Reactive Power Control to Improve Reliability of High Wind Power Converters Connected in Parallel

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Summary

In order to meet the increased demand for renewable energy sources, high power wind turbine systems of multi-MW range have been commercialized. Among the several topologies for high power WTSs developed in the last few years, the full-scale power converters connected in parallel are widely adopted in commercial products due to advantages of a power scalability and a potentially higher reliability in comparison to other topologies. On the other hand, as the power capacity of a single wind turbine is increasing, the high reliability has become one of the key factor to reduce maintenance and operation cost as well as to ensure the high power security. In many literature work based on the physics-of-failure approach, it has proven that the thermal cycling is the main stress source, which depends on the wind profile. Furthermore, the wind profile shows marked variations over time. Hence, in order for the highly reliable converters, it may be of interest to stabilize the thermal cycling from a control point of view. This paper presents a possibility of circulating reactive power among the parallel converters during wind variations, as losses in the power semiconductors can be modified depending on different reactive powers. Besides, by means of a centralized control via a high-speed communication, the synchronization of parallel converters can be not only achieved but the different reactive power with respect to individual converter can be also controlled properly.

Keywords-*High power wind turbine, parallel converters, reliability, thermal cycling stabilization, circulating reactive power, centralized control*

1. Introduction

As a response to the increasing demand for the renewable energy sources, the wind turbine systems have been continuously installed over the past decades and their accumulated power capacity has reached up to 390 GW globally in 2014 as shown in Fig. 1 [1]. Besides, the power capacity of individual wind turbine has been increased up to multi-MW range in commercially-available products in order to increase the power density and reduce the price per kilowatt [2]-[4]. As a preferred topology solution, the full-scale power converter satisfies the strict grid code due to the wider control range of the reactive power than the reduced-scale power converter [3]. In addition, the full-scale power converters are connected in parallel [3]. However, if the two-level topology is considered for high power wind turbine systems, there could still exist limitations on the power device rating and reliability due to relatively high *dv/dt* stress. Furthermore, it leads the bulky output filter. The multilevel topologies have become a popular candidate in high power wind turbine application, because of the lower *dv/dt* stress and output filter with the ability of multilevel output voltage.

On the other hand, the high power wind turbines tend to be installed at remote area and at offshore for more wind energy production, but leading to considerable increase of repair and maintenance cost than ever before. As a result, the high reliability and the longer lifetime are significantly emphasized in order to ensure the power security as well as to reduce the cost. Investigations on the failure rate of each component, figured out that power modules in a power converter are the main failure cause [5]-[7]. Hence, improving the power module's reliability definitely contributes to the higher reliable wind turbine system. The failure mechanism for the power module is related to thermal cycling, which is the heating up and the cooling down over and over, since it causes mechanical fatigue on the solder joints due to mismatched thermal expansion coefficient of different materials [8]-[10]. Therefore, based on the physics-of-failure approach [11], the number of cycles to failure N_f can be expressed depending on the junction temperature fluctuation ΔT_j and the mean junction temperature $T_{j,mean}$.

$$N_f = a_1 \cdot \left(\Delta T_j\right)^{-a_2} \cdot e^{-a_3 T_{j,mean}} \tag{1}$$

where a_1 and a_2 are parameters determined by experimental data and related to the physical characteristics of the power module, a_3 is a constant calculated with the activation energy and Boltzmann constant. In (1), the ΔT_j is to be a major influence for the lifetime with $a_2 \approx 5$ [12]. Consequently, minimization of the thermal cycling can serve the improved reliability of the power module.

In real environment, the wind profile shows marked variations over time, which causes fickle thermal cycling in power converters. This paper presents the reactive power circulation method among the parallel converters from control point of view, as the losses generated on power modules can be effectively modified in order to stabilize the thermal cycling during wind variation. Considering the generator-side converters, the circulated reactive power does not affect the generator control performance. Hence, as shown in Fig. 2, each converter is individually controlled by a corresponding local controller and all of the local controllers are centralized via a high-speed communication in order to synchronize them as well as to instruct them to regulate different reactive power in accordance with wind profile and converter's condition. In chapter 2, the investigated wind turbine system is briefly described. The principle of the circulating reactive power and its effect on thermal cycling is investigated in chapter 3. Before concluding this paper in chapter 5, the developed power converter is described and its basic operation is verified in chapter 4.

