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Direct Torque Control for Doubly Fed Induction Machine-Based Wind Turbines under Voltage Dips

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ABSTRACT

This paper proposes a rotor flux amplitude reference generation strategy for Doubly Fed Induction Machine (DFIM) based wind turbines. It is specially designed to address perturbations, such as voltage dips, keeping controlled the torque of the wind turbine, and considerably reducing the stator and rotor over currents during faults. This is done by; a Direct Torque Control (DTC) strategy that provides fast dynamic response accompanies the overall control of the wind turbine. Despite the fact that the proposed control does not totally eliminate the necessity of the typical crowbar protection for this kind of turbines, it eliminates the activation of this protection during low depth voltage dips.

Comparing the simulation results of without reference generation of flux and with reference generation strategy. The model is developed by using MATLAB/Simulink.

Key Words: *Direct Torque Control (DTC), Doubly Fed Induction Machine (DFIM), Wind Turbine, Mathematical Modeling*

I. INTRODUCTION

This Project 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. This reduced converter design provokes that when the machine is affected by voltage dips, it needs a special crowbar protection in order to avoid damages in the wind turbine and meet the grid-code requirements.

The main objective of the control strategy proposed in this project is to eliminate the necessity of the crowbar protection when a low-depth voltage dip occurs. 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.

It is well known that the basic concept of direct torque control of induction motor drives is to control both stator flux and electromagnetic torque of machine simultaneously. Both torque and flux of a DTC –based drive are controlled in the manner of closed loop system without using current loop in comparison with the conventional vector-controlled drives. In principle, the DTC-based drives require the knowledge of stator resistance only, and thereby decreasing the associated sensitivity to parameter variations. Moreover, the DTC –based drives do not require fulfilling the coordinate transformation between stationary frame and synchronous frame, in comparison with the conventional vector-controlled drives.

Since a DTC-based drives selects the inverter switching does not state using switching table, current controllers nor is pulse width modulation required, thereby providing fast torque response. However, this switching-table-based DTC approach is accompanied by disadvantages.

For digital implementation, the system sampling frequency for the calculations of torque and flux should be very fast in order to avoid good tracking performance and limit the errors of torque and flux within the specified bands, respectively. the inverter switching frequency, which varies with speed of drives and associated error bands, is very low in comparison with the system sampling frequency ; a sampling of 40KHz gives the inverter switching frequency about 3khz. Although the inverter switching frequency can be increased by mixing high frequency dither signals with the error signals of torque and flux, respectively, the inverter switching frequency is not constant for small error bands and difficulty of designing inverter output filter becomes difficult. For the DTC based drives, the torque ripple is significantly for not invoking the zero inverter switching states; especially at motor start-up or under transient state.

II. Direct Torque Control

Direct Torque Control (DTC) is a method that has emerged to become one possible alternative to the well-known Vector Control of Induction Motors [1–3]. This method provides a good performance with a simpler structure and control diagram. In DTC it is possible to control directly the stator flux and the torque by selecting the appropriate VSI state. The main advantages offered by DTC are:

– Decoupled control of torque and stator flux.

– Excellent torque dynamics with minimal response time.

– Inherent motion-sensor less control method since the motor speed is not required to achieve the torque control.

– Absence of coordinate transformation (required in Field Oriented Control (FOC)).

– Absence of voltage modulator, as well as other controllers such as PID and current controllers (used in FOC).

– Robustness for rotor parameters variation. Only the stator resistance is needed for the torque and stator flux estimator.

These merits are counterbalanced by some drawbacks:

– Possible problems during starting and low speed operation and during changes in torque command. Requirement of torque and flux estimators, implying the consequent parameters identification (the same as for other vector controls).

– Variable switching frequency caused by the hysteresis controllers employed.

– Inherent torque and stator flux ripples.

– Flux and current distortion caused by sector changes of the flux position.

– Higher harmonic distortion of the stator voltage and current waveforms compared to other methods such as FOC.

– Acoustical noise produced due to the variable switching frequency. This noise can be particularly high at low speed operation.

A variety of techniques have been proposed to overcome some of the drawbacks present in DTC. Some solutions proposed are: DTC with Space Vector Modulation (SVM); the use of a duty--ratio controller to introduce a modulation between active vectors chosen from the look-up table and the zero vectors; use of artificial intelligence techniques, such as Neuro-Fuzzy controllers with SVM. These methods achieve some improvements such as torque ripple reduction and fixed switching frequency operation. However, the complexity of the control is considerably increased.

