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The Study of a Direct Power Control Strategy for Grid Connected Voltage Source Converter under Unbalanced Grid Voltage

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Abstract

In this paper, we focus on the need for enhance the adaptive capability of the voltage source converter (VSC) under unbalanced grid voltage conditions. A new direct power control (DPC) design strategy for VSC under unbalanced grid voltage conditions is proposed. Based on the analysis of power characteristics of a full rated converter, fluctuation mechanism on DC bus voltage of converter are studied, and the mathematic model of the grid side VSC under synchronous reference frame is built. To implement three different control target of constant DC bus voltage and power, or sinusoidal balanced line current, the proportional integral resonant (PIR) regulator is integrated with the traditional DPC to eliminate the ripple of the DC bus voltage and power. The proposed control strategy possesses such advantages without positive and negative sequence decomposition. Finally, the simulations works is developed to validate the proposed method. The simulation results show that the new DPC integrated with PIR can good elimination of the DC bus voltage ripples and power oscillation, enhance the ride through capability of the directly driven with permanent magnet synchronous generator system under unbalanced grid faults conditions, and can provide fast dynamic response.

***Keywords**: direct power control, voltage source converter, unbalanced grid voltage, resonant regulator, double frequency ripple*

1. Introduction

Wind power has become an important way to solve the world's energy shortage. Many countries pay more and more attentions to wind power generation. The directly driven with permanent magnet synchronous generator (D-PMSG) system has features of higher generation efficiency, simpler structure, high precision and good operation reliability. The D-PMSG system has become a primary technology direction of modern wind turbine generation systems. With the improve of the capacity of the D-PMSG, its importance to the grid has become increasingly evident so that it would have a direct impact on the stability and power quality of the connected grid [1]. For D-PMSG wind power system with back-to-back PWM voltage source converter, in the conventional control method [2], the generator rotor speed is controlled by the generator side converter, and the grid side converter control the DC bus voltage. These features, however, are less readily realized under unbalanced grid voltage conditions. Studies show that, equipping with auxiliary inverter on the grid side [3], increasing the rated capacity of power switch device, STATCOM operation mode control, adding crowbar dissipative element in different positions and adding super capacitor[4-6] can limit the increasing of the DC bus voltage and improve the grid connected power quality of D-PMSG. But if the grid voltage becomes unbalanced, such as two phase-to-ground fault and single-phase earth fault, there will still be voltage ripples appearing on the DC side, thus affecting the stability of wind power systems work [7]. The control and operation of the grid side VSC under unbalanced grid conditions has become a subject of intense research.

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Under unbalanced grid conditions, many control schemes have been proposed to control the VSC, such as Vector Control (VC) [8]. Vector Control has been based symmetrical component theory. When it has been applied, the decomposition of the unbalanced system into the positive and negative sequences is inevitable, and the positive and negative sequences have been controlled by a Proportional Integral (PI) controller. But the decomposition of the unbalanced system will cause the stability and dynamic response of the system is seriously affected and the reference current calculation is extremely complicated. To solve this problem, Proportional Integral plus Resonant controller and multi frequency proportional resonant (MFPR) controller have been proposed. But only the decomposition of the current could be avoided. To enhance the dynamic response of the control system and robustness to grid disturbances, Direct Power Control (DPC) has been developed. But the conventional DPC will change the switching frequency continuously.

In order to completely overcome these faults, this paper investigates an improved DPC with proportional integral plus resonant controller, combine with the super-capacitors, it has been used to regulate the unbalanced current, the active and reactive input power of the VSC without involving sequential decomposition. Finally, the simulation results demonstrate that the proposed control strategy can eliminate the DC voltage fluctuation and enhance unbalanced grid faults ride through capability of D-PMSG. The remainder of this paper is organized as follows. In section 2, the power characteristics of the VSC under unbalanced grid voltage conditions are depicted. Section 3 describes the proposed DPC controller. Section 4 discusses the crowbar circuit with super capacitor. Section 5 shows the dynamic simulations works for verifying the proposed method. Finally, conclusions are drawn in Section 6.

2. Power Characteristics of the VSC under Unbalanced Grid Condition

The VSC of D-PMSG is full scale power converters, the energy from the generator all transfer to the grid through the VSC. So the converters are the core part and the vulnerabilities of the system. When the grid voltage dips under the condition of three phase symmetry, due to the converter to take limiting protection, power converter transmission capacity will be reduced, resulting in the machine side and grid side converter output unbalanced , causing DC bus voltage rise , endangering the safety of power electronic devices.

