Abstract—This paper investigates the control scheme of the permanent magnet synchronous generator (PMSG)-based wind turbines to improve the power system damping. Based on the analysis of the operation characteristics and control scheme of the PMSG-based wind turbines, the relationship between the dc side voltage fluctuation of the full scale power converter and the active power regulation of the PMSG is discussed, and a novel control strategy based on the energy transmission is proposed, which ensures the wind turbine provide the power support quickly and smoothly, and then the system damping is also improved using the novel active and the reactive power additional control scheme of the PMSG-based wind turbines, respectively. Finally, a three-machine system with 30% wind power penetration was used to validate the proposed control strategy. The simulation results show that the PMSG-based wind turbines not only have the fault ride through ability but also have the fast respond ability to damp the power system oscillations using the presented control strategies, so that the damping characteristic of the power system is improved.

I. INTRODUCTION

As wind generation achieves higher penetration levels, and becomes a more and more substantial portion of our electric energy supply, building the grid friendly wind farms will be an important future development direction of the wind industry. Since more stringent requirements are being placed on the modern wind farms, the maximum wind energy capture, the fault through ability, participation in the network power regulation and support the system stability, etc, are also required by the grid friendly wind farms [1-3]. Therefore, the control potential of the variable speed constant frequency wind turbine integrated by the electric power converter must be further explored. On the other hand, the low frequency oscillation of the power system always threatens the safe operation of the network [4-5]. Nevertheless, the problem is even worse, especially in regional power grid with the high wind turbine integrated by the electric power converter must be further explored. On the other hand, the low frequency oscillation of the power system always threatens the safe operation of the network [4-5]. Nevertheless, the problem is even worse, especially in regional power grid with the high wind penetration are performed to demonstrate the feasibility of the proposed schemes.

II. MODEL AND CONTROL OF PMSG

The proposed control strategies of PMSG are developed from the conventional control. Therefore, the dynamic model and MPPT control of the PMSG control system are briefly summarized at first.

In the synchronous dq reference frame, the flux vector, voltage vector, power, and electrical torque of PMSG can be expressed as

\[
\begin{align*}
\psi_s &= (L_d I_s + j L_q I_q) + \psi_f \\
V_s &= R_s I_s + \frac{d\psi_s}{dt} + j \omega_s \psi_s \\
P_s + j Q_s &= \frac{3}{2} V_s I_s \\
T_e &= -\frac{3}{2} p_a \text{Im}[\psi_s I_s]
\end{align*}
\]

(1)

where \(\omega_s\) is the grid synchronous angular speed. \(V_s\) and \(I_s\) are the stator voltage and the stator current vectors respectively. \(\psi_s\) and \(\psi_f\) are the stator and rotor flux respectively. \(R_s\) is the stator resistance, and \(L_d\) and \(L_q\) are the d-axis and q-axis stator inductances respectively. \(P_s\) and \(Q_s\) are the stator output active and reactive power respectively. \(T_e\) is the electrical torque, and \(p_a\) is the number of PMSG’s pole pairs.

At present, the PMSG-based wind turbines have been widely used, due to their wider speed range, the stronger capability of the low voltage ride through (LVRT), and the potential to support the system. However, in resent researches, the study of the stability of the power system with large PMSG-based wind farms integration is only with respect to the LVRT. In [6], the crowbar circuit shunted at the dc side of the full scale power converter was applied to consume the redundant energy during the system voltage sag. In [7], a control scheme was proposed to let the grid side converter operate in the STATCOM mode and provide the reactive power to improve the fault through ability of PMSG. In this paper, the fault recovery characteristic of the PMSG-based wind turbines and the capability to damp the network power oscillations will be deeply investigated.

This paper presents a novel fault recovery control strategy for the PMSG-based wind turbines, based on the study of the reasons which cause the full scale power converter to be in the unbalance condition after the system fault. And then the effect of the rotor speed regulation and the reactive power control on the system damping is discussed, furthermore, the new control schemes which can improve the system damping are proposed using the active and the reactive power regulation, respectively. Finally, Simulation studies with 30% of the wind penetration are performed to demonstrate the feasibility of the proposed schemes.
where \( \omega_s \) is the grid synchronous angular speed, \( V_s \) and \( I_s \) are the stator voltage and the stator current vectors respectively. \( \Psi_s \) and \( \Psi_r \) are the stator and rotor flux respectively. \( R_s \) is the stator resistance, and \( L_d \) and \( L_q \) are the d-axis and q-axis stator inductances respectively. \( P_{\text{max}} \) and \( Q_s \) are the stator output active and reactive power respectively. \( T_e \) is the electrical torque, and \( p_n \) is the number of PMSG’s pole pairs.

