Modeling and Power Control of 5th and 3rd order model for DFIG Applied of Wind Conversion System

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Abstract – *In this study, a comparison between the fifth-order model and the third-order model of the Doubly Fed Induction Generator (DFIG) is presented. This paper aims to study and analyze transient stability for the fifth-order and third-order models. The fifth-order model of the DFIG is based on five differentials equations. Neglecting the stator transients from the fifth-order model of the DFIG, we get the third-order. On startup and control of the power system that the third-order model produces better results than the fifth-order model in the transient regime. The performance of the two models on the startup and control of the power system is proved with the simulations (MATLAB/Simulink® software).*

Keywords: *DFIG, Transient stability, Wind energy, Vector control.*

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I. Introduction

Recently, Renewable Energy Sources (RES) are a natural alternative to conventional power generation. Among all RESs, wind power is the most promising and the fastest-growing. In this context, the electrical machines are generally divided into two groups: synchronous generators and induction generators. In induction generators, the DFIGs are used more than squirrel cage induction generators. The advantage of the DFIG is that the power transited by both converters, rotor side and grid side, is ± 30% of the total power supplied by the DFIG stator [1, 2]. On the other hand, the switching losses are lower, the manufacturing cost of the transformer is lower and the size of the passive filters is reduced, which implies a reduction in costs and additional losses. In addition, the possibility of control the active and reactive power of the DFIG stator, the reduction of stresses on the mechanical structure during the variation of wind speed, and the increase in the operating range, especially for low wind speeds where the maximum power can be easily converted [3].

Generally, the fifth-order model representation of the DFIG is more to use. The fifth-order model consists of five differential equations, representing the state variables of the stator, rotor, and generator speed. Although the fifth-order model is considered the most accurate, it has some problems [4]. Among these problems, the fifth-order model undoubtedly complicates the simulation model and represents a very long simulation time when dealing with a large wind farm. In addition, the fifth-order model of the DFIG is not suitable for transient stability studies because the interface with the voltage and current phases of the power system is not easily implemented [5]. The alternative to the fifth-order model in the study and analysis of the transient stability, including the wind farm, is the reduced-order models, which lower the computational requirements. Among all the reduced-order models, the third-order model is most used in wind energy applications [6, 7]. To obtain the third-order model, it is necessary to neglect the derivatives of stator flux linkages, which appear in the fifth-order model in Park's equations. The theoretical explanation of neglecting electrical transients is proposed in [8, 9]. In [10], proposed a theoretical study and comparison between three reduced-order models of induction machines. In [11], the authors presented a comparison between a fifth-order model and a third-order model of the DFIG in wind turbine applications. For the integration of the third-order model in the power system, we must neglect grid transients so that we have a coherent set of equations. An overview of various dynamic models of induction machines is presented in [12]. A simplified DFIG model for the representation of positive sequence and negative sequence components in wind energy conversion systems is proposed in [4].

In this context, several control schemes for DFIG have been proposed and developed in recent years. Among these schemes, vector control (with stator flux or voltage orientation) is the most widely used to control the active and reactive power of the stator DFIG. The decoupled control of the instantaneous active and reactive power of the stator has been achieved by controlling the rotor currents either using linear or nonlinear controllers. The linear control such as the classical Proportional-Integrator (PI) controller proposed in [12, 13]. On the other hand, there are non-linear controllers such as sliding mode control, backstepping, and fuzzy logic [1, 14, 15].

This paper deals with the detailed modeling of fifth and third-order models of the DFIG based on transient reactance. In addition, the comparison between fifth-order and third-order models of the DFIG is presented. This comparison was made between the two models in an open and closed loop. The main contribution of this paper is the study and analysis of transient stability, as well as to clarify the impact of both two models of the DFIG on the power system.

The paper is organized as follows: Section 2 gives a description of a DFIG in a wind power system. In Section 3, a detailed model of fifth-order and third-order for DFIG based on transient reactance is presented. In section 4, the control of the DFIG based on vector control with stator flux orientation is presented. The simulations results of the DFIG models mentioned in this work in the open and close loop are presented and discussed in Section 5. Finally, section 6 outlines the main conclusions of the paper.

