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Low Voltage Ride-Through of Doubly Fed Induction Machine using Direct Torque Control Strategy

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ABSTRACT

The wind turbines based Doubly Fed Induction Machine (DFIM) not able to support the voltage and the frequency of the grid during and immediately following the grid failure. This would cause major problems for the systems stability, but the turbines should stay connected to the grid in case of a failure. This can be achieved by using crowbar protection in particularly during voltage dips. When low depth voltage dips occur, the necessity of crowbar proctection can be eliminated by using proposed Direct Torque Control (DTC), with a proper rotor flux generation strategy, by which during the fault it will be possible to maintain the machine connected to grid, generating power from the wind, reducing the stator and rotor over currents, eliminating the torque oscillations that normally produce such voltage dips and fast dynamic response accompanies the overall control of the wind turbine.

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1. INTRODUCTION

The worldwide concern about the environment has led to increasing interest in technologies for generation of renewable electrical energy. One way of generating electricity from renewable sources is to use wind turbines. The most common type of wind turbine is the fixed-speed Wind Turbine (WT) with the Doubly Fed Induction Generator (DFIG) directly connected to the grid.

Today, the DFIG WT will be disconnected from the grid when large voltage dips appear in the grid. After the DFIG WT has been disconnected, it takes some time before the turbine is reconnected to the grid. This means that new WTs have to ride through these voltage dips. The DFIG system, of today, has a crowbar in the rotor circuit, which at large grid disturbances has to short circuit the rotor circuit in order to protect the converter. This leads to that the turbine must be disconnected from the grid, after large voltage dip.

In the literature there are some different methods to modify the DFIG system in order to accomplish voltage dip ride-through proposed. A method was proposed in which additional converter was used to substitute the Y point of the stator circuit [1], [2]. In [2], Kelber has shown that such a system can effectively damp the flux oscillations caused by voltage dips. All of these systems have different dynamical performance. Moreover, the efficiency and cost of the different voltage dip ride-through system might also influence the choice of system. Therefore, when modifying the DFIG system for voltage dip ride-through it is necessary to evaluate consequences for cost and efficiency. Any evaluation of different voltage dip ride-through methods for DFIG wind turbines and how they affect the efficiency is hard to find in the literature. Consequences for the efficiency is an important issue since, as mentioned earlier, one of the main advantage with the DFIG system was that losses of the power electronic equipment is reduced in comparison to a system where the power electronic equipment has to handle the total power. The grid disturbance response to fixed-speed wind turbines and wind turbines with DFIG were presented in [3]. In [4] anti-parallel thyristors is used in the stator circuit in order to achieve a quick (within 10 ms) disconnection of the stator circuit, and thereby be able to remagnetize the generator and reconnect the stator to the grid as fast as possible. Another option proposed in [5] is to use an “active” crowbar, which can break the short circuit current in the crowbar. One disadvantage with this system is that once the crowbar has been triggered, the turbine must be disconnected from the grid, since the current through the thyristor is a continuous dc current and can only be interrupted if the turbine is disconnected from the grid. In [6], a voltage dip ride-through system for a DFIG WT based on increased rating of the valves of the power electronic converter was investigated. The voltage dip response of a PWM rectifier for wind turbines that utilizes a full-power converter were studied in [7].

This paper focuses the analysis on the control of Doubly Fed Induction Machine (DFIM) based high-power wind turbines when they operate under presence of voltage dips. Most of the wind turbine manufacturers build this kind of wind turbines with a back-to-back converter sized to approximately 30% of the nominal power [8]. This reduced converter design provokes that when the machine is affected by voltage dips, it needs a special crowbar protection. [9] describes a solution that makes it possible for wind turbines using doubly-fed induction generators to stay connected to the grid during grid faults. The key of the solution is to limit the high current in the rotor in order to protect the converter and to provide a bypass for this current via a set of resistors that are connected to the rotor windings, in order to avoid damages in the wind turbine and meet the grid-code requirements; it is also described in [10]. In [11] investigation develops a control method to increase the probability of successful grid fault ride-through, given the current and voltage capabilities of the rotor-side converter. [12] proposes a novel crowbar control technique and a Stator Voltage Oriented Direct Power Control (SVODPC) strategy for the DFIG used in wind power generation systems. But this control scheme the DFIG can be able to ride through the severe grid voltage dips only. [13] – [15] proposes an improved control strategy for the crowbar protection to reduce its operation time. [16] presents a novel control strategy primarily based on the realtime adjustable resistance crowbar structure.

