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Direct Torque Control for Doubly Fed Induction Machine-Based Wind Turbines under Voltage Dips and Without Crowbar Protection

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Abstract: *This project proposes a rotor flux amplitude reference generation strategy for doubly fed induction machine 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. In addition, a direct torque controls 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. 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 letter 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.*

Keywords: *doubly fed induction machine (DFIM), direct torque control (DTC), crowbar protection etc.*

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 with the doubly fed induction generator directly connected to the grid. Energy is main criteria for human development in any country. Any country that can produce energy in large scale can become a developed country in a short time. Mainly energy sources can be divided into two categories. Renewable energy sources and Non-renewable energy sources. Alternatively energy sources are the energy sources different from those in wide spread use at the moments (which are referred to as conventional). Alternative energy sources include solar, wind, wave, and tidal, hydroelectric and geothermal energy. Although they each have their own drawbacks, none of these energy sources produces significant air pollution, unlike conventional sources. Fossil fuels are (Carbon or Hydrocarbon) the fuels derived from what was living material, and found underground or beneath the sea. The most common forms are coal, oil and natural gas. They take millions of years to form. Their energy is only oxygen in air to form carbon dioxide or carbon monoxide and water. Other elements within the fuels are also released into the air after combining with oxygen causing further pollution with SO_2 and nitrogen oxide gasses. In the case of coal, ash particles are also a problem. Non-renewable energy sources that exist in a limited amount on earth. Thus all available material could eventually be completely used up. Coal, Oil and gas are considered as non-renewable energy sources because the rate of their formation is so slow on human time scales that they are using them without being replaced. Generally wind energy is available in abundance. For conversion of this wind energy into electrical energy and induction generator is coupled with a wind mill offers an ideal solution. Wind energy is available in abundance in our environment. When compared with the conventional sources of energy, wind energy is clean, efficient, and sustainable form of energy. When the cost of supplying electricity to remote locations is expensive, wind energy provides a cost effective alternative. So to convert this wind energy into electrical energy, an induction generator will offer an ideal solution.

2. LITERATURE SURVEY

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 turbine s. The interaction with the grid becomes increasingly important then. 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. It is therefore worldwide recognized that to enable large-scale application of wind energy without compromising system stability, the turbines should stay connected t o 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.

2.1. Crowbar Protection

A crowbar circuit is a protection circuit that short-circuits ("crowbars") the supply line if the voltage or current exceed the limits. In general, the resulting short blows a fuse or triggers other protection effectively disconnecting the supply. It is achieved by an SCR or other silicon device, or by a mechanical shorting device. It is operated by putting a short circuit or low resistance path across the voltage source. Crowbar circuits are generally implemented using a thyristor or a trisil or thyratron as the shorting device. As triggered, they depend on the current-limiting circuitry of the power supply or, if it fails, the line fuse blows or tripping the circuit breaker.

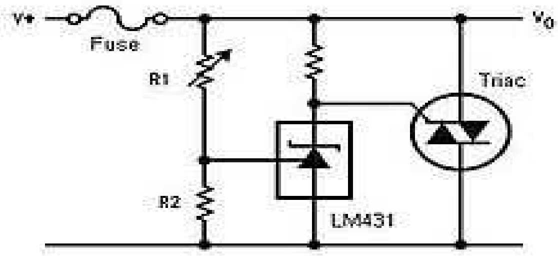

Fig-1. *Equivalent Circuit of Crowbar Protection*

A crowbar circuit is distinct from a clamp in that, once triggered; it pulls the voltage below the trigger level, usually close to ground. A clamp prevents the voltage from exceeding a preset level. Thus, a crowbar will not automatically y return to normal operation when the overvoltage condition is removed, power must be removed entirely to stop its conduction.

Recently, some papers have been published that discuss the protection of DFIGs during grid disturbance. 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 import ant during disturbances. Rotor currents or voltages that are too high might destruct the converter in the rotor circuit.

3. PROPOSED SYSTEM

3.1 Doubly-Fed Induction Generator

As the penetration of large scale wind turbines into electric power grids continues to increase, electric system operators are placing greater demands on wind turbine power plants. One of the most challenging new interconnection demands for the doubly fed induction generator (DFIG) architecture is its ability to ride through a short-term low or zero voltage event at the point of common coupling (PCC), resulting from a fault on the grid. During extreme voltage sags high per unit currents and shaft torque pulsations occur unless mitigating measures are taken. 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. In Figure 1, the wind turbine generation system together with the proposed control block diagram is illustrated.