II. DESCRIPTION OF DFIG IN WIND POWER SYSTEM

In Figure 1, the control scheme of a wind energy conversion system based on a DFIG is depicted.

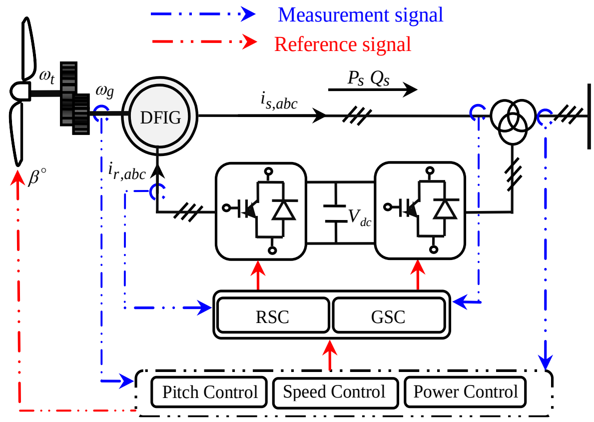

Figure 1. Control scheme of a wind energy conversion system based on a DFIG.

The DFIG consists of two three-phase windings, in stator and rotor. Generally, the stator of the DFIG is connected directly to the electrical network through three-phase lines while the rotor is connected to the electrical network through two bidirectional AC-DC and DC-AC converters. The converters on the generator side and on the grid side are modeled as a voltage. The main purpose of these converters is to change the frequency between the electrical network and the generator rotor, allowing the operation of wind turbine at variable speed. The Grid Side Converter (GSC) controls the DC bus voltage and the Rotor Side Converter (RSC) controls the active and reactive stator power.

III. MODELING OF DFIG IN WIND POWER SYSTEM

Typically, the electrical system part of a wind power system consists of a generator, a set of power electronics converters, and a control system. Generally, the induction machine is modeled using the well-known "T-form" equivalent circuit with self and mutual inductances [16]. The DFIG is generally represented by fifth-order differential equations of the flux linkages and shaft speed. According to a standard per-unit notation, can be represented this model in the $(d-q)$ rotating reference frame by the stator and rotor voltages equations which can be written as follows [4, 13]:

$$\begin{cases} \dfrac{1}{\omega_{base}}\dfrac{d\phi_{sd}}{dt} = v_{sd} + R_s i_{sd} + \phi_{sq} \\ \dfrac{1}{\omega_{base}}\dfrac{d\phi_{sq}}{dt} = v_{sq} + R_s i_{sq} - \phi_{sd} \end{cases} \tag{1}$$

$$\begin{cases} \dfrac{1}{\omega_{base}}\dfrac{d\phi_{rd}}{dt} = v_{rd} - R_r i_{rd} + s\phi_{rq} \\ \dfrac{1}{\omega_{base}}\dfrac{d\phi_{rq}}{dt} = v_{rq} - R_r i_{rq} - s\phi_{rd} \end{cases} \quad (2)$$

Where v_{sd}, v_{sq} and v_{rd}, v_{rq} are the stator and rotor voltages, respectively, i_{sd}, i_{sq} and i_{rd}, i_{rq} are the stator and rotor courants, respectively, ϕ_{sd}, ϕ_{sq} and ϕ_{rd}, ϕ_{rq} are the stator and rotor flux, R_s, R_r are the stator and rotor resistances, respectively, ω_s is the synchronous speed, ω_{base} is the synchronous speed base, s is the slip.

The electromagnetic relations can be expressed as follows:

$$(\Phi_s) = \begin{pmatrix} \phi_{sd} \\ \phi_{sq} \end{pmatrix} = \begin{pmatrix} -X_s i_{sd} + X_m i_{rd} \\ -X_s i_{sq} + X_m i_{rq} \end{pmatrix} \quad (3)$$

$$(\Phi_r) = \begin{pmatrix} \phi_{rd} \\ \phi_{rq} \end{pmatrix} = \begin{pmatrix} X_r i_{rq} - X_m i_{sd} \\ X_r i_{rq} - X_m i_{sq} \end{pmatrix} \quad (4)$$

With the stator and rotor reactance defined as follows: $X_s = X_{s\sigma} + X_m$, $X_r = X_{r\sigma} + X_m$,

Where $X_{s\sigma}, X_{r\sigma}$ is the stator and rotor leakage reactance, respectively.

