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SIX-PHASE INDUCTION GENERATOR CONTROL IN HEALTY AND FAULTY MODE CONNECTED TO SMART GRID

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Abstract- Today, the use of the multiphase machine is an interesting choice for demanding electrical drive applications in terms of vibration or acoustic discretion. This machine becomes in recent years an adequate solution for wind energy conversion systems in view of all the advantages of this machine. The increase in the number of phases implies an increase in the possibility of degraded operation while preserving an acceptable torque quality which guarantees an excellent service continuity of the wind conversion systems. This paper presents a simulation study of a wind power system based on the six-phase SCIG generator with a rated power of 149.2 kW. The grid part is controlled by a three-level NPC inverter. The part of the network is controlled by a three-level inverter of the NPC type. The simulation results showed the effectiveness of PI regulator in the healthy case of the machine. However, it has a weakness against unbalance in the machine which can be improved by more robust regulators.

Keywords: Matrix Converter, Double Star Asynchronous Machine, Wind Turbine, Intelligent Control, Predictive Control, Lyapunov Stability.

1. INTRODUCTION

In the recent year, multiphase machines are the most adopted solutions in the field of wind power conversion in the presence of supply phase faults. In addition, these machines are used for high power applications operating as a generator. In recent decades, electrical energy has become one of the most important factors in the daily life of human beings, and as a result, worldwide consumption is constantly increasing due to the many areas of activity and daily needs the require electricity. Much of this energy comes from fossil fuels, causing environmental problems. For the sustainable development, control and development of renewable energies have become one of the most important areas of research, in particular wind energy, which has evolved enormously in recent years [1]. Several works based on multiphase machines have been carried out in the recent literature [2-7]. C. Kalaivani and all presents a study of the performance of a seven-phase induction generator for various operating conditions. The simulation model is developed in MATLAB/SIMULINK. Advanced control is applied to the proposed variable speed Asymmetrical Six-Phase Induction Generator (ASIG) for a Wind Energy Conversion System (WECS) is grid-connected [3, 4].

Steady-state modelling with experimental analyses of a six-phase self-excited generator were discussed in [5]. Reference [6] presents a study on the evaluation of temperature and losses of multi-phase induction generator for electric vehicle applications. A transformer less study of a WECS system based on a twelve-phase generator has been proposed in [7]. For high power variable speed systems, the six-phase asynchronous generator can be an interesting solution. A stand-alone PWM (Pulse Width Modulation) inverter is a static converter that transforms energy from a DC source into variable frequency AC energy. The sinus-triangle PWM is realized by comparing a low frequency modulating wave (reference voltage) to a high frequency carrier wave of triangular shape. The switching times are determined by the intersection points between the carrier and the modulating wave. The switching frequency of the switches is fixed by the carrier.

The objective of this paper is to study the behavior of a six-phase asynchronous generator of power 149.2kW connected with the distribution network. The generator is controlled by the rotor flux-oriented control. After the introduction the article is organized by: the second section represents a description of the global system (power circuit). The modeling and the control blocks concerning the two converters on the generator side have been studied in section 3. In the same context, the control of the network side converter is exposed in the same section. Section 4 shows the discussions and comments on the results obtained by MATLAB/SIMULINK. We end with section 5 which is devoted to the conclusion of this study and the exposition of some research perspectives.

2. DESCRIPTIONOF THE SYSTEM

A six-phase asynchronous generator is fed by two three-phase inverters (Figure 1).

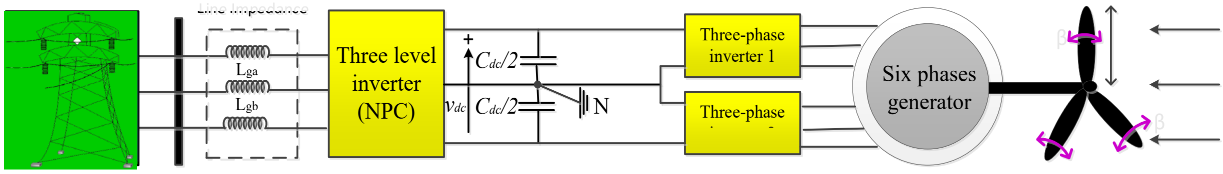

Figure 1. Global circuit

Each phase is thus supplied by its own inverter, which allows operation in degraded mode in the event of a power component or winding fault. The system is connected with the grid by a three-level inverter of NPC type to ensure power transfer with satisfied energy quality. The six-phase generator is driven by a wind turbine with three blades of radius R and are controlled by a wedge angle orientation system β to protect the system in the case of high wind speeds the turbine power is given by [8-12]:

$$P_t = \frac{1}{2}\rho\pi \times C_p(\lambda,\beta) R^2 v^3 \quad (1)$$

where, P_t is the turbine's mechanical power, while β [º] is a symbol for the blades' pitch angle. The wind turbine's aerodynamic efficiency is described by the power coefficient C_p. One of the fundamental equations used to model C_p, a function of the blade's pitch angle β and speed ratio λ, can be written as follows [13]:

$$C_p(\alpha,\beta) = 0.51763\left[\frac{116}{\lambda_i} - 0.4\beta - 5\right] e^{\frac{-21}{\lambda_i}} + 0.006795\lambda \quad (2)$$

$$\frac{1}{\lambda_i} = \frac{1}{\lambda + 0.08\beta} - \frac{0.035}{\beta^3 + 1} \quad (3)$$

where,

$$\lambda = \frac{\Omega_t R}{v} \quad (4)$$

where, Ω_t [rad/s] signifies mechanical speed of turbine.

3. CONTROLOFTHEPROPOSEDSYYSTEM

3.1. Converter Control on the Generator Side

To study the control of such an electric machine, it is necessary to know the behavior of the machine in transient regime (mathematical model). The modeling of a multiphase machine with a sinusoidal distribution of its flux is usually done by changing the reference frame in the rotor axis. This method called Park transformation which is already used for three-phase machines is adapted according to the number of phases of the machine. Since many machine speed/torque controllers use this reference frame in their control algorithm, keeping this reference frame in the case of multiphase machines allows the controller to be adapted relatively easily (from three phases to n phases) [14-15]. The six-phase asynchronous generator consists of a stator carrying two identical three-phase windings offset from each other by an electrical angle α=30° and a squirrel cage rotor. Figure 2 schematically represents the windings of this machine in the park frame of reference. The angles θr and $(\theta r - \alpha)$ represent the position of the rotor (phase ar) relative to star 1 (phase as1) and star 2 (phase as2), respectively. The quantities relative to the two stars (1and 2) will be noted by the indices 1 and 2, respectively.

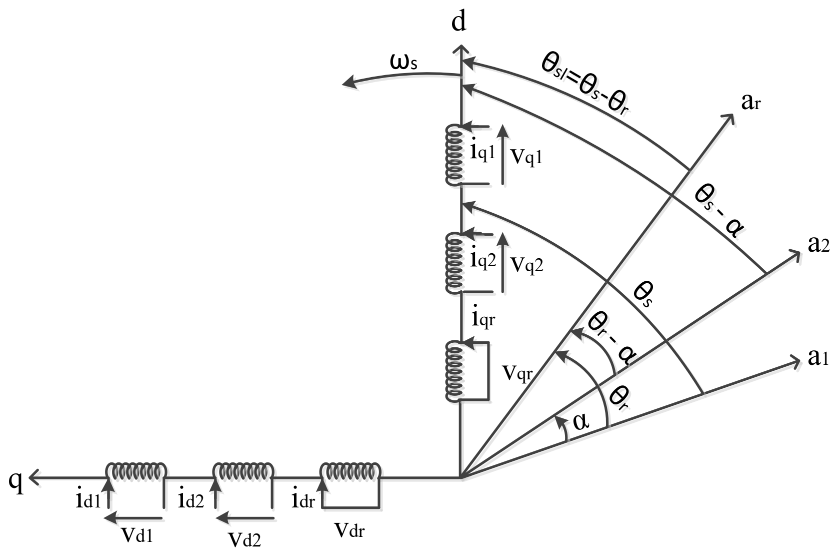

Figure 2. Representation of the six-phase machine in Park's reference frame

The systems of differential equations are:

$$
\begin{aligned}
&v_{d1} = R_1 i_{d1} + \frac{d}{dt}\varphi_{d1} + \omega_s \varphi_{q1} \\
&v_{q1} = R_1 i_{q1} + \frac{d}{dt}\varphi_{q1} + \omega_s \varphi_{d1} \\
&v_{d2} = R_1 i_{d2} + \frac{d}{dt}\varphi_{d2} + \omega_s \varphi_{q2} \\
&v_{q2} = R_1 i_{q2} + \frac{d}{dt}\varphi_{d2} + \omega_s \varphi_{q2} \\
&v_{dr} = 0 = R_r i_{dr} + \frac{d}{dt}\varphi_{dr} - \underbrace{(\omega_s - \omega_r)}_{\omega_{sl}}\varphi_{qr} \\
&v_{qr} = 0 = R_r i_{qr} + \frac{d}{dt}\varphi_{qr} - \underbrace{(\omega_s - \omega_r)}_{\omega_{sl}}\varphi_{dr}
\end{aligned}
\tag{5}
$$

where, v_{d1} and v_{q1}, i_{d1} and i_{q1}, φ_{d1} and φ_{q1} are respectively the voltages, currents and fluxes of star 1 in the Park reference frame (d,q), R_1 and R_2 are respectively the resistances of star 1 and 2, R_r is the resistance of the rotor, v_{d2} and v_{q2}, i_{d2} and i_{q2}, φ_{d2} and φ_{q2} are respectively the voltages, currents and fluxes of star 2 in the Park reference frame (d, q). ω_s, ω_r and ω_{sl} are respectively the stator, rotor and slip electrical rotation speeds. System of magnetic equations:

$$
\begin{aligned}
&\varphi_{d1} = L_1 i_{d1} + L_m (i_{d1} + i_{d2} + i_{dr}) \\
&\varphi_{q1} = L_1 i_{q1} + L_m (i_{q1} + i_{q2} + i_{qr}) \\
&\varphi_{d2} = L_2 i_{d2} + L_m (i_{d1} + i_{d2} + i_{dr}) \\
&\varphi_{q2} = L_2 i_{q2} + L_m (i_{q1} + i_{q2} + i_{qr}) \\
&\varphi_{dr} = L_r i_{dr} + L_m (i_{d1} + i_{d2} + i_{dr}) \\
&\varphi_{qr} = L_r i_{qr} + L_m (i_{q1} + i_{q2} + i_{qr})
\end{aligned}
\tag{6}
$$

where, L_1, L_2, L_r, and L_m, are respectively the inductances of the stator stars 1 and 2, of the rotor and mutual between stator/rotor with:

$$
\omega_s = \frac{d\theta_s}{dt},\ \omega_r = \frac{d\theta_r}{dt},\ \omega_{sl} = \frac{d\theta_s}{dt} - \frac{d\theta_r}{dt} \tag{7}
$$

The electromagnetic torque of the generator is given by:

$$
T_{em} = \frac{3}{2}\frac{p}{2}\frac{L_m}{L_r}\left[\left(i_{q1} + i_{q2}\right)\varphi_{dr} - \left(i_{d1} + i_{d2}\right)\varphi_{qr}\right] \tag{8}
$$

where, p is the number of pole pairs. The control of the six-phase asynchronous generator by flux orientation consists in regulating the flux by a component of the current and the torque by the other component. For this, it is necessary to choose a control law and a system of axes ensuring the decoupling of the flux and the torque, knowing that the expression of the electromagnetic torque (8) is a function of the stator currents and the rotor fluxes. However, by choosing the orientation of the rotor flux along the d-axis ($d_r = r$ and $q_r = 0$), the form of the electromagnetic torque is as follows [16-20]:

$$
T_{em} = \frac{2}{3}\frac{p}{2}\frac{L_m}{L_r}\left[\left(i_{q1} + i_{q2}\right)\varphi_{dr}\right] \tag{9}
$$

Using compensation control, the generator voltages are:

$$
\begin{aligned}
&v_{d1}^* = v_{d1r} - v_{d1c}\ ,\ v_{q1}^* = v_{q1r} - v_{q1c} \\
&v_{d2}^* = v_{d2r} - v_{d2c}\ ,\ v_{q2}^* = v_{q2r} - v_{q2c}
\end{aligned}
\tag{10}
$$

Such as control voltages are:

$$
\begin{aligned}
&v_{d1r} = R_1 i_{d1} + L_1 s i_{d1}\ ,\ v_{q1r} = R_1 i_{q1} + L_1 s i_{q1} \\
&v_{d2r} = R_2 i_{d2} + L_2 s i_{d2}\ ,\ v_{q2r} = R_2 i_{q2} + L_2 s i_{q2}
\end{aligned}
\tag{11}
$$

