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Control of a PMSG based wind energy generation system for power maximization and grid fault conditions

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Abstract

The study of a Wind Energy Conversion System (WECS) based on Permanent Magnet Synchronous Generator and interconnected to the electric network is described. The effectiveness of the WECS can be greatly improved, under Grid Fault, by using an appropriate control. So, the control strategy combines Maximum Power Point Tracking (MPPT) and a pitch control scheme to maximize the generated power. Consequently, WECS can not only capture the maximum wind energy, however it can also maintain the frequency and amplitude of the output voltage. Simulation results have shown the effectiveness of the proposed control strategy for WECS based on the PMSG.

Keywords: WECS; PMSG; MPPT; Vector Control; Variable-speed control; Grid fault.

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1. Introduction

Over the last years, with technological advancement, wind power has grown rapidly and becomes the most competitive form of renewable energy [1-2]. Furthermore, Variable Speed Wind Energy Conversion Systems (VS-WECS) are the dominant technologies in the present wind power industry for the reason that they possess several advantages, over the fixed velocity systems, as the ability to obtain Maximum Power Point Tracking (MPPT) control methodology in order to extract maximum power at different wind, higher overall efficiency, power quality and it can be controlled to reduce aerodynamic noise and mechanical stress on VS-WECS by absorbing the wind-power fluctuations [3-5]. On the other hand, with the increased penetration of VS-WECS into power systems all over the world, Wind Turbines Generators (WTGs) based on Permanent Magnet Synchronous Generators (PMSG) are becoming popular for

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variable-speed generation system and the use of the PMSG in large WTGs is growing rapidly. It is connected directly to the turbine without gearbox and so it can operate at low speeds [5-8]. Moreover, it can reduce again weight, losses, costs, demands maintenance requirements and, with the advance of power electronic technology, the wind farms are at present required to participate actively in electric network operation by appropriate generation control strategies. In the literature, different controlling types of VS-WECS can be seen [5-10]. They use power electronics in combination with aerodynamic controls to regulate power, speed and torque. In addition, the development in power electronic devices has further played an important role in the perfection of their controllability and reliability. Also, in the operation of the WTG, there is constantly the possibility of the faults for the system. One of the ordinary faults is short circuit. Consequently, due to the increased number of VS-WECS connected to the grid, instability of these systems and of the grid itself can occur.

In this context, this paper proposes a control strategy of PMSG wind energy generation system, and discusses back-to-back PWM converter control method. The WECS model includes a Wind Turbine (WT), a PMSG, PWM rectifier in generator-side, intermediate DC circuit and PWM inverter in grid-side. The function of the grid-side converter is to maintain the DC-link voltage constant and to control the reactive and active power on the grid independently whereas the generator-side rectifier is used to track the maximum wind power. The proposed approach is based on a Vector Control theory (VC) for regulate of both grid-side and machine converter. So, the proposed control law combines Space Vector Modulation (SVM) and Maximum Power Point Tracking (MPPT) control strategy to maximize the generated power under varying wind speed and the grid fault condition. The aim of the control is to maximize the extracted power with the lowest possible impact in the utility network frequency and voltage for fault conditions as well as for normal working conditions. Besides, a pitch control scheme for variable speed WTG is proposed in order to prevent WT damage from excessive wind speed.

The remainder of this paper is organized as follows. In Sections 2, the models of the WTG and PMSG are developed. In Section 3, Vector Control (VC) of the system will be presented. The simulations results are presented and analyzed in Section 4. Finally, some conclusions are given in Section 5.

2. System modeling

2.1. Wind turbine characteristic

A Wind Turbine (WT) can not fully capture wind energy. Then, the output power of the wind-turbine is described as [2]:

$$P_{Turbine} = \frac{1}{2}\rho\pi R^2 C_P(\lambda,\beta)v^3 \tag{1}$$

where, ρ is the air density ($\mathrm{kg/m^3}$), R is the blade radius (m), C_P is the performance coefficient of the turbine which is a function of the pitch angle of rotor blades β (in degrees) and v is the wind speed (in m/s). The tip-speed ratio λ is given by:

$$\lambda = \frac{\omega_m R}{v} \tag{2}$$

where R and ω_m are the blade length (in m) and the wind turbine rotor speed (in rad/sec), respectively. The wind turbine mechanical torque output T_m given as:

$$T_m = \frac{1}{2}\rho A C_P(\lambda,\beta)v^3\frac{1}{\omega_m} \tag{3}$$

A generic equation is used to model the coefficient of power conversion $C_P(\lambda,\beta)$ based on the modelling turbine characteristics described in [10] as:

$$\begin{aligned} C_P &= \frac{1}{2}\left(\frac{116}{\lambda_i} - 0.4\beta - 5\right)e^{-\left(\frac{21}{\lambda_i}\right)} \\ \frac{1}{\lambda_i} &= \frac{1}{\lambda + 0.08\beta} - \frac{0.035}{\beta^3 + 1} \end{aligned} \tag{4}$$

The coefficient of power conversion and the power are maximums at a certain value of tip speed ratio called optimum tip speed ratio λ_{opt}. Therefore, the maximum value of $C_P(\lambda,\beta)$, that is $C_{P_{\max}} = 0.41$, is achieved for $\lambda_{opt} = 8.1$ and for $\beta = 0^\circ$. Besides, any change in the wind velocity or the generator speed induces change in the tip speed ratio leading to power coefficient variation. Consequently, the extracted power is affected. This power is maximized at the particular rotational speed for various wind and it is obligatory to keep the PMSG speed at an optimum value of the tip speed ratio, λ_{opt}. Accordingly, the system can operate at the peak of the $P(\omega_m)$ curve when the wind speed changes and the maximum power is extracted continuously from the wind (MPPT control) [1]. That is shown in Fig.1

2.2. PMSG modeling

The mathematical model of a PMSG is usually defined in the rotating reference frame *d*-*q* as follows [2]:

$$v_{gq} = \left(R_g + p.L_q\right).i_q + \omega_e L_d i_d + \omega_e \psi_f \tag{5}$$

$$v_{gd} = \left(R_g + pL_d\right)i_d - \omega_e L_q i_q \tag{6}$$

where v_{gd} and v_{gq} are the direct stator and quadrature stator voltage, respectively. i_d and i_q are the direct stator and quadrature stator current, respectively. R_g is the stator resistance, L_q and L_d are the

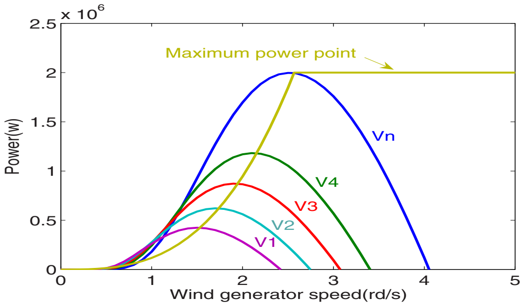

Fig.1. Wind generator power curves at various wind speed

inductances of the generator on the q and d axis, ψ_f is the permanent magnetic flux and ω_e is the electrical rotating speed of the generator, defined by:

$$\omega_e = p_n \omega_m \tag{7}$$

where p_n is the number of pole pairs of the generator and ω_m is the mechanical angular speed. The electromagnetic torque can be described as:

$$T_e = \frac{3}{2} p_n \left[\psi_f i_q - \left(L_d - L_q \right) i_d i_q \right] \tag{8}$$

If $i_d = 0$, the electromagnetic torque is expressed as:

$$T_e = \frac{3}{2} p_n \psi_f i_q \tag{9}$$

The dynamic equation of the wind turbine is described by:

$$J \frac{d\omega_m}{dt} = T_e - T_m - F\omega_m \tag{10}$$

where J is the moment of inertia , F is the viscous friction coefficient and T_m is the mechanical torque developed by the wind turbine .

3. Control strategy of the VS-WECS

3.1. Maximum Power Point Tracking (MPPT) and Pitch Control

The objective of MPPT controller is to generate the reference velocity command which will enable the VS-WECS to extract maximum power at different wind speeds. For this reason, when the wind speed changes, the velocity of WTG is controlled to follow the maximum power point trajectory and, the optimum rotational speed of the PMSG can be simply estimated as follows [5]:

$$\omega_{m-opt} = \frac{v\lambda_{opt}}{R} \tag{11}$$

The maximum extracted power of the WTG is given as :

$$P_{Turbine\_\max} = \frac{1}{2} \rho A C_{P\max} \left(\frac{R\omega_{m-opt}}{\lambda_{opt}} \right)^3 \tag{12}$$

As a result, the MPPT controller computes the optimum velocity of WTG : ω_{m-opt} and by regulating the generator speed in different wind velocities, the maximum power $P_{Turbine\_\max}$ is extracted. Besides, if the wind speed reached the nominal value of WT, the system of Pitch Angle controller enters in operation to prevent WT damage from excessive wind speed. Thus, by reducing the coefficient C_p, both the power and rotor speed are maintained for above rated wind speeds. Moreover, the blade pitch angle β, will increase until the PMSG is at the rated speed. The implemented pitch angle system is shown in Fig. 2 where P_g is the generated power.