Worldwide, there is an ambition to install a large amount of wind power and to increase the share of energy consumption that is produced by wind turbines. The interaction with the grid becomes increasingly important then [17]. This can be understood as follows. When all wind turbines would be disconnected in case of a grid failure, these renewable generators will-unlike conventional power plants-not be able to support the voltage and the frequency of the grid during and immediately following the grid failure. This would cause major problems for the systems stability [18]. It is therefore worldwide recognized that to enable large-scale application of wind energy without compromising system stability, the turbines should stay connected to the grid in case of a failure. They should-similar to conventional power plants-supply active and reactive power for frequency and voltage support immediately after the fault has been cleared, which is normally within a fraction of a second, as mentioned previously.

More papers are published that discuss the protection of DFIGs during grid disturbances [19]–[22]. However, most papers give little information on the way the protection scheme is implemented. Further, they give only limited information on the behavior of the rotor voltage and current during disturbances, while these signals are important during disturbances. Rotor currents or voltages that are too high might destruct the converter in the rotor circuit. The main objective of the control strategy proposed in this paper is to eliminate the necessity of the crowbar protection when low-depth voltage dips occur. Hence, by using Direct Torque Control (DTC), with a proper rotor flux generation strategy, during the fault it will be possible to maintain the machine connected to the grid, generating power from the wind, reducing over currents, and eliminating the torque oscillations that normally produce such voltage dips. Reviewing the literature mentioned above, the proposed DTC with a proper rotor flux generation strategy implementation, the necessity of crowbar can be eliminated at low voltage dips making it cost effective, reducing bulkiness and reducing circuitry besides the above mentioned advantages of the proposed strategy.

In Fig. 1, the wind turbine generation system together with the proposed control block diagram is illustrated.

The DFIM is supplied by a back-to-back converter through the rotor, while the stator is directly connected to the grid. The back-to-back converter consists of two converters, i.e., machine-side converter and grid-side converter that are connected “back-to-back.” Between the two converters a dc-link capacitor is placed, as energy storage, in order to keep the voltage variations (or ripple) in the dc-link voltage small. With the machine-side converter it is possible to control the torque or the speed of the DFIG and also the power factor at the stator terminals, while the main objective for the grid-side converter is to keep the dc-link voltage constant.

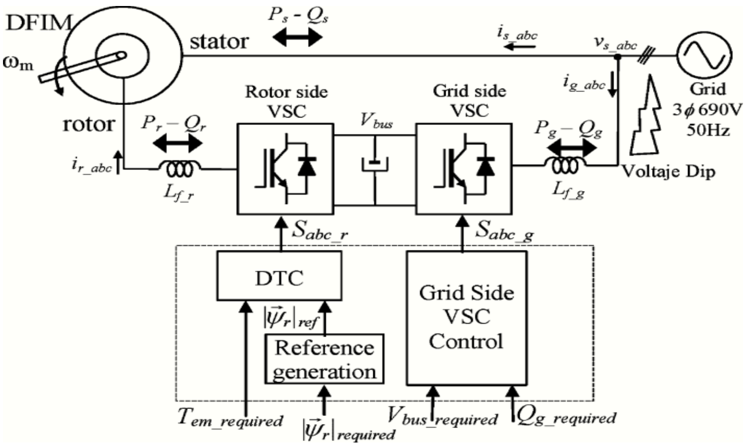


Figure 1. Wind energy generation system based on the DFIM

This paper only considers the control strategy corresponding to the rotor side converter. The grid-side converter is in charge to keep controlled the dc bus voltage of the back-to-back converter and the reactive power is exchanged through the grid by this. As can be noticed from Fig. 1, the DFIM control is divided into two different control blocks. A DTC that controls the machine's torque (T_{em}) and the rotor flux amplitude ($|\psi_r|$) with high dynamic capacity, and a second block that generates the rotor flux amplitude reference, in order to handle with the voltage dips. The simulink model of the wind energy generation system based on DFIM is shown in Fig. 3. The Fig. 3 will be same for both without reference and with reference generation. The rotor flux reference generation strategy is shown in Fig. 4, which is the only addition to the with reference generation.

