Thermal analysis of multi-MW two-level generator side converters with reduced common-mode-voltage modulation methods for wind turbines

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Suggested Citation
Abstract – Thermal performance is one of the main indicators of power converter, since it is related to both the cost of cooling system and the reliability of the power converter. Moreover, the common-mode voltage in motor driver may damage the bearing of the motor and also cause failure. Therefore, both the thermal performance and common-mode voltage of the converter should be taken into account during the selection process of the modulation strategies. In this paper, based on the generator side converter of a 3 MW wind power system, the common-mode-voltage reduced modulation strategies are compared with the conventional-60° discontinuous PWM, where the common-mode voltage, power losses and thermal performance are all taken into account. In detail, the common-mode voltages are investigated both in time domain and spectrum. The power loss distribution of the power converter with the two modulation strategies is analyzed. Finally, the junction temperature and temperature of the power devices in the converter are obtained based on the thermal model by simulations and compared between the two modulation strategies.

Keywords - Modulation strategy; common-mode voltage; thermal performance; wind power converter

I. INTRODUCTION

Modern wind power technology developed very fast during the last decades and is still booming today. Meanwhile power electronics plays more and more critical role in wind power system [1-4]. The power device is from uncontrolled one to fully controlled one, and the power rating is from partial scale to full scale. In large scale Wind Turbine Systems (WTS), the thermal performance of the power converter is becoming a critical indicator because of two main reasons: 1. complexity and cost of the cooling system will increase the cost of the converter; 2. the thermal excursion in the power device may accelerate its failure [5-7]. The power module’s failure mechanism caused by thermal cycling can be understood as the fatigue of the solder joints between the different layers with different thermal expansion coefficients. Actually, both the mean temperature and temperature cycling have impact on the lifetime of the power devices, which has been considered in Coffin-Manson-Arrhenius Model and verified by test experiment [6], [7]. Thus, the lifetime of power converters can be evaluated and improved by thermal-oriented investigation as well as a good understanding of the mission profile combined with robust design [8]. Three-level neutral point clamped back-to-back converter topology, which achieves smaller size of filters and higher voltage handling capability, is a good choice in large scale wind power application, but the unequal thermal performance between the outer and inner switching devices in a switching arm might lead to uneven lifetime of power switching devices [8]. Power fluctuation may cause thermal excursion in power converter, while reactive power can be regulated to deal with it by heating the power device [9]. Optimization regarding to the modulation strategies may be one of the most feasible approaches in order to improve the reliability of the power converter, since no more hardware is needed and the method is not complex, either. The impacts of different modulation strategies on thermal performance of the power converter were compared and the Conventional-60° Discontinuous PWM (CONV-60° DPWM) was found to be the most optimal in power losses and thermal aspect [10], [11]. But Common-Mode (CM) Voltage in the power converter was not considered.

The CM voltage in power converters may cause CM current between the converters and ground, which would lead to safety issue [12], [13]. In fact, in motor driver the CM current may induce failure of the bearings and thereby also reduce the reliability of the system [13]. Thus, the CM voltage caused by modulation strategies was investigated and it was found that common-mode voltage could be reduced if no zero vectors are applied in the modulation strategies [14-16]. Among the CM voltage reduced modulation strategies, the active zero state PWM (AZSPWM) and near state PWM (NSPWM) were found to be the most feasible.

Therefore, the scope of this paper is to investigate the thermal performance of the CM voltage reduced modulation strategies, AZSPWM and NSPWM, by comparing them with the CONV-60° DPWM. In section II, a 3 MW Permanent Magnetic Synchronous Generator (PMSG) based WTS with a single stage gearbox is modelled. In section III, the CM voltages are compared both in time domain and spectrum between the different PWM methods. The loss distribution in
the power converter is investigated in Section IV. Finally, thermal model is established and thermal performance of the power converter with different modulation strategies are compared in Section V.