3.2. Control of the PMSG side rectifier with MPPT and Vector Control

The generator-side rectifier is used to regulate the velocity of WTG, which enables optimal speed tracking for the optimal power capture from any particular wind speed. The proposed MPPT controller generates ω_{m-opt}, the reference speed of the generator, which when applied to the velocity control loop of the PMSG side converter control system, maximum power will be produced by the VS-WECS. For this reason, Vector Control (VC) is adopted and the control scheme shown in Fig.3 is used as the control strategy for the generator side rectifier with double closed loop regulate. So, in the inside loop, the current controllers are used to regulate q-axis and d-axis stator current to follow the command, whereas a velocity controller is used in the outside loop to regulate the WTG speed in order to follow the command value ω_{m-opt}, and produces corresponding q-axis current command i_{qr}. Furthermore, u_{sq} is obtained by the error of i_{qr} and i_q where i_{qr} is the reference current, and this error is delivered to a PI controller. So as to reduce the copper loss, the d-axis current component i_{dr} is set to zero. Also, voltage feed forward compensations, Δu_{sq} and Δu_{sd} are added into the control strategy to improve the dynamic response. Finally, we use PWM to produce the control signal to implement the vector control for the generator.

3.3. Grid-side controller strategy

The objectives of grid-side inverter are to deliver the energy from the PMSG side to the electric network, to regulate the DC-link voltage and to achieve unity power factor [2]. For this reason, Direct Power Control (DPC) is adopted to control instantaneous values of reactive power and active power of network connection, respectively. Moreover, the input reactive power and active power are decoupling controlled in d-q synchronous reference frame. Accordingly, the PI control loops are used [11]. The controller is depicted in Fig. 3. So, in the inner control loops, active and reactive powers are controlled respectively, although the outer control loop is used for the DC voltage controller. Besides, compensation terms are added as shown in Fig. 3, to compensate the cross-coupling effect due to the output filter in the synchronous rotating reference frame.

If the grid voltage space vector $\vec{u}$ is oriented on d-axis:

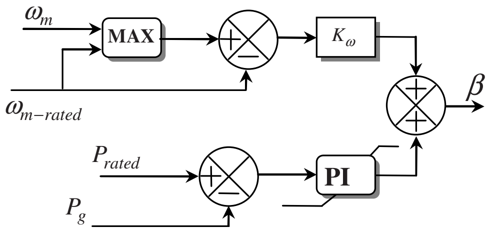

Fig.2. VS-WECS Pitch angle controller.

$$\begin{aligned} v_d &= V \\ v_q &= 0 \end{aligned} \tag{13}$$

where v_d and v_q are the grid voltage components in the d-axis q-axis voltage components, respectively . In the rotating dq reference frame, the voltage balance across the inductor L_f is given by [2]:

$$L_f \frac{di_{d-f}}{dt} = e_d - R_f i_{d-f} + \omega L_f i_{q-f} - V \tag{14}$$

$$L_f \frac{di_{q-f}}{dt} = e_q - R_f i_{q-f} - \omega L_f i_{d-f} \tag{15}$$

where L_f and R_f are the filter inductance and resistance respectively, e_d and e_q are the inverter d-axis q-axis voltage components, respectively.