The fifth differential equation describing mechanical motion is:

$$\frac{2H}{\omega_s}\frac{d\omega_g}{dt} = T_{mec} - T_{em} \quad (5)$$

Where H is the inertia constant in seconds T_{mec} is the mechanical torque and T_{em} is the electromagnetic torque.

III.1.1. Fifth-order model of the DFIG

In this section, model fifth-order based on transient reactance and internal voltage components are presented. According to equation (4), the rotor currents, as follows:

$$\begin{cases} i_{rd} = \dfrac{\phi_{rd} + X_m i_{sd}}{X_r} \\ i_{rq} = \dfrac{\phi_{rq} + X_m i_{sq}}{X_r} \end{cases} \quad (6)$$

Substituting equation (6) into equation (3), we get the stator flux as follows:

$$\begin{cases} \phi_{sd} = -X' i_{sd} + E'_q \\ \phi_{sq} = -X' i_{sq} - E'_d \end{cases} \quad (7)$$

With $E'_d = -\dfrac{X_m}{X_r}\phi_{rq}, E'_q = \dfrac{X_m}{X_r}\phi_{rd}, X'_s = X_s - \dfrac{X_m^2}{X_r}$

After substituting equations (6) and (7) into equations (1) and (2), the fifth-order model of the DFIG behind a transient reactance is obtained:

$$\begin{cases} \mu\dfrac{di_{sd}}{dt} = \left(-R_s - \dfrac{(X_s - X'_s)}{T'}\right)i_{sd} + (1 - s\omega_s)E'_d + \ldots \\ \quad X'_s i_{sq} - \dfrac{1}{T'}E'_q + kv_{rd} - v_{sd} \\ \mu\dfrac{di_{sq}}{dt} = \left(-R_s + \dfrac{(X_s - X'_s)}{T'}\right)i_{sq} + (1 - s\omega_s)E'_q - \ldots \\ \quad X'_s i_{sd} + \dfrac{1}{T'}E'_d + kv_{rq} - v_{sq} \end{cases} \quad (8)$$

$$\begin{cases} \dfrac{dE'_d}{dt} = -\dfrac{1}{T'}\left(E'_d - (X_s - X'_s)i_{sq}\right) + s\omega_s E'_q - kv_{rq} \\ \dfrac{dE'_q}{dt} = -\dfrac{1}{T'}\left(E'_q + (X_s - X'_s)i_{sd}\right) - s\omega_s E'_d + kv_{rd} \end{cases} \quad (9)$$

With constants defined as follows:

$$\mu = \frac{X'_s}{\omega_s},\ k = \omega_s\frac{X_m}{X_r},\ T' = \frac{X_r}{\omega_s R_r},$$

Where T' is the transient open circuit time constant, X'_s is the transient reactance, E'_d and E'_q are the internal voltage components of induction generator.

The electromagnetic torque is calculated based on internal voltage as follows:

$$T_{em} = E'_d i_{sd} + E'_q i_{sq} \quad (10)$$

III.1.2. Third-order model of the DFIG

By neglecting the stator transients in the fifth-order model of a DFIG, a third order model is obtained. The third order model frequently used in transient stability studies. The following equations describe the third-order model of the DFIG in the $(d-q)$ rotating reference frame [7].

$$\begin{cases} v_{sd} = -R_s i_{sd} - \phi_{sq} \\ v_{sq} = -R_s i_{sq} + \phi_{sd} \end{cases} \quad (11)$$

$$\begin{cases} v_{rd} = R_r i_{rd} - s\phi_{rq} + \dfrac{1}{\omega_{base}} \dfrac{d\phi_{rd}}{dt} \\ v_{rq} = R_r i_{rq} + s\phi_{rd} + \dfrac{1}{\omega_{base}} \dfrac{d\phi_{rq}}{dt} \end{cases} \quad (12)$$