2. Description of the wind system under investigation

The full-scale back-to-back converter enables to control the full variable speed of generator connected to the grid and can be divided into the generator-side converter and the grid-side converter. The generator-side converter performs the variable voltage variable frequency operation in order to provide the controllability in the entire speed of the wind turbine, whereas the grid-side

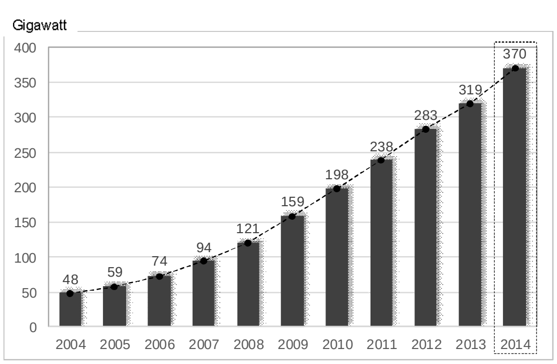


Figure 1: Wind power global capacity [1].

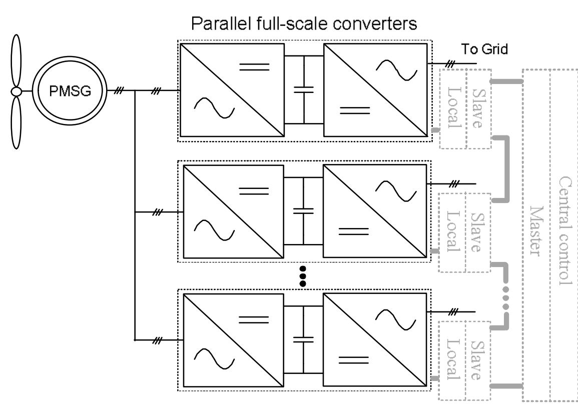


Figure 2: Parallel converters for wind turbine controlled via high-speed communication.

converter carries out the fixed voltage fixed frequency operation in normal grid condition [13]-[15]. However, in the following analysis, only the generator-side converter connected in parallel is considered, assuming the normal grid condition and the grid-side converter controlled properly.

The main purpose of the generator-side converter is to extract the maximum available power by means of a maximum power point tracking algorithm [16] and to control the active power and the reactive power independently, which is usually achieved by the field oriented method [17]. In Fig. 3, the control ability is verified by implementing to 2MW wind turbine with permanent magnetic synchronous generator and two converters connected in parallel. The output power is generated corresponding to the wind speed and the total power is equally split into two converters. Furthermore, it should be noted that the currents of each converter are in phase since the reactive power circulation method is not activated.

3. Reactive power circulation

3.1 Capability of parallel converters for reactive power circulation

The reactive power fed to a generator should be kept at a certain level under normal operation condition in order to excite the generator and especially in the case of PMSG, the reactive power is set to zero in order to minimize the copper losses [18]. In other words, it means that there is no flexibility on the reactive power control in the generator-side converter. However, by employing the parallel converters, the range of reactive power control can be extended and the principle is shown in Fig. 4. The active power generated by the wind turbine is delivered to the power converters, meanwhile, the reactive power is locally circulated between the converters. Hence, the circulated reactive power does not affect the generator operation, but influences on the behavior of the thermal cycling. As the reactive power is independent from the generator control, the maximum available reactive power circulated between the converters, is restricted by only the ratings of the power module and the active power presently generated by the wind turbine system as (2).

$$-\sqrt{S_m^2 - P_c^2} < Q_m < \sqrt{S_m^2 - P_c^2} \tag{2}$$

where S_m is the rated apparent power that is determined by the power module's specifications, P_c is the active power from the wind turbine, and Q_m presents the reactive power. The negative Q_m is defined as an under-excited reactive power, whereas an over-excited reactive power is the positive Q_m. In addition, the individual converters cope with same amount of active power (P_{c1}=P_{c2}) and reactive power ($|-Q_m|=|+Q_m|$), but the reactive power is regulated in opposite direction in order to compensate each other as shown in Fig. 5. Finally, the apparent powers have same magnitude

