Improvement of LVRT Characteristic of SCIG Wind Turbine System by Incorporating PMSG

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Abstract

A configuration of permanent magnet synchronous generator (PMSG) wind farm coordinated with squirrel-cage induction generator (SCIG) wind farm is proposed for achieving certain optimal operating performance and economic benefits. SCIG's poor capability of reactive power control can be supported by PMSG installed nearby the SCIG wind farm by controlling reactive power of a grid-side converter connected to the PMSG wind turbine. During grid faults, the control priority to the grid-side converter is automatically changed, that is, controlling voltage at the point of common coupling (PCC) is prior to controlling the DC-link voltage. The effectiveness of the proposed control strategies is proven by simulation results. These illustrate the precise reactive power and voltage responses, which supports the SCIG-based wind farm to ride through the grid fault without installation of any additional devices.

Keywords: Permanent magnet synchronous generator, squirrel-cage induction generator, low voltage ride through (LVRT), wind turbine, reactive power compensation, voltage recovery

1. Introduction

Due to a number of reasons such as a rise in fossil fuel prices, the awareness of environment issues and an increasing concern about energy security, renewable energy sources have attracted a lot of attention [1-3]. Among those energy sources, wind energy is currently the most cost-effective one to produce electricity with significant growth of power capacity. Fast development of wind power generation has led to the requirements for integration of wind farm into the network without compromising power system stability. Grid operators require wind farms to remain connected stably to the network during severe grid faults and to support the grid restoration by supplying ancillary services, especially in places where wind turbines provide a significant part of the total power [4].

Various wind turbine concepts have been developed to maximize annual energy capture, minimize cost, improve power quality, and ensure safety together with the growth of wind energy [5]. Historically, a SCIG wind turbine had been widely used in commercial because of its advantages such as robustness, easy and relatively cheap mass production. It also operates at a constant rotating speed when it is connected to a large grid, providing stable frequency control. However, with an increasing penetration level of wind turbines, the market share of SCIG wind turbines has decreased because it has poor capabilities to meet the new challenges of the grid connection requirements and makes it difficult to support grid voltage control. On the other hand, variable speed operation of wind turbines draws lots of attention due to the high ability of complying with grid requirements especially in case of PMSG wind turbine with a full-scale converter. Because of its full-scale converter, it can absorb or supply a large

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amount of reactive power to the grid. When a fault occurs, the grid-side converter can provide reactive power up to its rated value to help ride through the fault.
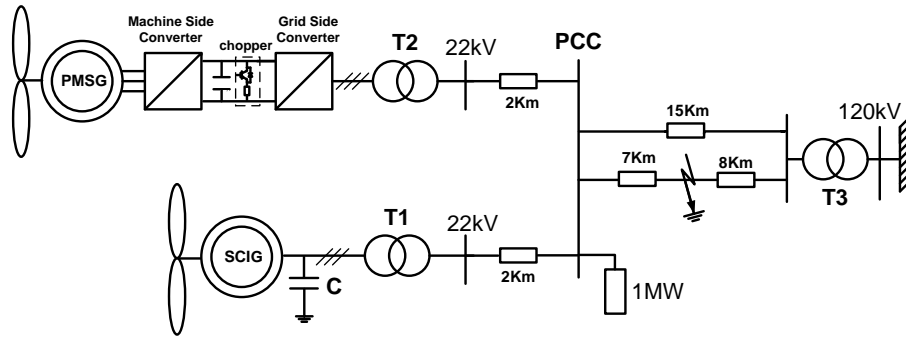

Figure 1. Closely Connected SCIG and PMSG based Wind Farm

Various control strategies for PMSG wind turbine system have been presented in the literature. In [6-8], the control strategies aim to promise the proper operation of PMSG-based wind turbine in normal operating range. In the scope of those papers, the grid support capability of variable speed wind turbine systems has not been considered. To satisfy a LVRT requirement of wind turbines while obtaining enough torsional damping, an alternatives design of the converter control has been proposed in [9] and [10]. However, such a strategy is complex and its advantage is limited by the converter capacity.

In this paper, a control strategy for a MW class PMSG-based wind turbine system located closely to the SCIG-based wind farm is proposed in order to improve LVRT characteristics of SCIG wind turbines by compensating the reactive power which is absorbed by the SCIG-based wind farm. This configuration might be cost-effective solution to enhance LVRT capability of the existing SCIG wind farm. In the normal condition, the control method guarantees the efficient and reliable operation of the PMSG-based wind energy system. During grid faults, the control priority to the grid-side converter is automatically changed, that is, controlling voltage at the PCC is prior to controlling the DC-link voltage. By this approach, converter capacity is efficiently utilized for LVRT capability enhancement of PMSG-based wind turbine and SCIG-based wind turbine.

