NEW MATHEMATICAL MODELS TO REPRESENT VARIABLE SPEED WIND GENERATION SYSTEMS IN TRANSIENT STABILITY STUDIES

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Abstract – **Wind generation is today based on two different technologies that are represented respectively by fixed speed and variable speed wind turbine generation systems. In this perspective it is presented in this paper a detailed discussion of mathematical models to represent variable speed wind generation systems that include the application of doubly fed induction generators, and synchronous generators with permanent magnet and rotor field excitations. The static converters used in these generation systems, to decouple the electrical frequency of the grid and the mechanical frequency of the rotor, are modeled as current controlled voltage sources. Simulation results regarding the dynamic behaviors of the variable speed generation systems, as compared to a fixed speed cage induction generator system, are presented and discussed. This discussion is focused on the main differences between these technologies and the transient impacts they can cause in the electrical grid voltage when fault events occur. The results obtained so far are consistent in indicating the superior performance observed for variable speed technologies.**

Index Terms — Variable Speed Wind Generators, Fixed Speed Wind Generators, Transient Stability, synchronous and induction generators models, static converters models.

1 INTRODUCTION

The widespread growth of wind generation connected to the utilities electrical grids has emphasized the need to carry out specific studies concerning the transient stability of these systems. These studies must focus on the different wind generation technologies that are available in the market, and make comparison among them related to the transient stability margin and the degree of controllability that may be obtained with each one [1]-[3].

Requirements in terms of power controllability during normal operation, to allow some degree of control over reactive power and active power production, and in the event of grid abnormalities, e.g. grid faults, have increased, leading to the development of a new generation of WECS - the variable speed wind generating systems. Today this technology is well represented by the doubly-fed induction generator, and the synchronous permanent magnet and rotor excitation generators.

The transient studies in order to investigate stability problems of these generation systems connected to electrical grids must be carried out with the utilization of accurate dynamic models to represent the transient behavior of the wind generator variables [3] [4].

An important aspect to be considered in modeling variable speed wind generation systems is the behavior of the static converters, which are invariably present in this type of technology. The models utilized to these components must adhere to the general simplifying assumptions that must be done to consider the interconnection of the wind generation to the electrical power system.

Following this principle this paper presents a new approach to model variable speed wind generation, where static converters are modeled as voltage source for both the DFIG and synchronous generators [3]. An advantage of the proposed representation is that it creates the possibility to model both converters used with the variable speed schemes based on the synchronous generator, namely the permanent magnet and the wounded rotor generators, by similar models without loss of generality. The main differences in the behaviors of the generators are compensated by the static converters and their controls.

It is also focused in this paper an analysis related to the transient stability margin that may be obtained with the utilization of the variable speed technology compared with the performance of the squirrel cage induction generator. A real electrical network is used in the simulation studies performed in this paper.

In the following the proposed models to represent the wind generators with variable speed technologies will be presented. Modeling related to the converters is developed in sections III. The electrical network used in this paper and the results obtained are presented in Section IV. Finally section V presents the conclusions. Models to represent wind turbines and asynchronous generators for fixed speed arrangements may be found in references [2], [3] and [5].

2 MODELS

2.1 Asynchronous Induction Generator

The adjustable speed generator (DFIG) has a structure similar to a wound rotor induction machine using slip rings to allow current into or out of the rotating secondary winding. To enable dynamic modeling of the DFIG based wind turbine under different wind speeds, it is important to understand the required configuration of the system and to consider that this kind of machine has to be fed from both the rotor and stator sides, [4], [6].

The wind system with a doubly fed induction generator and a bi-directional power converter is shown in Fig. 1. The system has typically two AC/DC IGBT power converters, linked by a DC bus. In this scheme, converters decouple the rotational speed of the generator from the frequency of the grid enabling variable speed operation of the wind turbine. The range of variation of slip, s, determines the sizes of converters C_1 and C_2, whose sizes are a fraction of the rated power. The rotor speed can approximately vary between 0.65 to 1.35 p.u., i.e., the rotor speed can vary ±0.35 p.u. around synchronous speed.

