A Reduced Model for Grid Connected Wind Turbines with Permanent Magnet Generators

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***Abstract*— This paper presents a reduced order model for grid connected wind turbines with permanent magnet generators. The model is based on the field oriented control of the generator, considering that the machine terminals are fed by an ideal current regulated voltage source. This assumption makes the order of the synchronous machine model to be reduced to the first one while it still allows representing with good accuracy the main wind turbine control schemes used. A wind park composed of 20 turbines of 1MW connected to a real power system is simulated to compare the responses of the detailed and reduced order models.**

***Keywords* - Grid connected wind farms, modeling and control, permanent magnet generator, wind turbines**

I. INTRODUCTION

The use of renewable energy sources for electricity supply has been increasing in most countries around the world as a result of several factors, being the green house effect one of concerns. Besides the reasons for environmentally friend generation, the wind turbines appear currently as the most prominent alternative for clean electricity production. There are several reasons for this choice, such as the technological developments in the wind turbines construction, specially in the high power range, with more efficient units and better control capabilities, made available with their connection to the grid through power electronic converters. Last but not the least, the high reliability that the wind turbines achieved during the last decade also contribute to their large usage for renewable energy production. In particular, the permanent magnet generator (PMG) has the great advantage of not requiring the gearbox, thus reducing the noise, losses, the need for maintenance and cost of the mechanical transmission system [2].

Modeling wind farms in simulation tools for analysis of large electrical power system transient studies is essential in order to correctly evaluate the effects of connecting these new sources on the power system stability and quality. Detailed wind turbine models generally include: the wind speed and how its kinetic energy is converted to mechanical torque; the mechanical transmission system between the rotor and the electrical generator; the electrical generator; the $ac-dc-ac$ converter (if it exists) and the associated control schemes, which are used for regulating flux, electromagnetic torque, active and reactive power, dc bus voltage, etc.; the frequency converter output filter and the electrical equipment necessary for integrating the power from the wind farm into the grid.

The wind farm is usually represented by one single equivalent turbine that characterize the dynamical behavior of the entire wind farm. Many works have been presented in recent years about dynamic models and control techniques of wind turbines [3],[4],[5],[6],[7],[8]. The simulation tools most frequently used for analyzing power electronics and vector controlled ac machines are not suitable for large power system simulations or are very expensive limiting the wide use from the academic and scientific community. On the other hand, the most popular simulation program for power system transient analysis do not include detailed wind farm models as described above in their libraries. This is the case of ATP (Alternative Transient Program). Additionally, a wind farm model that represents the frequency converters operation and all the demanded control loops requires generally a small calculation time step, increasing the computational burden, specially when the wind farm is connected to a large power system. Sometimes, depending on the size of the power system, the simulation is unfeasible.

In this paper, a simplified model is presented in order to reduce the computational effort of simulating grid connected wind farms driven by PMG in ATP, which is a free software and widely used tool around the world for power system transient studies. Some considerations are presented showing how the time step for the simulation can be increased with the reduced models hence reducing the computacional burden. Simulation of events such as short circuits are used to compare the dynamic responses of the detailed and reduced models.

II. DETAILED MODEL OF THE WIND TURBINE AND PMG

A. *Wind and Mechanical Sub Model*

The mechanical power that is converted into the electrical form in a wind turbine can be characterized by [9]:

$$P = \frac{1}{2}\rho A C_p(\lambda, \beta) V^3, \qquad (1)$$

where ρ is the air density, A is the area swept by the turbine rotor πR^2, $C_p(\lambda, \beta)$ is the power coefficient, which can be understood as the conversion efficiency of the turbine and V is the wind speed. This parameter depends on the blade angle β and on the tip speed ratio (λ) that can be defined as

$$\lambda = \frac{\omega_t R}{V}, \qquad (2)$$

where $\omega_t R$ is the blade tip speed and R is the turbine rotor radius.

The wind speed acting on each wind turbine in a wind farm is different due do several factors. For power system analysis it is usual to model the wind speed as a single one acting on all wind turbines at the same time, also wind turbine is usually scaled up to represent the power produced by the wind farm[3]-[11].