2. Models for grid-connected SCIG and PMSG Wind Farm

The coordinated wind power system schematic is shown in Figure 1, where 9 MW SCIG and 10 MW PMSG based wind farms are closely connected. The PMSG-based wind farm consists of five 2 MW turbines whereas the SCIG-based wind farm consists of six 1.5 MW turbines. Both wind farms are connected to a 120 kV grid by step-up transformers with the same distances from the grid connection point. The wind farms are integrated into the grid by 15 km transmission lines.

2.1. SCIG –based Wind Turbine System Model

The induction machine model is obtained from [11]. The equivalent d-q circuits of squirrel cage induction generator are shown in Figure 2. The relationship between the stator voltage, the rotor voltage, the currents and the fluxes in the synchronous reference frame (d-q frame) are given by the following equations.

$$v_{ds} = -r_s i_{ds} - \omega_s \psi_{qs} + \frac{d}{dt}\psi_{ds} \tag{1}$$

$$v_{qs} = -r_s i_{qs} + \omega_s \psi_{ds} + \frac{d}{dt}\psi_{qs} \tag{2}$$

$$v'_{dr} = -r'_r i'_{dr} - (\omega_s - \omega_r)\psi'_{qr} + \frac{d}{dt}\psi'_{dr} = 0 \tag{3}$$

$$v'_{qr} = -r'_r i'_{qr} + (\omega_s - \omega_r)\psi'_{dr} + \frac{d}{dt}\psi'_{qr} = 0 \tag{4}$$

$$\psi_{ds} = -L_s i_{ds} + L_m i'_{dr} \tag{5}$$

$$\psi_{qs} = -L_s i_{qs} + L_m i'_{qr} \tag{6}$$

$$\psi'_{dr} = -L'_r i'_{dr} + L_m i_{ds} \tag{7}$$

$$\psi'_{qr} = -L'_r i'_{qr} + L_m i_{qs} \tag{8}$$

$$L_s = L_{ls} + L_m \tag{9}$$

$$L'_r = L'_{lr} + L_m \tag{10}$$

where v_{dqs}, v'_{dqr} are the stator and rotor voltages, i_{dqs}, i_{dqr} are the stator and rotor currents, ψ_{dqs}, ψ'_{dqr} are the stator and rotor fluxes, r_s, r'_r are the stator and rotor resistances, L_{ls}, L'_{lr} are the stator, rotor leakage inductances, L_m is the magnetizing inductance, ω_s is the synchronous speed and ω_r is the rotor speed. All rotor parameters are referred to the stator.
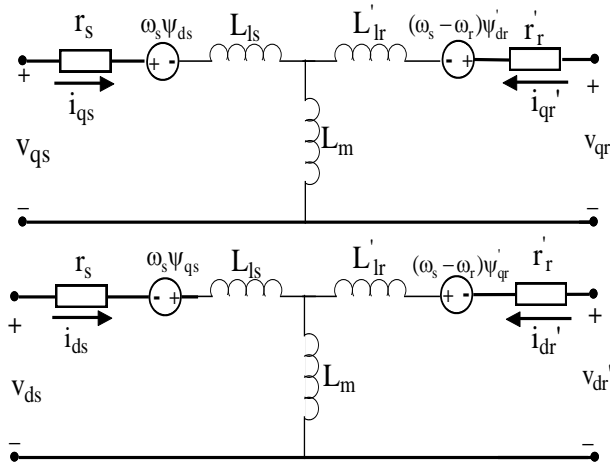

Figure 2. Equivalent d-q Circuits of SCIG

For a fixed speed wind turbine generator system, detailed drive train model is very important for correct representation of the transient behavior. Therefore, a two-mass model has been chosen, which is described by the following equations [12].

$$\frac{d\omega_{wr}}{dt} = \frac{T_{wt} - K_s.\gamma}{2H_{wt}} \tag{11}$$

$$\frac{d\omega_r}{dt} = \frac{K_s.\gamma - T_e}{2H_g} \tag{12}$$

$$\frac{d\gamma}{dt} = 2\pi f(\omega_{wr} - \omega_r) \tag{13}$$

where f is the nominal grid frequency, T is the torque, γ is the angular displacement between the two ends of the shaft, H is the inertia constant, K_s is the shaft stiffness, ω_{wr} is the rotational speed of wind turbine rotor, ω_r is the rotational speed of generator.