Thus, the compensation voltages:

$$
\begin{aligned}
&v_{d1c} = \omega_s^*\left(L_1 i_{q1} + \tau_r \varphi_r^* \omega_{sl}^*\right)\ ,\ v_{q1c} = \omega_s^*\left(L_1 i_{d1} + \varphi_r^*\right) \\
&v_{d2c} = \omega_s^*\left(L_2 i_{q2} + \tau_r \varphi_r^* \omega_{sl}^*\right)\ ,\ v_{q2c} = \omega_s^*\left(L_2 i_{d2} + \varphi_r^*\right)
\end{aligned}
\tag{12}
$$

where, $s = \frac{d}{dt}$ is the Laplace operator and $\tau_r = \frac{L_r}{R_r}$ is the time constant finally the rotor speed Ω_r is given by:

$$
J\frac{d\Omega_r}{dt} + f\Omega_r = T_{em} - T_t \tag{13}
$$

where, J is the inertia and f is the friction so T_t is the torque of the turbine.

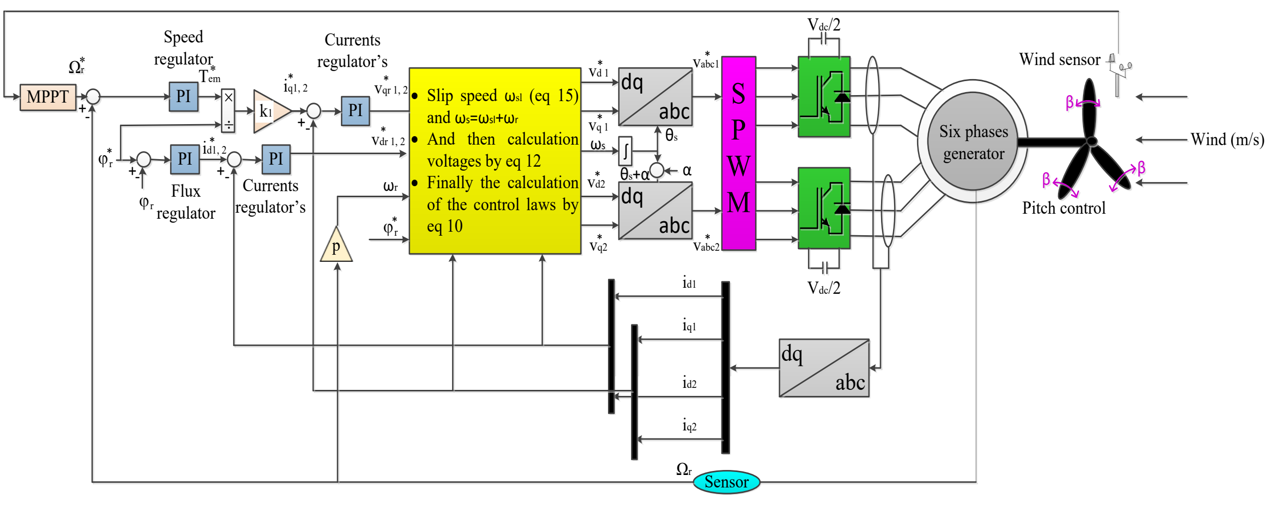

Figure 3. Schematic representation of the FOC command

The rotor speed of the electric field can be obtained by using the following equation:

$$\omega_r = p\omega_r \quad (14)$$

After orientation of the rotor flux towards the direct axis (*d*), the slip speed becomes [21]:

$$\omega_{sl} = \left(\frac{L_m}{\tau_r}\right)\left(\frac{i_{q1}+i_{q2}}{\varphi_r}\right) \quad (15)$$

With the gain k_1 is given by:

$$k_1 = \frac{2}{2}\frac{p}{3}\frac{L_r}{L_m} \quad (16)$$

We use six PI controllers as shown in Figure 3 to the implementation of rotor flux-oriented control. External PI controllers are used to control speed and flux control, which generate reference currents $i^*_{d1,2}$ and $i^*_{q1,2}$ (knowing that $i^*_{d1} = i^*_{d2}$ and $i^*_{q1} = i^*_{q2}$)

3.2. Control of The Inverter on The Mains Side

The model in the park frame is given by the following Equation:

$$\frac{d}{dt}\begin{pmatrix} i_{dg} \\ i_{qg} \end{pmatrix} = \begin{pmatrix} -\frac{R_g}{L_g} & \omega_g \\ \omega_g & -\frac{R_g}{L_g} \end{pmatrix}\begin{pmatrix} i_{dg} \\ i_{qg} \end{pmatrix} + \frac{1}{L_g}\begin{pmatrix} v_{dg}-v_{id} \\ v_{qg}-v_{iq} \end{pmatrix} \quad (17)$$

where, R_g and L_g are respectively the resistance and the leakage inductance of the network side transformer, v_{dg} and v_{qg} are the network voltages, and v_{id} and v_{iq} are the inverter voltages.

