

Analytical Review of Model Simplification Aspects for Wind Turbine Based Doubly Fed Induction Generator.

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ABSTRACT

There has been a fast growing demand for the application of doubly fed induction generators (DFIG) in wind power plants in recent years. They have in particular dominated the market in last two years. DFIG is an ideal candidate to satisfy the requirements of the recently proposed challenging grid codes. In order to investigate the transient response of doubly fed induction generator (DFIG) under various disturbances, an accurate modeling is required. In this paper simulation results of transient responses of DFIG during faults for different order models are reviewed. However, many uncertainties still exist regarding validated comprehensive DFIG models. This paper attempts to clarify the ambiguities in various model orders. Impact of various orders such as fifth, third and simplified model, accurate model including saturation, excluding saturation is discussed here. A brief review of assumptions and considerations with the choice of reference frames is also included.

KEY WORDS: DFIG, Electric variables control, Flux Saturation, Induction Machine, Machine Models, Power system transient stability, Wind energy generation

I. INTRODUCTION

Share of wind energy in the power system has been increasing with the time. The use of variable speed wind energy conversion systems is becoming more popular due to the development in the field of power electronics. Currently, the doubly fed induction generator (DFIG) wind turbines dominate the market due to cost-effective provision of variable-speed operation with constant frequency. DFIG is a wound rotor induction generator in which rotor winding is fed through back to back variable frequency variable voltage source convertors. Their ability to control electrical torque and reactive power offer superior performance concerning system stability. With changing wind speed, one can adjust the frequency of the injected rotor voltage of the DFIG to obtain a constant-frequency at the stator. Adequate modeling of these systems and clear understanding of the effects of different simplifications is paramount if reliable results of simulations of power systems with high penetration of DFIG-based wind plants are sought. Efficient modeling and simulation techniques for induction generators will facilitate the research on wind turbine generation. The wind energy industry is rather opaque regarding modeling as most of the data is usually confidential or requires rigorous field or laboratory experiments. The DFIG mathematical models are simplified either in order to save computational time or to eliminate the requirement for hard-to-obtain data. In order to investigate the impacts of DFIGs installations on the operation and control of the power system, accurate models are required. A fifth order and reduced order (3rd) machine models are discussed. To derive more accuracy in these modeling orders more simplified and accurate models are also included in the review. The response of the DFIG for voltage control (VC) and its performance during a network fault especially voltage sags are addressed. Here presented is the analysis of the previously published papers, this paper aims to clarify some of the uncertainties associated with DFIG modeling. It also provides numerous simulation results that illustrate the influence of different parameters and modeling on transient operation of DFIG-based wind plants.

In this paper, Section II takes the overview of the assumptions to be made along with the choice of reference frame for particular modeling. Section III focuses on equations of various modeling and their simplifications. Section IV includes the results of simulations performed to validate the previous. Section V analyses those results from utility point of view and section VI concludes.

1.1. Overview of Considerations

Three phase stator and rotor windings of an induction machine can be represented by two sets of orthogonal fictitious coils. d-q or two axis model for the study of transient behavior has proven to be reliable and accurate. Though rotation of the d-q axis can be arbitrary, three reference speeds i.e reference frames as follows,

- The stationary reference frame - the d,q axes do not rotate;
- The synchronously rotating reference frame - the d,q axes rotate at synchronous speed;
- The rotor reference frame - the d,q axes rotate at rotor speed.

Following explains choice of reference frame as elaborated in [9]

A. Stationary reference frame

When $\theta = 0$; the d, q axes do not rotate therefore it called as stationary reference frame. Also the +d-axis is chosen to coincide with the stator phase A axis.

If the bus-bar voltages are

$$\begin{aligned} V_{as} &= V_m \cos(\omega_{st} + \gamma) \\ V_{bs} &= V_m \cos(\omega_{st} + \gamma - \lambda) \\ V_{cs} &= V_m \cos(\omega_{st} + \gamma + \lambda) \end{aligned} \quad \dots (1)$$

If the motor terminals are directly connected to bus-bar and by using parks transformation

$$\begin{aligned} V_{ds} &= V_m \cos(\omega_{st} + \gamma) \\ V_{qs} &= -V_m \sin(\omega_{st} + \gamma) \end{aligned} \quad \dots (2)$$

From the above equations; the voltage applied to the stator d-axis coil, is the same as the stator phase A voltage. i.e $V_{as} = V_{ds}$ where V_{as} is a stator phase A voltage and V_{ds} is stator d-axis coil voltage. This means that the stator d-axis current I_{ds} exactly equal to the phase A current I_{as} therefore it is not necessary to compute I_{as} separately at each step of integration process through inverse parks transformation This saves computer time and hence is an advantage of the stationary reference frame.

B. Synchronously rotating reference frame

When $\theta = \omega_{st}t$; the d, q axes rotate at synchronous speed. Therefore it is called synchronously rotating frame, without any capacitor the terminal voltage changes from eqn (2) to

$$\begin{aligned} V_{ds} &= V_m \cos \gamma \\ V_{qs} &= -V_m \sin \gamma \end{aligned} \quad \dots(3)$$

This means that the stator voltages are DC quantities and this has advantages in the field of feedback controller design when the motor equations are linearized around a steady operating point. In this frame we can use larger step length while digital integration; since the variables are slowly changing DC quantities during transient conditions.

C. Rotor reference frame

When $\theta = \omega_r t$; The d, q reference frame rotate at rotor speed therefore it is called rotor reference frame, also the d-axis position coincides with the rotor phase A axis. Without any capacitors the terminal voltages changes from eqn (2)

$$\begin{aligned} V_{ds} &= V_m \cos(\omega_{st} + \gamma) \\ V_{qs} &= -V_m \sin(\omega_{st} + \gamma) \end{aligned} \quad \dots (4)$$

The d, q voltages are therefore of slip frequency and the d-axis rotor current behaves exactly as the phase A rotor current does. This means that it is not necessary to compute the phase A rotor current I_{ar} at each step of the digital integration process through the inverse of Park's transform. This saves computer time and hence is an advantage of the rotor reference frame when studying rotor quantities. The model of an induction generator can have various orders. 5th order model is considered to be a full order model for an induction generator. When fifth i.e full order model is to be used, it demands consideration of differential equations for the whole network as stator circuit is directly connected to the stator circuit. Simplified fifth order doesn't take into

account certain terms with low weight and employs the FOC algorithm. Third order model excludes stator dynamics reducing the step size for computations. Differential equations of previous order are ignored while developing this stage. In these orders effect of flux saturation is usually given no importance but its inclusion leads to an accurate model. Per unit representation are desirable to be used while analysis as it enables the conversion of whole system to pu quantities on a single power base.