2.2. PMSG-based Wind Turbine System Model

A PMSG wind turbine uses a synchronous generator with its rotor is excited by a large number of permanent magnets and its stator windings are connected to grid through a full-scale power converter [9]. The full-scale power converter is used to control the speed of the generator and the power flow to the grid. This converter includes two parts namely the machine-side converter (MSC) and the grid-side converter (GSC) linked by a DC-bus. The mathematical model of a synchronous generator is described in [13]. In this paper a brief overview is provided in order to present the most important features of the PMSG used in wind turbines.

Figure 3 shows the equivalent electric circuits of PMSG in rotor-oriented d-q reference frame. The voltage equations of the generator, expressed per unit in a generator convention, can be expressed as follows.

$$v_{ds} = -(R_s i_{ds} + L_d \frac{di_{ds}}{dt}) + \omega_e L_q i_{qs} \tag{14}$$

$$v_{qs} = -(R_s i_{qs} + L_q \frac{di_{qs}}{dt}) - \omega_e L_d i_{ds} + \omega_e \Psi_{PM} \tag{15}$$

$$L_d = L_{ls} + L_{md}$$
$$L_q = L_{ls} + L_{mq}$$

The active, reactive powers and the electromagnetic torque of the synchronous generator are given by

$$P_s = v_{ds}i_{ds} + v_{qs}i_{qs} \tag{16}$$

$$Q_s = v_{ds}i_{qs} - v_{qs}i_{ds} \tag{17}$$

$$T_e = p[\Psi_{PM}i_{qs} + (L_d - L_q)i_{ds}i_{qs}] \tag{18}$$

where v_{ds} and v_{qs} are the terminal stator voltages, i_{ds} and i_{qs} are the stator currents, L_d and L_q are the stator inductances in the dq reference frame, R_s is the stator resistance, L_{ls} is the stator leakage inductance, L_{md} and L_{mq} are the mutual inductances, Ψ_{PM} is the flux linkage produced by the permanent magnet, ω_e is the electrical speed, p is the number of pole pairs.
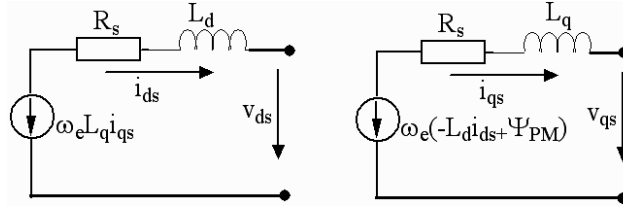
Figure 3. Equivalent d-q Circuits of PMSG

As mentioned in reference [12], in a variable speed wind turbine system, the drive train properties have almost no effect on the grid side characteristics due to the decoupling effect of the power electronic converter. Therefore, the simple one-mass lumped model is considered. The mechanical equation for a single shaft model is

$$\frac{d\omega_m}{dt} = \frac{1}{2H}(T_m - T_e)$$ (19)

where H is the total inertia constant of the lumped rotating system, T_m is the mechanical torque, T_e is the electrical torque, ω_m is the mechanical rotational speed.

A DC-link capacitor provides a short-term intermediate energy storage, which decouples the generator-side converter and the grid-side converter. If the losses are neglected, the DC-link dynamics is expressed as

$$\frac{1}{2}C\frac{dV_{dc}^2(t)}{dt} = P_{gen}(t) - P_{grid}(t)$$ (20)

A constant DC-link voltage is required to ensure active power transmission from PMSG terminal to the grid. Once there are any imbalances in powers P_{gen} and P_{grid}, the difference in power is stored in the DC-link capacitor and leads to an increase in the DC-link voltage.

3. Coordinated Control of PMSG for LVRT Characteristic Improvement of SCIG

In this section, the control strategy applied to the full scale power converter of PMSG wind turbine system is investigated. This control strategy not only aims to guarantee the proper operation and LVRT capability of the PMSG-based wind turbine but also aims to enhance LVRT characteristic of the nearby SCIG-based wind turbine. The converter control of PMSG wind turbine system is designed in such a way to maintain the voltage at point of common coupling (V_{PCC}) at a desired reference level.