Under unbalanced network conditions, assuming no zero sequence components exist, the three-phase quantities such as voltage $(U_{\mathrm{ga}}\ U_{\mathrm{gb}}\ U_{\mathrm{gc}})^{\mathrm{T}}$, current$(I_{\mathrm{ga}}\ I_{\mathrm{gb}}\ I_{\mathrm{gc}})^{\mathrm{T}}$ may be decomposed into positive sequence components $(U_{\mathrm{ga}}^{\mathrm{P}}\ U_{\mathrm{gb}}^{\mathrm{P}}\ U_{\mathrm{gc}}^{\mathrm{P}})^{\mathrm{T}}$, $(I_{\mathrm{ga}}^{\mathrm{P}}\ I_{\mathrm{gb}}^{\mathrm{P}}\ I_{\mathrm{gc}}^{\mathrm{P}})^{\mathrm{T}}$ and negative sequence components $(U_{\mathrm{ga}}^{\mathrm{N}}\ U_{\mathrm{gb}}^{\mathrm{N}}\ U_{\mathrm{gc}}^{\mathrm{N}})^{\mathrm{T}}$, $(I_{\mathrm{ga}}^{\mathrm{N}}\ I_{\mathrm{gb}}^{\mathrm{N}}\ I_{\mathrm{gc}}^{\mathrm{N}})^{\mathrm{T}}$. According to the principle of constant amplitude, positive and negative sequence components of voltage and current have been converted to two-phase stationary α-β reference frame as

$$\begin{cases} U_g = U_g^P + U_g^N = U_{gdq}^P e^{j\omega_g t} + U_{gdq}^N e^{-j\omega_g t} = U_{g\alpha}^P + jU_{g\beta}^P + U_{g\alpha}^N + jU_{g\beta}^N \\ I_g = I_g^P + I_g^N = I_{gdq}^P e^{j\omega_g t} + I_{gdq}^N e^{-j\omega_g t} = I_{g\alpha}^P + jI_{g\beta}^P + I_{g\alpha}^N + jI_{g\beta}^N \end{cases} \tag{1}$$

Where ω_{g} is the grid voltage angular frequency, '*dq*' is the *d*-*q* axis component and

$$\begin{cases} U_g^P = U_{g\alpha}^P + jU_{g\beta}^P \\ U_g^N = U_{g\alpha}^N + jU_{g\beta}^N \\ I_g^P = I_{g\alpha}^P + jI_{g\beta}^P \\ I_g^N = I_{g\alpha}^N + jI_{g\beta}^N \end{cases} \tag{2}$$

$$\begin{cases} U_{gdq}^P = U_{gd}^P + jU_{gq}^P \\ U_{gdq}^N = U_{gd}^N + jU_{gq}^N \\ I_{gdq}^P = I_{gd}^P + jI_{gq}^P \\ I_{gdq}^N = I_{gd}^N + jI_{gq}^N \end{cases} \tag{3}$$

Equation (2) is voltage and current vector of two-phase stationary α-β reference frame respectively. Equation (3) is voltage and current vector in the positive and negative sequence *d*-*q* reference frame rotating at the synchronization speed. According to instantaneous power theory, with unbalanced voltage supply, the output complex power of grid side converter can be given by

$$S = \frac{3}{2}U_g I_g^{\wedge} = P_g + jQ_g = \frac{3}{2}(U_{gdq}^P e^{j\omega_g t} + U_{gdq}^N e^{-j\omega_g t})(I_{gdq}^P e^{j\omega_g t} + I_{gdq}^N e^{-j\omega_g t})^{\wedge} \tag{4}$$

Where P_g is active power, Q_g is reactive power, '^' means the conjugate complex of the space vectors. Negative sequence components of voltage and current have been converted to positive sequence synchronous rotating reference frame, yields

$$\begin{cases} U_g^N = U_{gdq}^N e^{-j\omega_g t} = (U_{gdq}^N e^{-j2\omega_g t})e^{-j\omega_g t} \\ I_g^N = I_{gdq}^N e^{-j\omega_g t} = (I_{gdq}^N e^{-j2\omega_g t})e^{-j\omega_g t} \end{cases} \tag{5}$$

Based on equation (5), equation (4) can be simplified as

$$\begin{cases} P_g = P_{g0} + P_{g1}\cos(2\omega_g t) + P_{g2}\sin(2\omega_g t) \\ Q_g = Q_{g0} + Q_{g1}\cos(2\omega_g t) + Q_{g2}\sin(2\omega_g t) \end{cases} \tag{6}$$

