Reduced Order Model for Grid Connected Wind Turbines with Doubly Fed Induction Generators

A. Samuel Neto, S. L. A. Ferreira, J. P. Arruda, F. A. S. Neves, P. A. C. Rosas, M. C. Cavalcanti
Departamento de Engenharia Elétrica e Sistemas de Potência
Universidade Federal de Pernambuco
Recife - PE, Brazil
Email: asneto01@yahoo.com.br, slaf@infonet.com.br, josue_p_arruda@yahoo.com.br, fneves@ufpe.br,
prosas@ufpe.br, marcelo.cavalcanti@ufpe.br

***Abstract*— This paper presents a reduced order model for grid connected wind turbines with doubly fed induction generators. The model is based on the field oriented control of the generator, considering that the rotor is fed by an ideal current regulated voltage source. This assumption makes the order if the induction machine model to be reduced to three but still allows representing with good accuracy the main wind turbine control schemes used. A wind park composed of 10 turbines of 2MW connected to a real power system is simulated for comparing the responses of the complete and reduced order models.**

I. Introduction

The use of renewable energy sources for electrical energy generation has been increasing in most countries around the world. Among the alternatives for clean electricity production, the most prominent is probably the use of wind turbines. The main reasons for this choice are the technological developments in wind turbines construction, with the production of large of amount power and more efficient units, and the control capabilities made available with their connection to the grid through power electronic converters.

Modeling wind farms in simulation programs for analysis of large electrical power system transient studies is essential for evaluating the effects of connecting these new sources over the system stability and power quality. Detailed wind turbine models generally include: the wind speed and how its kinetic energy is used for producing mechanical torque; the mechanical transmission system between the rotor and the electrical generator axes; 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 connecting the wind farm to the grid.

The wind farm is usually represented by one single equivalent turbine. Many works have been presented in recent years about dynamic models and control techniques of wind turbines with doubly fed induction generator [1]-[5]. 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. On the other hand, the most popular simulation programs 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 Transients Program). Additionally, a wind farm model that represents the frequency converters and all the 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 article, a simplified model is presented in order to reduce the computational effort of simulating grid connected wind farms driven by doubly fed induction generators (DFIG) in ATP, which is a software free and one of the most used programs around the world for power system transient studies. Some considerations are presented to show how the time step for the simulation can be increased with the reduced models. Simulation results are used to compare the dynamic responses of complete and reduced models.

II. Complete Model of DFIG Driven Wind Turbine

A. Input Power and Mechanical Parts

The mechanical power converted into electrical form in a wind turbine can be characterized by [6]:

$$P = \frac{1}{2}\rho A C_p V^3, \tag{1}$$

where ρ is the air density, A is the area swept by the turbine rotor πR^2, C_p is the power coefficient, which can be understood as the conversion efficiency of the turbine and V is the wind speed. The tip speed ratio (λ) is defined as

$$\lambda = \frac{\omega_t R}{V}, \tag{2}$$

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.

The power coefficient C_p varies with the wind speed, the rotor angular speed and the pitch blades angle β. Fixed 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, empirical power coefficient is used here as proposed in [1]:

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

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 gearbox speed relation G:

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

B. Doubly fed induction generator - DFIG

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

$$\begin{array}{l} \overrightarrow{v_s} = R_s\overrightarrow{i_s} + \frac{d}{dt}\overrightarrow{\lambda_s} + j\omega_a\overrightarrow{\lambda_s} \\ \overrightarrow{v_r} = R_r\overrightarrow{i_r} + \frac{d}{dt}\overrightarrow{\lambda_r} + j(\omega_a - \omega_r)\overrightarrow{\lambda_r} \\ \frac{2J}{poles}\frac{d}{dt}\omega_r = T_e - T_{mec} - \frac{2b}{poles}\omega_r \end{array} \tag{6}$$

where $\overrightarrow{v}$, $\overrightarrow{i}$ and $\overrightarrow{\lambda}$ are used for voltage, current and flux space vectors and the subscripts s and r are used to indicate stator and rotor quantities, respectively; R_s and R_r are the stator and rotor resistances; ω_r is the rotor angular speed in electrical radians per second; J is the complete inertia, included the wind turbine aerodynamic rotor; b is the viscous friction coefficient; T_e and T_{mec} are the electromagnetic and external torques.

