Wind Turbines under Power-Grid Partial Islanding

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Abstract. This paper proposes a study about a partial islanding system composed by a wind turbine based on doubly-fed induction generator (DFIG), a wind turbine based on permanent magnet synchronous generator (PMSG), an active filter, capacitor banks, non-linear load, and the grid power. Mathematical model of systems are performed by both field-oriented control (FOC) and virtual grid flux oriented control (VOC). The objective is to analyze the voltage and frequency of point of common coupling (PCC) due to the islanding of grid-connected electrical power systems and then the insertion of the non-linear load on the system. In order to compare methods to improve the power quality in PCC the use of capacitor banks and active filter are considered in this work. The whole simulation model is developed in PSCAD/EMTDC environment. The simulation results are presented and discussed.

Key words

Wind turbine islanding, PMSG, DFIG, field-oriented control, power filters.

1. Introduction

The global consumption of energy will grow at an annual average of 2% between the years of 2003 and 2030. The forecast for the growth of demand for energy specifically in the electric form is even greater i.e. 2.7% to the year, according to the U. S. Department of Energy, through of International Energy Outlook 2006 (IEO) report of Energy Information Administration (EIA) [1].

On the other hand, the renewable energies are the main generation choice for connected with the distribution network, reduce losses and improve the reliability of the power system. This is called distributed generation. Because of the pollution and undesirable environmental

effects of fossil fuel, the wind energy is increasing the use over these years [2-3].

The use of wind energy can guarantee the energy produce close to the load. The microgrid voltage is the distribution or sub-distribution voltage levels. The microsource must to keep the voltage and frequency constant independent of the load [2].

The wind generation includes fixed-speed system and variable-speed system. The variable-speed wind power generation is a tendency in nowadays wind generation development because it can operate on the maximum power point of the machine. This system include synchronous and asynchronous generator.

PMSG generate the output voltage without a constant frequency. The AC-DC-AC converter is responsible to controlling the frequency and to make the variable voltage constant. The PMSG does not need the gearbox and has a light mass and high efficiency. The whole power generated need to pass through the converter, so, the rated power of the converter must to be the same rated power of the generator [4].

In wind turbines based on DFIG, the stator is directly connected to the grid and the rotor is excited by three phase converter which can regulate both active and reactive power of stator machine through control of dq -axis rotor currents. The rated power of the back-to-back converter is smaller than the generator rated power, this converter must be specified by the slip power, which is approximately 25% of the rated power of the generator. The DFIG is heavier than the PMSG and needs the gearbox, which causes the whole system heaviest [4]. The whole system is shown in Figure 1.

Fig. 1. The full system simulated.

2. Machine Modeling

In this section the mathematical models of wound rotor induction generator and permanent magnet synchronous generator will be developed in dq rotating coordinate system. Both models are based on the field-oriented control. However, DFIG system uses the reference frame fixed in the stator magnetic flux, while the PMSG uses the reference frame positioned in the rotor flux.

A. DFIG Model

The DFIG stator voltage equation is shown in (1).

$$\vec{v}_s^s = R_s \vec{i}_s^s + \frac{d\vec{\psi}_s^s}{dt} \quad (1)$$

The stator voltage equation in the dq reference frame rotating at the angular frequency ω_s are as follows in (2) and (3) [5-6].

$$v_{sd} = R_s i_{sd} + \frac{d\psi_{sd}}{dt} - \omega_s \psi_{sq} \quad (2)$$

$$v_{sq} = R_s i_{sq} + \frac{d\psi_{sq}}{dt} + \omega_s \psi_{sd} \quad (3)$$

Where R_s is the stator resistance, and ψ_s the stator magnetic flux.

The stator magnetic flux, in dq reference frame, is as follow in (4) and (5).

$$\psi_{sd} = L_s i_{sd} + L_m i_{rd} \quad (4)$$

$$\psi_{sq} = L_s i_{sq} + L_m i_{rq} \quad (5)$$

Where L_s is the stator inductance and L_m is the magnetizing inductance.