II. VARIOUS MODELS OF DFIG

A. Fifth order model

The references [1][2][3][9] shows the fifth order model of the induction machine in Synchronous reference frame. However in this model effect of main flux and leakage flux is neglected.

The equations (5) and (6) gives d and q axis voltages of stator and rotor windings respectively,

$$\begin{cases} \bar{v}_{ds} = \bar{R}_s \times \bar{i}_{ds} - \bar{\lambda}_{qs} + \frac{1}{\omega_s} \frac{d}{dt} \bar{\lambda}_{ds} \\ \bar{v}_{qs} = \bar{R}_s \times \bar{i}_{qs} + \bar{\lambda}_{ds} + \frac{1}{\omega_s} \frac{d}{dt} \bar{\lambda}_{qs} \end{cases} \dots (5)$$

$$\begin{cases} \bar{v}_{dr} = \bar{R}_r \times \bar{i}_{dr} - s \times \bar{\lambda}_{qr} + \frac{1}{\omega_s} \frac{d}{dt} \bar{\lambda}_{dr} \\ \bar{v}_{qr} = \bar{R}_r \times \bar{i}_{qr} + s \times \bar{\lambda}_{dr} + \frac{1}{\omega_s} \frac{d}{dt} \bar{\lambda}_{qr} \end{cases} \dots (6)$$

Equation (7) represents stator and rotor flux in d-q synchronous reference frame respectively,

$$\begin{cases} \bar{\lambda}_{ds} = \bar{L}_{ss} \times \bar{i}_{ds} + \bar{L}_m \times \bar{i}_{dr} \\ \bar{\lambda}_{qs} = \bar{L}_{ss} \times \bar{i}_{qs} + \bar{L}_m \times \bar{i}_{qr} \\ \bar{\lambda}_{dr} = \bar{L}_{rr} \times \bar{i}_{dr} + \bar{L}_m \times \bar{i}_{ds} \\ \bar{\lambda}_{qr} = \bar{L}_{rr} \times \bar{i}_{qr} + \bar{L}_m \times \bar{i}_{qs} \end{cases} \dots (7)$$

As in [3] voltage behind a transient model for DFIG can be obtained, by defining e_d and e_q ,

$$\bar{e}_d = -\frac{\bar{L}_m}{\bar{L}_{rr}} \bar{\lambda}_{qr} \quad \text{and} \quad \bar{e}_q = \frac{\bar{L}_m}{\bar{L}_{rr}} \bar{\lambda}_{dr} \dots (8)$$

And with some manipulations,

$$\begin{cases} \bar{v}_{ds} = \bar{R}_s \times \bar{i}_{ds} - \bar{X}_1 \times \bar{i}_{qs} + \bar{e}_d + \frac{\bar{X}_1}{\omega_s} \frac{d}{dt} \bar{i}_{ds} + \frac{1}{\omega_s} \frac{d}{dt} \bar{e}_q \\ \bar{v}_{qs} = \bar{R}_s \times \bar{i}_{qs} + \bar{X}_1 \times \bar{i}_{ds} + \bar{e}_q + \frac{\bar{X}_1}{\omega_s} \frac{d}{dt} \bar{i}_{qs} - \frac{1}{\omega_s} \frac{d}{dt} \bar{e}_d \end{cases} \dots (9)$$

$$\begin{cases} \bar{i}_{dr} = \left(\frac{\bar{\lambda}_{dr} - \bar{L}_m \times \bar{i}_{ds}}{\bar{L}_{rr}} \right) = \frac{1}{\bar{L}_m} \bar{e}_q - \frac{\bar{L}_m}{\bar{L}_{rr}} \bar{i}_{ds} \\ \bar{i}_{qr} = \left(\frac{\bar{\lambda}_{qr} - \bar{L}_m \times \bar{i}_{qs}}{\bar{L}_{rr}} \right) = -\frac{1}{\bar{L}_m} \bar{e}_d - \frac{\bar{L}_m}{\bar{L}_{rr}} \bar{i}_{qs} \end{cases} \dots (10)$$

The electromagnetic torque,

$$T_e = \bar{L}_m (\bar{i}_{dr} \times \bar{i}_{qs} - \bar{i}_{qr} \times \bar{i}_{ds}) \dots (11)$$

And finally mechanical torque,

$$\frac{d\omega_r}{dt} = \frac{1}{J} \times (T_m - T_e) \dots (12)$$

These constitute fifth order model which includes stator transients and state variables are stator and rotor flux components and the rotor speed as well. Current components based state space model can possibly be derived by putting stator and rotor flux equations in voltage equations of the same. [1][2][3][5]

B. Third order model-

Neglecting the rate of change of stator flux linkage is a standard method of reducing the order of the induction generator model. The reduced i.e third order model can be derived by ignoring the differential term in equation (5). Neglecting the stator transients,

The reduced order d and q axis stator and rotor voltages,

$$\begin{cases} \bar{v}_{ds} = \bar{R}_s \times \bar{i}_{ds} - \bar{\lambda}_{qs} \\ \bar{v}_{qs} = \bar{R}_s \times \bar{i}_{qs} + \bar{\lambda}_{ds} \end{cases} \dots (13)$$

$$\begin{cases} \bar{v}_{dr} = \bar{R}_r \times \bar{i}_{dr} - s \times \bar{\lambda}_{qr} + \frac{1}{\omega_s} \frac{d}{dt} \bar{\lambda}_{dr} \\ \bar{v}_{qr} = \bar{R}_r \times \bar{i}_{qr} + s \times \bar{\lambda}_{dr} + \frac{1}{\omega_s} \frac{d}{dt} \bar{\lambda}_{qr} \end{cases} \dots (14)$$