The power coefficient C_p depends on the tip speed ratio and on the pitch blades angle β. Constant angular speed wind turbines are designed to reach maximum C_p for rated wind speed. If the wind speed is different from that, the maximum power extraction is not achieved. In variable speed wind turbines, the maximum power coefficient can be tracked. Using (3), the optimum tip speed ratio λ^{opt} can be determined and, given the wind speed, the optimum rotor angular speed ω_t^{opt} can be obtained. Some wind turbines use the blade angle to control the torque and therefore it is possible to reduce the torque when the wind speed reaches a specific value and maintain the safe operation of the wind turbine.

Usually the wind turbines manufacturers do not publish the blade control strategy and therefore the power coefficient is not explicit. Hence, an empirical power coefficient is used here as proposed in [4]:

$$C_p(\lambda,\beta) = 0.22\left(\frac{116}{\lambda_i} - 0.4\beta - 5\right)e^{\frac{-12.5}{\lambda_i}}, \tag{3}$$

where λ_i is obtained from

$$\frac{1}{\lambda_i} = \frac{1}{\lambda + 0.08\beta} - \frac{0.035}{\beta^3 + 1}. \tag{4}$$

The generator angular speed w_r in electrical radians per second is obtained using the following relation:

$$\omega_r = \frac{poles}{2}\omega_t. \tag{5}$$

B. Permanent Magnet Generator - PMG

The most frequently used permanent magnet machine equations for simulating converter-fed vector controlled drives, in a dq reference frame rotating in an arbitrary speed ω_a, are:

$$\begin{aligned} v_{sd} &= R_s i_{sd} + \tfrac{d}{dt}\lambda_{sd} - \omega_a \lambda_{sq} \\ v_{sq} &= R_s i_{sq} + \tfrac{d}{dt}\lambda_{sq} + \omega_a \lambda_{sd} \\ \tfrac{2J}{poles}\tfrac{d}{dt}\omega_r &= T_e - T_{mec} - \tfrac{2b}{poles}\omega_r \end{aligned} \tag{6}$$

where v_{sd} and v_{sq}, i_{sd} and i_{sq}, λ_{sd} and λ_{sq} are the direct and quadrature axis components of the stator voltage vector $\overrightarrow{v_s}$, stator current vector $\overrightarrow{i_s}$ and stator flux vector $\overrightarrow{\lambda_s}$, respectively; R_s is the stator resistance; ω_r is the rotor angular speed in electrical radians per second; J is the total inertia, including the wind turbine aerodynamic rotor as presented in [4]; b is the viscous friction coefficient; T_e and T_{mec} are the electromagnetic and external torques.

The flux-current relations are:

$$\begin{aligned} \lambda_{sd} &= L_{sd} i_{sd} + \Lambda \\ \lambda_{sq} &= L_{sq} i_{sq} \end{aligned} \tag{7}$$

where L_{sd}, L_{sq} are the stator direct and quadrature axis inductances, and Λ is the permanent magnet flux.

The machine electromagnetic torque is

$$\begin{aligned} T_e &= \tfrac{3}{2}\tfrac{poles}{2}(\lambda_{sd} i_{sq} - \lambda_{sq} i_{sd}) \\ &= \tfrac{3}{2}\tfrac{poles}{2}(\Lambda i_{sq} + (L_{sd} - L_{sq}) i_{sd} i_{sq}). \end{aligned} \tag{8}$$

The total active power delivered to the stator terminals, minus the time rate of change of the stored magnetic energy, is

$$P_s = \frac{3}{2}[\omega_a(\Lambda i_{sq} + (L_{sd} - L_{sq}) i_{sd} i_{sq}) + R_s({i_{sd}}^2 + {i_{sq}}^2)]. \tag{9}$$

Since the machine model was written using a motor notation, i. e., an active power flow from the power system to the machine was considered positive, a negative mechanical torque should be imposed to represent a generator operation.

C. $AC - DC - AC$ Converter

The usual converter topology is represented in most simulation programs, which consists of two back-to-back connected, two-level $dc-ac$ fully controlled converters. The vector PWM scheme or some equivalent method for the ac output voltages synthesis is simulated.

