A DFIG WTG uses two convertors namely grid side and rotor side. DFIG can operate both in super-synchronous and sub-synchronous modes requiring the convertor to work bi-directionally [9].



**Figure 1.** DFIG wind unit components.

## 3. DFIG Based WTG's Sub-systems

In previous reliability models of wind turbines, just a few major elements were considered, and when more elements are used, usually series reliability models have been employed [3, 4]. However, in order to study the reliability

of a wind turbine, a precise reliability model must be designed based on all comprising elements and relations of each component with grid as well as failure and repair rate of each component. In order to prevent complexity in the mentioned model, here a wind unit is divided into 3 systems:

1. Electrical system
2. Mechanical system
3. Structural system

Each part is subdivided into smaller sub-systems:

- The electrical system is composed of two sub-systems namely control and generator. The former includes three components: sensors, controllers and convertors.
- The mechanical system is composed of gearbox, mechanical brake and hydraulic sub-systems. The gearbox sub-system includes two parts: gearbox and drive train.
- The structural system involves two sub-systems: rotating parts and tower. The later is composed of yaw motor and pitch motor, while the former includes structure and hub.

This classification is also depicted in Figure 2.

### 4. Historical Data Analysis

As mentioned before, a wind unit is divided into systems, sub-systems and different system components. It is required to know the reliability parameters for each of these components. Real data obtained from wind power plants are available in literature and are used here. For instance, the reliability parameters of wind unit components in different countries

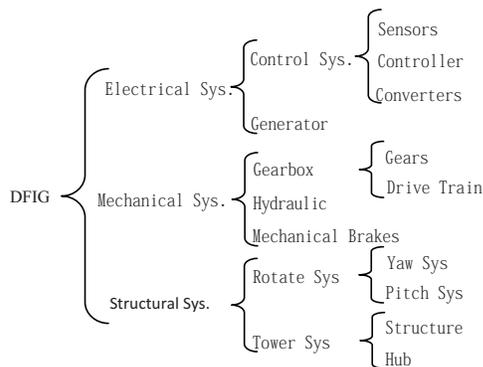


Figure 2. DFIG wind unit sub-systems.

are summarized in Table 1. In [10], various discussions have been directed on results analysis which is not in the scope of this paper. Table 2 shows the parameters of reliability derived in [13] which is used here.

### 5. Reliability Modeling of DFIG Based WTG Systems

Relations of reliability for series and parallel networks as well as failure and repair rates are described in the literature [15–16]. In this section, reliability of DFIG unit systems and sub-systems are calculated as follows.

Table 1. Reliability Parameters References

Reference	Country	Year	Turbine Number
Durham University, UK [11]	England	1994–2004	1000
Landwirtschaftskammer, Schleswig-Holstein [12]	Germany	1994–2004	650
Driftuppföljning av vindkraftverk, årsrapport [13]	Sweden	2000–2004	723
Felanalys [14]	Sweden	1989–2005	786

Table 2. Reliability parameters for DFIG components

Component	MTTR (Hours)	Failure Rate (f/Year)
Structure	0.6	0.006
Yaw Sys	6.6	0.026
Hydraulic	2.6	0.061
Mechanical brakes	0.6	0.005
Gears	11.6	0.045
Sensors	2.7	0.054
Drive Train	1.2	0.004
Controller	9.2	0.05
Converters	7.2	0.067
Generator	4.5	0.021
Pitch Sys	4.7	0.052
Hub	0	0.001
<b>Total</b>	<b>52.4</b>	<b>0.402</b>

### 5.1 Electrical System

The electrical system employs two series sub-systems: Generator and Control sub-systems. The reliability parameters of generator sub-system using Table 2 is as follows:

$$\lambda_{Generator} = 0.021(f / year)$$

$$MTTR_{Generator} = 4.5(Hour)$$

where,  $\lambda$  is the failure rate in a year and MTTR is the mean time to repair.

The control sub-system is composed of sensors, controllers and convertors. Considering the functional nature of sensors, formation of series network does not produce a precise model. Failure of each sensor does not lead to the failure of the whole network; however it increases network MTTR. Therefore, Figure 3 proposed as a reliability network of the control subsystems.