It can be seen from (2) that the decoupled control of the electromagnetic power/torque and the stator reactive power can be achieved by regulating the d- and q-axis rotor currents respectively.

Fig. 1 shows the overall vector control scheme of the rotor side converter (RSC). The outer-loop control regulates the electromagnetic power and reactive power independently and generates the reference signals \( I_{d}^* \) and \( I_{q}^* \) for the inner-loop current regulation.

In the synchronous dq reference frame, voltage vector, dc side voltage and power of the grid side converter (GSC) can be expressed as

\[
\begin{align*}
V_g &= R_{\text{dc}} I_g + j \omega_c L_s I_g + L_c \frac{dI_g}{dt} + V_s \\
C \frac{dV_{\text{dc}}}{dt} &= \frac{P_0}{V_{\text{dc}}} - \frac{P_g}{V_{\text{dc}}} \\
P_g + j Q_s &= \frac{3}{2} V_g I_g^*
\end{align*}
\]

Using grid voltage oriented control, ignoring resistance \( R_c \) and the transient state of the inductance \( L_c \), the electrical torque, total output active power and stator reactive power can be given by

\[
\begin{align*}
P_g &= \frac{3}{2} V_g I_g^* \\
Q_s &= \frac{3}{2} V_r I_q^*
\end{align*}
\]

Fig. 1 Outer loop power control diagram of the generator side converter

Fig. 2 Maximum wind power point tracking curve

As illustrated in Fig.1, the reference signal of the electromagnetic power \( P_{\text{opt}}^* \) is determined by the MPPT curve, which is shown in Fig.2. According to Fig.2, the reference value of the electromagnetic power can be expressed as

\[
P_{\text{opt}}^* = \begin{cases} 
k_{\text{opt}} \alpha^3 & (\alpha \leq \alpha_t) \\
(P_{\text{max}} - k_{\text{opt}} \alpha^3) + P_{\text{max}} (\alpha - \alpha_{\text{max}}) & (\alpha_t < \alpha < \alpha_{\text{max}}) \\
P_{\text{max}} & (\alpha > \alpha_{\text{max}}) 
\end{cases}
\]

where \( k_{\text{opt}} \) is the coefficient of the curve \( P_{\text{opt}}^* \), \( \alpha_t \) is the cut-in angular speed, \( \omega_1 \) is the initial angular speed in the speed constant stage, \( \omega_{\text{max}} \) is the maximum angular speed, \( P_{\text{max}} \) is the maximum active power output of the PMSG.

Under the above control strategies, the power system oscillations can be isolated using the full scale power converter. Nevertheless, overvoltage, overcurrent, damping ability, etc. problems caused by the power system oscillations and the grid voltage dip of the converters is still not reasonably solved. So the PMSG cannot contribute to system stability in case of system power oscillations. In order to emulate the dynamic damping response as synchronous generators equipped with the power system stabilizer (PSS) using PMSG, an improved control scheme by introducing the dc side voltage deviation needs to be investigated, which ensures the wind turbines provide the power support quickly and smoothly.

III. FAULT RECOVERY CONTROL OF THE PMSG-BASED WIND TURBINE

A. Control principle

Since the PMSG-based wind turbine is operated at the normal mode, the grid side converter regulates the dc side voltage. In order to maintain a constant dc voltage, the active
power output from the PMSG must match the fluctuant power transmitted by the grid side converter during fault. In other words, the active power output generated by the PMSG should be adjusted immediately after system fault.

For the dc side capacitor, the charging and discharging power during the fault is given as

$$\Delta P_{dc} = CV_{dc} \frac{dV_{dc}}{dt}$$  \hspace{1cm} (6)

During the system fault, if $\Delta P_e$ generated by the PMSG is injected into the dc side capacitor by detecting abnormal dc side voltage, and satisfied with $\Delta P_e=\Delta P_{dc}$, the dc side voltage fluctuation will be weakened.