$$C\frac{dU_{dc}}{dt} = \frac{3}{2}\left(\frac{v_d}{U_{dc}} i_{d-f} + \frac{v_q}{U_{dc}} i_{q-f}\right) - i_{dc} \tag{16}$$

where U_{dc} is the dc-bus voltage, i_{dc} is the grid side transmission line current, i_{d-f} and i_{q-f} are the d-axis current and q- axis current of electric network. Hence, the active power and reactive power can be expressed as:

$$P = \frac{3}{2} V i_{d-f} \tag{17}$$

$$Q = \frac{3}{2} V i_{q-f} \tag{18}$$

Therefore, according to the equation (14), (15), (17) and (18), Q and P are defined as the control variables, and the power control model can be expressed:

$$\frac{3}{2} V e_d = R_f P + L_f \frac{dP}{dt} - \omega L_f Q + \frac{3}{2} V^2 \tag{19}$$

$$\frac{3}{2} V e_q = R_f Q + L_f \frac{dQ}{dt} + \omega L_f P \tag{20}$$

Consequently, to provide decoupled control of active power and reactive power, the output power from the grid side converter, in the synchronous reference frame, could be formulated as:

$$\frac{3}{2} V e_d = P_0 - \omega L_f Q + \frac{3}{2} V^2 \tag{21}$$

$$\frac{3}{2} V e_q = Q_0 + \omega L_f P \tag{22}$$

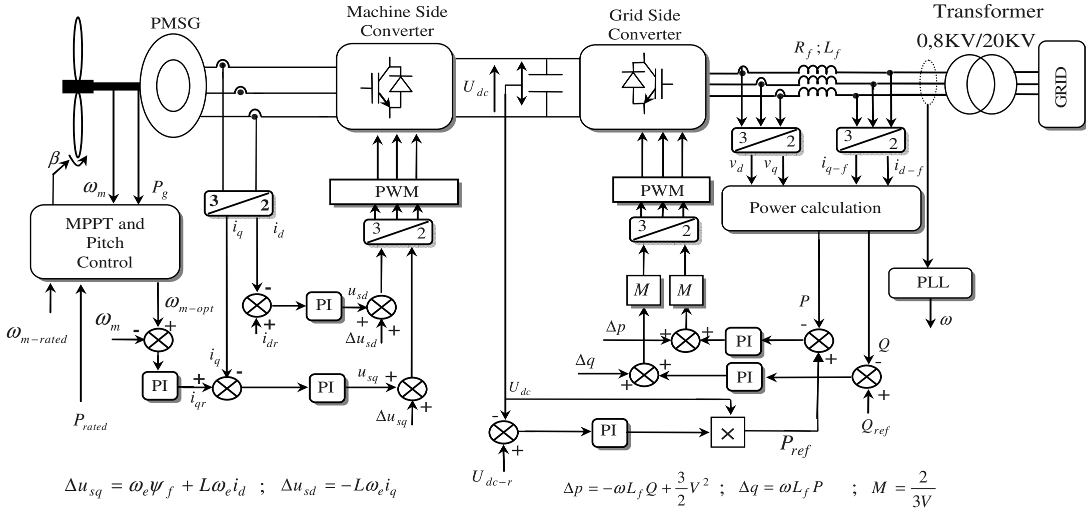

Fig. 3. Schematic of control strategy for VS-WECS based on the PMSG.

Substitute (19) and (20) into (21) and (22), then:

$$R_f P + L_f \frac{dP}{dt} = P_0 \tag{23}$$

$$R_f Q + L_f \frac{dQ}{dt} = Q_0 \tag{24}$$

As a result, Q_0 and P_0 can be completed all the way through defining the power feedback loops as follows:

$$Q_0 = K_P(Q_{ref} - Q) + K_I \int (Q_{ref} - Q)dt \tag{25}$$

$$P_0 = K_P(P_{ref} - P) + K_I \int (P_{ref} - P)dt \tag{26}$$

Where Q_{ref} and P_{ref} are respectively rated active power and rated reactive power. P_{ref} is used to maintain a constant output voltage and Q_{ref} is determined by the power factor. We use the voltage regulator with PI control. So, rated active power P_{ref} can be expressed as [11]:

$$P_{ref} = U_{dc}(\dot{k}_p(U_{dc-r} - U_{dc}) + \dot{k}_I(\int (U_{dc-r} - U_{dc})dt)) \tag{27}$$

Fig. 3 illustrates the control block diagram of grid-side PWM inverter based on the above strategy. There are two closed-loops controls and PWM is used to produce the control signal in order to control the grid-side converter.