When stator transients are neglected (9) can be reduced to,

$$\begin{cases} \bar{v}_{ds} = \bar{R}_s \times \bar{i}_{ds} - \bar{X}_1 \times \bar{i}_{qs} + \bar{e}_d \\ \bar{v}_{qs} = \bar{R}_s \times \bar{i}_{qs} + \bar{X}_1 \times \bar{i}_{ds} + \bar{e}_q \end{cases} \dots (15)$$

$$\begin{cases} \bar{i}_{ds} = \frac{1}{\bar{L}_{ss}} \bar{v}_{qs} - \frac{\bar{L}_m}{\bar{L}_{ss}} \bar{i}_{dr} \\ \bar{i}_{qs} = -\frac{1}{\bar{L}_{ss}} \bar{v}_{ds} - \frac{\bar{L}_m}{\bar{L}_{ss}} \bar{i}_{qr} \end{cases} \dots (16)$$

The electromagnetic torque,

$$T_e = -\frac{\bar{L}_m}{\bar{L}_{ss}}(\bar{i}_{dr} \times \bar{v}_{ds} + \bar{i}_{qr} \times \bar{v}_{qs}) \quad \dots (17)$$

In the third order model state variables are two components of the rotor flux linkage and rotor speed.

C. Simplified modeling of DFIG-

To study behavior of DFIG-based WTs under generic conditions the fifth-order model is popular. But this kind of model raises a complicated system. A complex analysis under transient conditions, the high computational cost of the equation in standards simulators necessitates development of aggregated models.

Considering

1) A field-oriented control (FOC) algorithm for the rotor side converter acts as a current source.
 2) Synchronous reference frame. Certain low weight components of the equations in the system and the stator electric transient are neglected. Simplified fifth order model enables simplification of some terms of the stator voltage. FOC algorithm regulates dq components of the rotor currents to be injected to the DFIG to perform a decoupled control of the positive sequence of P and Q. Considering the voltage and flux equations of stator and rotor in fifth order model (eq. 5, 6, 7) linear and applying the Laplace transform, the stator currents in the synchronous reference frame are obtained. Some necessary manipulations with abovementioned considerations give the simplified model as in [3],

$$\begin{aligned} i_{ds} &= \frac{1}{L_s} \frac{\omega_s}{s^2 + 2(R_s/L_s)s + \omega_s^2} v_{qs} - \frac{L_m}{L_s} i_{dr} \\ i_{qs} &= \frac{1}{L_s} \frac{s + R_s/L_s}{s^2 + 2(R_s/L_s)s + \omega_s^2} v_{qs} - \frac{L_m}{L_s} i_{qr}. \end{aligned} \quad \dots (18)$$

It can be easily observed that the stator voltage and rotor current appear as input variables. Any variation in the stator voltage will introduce oscillations in the *dq* components of the stator currents in the synchronous reference frame.

Accuracy of the simplified model with respect to the resolution of a fifth order are observed by plotting responses of both systems on same graph as in [3].

D. Accurate model-

By reducing the order of the generator computational time can be considerably reduced. Reduced order can be achieved by neglecting differential term in the voltage equations of the machine. [1-4][9] The effect of leakage flux saturation is usually neglected in these papers. In some papers saturation effect is considered but lacks the comparative study among different orders of DFIG model with saturation effect during three phase sag, this is proposed in [4] developing an accurate model. Better representation of the induction machine with saturation under transient condition demands the consideration of variation in the stator and rotor leakage inductances due to saturation in the leakage flux path in saturation effect. To account effect of saturation in leakage flux path, unsaturated stator and rotor leakage reactances in dynamic models in [1-4] are modified by saturation factor *K_{sat}*.

K_{sat} is introduced as follows,

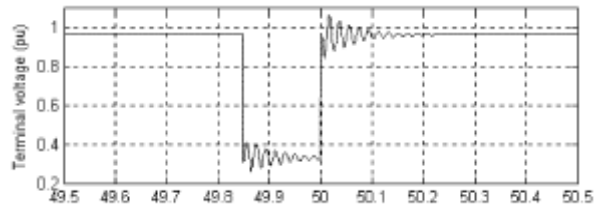
$$K_{sat} = \begin{cases} 1 & I \leq I_{sat} \\ \frac{2}{\pi} (\tan^{-1}(\frac{\gamma}{\sqrt{1-\gamma}}) + \gamma\sqrt{1-\gamma}) & I > I_{sat} \end{cases} \quad \dots (19)$$

Where γ is equal to the ratio between current at which the saturation begins, *I_{sat}*, to the current through the leakage reactance. [4][6]

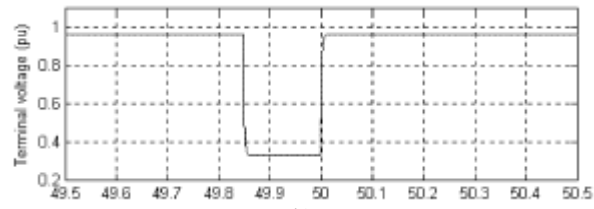
In [4] a 50% voltage sag is considered for simulation. At $t = 5s$, a voltage sag happens. Then at $t = 7s$ the voltage is restored to its presage value, i.e. 1 pu.

III. RESULTS

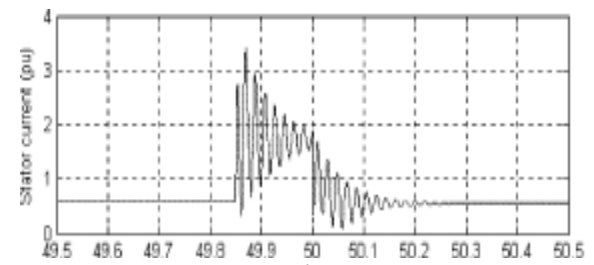
Simulations carried out to investigate the performance of the DFIG during a system fault in [2]. A fault is applied $t= 49.85$ s and cleared after 150 ms.