The reactive power absorbed by the induction generators during large duration network voltage sags can be provided without installation of any additional devices. The power converter control is generally comprised of the machine side converter control and grid side converter control. This paper focuses primarily on the control strategy for the grid side converter to support reactive power for voltage control purpose in case of grid disturbances.
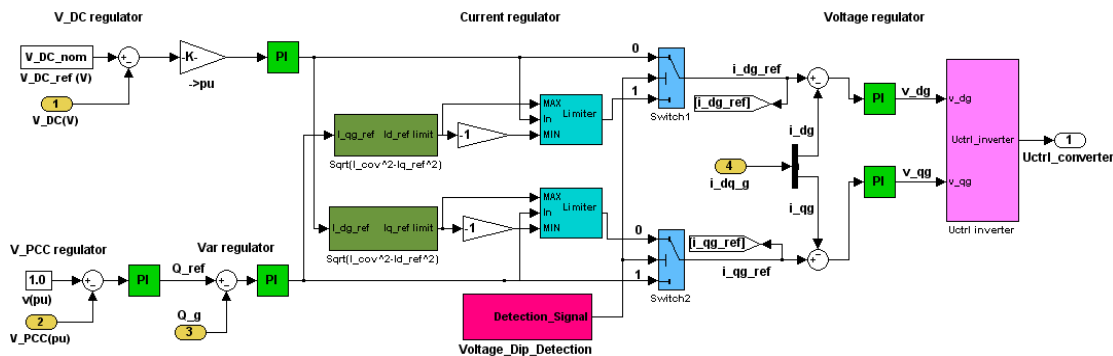
3.1. Grid Side Converter (GSC) Control

Conventionally, the aim of the controller applied to grid side converter is to keep the DC-link voltage constant, thereby ensuring that the entire active power generated by the generator is delivered to the grid. In addition, it is used to control the reactive power fed to the network.

In this study, the objective of this controller is to keep DC-link voltage and grid voltage (V_{PCC}) at their rated value. Besides, a reasonable order of control priority is established for purpose of grid voltage support. Hence, the grid side converter not only takes the responsibility for keeping the PMSG running properly but also provides adequate response of dynamic reactive power compensation for the fast voltage recovery after fault clearance.

The GSC control scheme and the control implementation using MATLAB/Simulink are depicted in Figure 4. The GSC controls the exchange of active power between the DC-bus and the grid by regulating the DC-link voltage to its reference value and controls the grid voltage (V_{PCC}) to its rated value by controlling reactive power. This controller uses a grid voltage-oriented d-q reference frame, meaning that the d-axis of the reference frame is oriented along the grid voltage. This implies that in the grid side converter control, the constant DC voltage and grid voltage control can be achieved by controlling d-q current components accordingly.
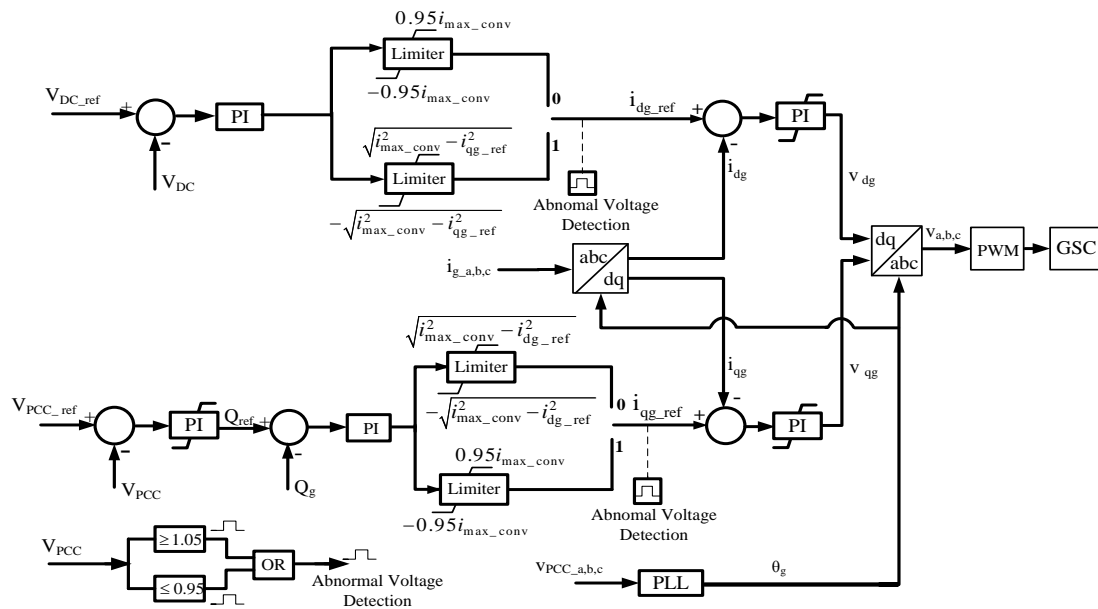
a) GSC Control Scheme

b) GSC Control Implementation using MATLAB /Simulink

Figure 4. Generic Control of Grid Side Converter of PMSG

As illustrated in Figure 4(a), two control channels are used to control DC voltage and grid voltage. The first is used to set d-axis current reference depending on the difference between the desired and actual DC voltage value. The second tries to adjust the grid voltage to the rated value by setting the reactive power reference. A reactive power error signal via a PI controller then defines the q-axis current reference. After that, the inner current control loop regulates the i_{dqg} and defines the reference voltage $v_{dqg.}$ Subsequently, two reference voltage components v_{dg} and v_{qg} are used to compute the three-phase sinusoidal voltage that generates switching signal for GSC after PWM processing.