A different approach to improve DTC features is to employ different converter topologies from the standard two-level VSI. Some authors have presented different implementations of DTC for the three-level Neutral Point Clamped (NPC) VSI [10–15]. This work will present a new control scheme based on DTC designed to be applied to an Induction Motor fed with a three-level VSI. The major advantage of the three-level VSI topology when applied to DTC is the increase in the number of voltage vectors available. This means the number of possibilities in the vector selection process is greatly increased and may lead to a more accurate control system, which may result in a reduction in the torque and flux ripples. This is of course achieved, at the expense of an increase in the complexity of the vector selection process.

To understand the answer to this question we have to understand that the basic function of a variable speed drive (VSD) is to control the flow of energy from the mains to the process. Energy is supplied to the process through the motor shaft. Two physical quantities describe the state of the shaft: torque and speed. To control the flow of energy we must therefore, ultimately, control these quantities.

In practice, either one of them is controlled or we speak of "torque control" or "speed control". When the VSD operates in torque control mode, the speed is determined by the load. Likewise, when operated in speed control, the torque is determined by the load. Initially, DC motors were used as VSDs because they could easily achieve the required speed and torque without the need for sophisticated electronics.

However, the evolution of AC variable speed drive technology has been driven partly by the desire to emulate the excellent performance of the DC motor, such as fast torque response and speed accuracy, while using rugged, inexpensive and maintenance free AC motors.

III. MATHEMATICAL ANALYSIS

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

$$\vec{v}_s^s = R_s \vec{i}_s^s + \frac{d\vec{\Psi}_s^s}{dt}. \quad (1)$$

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)*

$$\Psi_{\alpha s} = K_1 e^{-K_2 t} + K_3 \cos(\omega_s t + K_4),$$
$$\Psi_{\beta s} = K_5 e^{-K_2 t} + K_3 \sin(\omega_s t + K_4). \quad (2)$$

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

$$\vec{i}_s^s = \frac{L_h}{\sigma L_r L_s}\left(\frac{L_r}{L_h}\vec{\Psi}_s^s - \vec{\Psi}_r^s\right),$$
$$\vec{i}_r^s = \frac{L_h}{\sigma L_r L_s}\left(\frac{L_s}{L_h}\vec{\Psi}_r^s - \vec{\Psi}_s^s\right). \quad (3)$$

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, it will be later shown that the quality of the currents is substantially improved with this oscillatory rotor flux, rather than with constant flux.

As depicted in Fig. 3.1, the proposed rotor flux amplitude reference generation strategy, adds a term ($|\vec{\psi}_r|$) to the required reference rotor flux amplitude according to the following expression:

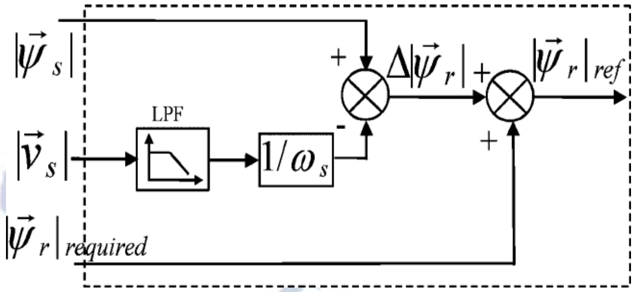

Fig. 3.1. Rotor flux reference generation strategy.

$$\Delta|\vec{\psi}_r| = |\vec{\psi}_s| - \frac{|\vec{v}_s|}{\omega_s}. \quad (4)$$

With $|\vec{\psi}_s|$, the estimated stator flux amplitude and $|v_s|$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. 3.1. It must be highlighted that constants

$K_1 – K_5$ From (2) are not needed in the rotor flux reference generation reducing its complexity. Note that at steady state without dips presence, the term ($|\vec{\psi}_r|$) 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.

IV. SIMULATION RESULTS

In Fig. 4.1, 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. This letter 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. 6.9, 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 (|*or* |) with high dynamic capacity, and a second block that generates the rotor flux amplitude reference, in order to handle with the voltage dips.

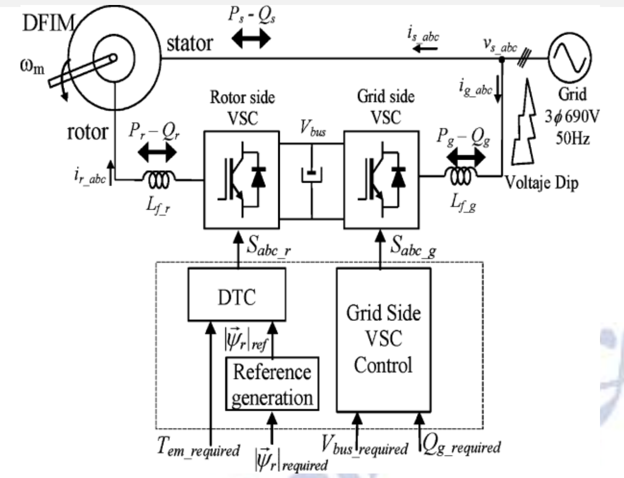

Fig. 4.1. Wind energy generation system based on the DFIM.