The same equations are obtained for the rotor, using the rotor resistance R_r , the rotor flux ψ_r and the rotor inductance L_r . The reactive power obtained with these equations is shown below in (6) and (7) [6-7].

$$P_s = -v_{sq} \frac{L_s}{L_m} i_{rq} \quad (6)$$

$$Q_s = -\frac{L_s}{L_m} \left[\frac{v_{sq}^2}{L_m \omega_s} - v_{sq} i_{rd} \right] \quad (7)$$

The vector control diagram of DFIG is shown in Figure 2 (a).

B. PMSG Model

The stator voltage equation in the dq reference frame rotating for DFIG in (2) and (3) is similar to PMSG. However, the magnetic flux is different, as follow in (8) and (9).

$$\psi_{gd} = L_s \cdot i_{sd} + \psi_{pm} \quad (8)$$

$$\psi_{gq} = L_s \cdot i_{sd} \quad (9)$$

Where L_s is the stator inductance and ψ_{pm} is the permanent magnetic flux.

Fig. 2. (a) DFIG Vector diagram in the dq reference frame considering a field-oriented control (stator flux); (b) PMSG Vector diagram in the dq reference frame considering a field-oriented control (rotor flux).

The d-q generator voltages are shown below in (10) and (11).

$$v_{sd} = R_s i_{sd} + L_s \frac{di_{sd}}{dt} - \omega_e L_s i_{sq} \quad (10)$$

$$v_{sq} = R_s i_{sq} + L_s \frac{di_{sq}}{dt} + \omega_e (L_s i_{sd} + \psi_{pm}) \quad (11)$$

Where R_s is the stator resistance and ω_e is the angular frequency.

The electrical torque of the machine is follow in (12).

$$T_e = \frac{3}{2} \cdot \frac{N_p}{2} \cdot \psi_{pm} \cdot i_{sq} \quad (12)$$

Where N_p is the machine pole number.

The vector control diagram of PMSG is shown in Figure 2 (b).

C. Active Filter

An active power filter with shunt configuration was used in the simulation of this work. The control strategy adopted was based on *pq Theory* [8-9]. The theory of instantaneous active and reactive power originally presented in [8] is widely used in modeling and control of active power filters. This theory can be applied to situations of steady state as in transient and in the presence of harmonics. Figure 3 shows the structure of the active filter.

Fig. 3. Active power filter configuration.

According to the *pq theory*, both the real and imaginary power can be divided in constant and oscillating portions. It means that,

$$p = \bar{p} + \tilde{p} \quad (13)$$

$$q = \bar{q} + \tilde{q} \quad (14)$$

Equation (13) shows the real power, and (14) shows the imaginary power. The bar and tilde signals above the variables indicates the constant (bar) and oscillating (tilde) portions.

The idea behind the active filtering performed in this paper is from the reading of the current drawn by a nonlinear load and the PCC voltage, the control system calculates the current compensation which must be synthesized by the active filter, in other words, by the grid side converter (GSC).

Based on this control strategy, the grid side converter controls the DC-link voltage, while it compensates the current drained by a nonlinear load, if it exists.

Based on that theory is possible compensate constant and oscillating portion of the real power, and constant and oscillating portion of the imaginary power. In that study we choice to compensate the oscillation portion of the real power (because, of course, does not make sense to compensate for the constant portion), and all the imaginary power.

3. Simulation Results

The system was simulated with the strong grid and any load until $t = 1s$. After this, the infinity bus goes away and the machines were connected to a weak grid with SCR (*Short Circuit Ratio*) equal to 14. At $t = 2s$, the non-linear load is connected to the bus, after that at $t = 3s$, a power active filter is connected in the non-linear load to compensate the distorted current drain from the power system. And finally, at $t = 4s$, the capacitor banks begins its operation. During all the simulation, the wind speed was considered constant. The wind turbine based on DFIG provides 1.9MW to the power system and the wind turbine based on PMSG provides 2.0MW.

Figure 4 shows the behavior of the aggregate value of the voltage at PCC. On shutdown of the strong grid, there is an oscillation due to the low SCR value of the weak grid, despite the provision of reactive power by the PMSG. The oscillation in the waveform's aggregate value of the PCC voltage is worse when the load is connected to the system, and this is corrected with the capacitor bank. Figure 4 displays the behavior of the voltage frequency at the PCC. While the load is not connected to the system, the power supplied by the DFIG causes the frequency value increases.

