PERFORMANCES OF SATURATED DOUBLY-FED INDUCTION GENERATOR DURING TRANSIENT STATE

Elhadj BOUNADJA **Mohand Oulhadj MAHMOUDI**
Ecole Nationale Polytechnique d'Alger, Algeria.
hbounadja@yahoo.fr momahmoudi@yahoo.fr

Abdelkader DJAHBAR
University of Chlef, Algeria.
a_djahbar@yahoo.fr

Abstract: *The transient state performances of the Doubly-Fed Induction Generators (DFIG) has frequently determined by a models based on the constant parameters. So, an accurate analysis of these performances required necessarily considers the magnetic saturation effects. In this paper, a simple procedure is proposed to characterise the machine's mutual and leakage fluxes saturation. Three models are developed to predict the transient performances of a saturated DFIG. The results calculated by the model that considers only mutual flux saturation and the ones by the model that includes both mutual and leakage fluxes saturation are compared with the results when the saturation is ignored in DFIG modelling. To validate the developed models and investigate the transient performances of the saturated DFIG, a simulation is made during transient conditions such as direct starting, voltage sag and short-circuits at the terminal of the machine. The model that considers saturation both in the mutual and the leakage flux paths produces the most accurate transient responses*

Key words: *Doubly-fed induction generator (DFIG), Leakage flux saturation, Mutual flux saturation, Modeling, transient state performances.*

1. Introduction

In the previous decades and after increasing of oil prices, overall awareness for renewable energy sources has been increasing intensively. Wind energy in particular, has received an immense impulse, reflected in great technology advances regarding reliability and cost-efficiency. Wind turbines generate a few quantity of the word electricity consumption [1]. These wind turbines are usually based on a Doubly-Fed Induction Generator (DFIG).

In recent years, many papers investigate the DFIG from various aspects. However, in those investigations, the DFIG is modelled with some simplifying assumptions, among which, the magnetic saturation is ignored as in [1-6]. In reality however, this phenomenon is present in all electrical machines. Moreover, the performance and the accurate identification of the machine parameters depend significantly on the saturation of the mutual and leakage fluxes. For this purpose and in order to achieve a better representation of the DFIG, saturation must be incorporated in their mathematic modelling. It has been found for other type of machines, that the inclusion of the saturation effects gives more realistic results [7-9, 16, 19, 20].

In [7-12, 19], the saturation is taken into account of the mutual flux paths only for squirrel-cage and self-excited induction machines. In these works, the effect of leakage flux saturation is ignored. In [13, 14], the DFIG model proposed, include only the saturation effect in the mutual flux. In [15], the saturation of the leakage flux is considered in the machine model but the mutual flux saturation is neglected. On the other hand, for DFIG, the magnetic saturation of both the mutual and the leakage fluxes is neglected.

In this paper, the effect of saturation in the mutual flux and the leakage flux on the transient performance of the DFIG is investigated. For that, three models are considered. The first model is the unsaturated model in which the saturation effect is completely ignored. The second model considers the saturation only in the mutual flux paths while the third model considers saturation both in the mutual and leakage fluxes paths. In the second model, a saturation factor K_{sm} is used to adjust the unsaturated mutual inductance and the saturation in the leakage inductances is ignored. In the third model, the saturation factor K_{sm} is used to adjust the unsaturated mutual inductance and another saturation factor $K_{s\sigma}$ is used to adjust both the unsaturated stator and rotor leakage inductances. These saturation factors are based on the nonlinear function found in [10]. Using these DFIG models, the transient stator and rotor currents and the electromagnetic torque during direct starting, voltage sag and short-circuits at the terminal of the machine have been calculated. Moreover, The results calculated by the model that considers only mutual flux saturation and the ones by the model that includes both mutual and leakage flux saturation are compared with the results when the saturation is ignored in DFIG modelling.

2. The DFIG model

In this section, three models of the DFIG are developed. In the first model, effect of flux saturation is completely ignored. Then the mutual flux saturation is considered to develop the second model. In the third model both the main flux saturation and the saturation in the leakage flux paths are integrated in the unsaturated model.