Taking into consideration the time frame of the studies, the converter switches are usually considered to be ideal. Hence the dead time, losses and voltage drops are neglected. The dc bus voltage V_{dc} is calculated from:

$$C\frac{d}{dt}V_{dc} = \frac{P_{in} - P_{out}}{V_{dc}}, \tag{10}$$

where C is the equivalent capacitance of the dc bus, $P_{in} - P_{out}$ is the net power flow through the dc bus.

D. Output Filter

The $ac-dc-ac$ converter is connected to the grid through an output filter. The output filter voltage-current relations, in a synchronous dq reference frame can be described as:

$$\overrightarrow{v}_{grid} = \overrightarrow{v}_{conv} + R\overrightarrow{i} + L\frac{d}{dt}\overrightarrow{i} + \omega L\overrightarrow{i}, \tag{11}$$

where $\overrightarrow{v}_{grid}$ and $\overrightarrow{v}_{conv}$ are the voltage vectors of the filter terminals connected to the grid and to the converter, respectively, $\overrightarrow{i}$ is the current vector through the filter inductor and ω is the power system angular frequency.

E. Wind Turbine Control

The wind turbine complete control scheme is illustrated in Fig. 1.

Given the wind speed and the optimum tip speed ratio, the turbine angular speed for Maximum Power Point Tracking (MPPT) is obtained from (2) and the corresponding generator angular speed in electrical radians per second from (5). Thus, for maximum power production, the generator angular speed is controlled using a vector control scheme.

Using a dq reference frame oriented by the permanent magnet position and imposing $i_{sd} = 0$, equation (8) shows that i_{sq} can be used for controlling the electromagnetic torque.

Neglecting the converter losses, the difference between the power delivered to the MSC (Machine Side Converter) by

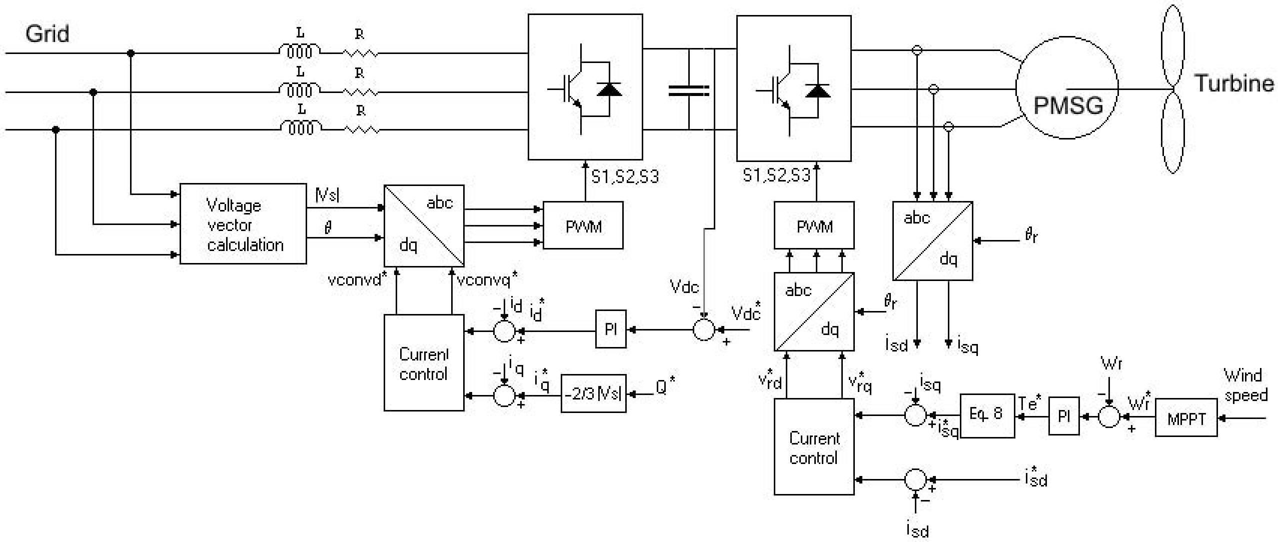

Fig. 1. Detailed model of the generator and MSC and GSC control scheme.

the stator circuit and the power absorbed by the grid through the Grid Side Converter (GSC) is stored in the DC link capacitor. Thus, the control of the active power flow through the converter to the grid is indirectly made by regulating the DC bus voltage. Using a dq reference frame oriented by the grid voltage vector, this power flow is given by:

$$P = \frac{3}{2} Re\{\overrightarrow{v}_{grid} \overrightarrow{i}^{\dagger}\} = \frac{3}{2} v_{gridd} i_d \tag{12}$$

Therefore, the d axis component of the filter inductor current i_d is used for the DC bus voltage control.