II. WIND POWER SYSTEM MODEL

The thermal performance evaluation of the generator side converter is based on the optimal concept of WTS, which utilizes not only a full-scale power converter and a permanent magnetic synchronous generator (PMSG), but also a single stage gearbox to improve the reliability and also avoid a large rotor diameter, as shown in Fig. 1. A two-level back-to-back converter, the preferred solution at 3 MW level, is chosen as the full-scale power converter. To the generator side, an active rectifier is employed for maximum power point tracking (MPPT) by regulating the rotating speed of the wind turbine. The aerodynamic and generator parameters of the WTS are obtained from [17] and listed in Table I.

![Fig.1. Generator side converter of the wind power system.](image)

### TABLE I. WIND POWER SYSTEM PARAMETERS FOR 3 MW POWER LEVEL

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Name</th>
<th>Value</th>
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<tr>
<td>Aerodynamic parameters</td>
<td>R</td>
<td>Blade radius</td>
</tr>
<tr>
<td></td>
<td>$V_{c_{in}}$</td>
<td>Cut-in wind speed</td>
</tr>
<tr>
<td></td>
<td>$V_{r_{in}}$</td>
<td>Rated wind speed</td>
</tr>
<tr>
<td></td>
<td>$V_{c_{off}}$</td>
<td>Cut-off wind speed</td>
</tr>
<tr>
<td></td>
<td>$C_{max}$</td>
<td>Maximum power coefficient</td>
</tr>
<tr>
<td></td>
<td>$\lambda_{opt}$</td>
<td>Optimal tip speed ratio</td>
</tr>
<tr>
<td>PMSG parameters</td>
<td>$n_r$</td>
<td>Rated rotor speed</td>
</tr>
<tr>
<td></td>
<td>$n_s$</td>
<td>Gear ratio</td>
</tr>
<tr>
<td></td>
<td>$N_p$</td>
<td>Number of pole pairs</td>
</tr>
<tr>
<td></td>
<td>$\psi_w$</td>
<td>Magnetic induced flux</td>
</tr>
<tr>
<td></td>
<td>$L_s$</td>
<td>Stator inductance</td>
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</table>

The dc bus voltage is 1100V, which is a common choice for WTS considering that the ac distribution line-to-line voltage is 690V. The switching frequency $f_s$ is fixed at 2 kHz and the maximum electrical frequency of the PMSG is 31.8 Hz. The control strategy is implemented in synchronous d-q reference frame, as shown in Fig. 2. On q-axis, the outer loop is the rotating speed regulating based MPPT control, and the inner loop is the current control, which is actually related to the electromagnetic torque of the wind power generator. On d-axis, the current reference $I_{\ast d}$ is set to be zero in order to avoid damaging the magnetism of the generator. The pitch control will be applied to limit the power absorbed from wind, when wind speed is above the rated value for nominal power.

![Fig.2. Control diagram of the generator side converter.](image)

### III. REDUCED COMMON-MODE-VOLTAGE MODEULATION STRATEGIES

In wind power generator the CM currents would flow through the parasitic capacitor between the inner ring and outer ring of the bearing, and damage the insulating layer between the two rings, thus the reliability of the system is reduced. The circuit loop of the common-mode current in the wind power system is shown in Fig. 3, where $v_{cm}$ is the CM voltage of the PWM converter, $L_s$ and $r$ represent the equivalent stator impedance of the generator, $C_1$ is the grounded capacitor connected to the neutral point of the DC link and $C_2$ is the parasitic capacitor of the bearing.

![Fig.3. Circuit loop of the common-mode current in wind power system.](image)

It can be seen that the CM voltage of the PWM converter $v_{cm}$, which is defined as the voltage between the neutral point of the DC link and that of the stator windings, is the only voltage source in the circuit. Therefore, it should be the main focus in order to reduce the bearing current. Compared with CM filters the relatively more cost-efficient approach is optimizing the modulation strategy, since it is one of the main causes of CM voltages. It was found that when
zero switching vectors are applied in modulation methods, the amplitude of CM voltage will be $V_{dc}/2$, while without zero vectors, CM voltage would not be larger than $V_{dc}/6$. Therefore, some no zero vectors CM voltage reducing modulation strategies were proposed [14], and the most feasible CM voltage reducing modulation methods are active zero state PWM and near state PWM.