To take the responsibility for keeping the PMSG running properly and provide adequate response of dynamic reactive power compensation, an order of control priority is proposed. In normal operation, the priority is given to maintaining DC-link voltage at constant value and the capability to manage the reactive power is varying. As shown in Figure 4(a), i_{dg_ref} and i_{qg_ref} are obtained from the output of PI controllers. Maximum i_{dg_ref} is set up to 95% of the maximum converter current ($i_{dg\_ref\_max}=0.95i_{max\_cov}$), and limitation of i_{qg_ref} used for controlling V_{PCC} is calculated as the following equation.

$$i_{qg\_ref\_max} = \sqrt{i^2{}_{max\_cov} - i^2{}_{dg\_ref}} \qquad (21)$$

where i_{max_conv} is the maximum current of GSC.

When a voltage dip is detected, the priority order is switched and then controlling V_{PCC} is a first priority. In this case, the maximum value of i_{qg_ref} is set to 95% of the converter rating like equation (22).

$$i_{qg\_ref\_max} = 0.95i_{max\_cov} \qquad (22)$$

It means that during voltage dip period, the GSC can provide reactive power up to 95% of the converter capacity. The GSC can inject a huge amount of reactive power to grid so that the voltage at PCC can be recovered as fast as possible. The remaining converter capacity for controlling V_{DC} can be expressed as the following equation.

$$i_{dg\_ref\_max} = \sqrt{i^2{}_{max\_cov} - i^2{}_{qg\_ref}} \qquad (23)$$

As clearly observed in Figure 4(a), the priority order is switched by changing position of the connection in the control configuration. When the system is operating in normal condition, the inner current control loop is connected to "0" position. When an abnormal voltage is detected, this inner current control loop is switched from "0" position to "1". When the voltage at PCC reaches above 95% of its rated value, the priority is reestablished as normal operation and the inner current control loop is connected to "0" position again. This control approach is implemented by using MATLAB/Simulink as shown in Figure 4(b).

Because of high demand reactive power compensation during severe faults, most of the converter capacity is used for controlling V_{PCC}. Hence the capacity used for controlling V_{DC} at this time may be insufficient, for this reason the DC-link voltage may increase and take long time to go back to pre-fault value. In order to correct this problem, a chopper can be used to dissipate excess stored energy in DC capacitor. When the fault disappears and the capability to maintain constant V_{DC} is brought back, the V_{DC} is reduced gradually to the rated value, helping the transfer of active power to grid.

3.2. Machine Side Converter (MSC) Control

The controller of machine side converter is organized as illustrated in Figure 5. This controller has a structure of two loops in cascade; an inner current control loop and an outer loop. The inner current control loop controls the d-q currents to the reference values while the outer control loop controls active power and stator voltage. In order to capture the optimal power out of the wind, a maximum power point tracking (MPPT) is implemented by using characteristic P-ω look-up table. The reference power signal P_{ref} is generated based on the measured generator speed ω_{meas}. In order to avoid the risk of over-voltage and saturation of the converter due to over-speed, the stator voltage is controlled instead of reactive power [6].

The control is implemented in a stator voltage-oriented d-q reference frame so that the stator voltage is as following.

$$v_s = v_{ds} + jO \tag{24}$$

Thus, the active and reactive powers can be expressed as the following equations.

$$P_s = v_{ds}i_{ds} \tag{25}$$

$$Q_s = v_{ds}i_{qs} \tag{26}$$

The active power depends on the d-component of stator current while the reactive power depends on the q-component of the current only. This means that in the machine side converter's controller, the active power is controlled by the d- component current whereas the stator voltage is controlled by means of the q-component current.

As shown in Figure 5, the reference value of d-component current depends on the difference between the desired and actual active power. On the other hand, the reference value of q-component current is based on a stator voltage error signal. Consequently, the d-q voltage control signals of the converter are obtained by comparing the reference values with the actual values of generator stator d-q component currents. These two voltages v_{ds} and v_{qs} generated by the PI controllers are then used to compute the three-phase sinusoidal voltage to control PMSG after PWM processing.