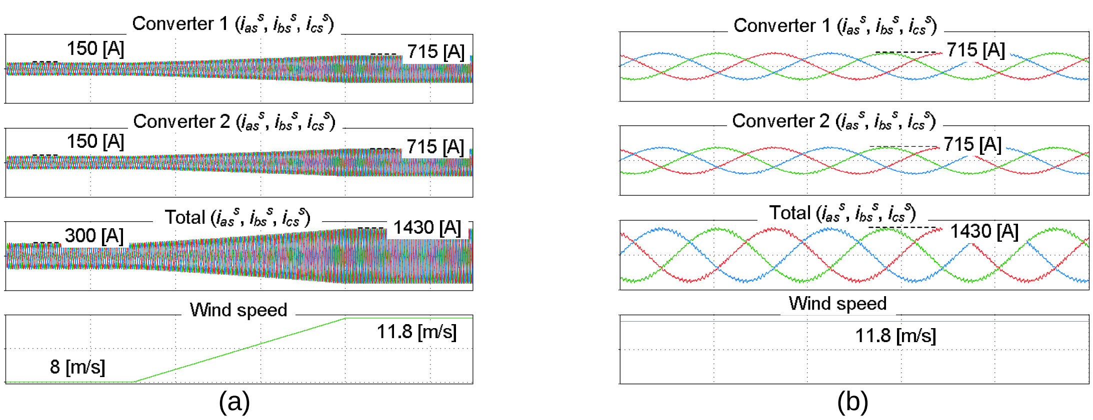


Figure 3: Verification of generator-side converter control without reactive power circulation. (a) Dynamic characteristic (8 m/s to 11.8 m/s) and (b) Steady state characteristic (11.8 m/s).

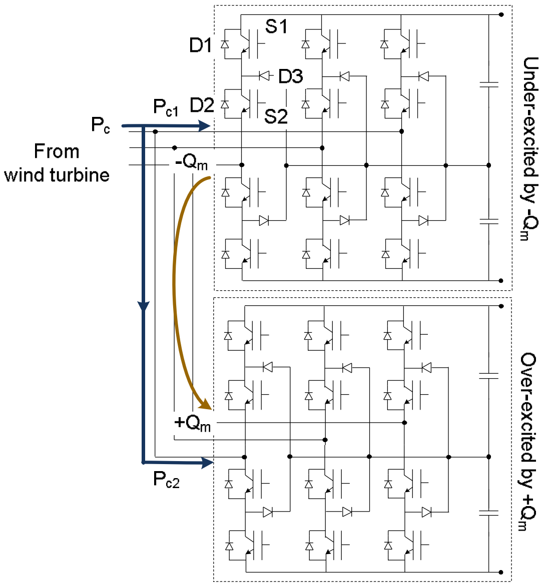


Figure 4: Principle of reactive power circulation.

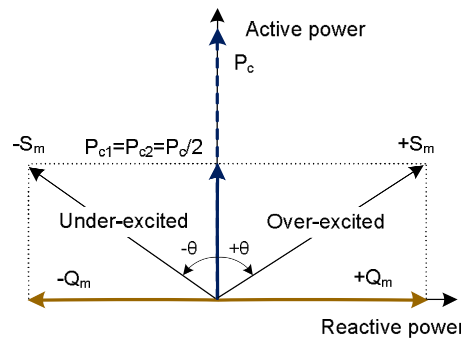


Figure 5: Phasor diagram with reactive power circulation.

($|-S_m|=|+S_m|$) and are out of phase $\pm\theta$ in accordance with the over-excited and the under-excited operation.

3.2 Possibility of thermal cycling stabilization

The power losses of the module directly affect its thermal distribution. The losses generated according to various wind speed from 4 m/s to 12 m/s, are verified in Fig. 6. The cut-in wind speed is 4 m/s and the rated power is generated at 12 m/s. Since the highest losses are produced at the inner IGBT S2 (see Fig. 4) in overall operation region, the device can be regarded as the most stressed component. Therefore, S2 could be the major failure reason due to the wear-out and alleviating its stress could improve reliability of whole converter. For the analysis of loss distribution and thermal cycling, an IGBT module of 1200 V/600 A with freewheeling diodes is considered and clamping diodes have identical electrical and thermal characteristics of the freewheeling diode.

As described before, the operation of the method can be divided into three categories: under-excited reactive power, without reactive power, and over-excited reactive power and they have different effects on the loss distribution. The loss distribution in which three different reactive power,

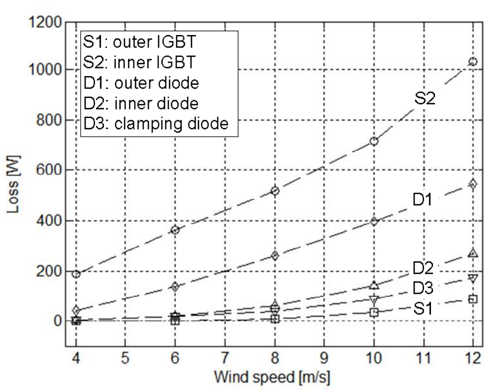


Figure 6: Loss distribution of power module according to wind speed.