When the wind turbine is affected by a voltage dip, it will need to address three main problems: from the control strategy point of view, the dip produces control difficulties, since it is a perturbation in the winding of the machine that is not being directly controlled (the stator); the dip generates a disturbance in the stator flux, making necessary higher rotor voltage to maintain control on the machine currents; and if not special improvements are adopted, the power delivered through the rotor by the back-to-back converter, will be increased due to the increase of voltage and currents [10] in the rotor of the machine, provoking finally, an increase of the dc bus voltage [11].

Taking into account this, depending on the dip depth and asymmetry, together with the machine operation conditions at the moment of the dip (speed, torque, mechanical power, etc.), implies that the necessity of the crowbar protection is inevitable in many faulty situations. However, in this paper, a control strategy that eliminates the necessity of the crowbar activation in some low depth voltage dips is proposed.

2. RESEARCH METHOD

When a voltage dip occurs, the stator flux evolution of the machine is imposed by the stator voltage equation

$$v_s^s = R_s i_s^s + \frac{d\Psi_s^s}{dt} \tag{1}$$

In general, since very high stator currents are not allowed, the stator flux evolution can be approximated by the addition of a sinusoidal and an exponential term [1] (neglecting Rs)

$$\begin{aligned}\Psi_{\alpha s} &= K_1 e^{-K_2 t} + K_3 \cos(\omega_s t + K_4)\\ \Psi_{\beta s} &= K_5 e^{-K_2 t} + K_3 \sin(\omega_s t + K_4)\end{aligned} \tag{2}$$

Sinusoidal currents exchange with the grid will be always preferred by the application during the fault. It means that the stator and rotor currents should be sinusoidal.

However, by checking the expressions that relate the stator and rotor currents as a function of the fluxes

$$i_s^s = \left(\frac{L_h}{\sigma L_r L_s}\right)\left(\frac{L_r}{L_h}\Psi_s^s - \Psi_r^s\right)$$

$$i_r^s = \left(\frac{L_h}{\sigma L_r L_s}\right)\left(\frac{L_s}{L_h}\Psi_r^s - \Psi_s^s\right) \tag{3}$$

It is appreciated that it is very hard to achieve sinusoidal currents exchange, since only the rotor flux amplitude is controlled by a DTC technique.

Consequently, as proposed in next section, a solution that reasonably cancels the exponential terms from (3) is to generate equal oscillation in the rotor flux amplitude and in the stator flux amplitude. Finally, as it will be later shown that the quality of the currents is substantially improved with this oscillatory rotor flux, rather than with constant flux.

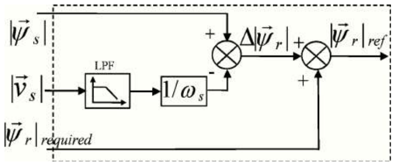


Figure 2. Rotor flux reference generation strategy

As depicted in Fig. 2, the proposed rotor flux amplitude reference generation strategy, adds a term ($\Delta|\boldsymbol{\psi}_\mathbf{r}|$) to the required reference rotor flux amplitude according to the following expression:

$$\Delta|\psi_r| = |\psi_s| - \left(\frac{|v_s|}{\omega_s}\right) \tag{4}$$

$$\psi_s = L_s i_s + L_h i_r$$

$$\psi_r = L_r i_r + L_h i_s$$

or

$$\psi_s = \sqrt{\psi_{ds}^2 + \psi_{qs}^2}$$

$$\psi_r = \sqrt{\psi_{dr}^2 + \psi_{qr}^2} \tag{5}$$

With $|\boldsymbol{\psi}_\mathbf{s}|$, the estimated stator flux amplitude and $|\boldsymbol{v}_\mathrm{s}|$ voltage of the grid (not affected by the dip). This voltage can be calculated by several methods, for instance, using a simple small bandwidth low-pass filter, as illustrated in Fig. 3. It must be highlighted that constants K_1 - K_5 from (2) are not needed in the rotor flux reference generation reducing its complexity.

