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Reactive Power Control Methods for Improved Reliability of Wind Power Inverters under Wind Speed Variations

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Abstract - The thermal cycling of power switching devices may lead to failures that compromise the reliability of power converters. Wind Turbine Systems (WTS) are especially subject to severe thermal cycling which may be caused by the wind speed variations or power grid faults. This paper proposes a control method to relieve the thermal cycling of power switching devices under severe wind speed variations, by circulating reactive power among the parallel power converters in a WTS or among the WTS's in a wind park. The amount of reactive power is adjusted to limit the junction temperature fluctuation in the most stressed devices. The possible modelbased control system for the proposed method is demonstrated, designed and simulated based on the Three-level Neutral-Point-Clamped (3L-NPC) grid-connected converters. It is concluded that with the proposed reactive power control method, the junction temperature fluctuation in the most stressed devices of 3L-NPC wind power inverter under severe wind speed variations can be significantly stabilized, and the reliability of the power converter can thereby be improved while the increased stress of the other devices in the same power converter and in the paralleled ones is still acceptable.

Index Terms – 3L-NPC, Thermal cycling, Wind power, Reactive power control.

I. INTRODUCTION

The European Union has committed itself to source 20% of its energy from renewables by 2020 [1]. As the most promising candidate, the wind energy production integrated into the power grid is booming up all over the world. Meanwhile, the power capacity of a single wind turbine is increasing continuously to reduce the price pr. produced kWh, as the cutting-edge achievement, 7 MW offshore wind turbines have already been presented on the market [2]-[4]. Consequently, due to much more significant impacts to the power grid than ever before, the wind power generation system is required to be more reliable and able to withstand both grid and environment disturbances [5]-[8].

The growing requirements for reliability and grid integration push the solutions of wind power generation system from Doubly Fed Induction Generator (DFIG) with partial-rated power converter to Synchronous or Asynchronous Generator with full-scale power converter. In the full-scale power converter solutions, there are more flexibilities to control the reactive power, and it is easier to satisfy the grid voltage support requirements under both normal and fault conditions of the power grid [9]-[11].

However, compared to the partial-rated power converters, the full-scale power conversion system may suffer from higher stress of the power semiconductor devices especially under some extreme environment or grid disturbances. According to most of the reliability models for power semiconductors [12]-[14], the life time of the power converter is closely related to the thermal cycling performance - both average mean junction temperature and temperature fluctuation amplitude which are decided by the power loading as well as the device and the heat sink capacities. Therefore, it is important to estimate and relieve the thermal cycling of power devices under the most adverse operation conditions (e. g. the presence of wind gusts) when designing the wind power generation system.

This paper aims at investigating a possible reactive power control method to stabilize the thermal cycling of power semiconductor devices and thereby improve the reliability of WTS. Finally the control effects are validated and evaluated by simulations based on the Three-level Neutral-Point-Clamped (3L-NPC) converter topology.

II. IMPACT OF WIND SPEED VARIATIONS TO THE 3L-NPC GRID-CONNECTED CONVERTER

As the most commercialized multilevel topology which is widely used in the high-power medium-voltage drives for industry, mining, and traction applications [15], [16], the three-level neutral-point-clamped (3L-NPC) converter seems to be a promising candidate for the Multi-MW full-scale wind power conversion system [17]-[19], as shown in Fig. 1. This converter is chosen and basically designed based on a 10 MW wind turbine as a case study [17], [18], [20], where the major design parameters are summarized in Table I. For simplicity of analysis, the power grid is considered as three ideal AC voltage sources, and the DC bus capacitance is assumed to be large.

A. Control of wind turbine and power converter

According to the [22] and [23], a wind speed model which takes into account the mean speed, speed ramp, wind gust, and turbulence effects is applied and the generated wind speed variation is shown in Fig. 3 (a). The wind speed



Fig. 1. Three-level Neutral point clamped converter used in a wind turbine.

 Table I. Parameters of three-level Neural Point Clamped inverter for case study.