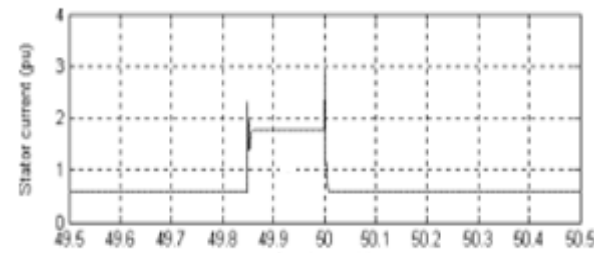
a)



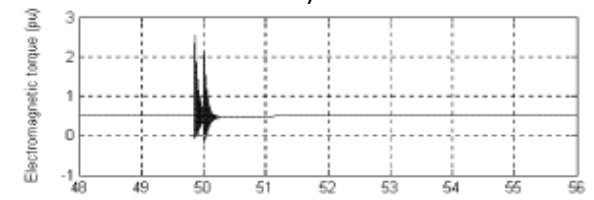
b)



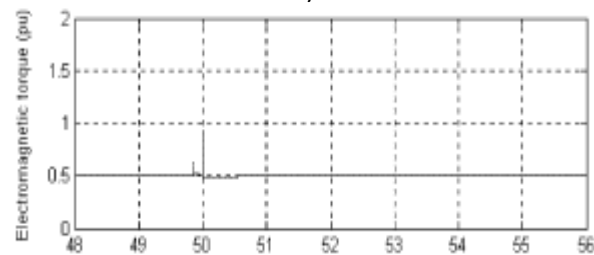
c)



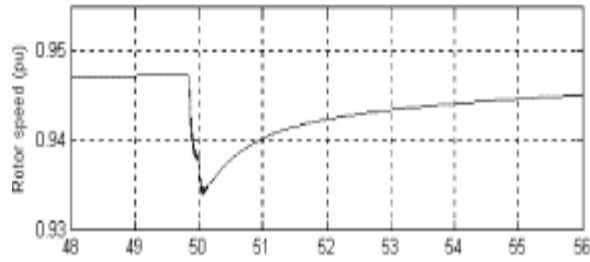
d)



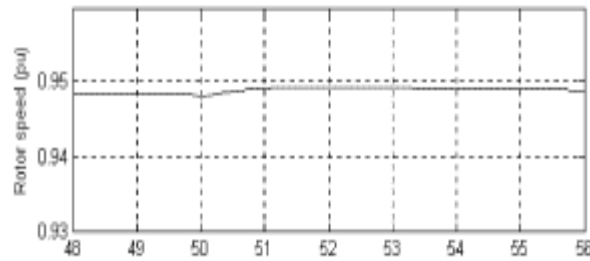
e)



f)



g)



h)

Fig. 1. Response of DFIG to the system fault (all are in pu)

Similar set of results as in fig. 1(a)-(f) for fifth order and third order modeling respectively are obtained for terminal voltage, rotor speed, stator current and electromagnetic torque.

Another investigation of the Influence of various models can be seen in [9] as follows, the third and fifth order, modeled in rotor reference frame.

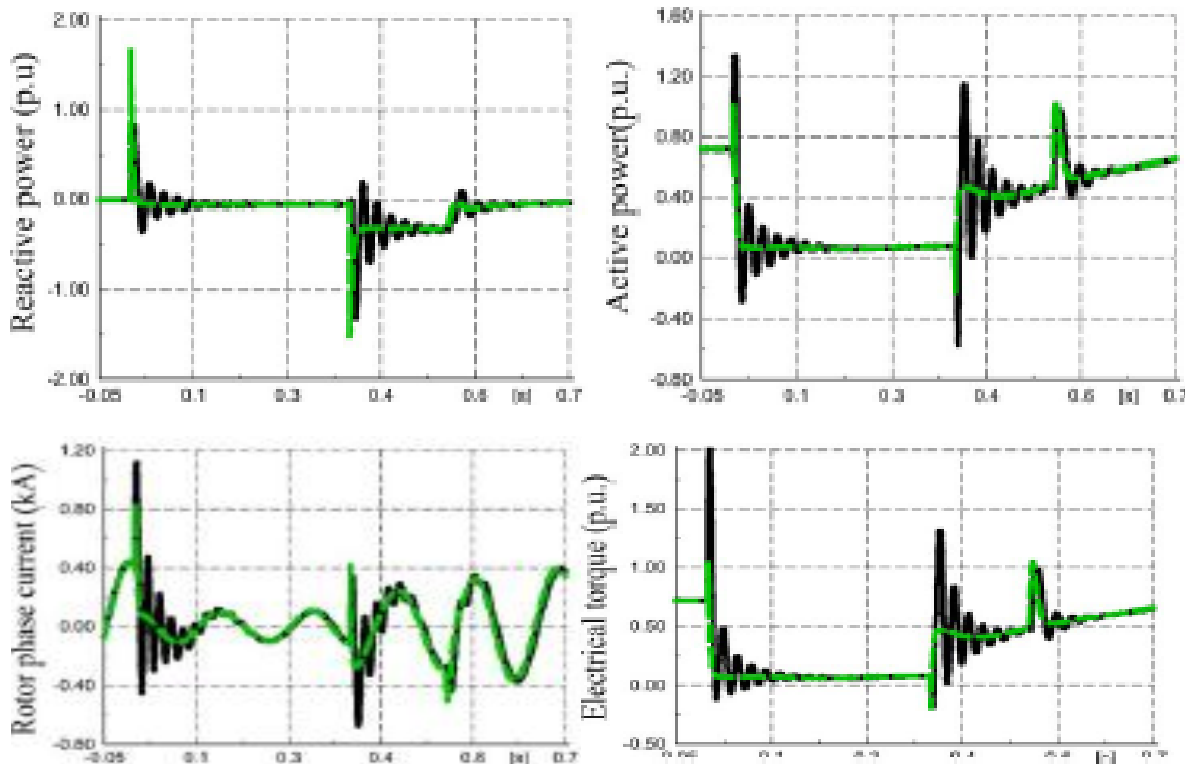


Fig. 2(a) DFIG response to a 350 ms short circuit applied at 0s and removed crowbar at 0.5s.