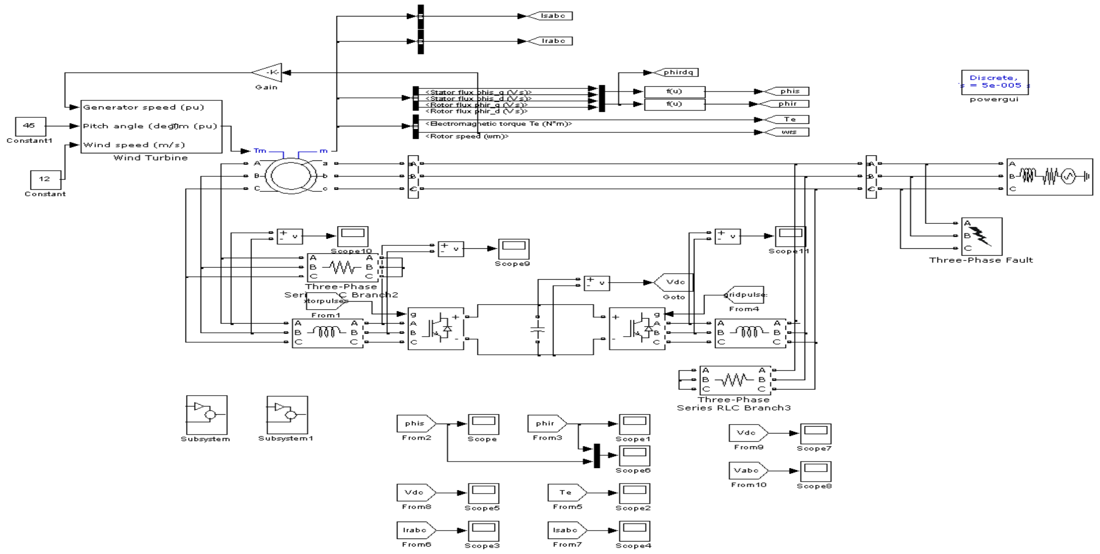


Figure 3. MATLAB/Simulink model of proposed control strategy

Fig. 4 shows the simulink model of rotor flux generation strategy which depicts the actual model of proposed rotor flux amplitude reference generation strategy.

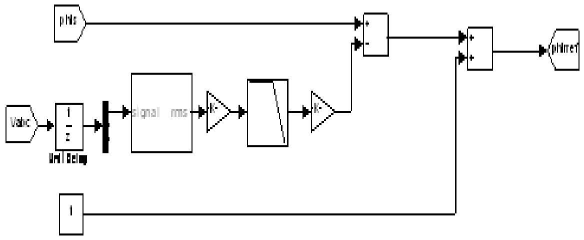


Figure 4. MATLAB/Simulink model of reference flux generation strategy

Note that at steady state without dips presence, $\Delta|\psi_r|$ the term will be zero. However, when a dip occurs, the added term to the rotor flux reference will be approximately equal to the oscillations provoked by the dip in the stator flux amplitude. For simpler understanding, the voltage drop in the stator resistance has been neglected. The magnitude of stator flux and rotor flux can be calculated by (5) by knowing the values of stator, rotor self inductance, mutual inductance and stator, rotor currents at that instance or the values of stator and rotor flux can be calculated by taking the square root of summation of squares of direct and quadrature axis fluxes of stator and rotor respectively as mentioned in (5).