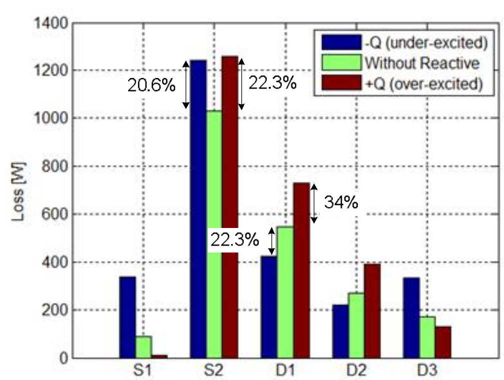


Figure 7: Loss distribution with different reactive powers.

is shown in Fig. 7. Both over- and under-excited conditions lead to more losses on the S2 than without reactive power, meanwhile the over-excited reactive power causes more losses on the D1 and D2 and the under-excited reactive power generates more losses on the S1 and D3. Finally, it can be concluded that the adjustable loss distribution, can support to stabilize the thermal cycling when the wind speed is changing.

The reactive power circulation is used in order to stabilize the thermal cycling and its simulation results are shown in Fig. 8 when the wind speed is varied from 12 m/s to 10.5 m/s and vice versa at 2 s and 4.5 s, respectively. It is considered that inertia of the generator is much lower than actual value and the thermal capacitance of heatsink is neglected as well so as to cut down on the simulation time [19]. These assumptions have no impact on the results, but only influence on the simulation time. The ambient temperature is invariable during the operation for simplified analysis and the four-layers Foster thermal network is considered. By the considered wind profile, the temperature on the S2 and the D1 is fluctuated 21 K and 16 K without circulating the reactive power, respectively. On the other hand, by the under-excited reactive power, the fluctuation on the S2 is reduced from 21 K to 15 K while that on the D1 increases from 16 K to 21 K. However, the fluctuation on the both S2 and D1 significantly decreases to 16 K and 10 K by the over-excited reactive power, respectively.

4. Developed power converter

To verify the impact of the reactive power on the thermal cycling, a three-phase three-level NPC Power-Stack of 1 MVA is developed and installed in a test bench for electrical low power testing (up to 20 kW) as shown in Fig. 9. The specification of the Power-Stack is described in Table 1. The test bench consists of the Power-Stack, a control unit with an Infineon TriCore microcontroller, and a scaled down water cooling system with minimized closed cycle cooling system with a heat exchanger [20], [21].

More precisely, the Power-Stack consists of a DC-link with film capacitors (each film capacitor with 1100 V/400 uF), three NPC phase-leg modules, and three phase-leg IGBT gate driver boards. The DC-link voltage is designed for a maximum voltage of 1500 V, the AC output voltage is 950 V, and the RMS phase current is designed for 600 A. The rating power of the Power-Stack is