Where P_{g0} and Q_{g0} are the average power outputs, while P_{g1}, Q_{g1} and P_{g2}, Q_{g2} are the cosine and sine power pulsations with double grid frequency, respectively, and

$$\begin{cases} P_{g0} = \frac{3}{2}(U_{gd}^P I_{gd}^P + U_{gq}^P I_{gq}^P + U_{gd}^N I_{gd}^N + U_{gq}^N I_{gq}^N) \\ P_{g1} = \frac{3}{2}(U_{gd}^P I_{gd}^N + U_{gq}^P I_{gq}^N + U_{gd}^N I_{gd}^P + U_{gq}^N I_{gq}^P) \\ P_{g2} = \frac{3}{2}(U_{gq}^N I_{gd}^P - U_{gd}^N I_{gq}^P - U_{gq}^P I_{gd}^P + U_{gd}^P I_{gq}^N) \end{cases} \tag{7}$$

$$\begin{cases} Q_{g0} = \frac{3}{2}(U_{gq}^P I_{gd}^P - U_{gd}^P I_{gq}^P + U_{gq}^N I_{gd}^N - U_{gd}^N I_{gq}^N) \\ Q_{g1} = \frac{3}{2}(U_{gq}^P I_{gd}^N - U_{gd}^P I_{gq}^N + U_{gq}^N I_{gd}^P - U_{gd}^N I_{gq}^P) \\ Q_{g2} = \frac{3}{2}(U_{gd}^P I_{gd}^N + U_{gq}^P I_{gq}^N - U_{gd}^N I_{gd}^P - U_{gq}^N I_{gq}^P) \end{cases} \tag{8}$$

The D-PMSG is connected to the grid through back-to-back PWM converters, the Figure 1 is the chart of the D-PMSG power flowing.

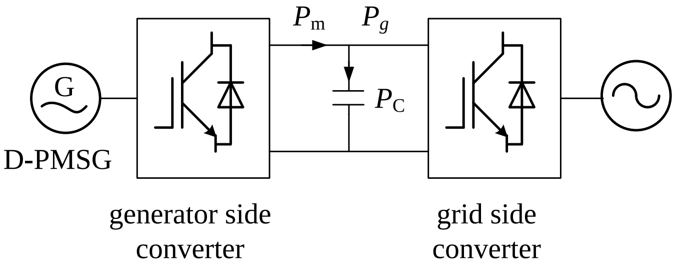


Figure 1. The Chart of D-PMSG Power Flowing

Figure 1 shows the DC bus capacitance transient power P_C can be expressed as

$$P_C = P_m - P_g = P_m - (P_{g0} + P_{g1}\cos(2\omega_g t) + P_{g2}\sin(2\omega_g t)) \tag{9}$$

Where P_m is instantaneous active power of generator, P_g is instantaneous active power of grid. Equation (9) indicates that the output power of grid side converter has the second harmonic components under the unbalanced network conditions. But the power of the generator side has no the second harmonic components and its converter still work under the balanced network conditions. So the DC voltage fluctuation would be arisen in power transmission and affect the stability of the system.

Figure 2 shows the power circuit of the three phase grid connected VSC.

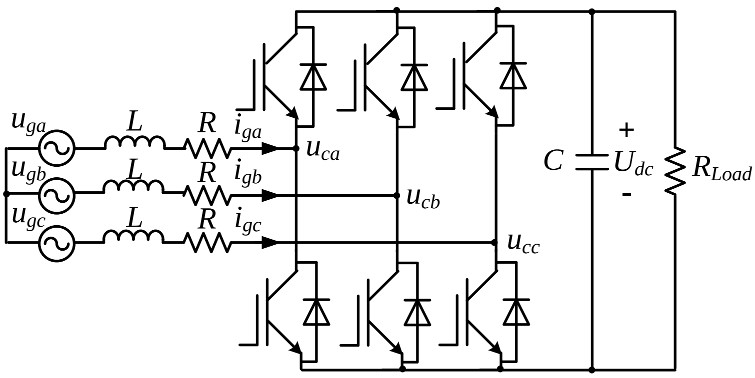


Figure 2. Power Circuit of the Three Phases VSC

The system considered here is a simplified model of grid connected VSC. L and R are inductance and resistance parallel in the grid; u_{ca}, u_{cb} and u_{cc} are three phase voltage of converter; u_{ga}, u_{gb} and u_{gc} are three phase voltage of the grid; i_{ga}, i_{gb} and i_{gc} are three phase output current of the converter; U_{dc} is the voltage of the DC voltage in DC side. The grid connected converter model in the positive d-q reference frame is represented by as [9].