### A. Active Zero State PWM

The Active Zero State PWM (AZSPWM) method is similar to SVPWM method, which uses the two adjacent active vectors to synthesize the reference voltage, and the difference is that the AZSPWM method employs two opposite active vectors to synthesize zero vectors instead, as illustrated in Fig. 4(a). In application of AZSPWM, the switches of the two phases would switch simultaneously in a short period, which will lead to sharply reversing the line-to-line voltage and be harmful to the machine. In order to avoid this issue, the modified AZSPWM (MAZSPWM) inserting zero-voltage time intervals between pulse reversals can be applied instead [15]. Since it is the same with AZSPWM theoretically, the simpler one AZSPWM will be employed for analysis.

### B. Near State PWM

The sectors of the Near State PWM (NSPWM) method are defined in another way, as seen in Fig. 4(b). The active vectors lie in the middle of the sectors, and three adjacent vectors are applied to synthesize the reference voltage. As it can be seen, in each sector the switches of one phase are kept open or closed, which is similar to discontinue PWM. It should be noted that since zero vectors cannot be synthesized by the three adjacent active vectors, NSPWM only does work at high

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**Fig. 4.** Voltage vectors of the reduced common-mode-voltage modulation methods.

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modulation index, and the boundary is 0.67, where modulation index \( M \) is defined as the ratio of the peak value of phase voltage and half of the dc bus voltage. Therefore, NSPWM is combined with AZSPWM in order to control the variable speed wind turbine, as shown in Fig. 5.

Comparison of the CM voltages and spectrum of the converter with different modulations at various wind speeds is shown in Fig. 6. The upper part shows the CM voltages in time domain. As mentioned above, the amplitude with NSPWM+AZSPWM is only 1/3 of that with CONV-60° DPWM. The lower part shows the spectrum of the CM voltages. Generally, the CM voltages with NSPWM+AZSPWM are much lower than with CONV-60° DPWM at switching frequency especially at high wind speed. In detail, when CONV-60° DPWM is applied, the CM voltage with low frequency will increase as the wind speed and modulation index decrease. However, the thing is different for NSPWM+AZSPWM: at high wind speed, where the modulation index is high and NSPWM is applied, CM voltages with low frequency will increase as the wind speed and modulation index decrease. Conversely, at low wind speed, where the modulation index is low and AZSPWM is employed, CM voltages with low frequency are almost the same with that of CONV-60° DPWM.

IV. POWER LOSSES IN THE METHODS

In order to evaluate the thermal performance of the generator side converter, the power losses need to be obtained first. Assuming the three-phase loads of the converter are totally balanced, all the six switches of the converter would have the same power loss and thermal performance. Therefore, the power losses and temperature of S1 and D1, which are short for IGBT1 and Diode1 respectively, will be analyzed as representative of the generator side converter. Firstly, the power losses of the power devices are calculated by the model in [18], and the detail is following:

For IGBT:

\[
P_{\text{loss}} = P_{\text{cond}} + P_{\text{sw}}
\]

(1)

\[
P_{\text{cond,IGBT}} = \frac{1}{T} \int_{t_0}^{t_1} V_{CE}(t) \cdot I_C(t) \cdot dt
\]

(2)

\[
P_{\text{sw,IGBT}} = \frac{1}{T} \sum_{k=0}^{n} (E_{sw}(k) + E_{off}(k))
\]

(3)

For Diode:

\[
P_{\text{cond,Diode}} = \frac{1}{T} \int_{t_0}^{t_1} V_F(t) \cdot I_F(t) \cdot dt
\]