A. Unsaturated DFIG model

The two-axis equivalent circuit for a doubly-fed induction generator is shown in figure 1 [16]. The voltages equations of the DFIG in the synchronous *d-q* reference frame are given by:

$$\begin{cases} v_{ds} = R_s i_{ds} + \frac{d}{dt}\psi_{ds} - \omega_s \psi_{qs} \\ v_{qs} = R_s i_{qs} + \frac{d}{dt}\psi_{qs} + \omega_s \psi_{ds} \\ v_{dr} = R_r i_{dr} + \frac{d}{dt}\psi_{dr} - \omega_r \psi_{qr} \\ v_{qr} = R_r i_{qr} + \frac{d}{dt}\psi_{qr} + \omega_r \psi_{dr} \end{cases} \quad (1)$$

In (1), the rotor frequency ω_r is given by:

$$\omega_r = \omega_s - \omega_m = s\omega_s \quad (2)$$

The flux linkages in (1) are obtained from the following equation system:

$$\begin{cases} \psi_{ds} = L_s i_{ds} + L_m i_{dr} \\ \psi_{qs} = L_s i_{qs} + L_m i_{qr} \\ \psi_{dr} = L_r i_{dr} + L_m i_{ds} \\ \psi_{qr} = L_r i_{qr} + L_m i_{qs} \end{cases} \quad (3)$$

The equation system (3) is used to calculate the stator and rotor currents:

$$\begin{cases} i_{ds} = \frac{1}{\sigma L_s L_r}(L_r \psi_{ds} - L_m \psi_{dr}) \\ i_{qs} = \frac{1}{\sigma L_s L_r}(L_r \psi_{qs} - L_m \psi_{qr}) \\ i_{dr} = \frac{1}{\sigma L_s L_r}(L_s \psi_{dr} - L_m \psi_{ds}) \\ i_{qr} = \frac{1}{\sigma L_s L_r}(L_s \psi_{qr} - L_m \psi_{qs}) \end{cases} \quad (4)$$

With:

$$\sigma = 1 - \frac{L_m^2}{L_s L_r}, \; L_s = L_{s\sigma} + L_m, \; L_r = L_{r\sigma} + L_m \quad (5)$$

The electromagnetic torque T_{em} can be written in the following form:

$$T_{em} = p\frac{L_m}{L_s}(\psi_{ds} i_{qr} - \psi_{qs} i_{dr}) \quad (6)$$

B. DFIG model considering the mutual flux saturation

A model of DFIG considering the mutual flux saturation can be developed using the unsaturated model developed in the section 2.A. In this approach, the unsaturated mutual inductance L_m in (3) to (6) is replaced by its corresponding saturated value L_{ms}. This saturated mutual inductance is obtained by adjusting the corresponding unsaturated value, L_m, with a saturation factor K_{sm}, corresponding to the saturation condition.

From figure 1, the magnetizing current can be calculated by:

$$i_m = \sqrt{i_{dm}^2 + i_{qm}^2} \quad (7)$$

Where:

$$i_{dm} = i_{ds} + i_{dr}, \; i_{qm} = i_{qs} + i_{qr} \quad (8)$$

The saturated mutual inductance L_{ms} can be expressed as a function of the magnetizing current i_m as:

$$L_{ms} = \begin{cases} L_m & i_m < I_{msat} \\ K_{sm}(i_m).L_m & i_m \geq I_{msat} \end{cases} \quad (9)$$

The saturation factor K_{sm} can be represented by the function [10]:

$$K_{sm}(i_m) = \begin{cases} 1 & i_m < I_{msat} \\ \frac{2}{\pi}\left[\arcsin(\frac{I_{msat}}{i_m}) + 0{,}5\sin(2\arcsin(\frac{I_{msat}}{i_m}))\right] & i_m \geq I_{msat} \end{cases} \quad (10)$$

Where I_{msat} represent the magnetizing current at which the saturation begins. Its value is around *0.5 pu*, i.e $0.7 \times I_n$ [13].