$$\begin{cases} u_{gd}^{+} = Ri_{gd}^{+} - \omega_g L i_{gq}^{+} + L\dfrac{di_{gd}^{+}}{dt} + u_{cd}^{+} \\ u_{gq}^{+} = Ri_{gq}^{+} - \omega_g L i_{gd}^{+} + L\dfrac{di_{gq}^{+}}{dt} + u_{cq}^{+} \end{cases} \tag{10}$$

Where the superscript '+' denotes that the quantity have been transformed into the positive synchronous reference frame. The output active power P_g and reactive power Q_g from the grid connected converter are expressed as

$$\begin{cases} P_g = \frac{3}{2}(u_{gd}^+ i_{gd}^+ + u_{gq}^+ i_{gq}^+) \\ Q_g = \frac{3}{2}(u_{gq}^+ i_{gd}^+ - u_{gd}^+ i_{gq}^+) \end{cases} \tag{11}$$

When the d^+ of the synchronous frame is fixed to the grid voltage, equation (10) and equation (11) can be simplified as

$$\begin{cases} u_{gd}^+ = Ri_{gd}^+ - \omega_g L i_{gq}^+ + L\frac{di_{gd}^+}{dt} + u_{cd}^+ \\ 0 = Ri_{gq}^+ - \omega_g L i_{gd}^+ + L\frac{di_{gq}^+}{dt} + u_{cq}^+ \end{cases} \tag{12}$$

$$\begin{cases} P_g = \frac{3}{2}u_{gd}^+ i_{gd}^+ \\ Q_g = -\frac{3}{2}u_{gd}^+ i_{gq}^+ \end{cases} \tag{13}$$

Substituting equation (13) into equation (12), the voltage of the of converter can be calculated as

$$\begin{cases} u_{cd}^+ = -\frac{2}{3}\frac{R}{u_{gd}^+}P_g - \frac{2}{3}\frac{\omega_g L}{u_{gd}^+}Q_g - \frac{2}{3}\frac{L}{u_{gd}^+}\frac{dP_g}{dt} + u_{gd}^+ \\ u_{cq}^+ = \frac{2}{3}\frac{R}{u_{gd}^+}Q_g - \frac{2}{3}\frac{\omega_g L}{u_{gd}^+}P_g + \frac{2}{3}\frac{L}{u_{gd}^+}\frac{dQ_g}{dt} \end{cases} \tag{14}$$

Under balance condition supply, to achieve a zero steady error control for PWM rectifier instantaneous active and reactive power, references voltage of the converter can be expressed as

$$\begin{cases} u_{cd} = -G_{PI}(S)(P_g^* - P_g) - \frac{2}{3}\frac{\omega_g L}{u_{gd}^+}Q_g + u_g \\ u_{cq} = G_{PI}(S)(Q_g^* - Q_g) - \frac{2}{3}\frac{\omega_g L}{u_{gd}^+}P_g \end{cases} \tag{15}$$

Where $G_{PI}(s)$ is the transfer function of PI regulator and '*' means the reference value of quantity. Equation (15) indicates that the active and reactive power inputs can be fully controlled by directly regulating the converter voltage according to the power errors. This makes the conventional vector control schemes much easier. But the power has the double grid frequency under unbalanced conditions, and PI regulator can't provide sufficient amplitude gain multiplier of AC component to achieve zero steady state error control [10]. So the conventional DPC can't ensure control target and the capability of faults ride through of PWM rectifier is seriously affected.

3. DPC Design Based Proportional Integral Resonant Controller

3.1. Controller Design

The transfer functions of PI controller in S domain is

$$G_{PI}(S) = K_p + \frac{K_i}{s} \tag{16}$$

Where K_p and K_i are proportional and integral parameters responsible for regulating the DC component respectively. The transfer functions of PR controller in S domain is

$$G_{PR}(S) = K_p + \frac{2K_r\omega_c s}{s^2 + 2\omega_c s + \omega_r^{\ 2}} \tag{17}$$

Where K_r is the resonant parameters, which serves as the gain of a generalized AC integrator, and which can be tuned to shift the vertical magnitude response at the frequency bandwidth of the resonant controller so as to make it more stable and less sensitive to the possible frequency variations. ω_r is resonance frequency. ω_c is adopting to widen the frequency bandwidth. When $G_{PR}(S)$ and $G_{PI}(S)$ are connected in parallel, just adjust the K_p [11], $G_{PIR}(S)$ can be obtained as

$$G_{PR}(S) = K_p + \frac{K_i}{s}\frac{2K_r\omega_c s}{s^2 + 2\omega_c s + \omega_r^{\ 2}} \tag{18}$$

PI regulator can't provide sufficient amplitude gain multiplier of AC component to achieve zero steady state error control, but resonant controller can provide zero steady state error control for AC signal with the same resonant frequency [12]. If the PI controller and resonator controller in parallel as a PIR controller, we can eliminate the power pulsations and DC bus voltage ripples produced by the transient unbalanced grid faults through adjusting the resonance frequency of the PIR controller.