The torque can vary between plus/minus the rated torque. However, the rated power limits the torque for rotor speeds above synchronous. Because of mechanical restrictions, a practical speed range could be between 0.7 and 1.1 p.u., [6]. Since the stator of the machine is connected to the grid, the flux is mainly determined by the voltage and frequency of the grid. It is also possible to control the power factor or the reactive power in the stator circuit, in a similar way as for the synchronous generator.

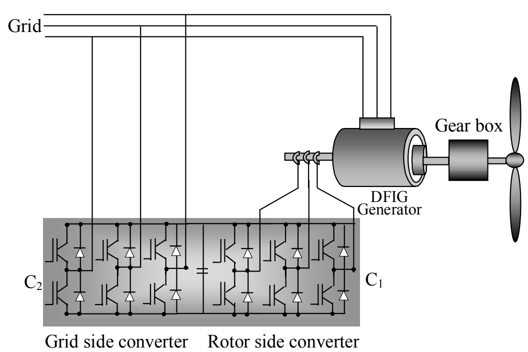

Fig. 1 - Wind System with a DFIG

The models developed in this paper for the representation of squirrel cage and doubly-fed induction generators were based on the d-q Park transformation taking as reference an axis that rotates in the synchronous speed [7], [8].

When representing asynchronous generators in power systems transient stability studies it is an usual practice to reduce the fourth order differential equation dynamic system as presented in [9], to a second order voltage differential equation model, based on the voltage behind a transient reactance. In this case stator transients are ignored what means that the DC component of the transient current of the generator may be neglected, because it presents a faster decaying as compared with the AC components.

The model for asynchronous wind generators used in this paper is summarized by equations (1)-(6) as follows, [8]:

$$v_{ds} = -R_s i_{ds} + X' i_{qs} + v'_d \qquad (1)$$

$$v_{qs} = -R_s i_{qs} - X' i_{ds} + v'_q \qquad (2)$$

Rotor differential equations of the doubly-fed induction generator:

$$\frac{dv'_d}{dt} = -\frac{1}{T_o}\left[v'_d + \left(X - X'\right) i_{qs}\right] - s\omega_s v'_q + \omega_s \frac{L_m}{L_{rr}} v_{qr} \qquad (3)$$

$$\frac{dv'_q}{dt} = -\frac{1}{T_o}\left[v'_q + \left(X - X'\right) i_{ds}\right] - s\omega_s v'_d + \omega_s \frac{L_m}{L_{rr}} v_{dr} \qquad (4)$$

For the squirrel cage induction generator it is sufficient to ignore the terms v_{dr} and v_{qr} in equations (3) and (4).

The electromagnetic torque and the reactive power relationships for the DFIG are given by, [6]:

$$T_{EA} = v'_d i_{ds} + v'_q i_{qs} \qquad (5)$$

$$Q_a = v_{qs} i_{ds} - v_{ds} i_{qs} \qquad (6)$$

2.2 Synchronous Generator with Rotor Field Excitation

Synchronous generators with rotor field excitation, when used in wind systems are usually salient pole machines having many magnetic poles in order to operate in a low speed regime. This aspect also permits that the electrical generator and the wind turbine shafts may be directly coupled, [10]. The rotor saliency contributes to the increase in the transient electromagnetic torque, which may introduce damping during variable wind conditions resulting in a more stable operation for the electrical machine.

The wounded rotor synchronous machine presents a feedback loop connecting the rotor field winding and the electrical grid through a rectifier, which permit that the machine terminal voltage may be regulated automatically. Fig. 2 illustrates this arrangement.