Fig. 4. The aggregate value of bus voltage.

Fig. 5. The grid frequency.

Fig. 6. The DC-link voltage.

Fig. 7. The PCC voltage: start of islanding.

Fig. 8. The PCC voltage: capacitor bank turned on.

Fig. 9. Currents in phase *a*: nonlinear load, active filter and compensated currents.

Fig. 10. Grid active power.

Fig. 11. Grid reactive power.

Upon the occurrence of an islanding, the frequency and voltage of the isolated subsystem dynamically vary depending on the unbalance of active and reactive power, that is, the difference between the active and reactive power generated and consumed. Thus, as larger the unbalance is, the higher will be both voltage and frequency variations.

Figure 6 shows the DC-link voltage of both DFIG and active power filter. There is no visible change when the infinity bus goes away. However, with the injection of the load, there is a ripple that is quickly attenuated by the control system. The same occurs with the active filter DC-link.

Fig. 12. Generated and consumed active power.

Fig. 13. Total harmonic distortion of the voltage at the PCC.

It observes in Figures 7 and 8 the PCC voltage waveform. Figure 7 shows the start of partial islanding and it's possible to observe a very important oscillating in the PCC voltage. However, there is a significant reduction on the voltage distortion when the capacitor bank is connected to the system, as shown in Figure 8.

Figure 9 shows the waveforms (phase *a*) of the nonlinear load current, active power filter current and the drained current from power grid after the compensation.

It is possible to note that even during a strong oscillation at the PCC voltage, the active filter was able to compensate adequately the current drained by the nonlinear load.

Figure 10 and 11 shows, respectively, the active and reactive power on the system to the strong and weak grid. When the load is connected to the system, the weak grid supply the active and reactive power required by the system. After connecting the capacitor bank, due to the ohmic losses of the bank, the active power consumption increases, beyond the increases of the reactive energy circulating in the system.

Figure 12 shows that in the initial moments after the islanding, almost all the power generated is injected to the source. This means that in these instants the difference between the active power generated and consumed is too large, and given that an islanded system represents a weak grid, the active power injected into the power grid will cause oscillation in the system frequency.

The total harmonic distortion of the voltage at the point of common coupling is depicted in Figure 13. In the initial moments of the islanding, this value reached the level close to 30%, an excessively high value. After the active filter to be turned on, the THD value decreased modestly, however, still remained far above the levels allowed by the grid codes.

4. Discussion

As is known, frequency variations may cause a motor to run faster or slower to match the frequency of the input power. This would cause the motor to run inefficiently and/or lead to added heat and degradation of the motor through increased motor speed and/or additional current draw.

The search for the solution of the frequency variation is extremely important in power systems, especially when it comes to weak grids, since frequency variation is extremely rare in stable utility power systems, especially in strong power grid.

The capacitor bank offers a low impedance path for the harmonic voltage (decreasing, by this way, the oscillating active power) present at the point of common coupling.

Thus, the solution through capacitor banks to give power quality, as indicated in this study, still is widely used. Simulation results presented in this paper proved that.

5. Conclusion

In this paper was presented a system composed by DFIG and PMSG in a microgrid, non-linear load, active power filter and capacitor bank. It was verified that upon the occurrence of an islanding, the frequency and voltage at the PCC varied dynamically as consequence of the difference between the active and reactive power generated and consumed. Although the objective of this work is analyze the magnitude of the voltage, when the strong grid was disconnected, even with the reactive power injection from machine, under certain conditions, it's not possible improve the magnitude of the PCC voltage.

An active power filter was used to compensate the non-linear current drained by the load, however, this action was not enough to improve the voltage distortion at PCC.

At this simulation, a capacitor bank was used to improve the PCC voltage. This one was connected to a series resistance (to increase the damping) in order to avoid resonance with the grid inductance. It is very difficult to adjust the capacitor bank value in practice due to the poor information about the grid parameters during the islanding. Another problem with respect to this is that the use of capacitor banks in the presence of high switching frequency produced by the converters can lead to maintenance problems. Despite that, this solution is still very used in nowadays.

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