The stator and rotor flux-current relations are:

$$\begin{array}{l} \overrightarrow{\lambda_s} = L_s\overrightarrow{i_s} + L_m\overrightarrow{i_r} \\ \overrightarrow{\lambda_r} = L_m\overrightarrow{i_s} + L_r\overrightarrow{i_r} \end{array} \tag{7}$$

where L_s, L_r and L_m are the stator, rotor and mutual inductances, respectively. Using a stator flux vector oriented reference frame, the total active power minus the copper losses and time rate of change of the stored magnetic energy delivered to the stator and rotor terminals is

$$P_g = P_s + P_r = -\frac{3}{2}\omega_r\frac{L_m}{L_s}\lambda_{sd}i_{rq}. \tag{8}$$

while the stator and rotor absorbed reactive powers are:

$$Q_s = \frac{3}{2}\frac{\omega}{L_s}(|\overrightarrow{\lambda_s}|^2 - L_m\lambda_{sd}i_{rd}) \tag{9}$$

and

$$Q_r = (\omega - \omega_r)(\frac{3}{2}\sigma L_r|\overrightarrow{i_r}|^2 + \frac{3}{2}\frac{L_m}{L_s}\lambda_{sd}i_{rd}). \tag{10}$$

The total active power supplied to the machine by the power system is equal to $\frac{2}{poles}\omega_r T_e$ plus the machine losses. In a stator flux oriented reference frame, the induction machine electromagnetic torque is

$$T_e = -\frac{3}{2}\frac{poles}{2}\frac{L_m}{L_s}\lambda_{sd}i_{rq}. \tag{11}$$

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

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:

$$C\frac{d}{dt}V_{dc} = \frac{P_{in} - P_{out}}{V_{dc}}, \tag{12}$$

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

$$\overrightarrow{v}_{grid} = \overrightarrow{v}_{conv} + R\overrightarrow{i} + L\frac{d}{dt}\overrightarrow{i} + \omega L\overrightarrow{i}, \tag{13}$$

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.

Since the machine stator terminals are connected to the power system, there is no need to control the stator flux vector magnitude. Considering that the stator flux magnitude is known (obtained using a flux estimator), Equation (11) shows that i_{rq} can be used for imposing the reference electromagnetic torque. Similarly, considering that Q_s^* is the reference reactive power to be absorbed from the grid, the corresponding d axis rotor current can be calculated from 10:

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

$$Q = \frac{3}{2} Im\{\overrightarrow{v}_{grid}\overrightarrow{i}^{\dagger}\} = -\frac{3}{2} v_{gridd} i_q \quad (16)$$

and i_q is used for imposing the desired reactive power.

