Transient response of doubly fed induction generator under voltage sag using an accurate model

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***Abstract*-** **In order to investigate the transient response of doubly fed induction generator (DFIG) under grid disturbances, an accurate model is required. In this paper transient response of DFIG during voltage sag considering saturation effect of leakage flux for different order models is simulated. Then, rotor over-current due to voltage sag and factors that affect it, is investigated.**

NOMONCLATURE

Symbols	
I	Effective phase current
i	Current
u	Voltage
R	Resistance
X	Reactance
ψ	Flux
ω	Angular velocity
H	Combined inertia of wind turbine and DFIG rotor
γ	Current ratio
K	Saturation factor
Subscript	
m	Mutual
d	d axis component
q	q axis component
r	Rotor
s	Stator
M	Mechanical
cb	Crowbar
max	Maximum
sat	Saturation
b	Base
l	Leakage

I. Introduction

Due to the increasing concern about CO_2 emissions, renewable energy systems and specially wind energy generation have attracted great interest in recent years. Large wind farm have been installed or planed around the world and the power rating of the wind turbine is increasing. Nowadays, the most widely used wind turbine in wind farm is based on doubly fed induction generator (DFIG) due to noticeable advantages: the various speed generation, the decoupled control of active and reactive power and the improvement of the power quality. However, wind turbines based on the DFIG are very sensitive to grid disturbance, especially to voltage dips [1]. in recent years, many papers investigated it from various aspect. For studying a DFIG, at first an accurate model is needed. In some papers different order model was proposed [2-5]. The computational time can be ameliorated by reducing the order of the generator. The reduce order is obtained by neglecting differential term in the voltage equation of the machine [5].in these papers the effect of leakage flux saturation is usually neglected. In other kind of papers saturation effect was considered, but investigation doesn't perform for different orders. X_s, and X_r aren't constant in these papers, but vary depend on current pass through them [6,7]. According to mentioned above, the voltage dip could cause over-voltage and over-current in rotor winding and consequently damaged the rotor side converter. So studying the transient behavior of DFIG during the three phase voltage dip is very important.

The aim of this work is to present a comparative study among different orders of the DFIG model accompany with saturation effect during three phase voltage sag and at next step the most accurate model was used to show rotor over-current. Finally various factors reducing the maximum value of over-current is investigated.

II. unsaturated induction generator model

in this section the unsaturated model for DFIG is given.

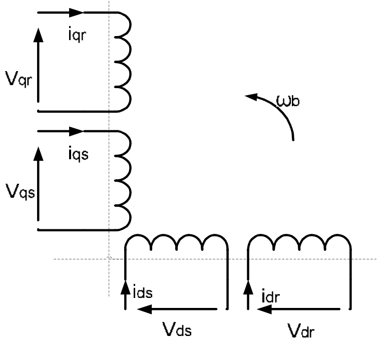


Figure 1. direct (d) and quadrature (q) representation of induction machine.

The voltage equations for the induction generator are given below, where all quantities except the angular frequency, ω_b, are in pu.

$$u_{ds} = -R_s i_{ds} + \psi_{qs} - \frac{1}{\omega_b}\frac{d\psi_{ds}}{dt} \tag{1}$$

$$u_{qs} = -R_s i_{qs} - \psi_{ds} - \frac{1}{\omega_b}\frac{d\psi_{qs}}{dt} \tag{2}$$

$$u_{dr} = -R_r i_{dr} + (1-\omega_m)\psi_{qr} - \frac{1}{\omega_0}\frac{d\psi_{dr}}{dt} \tag{3}$$

$$u_{qr} = -R_r i_{qr} - (1-\omega_m)\psi_{dr} - \frac{1}{\omega_0}\frac{d\psi_{qr}}{dt} \tag{4}$$

Using these equations, a model for both the squirrel cage and wound rotor generators can be developed. the difference between these two generators lies in the rotor: the first one has short circuited winding, so rotor voltage is zero, and the second one has these winding fed by a converter, responsible of controlling the generator[5]. Flux linkage used in previous equation, is obtained from (5) and (6):

$$\begin{cases}\psi_{qs} = X_s i_{qs} + X_m i_{qr} \\ \psi_{ds} = X_s i_{ds} + X_m i_{dr}\end{cases} \tag{5}$$

$$\begin{cases}\psi_{qr} = X_m i_{qs} + X_r i_{qr} \\ \psi_{dr} = X_m i_{ds} + X_r i_{dr}\end{cases} \tag{6}$$

The electromagnetic torque is calculated by

$$T_e = \psi_{ds} i_{qs} \_ \psi_{qs} i_{ds} \tag{7}$$

Finally if T_M is the mechanical torque dependent upon the local wind speed:

$$T_M \_ T_e = 2H\frac{d\omega_M}{dt} \tag{8}$$

The model of an induction generator can have various orders, such as 1, 3 or 5.the fifth-order model is considered to be a full order model for an induction generator. The third-order model ignores the stator dynamics and is widely used in power system transient stability analysis. The first order model ignores both the stator and rotor dynamics. The only differential equation left is the swing equation. This model is suitable for long term power system dynamic study including the induction motor load characteristics [4]. Table 1 briefly describe above sentences [5].