Rated output active power P_o	10 MW
DC bus voltage V_{dc}	5.6 kV DC
*Rated primary side voltage V_p	3.3 kV rms
Rated line-to-line grid voltage V_g	20 kV rms
Rated load current Iload	1.75 kA rms
Carrier frequency f_c	750 Hz
Filter inductance L_f	1.1 mH (0.25 p.u.)

* Line-to-line voltage in the primary windings of transformer.

is corresponding to a wind roughness class of 3 and fluctuates between 7.5 m/s to 12 m/s within 20 seconds.

The generated active power of wind turbine can be expressed as:

$$P_o = \frac{1}{2} \rho \pi R^2 C_p(\beta, \omega_r, v_w) \tag{1}$$

where the air density ρ =1.225 kg/m³, turbine radius *R*=85 m. The power coefficient C_p which is related to the pitch angle β , rotation speed ω_r , and wind speed v_w can be written as:

$$C_{p}(\beta,\omega_{r},v_{w}) = 0.5176 \cdot (\frac{116}{\chi} - 0.4\beta - 5)e^{\frac{-21}{\chi}} + 0.0035\lambda(\omega_{r},v_{w})$$
(2)

where

$$X = 1/(\frac{1}{\lambda + 0.08\beta} - \frac{0.035}{\beta^3 + 1}) \text{ and } \lambda = \omega_r R / v_w$$
(3)

More detail operation and parameters of the wind turbine model can be found in [18], [20], [21].

Regarding to the current references of the power converter, the active current reference I_p is accordingly changed with the wind speed, while the reactive current reference I_q is normally controlled at zero if the grid voltage is at rated and normal value. Assuming that all the generated mechanical power of wind turbines is directly transferred to the electrical power delivered into the power grid, then the current references I_d and I_q of converter can be expressed as:

$$I_d = \frac{2\sqrt{3}P_o(v_w)}{3 \cdot V_{ll}} \quad \text{and} \quad I_q = 0 \tag{4}$$

The current references I_d and I_q of the 3L-NPC gridconnected converter correspond to the pre-generated wind speed variation is also shown in Fig. 3 (a).

B. Effects of wind variations on the reliability of 3L-NPC converter

According to (4), the active current reference of wind power converter should be changed with the wind speeds. Therefore it is interesting to investigate the impacts of wind speed variation on the loading behavior of power switching devices in the wind power converter.

The loss model of power device shares the same idea in [24], [25], which is a commonly accepted method for loss evaluation of power semiconductors. The conduction loss and switching loss are accumulated by switching cycles according to the information of conduction voltage as well as switching energy in relation to the load current provided by the datasheets of manufacturers. The simulation is carried out based on PLECS Blockset in Simulink [26]. The presspack IGCT 5SHY 40L4511 (4.5 kV/ 3.6 kA) and recommended diodes 5SDF 10H4503 [27] are chosen as the power switching devices in this paper.

The thermal models for a single switch and clamping diode are indicated in Fig. 2 [26]-[28] in which the thermal impedance from junction to case $Z_{T/D(j-c)}$ is modeled as a multi-layer Foster RC network. Each of the thermal parameters can be found from the manufacturer datasheets.

It is noted that normally the IGBT manufacturer will only provide thermal parameters inside IGBT modules with Foster RC network. In order to establish the complete thermal models from junction to the ambient, the thermal impedance of $Z_{T/D(j-c)}$ has to be transferred to the equivalent Cauer RC network to facilitate the thermal impedance extension outside IGCT [26]. Because the temperature of the heat sink T_H is normally much lower and more stable compared to the junction temperature T_j in a properly designed converter system, the heat sink temperature is considered as a constant value at 60 °C in this paper. However, the heat sink temperature may strongly depend on the operation site and the design of the heat sink system.

Fig. 3 (b) shows the junction temperature response of each switching device in the designed 3L-NPC inverter under the predefined wind speed variation and



Fig. 2. Thermal models for the used power devices.