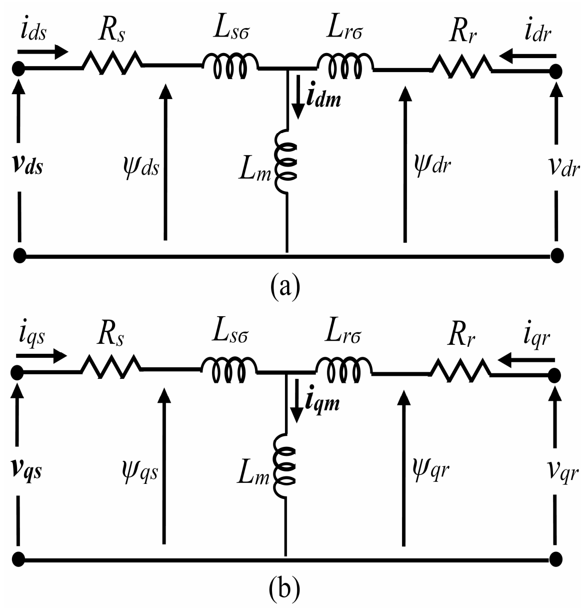


Fig.1: Equivalent circuits of a DFIG: (a) on d-axis, (b) on q-axis

C. DFIG model considering the mutual and leakage flux saturation

The saturation representation in the DFIG modeling should also include the variation in the stator and rotor leakage inductances due to saturation in the leakage flux paths. In this model, the effect of the mutual flux saturation is represented by adjusting the unsaturated mutual inductance with the saturation factor K_{sm} as demonstrated in section 2.B.Then in order to take the saturation in the leakage flux paths into account in the model developed in Section 2.A, the unsaturated stator and rotor leakage inductances ($L_{s\sigma}$, $L_{r\sigma}$) in (5) are replaced by their corresponding saturated values ($L_{s\sigma s}$, $L_{r\sigma s}$). These saturated stator and rotor leakage inductances are obtained by adjusting their respective unsaturated values with a saturation factor, $K_{s\sigma}$ corresponding to the stator and rotor currents, respectively.

The saturated leakages inductances are expressed as a function of the stator current i_s and the rotor current i_r currents by:

$$L_{s\sigma s}(i_s) = \begin{cases} L_{s\sigma} & i_s < I_{sat} \\ K_{s\sigma}(i_s).L_{s\sigma} & i_s \geq I_{sat} \end{cases} \tag{11}$$

$$L_{r\sigma s}(i_r) = \begin{cases} L_{r\sigma} & i_r < I_{sat} \\ K_{s\sigma}(i_r).L_{r\sigma} & i_r \geq I_{sat} \end{cases} \tag{12}$$

The saturation factor $K_{s\sigma}$ can be represented by the function [10]:

$$K_{s\sigma}(i) = \begin{cases} 1 & i < I_{msat} \\ \frac{2}{\pi}\left[\arcsin(\frac{I_{sat}}{i}) + 0{,}5\sin(2\arcsin(\frac{I_{sat}}{i})\right] & i \geq I_{msat} \end{cases} \tag{13}$$

The limiting value of the current I_{sat} at which the saturation begins is typically in the range of *1,3-3 pu*, i.e. $1{,}8\times I_n$–$4{,}2\times I_n$ [15,17,18].

3. SIMULATION RESULTS

In order to verify the developed models and see the behavior of the DFIG, it's necessary to compare the dynamic results of the proposed models with the results of the unsaturated DFIG model. All simulations are achieved by Matlab/Simulink and the machine parameters are listed in Appendix B.

The DFIG, investigated in this paper, is excited on the stator by a perfect three-phase voltage system (220V, 50 Hz). The generator rotor is supplied with a reduced three-phase voltage (s×220, s×50 Hz) according to the equation (2). The machine rotor is driven with a super-synchronous speed of 180 rd/s.

The transient performances have been calculated for three saturation cases. In the first case, both the main flux and leakage flux saturation have been ignored. In the second case, the effect of the main flux saturation is considered while the effect of the saturation in the leakage flux paths is ignored. In the third case, both the main flux and leakage flux saturation are considered in the machine modeling.

For taking saturation effect into account in the mutual flux for the investigated DFIG, I_{msat} in (10) was taken to be equal to $0.7\times I_n = 6\ A$. Where I_n represent the rated current given in appendix B.

The mutual flux saturation factor K_{sm} which is used to determine the saturated value of the magnetizing inductance L_{ms} is shown in figure 2.

In order to take the leakage flux saturation into account for this machine, I_{sat} in (13) was taken to be equal to $1.8\times I_n = 15.8\ A$. This Leakage flux saturation factor $K_{s\sigma}$ curve is plotted in figure 3.

The transients state considered in this investigation are done during DFIG direct starting, voltage sag and short-circuit at the machine terminals.