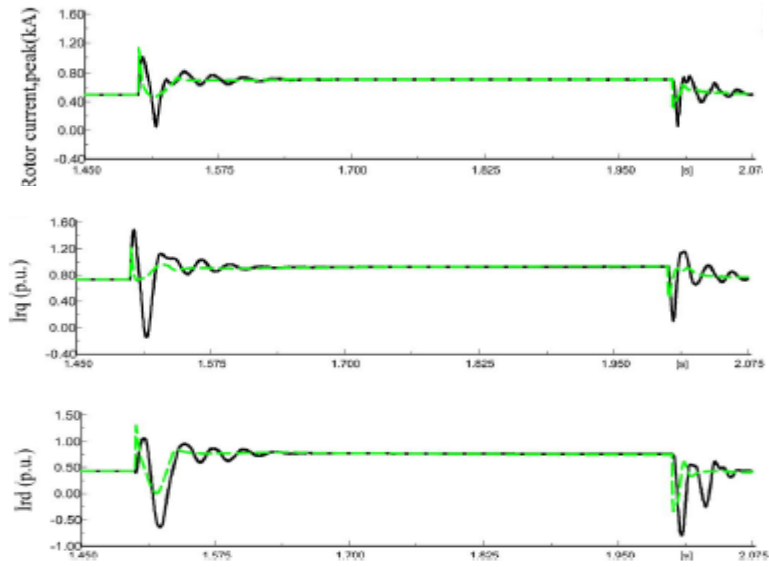
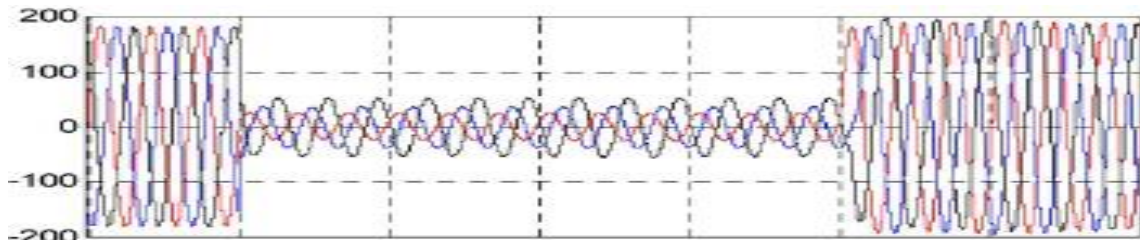
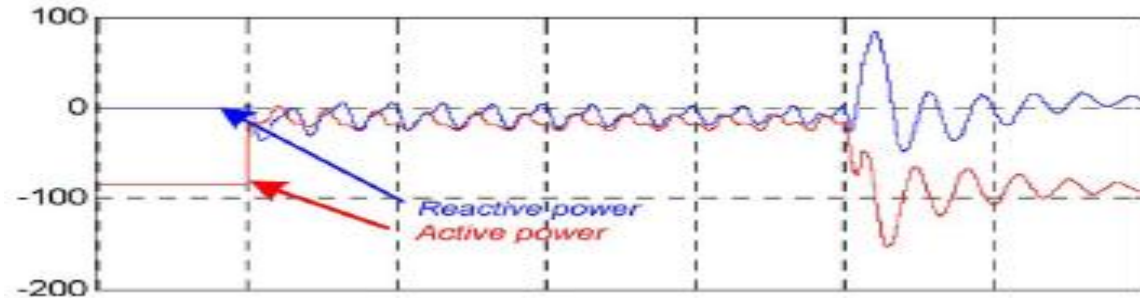


Fig. 2(b) The rotor current response when simulated for 20 % voltage sag with no crowbar operation

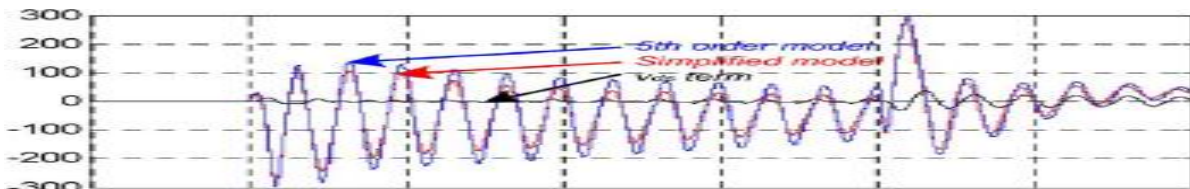
Behavior of DFIG model under three phase to ground fault, one phase to ground fault, two phase to ground fault with simplified and fifth order model as derived in [2] are as follows,



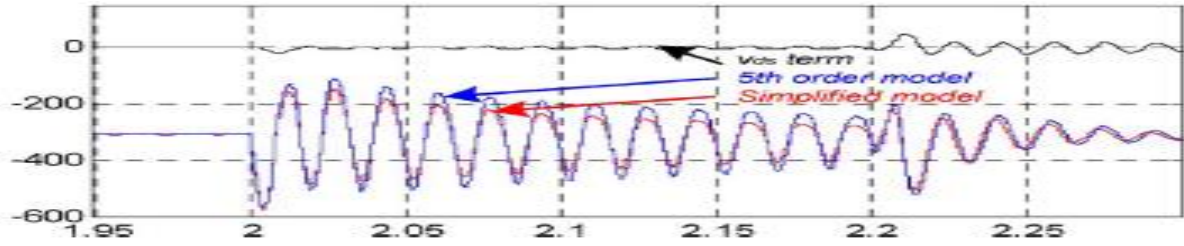
(a) Grid voltage waveforms



(b) Active and reactive power (in kVA).