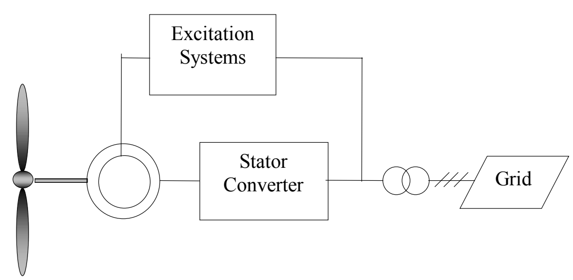

Fig. 2 – Wounded Rotor Synchronous Generator

If stator transients are ignored as been faster than those in the rotor, one may utilize model 4 suggested in [7] to represent the wounded rotor synchronous generator connected to a wind turbine for the purpose of transient stabilities analysis. In this model a field and a damper winding are considered on the direct axis in order to take into account the transient and sub-transient behavior respectively in this axis. On the quadrature axis a damper winding is considered having sub-transient time constant. The equivalent automatic voltage regulator used is an IEEE Type 1 model, [9].

2.3 Permanent Magnet Synchronous Generator

The DC excitation of the field winding can be provided by permanent magnets. Permanent magnet machines are characterized as having larger air gaps, which reduce flux linkage, even in machines with many electromagnetic poles, [10]. The practical consequence of this aspect is the possibility to manufacture low rotational speed generators with relatively small sizes with respect to rated power that can be achieved. In this case the electrical generator operates at low rotation speeds, being directly couple to the wind turbine shaft with no need for gearbox, as illustrated in Fig.3.

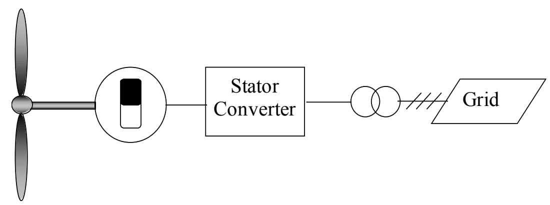

Fig. 3 - Synchronous Generators with permanent magnet

One obvious change when replacing the electrical excitation by a permanent magnet is the elimination of the copper losses. On the other hand, the magnet characteristic is assumed no change with the time. So, the equations which describe this machine are similar the ones which describe the conventional synchronous machine in terms of the flux linkage [9], as follows:

The dynamic equations of the permanent magnet induction generator are presented as follows, as function of the magnetic linkage:

$$V_d = -r_s I_d - \omega\psi_q - \frac{d\psi_d}{dt} \qquad (7)$$

$$V_q = -r_s I_q + \omega\psi_d - \frac{d\psi_q}{dt} \qquad (8)$$

ω is the angular speed of the generator expressed in (rad/s) and ψ_d and ψ_q (magnetic flux linkages in d-axis and q-axis) are given by:

$$\psi_d = K\varphi_f + L_d I_d \qquad (9)$$

$$\psi_q = L_q\ I_q \qquad (10)$$

Substituting the magnetic flux linkages given by equations (9) and (10), in equations (7) and (8), and rearranging the resulting expressions in the d-axis and q-axis using the respective reactances one may obtain:

$$\frac{dI_d}{dt} = -\frac{\omega_s}{X_d} r_s I_d - \frac{\omega}{X_d} X_q I_q + \frac{\omega_s \sqrt{3} V_G \text{ sen } \delta}{X_d} \qquad (11)$$

$$\frac{dI_q}{dt} = -\frac{\omega_s}{X_q} r_s I_q + \frac{\omega E}{X_q} + \frac{\omega}{X_q} X_d I_d - \frac{\omega_s \sqrt{3} V_G \cos\delta}{X_q} \qquad (12)$$

Where V are voltages I are currents and X are reactances of the stator. Indices d and q are relative to the direct axis and the quadrature axis; L_d e L_q are d-axis and q-axis inductances respectively; φ_f is the magnetic flux due to the permanent magnet; E is the electromotive force generated by the permanent magnet and is equal to $\sqrt{3}\omega_s K\varphi_f$; ω_s is the synchronous speed in (rad/s); δ is the loading angle and V_G is the terminal voltage.