3.2. An Improved DPC Control Strategy Design

This paper investigates an improved DPC scheme based on PR controller and PIR controller under unbalanced voltage conditions. Different from the classical DPC scheme, the resonant controllers applied is suggested in this paper, making it possible for the active and reactive input power of the grid connected converter to be fully regulated without involving sequential decomposition.

Referring to equation (9) and equation (15), if the pulsations are included, the power can't be fully regulated with only PI controller. For regulating the power directly, a PR controller tuned at the known pulsation frequency and the output voltage of the grid connected can be given by

$$\begin{cases} u_{cd} = -[K_p + \dfrac{2K_r\omega_c s}{s^2 + 2\omega_c s + \omega_r^{\ 2}}](P_g^* - P_g) - \dfrac{2}{3}\dfrac{\omega_g L}{u_{gd}^+}Q_g + u_g \\ u_{cq} = [K_p + \dfrac{2K_r\omega_c s}{s^2 + 2\omega_c s + \omega_r^{\ 2}}](Q_g^* - Q_g) - \dfrac{2}{3}\dfrac{\omega_g L}{u_{gd}^+}P_g \end{cases} \tag{19}$$

Equation (19) shows that the power errors can be regulated to zero even if there are double grid frequency existing in the input power. Equation (20) shows that the power in the stationary α-β reference frame.

$$\begin{cases} P_g = \dfrac{3}{2}(u_{g\alpha}i_{g\alpha} + u_{g\beta}i_{g\beta}) \\ Q_g = \dfrac{3}{2}(u_{g\beta}i_{g\alpha} - u_{g\alpha}i_{g\beta}) \end{cases} \tag{20}$$

The active power of grid connected converter is usually generated by PI controller, which regulates the DC bus voltage. But if the ripples appear on the DC bus, the PI controller can't work properly owing to the lack of a gain high enough at the ripple frequency. In order to completely overcome this drawback, the resonant controllers applied is suggested, it will tune at the double grid frequency can be incorporated into the DC voltage regulator as

$$P_g^* = [K_p + \frac{K_i}{s} \frac{2K_r \omega_c s}{s^2 + 2\omega_c s + \omega_r^2}](U_{dc}^* - U_{dc}) \tag{21}$$

According to equation (21), the error between DC bus voltage and the reference can be minimized to zero by the PIR controller. Based on the above design rules, the diagram of the proposed resonant control system is shown in Figure 3.

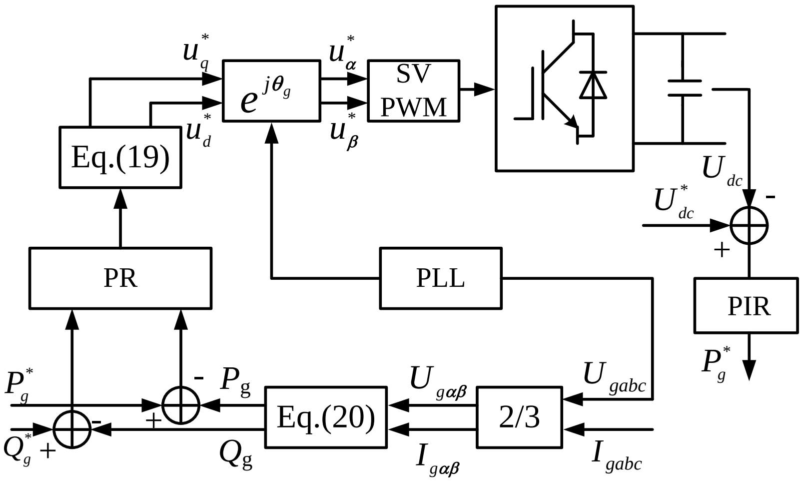


Figure 3. The Diagram of the Resonant Based DPC for PWM Rectifier

As can be seen from the Figure 3, a phase locked loop (PLL) is used to track the frequency and phase angle of the positive sequence grid voltage. The power errors are regulated by PR controller, and then the converter output voltage is calculated by equation (19). A PIR controller tuned at the double grid frequency is adapted to the error between the reference and measured DC bus voltage to eliminate the DC bus voltage fluctuation.