3. RESULTS AND DISCUSSION

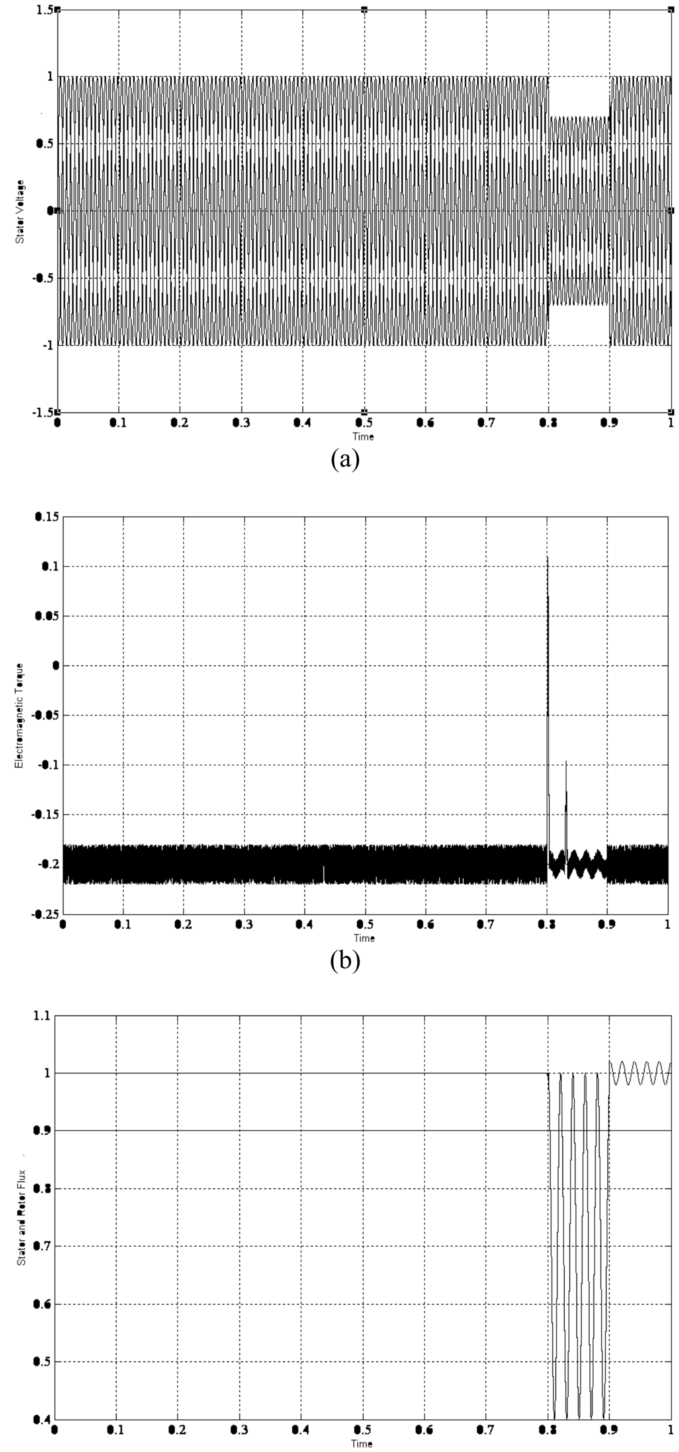
The simulated wind turbine is a 2 MW, 690 V, N_s/N_r = 1/3 and two pair of poles DFIM. Since the losses in the power electronic converter depend on the current through the valves, it is important to have a stator-to-rotor urns ratio of the DFIG that minimizes the rotor current without exceeding the maximum available rotor voltage. Here as mentioned previously, the stator-to-rotor turns ratio, N_s/N_r is 0.33, the rotor current is approximately 0.33 times smaller than the stator current, if the magnetizing current is neglected.

The main objective of this simulation validation is to show the DFIM behavior when a low depth [in this case 30%, as illustrated in Fig. 5(a)] symmetric voltage dip occurs with and without the proposed flux reference generation strategy and at nearly constant speed. The simulations are performed in MATLAB/Simulink.

The flux dynamics of the DFIG are strongly influenced by a pair of poorly damped poles, with an oscillating frequency close to the line frequency. Due to the poorly damped poles, in case of a voltage dip, the flux will enter a damped oscillation. It is essential that the magnitude of the rotor current is below the rated value of the converter in order not to force the crowbar, if employed, to go into action, and thereby lose control of the rotor currents and thus the power production.

A symmetrical fault is created at 0.8 secs and the fault is cleared off once the simulation time reaches 0.9 secs, after which the voltage starts to recover to normal value as shown in Fig. 5(a). During the dip, it is desired to maintain the torque controlled to the required value (20%), allowing to eliminate mechanical stresses to the wind turbine. This issue is achieved, as shown in Fig. 5(b) and 6(b), only if the oscillatory rotor flux is generated. For this purpose, the rotor flux is generated according to the block diagram of Fig. 2, generating an equivalent oscillation to the stator flux amplitude [see Fig. 6(c)]. The oscillations close to 50 Hz, caused by the poorly damped poles due to the voltage dip, which is clearly seen. It must be pointed out that DTC during faults is a well-suited control strategy to reach quick flux control dynamics, as well as to dominate the situation, eliminating torque perturbations and avoiding mechanical stresses. Consequently, the proposed control schema maintains the stator and rotor currents under their safety limits, avoiding high over currents, as shown in Fig. 6(d) and (e), either in the voltage fall or rise. The proposed strategy is analyzed for voltage fall which is created by using three phase fault block. However, as predicted in theory, it is hard to avoid a deterioration of the quality of these currents. Nevertheless, if the rotor flux is maintained constant, the currents will go further till their limit values, as shown in Fig. 5(d) and (e), provoking in a real case, a disconnection of the wind turbine or an activation of the crowbar protection. Moreover, by mitigating the over currents of the rotor, the back-to-back converter is less affected by this perturbation, producing short dc bus voltage oscillations, as illustrated in Fig. 6(a).