The total electromagnetic torque produced in the air gap of the permanent magnet synchronous generator is given in pu by:

$$T_E = \frac{1}{3}\left\{K\varphi_f \omega_s I_q - I_d I_q \left(X_d - X_q\right)\right\} \qquad (13)$$

Reactive power of the permanent magnet synchronous generator is:

$$Q_G = V_q I_d - V_d I_q \qquad (14)$$

3 MODELS OF THE CONVERTERS

3.1Vector Control of the DFIG

The vector diagram of voltages, flux and currents expressed in d and q axis co-ordinates is shown in Fig. 4. In this case, v' representing the resulting internal voltage is δ' ahead in phase from the terminal voltage, v, indicating generating operation. The flux linkage vector in the rotor circuit, Ψ_r', is located 90 degrees behind the internal voltage vector, [3].

Considering that the phase angle δ' is relatively small, the magnitude of the rotor circuit current vector i_r can be changed effectively by changing the d-axis component of the rotor circuit current, i_{dr}. Similarly, changing the q-axis component of the rotor circuit current can change the phase of the rotor circuit current. Thus the voltage or reactive power control can be carried out by changing the d axis component of the rotor circuit voltage, and speed or torque control can be accomplished by changing the q axis component of the rotor circuit voltage.

If the dynamics of the rotor is considered, the excitation control system of doubly fed machines will be considered with two levels of controllers: Rotor current controller in an inner level and both voltage and speed controllers at the outer level. In this case, the magnitude and phase of the internal voltage of the rotating machine can then be controlled within a specified range of rotor speed by changing d and q axis components of the rotor current vector with the two-excitation controllers. The values for gains and time constants of the controllers presented in Fig. 5 can be found in [3].

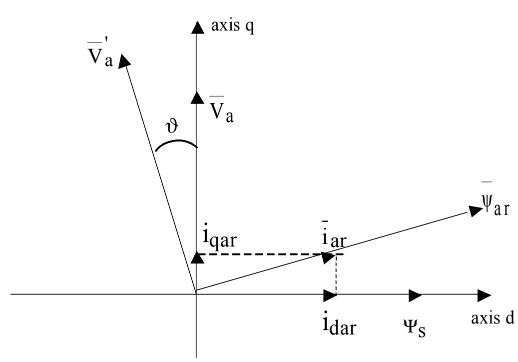

Fig. 4 – Vector Diagram of the DFIG

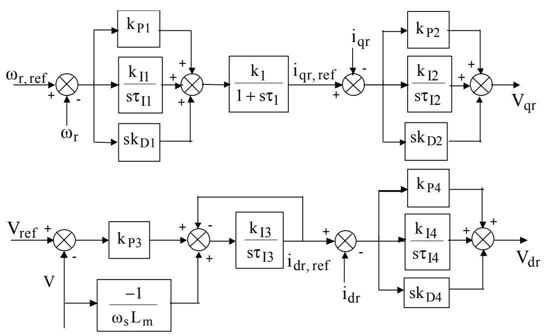

Fig. 5 – Control Loops of the DFIG [3]

3.2 Models of the converters of the Synchronous Generators

Differently of the DFIG wind generators where the active and reactive power flow directly between the stator and the grid, synchronous wind generators are connected to the electrical grid through static converters. In this way it is necessary to model both the converter connected to the generator as well as the converter connected to the electrical grid, which one processes the whole power generated by the machine.

3.2.1 Converter connected to the Generator

The converter connected to the stator side can control active and reactive powers using vector control in a similar way that is done with doubly-fed induction generators (DFIG), being necessary only to define an adequate orientation for the vectors representing the stator voltage and flux linkage along the d-axis and q-axis respectively.

In this way, as the converter is connected to the machine stator, the active power may be controlled by the current in the q-axis, namely the stator Iq current, or equivalently by the angular displacement between the terminal voltage and the excitation voltage, in the case of the permanent magnet synchronous machine, or between the sub-transient voltage for the wounded rotor synchronous machine. Reactive power may be controlled by the d-axis stator current, Id, or by the magnitude of the terminal voltage, according to the control loops as presented in Fig. 6 for the converter connected to the stator of the synchronous generators.