Analogously, the reactive power delivered to the grid by the GSC is:

$$Q = \frac{3}{2} Im\{\overrightarrow{v}_{grid} \overrightarrow{i}^{\dagger}\} = -\frac{3}{2} v_{gridd} i_q \tag{13}$$

and i_q is used for imposing the desired reactive power.

The outputs of the active and reactive power controllers are, then, the reference currents i_d^* and i_q^* for closed loop control. The current controllers outputs are the reference voltages of the GSC: v_{convd}^* and v_{convq}^*. Again, a PWM method is applied for the GSC switches command.

III. Proposed Reduced Model

When the PWM operation of the MSC and GSC is considered in the simulation program, the instant when any of the converter switches close or open must be accurately represented. For this reason, the simulation requires the use of a time step much smaller than the switching period. Even if these converters were considered as ideal controlled voltage sources, the closed loop controlled current (i_{sd}, i_{sq}, i_d and i_q) responses would be very fast and might require a small time step for accurate simulation response.

In the reduced model presented here, the generator stator current components and also the GSC output filter current components are considered to be ideally imposed. This assumption greatly simplifies the system model, since the synchronous machine model has its order reduced to one due to the previous assumption of stator currents ideal imposition.

Using a dq reference frame oriented by the permanent magnet position and considering that i_{sd} is ideally maintained equal to zero and

$$i_{sq} = \frac{T_e^*}{\frac{3}{2}\frac{poles}{2}\Lambda}. \tag{14}$$

Then equation (8) shows that the reference electromagnetic torque is ideally imposed.

The grid side converter and current controllers are also assumed ideal. Further, the active power injected into the DC bus by the stator circuit is considered to be instantaneously transferred to the grid. This assumption makes the DC bus voltage to be maintained equal to the desired value. So, the DC bus voltage does not need to be included in the model. Thus, the value of the d axis current of the filter inductor in a grid voltage vector reference frame which should be imposed for ideal DC bus voltage control can be obtained by forcing $P^* = P_s$, or, from (9):

$$i_d = \frac{\frac{3}{2}\omega_r \Lambda i_{sq} + R_s {i_{sq}}^2}{\frac{3}{2} v_{gridd}}. \tag{15}$$

The q axis current component is calculated for controlling the GSC reactive power injection:

$$i_q = -\frac{2}{3}\frac{Q^*}{v_{gridd}}. \tag{16}$$

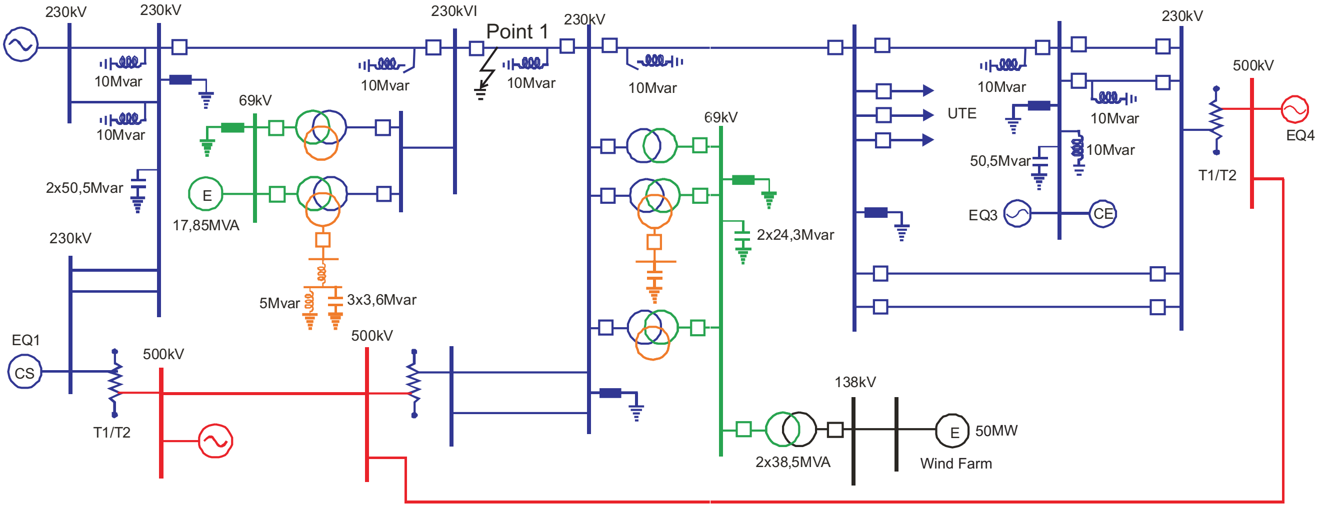

Fig. 2. Simulated power system.

where Q^* is the desired reactive power delivered to the converter by the grid.

Fig. 3 depicts the reduced model of the machine and the schemes for maximum power point tracking, machine side converter control, and also for the grid side converter real and reactive power control.

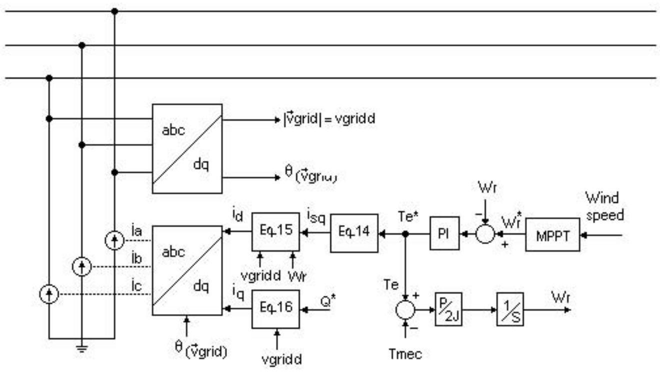

Fig. 3. Reduced model of the generator and MSC control scheme .

IV. Detailed and Reduced Models Dynamic Behavior

The detailed model dynamic response can be characterized by analyzing each closed loop control subsystem presented in Fig. 1.

For example, the active power control for achieving MPPT is performed according to the block diagram of Fig. 4. The parameters of the PI controllers are chosen for obtaining fast and precise dynamic responses. However, it makes no sense

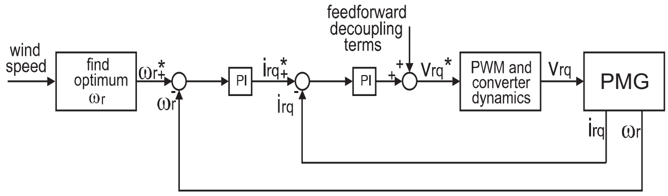

Fig. 4. Control scheme for MPPT in the detailed model.

trying to impose a closed loop dynamic response faster than that of the controller output quantity. For example, it would not be reasonable to set the PI gains for a current dynamic response with a time constant smaller than one switching period of the converter. It is then usual to calculate the PI gains of the current control loops so that the two closed loop response time constants are equal to 5 times and 25 times the converter switching period, approximately. For determining the closed loop transfer function, the converter dynamics is generally neglected, due to its much faster response. The same criterion is frequently used for calculating the rotor speed PI controller parameters, i.e., these parameters are chosen so that the two time constants of the closed loop angular speed transfer function are equal to 5 times and 25 times the biggest time constant of the current response. The other control subsystems of Fig. 1 may be analyzed in the same way for estimating the PI gains and the closed loop time constants of each subsystem.

For the simulation of a wind driven PMG using the detailed model, the time step to be used must be considerably lower than the time constants of the fastest varying quantities (or the smallest time constants), which are the MSC and GSC output voltages. Considering space vector PWM, four different output voltage vectors are applied each switching period (two active and two zero voltage vectors). The simulation time step must then be much smaller than the switching period.