A. Direct starting

The performance of the DFIG with the developed models during direct starting is investigated by calculating the *d-q* stator and rotor currents, as well as the electromagnetic torque as shown in figure 4.

Figures 4a, 4.b, 4.c and 4.d show some of the dynamic responses of the *d-q* stator and rotor currents.

It can be noticed that the effect of the saturation is to increase the stator and rotor currents of the generator during the direct starting. However, the saturation has an insignificant effect on the steady-state values of the generator currents.

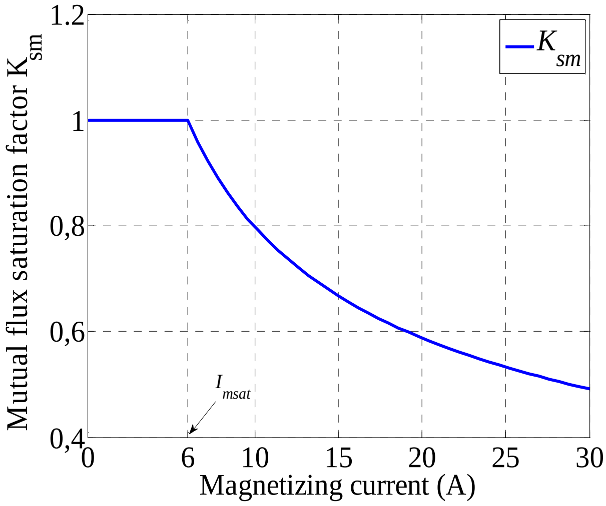


Fig.2. Main flux saturation factor K_{sm}.

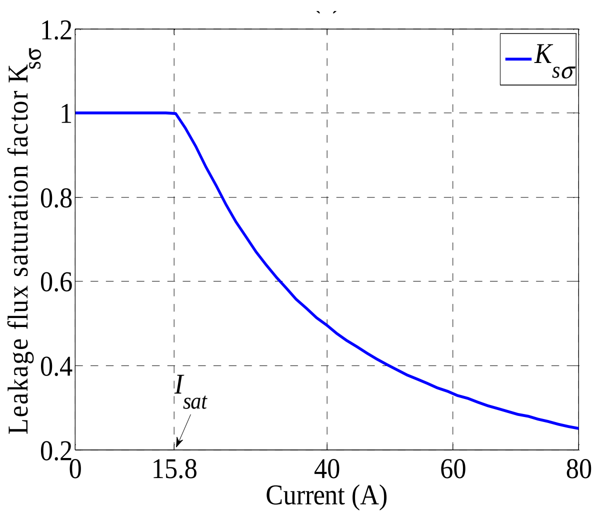


Fig.3. Leakage flux saturation factor $K_{s\sigma}$.

The effect of saturation on the electromagnetic torque during the direct starting is shown in figure 4.e. It can be noticed that the effect of saturation is important in the transient state compared to a small value in steady state. This developed torque reaches their steady-state values faster by the model that considers both the main and the leakage flux saturation. In addition, it can be seen from this transient case that there is a discrepancy between the results calculated by the model that considers only mutual flux saturation and the ones by the model that includes both mutual and leakage flux saturation. However, oscillations of these performances are damped quickly than the ones without saturation and the ones by the model that includes only mutual flux saturation.

B. Voltage sag

In this test, we consider that the machine terminal voltage sag to 75% of the pre-sag value, according to the IEEE definitions for power quality [20]. In this investigation, it is assumed that the pre-sag value of the terminal voltage is 220 V. At t = 0.1 s, a voltage sag to 75% occurs, i.e. 165 V, then at t = 0.2 s the voltage is recovered to its pre-sag value 220 V.

The effect of saturation on the dynamic responses of the generator associated with such procedures is as shown in figure 5. It can be noticed that the effect of leakage flux saturation is to increase the machine currents, at the restoration of the pre-voltage sag, when compared to the results calculated by considering only the main flux saturation and by ignoring saturation (figures 5.a, 5.b, 5.c and 5.d). However, oscillations of these currents are damped quickly than the ones without saturation and the ones by the model that includes only mutual flux saturation. It can also be noticed, as shown in figures 5.e that the effect of saturation on the electromagnetic torque appears in the restoration of the pre-voltage sag. In this transient condition it can be seen that there is a difference between the results calculated by the model that considers only mutual flux saturation and the ones by the model considering both mutual and leakage flux saturation effect.