When the wind turbine is affected by a voltage dip, it will need to address three main problems: 1) 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); 2) the dip generates a disturbance in the stator flux, making necessary higher rotor voltage to maintain control on the machine currents; and 3) 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 [2] in the rotor of the machine, provoking finally, an increase of the dc bus voltage [3]. 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 letter, a control strategy that eliminates the necessity of the crowbar activation in some low depth voltage dips is proposed.

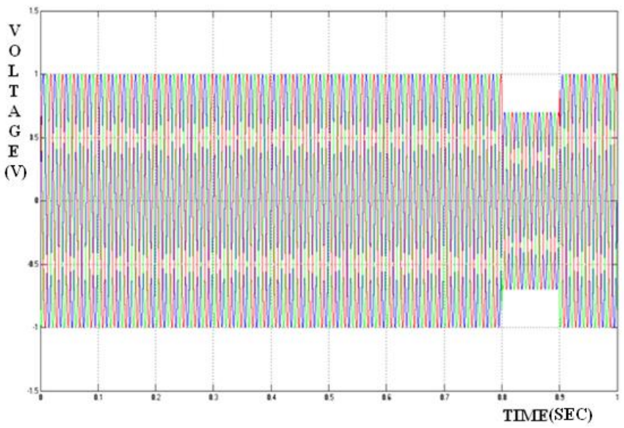

Fig. 4.2. (a) Simulation comparison of DFIM behavior, without and with proposed reference generation - Stator voltage.

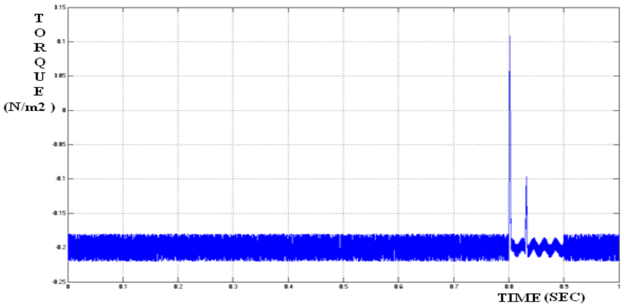

Fig. 4.2. (b) Simulation comparison of DFIM behavior - Torque without reference.

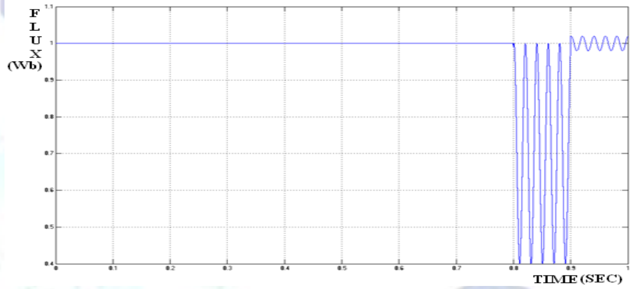

Fig.4.2. (c) Simulation comparison of DFIM behavior - Flux without reference

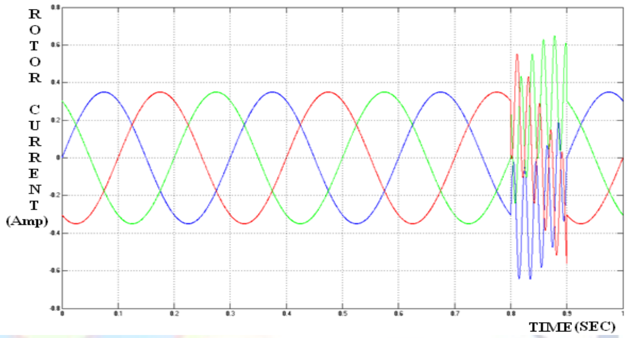

Fig. 4.2. (d) Simulation comparison of DFIM behavior, without and with proposed reference generation - Rotor current without reference.