(a) Wind speed variations and current references

Fig. 3. Wind gust operation of 3L-NPC inverter without reactive power control.

corresponding current references in Fig. 3 (a). It can be seen that as the one of the most stressed devices, the clamping diode D_{npc} achieves the highest junction temperature level during almost the whole range of wind speed variation, and the maximum thermal fluctuation amplitude ΔT_{jmax} in D_{npc} achieves 32 $^{\circ}$ C for the rising edge and 25 $^{\circ}$ C for the falling edge.

Based on the important Coffin-masson reliability model, the thermal cycling is the major failure mechanism of power switching devices [12]-[14]. A series test data from the manufacturer is shown in Fig. 4 [29], in which the life time of power devices significanly reduces as the increase of temperature flucturation junction amplitude ΔT_i . Consequently, one effective way to improve the reliability of wind power converter is to reduce the junction temperature fluctuation in the most stressed devices.

III. IMPACTS OF REACTIVE POWER TO THE THERMAL LOADING OF POWER DEVICES

Because the junction temperature of the power devices is proportional to the consumed power losses in the devices, one idea to reduce the junction temperature fluctuation is to



Fig. 4. Lifetime of power switching devices vs. ΔT_i and T_{im} [29].

increase the device losses at the time with lower junction temperatures in a wind speed variation.

It is well known that the consumed losses of power switching devices are domained by the delivered power of converter. In a grid connected wind power inverter, the delivered active power is set according to the input power from wind turbines in order to maintain the DC bus voltage. The reactive power is limited or specifically requested in some conditions by the grid codes. However the reactive power handling capability of the power converter depends also by the current and voltage rating limits of the devices.

The maximum operating ranges of the reactive power in a grid-connected converter are restrained by the conditions as:

$$-\sqrt{S^2 - P^2} \le Q \le \sqrt{S^2 - P^2} \tag{5}$$

and

$$M_{ll} \le 1 \tag{6}$$

where the modulation index M_{ll} for line to line voltage can be calculated by:

$$M_{ll} = \frac{\sqrt{6 \cdot V_c}}{V_{dc}} \tag{7}$$

where V_c is the converter output voltage.

The output waveforms and thermal cycling of the 3L-NPC inverter under various reactive power operation boundaries are shown in Fig. 5 and Fig. 6 respectively, in which the active power P is set at 0.63 p.u. with 10 m/s wind speed. The conditions with maxmium underexcited reactive power Q_{-max} =-0.82 p.u. (current limits), no reactive power Q=0 p.u., and maxmium overexcited reactive power $Q_{+max}=0.5$ p.u. (voltage limits) are indicated.

The loss simulation results are presented in Fig. 7, in which three given reactive power conditions are compared. It can be seen that the maximum underexcited reactive power operation (with Q-max=-0.82 p.u.) consumes significant more loss in the outer switch T1, outer diode D1, inner switch T2 and clamping diode Dnpc of 3L-NPC converter compared to the situation without any reactive



(a) Q_{-max} =-0.82 p.u.

Fig. 5. Output waveforms of 3L-NPC inverter under different reactive power (P=0.63 p.u., 10 m/s wind speed), output voltage pulses (Green), grid voltage (blue), phase current (red).



Fig. 6. Thermal cycling of 3L-NPC inverter under different reactive powers (P=0.63 p.u., 10 m/s wind speed).

power (Q=0). The major loss difference between maximum underexcited and overexcited (with $Q_{+max}=0.55$ p.u.) reactive power operation the stress on the clamping diode. In fact the later condition stresses less D_{npc}.

As it can be seen from Fig. 6 and Fig. 7, by introducing the reactive power to wind power converter, it is possible to modify the thermal cycling of the power devices. Especially, the underexcited reactive power can significantly increase the junction temperature in the most stressed devices (outer switches T1 and clamping diode D_{npc}). This feature can be utilized by introducing some underexcited reactive power at the lower wind speeds of a wind gust, the junction temperature fluctuation in the most stressed devices can thereby be stabilized and kept relative constant at a higher value.