As shown in section III, in the reduced model, the MSC and GSC converters are assumed to behave as ideal current regulated voltage source inverters, i.e., the machine is considered to be fed by ideal controlled current sources. As a consequence, the reduced model time constants are those that characterize the closed loop speed control. The simulation time step for the reduced model must be small as compared to this time constant, which is much bigger than the converter switching period.

V. Simulation Results

In order to verify the transient responses of the reduced model as compared to those of the detailed model, a test case was created and different events were simulated, including a short circuit in the power system. In the test case, a part of a regional 500/230/138/69kV power system is modeled and also the entire distribution grid till the wind farm point of common coupling (PCC). The wind farm has 20 wind turbines of 1MW each resulting in a 20MW wind farm rated capacity. The power system components, such as the lines, transformers, capacitor and reactor banks, etc. are included in the simulation program using the elements available in the ATP libraries. The wind turbine, PMG and the GSC and MSC controllers were represented using TACS (Transient Analysis of Control Systems). Current sources with values determined in the TACS elements are used to represent the interaction between the power system and the wind generation system.

The simulated power system with the wind farm connected is shown in Fig. 2.

Fig. 5 to Fig. 10 show the transient responses of the detailed and reduced models to a short-circuit at point 1 in fig. 2.

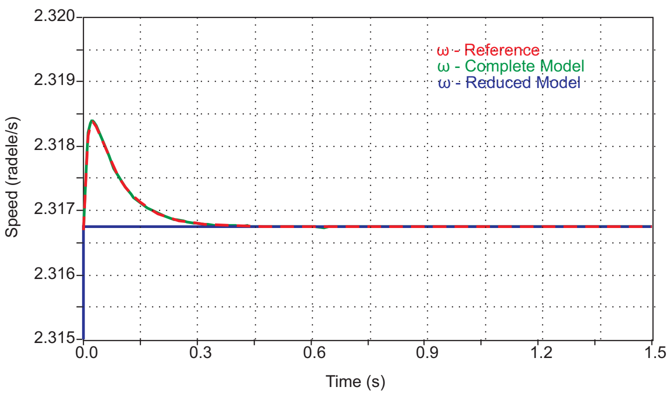

Fig. 5. Rotor electrical angular speed.

As expected, those responses are very similar, since the same control scheme was represented in both simulation programs. However, the effects of the converter switchings and non-ideal current control make the reduced model responses smoother. It is seen that the optimum speed is tracked in both models, although the oscillations that appear in the electromagnetic torque are reduced in the reduced model, due to the assumption of ideal current controlled voltage source converters. The oscillations are also reduced in the active and reactive power components obtained with the reduced model.

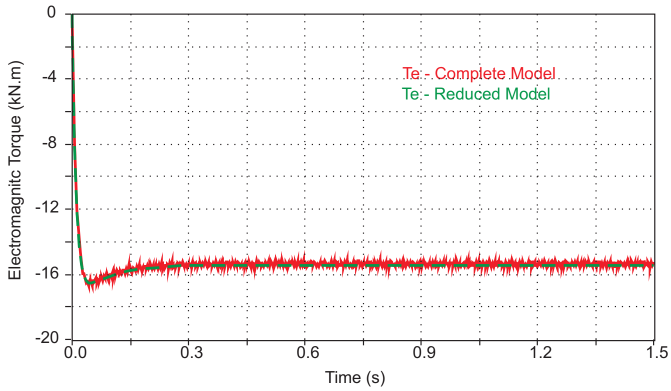

Fig. 6. Electromagnetic torque.

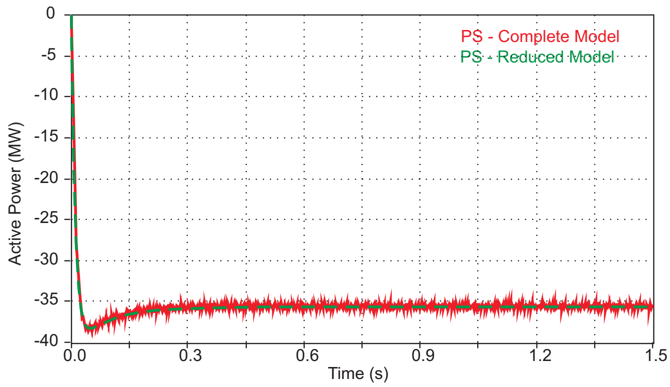

Fig. 7. Active power delivered to the stator terminals.