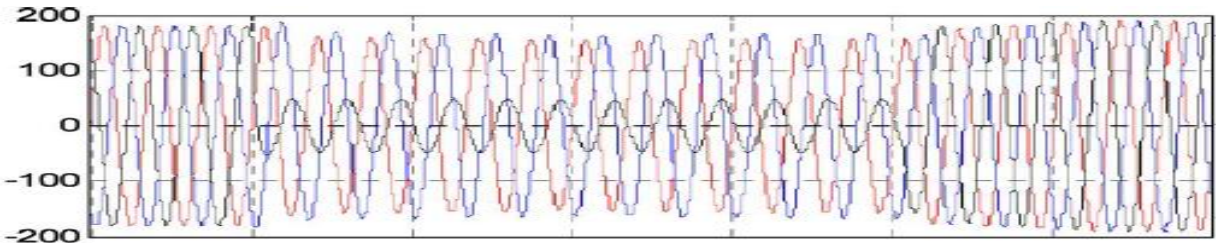


(c) i_{sq} performance

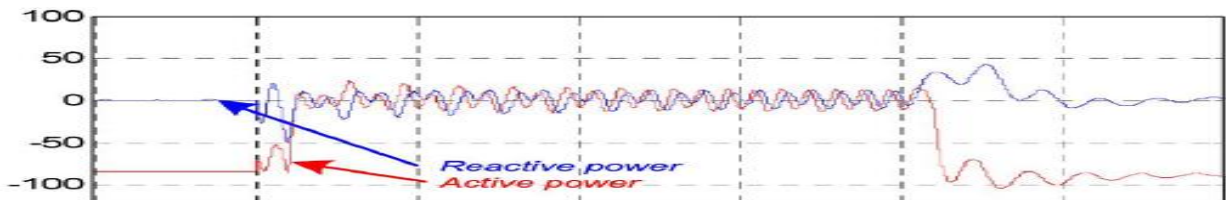


(d) i_{sd} performance

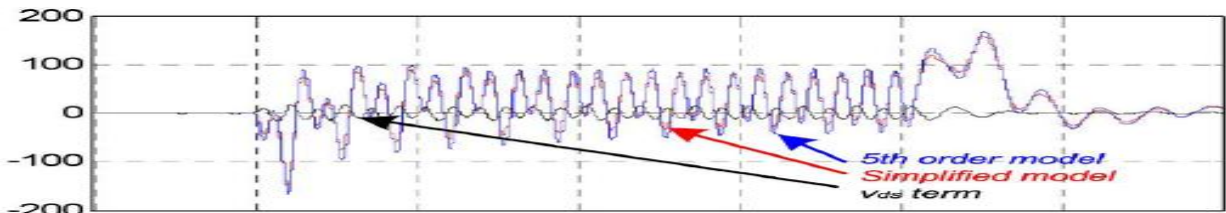
Fig. 3.1 Behavior of the DFIG models under three-phase-to-ground faults with the simplified and fifth-order models.



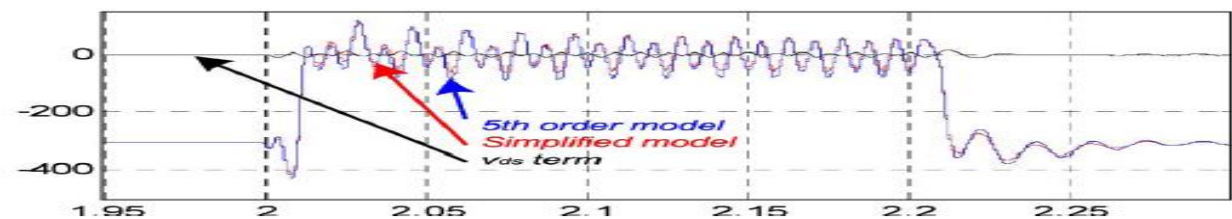
(a) Grid voltage waveforms.



(b) Active and reactive power (in kVA).



(c) i_{sq} performance



(d) i_{sd} performance

Fig.3.2 Behavior of the DFIG models under one-phase-to-ground faults with the simplified and fifth-order models.