Substituting equations (6) and (7) in equations (11) and (12), respectively, it is obtained a third-order model of the DFIG behind transient reactance, given by the following electrical equations:

$$\begin{cases} v_{sd} = -R_s i_{sd} + X'_s i_{sq} + E'_d \\ v_{sq} = -R_s i_{sq} - X'_s i_{sd} + E'_q \end{cases} \quad (13)$$

$$\begin{cases} \dfrac{dE'_d}{dt} = -\dfrac{1}{T'}\left(E'_d - (X_s - X'_s) i_{sq}\right) + s\omega_s E'_q - k v_{rq} \\ \dfrac{dE'_q}{dt} = -\dfrac{1}{T'}\left(E'_q + (X_s - X'_s) i_{sd}\right) - s\omega_s E'_d + k v_{rd} \end{cases} \quad (14)$$

IV. CONTROL OF DFIG IN WIND POWER SYSTEM

IV.1. Decoupling of the active and reactive powers

The following steps must be taken to connect the DFIG to the grid. The first step is to synchronize the stator voltage with the grid voltage, the second step is to connect the stator to the grid and the last step is to regulate the active/reactive power between the DFIG and the grid. In order to facilitate the control of the stator active and reactive powers injected into the electrical network, it is necessary to realize an independent control by the orientation of the stator flux. The objective of this choice is that the rotor currents are directly related to the stator active and reactive powers. An adapted control of these currents allows controlling the power exchanged between the DFIG stator and the network. If the stator flux is linked to the d-axis of the frame we have [12, 13]:

$$\phi_{sd} = \phi_s \Rightarrow \phi_{sq} = 0 \quad (15)$$

Neglecting the stator voltage drop and assuming that the network system is perfectly stable, with a single voltage that conducts a constant flux to the stator, we can easily deduce the voltages as follows:

$$\begin{cases} v_{sd} = 0 \\ v_{sq} = \omega_s \phi_{sd} = V_s \end{cases} \quad (16)$$

Where V_S is the value of the grid voltage.

From the orientation of the stator flux, the fluxes equations of DFIG stator are simplified as below:

$$\begin{cases} \phi_s = -X_s i_{sd} + X_m i_{rd} \\ 0 = -X_s i_{sq} + X_m i_{rq} \end{cases} \quad (17)$$

Using equation (17), the stator currents equation becomes the following:

$$\begin{cases} i_{sd} = -\dfrac{1}{X_s}\phi_s + \dfrac{X_m}{X_s} i_{rd} \\ i_{sq} = \dfrac{X_m}{X_s} i_{rq} \end{cases} \quad (18)$$

Substituting equation (18) in equation (4), we obtain the following expression:

$$\begin{cases} \phi_{rd} = \left(X_r - \dfrac{X_m^2}{X_s}\right) i_{rd} + \dfrac{X_m}{X_s}\phi_s \\ \phi_{rq} = \left(X_r - \dfrac{X_m^2}{X_s}\right) i_{rq} \end{cases} \quad (19)$$

By substituting equation (19) in equation (2), we obtain the following expression:

$$\begin{cases} v_{rd} = R_r i_{rd} - s\omega_s \left(\dfrac{X_r - X_m^2}{X_s}\right) i_{rq} + \left(\dfrac{X_r - X_m^2}{X_s}\right)\dfrac{di_{rd}}{dt} + .. \\ \qquad \dfrac{X_m}{X_s}\dfrac{d\phi_s}{dt} \\ v_{rq} = R_r i_{rq} - s\omega_s \left(\dfrac{X_r - X_m^2}{X_s}\right) i_{rd} + s\omega_s \dfrac{X_m}{X_s}\phi_s + ... \\ \qquad \left(\dfrac{X_r - X_m^2}{X_s}\right)\dfrac{di_{rq}}{dt} \end{cases}$$

(20)

By simplifying equation (20), we obtain:

$$\begin{cases} v_{dr} = \left(X_r - \dfrac{X_m^2}{X_s}\right)\dfrac{di_{rd}}{dt} + R_r i_{rq} + E_{a,d} \\ v_{qr} = \left(X_r - \dfrac{X_m^2}{X_s}\right)\dfrac{di_{rq}}{dt} + R_r i_{rq} + E_{a,q} \end{cases} \quad (21)$$