Using compensation decoupling, the inverter voltages are written as:

$$\begin{cases} v_{id} = e_{id} + v_{id1} \\ v_{iq} = e_{iq} + e_{iq1} \end{cases} \quad (18)$$

With order terms are:

$$\begin{cases} v_{id} = L_g \frac{di_{dg}}{dt} \\ v_{iq} = L_g \frac{di_{qg}}{dt} \end{cases} \quad (19)$$

And the compensation terms are:

$$\begin{cases} e_{id} = -R_g i_{dg} + L_g \omega_g i_{qg} + v_{dg} \\ e_{iq} = -L_g \omega_g i_{dg} - R_g i_{qg} + v_{qg} \end{cases} \quad (20)$$

The DC voltage of the three-level inverter is modeled by [22]:

$$\frac{dv_{dc}}{dt} = \frac{i_{dc}}{2c_{dc}} \quad (21)$$

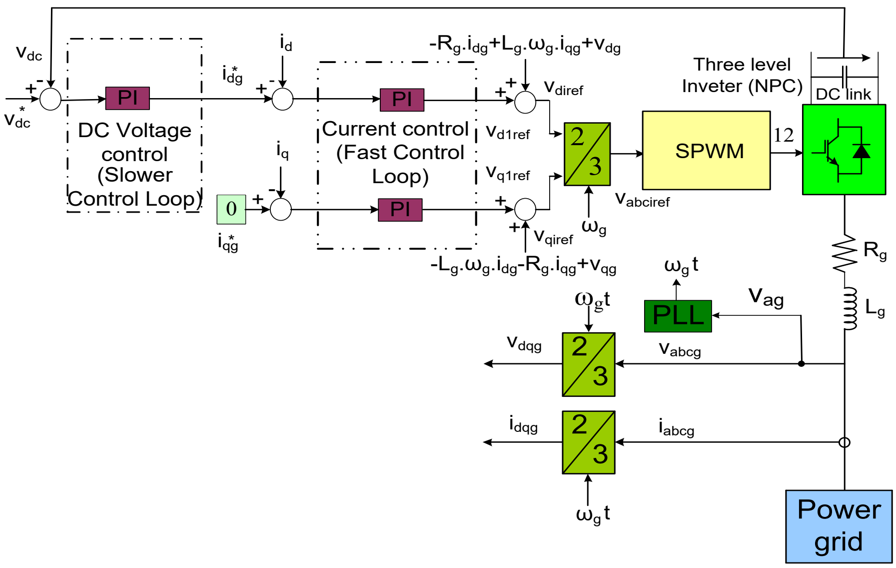

Figure 4. Control for the grid-side converter

The necessary measurements for the control system Figure 4 (for the DC side and the mains side) are voltages and currents on the source side as well as the voltage value on the DC side. These alternating variables of voltage and current are transformed into continuous d- and q-axis components as soon as these signals have the same frequency as the network [23-24]. This further requires the use of a Phase Locked Loop (PLL) to determine the network phase $\omega_g t$.

4. RESULTS AND DISCUSSION

The model used in this article it is composed in two big parts: the first it is the power circuit realized by the blocks SimPowerSystem® of software MATLAB/SIMULINK. This part includes the wind turbine, the six-phase generator, the two converters between them, a capacitor as well as a transformer and a main network. The second part is the control part which contains the PWM control blocks and the regulators used. Table 1 shows the parameter values of the simulated model.