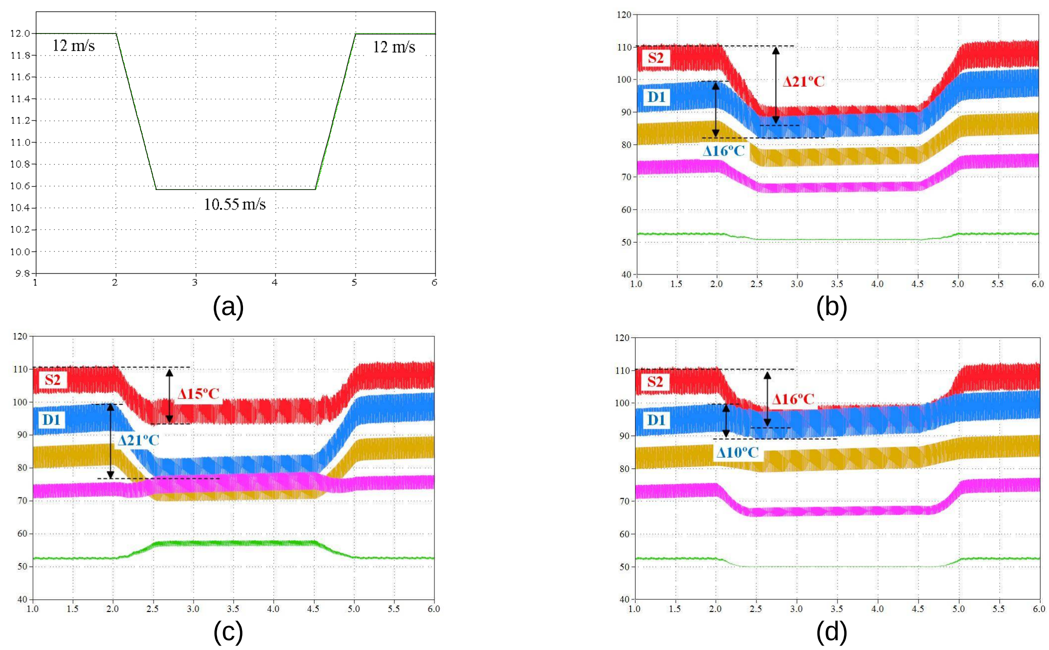


Figure 8: Impact of reactive power on thermal cycling. (a) Wind profile, (b) without reactive power, (c) under-excited reactive power, and (d) over-excited reactive power.

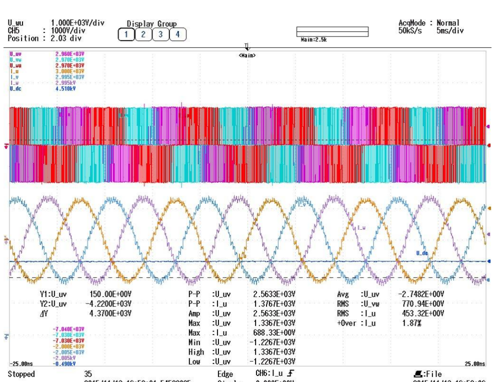
approximately 1 MVA and the size is 1100*300*200 mm. One of the key characteristics for the Power-Stack is to achieve a highly power density that could be employed both for the generator-side and the grid-side operation. The IGBT gate driver is optimized for the NPC phase-leg module with fault detection. The driver is designed for the minimized available space and a low inductive connection. Four galvanic isolated islands for the four IGBTs are created, the signals for fault and the four semiconductors is transmitted via optical fibres. The four layers PCB design is also optimized for a low EMI interconnection. The semiconductor gate voltage is between -9V and 15V and can support the gate with max current of 16A peak. The water cooler can handle three semiconductor modules (three-phase NPC), and with this water cooler a homogeneously cooling of the large flat baseplate of the module is possible.

Fig. 10 shows the preliminary experimental results of the Power-Stack in order to verify its power capability, which is performed with 1 MW test bench. This is achieved by open-loop control with a dc-link voltage of 1200 V. The line-to-line voltage and current waveforms are shown, when the output currents are 600 A/100 Hz and 600 A/50 Hz for the generator-side and the grid-side operation, respectively.

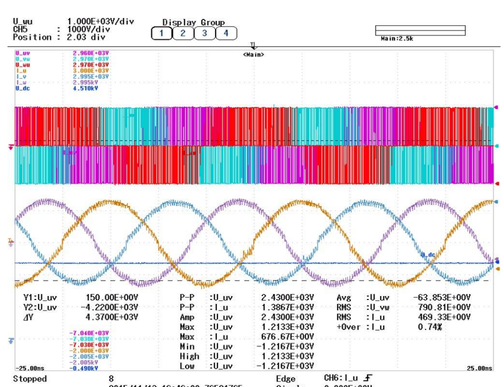
Figure 9: Test bench for Power-Stack at low power (up to 20 kW).

Table 1. Specification of Power-Stack.

Name	Value
Rated Power	1 MVA
Primary side voltage	950 V
Rated current	600 A
DC-link voltage	1500 V
Semiconductor type	IGBT
IGBT voltage class	1200 V
Topology	Three-level NPC
Size	1100*300*200 mm



(a)



(b)

Figure 10: Experimental results of line-to-line voltages and phase currents (a) in generator-side operation with *cos(φ)=-1*, (b) grid-side operation with *cos(φ)=1*.

5. Conclusion

In this paper, the possibility of reactive power circulation to improve reliability of parallel converter was verified. Focusing on the generator-side converters, the power losses according to the wind speed was analyzed and it was discovered that the inner IGBT is the most stressed device. In addition, it was also verified that the reactive power has the influence on the loss distribution of the power module, without affecting the generator control. Hence, the reactive power circulation was implemented in order to stabilize the thermal cycling, which directly affects the power module's reliability, during wind speed variation. The effect was shown by the simulation results, and finally the developed power converter was described.

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