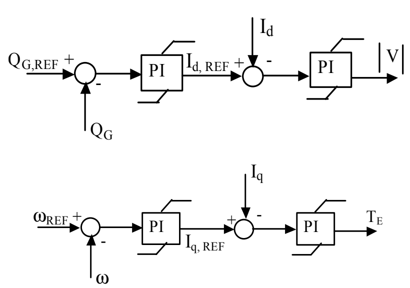

Fig. 6- Dual Static Converter Connected to the Stator of the Generator – Active and Reactive Powers Control

For wounded rotor synchronous machines, even the converter connected to the stator, or to the field winding, or both may exert the reactive power control.

3.2.2-Converter Connected to the Electrical Grid

Fig. 7 is a simplified representation for the synchronous machine connected to the electrical grid through a static converter. In this representation, Vc is the converter voltage. In steady state conditions the generator and converter output powers are equal, which results also equal currents J1 = J2.

On the other hand, for a disturbing condition occurring in the electrical system, an unbalance between the output powers of the converter and the synchronous generator will appears which will provoke a fluctuation on the voltage Ucc, due to the current change in the DC link. In this way, the converter connected to the electrical grid must have an independent control of the DC voltage during disturbance events. As the converter connected to the electrical grid also have the function of controlling the power factor wind generation, they must have a control loop for controlling reactive power. The control loops for this converter are represented schematically in Fig. 8.

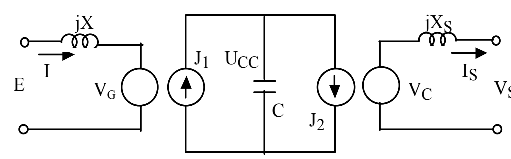

Fig. 7- Simplified Representation of the Converter Connected to the Electrical Grid

The grid side converter is controlled using a synchronous reference frame (α,β), [11]. The α-axis is chosen to be oriented along the converter terminal voltage, Vc, which is defined as a function of α and β as $V_s = V_\alpha + jV_\beta = V_\alpha$, once $V_\beta=0$. The active part of the complex current becomes I_α and the reactive part is I_β. The ouput power of the converter may be written as:

$$S=P_s+jQ_s=V_\alpha(I_\alpha-jI_\beta)=V_\alpha I_\alpha-jV_\alpha I_\beta \qquad (15)$$

The DC link voltage control is carried out by two PI controllers, series connected, as illustrated in Fig. 8. The voltage of the DC link and the active output power of the grid side converter are controlled by the current I_α, in response to changes detected in the voltage Ucc.

Reactive power is controlled directly by the reactive current I_β. If the converter is to operate with unity power factor, the reference for the reactive current must be set equal to zero.

The output signals in the converter model are the voltages along the α-axis and β-axis, which are obtained by the product of the electrical current and reactance that connects the converter to the electrical grid (X_s), as presented in Fig. 8.

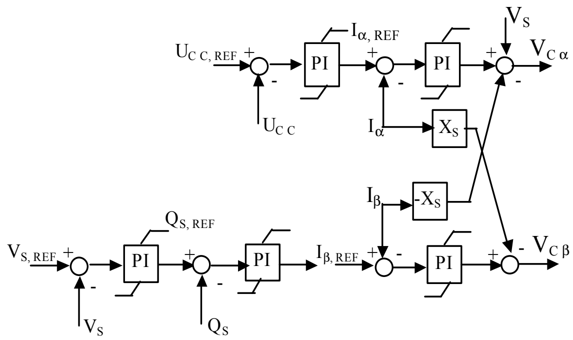

Fig. 8 -Control Loops for the Converter Connected to the Electrical Grid

4 RESULTS

The electrical grid used in this investigation to evaluate the dynamic behavior of the wind generators is similar to the one described in [7]. The original system of this reference was modified to include a wind farm.