The block named X is used to model the effect of sensor failure on system MTTR. Thus, the repair rate of block X must be calculated. So, it is possible to get an accurate model of control sub-system by calculating reliability criteria of block X. Assuming that in sensor failure condition the MMTR of control sub-system is doubled:

Control sub sys. repair rate when sensors are available :

$$\mu_{eq1} = \frac{\lambda_1 + \lambda_2}{\lambda_1/\mu_1 + \lambda_2/\mu_2} \tag{1}$$

Control sub sys. repair rate when sensors are unavailable :

$$\mu_{eq2} = \frac{\mu_{eq1}}{2} \tag{2}$$

$\mu_x$  is the inverse of MTTR and can be obtained based on  $\mu_1$ ,  $\mu_2$  and  $\mu_3$  from (1) and (2). If  $\lambda_x = \lambda_3$  (i.e. sensor failure has no effect on other components failure rate), reliability parameters of control sub-system can be obtained as follows:

$$\lambda_{control} = 0.10067(f / year)$$

$$MTTR_{control} = 9.147(Hour)$$

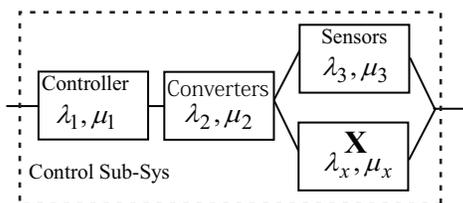


Figure 3. Reliability network of Control Sub-Sys.

Thus, parameters of the Electrical system can be calculated based on those of generator and control subsystems:

$$\lambda_{Elec.Sys} = 0.12197(f / year)$$

$$MTTR_{Elec.Sys} = 9.156148(Hour)$$

### 5.2 Mechanical System

As mentioned before, this system includes gearbox, hydraulic and mechanical brake sub-systems. First reliability parameter should be calculated for each sub-system. Reliability parameters of gearbox sub-system are calculated through two distinct series component: gearbox and drive train. So:

$$\lambda_{Gearbox} = 0.049(f / year)$$

$$MTTR_{Gearbox} = 10.75102(Hour)$$

For modeling reliability of auxiliary components, auxiliary mechanical brake is assumed to have the same repair rate of the component and to have a failure rate equal to half failure rate of the component. Switching (between main and auxiliary component) probability and time of installation have been neglected here. So the reliable network proposed for mechanical system is as Figure 4:

Since the failure rates of auxiliary and main components are not equal, mutual exclusive failure events could be used, as shown in Figure 5. So,

$$R(t)_{Brake} = R_1(t) + R_2(t) \tag{3}$$

where,  $R_1(t)$  is the main brake availability until time  $t_1$  and  $R_2(t)$  is the probability of having a failure in main brake at time  $t_1$  and auxiliary brake being available from  $t_1$  to  $t$ . Thus considering Figure 5:

$$R_1(t) = e^{-\lambda_1 t} \tag{4}$$

$$R_2(t) = \int_{t_1=0}^t \text{Pr ob.}[(\text{Main brake failure in time } t_1) \times (\text{auxiliary availability from } t_1 \text{ to } t)] dt_1 \tag{5}$$

So,

$$R_2(t) = \int_{t_1=0}^t \lambda_1 e^{-\lambda_1 t_1} e^{-\lambda_2 (t-t_1)} dt_1 \tag{6}$$

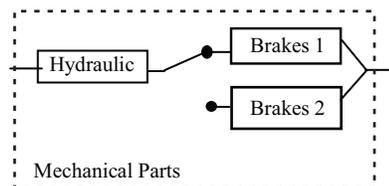


Figure 4. Reliability network for Mechanical system.

$$R_2(t) = \frac{\lambda_1}{\lambda_1 - \lambda_2} [e^{-\lambda_2 t} - e^{-\lambda_1 t}] \tag{7}$$

From Figure 4, the hydraulic system and brakes are series, so:

$$R(t)_{Mech.System} = R(t)_{Brake} \times R(t)_{Hydraulic} \tag{8}$$

where,

$$R(t)_{Hydraulic} = \frac{\mu_{Hydraulic}}{\lambda_{Hydraulic} + \mu_{Hydraulic}} \tag{9}$$

Therefore, equivalent failure rate for the mechanical system ( $\lambda_{mech}$ ) can be calculated:

$$\begin{aligned} MTTF &= \frac{1}{\lambda_{mech}} \\ &= R(t)_{Hydraulic} \times \int_0^{\infty} (e^{-\lambda_1 t} + \frac{\lambda_1}{\lambda_1 - \lambda_2} [e^{-\lambda_2 t} - e^{-\lambda_1 t}]) dt \end{aligned} \tag{10}$$