4. Simulation results

The complete VS-WECS with PMSG was simulated by Matlab/Simulink using the parameters given in Table 1. During the simulation, for the grid side inverter, Q_{ref} , is set to zero. The topology of the studied VS-WECS based on PMSG connected distribution network is depicted in Fig. 4. The grid voltage phase lock loop (PLL) is implemented. Fig.5 illustrates the profile of wind velocity and rated wind speed considered in the simulation (v_n =12.4 m/s). Fig. 6 to Fig. 9 show the simulation results of pitch angle, coefficient of power conversion C_p , power generated and rotor angular velocity for generator. It can be seen that, if the wind speed increases, then rotor angular velocity of PMSG increases proportionally too, with a limitation. This speed limit will be obtained by the pitch angle variations. When the VS-WECS operates under MPPT control, the performance coefficient C_p is maintained to its maximum value ($C_{P\max} = 0.41$) and the pitch angle is $\beta = 0^\circ$. But, if the wind speed reaches the rated wind velocity of the turbine (v_n =12.4 m/s), C_p is decreasing because the operation of the pitch angle control is actuated and β increases. So, rotational speed and power generated are keeping constants. As a result, the limitation of the power captured and of the turbine velocity is carried out using the pitch control. Fig. 9 illustrates the waveforms of the optimum speed and the speed of PMSG. It is seen that the speed follows the optimum speed quite well. Fig.10 shows the simulation result of DC link voltage that remains a constant value. Therefore, this proves the effectiveness of the established regulators. Fig.11 illustrates the waveform of RMS lines ground voltages at Bus 5 during the grid fault period. Fig.12 and Fig.13 show the variation and a closer observation of three phase voltage and current of three phase voltage at Bus 5. The fault event is a three-phase to ground short-circuit fault, at the Bus 1 of the 1 MW loads, and it is introduced at t = 4s for 150 ms. As illustrated in Fig. 11 and Fig.12, a three-phase grid short circuit fault at 4 s forces the grid voltage to drop from 100% to 4% of its nominal values and the voltage dip lasts for 150ms as it is shown in Fig.12. After faults removed, the grid voltage recovers and the three voltages take their initial values. It is obvious from Fig. 10 that the DC link voltage remains a constant value and the three phase voltage variations will not be transferred to the DC link voltage. So, the DC link voltage has been controlled to enhance dynamic performance of the VS-WECS. Besides, the power is generated with the lowest possible impact in the utility network frequency and voltage for fault conditions as well as for normal working conditions.

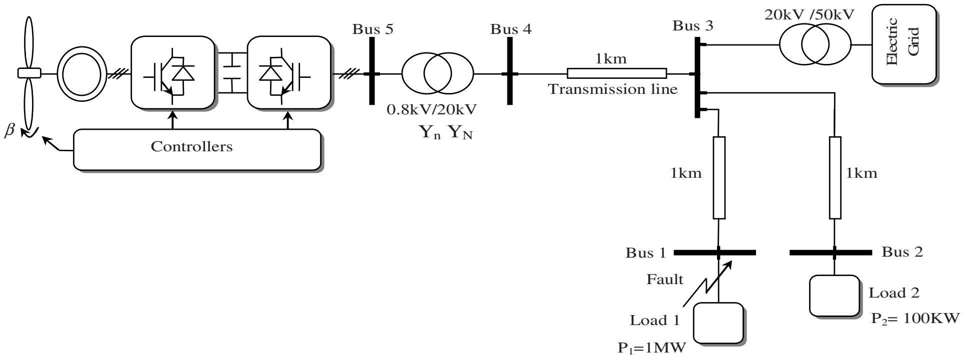

Fig. 4. Configuration of the system.

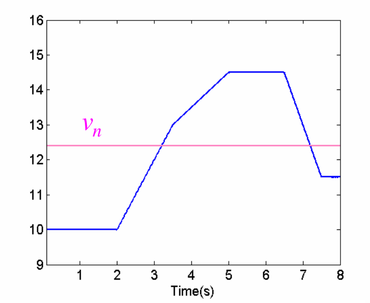

Fig. 5. Instantaneous wind speed (m/s).

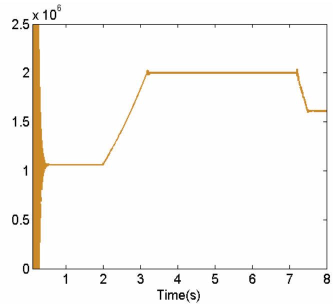

Fig. 8. Generated power (W).

