Reliability Study of Wind Turbine Power Converter with Multiple Wind Speed

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Abstract. Power converter is a significant device in the wind turbine systems (WTS). This paper proposes a novel reliability evaluation strategy for the power converter of wind turbine with multiple wind speed, which named discrete state probability analysis method. Using the data of a wind farm wind speed and ambient temperature in Zhangcheng area of Hebei province. In addition, including the parameter of the wind turbine generator and the power converter. The results show that the reliability of the wind turbine power converter is affected significantly by multiple wind speed. The effect of the proposed method is demonstrated by the calculating example.

1. Introduction
Over the past decade, the size of the wind turbine and the capacity of the power converter having been increasing, especially in China [1]. Wind turbines are mostly built in areas with abundant wind resources, and natural conditions in these areas are relatively complex. The operating ambient of power converters is extremely harsh. High temperature or cold, shock or vibration, humidity or moisture, contaminants and dusts are the dominant factors, which lead to most of the failure occurrence with power converter. Research institutions at home and abroad found that the power converter system has the highest failure rate in the main devices of the wind turbines [2].

Many studies have already been put through to evaluate the reliability of the power converter of wind turbine. As stated in [3], the reliabilities of power converter with low speed and medium speed wind turbine are compared. The results shows the lifespan of power converter with low speed wind turbine is lower than the one with medium speed wind turbine. However, the effect of the difference of ambient temperature between 2 kinds of wind turbine on reliability is ignored. [4] Proposes a strategy to evaluate the reliability of the power converter of wind speed, but which is for many series links and result in high reliability error. [5] Through analyses and uses neutral shift to improve the reliability of power converter.
In summary, the thermal stress is the main factor of power converter fault as usual. Losses are the significant factor for the thermal stress. For certain semiconductor components, electrical operation parameters are the key to determine the losses. Multiple wind speed will directly lead to a variety of electrical operation parameters. In other words, the multiple wind speed indirectly affects the failure rate of the wind turbine power converter.

This paper proposes a novel method to evaluate the reliability of wind turbine power converter with multiple wind speed. This method can be named discrete state probability analysis method. The basic steps as follow: 1, calculate the electrical operation parameters of the power converter at multiple wind speed. 2, the corresponding component power losses and temperature parameters are calculated. 3, failure rate model of power converter is established with the discrete state probability under operation. 4, according to the multiple wind speed, the reliability indexes of power converter are obtained.

The rest of this paper is organized as follows. In Section 2, the focused topologies of the permanent-magnet synchronous generator (PMSG) and mathematical models are established, respectively. A calculating example is used in Section 3 to prove that the reliability of the wind turbine power converter is significantly affected by the wind speed, followed by conclusions in Section 4.

2. Topologies and Models

With the sustained growth of wind power influence, the grid codes are regularly update, and which have become stricter and stricter [6]. More and more wind farms operators turn to using the wind turbine equipped with the PMSG based on the full-scale power converter, because of its richer low-voltage ride-through capability. Fig. 1 shows the typical topology of PMSG based wind turbine systems, which consists of blade, PMSG, machine-side converter (MSC), DC-Link, grid-side converter (GSC), filter, transformer, and feed energy to grid finally.

![Figure 1. The topology of PMSG equipped with the full-scale power converter.](image_url)

2.1. Effect of Wind speed to Electrical Operation Parameters

The most commonly used models for calculating wind turbine generator output power and voltage from wind speed are as follows:

1) The model of wind turbine output power from wind speed can be expressed:

\[
P_t = \begin{cases} 
0, & 0 \leq V_t < V_{ci} \\
(A + BV_t + CV_t) \times P_r, & V_{ci} \leq V_t \leq V_r \\
P_r, & V_r \leq V_t \leq V_{co} \\
0, & V_t \geq V_{co}
\end{cases}
\]  

(1)

Where \( P_t \) and \( P_r \) are the output power at time \( t \) and rated power of the generator, respectively; \( V_r \), \( V_{ci} \), \( V_r \) and \( V_{co} \) are the wind speed at time \( t \), cut-in, rated and cut-out wind speed, respectively. The
A, B and C are the constants related different wind farm, and can be calculated through $V_{ci}$, $V_r$ and $V_{co}$.