Table 1. Parameters used in simulation

Grid	
RMS Voltage, v_s [v]	400
Frequency, f_s [Hz]	50
Transformer	
Leakage resistance, R_g [Ω]	0.2
The leakage inductance, L_g [mH]	2
Turbine	
The air density, $\rho\left[\text{kg}\times\text{m}^{-2}\right]$	1.225
Mechanical rate power, $P_{m,n}$ [kw]	149.2
Turbine radius, R[m]	10.5
Rated wind speed, $v_n\left[\text{m.s}^{-1}\right]$	12
Multiplication ratio, G	17.1806
SCIG	
Rated power, P [kw]	149.2
Nominal frequency, $f_{g,n}$ [Hz]	50
Stator resistance, R_s [mΩ]	14.85
Stator Leakage Inductance, L_{ls} [mΩ]	0.3027
Rotor resistance, R_r [mΩ]	9.295
Rotor Leakage Inductance, L_{ls} [mH]	0.3027
Mutual inductance, L_m [mH]	10.46
Inertia, $J\left[\text{kg}\times\text{m}^{-2}\right]$	3.1
Coefficient of friction, $f\left[N.m.s.rad^{-1}\right]$	0.08
Number of pole pairs, p	2
DC Side Controller	
Voltage Controller Proportional Gain DC, k_{pdc}	2
Voltage Controller Integral Gain DC, k_{idc}	100
Grid side controller	
Current regulator proportional gain, k_{pc}	6
Current regulator integral gain, k_{ic}	4500

4.1. Wind Change

Figure 5 shows the wind profile and the angularity of the generator rotor shaft. The variations of the generator speed are adapted to the variation of the wind speed. At start-up and during no-load operation, the speed (Ω_r (rad/s)) reaches its set value at t=1s and without overshoot. An increase in the wind speed allows an acceleration of the rotor speed which can increase the flux in the stator circuit of the generator. A drop in the speed of the generator's rotor axis is shown in Figure 5.

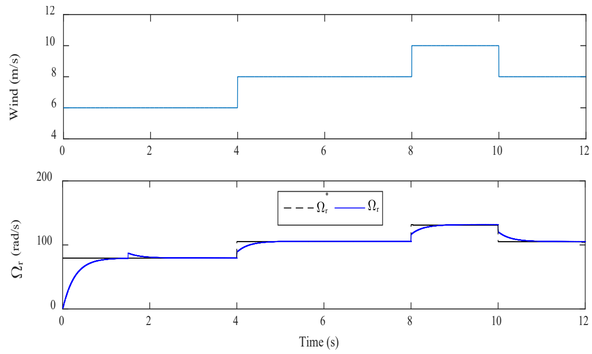

Figure 5. Wind profile and rotor speed

The six stator currents (stars 1 and 2) have an inrush current of about five times the rated current, and then during steady state they evolve in a sinusoidal manner as shown in Figure 6. The shape of the DC voltage is shown in Figure 6. It can be seen that the tracking of the DC bus voltage is almost perfect with short transient regimes depending on the changes in wind speed.

The active and reactive power of the network is shown in Figure 7. The active and reactive power of the grid are presented in Figure 7. It can be seen that the active power of the grid has a negative sign and the reactive power is kept constant and zero throughout the simulation, so that the power factor is unity. The significance of the negative sign that the generator produces power to the distribution network. The power variations between -20 kW and -90 kW are due to the wind profile shown in Figure 5.

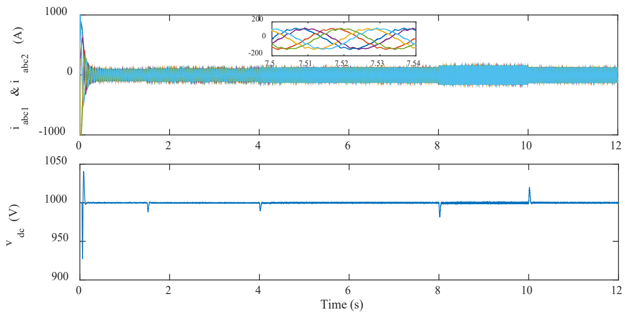

Figure 6. The waveforms of the six generator currents and the DC voltage

At start-up and during operation at a wind speed of 6 m/s, in this mode, the current reaches a value of 950 A and the speed returns to its set value for 1.5 s. in the same situation, the network power reaches the value of -20 KW. During the changes of the profile of the wind at the instants [4, 8, 10 s] corresponding to the variations of its speeds [8, 10, 8 m/s], one notices a good continuation of the speed of the generator. Subsequently, the generator always provides maximum power regardless of variations in wind speed thanks to the MPPT algorithm used in the control system.