As already mentioned, the reactive power is limited by



Fig. 7. Loss distribution of 3L-NPC inverter with different extreme reactive powers (P=0.63 p.u.).

grid codes, which normally define a much narrower region for the allowable reactive power than the converter ability, in terms of current and voltage limits, as claimed in [8], [19]. Therefore, the thermal cycling controllability by introducing reactive power in case of one WTS with one grid converter is severely limited. The situation is different in case of a wind park or in case of a WTS with more power converters in parallel.

IV. RELIABILITY-OPTIMIZED CONTROL UNDER WIND SPEED VARIATIONS

The basic idea of the proposed control method is to circulate the reactive power among the wind power converters either paralleled in a wind park or paralleled in a multi-cell power conversion system [17], as show in Fig. 8 (a) and Fig. 8 (b) respectively. It can be seen that the reactive power is only circulated among parallel converters and will not be injected into the power grid.

Then the target of the reliability-optimized control is to maintain the average junction temperature of the most stressed device D_{npc} at the given fixed level (temperature reference). By adjusting the amount of reactive power circulated among the power converters, it is possible to change the device loss dissipation and thereby make the real device junction temperature trace the given temperature reference. Consequently, the junction temperature fluctuation can be more stabilized. On this control process the information of the junction temperature inside the target power devices should be needed in order to close the control







(b) Parallel converters in a multi-cell converter system.
 Fig. 8. Reactive power circulated in paralleled wind power converters.

feedback loop. As a result, this paper also proposes some possible junction temperature estimation methods based on the loss and thermal models of power switching devices.

The basic control diagram is demonstrated in Fig. 9. For simplicity, the active current reference i_{dref} is generated with the wind speed referring to the wind turbine model as shown in (4). A PI-controller is used to control the error between temperature reference T_{jmref} and the estimated junction temperature T_{jmE} , and then the output of PI controller is used as the reactive current reference i_{qref} for the target converter. It is noted that a reverse direction reactive current reference $-i_{qref}$ is generated for the other parallelled converters for compensating the reactive power and meet the grid codes limits.

V. ONLINE LOSS AND THERMAL ESTIMATION METHOD

In the proposed control system shown in Fig. 9, a modelbased loss estimation method is important to accurately estimate the junction temperature of target power devices.



Fig. 9. Junction temperature control with PI-controller for wind power inverter.

The inputs of this estimation block are the measured voltages, currents and ambient temperature from the converter. Two possible methods for the online loss estimation are presented in the following.

A. Instantaneous loss-based method

In this loss estimation method, the conduction loss and switching loss at each switching cycle are calculated and updated instantaneously, as shown in Fig. 10. The measured load current i_{load} , duty ratio m, DC bus voltage V_{dc} of the converter are the inputs of the loss model at each switching cycle. It is noted that a sliding average block with fundamental cycle period is used to accumulate the instantaneous losses, and generating average loss which can determine the mean junction temperature of target devices.



Fig. 10. Instantaneous loss estimation method for D_{npc} of 3L-NPC converter.

As an example, the instantaneous switching loss of the clamping diode p_{swDnpc} can be expressed as:

$$p_{swDnpc} = \begin{cases} f_s \cdot E_{rr}(i_{laod}) & \text{if } i_{load} > 0 \& m > 0\\ 0 & \text{else} \end{cases}$$
(8)

where f_s is the switching frequency, E_{rr} is the reverse recovery switching loss of D_{npc} which can be found from datasheet.

The instantaneous conduction loss of the clamping diode $p_{conDnpc}$ can be expressed as:

$$p_{conDnpc} = \begin{cases} v_F(i_{laod}) \cdot i_{load} \cdot d_{Dnpc} & \text{if } i_{load} > 0\\ 0 & \text{else} \end{cases}$$
(9)

where the v_F is the conduction voltage of D_{npc} which is related to the load current i_{load} . d_{Dnpc} represents the duty ratio for D_{npc} and can be expressed as:

$$d_{Dnpc} = 1 - |m| \tag{10}$$

where m is the modulation reference for 3L-NPC converter and ranges from -1 to 1.