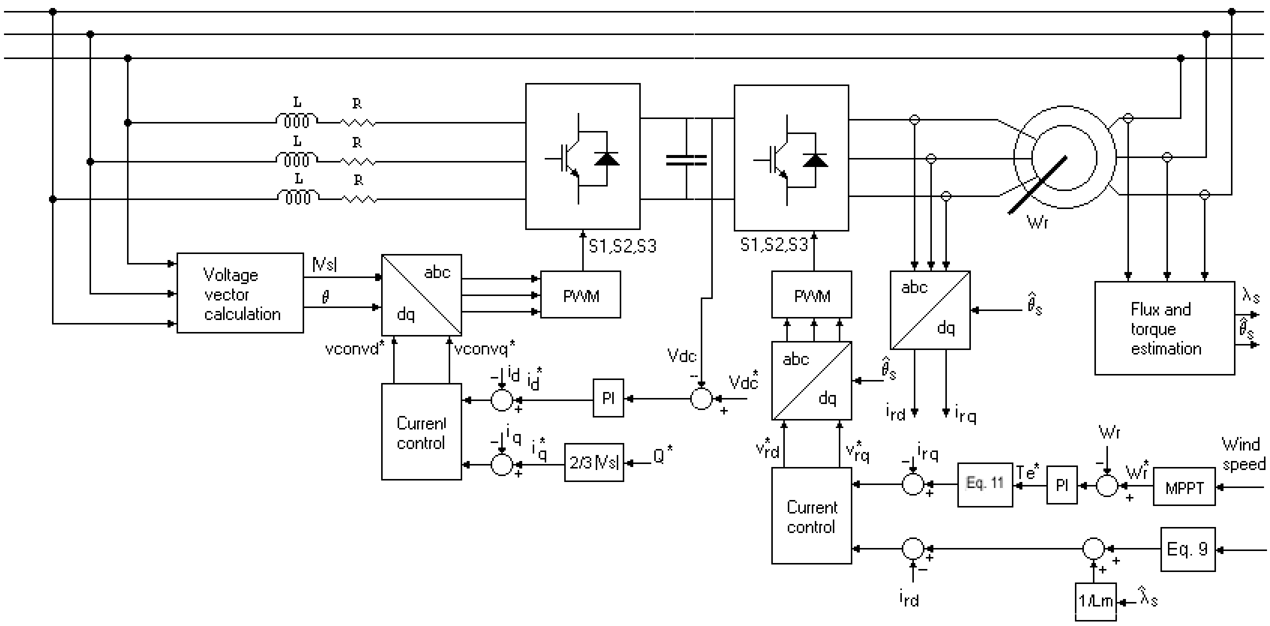

Fig. 1. Complete model of the generator and MSC and GSC control scheme.

$$i_{rd}^* = \frac{\hat{\lambda}_{sd}}{L_m} - \frac{Q_s^*}{\frac{3}{2}\frac{L_m}{L_s}\omega\hat{\lambda}_{sd}}. \quad (14)$$

The rotor reference currents i_{rd}^* and i_{rq}^* are compared to the measured values previously transformed to a stator flux oriented dq reference frame, and then the errors feed current controllers. These current controllers outputs are the command voltages v_{rd}^* and v_{rq}^* used to obtain the reference phase voltages. A PWM scheme is then applied for the machine side converter (MSC) switches command.

Neglecting the converter losses, the difference between the power delivered to the MSC by the rotor 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:

$$P = \frac{3}{2} Re\{\overrightarrow{v}_{grid}\overrightarrow{i}^{\dagger}\} = \frac{3}{2} v_{gridd} i_d \quad (15)$$

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

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. 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_{rd}, i_{rq}, i_d and i_q) responses are very fast and and might require a small time step for accurate simulation response.

In the reduced model presented here, the generator rotor 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 induction machine model has its order reduced to three due to the previous assumption of the rotor currents imposition.

In a stationary reference frame, the stator voltage equation, in terms of the stator flux and rotor current can be written as:

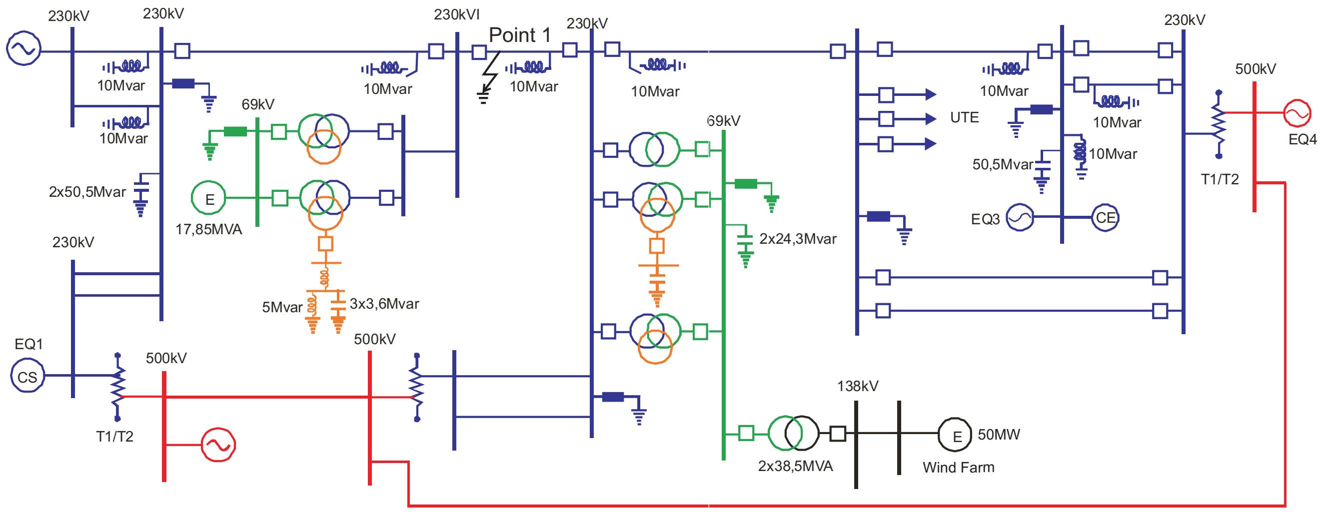

Fig. 2. Simulated power system.

$$\begin{cases} \frac{d}{dt}\lambda_{s\alpha} = -\frac{R_s}{L_s}\lambda_{s\alpha} + (v_{s\alpha} + \frac{L_m}{\tau_s} i_{r\alpha}) \\ \frac{d}{dt}\lambda_{s\beta} = -\frac{R_s}{L_s}\lambda_{s\beta} + (v_{s\beta} + \frac{L_m}{\tau_s} i_{r\beta}) \end{cases} . \tag{17}$$

The mechanical equation together with (17) are sufficient to describe the induction machine behavior.

Fig. 3 depicts the reduced model of the machine and the schemes for the stator side power control and maximum power point tracking.

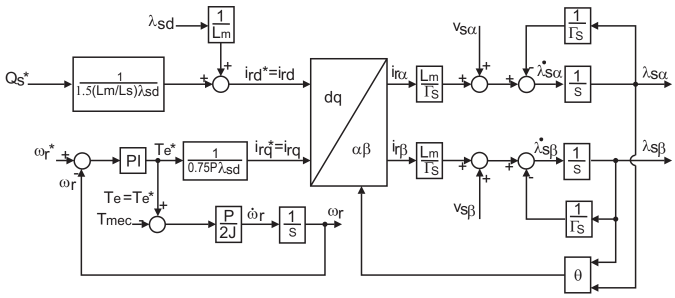

Fig. 3. Reduced model of the generator and MSC control scheme .

The grid side converter and current controllers are also assumed ideal. Further, the active power injected into the DC bus by the rotor 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 do not need to be included in the model. The d axis current of the filter inductor in a grid voltage vector reference frame is then:

$$i_d = \frac{2}{3}\frac{P_r}{v_{gridd}}. \tag{18}$$

Similarly, the q axis current component is obtained from:

$$i_q = -\frac{2}{3}\frac{Q^*}{v_{gridd}}. \tag{19}$$

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

The reduced model of the GSC control is shown schematically in Fig 4.

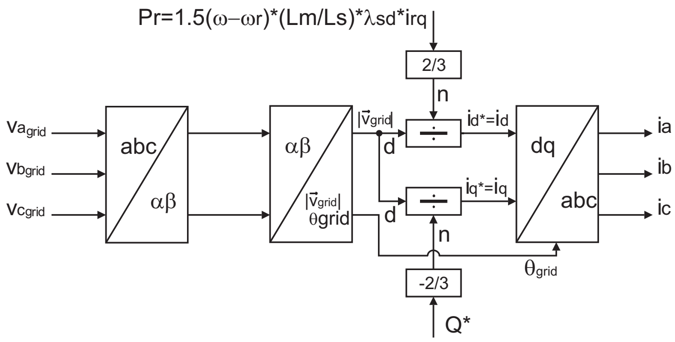

Fig. 4. Reduced model of the grid side converter control scheme .