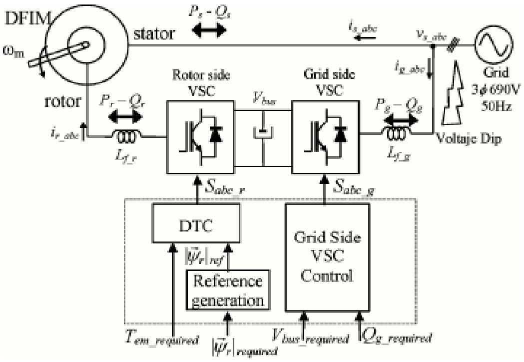

Figure 1. *Wind energy generation system based on the DFIM*

The DFIM is supplied by a back-to-back converter through the rotor, while the stator is directly Connected to the grid. 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 Figure 1, the DFIM control is divided into two different control blocks.

3.2 Types of Double Fed Induction Generator

3.2.1 Brushless Doubly-Fed Induction Electric Generator

Brushless doubly-fed induction electric generator (i.e., electric motors or electric generators) are constructed by adjacently placing two multiphase winding sets with unlike pole-pairs on the stator body. With unlike pole-pairs between the two winding sets, low frequency magnetic induction is assured over the speed range. One of the stator winding sets (power winding) is connected to the grid and the other winding set (control winding) is supplied from a frequency converter. The shaft speed is adjusted by varying the frequency of the control winding. As a doubly-fed electric machine, the rating of the frequency converter need only be fraction of the machine rating.

3.2.2 Brushless Wound-Rotor Doubly-Fed Electric Generator

The brushless wound-rotor doubly-fed electric generator (i.e., electric motor or electric generator) incorporates the electromagnetic structure of the wound-rotor doubly-fed electric machine, but replaces the traditional multiphase slip ring assembly with a brushless means to independently power the rotor winding set (i.e., doubly-fed) with multiphase AC power. The torque of the wound-rotor doubly-fed electric machine is dependent on both slip and position, which is a classic condition for instability.

For stable operation, the frequency and phase of the multiphase AC power must be synchronized and fixed instantaneously to the speed and position of the shaft, which is not trivial at any speed and particularly difficult about synchronous speed where induction no longer exists. If these conditions are met, all the attractive attributes of the wound-rotor doubly-fed electric machine, such as high power density, low cost, ultra-high efficiency, and ultra-high torque potential, are realized without the traditional slip-ring assembly and instability problems. One company has patented and is selling a brushless, fully stable, synchronous wound-rotor doubly-fed electric machine with symmetric quality of motoring or generating. Another brushless wound-rotor construction invented by Lars Gertmar has been described in the patent application.

3.2.3 Wound-Rotor Doubly-Fed Electric Generator

Two multiphase winding sets with similar pole-pairs are placed on the rotor and stator bodies, respectively. The wound-rotor doubly-fed electric machine is the only electric machine with two independent active winding sets, the rotor and stator winding sets, occupying the same core volume as other electric machines. Since the rotor winding set actively participates in the energy conversion process with the stator winding set, utilization of the magnetic core real estate is optimized.

3.2.4 Double Fed Induction Generator

DFIG is an abbreviation for Double Fed Induction Generator, a generating principle widely used in wind turbines.

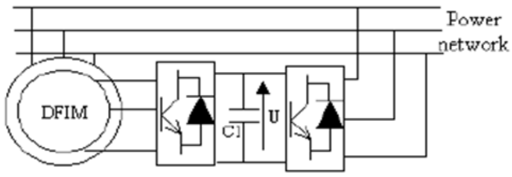

Fig: 2.1. *Doubly Fed-Induction Generator*

2.5 Principle of a Double Fed Induction Generator Connected to a Wind Turbine

The principle of the DFIG is that rotor windings are connected to the grid via slip rings and back-to-back voltage source converter that controls both the rotor and the grid currents. Thus rotor frequency can freely differ from the grid frequency (50 or 60 Hz). By using the converter to control the rotor currents, it is possible to adjust the active and reactive power fed to the grid from the stator independently of the generator's turning speed. The control principle used is either the two-axis current vector control or direct torque control (DTC). DTC has turned out to have better stability than current vector control especially when high reactive currents are required from the generator.

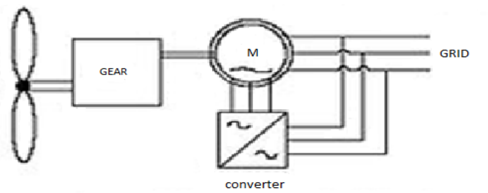

Fig: 2.2. *Principle of DFIG Connected to a Wind Turbine*

The doubly-fed generator rotors are typically wound with 2 to 3 times the number of turns of the stator. This means that the rotor voltages will be higher and currents respectively lower. Thus in the typical ± 30 % operational speed range around the synchronous speed, the rated current of the converter is accordingly lower which leads to a lower cost of the converter. The drawback is that controlled operation outside the operational speed range is impossible because of the higher than rated rotor voltage. Further, the voltage transients due to the grid disturbances (three- and two-phase voltage dips, especially) will also be magnified. In order to prevent high rotor voltages - and high currents resulting from these voltages - from destroying the IGBTs and diodes of the converter, a protection circuit (called crowbar) is used.