4. Simulation Results

4.1. LVRT Characteristic of SCIG-based Wind Farm

In the simulation study, the most severe fault is considered and it is assumed that wind speed is constant at the rated speed, so the system is operating at the rated capacity when the grid fault occurs. Obviously, this is due to the fact that wind speed does not change dramatically during the short time of the simulation.
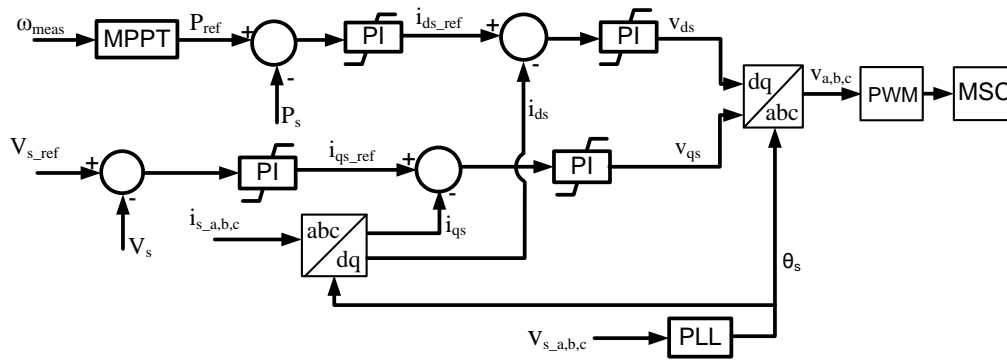
Figure 5. Generic Control of Machine Side Converter of PMSG

The behavior of a SCIG based wind farm under fault conditions has been studied using the configuration presented in Figure 1 by excluding PMSG wind farm. The wind farm consists of six SCIG wind turbines, each of 1.5 MW rated power, local load of 1 MW, and 150 KVAr capacitor bank connected to the terminal of each SCIG for reactive power compensation. A three phase fault was applied at the middle of the second transmission line and was cleared by removing the line. Two cases of fault durations, 0.15s and 0.2s, were simulated to investigate LVRT characteristic of the SCIG wind turbine system. The active power output, the rotor speed of SCIG, the voltage and the reactive power at PCC are given in Figure 6. This illustrates that during network fault, the terminal voltage reduces and the reactive power absorbed by the induction generator increases. From Figure 6(a) and Figure 6(b), when the fault duration increases from 150ms to 200ms, the reactive power consumption by SCIGs is higher and the voltage is depressed further. With a significant voltage drop at the generator terminals, the rotor continues to over-speed as illustrated in Figure 6(d). At this point, the network is unable to meet the wind farm reactive power requirement and then, the voltage fails to recover.

When a severe fault occurs, the SCIG wind turbine system is easily over speeded, results in increased reactive power absorption. This effectively prevents fast voltage recovery and may induce a stability problem for the power system. Therefore, to reserve the LVRT capability, external reactive power compensations would be installed alongside with the SCIG wind turbines.

**4.2. LVRT Characteristic of SCIG Coordinated PMSG Wind Farm**

The simulated system of closely connected SCIG and PMSG-based wind farm was configured as shown in Figure 1. The worst fault was assumed to occur at 5 s when the system is operating at the rated capacity. The circuit breakers (CB) on the faulted line were opened at 5.2 s.

Figure 7 shows the simulation results with both conventional control scheme and proposed control scheme. As observed in Figure 7(a) and 7(e), the grid voltage drops significantly because of high reactive power consumption by SCIGs. Without proposed control (dotted lines), the GSC has limited capability to inject reactive power into PCC for supporting the voltage and cannot provide necessary reactive power demanded by SCIGs whereas the PMSG control system attempts to raise the voltage by producing maximum available reactive power. As shown in Figure 7(f), SCIGs are over speeding and PCC voltage collapses when the conventional controller is applied. In contrast, with the proposed control, the GSC provides a

huge amount of available reactive power during the symmetrical fault as shown in Figure 7(b) and 7(c), leading the PCC voltage to its pre-fault level. Because the required reactive power of the induction generators is sufficiently provided by the PMSG-based wind farm, the electromagnetic torques of induction generators are restored quickly. Hence, fast achievement of torque balancing gives rise to the rotor speed of SCIG to become stable as shown in Figure 7(f).