With $E_{a,d}$ and $E_{a,d}$ are the crosses coupling terms between the d axis and q axis:

$$\begin{cases} E_{a,d} = -s\omega_s \left(X_r - \dfrac{X_m^2}{X_s}\right) i_{rq} \\ E_{a,q} = s\omega_s \left(X_r - \dfrac{X_m^2}{X_s}\right) i_{rd} + s\omega_s \dfrac{X_m}{X_s}\phi_s \end{cases} \quad (22)$$

Using equation (21), the rotor current equation becomes the following:

$$\begin{cases} i_{rd} = \dfrac{1}{(\eta \cdot s + R_r)}(v_{rd} - E_{a,d}) \\ i_{rq} = \dfrac{1}{(\eta \cdot s + R_r)}(v_{rq} - E_{a,q}) \end{cases} \tag{23}$$

With $\eta = X_r - \dfrac{X_m^2}{X_s}$

The active and reactive power of the DFIG can be expressed by:

$$\begin{cases} P_s = V_s i_{sq} \\ Q_s = V_s i_{sd} \end{cases} \tag{24}$$

By substituting the stator currents by their expressions given in (18), the stator active and reactive power can then be expressed only as a function of these rotor currents as:

$$\begin{cases} P_s = V_s \dfrac{X_m}{X_s} i_{rq} \\ Q_s = -\dfrac{V_s}{X_s}\phi_s + \dfrac{V_s X_m}{X_s} i_{rd} \end{cases} \tag{25}$$

By replacing the rotor currents with their values from equation (23) in equation (25), we obtain the following equations for the active and reactive powers:

$$\begin{cases} P_s = \dfrac{V_s X_m}{X_s}\left(\dfrac{v_{rq} + E_{a,q}}{(R_r + \eta \cdot p)}\right) \\ Q_s = -\dfrac{V_s^2}{X_s \omega_s} + \dfrac{V_s X_m}{X_s}\left(\dfrac{v_{rd} + E_{a,d}}{(R_r + \eta \cdot p)}\right) \end{cases} \tag{26}$$

IV.2. Indirect control power of DIFG

In the section, control without a power regulation loop is presented. These forces are controlled indirectly by tuning the direct and quadratic components of the rotor current with a proportional integration (PI) corrector. Simple and fast to implement PI corrector while offering acceptable performance. The indirect control without the power control loop of the DFIG connected directly to the network is shown in Figure 2.