4. Crowbar Circuit with Super Capacitor

According to the Grid guidelines for wind power grid integration, the grid connected wind turbines must have low voltage ride through (LVRT) capability. But the traditional LVRT control method with DC bus discharge circuit consumed extra power on the resistor in the form of heat energy, and reduced the efficiency of the system, and increased the environment temperature and the difficulty in the thermal design [13]. To deal with the problem, super capacitor energy storage system with the features of high rate charge and discharge capabilities is applied to this paper. By utilizing these features, the power fluctuation of DC bus could be controlled. The chart of D-PMSG with super capacitor is shown in Figure 4.

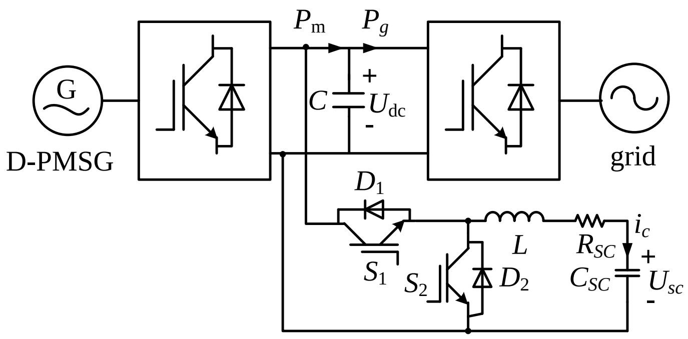


Figure 4. The Diagram of Crowbar Structure of the D-PMSG

Where S_1 and S_2 are switches, D_1 and D_2 are freewheeling diodes, R_{SC} and C_{SC} are equivalent resistance and equivalent capacitor of the super capacitor respectively, L is inductance, U_{SC} is the voltage of the super capacitor, i_C is current of the super capacitor. By adjusting the duty ratio of the S_1 and S_2 to control the switch is turned on or off, the charge and discharge of the super capacitor can be obtained. The double loop control block diagram of charge and discharge controller is shown in Figure 5. Outer voltage control loop guarantee the stability of output voltage, and inner inductance current control loop generates compensation current to enhance the stability of the output voltage [14].

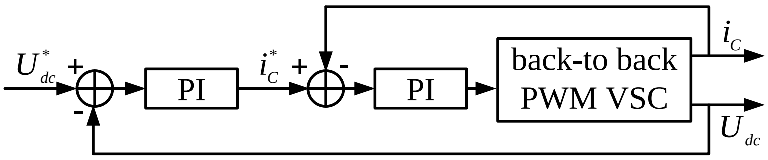
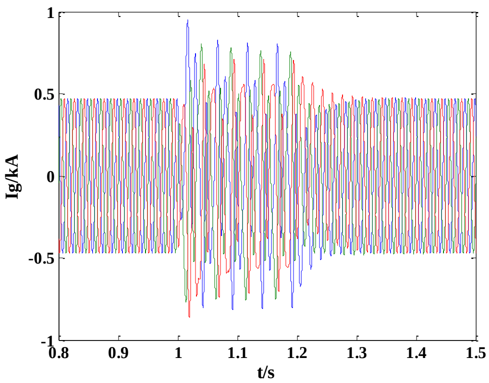


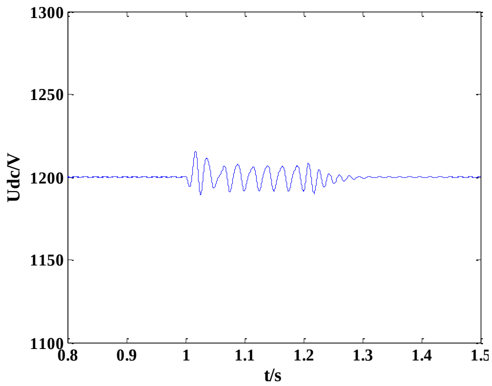
Figure 5. The Control Block Diagram of Charge and Discharge Controller