IV. Complete and Reduced Models Dynamic Behavior

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

For example, the active power control for achieving MPPT is performed according to the block diagram of Fig. 5. The parameters of the PI controllers are chosen for obtaining fast and precise dynamic responses. However, it makes no sense 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 that one switching

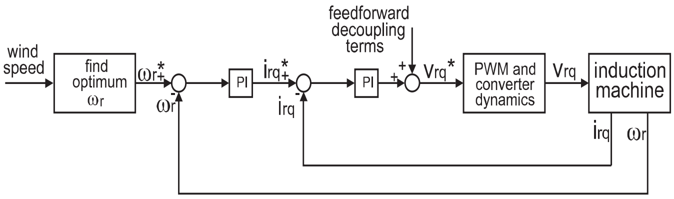

Fig. 5. Control scheme for MPPT in the complete model.

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 DFIG using the complete model, the time step to be used must be considerably lower than 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 stator flux behavior and the closed loop speed control. The simulation time step for the reduced model must be small as compared to these time constants, which are much bigger then the converter switching period.

V. Simulation Results

In order to verify the transient responses of the reduced model, a test case was created and different events were simulated, including wind speed variation and a short circuit. 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. The wind farm has 10 wind turbines of 2MW each resulting in a 20MW wind farm rated capacity 2. 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, induction generator 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 transient responses of the complete and reduced models to wind speed variations is presented below. Figs. 6, 7, 8show the rotor angular speed, electromagnetic torque, active power absorbed by the stator of the generator, total active power, respectively.

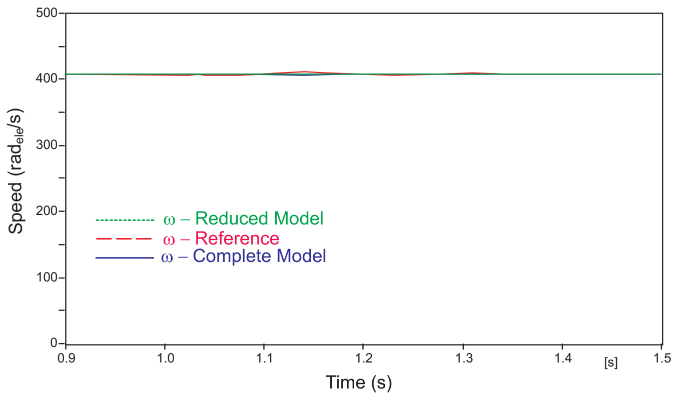

Fig. 6. Rotor electrical angular speed.

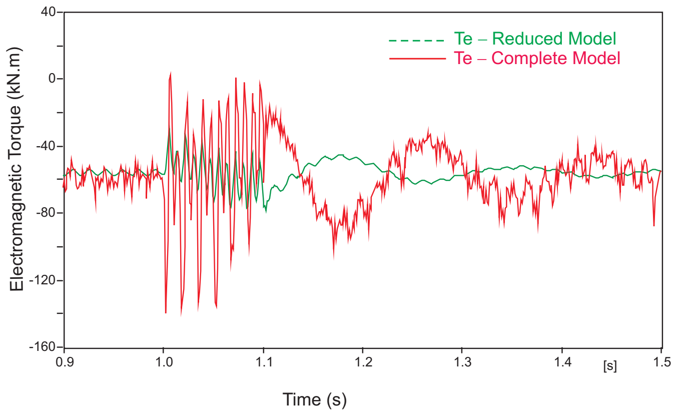

Fig. 7. Electromagnetic torque.

As expected, those responses are very similar, since the same control scheme were represented in both simulation programs. However, the effects of the converter switchings and non-ideal current control make the reduced model responses smoother.

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

Fig. 6 to Fig. 10 show the transient responses of the complete and reduced models to a short-circuit at point 1 in fig. 2.