2.6 DFIG Control

When the DFIG is connected to a network, connection must be done in three steps which are presented below. The first step is the regulation of the stator voltages with the network voltages as reference. The second step is the stator connection to this network. As the voltages of the two devices are synchronized, this connection can be done without problem. Once this connection is achieved, the third step, which constitutes the topic of this paper, is the power regulation between the stator and output.

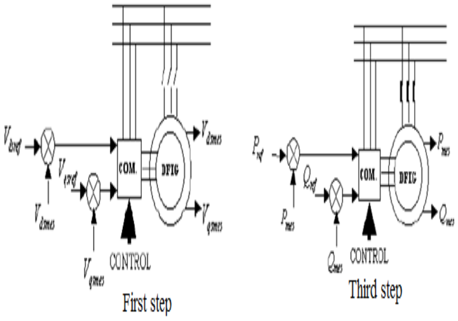

Fig 2.3. *DFIG Controllers*

4. Analytical Study

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

$$\vec{v}_s^s = R_s\,\vec{i}_s^s + \frac{\overrightarrow{d\Psi_s^s}}{dt}.$$

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 (neglecting *Rs)*

$$\Psi_{\alpha s} = K_1 e^{-k_{2t}} + K_3 \cos\,(\omega_s t + K_4),$$

$$\Psi_{\beta s} = K_5 e^{-k_2 t} + K_3 \sin\,(\omega_s t + K_4).$$

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

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

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

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.

4.1 Rotor Flux Reference Generation Strategy

As depicted in Fig. 3, the proposed rotor flux amplitude reference generation strategy, adds a term ($\Delta|\psi r|$) to the required reference rotor flux amplitude according to the following expression:

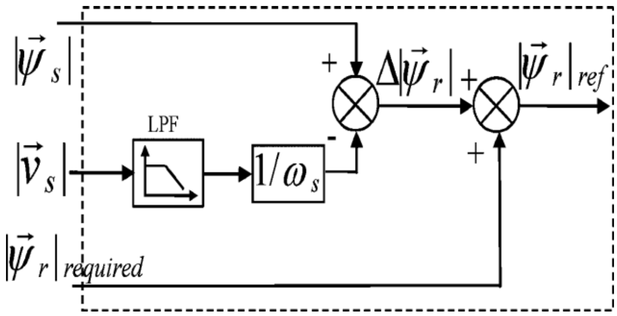

Fig 4.1. *Rotor flux reference generation strategy*

$$\Delta|\vec{\Psi}_r| = |\vec{\Psi}_s| - \frac{|\vec{v}_s|}{\omega_s}$$

With $|\_\psi\ s|$, the estimated stator flux amplitude and $|Vs|$ 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 $K1$–$K5$ from (2) are not needed in the rotor flux reference generation reducing its complexity. Note that at steady state without dips presence, the term $\Delta|\psi r$ |will be zero. However, when a dip occurs, the added term to the rotor flux reference will be approximately equal to the oscillation sprovoked by the dip in the stator flux amplitude. For simpler understanding, the voltage drop in the stator resistance has been neglected.

5. Simulation Results

The simulated wind turbine is a 2 MW, 690 V, *Ns* /*Nr* = 1/3and 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 1(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. (d) and (c), only if the oscillatory rotor flux is generated. For this purpose, the rotor flux is generated according to the block diagram of Fig. 3, generating equivalent oscillation to the stator flux amplitude [see Fig. (e)]. 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. (g) 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. (h) and (j), 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. (b). 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.