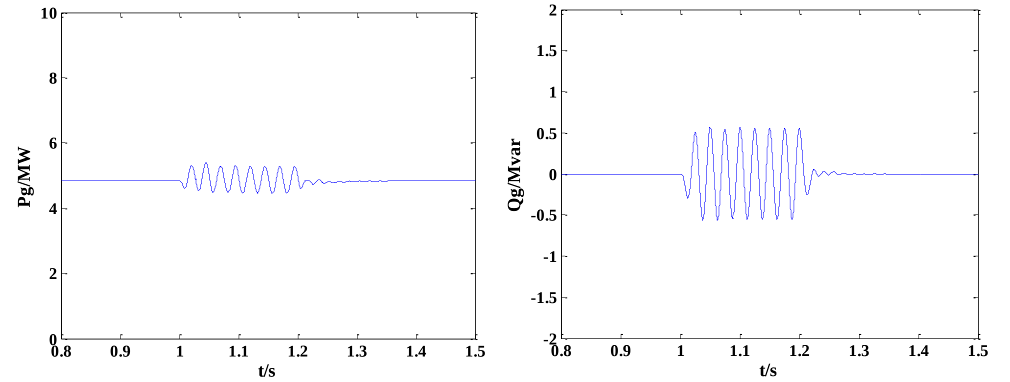
5. Simulation Results and Discussion

In order to validate the mathematical analysis and, hence, to establish the effectiveness of the proposed control scheme, simulations works were carried out for a D-PMSG based on wind power generation system. Performance of the proposed model was verified using SIMULINK/MATLAB. The D-PMSG was rated at 4.8 MW, stator voltage was 690V, and its line inductance and DC side capacitance were designed as 5 mH and 50 mF. The DC bus voltage was set at 1200V, and the switching frequency was set at 3 kHz. When the fault occur sat t=1s and remove at t=1.2s, the unbalanced grid voltage dip with phase voltage dropping to 70% of its normal value. Figure 6 shows the simulation results of the VSC under unbalanced condition with the proposed DPC applied.

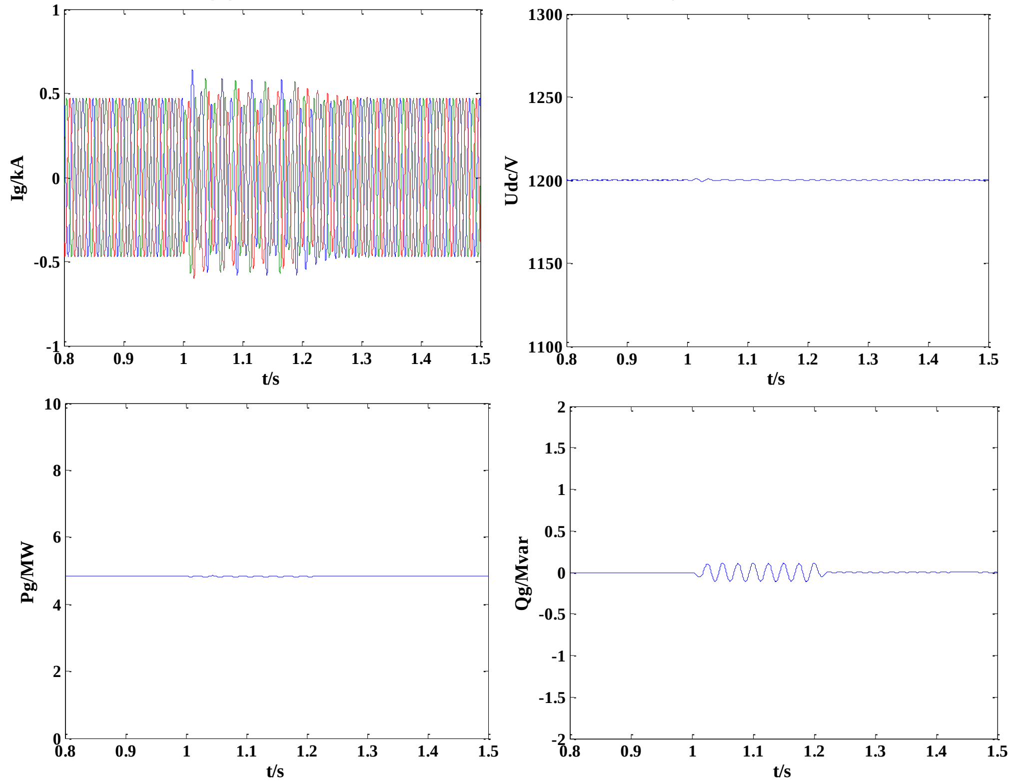
The simulation results are shown in the figure 6(a) with conventional DPC, the line current was seriously distorted when the grid voltage became unbalanced. Voltage ripples were generated on the DC bus and the pulsation were present obviously in both of the active and reactive power. The reason for which may be because the PI controller can't work properly owing to the lack of a gain high enough at the ripple frequency. The simulation results are shown in the Figure 6(b) with proposed DPC under grid voltage unbalanced. It can be seen that the active pulsation were disappeared almost, the DC bus voltage ripples became very small. But the reactive power pulsation were not removed completely, this is the cost of active power fluctuations disappeared.