It is seen that the optimum speed is tracked in both models, although some differences appear in the electromagnetic torque during the transient. These differences occur due to the approximations in the reduced model and appear also in

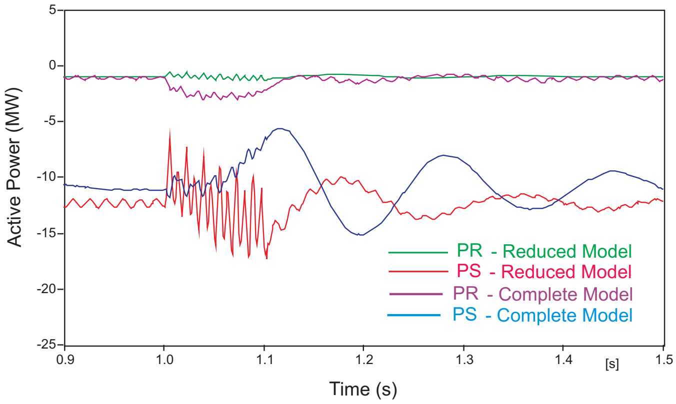

Fig. 8. Active power delivered to the stator terminals.

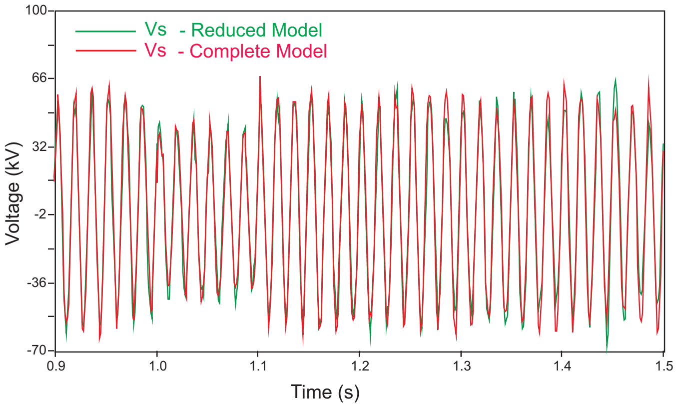

Fig. 9. Voltage.

the stator and rotor active power components. As expected, the oscillations in the reduced model are lower since ideal current controlled voltage source converters were assumed. Fig. 9 shows that the voltages at the point of common coupling obtained with the complete and reduced models were very similar. The same is true for the current in the faulted line, shown in Fig. 10.

It should be mentioned that for simulating a wind farm using the complete 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 computacional burden of the two models, the simulations presented were perfomed using the same time step. The simulations using the reduced model were 2 to 3 times faster.

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 in both rotor and stator circuits and also the power flow between the grid side converter and the power system. For this reason, the transient responses of a 20MW wind farm connected to a real power system simulated using the complete

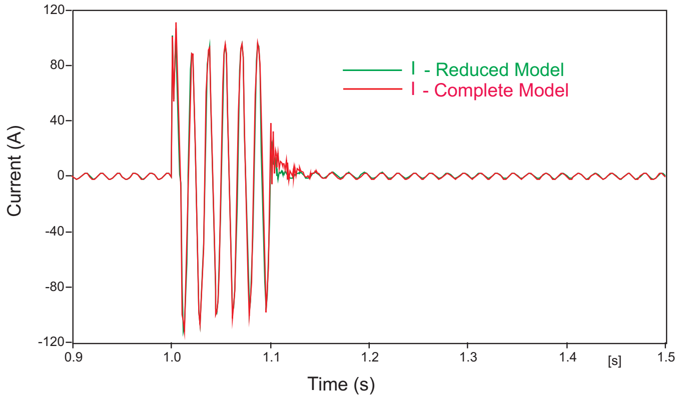

Fig. 10. Voltage.

and reduced models were very similar. The simulation results showed that that proposed reduced model is adequate for evaluating the effects of connecting wind farms with doubly fed induction generators to large power systems using ATP.

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