Table 1.
simplifications used in different order models

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

III. saturated induction generator model

for better representation of the induction machine under transient condition, saturation effect should also include the variation in the stator and rotor leakage inductances due to saturation in the leakage flux path. The effect of saturation in leakage flux path is considered by modifying the unsaturated stator and rotor leakage reactances with saturation factor K_{sat} [7]. K_{sat} is introduced as follow [6]:

$$K_{sat} = \begin{cases} 1 & I \le I_{sat} \\ \frac{2}{\pi}(\tan^{-1}(\frac{\gamma}{\sqrt{1-\gamma}}) + \gamma\sqrt{1-\gamma}) & I > I_{sat}\end{cases} \tag{9}$$

Where γ is equal to the ratio between current at which the saturation begins, I_{sat}, to the current through the leakage reactance. The saturation factor characteristic is shown in fig.2.

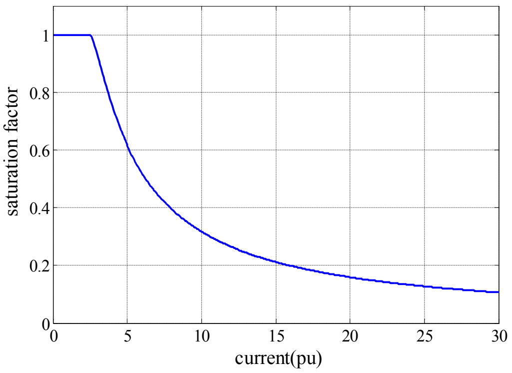
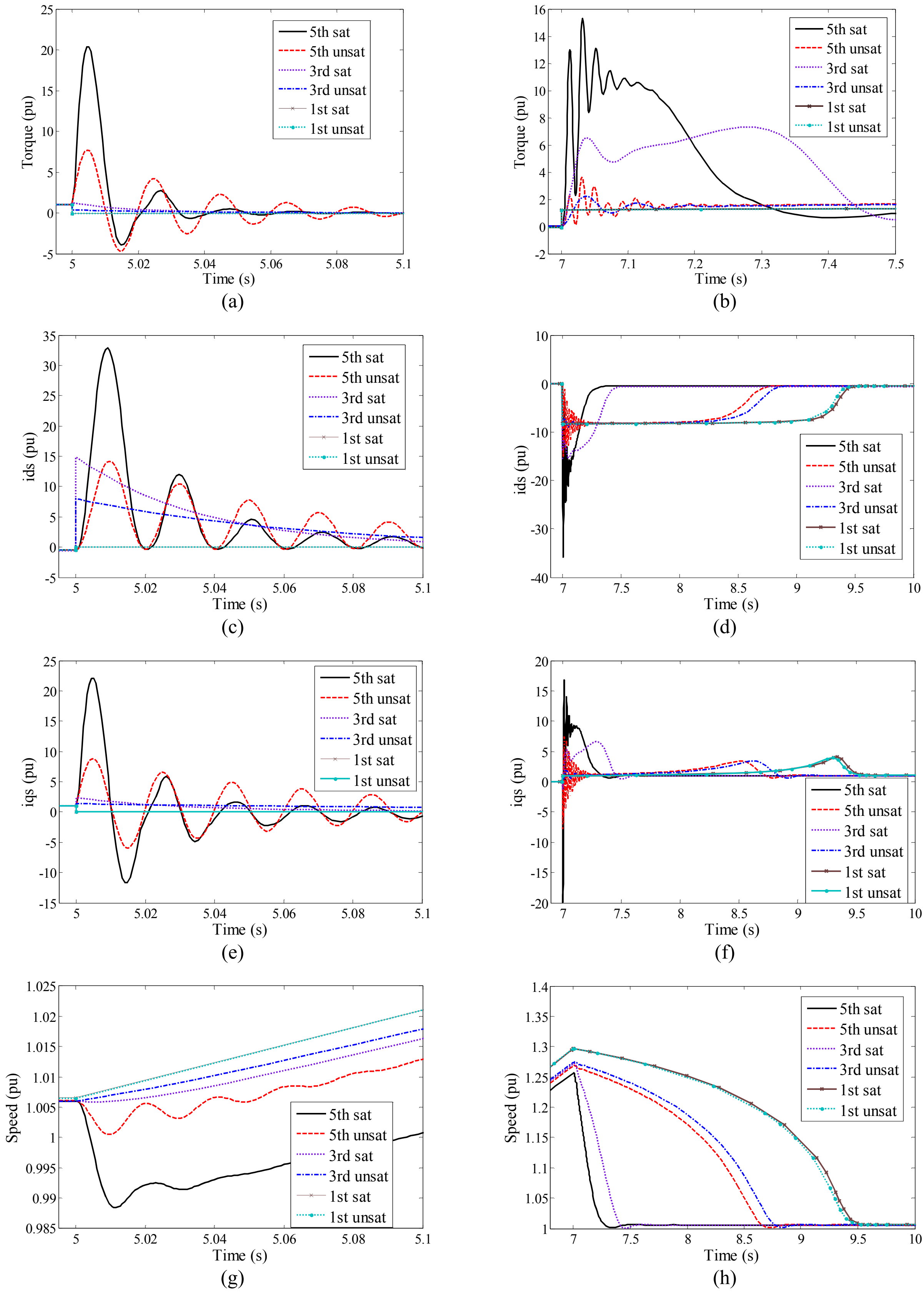