Since repair rate has been assumed to be the same for the main and auxiliary brake, Poisson distribution function can be used for calculating the equivalent repair rate [16]. The probability of  $n$  failure in time window  $[0, t]$   $Q_n(t)$  can be written as:

$$Q_n(t) = \frac{(\lambda t)^n e^{-\lambda t}}{n!} \tag{11}$$

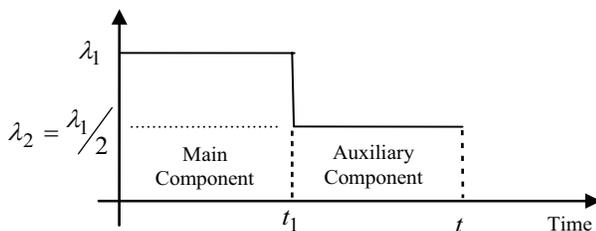
So,

$$\begin{aligned} Q(t)_{Brake} &= \\ Q_0(t) + Q_1(t) &= (1 + \mu_{Brake}) e^{-\mu_{Brake} t} \end{aligned} \tag{12}$$

Since the brake and hydraulic sub-systems are connected in series, so:

$$\begin{aligned} 1 - Q(t)_{Mech} \\ = (1 - Q(t)_{Brake})(1 - Q(t)_{Hydraulic}) \end{aligned} \tag{13}$$

which yields



**Figure 5.** Mutual exclusive events of main and auxiliary parts with different failure rates.

$$\begin{aligned} Q(t)_{Mech} &= (1 + \mu_{Brake}) e^{-\mu_{Brake} t} + e^{-\mu_{Hydraulic} t} \\ &- (1 + \mu_{Brake}) e^{-\mu_{Brake} t} \times e^{-\mu_{Hydraulic} t} \end{aligned} \tag{14}$$

In series components:

$$P_{UP} = 1 - Q(t) = \frac{\mu_{mech}}{\lambda_{mech} + \mu_{mech}} = \frac{\mu_1 \mu_2}{(\lambda_1 + \mu_1)(\lambda_2 + \mu_2)} \tag{15}$$

Subscripts 1 and 2 refer to the brake and hydraulic systems, respectively.

Equations (14) and (15) yield:

$$\begin{aligned} 1 - [(1 + \mu_{Brake}) e^{-\mu_{Brake} t} + e^{-\mu_{Hydraulic} t} \\ - (1 + \mu_{Brake}) e^{-\mu_{Brake} t} \times e^{-\mu_{Hydraulic} t}] \\ = \frac{\mu_{mech}}{\lambda_{mech} + \mu_{mech}} \end{aligned} \tag{16}$$

The only unknown variable in (16) is  $\mu_{mech}$  and is easily obtained using (16). Therefore, using (10) and (16):

$$\begin{aligned} \lambda_{Mech.Sys} &= 0.110192(f / year) \\ MTTR_{Mech.Sys} &= 6.309819(Hour) \end{aligned}$$

### 5.3 Structural System

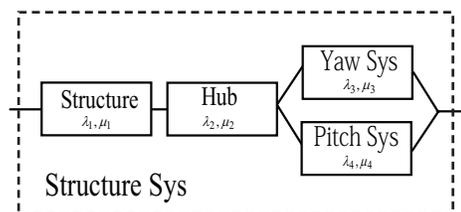
This system is composed of two sub-systems: tower and rotating parts (Figure 2). It is known that yaw and pitch motors can make improvements in WTG performance and MPT [17]; however, from viewpoint of reliability, their interconnection is parallel (Figure 6).

This results in:

$$\begin{aligned} \lambda_{struct.Sys} &= 0.022278(f / year) \\ MTTR_{Struct, Sys} &= 2.044176(Hour) \end{aligned}$$

## 6. The Final Model of DFIG Reliability

In previous section, the failure rate ( $\lambda$ ) and MTTR of individual systems of a DFIG were calculated and the corresponding results are summarized in Table 3.



**Figure 6.** Reliability network of structural system.

For repairable systems with constant and specific value of failure probability in any time (i.e. systems with exponential distribution) it is possible to use stationary Markov process to model the states of the systems [16].

In the proposed model, for DFIG, the wind unit was modelled by three systems in which the failure and repair rates of any system are computed. Considering two Up and Down states for each of these systems, wind unit can be modelled with eight states, and its state space diagram could be shown as Figure 7. In Figure 7, the probability of being in state “n” in the time “t+dt” or  $P_n(t+dt)$  is equal to the probability of being in state “n” until time “t” and not exiting from that state in interval “dt” plus the probability of not being in state “n” until time “t” and entering to that state during interval “dt”.