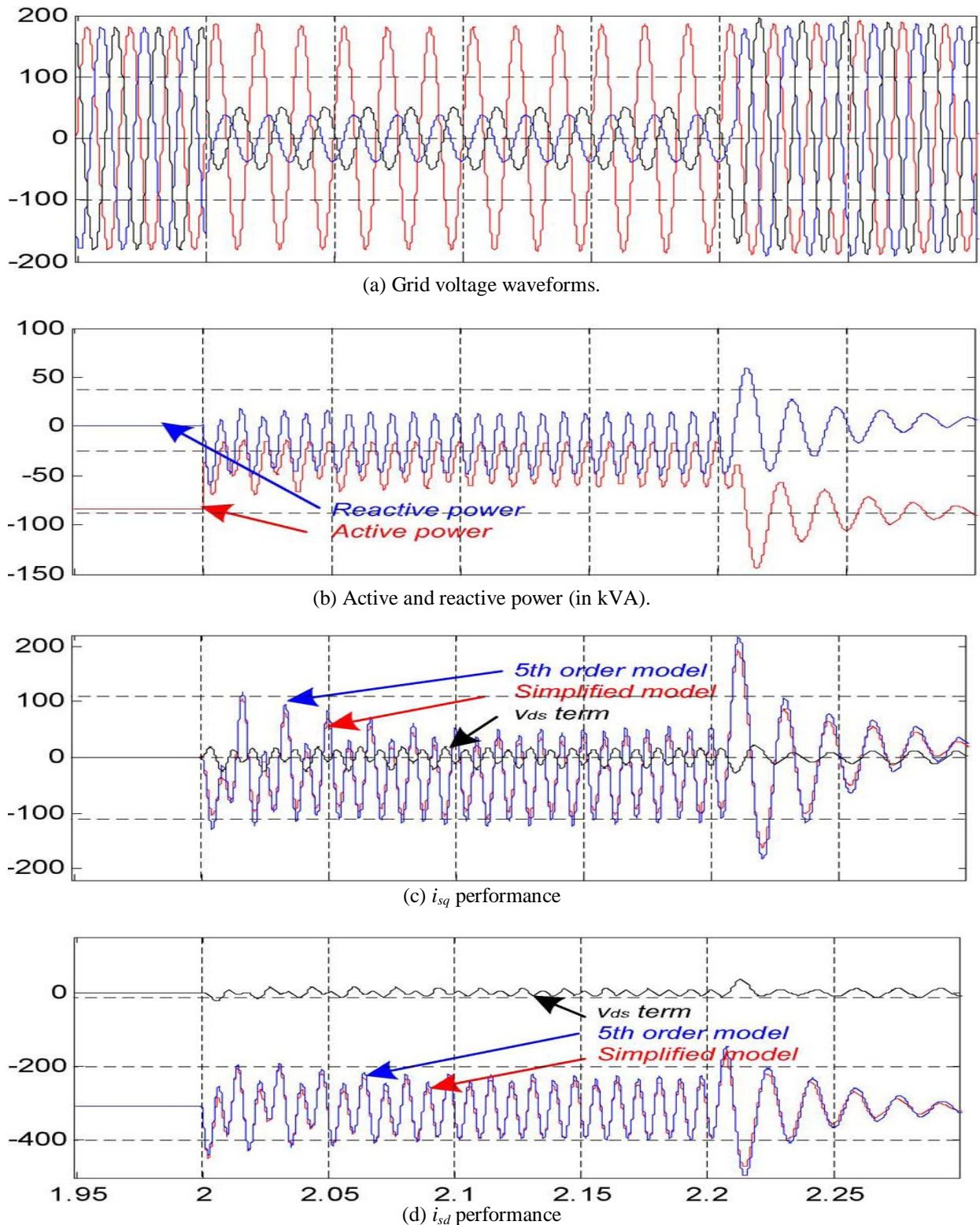
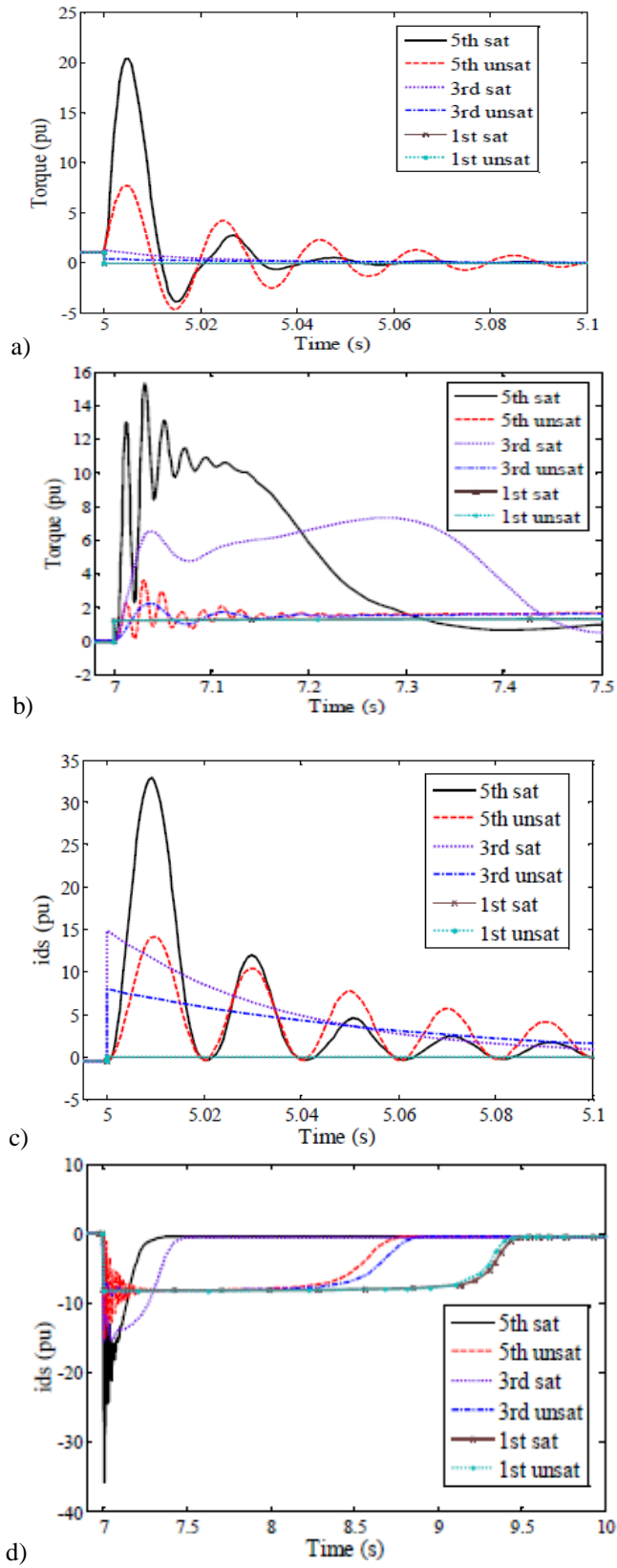


Fig. 3.3 Behavior of the DFIG models under two-phase-to-ground faults with the simplified and fifth-order models.

Following figure shows the simulation results obtained in [4] for Torque, i_{ds} , i_{qs} , speed for fifth, third and first order model including and excluding saturation effect.