For the PMSG, $\Delta P_e$ is the imbalance active power that results in the rotor swing. The kinetic energy change during the period $T_k$ is given as

$$\Delta E_k = \int_{t_k}^{t_k+T_k} \Delta P_e dt = \frac{J_p}{p_n} \left[ \omega_0^2 - \omega_1^2 \right]$$  \hspace{1cm} (7)

where $\Delta P_e = \frac{J_p}{p_n} \frac{d\omega}{dt}$, and $\omega$ is the rotor angular speed, $\omega_0$, $\omega_1$ are the rotor angular speed at the beginning and the end of $T_k$, $J_p$ is the actual inertia of the PMSG.

From (7), the kinetic energy change $\Delta E_k$ and the rotor speed $\omega_1$ can be obtained as

$$\Delta E_k = J_p (\omega_0^2 - \omega_1^2) / 2 p_n^2$$

$$\omega_1 = \sqrt{\omega_0^2 + 2 p_n^2 \Delta E_k / J_p}$$  \hspace{1cm} (8)

For the dc side, the energy change during the fault is stored in the capacitor can be expressed as

$$\Delta E_{dc} = \int_{t_k}^{t_k+T_k} \Delta P_{dc} dt = \frac{1}{2} C (V_{dc}^2 - V_{dc,N}^2)$$  \hspace{1cm} (9)

where $V_{dc,N}$ is the rated dc side voltage.

Thus, for the PMSG, the rotor speed modulation can be regulated shown in (5) as

$$\omega_1 = \sqrt{\omega_0^2 + 2 p_n^2 \Delta E_{dc,PMSG} / J_p}$$  \hspace{1cm} (10)

where $J_p$ is the virtual inertia of the PMSG. For a PMSG, $J_p$ is purely a control parameter and can be chosen based on the requirement of satisfactory system control and protection equipment. And the regulation range of the rotor speed can be adjusted by changing the value of $J_p$.

Assuming that the wind velocity and the mechanical power of the PMSG remain constant, the relationship between the active power reference at point A and that at point B can be expressed as

$$k_{opt, dc} \omega_1 = k_{opt} \omega_0$$  \hspace{1cm} (11)

Substituting (10) into (11), the fault recovery control curve coefficient $k_{opt, dc}$ can be calculated as

$$k_{opt, dc} = \frac{\omega_0}{\left( \omega_0^2 + (V_{dc}^2 - V_{dc,N}^2) / J_{vir} \right)^{1/2} k_{opt}}$$  \hspace{1cm} (12)

Therefore, the fault recovery control curve coefficient $k_{opt, dc}$ is the function of the dc side voltage deviation. The fault recovery control curves can be achieved by replacing $k_{opt}$ with $k_{opt, dc}$ in (3).

Fig. 4 shows the MPPT curve and the schematic diagram of the control method for the PMSG during the fault. In the normal operation mode, the active power reference value of the PMSG is obtained from the maximum power point tracking (MPPT) curve according to the measured rotor speed, and MPPT curve ($P_{opt}$) can be calculated in different operation stages given in (3).

The principle of the control scheme is to coordinate the unbalanced power of the full scale power converter, using the electric power of PMSG during the fault, and the regulation of the active power from the PMSG upon the detection of the abnormal dc voltage. As illustrated in Fig.4, while the wind velocity is 9m/s, the PMSG operates at point A under the MPPT control initially. Once the abnormal dc voltage is decreased, PMSG is switched from the MPPT control to the fault recovery control and the power tracking curve is shifted from the MPPT curve $P_{opt}$ to the fault recovery control curves immediately. The operating point of PMSG is thus moved from A to B where the corresponding rotor speed is $\omega_1$. And the kinetic energy according to the stored energy change of capacitor will be released with the decrease of the rotor speed.

In the meantime, the dc side voltage can be reasonable regulated during the fault. And the process of the dc voltage increase can be analyzed using a similar way as for the operating point following A→C shown in Fig.1.

After the dc side voltage dynamic response period, the dc voltage deviation will gradually reduce to zero. According to (12), the power reference curve will recover to MPPT curve, and the operating point is moved back from B to A. Thus the rotor speed of the PMSG recovers to the optimal value after the dynamic process.