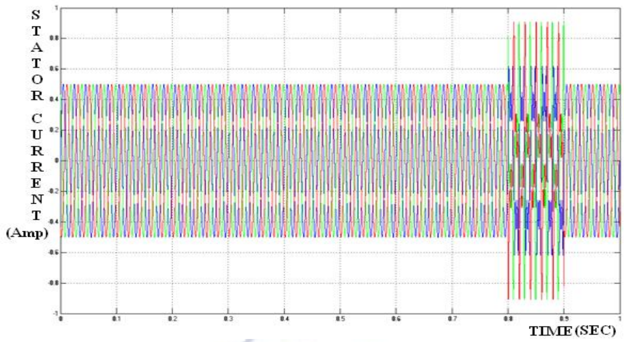

Fig. 4.2. (e) Simulation comparison of DFIM behavior - Stator current without reference

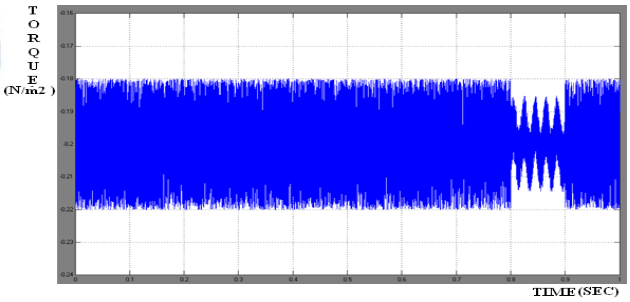

Fig. 4.2. (f) Simulation comparison of DFIM behavior -Torque with reference.

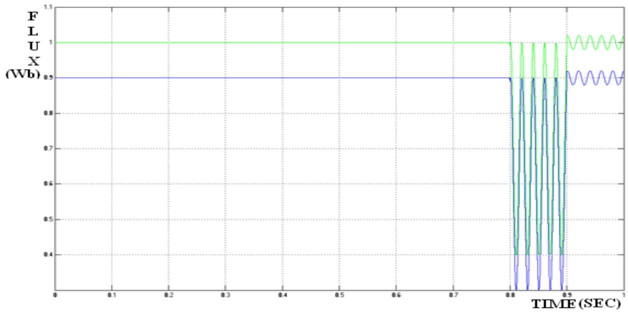

Fig. 4.2. (g) Simulation comparison of DFIM behavior, without and with proposed reference

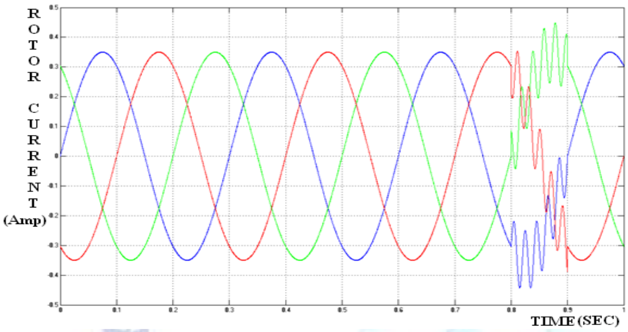

Fig. 4.2. (h) Simulation comparison of DFIM behavior - Rotor current with reference.

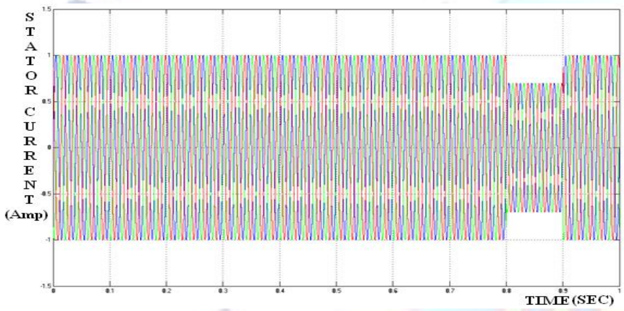

Fig. 4.2. (i) Simulation comparison of DFIM behavior - Stator current with reference.

The simulated wind turbine is a 2 MW, 690 V, *Ns* /*Nr* = 1/3 and two pair of poles DFIM. 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. 4.2(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. 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. 4.2(b) and (f), only if the oscillatory rotor flux is generated. For this purpose, the rotor flux is generated according to the block diagram of Fig. 4.1, generating an equivalent oscillation to the stator flux amplitude [see Fig. 4.2(g)]. 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. 4.2(h) and (i), either in the voltage fall or rise.

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. 6.10(d) and (e), provoking in a real case, a disconnection of the wind turbine or an activation of the crowbar protection. 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.). The performance will be limited only, when the rotor voltage required is higher than the available at a given dc bus voltage.

V. Conclusion

Simulation results have shown that the proposed control strategy 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. For future work, 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.

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 crow bar protection.

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