Finally, the total average loss in clamping diode $P_{avgDnpc}$ is acquired by slide accumulating and averaging the instantaneous losses:

$$P_{avgDnpc} = f_o \cdot \sum_{1/f_o} (p_{swDnpc} + p_{conDnpc})$$
(11)

where f_o is the fundamental frequency of power grid.

B. Analytical average loss-based method

Another loss estimation method which directly calculates the average loss of target power devices can be also applied, as shown in Fig. 11. In this loss estimation method, the analytical solution of average conduction loss and switching loss over a fundamental cycle are necessary. The measured load current i_{dq} in rotation frame, grid voltage v_{dq} in rotation frame, DC bus voltage V_{dc} has to be input to the loss models at each switching cycle. It is noted that because the average loss is directly acquired, the sliding average block in Fig. 10 can be avoided, but an extra circuit model block is needed to transfer the measured voltage and current to the average loss calculation.

The average conduction loss of the clamping diode $P_{conDnpc}$ can be acquired by integrating the instantaneous conduction loss $p_{conDnpc}$ over a fundamental cycle as:

$$P_{swDnpc} = f_o \cdot \int_{-1/2f_o}^{1/2f_o} p_{conDnpc} dt$$

$$= f_o \cdot \int_{0}^{1/2f_o + \varphi/2\pi f_o} f_s \cdot E_{rr}(i_{laod}) dt$$
(12)

Where the reverse recovery switching loss E_{rr} can be fitted from the loss-current curve on datasheet as:

$$E_{rr}(i_{laod}) = S_2 \cdot i_{load}^2 + S_1 \cdot i_{load} + S_0$$
(13)

The S₂, S₁ and S₀ are fitting parameters for E_{rr} .



Fig. 11. Average loss estimation method for D_{npc} of 3L-NPC converter.

Then the integral function (12) can be analytically solved as:

$$P_{swDnpc} = S_2 \cdot \frac{I_{max}^2}{4\omega} [2\pi + 2\varphi - \sin(2\varphi)] + S_1 \cdot \frac{I_{max}}{\omega} [1 + \cos(\varphi)] + S_0 \cdot \frac{\pi + \varphi}{\omega}$$
(14)

Where φ is the phase angle displacement between load current and converter output voltage, I_{max} is the amplitude for the load current, and $\omega = 2\pi f_o$.

Similarly, the average conduction loss of the clamping diode $P_{conDnpc}$ can be acquired by integrating the instantaneous conduction loss $p_{conDnpc}$ over a fundamental cycle as:

$$P_{conDnpc} = f_o \cdot \int_{-1/2f_o}^{1/2f_o} p_{conDnpc} dt$$

$$= f_o \cdot \int_{\phi/2\pi f_o}^{1/2f_o + \phi/2\pi f_o} (v_F(i_{load}) \cdot i_{load} \cdot d_{Dnpc}) dt$$
(15)

Where the conduction voltage of clamping diode v_F can be fitted from the voltage-current curve on datasheet as:

$$v_F(i_{load}) = V_{F0} + R_F \cdot i_{load}^{A_F}$$
(16)

The V_{F0} , R_F and A_F are fitting parameters for v_F .

Then the integral function (15) can be analytically solved as:

$$P_{conDnpc} = f_o \cdot V_{F0} \cdot \frac{I_{max}}{\omega} \left[2 + m \cdot \sin(\varphi) - m \cdot (\frac{\pi}{2} + \varphi) \cos(\varphi) \right]$$

+
$$f_o \cdot R_{F0} \cdot \frac{I_{max}^2}{\omega} \left[\frac{\pi}{2} - m \cdot \sin(\varphi) - m \cdot \frac{1}{3} \cos(2\varphi) \right]$$
(17)

It is noted that, in order to get the analytical solution for (14), and (17), the modulation reference m for 3L-NPC converter has to be sinusoidal without any third harmonic, and fitting parameter A_F for the conduction voltage has to be 1. Both of the limitation may lead to some inaccuracy to the estimated loss.