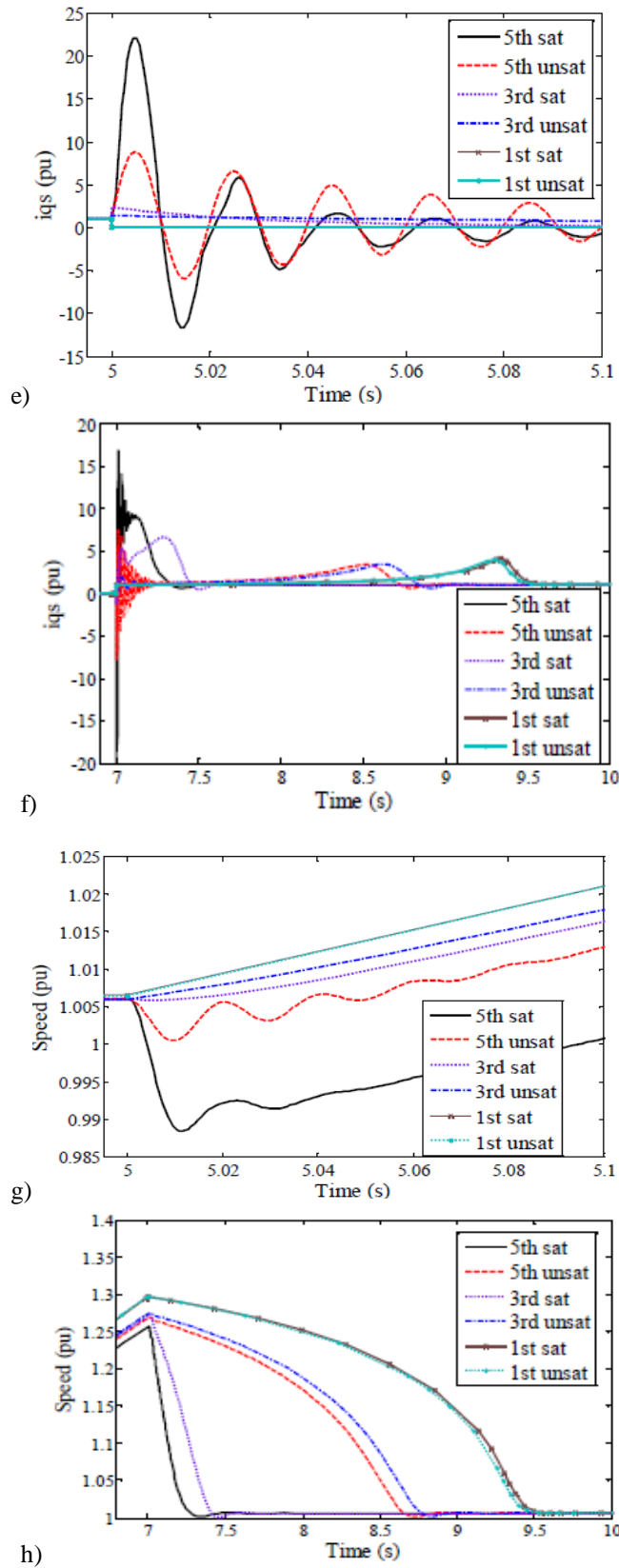


Fig. 4 DFIG transient response due to 50% voltage sag. (a) Torque at voltage sag occurrence, (b) torque at voltage recovery, (c) i_{ds} at voltage sag occurrence, (d) i_{ds} at voltage recovery, (e) i_{qs} at voltage sag occurrence, (f) i_{qs} at voltage recovery, (g) speed at voltage sag occurrence, and (h) speed at voltage recovery

IV. DISCUSSION

From the simulations in [2], the rotor current in pu appeared to be very similar to the stator current during the transient. When Machine is operated with increased short term rating of RSC components, the used control strategy and convertor ratings are the factors decide the rotor voltage applied to the DFIG during the network fault. From the fig.1 it can be seen that DFIG response during the fault is more elaborative in the 5th order generator model and includes the transient behavior of the stator current. The 3rd order model though gives a similar mean value of the stator current; details of the transient remain unobserved. In these results Stator flux transients in current, active and reactive power can be clearly traced in fifth order model which is not observed in third order, third order model appears not useful to account for operations of crowbar protection. If DFIG supports reactive power rotor phase A current is higher with fifth order model as seen in 2(a) instead overall peak rotor current is lower as seen in Fig. 2(b). Electrical torque and magnetization of the machine is controlled by q axis and d axis respectively with stator flux oriented reference frame. Fast stator flux change is allowed in third order due to ignored stator flux transients. [3][5] Compared to third order model, Transients in q axis current is higher & d axis current change is small with fifth order model attributes to higher rotor current in third order model. Abrupt stator flux change leads induction of higher rotor current in case of third order and a bit lower rotor current as stator flux change is slower.

For three phase fault, sudden reduction in voltage raises lower power injection in network which also has dependency on RSC control during fault. Perfect matching of dynamic performance of simplified model with fifth order model can be clearly observed in the behavior of i_{ds} and i_{qs} . Oscillations seen in i_{ds} and i_{qs} due to low damping (conditioned by R_s of second order transfer function of eq.18 which is very low in DFIG) in the system. When stator winding is affected by one phase to ground and two phases to ground fault, causes negative sequence voltage translated in 120 Hz oscillations at stator which can be observed higher in second case. Noticeable points in the results are Oscillating V_{ds} which is ignored as its multiplied by lower terms compared to v_{qs} evidenced the low influence and results of the fifth order are accurately tracked by results of simplified model, precisely describe the dynamic behavior of the DFIG. Fig 4. Shows the simulation results obtained in [4]. At the occurrence of the fault current and torque increases with saturation. Oscillations aren't observed in third and first order model but noticeably in fifth order model. Difference between Saturation and unsaturated model becomes visible as the order increases, hardly noticed in first order. There isn't fall in rotor speed for third and first order models but decreases for saturated and unsaturated model of fifth order. After recovery of fault fifth order model appeared faster to reach steady state than third and first order model. Only transient response of speed, torque and current is affected by saturation and not the steady state.

Table 1. Simplifications used in different order model

Fifth order	Third order	First order
$d\psi_{zq(d)}/dt \neq 0$	$d\psi_{zq(d)}/dt = 0$	$d\psi_{zq(d)}/dt = 0$
$d\psi_{rq(d)}/dt \neq 0$	$d\psi_{rq(d)}/dt \neq 0$	$d\psi_{rq(d)}/dt = 0$
$d\omega_m/dt \neq 0$	$d\omega_m/dt \neq 0$	$d\omega_m/dt \neq 0$

Table 1 shows simplifications employed in various modeling orders at a glance [4]

V. CONCLUSION

If the FOM is used for time-domain simulation, small integration step sizes are required as a result of the small time constants involved. The small integration time step, in addition to the large number of differential equations especially for the grid, results in considerable simulation efforts when studying large systems. These disadvantages limit the applicability of the FOM to small grids. For classical, phasor domain electro-mechanical dynamic studies of large power systems the simplicity and reduced computation time of the 3rd order model appears attractive. For more detailed representations of fault current contribution and investigation of the required ratings of the converters then the 5th order representation may be preferred. Two simple second order transfer functions permit to carry out simulation of large scale wind energy applications. This lead to considerable reduction in computational time as compared to fifth order in simulating behavior of Multiple DFIG. Though complex model can also do, this model appears to be the intuitive estimator for designing strategies of sag response improvement of DFIG. The stator and rotor current of DFIG calculated considering saturation effect are much higher than the values calculated by ignoring it. Rotor speed of saturated model attains steady state value faster as compared to unsaturated models; saturated fifth order reaches faster than others. So saturation effect can be incorporated more importantly to study the transient performance of DFIG and doesn't prove that much useful for steady state.

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