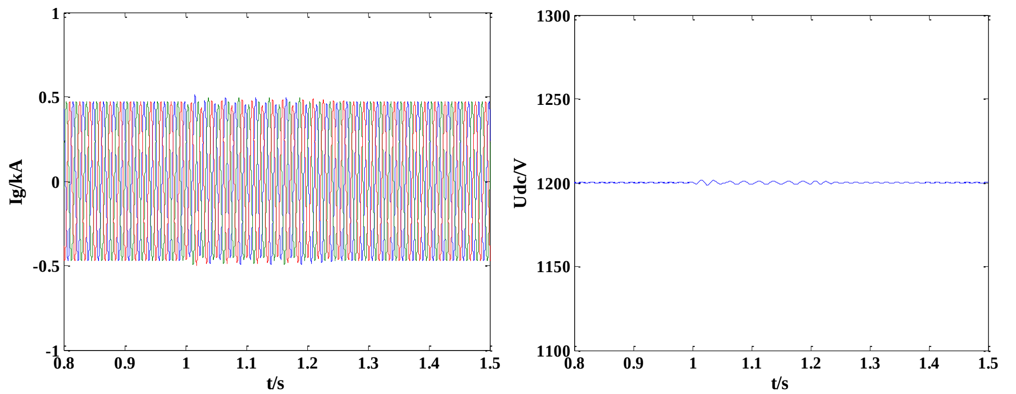


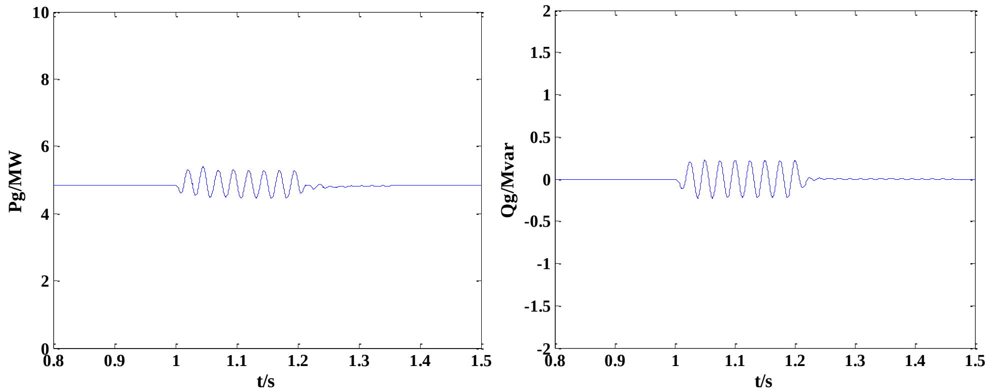


(a) Conventional DPC under Grid Voltage Unbalanced



(b) Proposed DPC under Grid Voltage Unbalanced





(c) Proposed DPC with Control Target Change from Constant Power to Sinusoidal Line Current

Figure 6. Simulation Results of the VSC under Unbalanced Condition with the Proposed DPC Applied

When we adjust the parameters make the control target become sinusoidal line current, then simulation results can be seen as the Figure 6(c), the current distortion is restrained, but the DC bus voltage ripples, the active and reactive power pulsations could not be eliminated. The reason for which may be because control targets are exclusive.

6. Conclusion

This paper has proposed an improved DPC design method for a D-PMSG based wind power generation system during grid voltage unbalanced, the detailed design of the DPC scheme is presented. Simulation results were presented to demonstrate the effectiveness of the proposed control scheme. Above of all, conclusions can be drawn as follows:

(1) Compared with the conventional DPC scheme under unbalanced conditions, the proposed scheme gets rid of the decomposition process of the positive and negative sequence and without any current calculation. Besides, the system performance is enhanced by the elimination of the DC bus voltage ripples by regulating the input power instead of the output power.

(2) The proposed DPC method, for elimination of the active and reactive power pulsations, a resonant controller tuned at the pulsation frequency is applied with PI controller.

(3) The simulation results show that the proposed DPC method can provide fast dynamic response and can enhance grid faults ride through capability of the D-PMSG under unbalanced conditions.

Acknowledgments

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