2) The model of wind turbine voltage from wind speed can be expressed,

$$
U_g = \begin{cases} 
0 & 0 \leq V_t < V_{ci} \\
K_{uf} K_{fo} V_t & V_{ci} \leq V_t < V_r \\
K_{uf} K_{fo} V_r & V_r \leq V_t < V_{co} \\
0 & V_t \geq V_{co}
\end{cases}
$$

(2)

Where constant $K_{uf} = \sqrt{2}\pi NK_N\phi$, where $N$, $K_N$ and $\phi$ are the winding turns, winding distribution coefficient, and magnetic flux of wind turbine generator, respectively. $K_{fo} = P_0 / 2\pi r$, where $P$ is the number of pole pairs, $\omega = \omega r / V_t$, in where $\omega$ is the angular velocity of generator rotor, and $r$ is the radius of blade.

3) The phase current of generator can be calculated,

$$
I = \frac{\sqrt{3}P_f}{\sqrt{2}U_g}
$$

(3)

2.2. Power Losses Model of Power Converter Components

The power loss of a diode and IGBT mainly consists of conduction losses and switching losses, respectively, which are represented below by con and sw.

1) Power losses of diode and an insulated gate bipolar transistor (IGBT) in power converter,

$$
P_d = P_{d,con} + P_{d,sw} = V_{F0} I \left( \frac{1}{2\pi} + \frac{M}{8} \cos \phi \right) + \gamma_F I^2 \left( \frac{1}{8} + \frac{M}{3\pi} \cos \phi \right) + \frac{1}{\pi} f_{sw} F_{rec} \frac{V_{dc} I}{V_{ref,d} I_{ref,d}}
$$

(4)

$$
P_{IGBT} = P_{IGBT,con} + P_{IGBT,sw} = V_{CEO} I \left( \frac{1}{2\pi} \pm \frac{M}{8} \cos \phi \right) + \gamma_{CE} I^2 \left( \frac{1}{8} \pm \frac{M}{3\pi} \cos \phi \right) + \frac{1}{\pi} f_{sw} \left( E_{ON} + E_{OFF} \right) \frac{V_{dc} I}{V_{ref,IGBT} I_{ref,IGBT}}
$$

(5)

$P_d$ and $P_{IGBT}$ are the power losses of diode and IGBT, respectively. $V_{F0}$ and $V_{CEO}$ are the voltage drops of diode and IGBT, respectively. $\gamma_F$ and $\gamma_{CE}$ are the resistances of diode and IGBT, respectively. $E_{rec}$ is the rated switching energy loss of diode. $E_{ON}$ and $E_{OFF}$ are the energy losses of on and off states, respectively. $I_{ref,d}$ and $V_{ref,d}$ are the reference commutation current and voltage of diode.
\( I_{\text{ref}, \text{IGBT}} \) and \( V_{\text{ref}, \text{IGBT}} \) are the reference commutation current and voltage of IGBT. \( V_{dc} \) is the voltage of DC-Link. \( f_w \) is the switching frequency. \( \Phi \) is the phase difference of voltage to current. \( M \) is the modulation index. The signs of \( \mp \) and \( \pm \) in (4) and (5), respectively. The upper sign should be used for GSC and the bottom one for MSC.

The total power losses of MSC or GSC is expressed,

\[
P_{\text{MSC/GSC}} = 6 \left( P_{\text{MSC/GSC}, d} + P_{\text{MSC/GSC, IGBT}} \right)
\]  

where the subscripts MSC and GSC represent machine-side converter and grid-side converter.