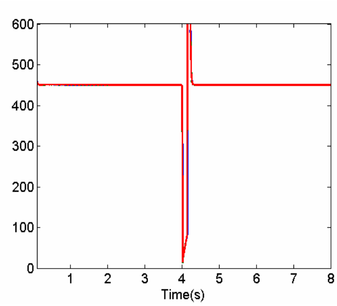

Fig. 11. RMS lines ground voltages at Bus 5 (V)

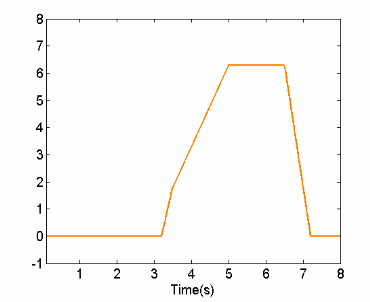

Fig. 6. Pitch angles β (in degree).

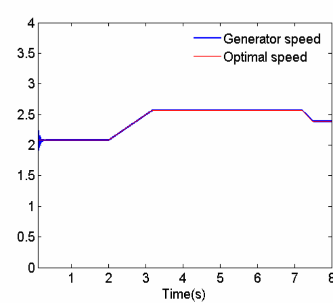

Fig. 9. Speed of PMSG (rd/s).

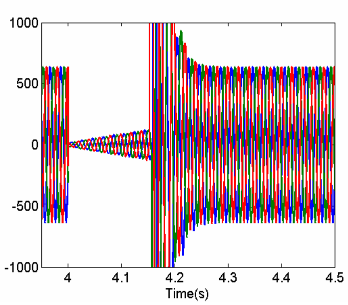

Fig. 12. Three phase voltage at Bus 5.

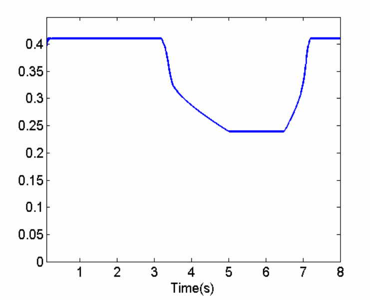

Fig. 7. Coefficient of power conversion.

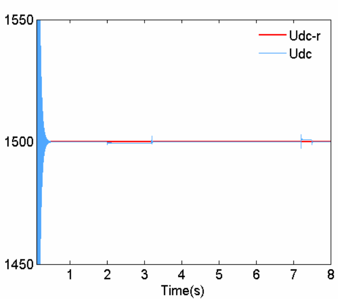

Fig. 10. DC link voltage (V).

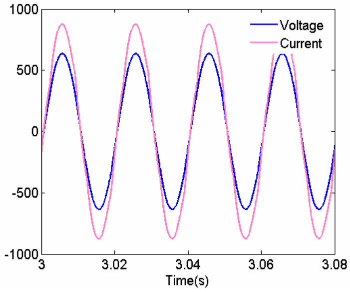

Fig. 13. The waveforms of three phase current and voltage of inverter.

5. Conclusions

This paper deals with a control strategy of the variable speed wind energy conversion system based on the PMSG and connected distribution network. A 2 MW PMSG variable speed wind power generation system is simulated to demonstrate the proposed control strategy during the grid fault. The control strategy can implement the theory of MPPT to adjust WTG velocity according to instantaneous wind speed. Moreover, control strategy based on Vector Control (VC) theory is applied for generator converter and for inverter. As the speed of WTG vary along the wind velocity change, the rectifier is used to track the maximum wind power, although the inverter can deliver the energy from the PMSG to the electric grid with unity power factor. Besides, Direct Power Control (DPC) of three phases PWM inverter is adopted and Grid-side reactive and active power decoupling method is applied. The employed control strategy can regulate both the reactive and active power independently. The performance of system has been demonstrated under varying wind conditions and the grid fault conditions. It is finally shown that the results proved the effectiveness of the employed control strategies.

Table 1. Parameters of the Power Synchronous Generator

Parameter	Value
P_r rated power	2 (Mw)
ω_m rated mechanical speed	2.57 (rd/s)
R stator resistance	0.008(Ω)
L_q , L_d stator d-axis and q-axis inductance	0.0003 (H)
ψ_f permanent magnet flux	3.86 (wb)
p_n pole pairs	60

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