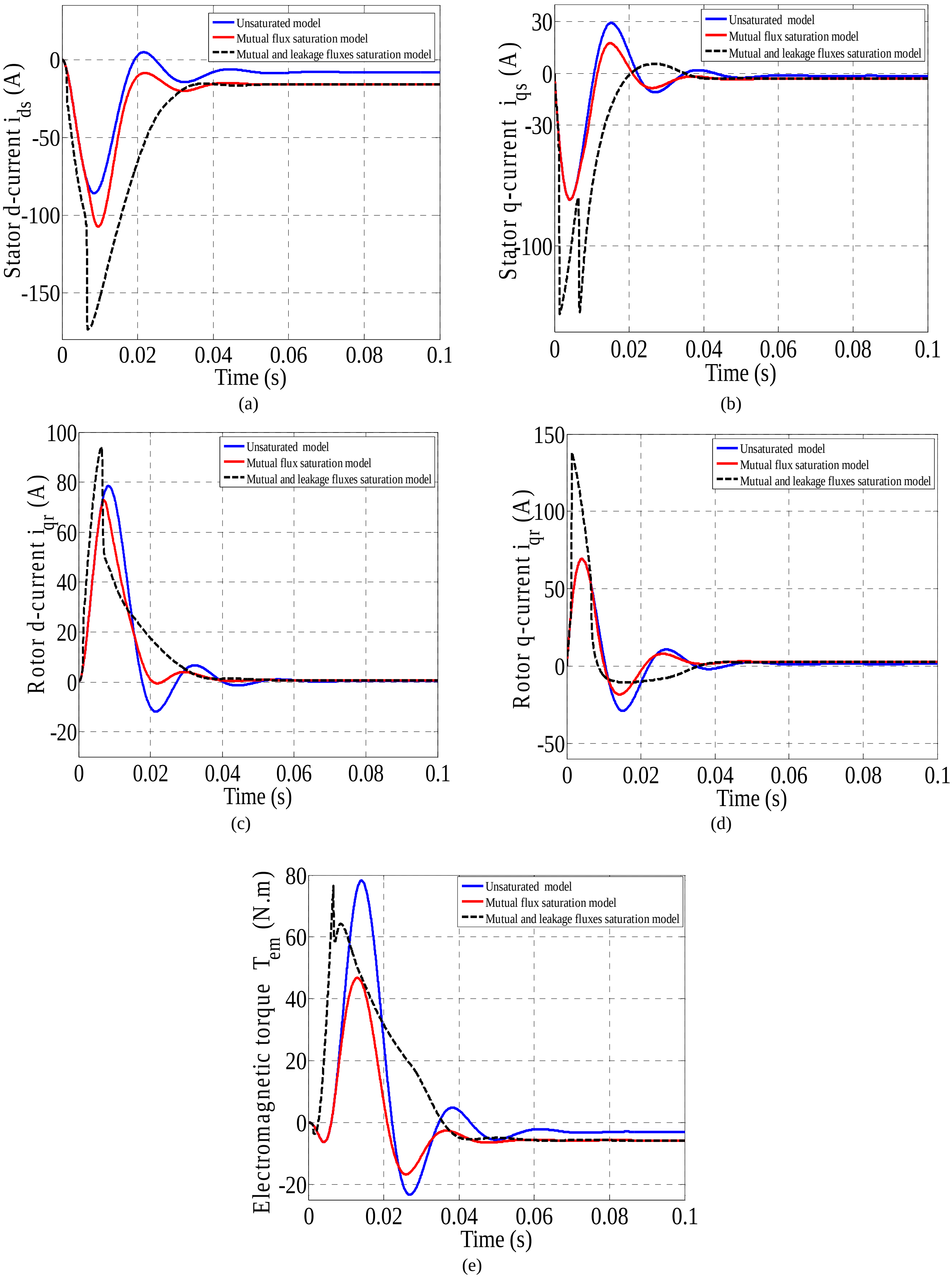


Fig.4. DFIG Transient performances during direct starting: (a) i_{ds}, (b) i_{qs}, (c) i_{dr}, (d) i_{qr}, (e) T_{em}