2.3. Temperature Parameters from Losses of Power Converter Components

The junction temperature of a diode or IGBT in MSC or GSC can be calculated by,

\[
T_{\text{MSC/GSC}, j} = T_a + R_{ha} \times P_{\text{MSC/GSC}} + R_{jh} \times P_{d/\text{IGBT}}
\]  

where \( T_a \) is the ambient temperature, \( R_{ha} \) and \( R_{jh} \) are the ambient temperature and thermal resistances from junction to heat sink and from heat sink to ambient, respectively, and can be obtained from manufacturer technology book. The board temperature \( T_{\text{MSC/GSC}, b} \) of MSC or GSC can be approximated calculated,

\[
T_{\text{MSC/GSC}, b} = T_a + R_{ha} \times P_{\text{MSC/GSC}}
\]  

2.4. Discrete State Probability Model of Power Converter

The probability of each state in the discrete state model can be calculated from wind speed data. The discrete state probability model is expressed,

\[
p(i) = \frac{t(i)}{T}, \quad i = 1, \ldots, N_s
\]  

where \( p(i) \) is the time scale in period \( T \) at the state \( i \) of converter, \( t(i) \) is the time length at the state \( i \) of converter. \( T \) is 1 year. \( N_s \) is number of discrete state.

2.5. Calculating the failure rate of converter

Using discrete state probability analysis model and method in [7], the failure rate of components in power converter is expressed,

\[
\lambda_{\text{com}} = \sum_{i}^{N_s} \left[ p(i) \left( \lambda_{0Th} \pi_{Thi} + \lambda_{0TC} \pi_{TCi} \right) \right] \pi_{In} \pi_{Pm} \pi_{Pr}
\]  

where \( \lambda_{\text{com}} \) is failure rate of a component of converter. \( N_s, i \) and \( p(i) \) have mentioned above. \( \lambda_{0Th} \) and \( \lambda_{0TC} \) are the failure rate of a component corresponding to thermal stress factor \( \pi_{Th} \) and
temperature cycling factor $\pi_{TC}$, respectively. $\pi_h$, $\pi_p$ and $\pi_p$ are the overstress factor, component quality factor and reliability control factor, which can be found out in [7]. $\pi_{Thi}$ and $\pi_{TCi}$ at state $i$ can be calculated from temperature parameters of power converter.

$$\pi_{Thi} = \alpha e^{\beta \left( 1 - \frac{1}{293 + 273} \right) \left( T_{MSC/GSC,j} + 273 \right)}$$  \hspace{1cm} (11)$$

$$\pi_{TCi} = \gamma \left( \frac{12 \times N_s}{t_i} \right)^{1414} e^{1414 \left[ \frac{1}{313} \left( \max \{ T_{MSC/GSC,b} \} + 273 \right) \right]}$$  \hspace{1cm} (12)$$

Where $\alpha$, $\beta$ and $\gamma$ are the constants.

2.6. Reliability Index of Power Converter

Fig.1 shows that, MSC and GSC consist of 6 diodes and IGBTs, respectively. Their failure rates are represented by,

$$\lambda_{MSC} = 6 \left( \lambda_{MSC,d} + \lambda_{MSC,IGBT} \right)$$  \hspace{1cm} (13)$$

$$\lambda_{GSC} = 6 \left( \lambda_{GSC,d} + \lambda_{GSC,IGBT} \right)$$  \hspace{1cm} (14)$$

Where $\lambda_{MSC,d}$ and $\lambda_{MSC,IGBT}$ are the failure rates of diode and IGBT in MSC, $\lambda_{GSC,d}$ and $\lambda_{GSC,IGBT}$ are the failure rates of diode and IGBT in GSC. The total failure of power converter is expressed by,

$$\lambda_C = \lambda_{MSC} + \lambda_{GSC}$$  \hspace{1cm} (15)$$

The mean time to failure $MTTF_C$ is

$$MTTF_C = \frac{1}{\lambda_C}$$  \hspace{1cm} (16)$$

2.7. Reliability Index of Power Converter

Based on the analysis above, Fig.2 is the reliability evaluation flow chart of wind turbine power converter with multiple wind speed.
3. Example Calculation
This paper focuses on the impacts of MSC and GSC with multiple wind speed. The reliabilities of DC-Link and filter are assumed 100%. The example data are took from 3 wind farms of a company in Zhangcheng area of Hebei province can be named the first-phase, the second-phase and the third-phase wind farm, which are nearby each other and with the same ambient temperature but the multiple annual mean wind speeds. The most significant 2.2-MW wind turbine parameters of 3 wind farms are listed in Table 1. The power converter parameters are listed in Table 2.