(4)

\[
P_{\text{sw,Diode}} = \frac{1}{T} \sum_{k=0}^{n} E_{off}(k)
\]

(5)

where \( P_{\text{loss}} \) is the total loss of the power device, \( P_{\text{cond}} \) is the conduction loss, \( P_{\text{sw}} \) is the switching loss, \( V_{CE} \) is the on-state voltage drop of the IGBT, \( I_C \) is the collector current of the IGBT, \( V_F \) is the forward voltage drop of the diode, \( I_F \) is the forward current of the diode, \( E_{sw} \) is the switching-off energy loss, \( E_{on} \) is the switching-on energy loss, \( T \) is the period of the mean power losses and \( n \) is the switching cycles number of the power device in time \( T \).

The data regarding the power losses of the power devices can be obtained in the product datasheet from the manufacturer, and in this application, the power modules employed in the generator side converter are the HiPak IGBT Modules SSNA 3600E170300 from ABB. Fig. 7 reveals both conduction loss and switching loss of the power devices with NSPWM in time domain. As shown, in sector IV IGBT1 has neither conduction loss nor switching loss since it is closed, while in sector I, Diode1 has no switching loss but conduction loss as the complementary IGBT in the same phase with IGBT1 is closed. These behaviors are quite similar to that of discontinuous PWM in time domain. Moreover, the instantaneous conduction loss and switching loss of IGBT1 is higher than those of Diode1, but since the conduction time of Diode1 is longer than that of IGBT1, the average power loss of the former one is higher, which is validated by Fig. 8.

Fig. 8 shows the comparison of the power loss distribution of the power device at various wind speeds. At high wind speed, the power loss of NSPWM is almost the same with that of CONV-60° DPWM, while at low wind speed, where the modulation method is transferred from NSPWM to AZSPWM, power loss of CONV-60° DPWM is relatively lower.
Moreover, conduction loss is dominant in Diode1, while switching loss is dominant in IGBT1. The power losses of the converter at wind speed over 12.5 m/s are the same with that of 12.5 m/s, therefore they are not shown.

The thermal capacitance of the heatsink is applied also has large impact on the shape of the heatsink. Furthermore, whether air cooling or water cooling is modelled, because it is related to the volume, material and thermal impedance from heatsink to ambient temperature sharing the heat sink is simplified as a thermal resistance and for IGBT1 a thermal impedance from the case to ambient temperature is assumed to be constant at 50°C.

Based on the thermal model mentioned above, the junction temperature with the two modulation strategies at full power rating is gained in time domain, as shown in Fig. 11. According to Fig. 8, at full power rating, NSPWM is employed in the hybrid modulation strategy. Therefore, both the mean junction temperature and temperature fluctuation of the power devices, and since the purpose is in order to find the relatively better modulation strategies in thermal aspect, the thermal impedance $Z_{th(c-a)}$ is ignored and the temperature of the heatsink $T_h$ is assumed to be constant at 50°C.

As seen in Fig. 12, both the mean junction temperature and the temperature fluctuation is about 6.5°C, where the mean junction temperature is 63°C and the temperature fluctuation is about 12°C. While the temperature of the IGBT1 is much lower, where the mean junction temperature is 50°C and its temperature fluctuation is about 14°C.

TABLE II. PARAMETERS OF THE THERMAL IMPEDANCE OF THE POWER DEVICES FROM JUNCTION TO CASE.