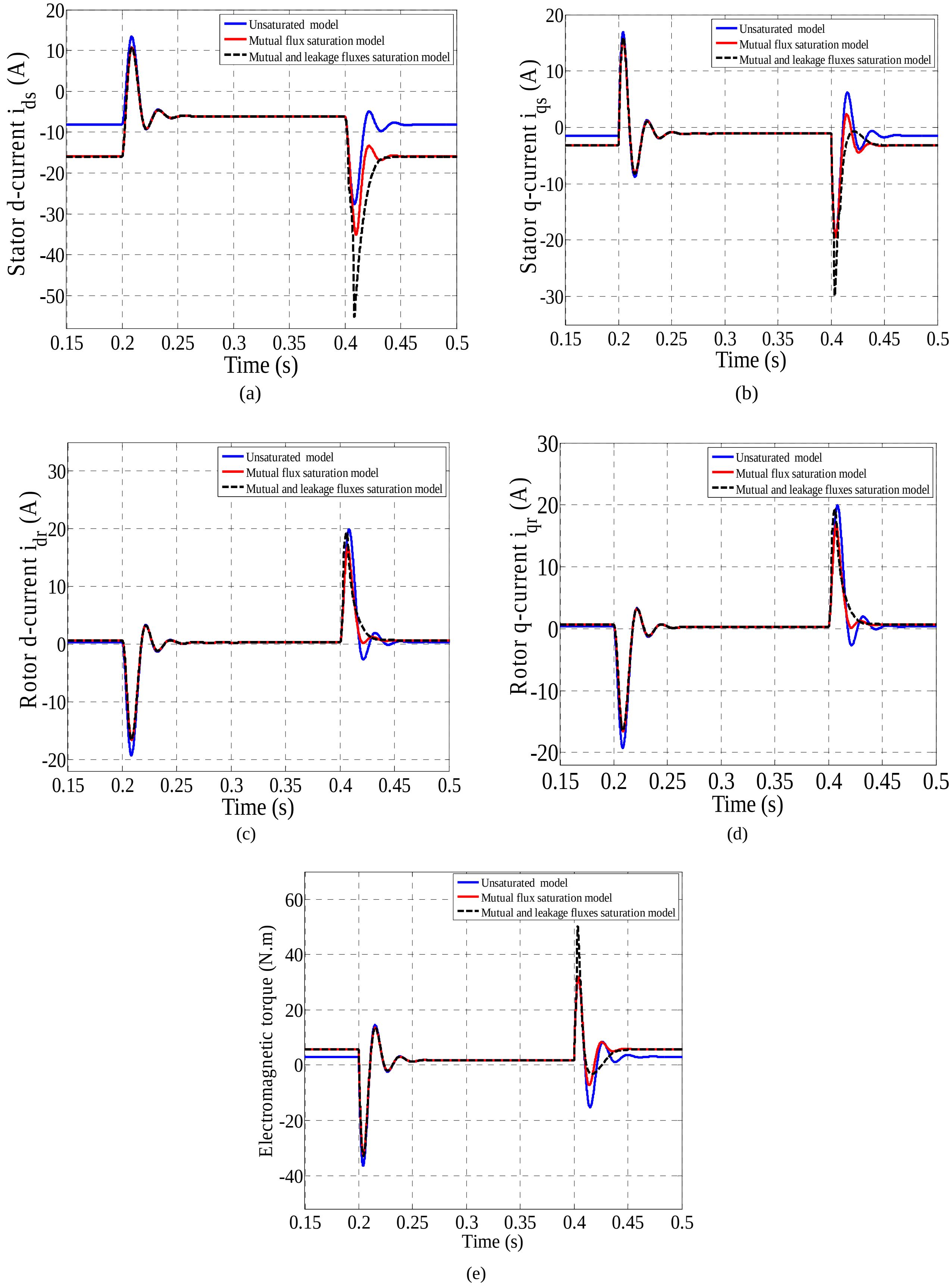
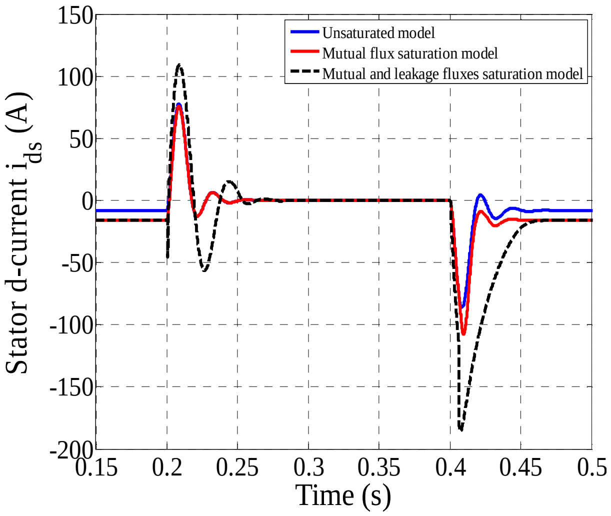
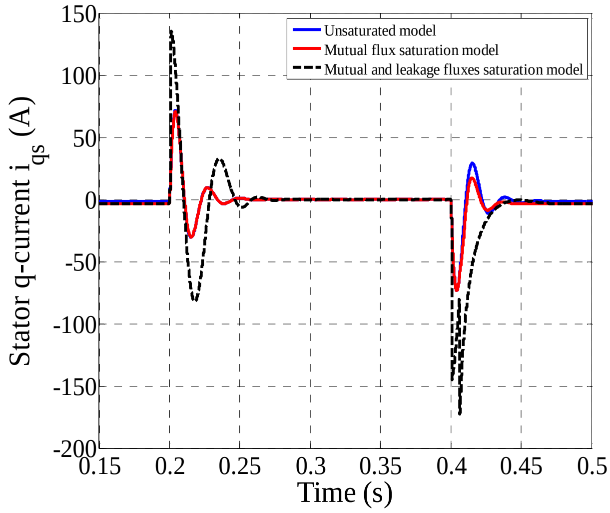