**Table 1. A 2.2-MW wind turbine Parameters.**

| Parameter               | Value                 |
|-------------------------|-----------------------|
| Rated power             | 2.2 MW                |
| Blade radius            | 47 m                  |
| Rated wind speed        | 12.3 m/s              |
| Cut-in wind speed       | 3.3 m/s               |
| Cut-off wind speed      | 26 m/s                |
| MSC voltage             | 0-760 V (AC)          |
| DC-Link voltage         | 0-1100 (DC)           |
| GSC voltage             | 690 V (AC)            |
| Grid frequency          | 47.5-52.5 Hz          |

**Table 2. Parameters of power converter.**

| Parameter               | Diode | IGBT |
|-------------------------|-------|------|
| $V_{ref}(V)$            | 1700  | 1700 |
| $I_{ref}(V)$            | 2400  | 2400 |
| $V_{CEsat}(V)$          | 1.9   | 1.9  |
| $V_{CEO}(V)$            | 0.81  | 1.54 |
| $E_{ON} + E_{OFF} (mJ)$ | 390   | 1070 |
| $R_{th}(K/kW)$          | 44    | 19   |
| $R_{th}(K/kW)$          | 0.454 |      |

Fig.3 is the probability distributions of wind speeds of the 3 wind farms. The annual mean wind speeds from the first phase to the third phase are 6.519 m/s, 6.103 m/s and 5.499 m/s. It can be seen from Fig.4 that the ambient temperatures of 3 wind farms are almost the same curve in 2017, which will make no difference for the reliability of power converter.
Figure 3. The probability distributions of wind speeds of 3 wind farms.

Figure 4. The ambient temperature curves of 3 wind farms in 2017.
Table 3. The reliability indexes of power converter.

|                          | First phase | Second phase | Third phase |
|--------------------------|-------------|--------------|-------------|
| Mean wind speed (m/s)    | 6.519       | 6.103        | 5.499       |
| Mean ambient temperature (°C) | 7.2         | 7.2          | 7.2         |
| Failure rate of MSC $\lambda_{MSC}$ | 0.4105     | 0.3177       | 0.2102      |
| Failure rate of GSC $\lambda_{GSC}$ | 0.0498     | 0.0401       | 0.0299      |
| Failure rate of power converter $\lambda_C$ | 0.4603     | 0.3578       | 0.2401      |
| $MTTF_C$ (year)         | 2.1725      | 2.7949       | 4.1649      |

After using the discrete state probability analysis method, and let $N_e$ is 20, the reliability indexes includes failure rates and MTTF of the wind turbine power converter in 3 phase wind farms are obtained, as showed in Table 3, which shows that the failure rates of the power converter vary to be higher with the wind speed increase. Table 3 also expresses that the failure rate of MSC is higher than GSC in a wind turbine power converter, which can be explained by (4) and (5).

4. Conclusion

This paper proposes a novel method to evaluate the reliability of the wind turbine power converter equipped with PMSG. First, the translation from the wind speed to electrical operation parameters can be achieved. Afterward, the power losses models and thermal stress models of components (diode and IGBT) in power converter are established. Finally, according to the discrete state probability analysis method to calculate the failure rate and MTTF of power converter, thus obtain the reliability indexes. The results of example illustrate that wind speeds have crucial effects on the reliability of wind turbine power converter. The higher wind speed brings the lower reliability performance on the power converter. Meanwhile, the failure rate of MSC of a wind turbine is higher than that of GSC.

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