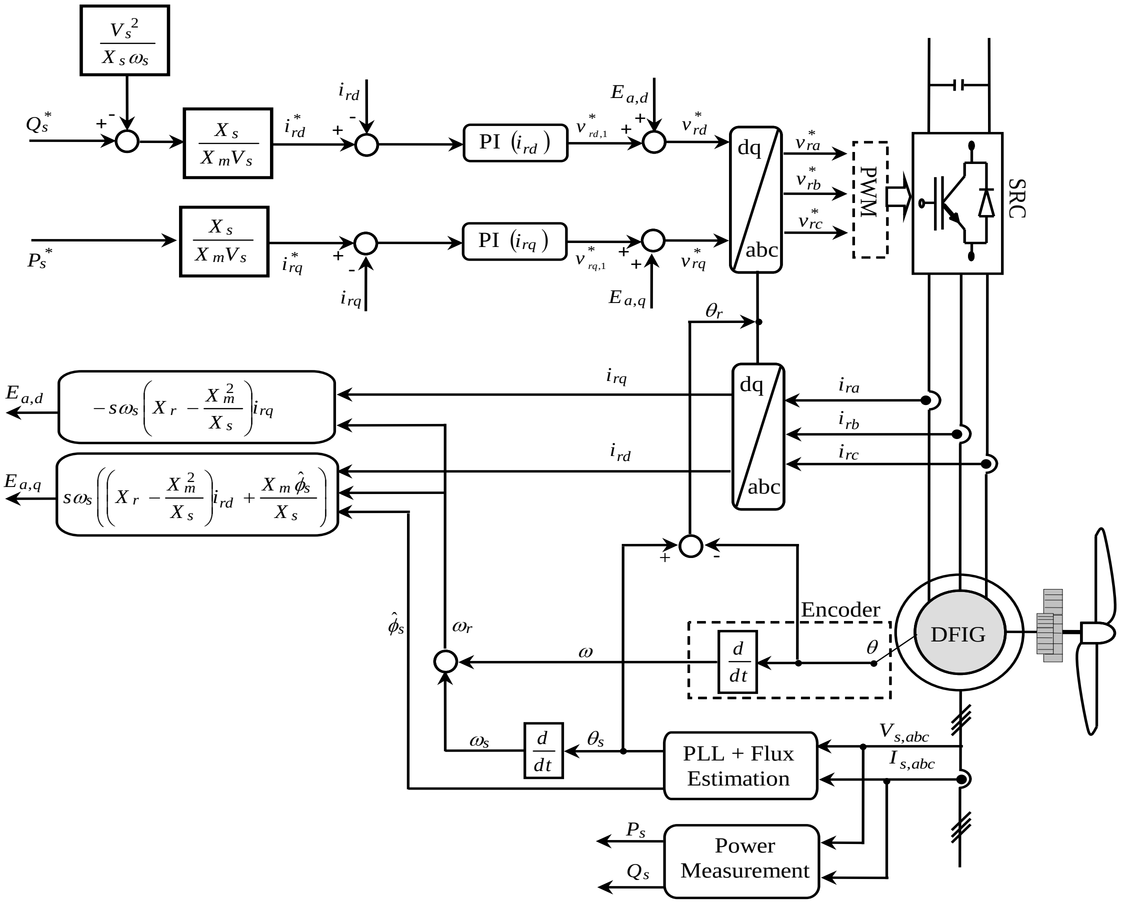

Figure 2. Indirect control without power control loop of the DFIG directly connected to the grid.

V. Simulation Results and Discussions

In this section, the comparison results between the fifth-order model and third-order model of the DFIG in the open-loop and close-loop are presented. This comparison is performed by simulations using MATLAB/ Simulink® software. The DFIG used for simulation was a 2 MW, 690 V and DFIG parameters are given in Appendix B. During the simulation period, the DFIG operates at nominal conditions. The total time of the simulation is fixed at 10s and Runge-Kutta integration is used with a 0.0001s time step.

Figure 3 shows the simulation results for the two DFIG models, fifth-order and third-order in an open loop. Figure 3a shows the generator speed applied to two models. This speed starts at 0.8 during the first five seconds of the simulation. Then it goes up to 0.95 p.u. 5 to 10 seconds. Figures 3b, 3c, 3d show respectively the electrom-agnetic torque and the currents of the stator on the $d-q$ axes.

Figure 4 shows the simulation results for the fifth-order model and third-order model of the DFIG in the closed-loop.

Figures 4a, 4b, 4c, 4d, 4e, 4f, show respectively the generator speed, the electromagnetic torque, the currents of the stator on the axes, the active and reactive power of the stator. According to the simulation results of figure 4, we notice that the active and reactive stator power (P_s, Q_s) generated by the DFIG follow their references power (P_s^*, Q_s^*) and there is a small error. Moreover, we notice that the currents (i_{sq}, i_{rq}) are promotional to the active power generated by the DFIG and that the currents (i_{sd}, i_{rd}) are promotional to the reactive power. Electro-magnetic torque has the same shape as active power because torque and active power are directly related to the quadrature rotor current.

Through the simulation results obtained in the open-loop and in closed-loop, the third-order model compared to the fifth-order model does not allow any disturbance in the magnitudes of the stator (direct and quadrature currents) and the electromagnetic torque during the DFIG start-up. Moreover, it can be concluded that the complete neglect of stator flux transients gives a stable response in the transient regime during the simulation process. Not neglecting stator flow transients, as noted above, can have critical effects on the integration of a large wind farm into the power grid. Although the dynamic behavior is similar for the two models in the permanent regime and when the generator speed changes, the third-order model is suitable for the study of transient stability.