6.1 Stator and DC Bus Voltage Waveforms

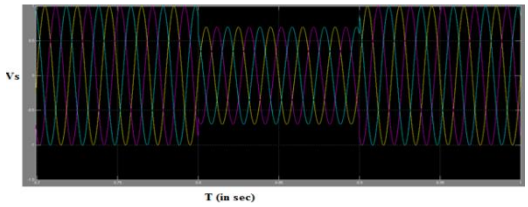

Figure (a). *Stator voltages*

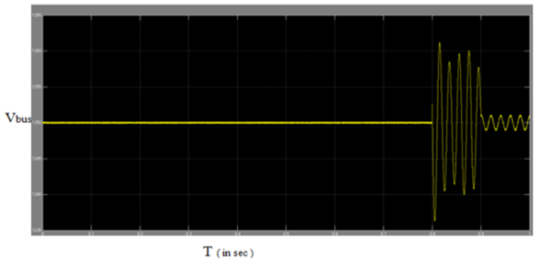

Figure (b). *D.C Bus voltage*

6.2 Torque Waveforms with and without Reference Generation Strategy

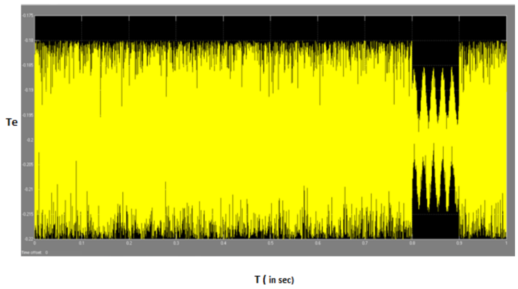

Figure (c). *torque with reference generation*

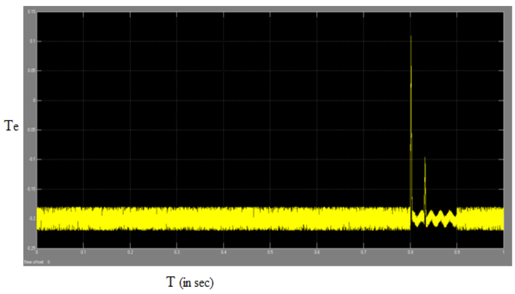

Figure (d). *torque without reference generation*

6.3 Stator and Rotor Flux Waveforms with and without Reference Generation Strategy

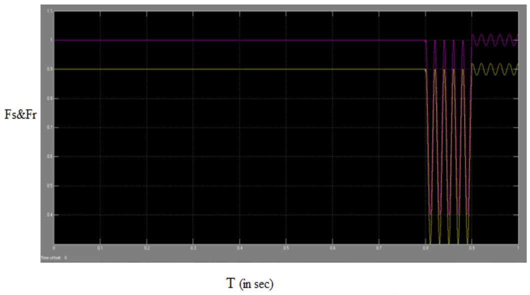

Figure (e). *Stator and rotor fluxes with reference generation*

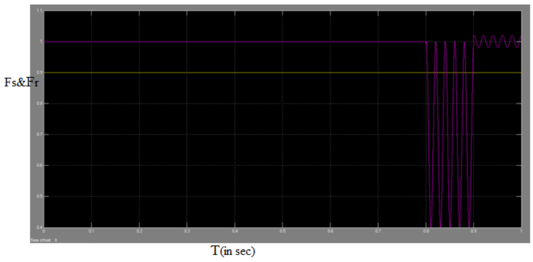

Figure (f). *Stator and rotor fluxes without reference generation*

6.4 Rotor Current Waveforms with and without Reference Generation Strategy

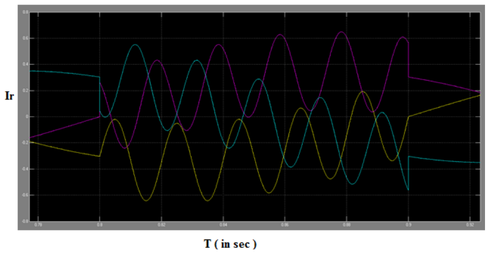

Figure (g). *rotor currents with reference generation*

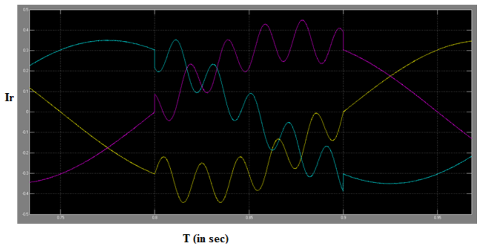

Figure (h). *rotor currents without reference generation*

6.5 Stator current waveforms with and without reference generation strategy

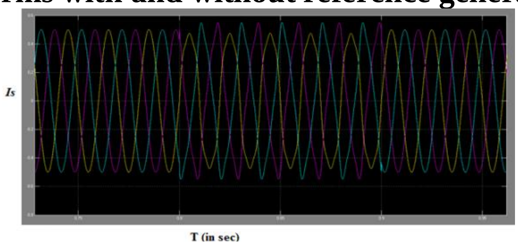

Figure (I). *stator currents with reference generation*

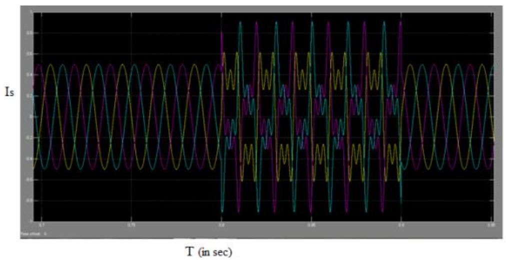

Figure (J). *stator currents without reference generation*

6. 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.

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