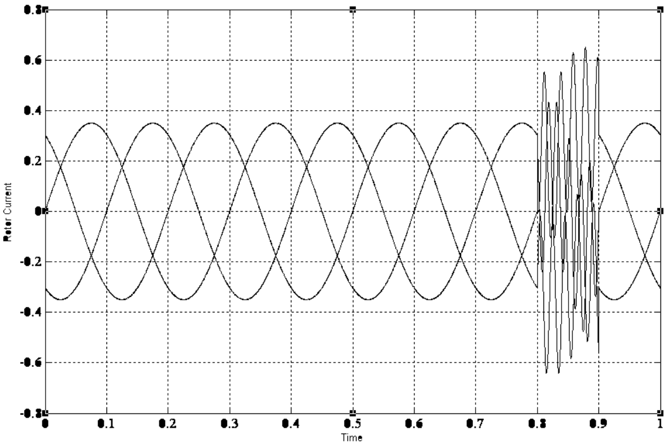
Finally, it can be said that the proposed control is useful at any operating point of the wind turbine, as well as at any type of faults (one phase, two phases, etc.). As shown in the Fig. 3, the proposed strategy is analyzed for three phases ground fault. The performance will be limited only, when the rotor voltage required is higher than the available at a given dc bus voltage.



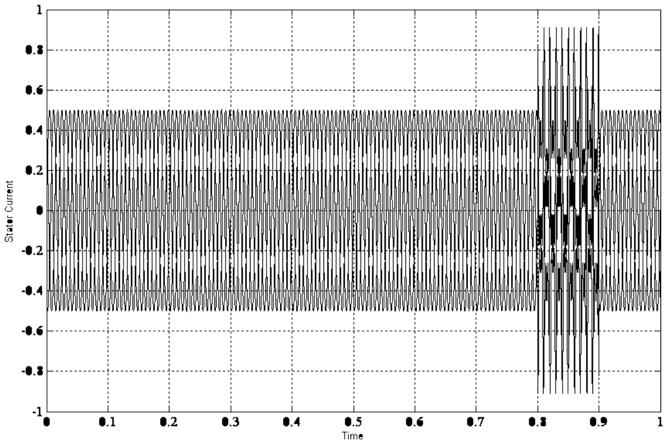
(a)

(b)

(c)

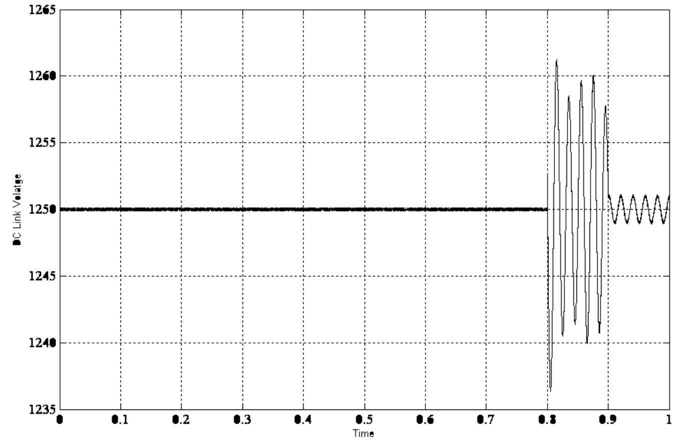


(d)

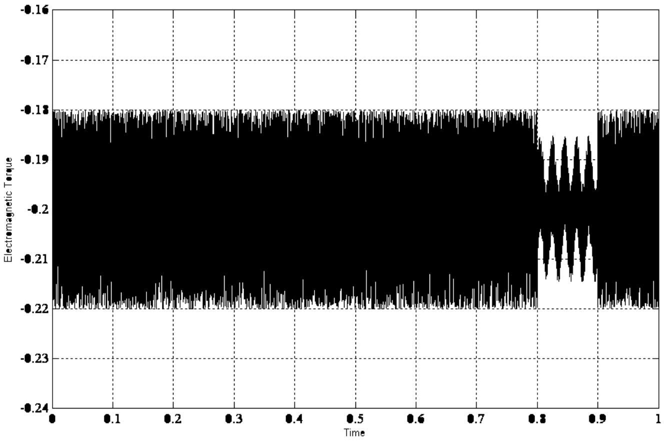


(e)