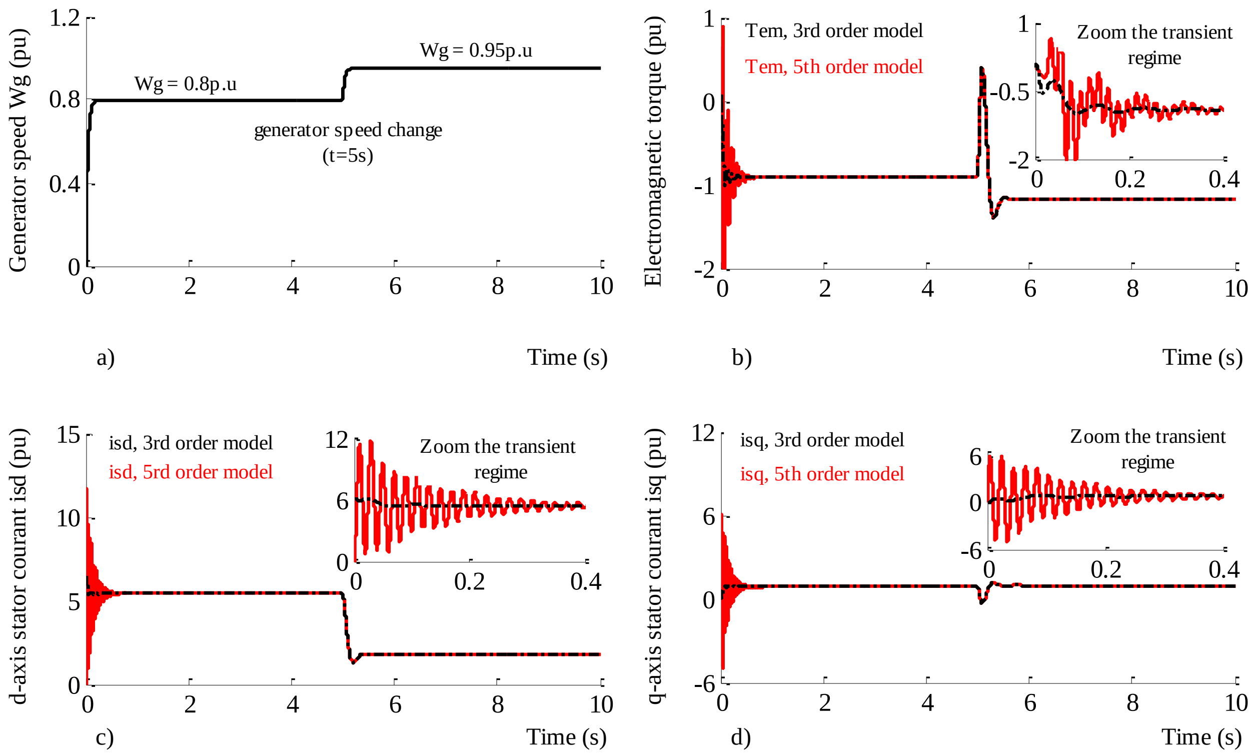

Figure 3. Comparison results between 5th and 3rd order model of the DFIG in the open-loop.