B. Controller design

The fault recovery control diagram of the PMSG is illustrated in Fig. 5. According to the dc side voltage error, the rotor speed feedback signal is given to adjust the active power output. When the grid side converter restores the control ability to stabilize the dc voltage, the rotor speed of the PMSG recovers to the optimal value. The washed out loop is adopted to avoid the controller being activated during normal operation.
IV. POWER OSCILLATION DAMPING CONTROL OF THE PMSG-BASED WIND TURBINE

As a PMSG is connected to the grid through a full scale power converter, which provides a variable stator frequency according to the actual rotor speed, there is any relative movement between the stator and the rotor field, which could induce a voltage in the damper winding. Furthermore, due to the permanent excitation, the PMSG has no field windings, in which transient currents could be induced or damped, respectively. Hence, in case of transient the PMSG-based wind turbines do not contribute to the system damping. Nevertheless, the damping power injected to the grid could be generated from the PMSG-based wind turbines by means of the independent control of the active and the reactive power.

A. Active power damping control

1. Control principle

Keeping stability and reliability of the PMSG during the system fault is the precondition for the active damping control, and therefore the damping controller should be activated after the fault recovery control.

Reference [8-11] indicated that the system damping could be improved by injecting the damping power generated from an external active power source. If the damping power changes with the rotor speed deviation, the system power oscillation could be damped, and the period of the fault recovery will be shorter. This can be explained by a simple two-order linearized swing equation with the equivalent rotor angle \( \delta \) as the state variable and also by considering the damping of the system. If the mechanical power is assumed to be constant compared with the electric power, then the linearized electric power \( \Delta P_{\text{sys}} \) can be expressed as

\[
\Delta P_{\text{sys}} = K \Delta \delta + D \frac{d\Delta \delta}{dt} 
\]

(13)

where \( D \) is the damping coefficient and \( K \) is the synchronizing torque coefficient. Then, the linearized swing equation can be written as

\[
H_{\text{sys}} \frac{d^2 \Delta \delta}{dt^2} + D \frac{d\Delta \delta}{dt} + K \Delta \delta = 0 
\]

(14)

where \( H_{\text{sys}} \) is the system inertia constant.

It can be reasoned that with injecting an additional electric power changing with the differential of rotor angle \( \delta \), the system damping can be improved. Hence, it is found that with an active power damping control loop of PMSG, the system could have a stronger damping characteristic.

According to the rotor speed change signal \( \Delta \omega_r \) of the conventional synchronous generator, the rotor speed change of the PMSG can be given as

\[
\Delta \omega_r = -k_p \frac{d\Delta \delta}{dt} = -k_p \cdot \Delta \omega_r 
\]

(15)

where \( k_p \) is the active damping control parameter.

Since the PMSG-based wind turbine is operated under normal condition, small disturbance equation of (6) and \( \Delta \omega_r \) can be expressed as

\[
\begin{align*}
\Delta \omega &= \left( -\frac{m_k}{J_{\omega}} \right) \delta \omega_r^2 \cdot \Delta \omega_r \quad (\omega_r < \omega_r^*) \\
\Delta \omega &= \left( \frac{P_{\text{max}}}{\omega_r^*} - k_p \omega_r^2 \right) \delta \omega_r^2 \cdot \Delta \omega_r \quad (\omega_r < \omega_r^*_{\text{max}}) \\
\Delta \omega &= 0 \quad (\omega_r > \omega_r^*_{\text{max}})
\end{align*}
\]

(16)

As previously discussed, the conclusion that can be drawn from (16) is that the damping power \( \Delta P_g \) contains the rotor speed change signal \( \Delta \omega_r \) and then the PMSG-base wind turbines are able to damp the system power oscillation in the MPPT and the constant speed range.

2. Controller design

The active power damping control diagram of the PMSG is illustrated in Fig. 6. According to network frequency error signal \( \Delta f \), the new rotor speed feedback signal is sent to the MPPT controller. The frequency error is processed through a washed out function to eliminate its steady-state DC component. The lead-lag damping regulators are applied to provide a phase shift on the interested frequency range. When the grid restores the normal operation, the rotor speed of the PMSG recovers to the optimal value.