Figure 2. saturation factor characteristic

IV. transient response of DFIG during voltage sag

short duration under voltages are called "voltage sags" or "voltage dips". The latter term is preferred by the IEC. Within the IEEE, the term voltage sag is used. According to the IEC, a supply voltage dip is a sudden reduction in the supply voltage to a value between 90% and 1% of the declared voltage, followed by a recovery between 10 ms and 1 minute later. For the IEEE a voltage drop is only a sag if the during sag voltage is between 10% and 90% of the nominal voltage [8]. In this paper 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. 1pu.



(a) (b)

(c) (d)

(e) (f)

(g) (h)

Figure 3. DFIG transient response due to 50% voltage sag. (a) torque at voltage sag occurrence, (b) torque at voltage recovery, (c) ids at voltage sag occurrence, (d) ids at voltage recovery, (e) iqs at voltage sag occurrence, (f) iqs at voltage recovery, (g) speed at voltage sag occurrence, and (h) speed at voltage recovery

The effect of saturation using different orders on the transient performances of the generator associated with such events is shown in fig.3. the machine used for simulation was a 2 MW, 690 V wind turbine and machine parameters are given in appendix.

The following results can be seen from above simulation:

1. after the fault occurred:

- the effect of leakage flux saturation is to increase the current and torque.
- In spite of fifth order model there isn't any oscillation in third and first order model.
- Difference between saturated and unsaturated of first order model is negligible, but for higher order model this is significant.
- The rotor speed decreases for saturated and unsaturated of fifth order model, but for other models there isn't any decrease in speed.

2. after the fault cleared:

- fifth order saturated model reach its steady state faster than the other models.
- Saturation doesn't affect the steady state value of torque, current and speed but it affects transient response of these variables.

V. rotor over-current due to voltage sag

The abrupt drop of the grid voltage causes over-voltages and over currents in the rotor windings that could even destroy the converter if no protection element is included. In [9] the factors that affect over-current was investigated mathematically. In this paper the effect of these factors is simulated considering an accurate model. For all simulation in this section fifth-order model considering saturation effect is used.

A. crowbar resistance

The first factor is rotor resistance. If we neglect the stator resistance, the amplitude of over-current is proportional to 1/Rr. So the solution to protect converter is to short circuit the rotor windings with the so-called crowbar resistance. There are two main requirements that give an upper and a lower limit to the resistance [7]:

1) the resistance should be high to limit the short circuit current .
2) on the other hand, it should be low to avoid a too high voltage in the rotor circuit.

A too high voltage can result in break down of the isolation material of the rotor and the converter. Fig.4 shows a simulation that uses crowbar resistance in series with rotor resistance as a solution to reduce rotor over-current. Simulation was done for different value of crowbar. When the voltage sag occurs the crowbar resistance is added to rotor resistance.

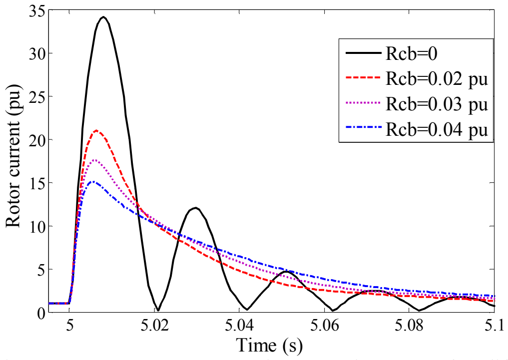


Figure 4. rotor over-current due to voltage sag for different crowbar resistance value

As shown in fig.4, the more the value of crowbar resistance, the less the maximum of rotor current. Table 2 shows the maximum of rotor current while the crowbar resistance changes.