So,

$$P_n(t + dt) = P_n(t) \times \left( 1 - \left( \sum_{k=1, k \neq n}^8 \text{Existing rates from "n"} \right) dt \right) + \sum_{k=1, k \neq n}^8 (P_k(t) \times (\text{Entering Rate from state "k" to state "n"})) dt \tag{17}$$

So,

$$\frac{d(P_n(t))}{dt} = \frac{P_n(t + dt) - P_n(t)}{dt} = \tag{18}$$

$$-P_n(t) \times \left( \sum_{k=1, k \neq n}^8 \text{Existing rates from state "n"} \right) + \sum_{k=1, k \neq n}^8 P_k(t) \times (\text{Existing rate from state "k" to state "n"})$$

The matrix form of (18) is as follows:

$$[P_1'(t) \dots P_8'(t)] = [P_1(t) \dots P_8(t)] \times P_m \tag{19}$$

In which  $P_m$  is written as (20):

$$P_m = \begin{bmatrix} 1 - \lambda_1 - \lambda_2 - \lambda_3 & \lambda_1 & \lambda_2 & 0 & 0 & 0 & 0 & 0 \\ \mu_1 & 1 - \lambda_2 - \lambda_3 - \mu_1 & 0 & 0 & 0 & 0 & 0 & 0 \\ \mu_2 & 0 & 1 - \lambda_1 - \lambda_3 - \mu_2 & 0 & 0 & 0 & 0 & 0 \\ \mu_3 & 0 & 0 & 1 - \lambda_1 - \lambda_2 - \mu_3 & 0 & 0 & 0 & 0 \\ 0 & \mu_2 & 0 & 0 & 1 - \lambda_3 - \mu_1 - \mu_2 & 0 & 0 & 0 \\ 0 & 0 & \mu_3 & 0 & 0 & 1 - \lambda_1 - \mu_2 - \mu_3 & 0 & 0 \\ 0 & 0 & 0 & \mu_3 & 0 & 0 & 1 - \lambda_1 - \lambda_2 - \mu_3 & 0 \\ 0 & 0 & 0 & 0 & \mu_2 & 0 & 0 & 1 - \lambda_2 - \mu_1 - \mu_3 \end{bmatrix} \tag{20}$$

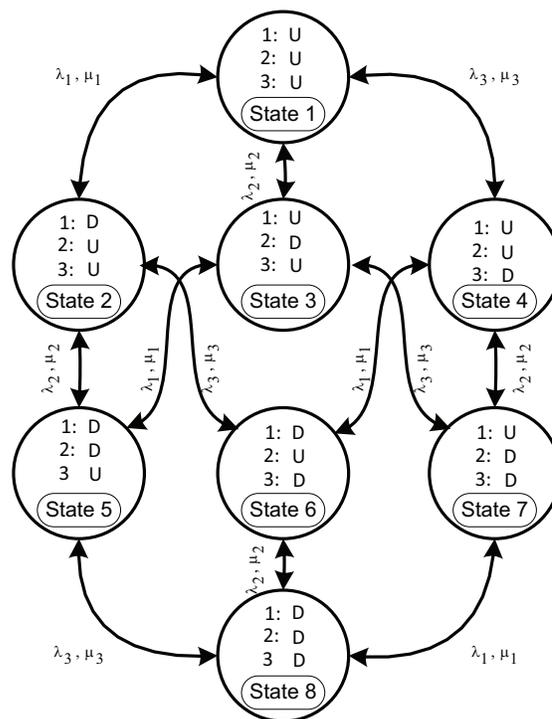


Figure 7. DFIG Space State Diagram.

Table 3. DGIG Reliability Parameters

System	λ(t/year)	MTTR(hour)
1 Electrical Sys.	0.12167	9.156148
2 Mechanical Sys.	0.110192	6.309819
3 Structural Sys.	0.022278	2.044176

Note that (19) consists of eight differential equations. Assuming that the starting state of wind unit is the first state yields:

$$[P_1(0)...P_8(0)]=[1 \ 0 \ 0 \ 0 \ 0 \ 0 \ 0 \ 0] \quad (21)$$

The modeled system is ergodic with limit values completely independent from initial conditions. Limiting values are as (22):

$$[P_1(t) \ \dots \ P_8(t)]=[0 \ 0 \ 0 \ 0 \ 0 \ 0 \ 0 \ 0] \quad (22)$$

Based on (19), we have:

$$\begin{cases} 0=[P_1(t) \ \dots \ P_8(t)] \times P_m \\ P_1(t)+P_2(t)+\dots+P_8(t)=1 \end{cases} \quad (23)$$

So, there are nine equations with eight unknowns, and consequently the limiting probability of allocating in eight states could be achieved by solving them. Since the three systems are electrical, mechanical and structural systems, respectively, the probability of availability of DFIG is equal to  $P_1(t)$  which could be calculated through (23):

$$DFIG \text{ Availability} = P_1(t) = 96.390\%$$

## 7. Calculations of Absorbing States

Absorbing state for a system with specific missions means a failure. One of the requirements of reliability is the accessibility to many time steps which prevents entering into absorbing states. These states are generally considered for systems which can be repaired. The term “absorbing state” is related to the number of repetitions that a system acts properly prior to entering an undesirable state.