The used synchronous and asynchronous generators are 660 kW rated power. The dynamic model of the wind farm includes an equivalent model of its internal electric network, thus an equivalent wind generator of 25 MW at 690 V is considered. The wind park is connected to the grid through 0.69 kV / 13.8 kV transformers. The static capacitor bank reinforces the excitation of the wind generators when cage generators are used.

Besides the wind farm generation, a conventional Diesel electric plant with a synchronous generator of 35 MVA connected to bus 3 and an infinite bus bar are delivering power to the electric load of this system, as viewed in Fig. 9. The model parameters of the speed and voltage regulators and synchronous generators of the Diesel units were obtained from [3] and [7]-[10]. The main characteristics of the wind parks are in the Appendix.

The p.u. values of the parameters of the electrical grid were obtained from [7]. The system dynamic behavior is simulated using original computing programs that were written in MATLAB^{TM}, version 6.5 for Windows.

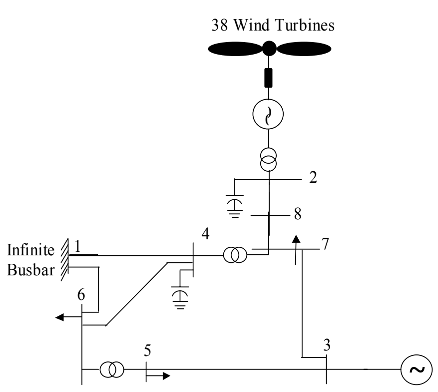

Fig. 9. Electrical Grid with Wind and Diesel Generation

A three-phase short circuit was simulated near bus 2 in line 2-8, beginning at the instant t = 1s. With the purpose of observing the action of the static converters in maintaining the transient stability of the wind system, the short circuit event was maintained for 300 ms indication.

Maintaining the short circuit for a long period is an indication that serves as a measure of the transient stability margin of the wind generators connected to the electrical grid. Once the objective of the simulation studies performed here is to evaluate also the robustness of the controllers during and after the fault period, line 2-8 was not disconnected from the electrical grid.

Fig 10 presents the dynamic behavior of the rotor speed of the wind generator when considering four different wind generator technologies, namely permanent magnet and rotor excited synchronous generators, doubly-fed induction generator, and squirrel cage induction generator. For a clear distinction among the different curves they are labeled as DFIG (for the doubly-fed induction generator), RESG (for the rotor excited synchronous generator), PMSG (for the permanent magnet synchronous generator).

In Fig. 10 it is clearly observed that the squirrel cage induction generator without any additional control (only stall control for the wind turbine) loose stability. This fact may be explained by the reduction that occurs in the generated active power, provoked by the voltage dip due to the short circuit event. The unbalance verified between the mechanical, that is maintained constant during the fault period, and electrical powers feeds the accelerating process of the wind turbine shaft, resulting in a progressive increase of the generator speed.

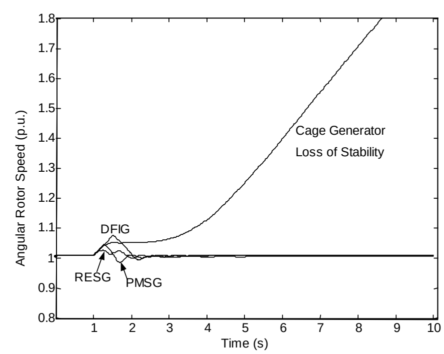

Fig. 10. Speed Behavior

As the rotor speed increases the active power tends to rise to values that may be greater than those before the fault period. This process, on the other hand, requires larger electrical currents, which produces larger voltage dips in lines and transformers that are located nearby the wind park installation. Due to this process the voltage at the squirrel cage induction generator terminals does not recover, as it is shown in Fig. 11 for the fixed speed wind system with cage generator.

The application of the short circuit initially results in a voltage oscillation that decreases to an inadequate operating point, in the case when the squirrel cage induction generator is used in fixed speed wind systems, as demonstrated in Fig. 11. On the other side, the action of the converters of the doubly-fed induction generator, and the synchronous generators met the active power balance, maintaining the system stability.