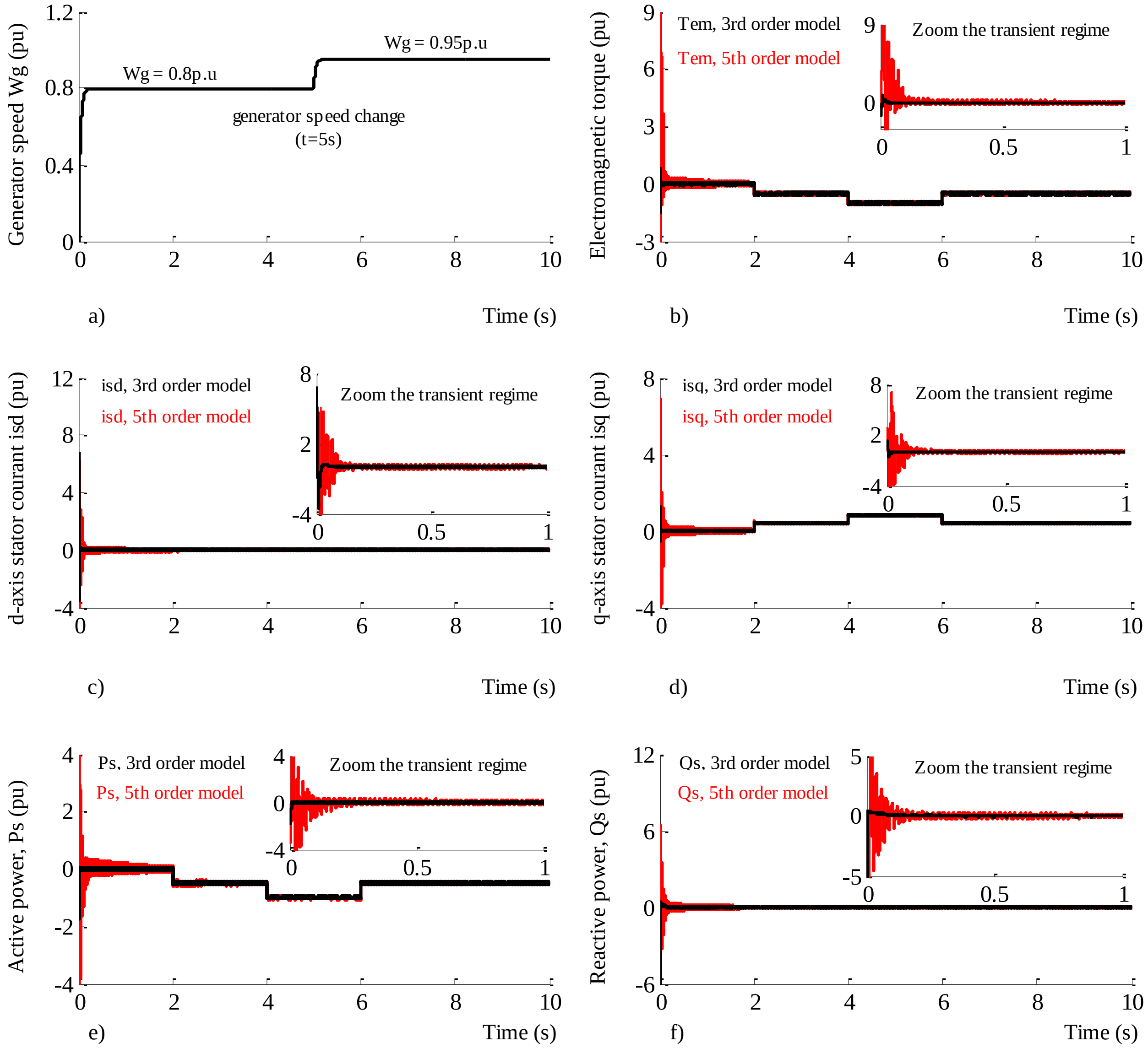

Figure 4. Comparison results between 5th and 3rd order model of the DFIG in close-loop.

IV. Conclusion

This paper presents the detailed model of the DFIG in the fifth-order and third-order based on the transient interaction. A comparison between the two open and closed loop models was also presented. Through the simulation results, it was found that the fifth-order model, although it gives an accurate representation of the dynamic performance of DFIG, but has an impact on the start-up of a DFIG and the insta-bility of the transient system. On the other hand, the third-order model adequately reproduces the transient current and torque responses of the DFIG at startup and stability of the transient system.

The results achieved allow the conclusion that the third-order model is suitable for the study and analysis of the transient stability of large-scale electrical systems. In addition, the third-order model for modeling and the study of the transient behavior of a wind farm integrated into the power grid than the fifth-order representation can be preferred.

Appendix A

Base values for the per-unit system converting.

The base voltage V_{base} =690 V, the base power S_{base}=2MW, the basic electrical speed $\omega_{base} = 2\pi f_{base}$, the base frequency f_{base} =50Hz.

Appendix B

The parameters of our system are in Table 1[11].

Table 1. WT parameters

Parameters	Symbol	Values
DFIG		
Stator resistance	R_s	0.0488 pu
Stator leakage reactance	$X_{\sigma s}$	0.09241 pu
Rotor resistance	R_r	0.0549 pu
Rotor leakage reactance	$X_{\sigma r}$	0.09955 pu
Magnetizing reactance	X_m	3.95279 pu
inertia	H	3.5 s

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