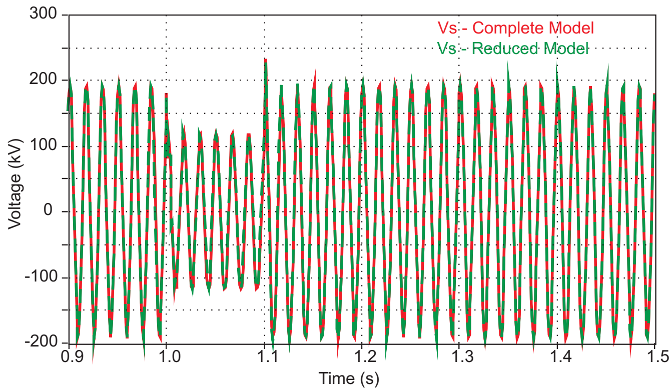

Fig. 8. Voltage comparisons at wind turbine terminals.

Fig. 8 shows that the voltages at the point of common coupling obtained with the detailed and reduced models were very similar. The same is true for the current in the faulted line, shown in Fig. 9.

It should be mentioned that for simulating a wind farm using the detailed model, a simulation time step of $1x10^{-6}$s could be necessary, depending on the switching frequency. A much bigger time step would be allowed if the reduced model were used. In order to compare the computational burden of the two models, the simulations presented were performed using the same time step. The simulations using the reduced model were 2 to 3 times faster.

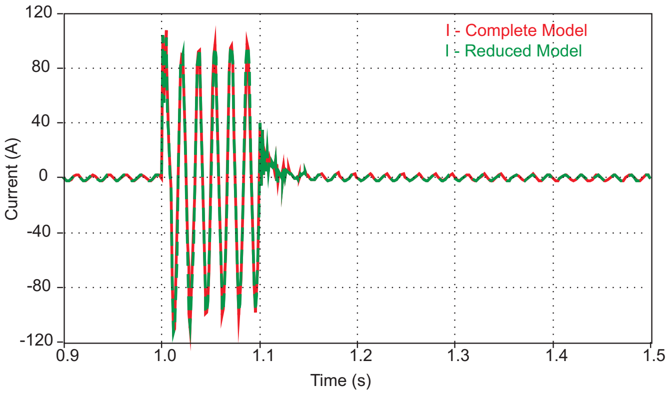

Fig. 9. Current comparison among the two proposed models.

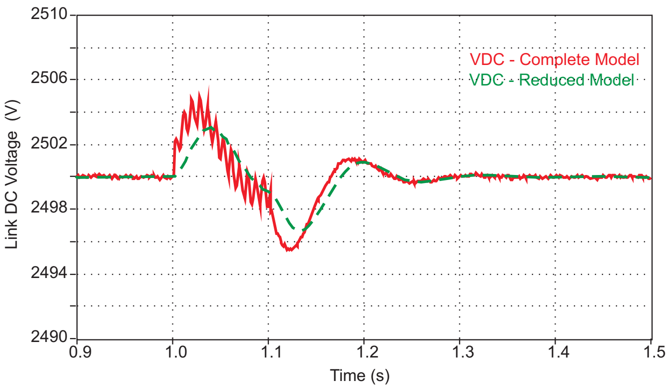

Fig. 10. DC link voltage comparison among the two proposed models.

VI. CONCLUSION

Despite the simplifying assumptions, the reduced model proposed in this paper allows representing with good accuracy the main controllers used to impose active and reactive power flow between the wind farm and the power system. For this reason, the transient responses of a 20MW wind farm connected to a real power system simulated using the detailed and reduced models were very similar. The simulation results showed that the proposed reduced model is adequate for evaluating the effects of connecting wind farms with permanent magnet synchronous generators to large power systems using ATP.

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