The balance between P_{grid} and P_{gen} is lost easily during the fault period, causing an increase in the DC voltage, and the instantaneous difference in power is stored in the DC-link capacitor. To protect DC capacitor from over-voltage, a chopper has been employed to dissipate the excess stored active power. As can be seen in Figure 7(g), the DC-link voltage is limited and goes back to rated value quickly because of the employment of the chopper. Besides, the similar observations can be made in active power transfer illustrated in Figure 7(d).
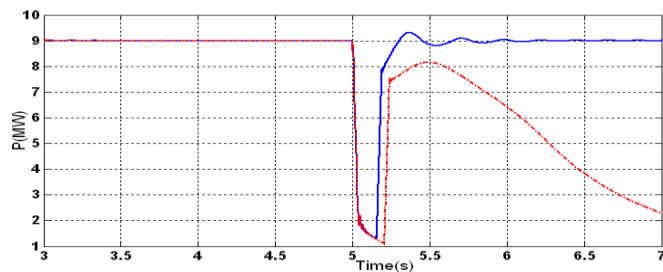
Simulation results shown in Figure 7 have proven that the quick and precise reactive power support provided by the PMSG wind turbines has led to a better re-magnetization of the induction generators, and thus participated in supporting LVRT characteristic of fixed speed SCIG wind turbines.
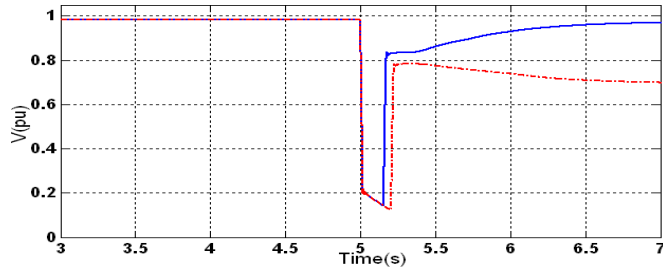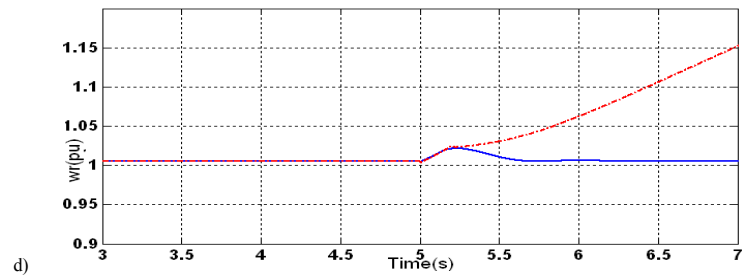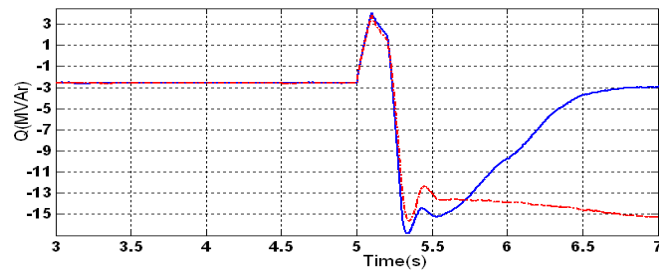

a) Voltage at PCC
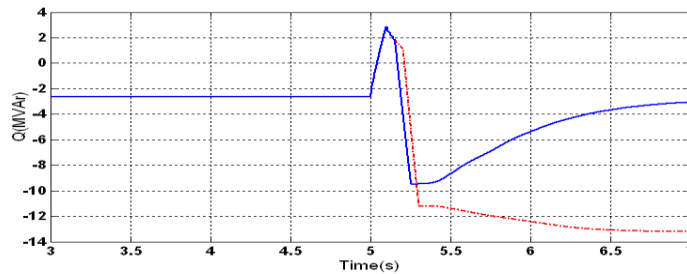
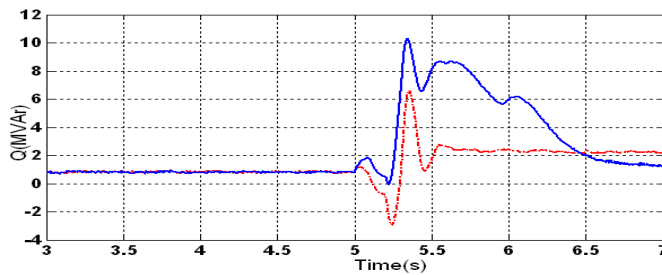**b) Reactive Power at PCC**

c) Active Power Output of SCIG
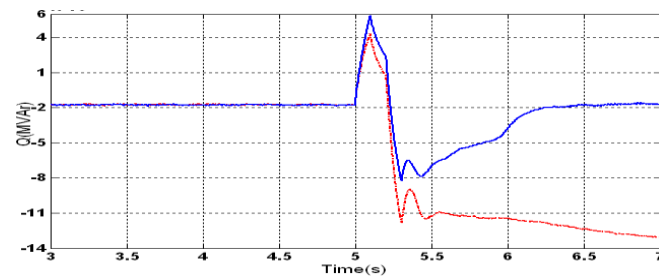
d) Rotor Speed