It can be seen from (14) and (17) that the following inputs are also needed: the load current amplitude I_{max} , the phase displacement between load current and the power converter output voltage φ and the modulation index M. This is done by the circuit model in Fig. 11, in which I_{max} is:

 $I_{\rm max} = \sqrt{i_d^2 + i_q^2}$

 φ is:

$$\varphi = -\arctan(\frac{V_{g\max} \cdot \sin(\theta) - \omega L_f I_{\max}}{V_{g\max} \cdot \cos(\theta)})$$
(19)

(18)

and M is:

$$M = 2 \cdot \sqrt{\left(V_{g\max} \cdot \cos(\theta)\right)^2 + \left(V_{g\max} \cdot \sin(\theta) - \omega L_f I_{\max}\right)^2} / V_{dc} \quad (20)$$

where L_f is the filter inductance, θ is the phase displacement between load current and grid voltage:

$$\theta = \arccos PF = \arctan(\frac{l_q}{i_d})$$
 (21)

and V_{gmax} is the amplitude of grid voltage,

$$V_{g\max} = \sqrt{v_d^2 + v_q^2}$$
(22)

C. Mean junction temperature calculation

After the average loss of target device is acquired by the loss estimation method, the estimated mean junction temperature T_{imE} can be calculated by:

$$T_{jmE} = P_{avgLoss} \cdot R_{thJA} + T_A \tag{23}$$

Where R_{thJA} is the thermal resistance from junction to case, and T_A is the measured ambient temperature of converter.

VI. SIMULATION RESULTS

Fig. 12 shows the thermal cycling performances of the power switching devices with the same wind speed variation (as defined in Fig. 2 (a)) by enabling the proposed thermal control method, in which the underexcited reactive current is

adjusted by the controller to keep the average junction temperature in the most stressed device (D_{npc}) constant when the wind speed is below 10.5 m/s, and the reactive current is kept at zero when the wind speed is above 11m/s to avoid over heat of the most stress device. It can be seen that junction temperature fluctuation amplitude in D_{npc} reduces from 32 °C (rising edge) and 25 °C (falling edge) without any reactive power control to 12 °C (rising edge) and 13 °C (falling edge) respectively with the proposed reliability optimized control.

Fig. 13 shows the situation for converter 2 in Fig. 8 which compensates the reactive power generated by the target converter. The amount of overexcited reactive current is adjusted to generate the underexcited reactive power consumed by the converter 1. As a result the overexcited reactive current reference in Fig. 13 (a) has the same amplitude but opposite direction compared to Fig. 12 (a). It can be seen that when enabling the reactive power compensation in paralleled converter 2 with overexcited reactive current, the maximum junction temperature of the most stressed devices D_{npc} in Fig. 13 (b), is not further more increased.

However, when introducing reactive power (either overexcited or underexcited) to the 3L-NPC inverter, the







Fig. 13. Wind gust operation of 3L-NPC inverter with compensating reactive power.

outer diode D_1 , inner switch T_2 inner diode D_2 are slightly more stressed compared to the situation without any reactive power control. It is worth highlighting that this effect will be reduced in case more power converters in parallel are considered as it will be typical in an high power WTS or in a wind park employing many WTS's.

VII. CONCLUSION

Large wind speed variations will lead to severe thermal cycling of some power switching devices in a 3L-NPC grid connected converter, which can be seen as the preferred choice for the next generation of 10 MW WTS to be adopted in large off-shore wind parks. Particularly the clamping diode and outer switch suffer from more adverse thermal cycling than the other devices when undergoing wind gusts.

The introduction of reactive current may change the thermal cycling behavior of power devices. This paper has proposed a reliability-optimized reactive power control method to relieve the junction temperature fluctuation of the clamping diodes leading to higher reliability according to the Coffin-Masson life time models, while the increased stresses to the other devices or paralleled converters are still acceptable.

The control strategies for junction temperature stabilization by reactive power are still open questions needed to be further investigated. They are closely related to the wind gust conditions, wind farm configurations, as well as grid codes requirements, etc. Taking into account all these factors can lead to an optimal control strategy to circulate the reactive power among parallel converters in a wind turbine system or among wind turbines systems in a wind park.

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