In the proposed model of wind unit, absorbing state is defined for more than one system failure. So, the states numbered 5, 6, 7 and 8 in Figure 7 denote absorbing states. Matrix Q is formed by removing columns and rows related to the absorbing state in matrix  $P_m$  in (20). Note that Q indi-

cates transient states and be used to obtain the matrix N which obtains the number of steps before going to absorbing states. The expected number of time steps in which the system remains in one of the absorbing state is:

$$E(X) = \sum_{i=0}^{\infty} x_i P_i \quad (24)$$

Thus, assuming all probabilities of the initial conditions will lead to:

$$N = I + Q + Q^2 + \dots + Q^{n-1} \quad (25)$$

Multiplying both side of (25) by  $(I-Q)$  yields:

$$[I - Q]N = I - Q^n, \lim_{n \rightarrow \infty} Q^n = 0 \quad (26)$$

So:

$$N = [I - Q]^{-1} \quad (27)$$

Q is obtained by removing 5<sup>th</sup>, 6<sup>th</sup>, 7<sup>th</sup> and 8<sup>th</sup> columns and rows from matrix  $P_m$  (20). Then, matrix N is obtained using (27):

N =

$$\begin{bmatrix} \lambda_1 + \lambda_2 + \lambda_3 & -\lambda_1 & -\lambda_2 & -\lambda_3 \\ -\mu_1 & \lambda_2 + \lambda_3 + \mu_1 & 0 & 0 \\ -\mu_2 & 0 & \lambda_1 + \lambda_3 + \mu_2 & 0 \\ -\mu_3 & 0 & 0 & \lambda_1 + \lambda_2 + \mu_3 \end{bmatrix}^{-1}$$

In this matrix, each  $N_{ij}$  shows the number of time steps where system has stopped in state  $j$  before entering an absorbing state, provided that the starting state is  $i$ . Therefore, it is possible to define MTTF for the whole DFIG unit system based on mentioned absorbing states provided that the starting point is state  $i$ :

$$MTTF = \sum_{k=1}^4 N_{ik} \quad (28)$$

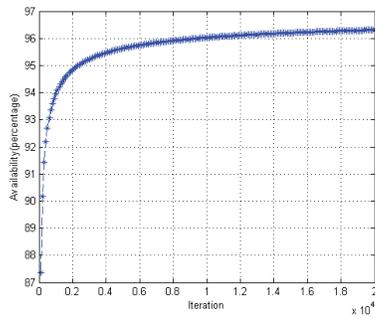
The obtained model has a suitable flexibility which can be modified based on operational conditions from wind unit, technology employed, statistical data and so on. Also different absorbing states could be chosen in this model.

## 8. Simulation

For simulation of proposed Wind Unit Model, Mont Carlo method has been used. The goal is calculating availability values for whole Wind Unit Based on reliability parameters in Table 2, with and without assumption of auxiliary brakes and comparing them. Table 4 and Figure 8 indicate the results. As Table 4 shows, by considering

**Table 4.** Availability of whole unit with and without considering auxiliary brake

Real Value	iteration	Without auxiliary brakes	With auxiliary brakes (proposed model)
87.36029%	100		
90.18115%	200		
92.68419%	500		
93.94572%	1000	95.4923%	96.3907%
96.02821%	10000		
96.3101%	20000		



**Figure 8.** Availability Convergence.

auxiliary components the calculated availability value converges to its real one more than 0.8% in this case.

## 9. Conclusions

In this paper a new reliability model of a DFIG based WTG is proposed based on reliability of its components. Also, a method is provided to model auxiliary components such as auxiliary brake in reliability calculations. Stationary Markov process is used to compute the reliability of the whole WTG system based on reliability of its subsystems. The proposed model is flexible since the failure rate and the mean time to repair can be calculated for different operational conditions and specifications based on DFIG technology.

## 10. List of Abbreviations and Symbols

$\lambda$	the failure rate in a year.
MTTR	the mean time to repair.
$\mu$	the failure rate in a year.
MTTF	the mean time to failure.
$R(t)$	the component availability until time $t$ .
$Q_n(t)$	the probability of $n$ failure in time window $[0, t]$ .
$Q_n(t)$	the probability of being in state “n” until time “t”.

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