Table 2

maximum of rotor current while the crowbar changes

$R_{cb}(\Omega)$	0	0.02	0.03	0.04
$I_{r\max}(A)$	34.12	20.96	17.51	15.02

B. depth of voltage dip

The second factor is depth of voltage dip. In fact, the more severe of voltage drop, the bigger of the rotor current amplitude was. To quantify sag magnitude in radial systems, the voltage divider model, shown in fig.5, can be used. The voltage at the DFIG terminals can be found from (10).

$$V_{sag} = \frac{Z_F}{Z_S + Z_F} E \tag{10}$$

Any fault impedance should be included in the feeder impedance Z_F .

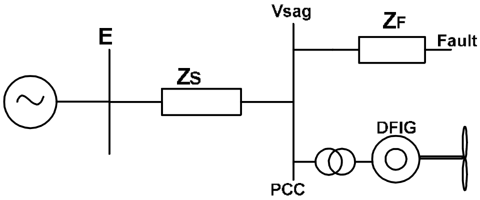


figure 5. voltage divider model for a voltage sag

It's seen from (10) that the sag becomes deeper for faults electrically closer to the DFIG (when Z_F becomes smaller), and for systems with a smaller fault level (when Z_S becomes larger). In (10) E=1 pu and $Z_F = z \times l$, with z the impedance of the feeder per unit length and l the distance between the fault and the pcc, leading to (11).

$$V_{sag} = \frac{zl}{Z_S + zl} \tag{11}$$

The sag magnitude as a function of the distance to the fault has been calculated for a typical 11 kV overhead line, resulting in fig.6.

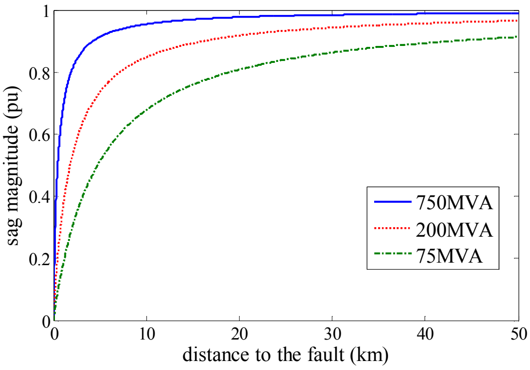


Figure 6. sag magnitude as a function of the distance to the fault, for faults on an 11 kV, overhead line.

The fault level is used to calculate the source impedance at the pcc. In this paper, 11 kV overhead line, and 200MVA fault level is considered. The impedance of overhead line is 0.117 + j0.315Ω per km[8]. Simulations are done for different distance between fault and pcc.

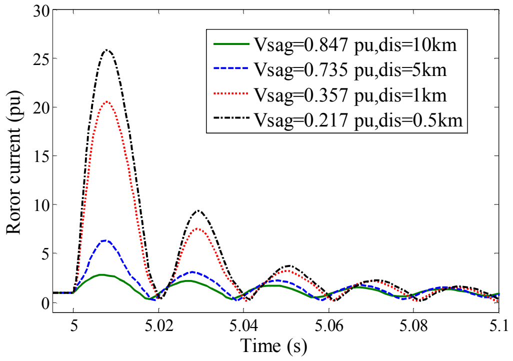


Figure 7. rotor over-current due to voltage sag for different distance between fault and pcc.

Fig.7 shows that the distance between fault and terminal of DFIG is an important factor for maximum amplitude of rotor current. For example when it is 500m, rotor maximum current is 25.8A, while it is 10km, rotor maximum current is 2.85A.

VI. Conclusion

In this paper transient performance of different order model of DFIG considering or ignoring saturation effect was compared. Then some parameters that affect rotor over-current due to voltage sag was simulated. The main findings can be summarized in the following points:

1. the stator and rotor current of DFIG calculated by considering the saturation effect are significantly higher than the ones that ignores it.
2. the rotor speed of saturated model reaches the steady state value faster than unsaturated model, and fifth order model reaches faster than the reduced orders.
3. it's crucial to incorporate the saturation effect to study the transient performance of DFIG, but it's not important for steady state study.
4. in the case of strong voltage sags, the induced voltage on rotor can even be higher than the stator voltage. In this situation, there appear over-current whose amplitude depends on the depth of the dip, the machine parameters, and the protection element.

Appendix

Rated power (W)	2000
Rated voltage (V)	690
Rated frequency (Hz)	50
X_m (pu)	3.188
R_s (pu)	0.00562
R_r (pu)	0.00575
X_{ls} (pu)	0.0708
X_{lr} (pu)	0.0486

$$X_S = X_m + X_{ls}$$
$$X_r = X_m + X_{lr}$$

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