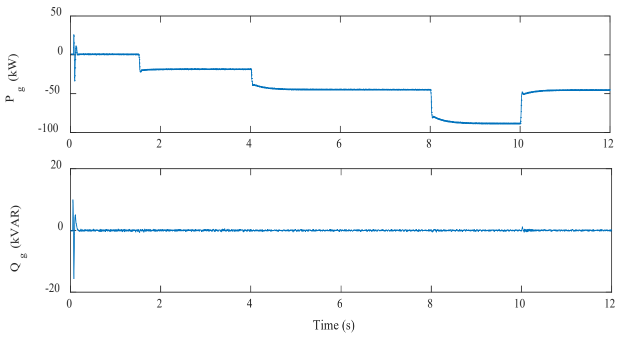

Figure 7. Instantaneous active and reactive power responses of network

4.2. Generator Phase Fault

In order to test the robustness of the rotor flux vector control with the indirect method, a test is performed which corresponds to the opening of the first phase of the six-phase generator. The wind speed is fixed at 6m/s. The fault is applied at time t=1s.

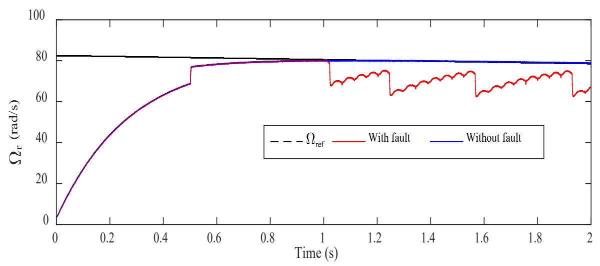

Figure 8. The rotor speed curve with and without fault

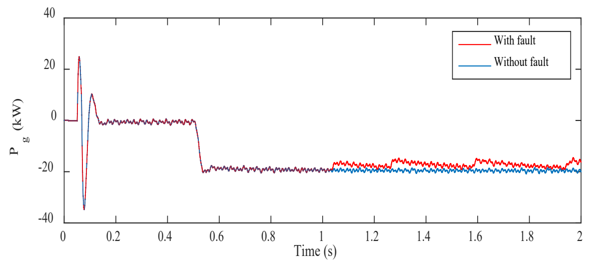

Figure 9. Network power response with and without fault

Figure 8 shows the rotor speed with and without the fault. It can be seen that with the fault the speed does not follow its reference perfectly. This response has a direct influence on the instantaneous active power of the network. A decrease of 16.66% (which implies a reduction of 3.33kW in average power) is observed on the power curve (see Figure 9). In addition, we can see ripples on the speed and active power curves of the network due to the imbalances created by the opening of the first phase.

In reference [26] a study in simulation and in practice on the FOC flux-oriented vector control of the six-phase generator has been proposed. However, no scenario on the degraded mode (operation with fault) was carried out in order to show the robustness or the weakness of the control. A fault-tolerant control associated with the FOC vector control of the six-phase generator is proposed in [27]. This check shows that despite the presence of the fault, the generator continues to supply energy but with ripples with power drops in the event of the absence of a phase. But the complexity of the control is imposed in this study. Our study is based on the recognition of the weak points of the FOC vector control in the face of external variations such as the absence of phase. This study, which can serve researchers in order to find more adequate commands in the face of these types of faults.

5. CONCLUSION

The six-phase generator offers an interesting alternative to reduce the negative stresses generated in wind energy conversion systems. Multi-phase machines (more than three phases) have several advantages over conventional three-phase machines, such as (i) reduced amplitude and increased frequency of torque pulsations, (ii) reduced harmonic currents of the rotor, (iii) the reduction of the current per phase without increasing the voltage per phase, (vi) the lowering of current harmonics in the DC link and greater reliability. By increasing the number of phases, it is also possible to increase the power/torque in an efficient way for a machine of the same size. These advantages pushed us to study this type of machine, in order to see the behavior of the machine when it is driven by an indirect vector control with oriented rotor flux and in order to improve the performances. The work in this paper aims to investigate PI controller control strategies to improve the dynamic responses of the SCIG generator with and without faults. Conventional control algorithms such as PI controllers can be sufficient if the system's accuracy and performance requirements are not overly strict. Control algorithms must be created to ensure the resilience of the process with respect to uncertainties on the parameters and their variations in the opposite situation, particularly when the controlled section is exposed to substantial nonlinearities and time variations. The simulation results obtained showed a good dynamic and performance in closed loop in the case of healthy operation. When the fault occurs, the results showed the weakness of the classical controller. In this context, perspectives are proposed to improve the behavior of the system in the presence of faults such as: robust, intelligent and non-linear controls.

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