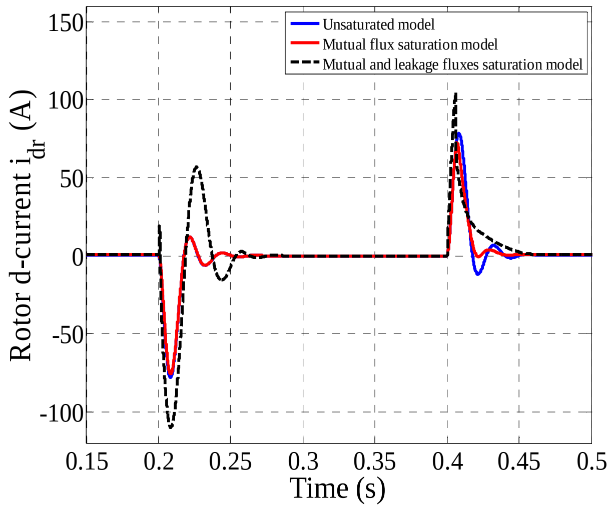
Fig.5. DFIG Transient performances due to the voltage sag: (a) i_{ds}, (b) i_{qs}, (c) i_{dr}, (d) i_{qr}, (e) T_{em}



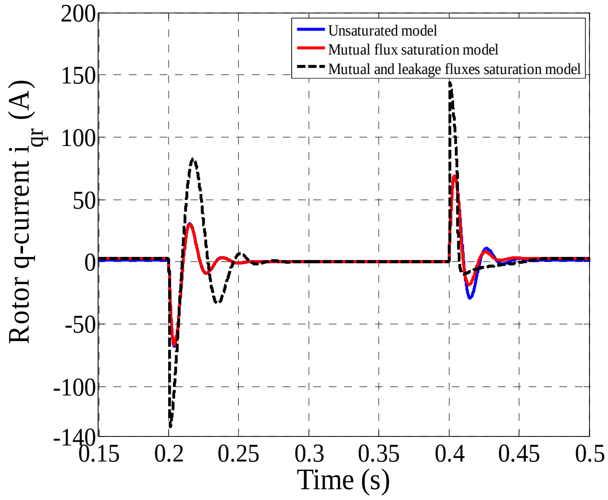
(a)