<p>| | | | | |</p>
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<tbody>
<tr>
<td>$R_{th}$ (K/kW)</td>
<td>5.059</td>
<td>1.201</td>
<td>0.495</td>
<td>0.246</td>
</tr>
<tr>
<td>$\tau_c$ (ms)</td>
<td>202.9</td>
<td>20.3</td>
<td>2.01</td>
<td>0.52</td>
</tr>
</tbody>
</table>

**V. THERMAL PERFORMANCES OF THE CONVERTER**

Thermal cycling is one of the main drivers for failure of IGBT modules, since it can accelerate the fatigue of the solder joints between the different layers in IGBT modules, which have different thermal expansion coefficients. Actually, in an IGBT module, the temperatures of the various solder joints are not the same, and their impacts on the lifetime of the IGBT module are also different [7]. However, as the purpose of this research is to compare the two modulation strategies in thermal aspect, it is sufficient to only consider the junction temperature of the chip, which is relatively easier to be obtained by simulations. The thermal model of the IGBT module from junction temperature to the ambient temperature sharing the same idea in [9] is shown in Fig. 9. Power loss of the device is considered to be a current source, and the temperature difference is similar to the voltage drop on the thermal impedance between the different parts of the power module. The thermal impedance from junction to case is defined as a four-layer foster RC network, as shown in Fig. 10, and the value of the thermal parameters of the power device can be acquired in the product datasheet from the manufacturer, which has been mentioned in section IV and listed in Table II. The thermal impedance from the case to heat sink is simplified as a thermal resistance and for IGBT1 and Diode1 they are set to be 0.003 K/W and 0.006 K/W respectively by experience. The thermal impedance from heatsink to ambient $Z_{th(a-h)}$ is complex to be modelled, because it is related to the volume, material and shape of the heatsink. Furthermore, whether air cooling or water cooling is applied also has large impact on $Z_{th(a-h)}$. In fact, the thermal capacitance of the heat sink is much larger than that of the power devices, and since the purpose is in order to find the relatively better modulation strategies in thermal aspect, the thermal impedance $Z_{th(c-a)}$ is ignored and the temperature of the heatsink $T_h$ is assumed to be constant at 50°C.

As seen in Fig. 12, both the mean junction temperature and the...
temperature fluctuation increase with the wind speed. However, when the wind speed is between the rated value 12.5 m/s and the cut-off speed 25 m/s, both the mean value and fluctuation of the junction temperature are constant since the generating power of the WTS is kept unchanged by pitch control as mentioned before. The diode has both higher mean junction temperature and temperature fluctuation than IGBT, and the difference also increases with the wind speed. Moreover, at high wind speed, where the modulation index is high and NSPWM works in AZSPWM+NSPWM modulation strategy, the temperature of the IGBT is a little lower than that of CONV-60° DPWM, while at low wind speed, where the modulation index is also low and AZSPWM operates, the opposite result is observed.

VI. CONCLUSION

In large scale wind power application, thermal performance and common-mode voltage of the generator side converter are two critical indicators. The former one is related to the cost of the cooling system and lifetime of the power devices, while the latter one may cause failure of the bearing in the wind generator. In this paper, based on the generator side converter of a 3 MW wind power system, the two most feasible common-mode voltage reduced modulation strategies, Active Zero State PWM and Near State PWM, are compared with the conventional-60° discontinuous PWM (CONV-60° DPWM), where the common-mode voltage, power losses and thermal performance are all taken into account. In detail, a 3 MW PMSG based wind power system with a single stage gearbox is modelled. Then, the common-mode voltages are compared both in time domain and spectrum. The power loss distribution of the power converter with the two modulation strategies is analyzed. Finally, the thermal model of the power converter is established, and the junction temperature and temperature of the power devices in the converter are obtained by simulations and compared between the two modulation strategies. It can be concluded that both near state PWM and active zero state PWM have lower common-mode-voltage than CONV-60° DPWM, and near state PWM NSPWM has the same power losses and junction temperature with it, while AZSPWM has relatively higher power losses and junction temperature than CONV-60° DPWM. But since AZSPWM only works at low wind speed, where both the power and the mean temperature are low, it is not as critical as the performance of NSPWM, which works at high wind speed and high power. Therefore, the modulation strategy that near state PWM combined with active zero state PWM is relatively optimal to be applied in the generator side converter of a large scale wind power system from common-mode voltage and thermal aspect.

REFERENCES