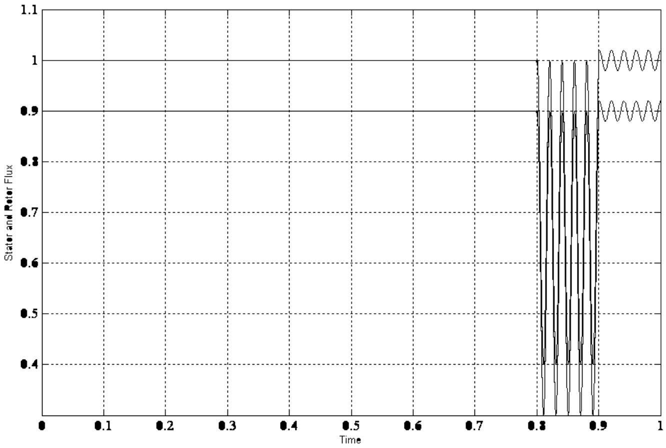
Figure 5. Simulation results of DFIM without proposed reference generation. (a) Stator voltage. (b) Torque (c) Stator and rotor fluxes (d) Rotor currents. (e) Stator currents w.r.t. time t in secs



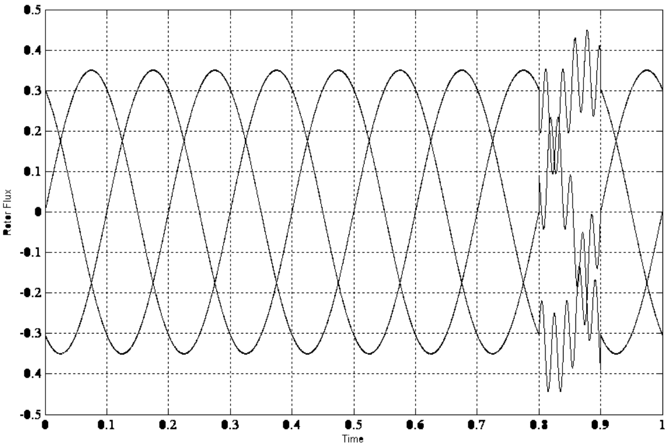
(a)


-0.16
-0.17
-0.18
-0.19
-0.2
-0.21
-0.22
-0.23
-0.24
Electromagnetic Torque
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
Time

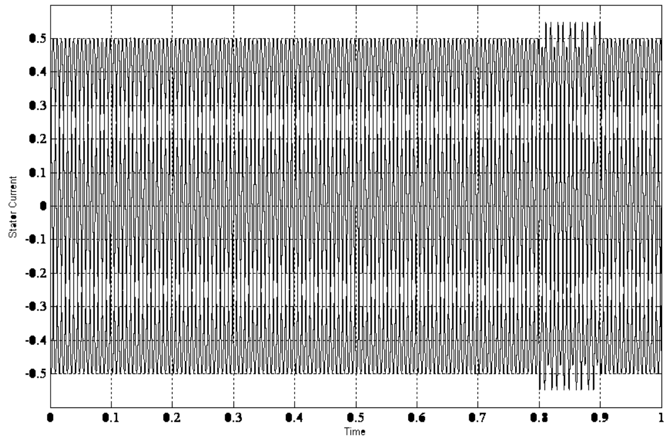
(b)


1.1
1
0.9
0.8
0.7
0.6
0.5
0.4
Stator and Rotor Flux
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
Time

(c)


0.5
0.4
0.3
0.2
0.1
0
-0.1
-0.2
-0.3
0.4
-0.5
Rotor Flux
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
Time

(d)



(e)

Figure 6. Simulation resultsof DFIM with proposed reference generation. (a) DC bus voltage. (b) Torque. (c) Stator and rotor fluxes. (d) Rotor currents (e) Stator currents w.r.t. time t in secs

4. CONCLUSION

The proposed control strategy of DTC for DFIM mitigates the necessity of the crowbar protection during low depth voltage dips. In fact, the dc bus voltage available in the back-to-back converter, determines the voltage dips depth that can be kept under control. Simulation results for without and with reference rotor flux generation is shown. DTC controls the machine torque and the rotor flux amplitude and the voltage dip is handled by the rotor flux reference generation.

It would be interesting to explore the possibility to generate a modified reference of rotor flux and torque, in order to be able to address deeper voltage dips without crowbar protection, which can be the future scope of the proposed control strategy.

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