It is observed for both the behaviors of speed and voltage that only a small difference exists with respect to the steady state values obtained with the DFIG and the synchronous generators in the variable speed wind systems. Also for the transient responses similar characteristics were obtained. These results demonstrate that the intrinsic differences of operating concepts for these machines are compensated by appropriated adjusted converter controllers.

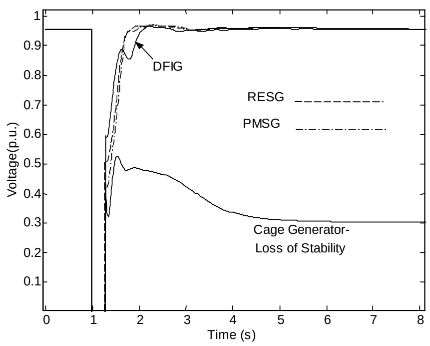

Fig. 11. Voltage Behavior

The output reactive power of the different generators can be seen in Fig. 12, and may also work as another indicator of the stability margin enhancement obtained with the use of variable speed wind systems. It is observed by the simulation results that there is an increase in the reactive demand to maintain the generator terminal voltage, when the asynchronous fixed speed generator is used, once that to generate active power the squirrel cage induction generator needs to be supplied with reactive power from the grid.

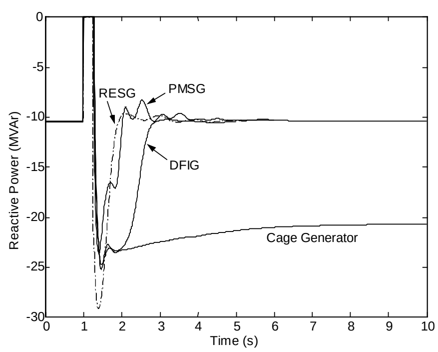

Fig. 12. Reactive Power Behavior

After the fault event there is an additional need for reactive power in order that the fixed speed Wind generation system be kept stable. This reactive power in part comes from the synchronous generators connected to the conventional systems of the electrical grid, and also can be complemented through dynamic reactive compensation (SVC, ASVC, Synchronous condenser) that are installed near by the wind park installation. This second alternative however, is considered economically less viable.

Another solution is constituted by the utilization of variable speed wind generation systems based on DFIG and Synchronous Generators, whose static converters can control independently reactive power and active power, as were show by simulation results presented.

The action of the static converters helped to maintain the transient stability margin of the generation system, permitting that the reactive power demanded by the wind park during the fault period returns to its original value when the fault was cleared.

5 CONCLUSIONS

In this paper adequate dynamic models were developed for the representation of the most important variable speed wind generators that are used today in wind parks worldwide, namely the doubly-fed asynchronous generator, the permanent magnet and rotor excited synchronous generators. The simulation results obtained for an electrical network example have demonstrated a good dynamic performance for all variable speed wind generators tested. The static converters and their controllers compensate small differences among operational characteristics of the different generators, so that the obtained results are very similar in respect with the interaction with the electrical power system.

The transient stability margin of variable speed wind systems was compared with that of the fixed speed wind systems, which are directly connected to the electrical grid. The obtained results have clearly demonstrated the superior dynamic performance presented by the variable speed wind generators in terms of a better controllability characteristic with respect to the connected electrical grid. Such a performance was possible due to the action of the static converters controllers.

6 APPENDIX

Induction Generator: Index 1 corresponds to the stator parameters and 2 to the rotor parameters in p.u. Rated generator power = 660 kW, Rated Voltage=690 V, Rated generator slip=2 %, R1=0.0067, R2=0.0058, X2=0.0506, X1=0.03, Magnetic Reactance = 2.31, synchronous speed = 1500 rpm, number of poles = 4.

Parameters of wind turbine: number of blades=3, rotor diameter =44 m, rated speed =14m/s, relationship of gears = 55, cut-in wind speed = 3 m/s, cut-off wind speed = 25 m/s.

7 AKNOWLEDGEMENT

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