**Figure 6. LVRT Characteristic of SCIG-based Wind Farm
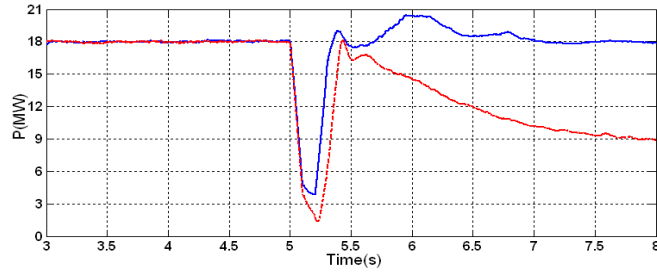(Solid line- fault Duration of 150ms & Dotted line -fault Duration of 200ms)**
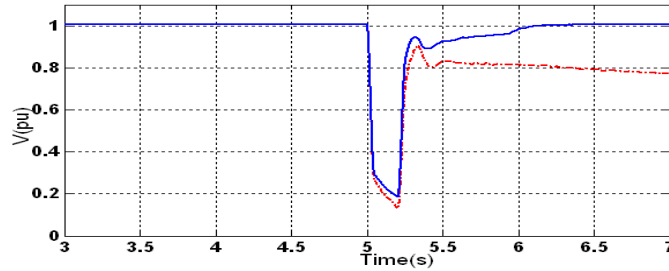

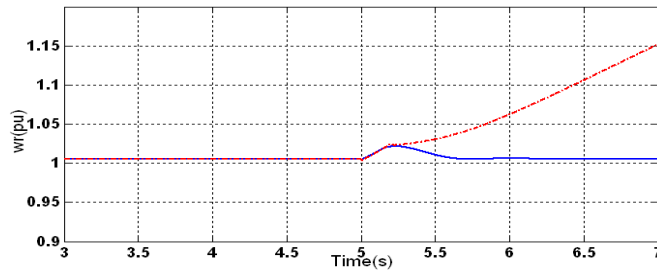**a) Reactive Power of SCIG at PCC**

b) Reactive Power of PMSG at PCC

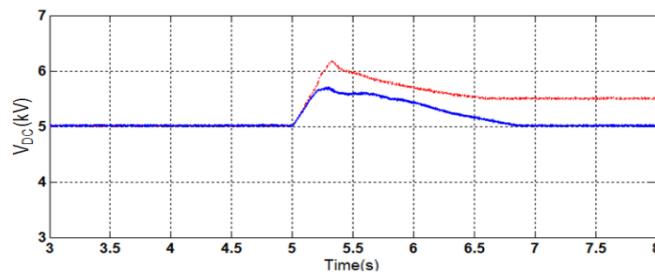
c) Total Reactive Power at PCC

d) Total Active Power at PCC

e) Voltage at PCC

f) Rotor Speed of SCIG

g) DC link Voltage

**Figure 7. LVRT Characteristic of SCIG Coordinated with PMSG Wind Farm
(Solid line- with Proposed Control & Dotted line- without Proposed Control)**

5. Conclusion

This paper proposed a control strategy for a PMSG-based wind turbine system located closely to the SCIG-based wind farm in order to improve LVRT characteristics of SCIG wind turbines by compensating the reactive power which is absorbed by the SCIG-based wind farm. This configuration might be cost-effective solution to enhance LVRT capability of the existing SCIG wind farm by taking the advantage of control flexibility of PMSG wind turbine system.

The reactive power control of the grid-side converter connected to the PMSG-based wind turbine system is investigated for a voltage control purpose. The proposed control system increased reactive power output of PMSG wind turbine during the voltage dip to compensate reactive power absorbed by the SCIG-based wind turbine.

The LVRT characteristics of the coordinated wind farms were analyzed in order to illustrate the positive influences of PMSG-based wind farm on SCIG-based wind farm stability. In addition, the effectiveness of the proposed control strategy to re-establish the voltage in case of grid fault has also been clearly observed. The simulation results have shown that the PMSG wind farm equipped with the proposed controller has provided the precise reactive power and voltage responses, which supports the SCIG-based wind farm to ride through the grid fault without any additional measures.

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