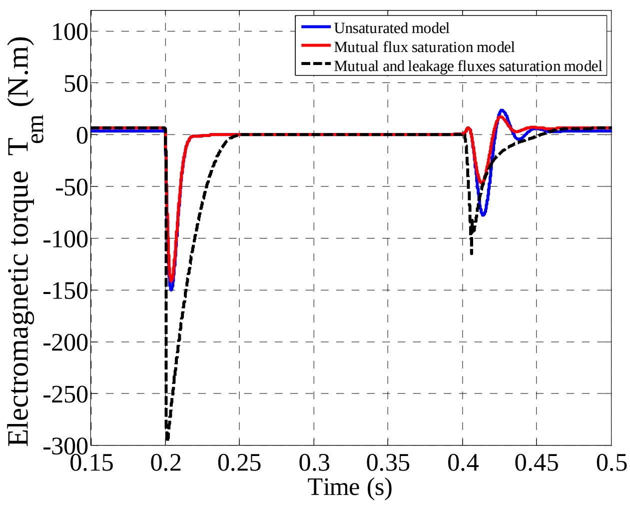
(b)



(c)



(d)



(e)

Fig.6. DFIG Transient performances due to short-circuit at machine terminals: (a) i_{ds}, (b) i_{qs}, (c) i_{dr}, (d) i_{qr}, (e) T_{em}

C. Short-circuit

In this analysis, it was clear that the value of the terminal voltage is 220 V before the default. At t = 0.2 s, a momentary interruption occurs then at t = 0.4 s the voltage is restored to its pre-fault value, i.e.220 V. The effect of saturation on the short- circuit performances of the generator under such dynamic condition is as shown in figure 6.

Short-circuit can be considered as a severe voltage drop in which the voltage sags to 0 V. It can be noticed from Fig. 6 that the above mentioned conclusions in the case of the voltage sag can also be applied in the case of short-circuit. In this case, the effect of leakage flux saturation is to increase the machine currents by 50–75 A when compared to the results calculated by considering only the main flux saturation and by ignoring saturation as shown in figures 6.a, 6.b, 6.c and 6.d. In the case of the torque, the increase is in the range of 150 N.m at the short-circuit occurrence (figure 6.e.).

It can be also seen from figure 6 that there is a discrepancy between the results calculated by the model that considers only mutual flux saturation and the ones by the model that includes both mutual and leakage flux saturation.

4. Conclusion

This paper examines the effect of both the mutual and the leakage flux saturation on the DFIG transient performances. According to the simulation results, it is shown that the DFIG transient responses calculated by mutual and leakage flux are considerably higher and reach their steady-state values faster than the ones calculated by ignoring the saturation or considering only the saturation in the mutual flux.

The model that includes the both mutual and leakage flux saturation produces the most accurate results. So is crucial to incorporate the effect of both the main and the leakage flux saturation in DFIG modeling to study its transient performances.

Since we have an idea on the accurate peak values in transient state of the DFIG, then it will be important to choose appropriate values of the semiconductor switches and other components of power electronics. This analysis may also be significant for future studies on the improved control strategies for DFIG-based wind conversion systems.

Appendix A

Table 1. List of symbols

Symbol	Significance
DFIG	Doubly-fed induction generator
v_{ds}, v_{qs}, v_{dr}, v_{qr}	d and q axis stator and rotor voltages,
ψ_{ds}, ψ_{qs}, ψ_{dr}, ψ_{qr}	d and q axis stator and rotor fluxes,
i_{ds}, i_{qs}, i_{dr}, i_{qr}	d and q axis stator and rotor currents,
R_s, R_r	Stator and rotor resistances,
L_s, L_r	Stator and rotor inductances,
$L_{s\sigma}$, $L_{r\sigma}$	Stator and rotor leakage inductances,
$L_{s\sigma s}$, $L_{r\sigma s}$	Stator and rotor saturated leakage inductances,
σ	Leakage coefficient
I_n	Rated current,
L_m	Mutual inductance,
L_{ms}	Saturated mutual inductance,
p	Number of pole pairs,
s	Generator slip,
ω_s, ω_r	Stator and rotor current frequencies (rd/s),
ω_m	Mechanical rotor frequency (rd/s),
T_{em}	Electromagnetic torque.

Appendix B

Table 2. Machine parameters

Parameters	Rated Value	Unit
Nominal power P_n	7.5	KW
Stator voltage V_n	220	V
Stator current I_n	8,6	A
Stator frequency f	50	Hz
Number of pairs poles p	2	
Nominal speed ω_m	144	rad/s
Stator resistance R_s	1.2	Ω
Rotor resistance R_r	1.8	Ω
Mutual inductance L_m	0.15	H
Leakage stator inductance $L_{\sigma s}$	0.0054	H
Leakage rotor inductance $L_{\sigma r}$	0.0068	H

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