A. Reactive power damping control

1. Control principle

The study of the network reactive power equipment [12-14] shows that the system damping could be improved through dynamic controlling of the reactive power to make the grid voltage change vary directly as the \( \Delta \omega_r \), but the quality of the grid voltage will be deteriorated.

The grid side converter connected wind turbines to the grid could also be operated as a reactive power source. Since the impact of the reactive power damping control on the stability of the PMSG is limited under the fault recovery control, the reactive power damping controller could be activated immediately after fault. If the reactive power output of the network reactive power equipment causes the grid voltage variation amplitude is

\[
\Delta V_g = -k_q \cdot \Delta \omega_r 
\]

(17)

where \( k_q \) is the reactive power control parameter. It was pointed out in [12-13] that the system damping can be improved.

2. Controller design

The reactive power damping control diagram of the PMSG is illustrated in Fig. 7. According to the signal \( \Delta f \), the voltage reference value is added to the normal PMSG reactive power.
controller in order to provide an extra reactive power during fault conditions. The washed out loop is adopted to avoid the controller being activated during normal operation. And the lead-lag damping regulators are applied to provide a phase shift on the interested frequency range. As previously discussed, the reactive power generated from the grid side converter will make the grid voltage change vary directly as the $\Delta \omega$.

$$\Delta \omega = \frac{1}{2} \frac{P}{Q}$$

Fig.7 Reactive power damping additional control diagram

V. SIMULATION STUDIES

Simulations have been carried out to illustrate the ability of the PMSG to damp the synchronous generator G1 is damped, and thus the system damping is improved. Fig. 9 (b) , (c) and (d) show that under the fault conditions. The washed out loop is adopted to avoid the controller being activated during the frequency fluctuation caused by the short circuit fault.

When the dc voltage recovers in the normal range, the fault recovery controller is disused, and then the active power damping control is activated. It can be seen clearly from Fig.9(e) that with the injecting damping power of the PMSG, the power oscillation of the synchronous generator G1 is damped, and thus the system damping is improved.

B Reactive power damping control

The proposed reactive power damping controller is activated immediately during the frequency fluctuation caused by the short circuit fault.

(a) Output active power of G1

(b) Output active power of the PMSG

(c) Active power of the GSC

(d) Rotor speed of the PMSG

(e) Output active power of G1

Fig. 9 Comparisons of the network dynamic response with the active power control
Based on the operation mode of PMSG, the reserve attenuated power oscillation of the synchronous generator G1 is activated earlier, the deteriorated to a small extent, as shown in Fig. 10(b). As the reactive power damping controller is activated, the attenuated power oscillation of the synchronous generator G1 is faster suppressed.

### Active and reactive power damping control

Based on the operation mode of PMSG, the reserve capacity of the wind turbines can be fully utilized with the active and reactive power damping control.

Fig. 11 Comparisons of the active output power of G1 with the active and the reactive power control

As illustrated in Fig.11, when the active and the reactive power damping controller are both activated, the system damping is further increased, and the damping effect is better. Hence, it can be reasoned that with the active and reactive power damping control loop of PMSG, the system damping will be stronger.

### VI. CONCLUSION

This paper investigates the fault recovery control and the power oscillation damping control of the PMSG-based wind turbines after system fault. The main conclusions drawn from the results in this paper are as follows:

1) The dc side voltage variation and the power regulation of the PMSG are indirectly associated through the interconversion between the charging and discharging energy of the capacitor and the rotor kinetic energy. Under the fault recovery control, it is evident that the unbalanced power of the full scale power converter is reduced, the PMSG-based wind turbines operation is smooth and satisfactory during the fault conditions, and the function of the fault recovery controller is fully achieved.

2) The damping power can be generated by controlling the active power of the PMSG when the wind turbine goes back to the normal operation. But the slight fluctuation of the dc side voltage is also caused during control.

3) The reactive power damping control has little effect on the fault recovery of the PMSG. So it can be activated immediately to damp the system power oscillations after the system fault.

4) The reserve capacity of the PMSG-based wind turbines can fully be utilized under the damping control of both the active and the reactive power. Thus, the system damping characteristic is further improved.

### REFERENCES


