DIRECT TORQUE CONTROL OF DOUBLY FED INDUCTION GENERATOR BASED WIND TURBINE UNDER VOLTAGE DIPS

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ABSTRACT

This paper focuses the analysis on the control of doubly fed induction generator (DFIG) based high-power wind turbines when they operate under presence of voltage dips. The main objective of the control strategy proposed for doubly fed induction generator based wind turbines is to eliminate the necessity of the crowbar protection when low-depth voltage dips occurs. A direct torque control fed induction generator control is divided into two different control blocks. The first block that controls the machine's torque and the rotor flux amplitude with high dynamic capacity by Direct Torque Control. The second block that generates the rotor flux amplitude reference in order to handle with the voltage dips. A direct torque control strategy that provides fast dynamic response accompanies the overall control of the wind turbine. The proposed control does not totally eliminate the necessity of the typical crowbar protection for turbines it eliminates the activation of this protection during low depth voltage dips. Due to voltage dip in the wind turbine causes three main problems they are control difficulties, disturbance in the stator flux, increase of voltage and currents in the rotor of the machine. The DC bus voltage available in the back-to-back converter determines the voltage dips depth that can be kept under control. The modeling of the complete system is done in MATLAB-SIMULINK. Simulation results show the proposed control strategy that mitigates the necessity of the crowbar protection during low depth voltage dips.

KEYWORDS- *DFIG, VSCF, CSCF, WECS*

I. INTRODUCTION

With exhausting of traditional energy resources and increasing concern of environment, renewable and clean energy is attracting more attention all over the world to overcome the increasing power demand. Out of all the renewable energy sources, wind energy and solar energy are reliable energy sources. Now a day, wind power is gaining a lot of importance because it is cost- effective, environmentally clean and safe renewable power source compared to fossil fuel and nuclear power generation. Asynchronous generators are more commonly used in systems upto 2MW, beyond which direct-driven permanent magnet synchronous machines are A Wind Energy Conversion System (WECS) can vary in size from a few hundred kilowatts to several megawatts. The size of the WECS mostly determines the choice of the preferred. A grid connected WECS should generate power at constant electrical frequency which is determined by the grid. Generally Squirrel cage rotor induction generators are used in medium power level grid-connected systems. The induction generator runs at near synchronous speed and draws the magnetizing current from the mains when it is connected to the constant frequency network, which results in Constant Speed Constant Frequency (CSCF) operation of generator. However the power capture due to fluctuating wind speed can be substantially improved if there is flexibility in varying the shaft speed.

In such variable Speed Constant Frequency (VSCF) application rotor side control of grid-connected wound rotor induction machine is an attractive solution. In double fed induction generator, the stator is directly connected to the three phase grid and the rotor is supplied by two back-to-back PWM converters as shown in Fig .1. Such an arrangement provides flexibility of operation at both sub-synchronous and super synchronous speeds [9][10].

In Doubly Fed Induction Generator the rotor side converter is controlled by using different control techniques like scalar control where the torque and flux have coupling effect, vector control where the torque and flux have decoupling effect and sensor-less vector control means the vector control without any speed sensor.

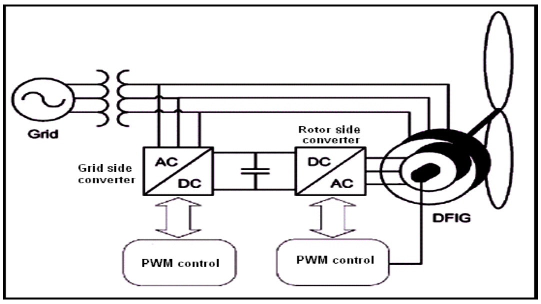

Figure1: Block diagram of Wind Energy Conversion System

Another scalar control technique is Direct Torque Control in which torque and flux of generator are directly controlled by converter voltage space vector selection through a look up table[11]. The technique used in the paper is to operate the DFIG through proper selection of voltage vectors .The operation of Doubly Fed Induction Generator during the voltage dips is explained by generating the three phase fault at the grid [2]. The crowbar protection is to be eliminated in DFIG during the fault in order to reduce losses and improve the efficiency of the machine. In order to eliminate that protection, DTC is operated with rotor flux generation[3][4][5].The comparison of DFIG behavior with and without the proposed rotor flux generation is observed through torque, stator and rotor fluxes, rotor currents, stator currents, DC bus voltage and stator voltage[6] [7][8].

When the wind turbine is affected by a voltage dip it will 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.
- The power delivered through the rotor by the back to back converter will be increased due to the increase of voltage and currents in the rotor of the machine finally an increase of the DC bus voltage.

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 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.

Section I briefs about the introduction to wind energy conversion system , section II explains mathematical modeling of DFIG, section III explains about Direct Torque Control technique, section IV explains about simulation of DTC of DFIG in WECS, section V shows the simulation results and finally Section VI gives the conclusions and future scope of this work.

II. MATHEMATICAL MODELING OF DFIG

The wind generation system studied in this paper consists of two components: the Doubly-Fed Induction Generator (DFIG) and the variable speed wind turbine. A detailed description of these two components is given below. The DFIG may be regarded as a slip-ring induction machine, whose stator winding is directly connected to the grid, and whose rotor winding is connected to the grid through a bidirectional frequency converter using back-to-back PWM voltage-source converters [9].

The electrical part of the DFIG is represented by a fourth-order state space model, which is constructed using the synchronously rotating reference frame (dq-frame), where the d-axis is oriented along the stator-flux vector position. The relation between the three phase quantities and the dq components is defined by Park's transformation. The voltage equations of the DFIG are

$$V_{ds} = R_s i_{ds} - \omega_s \psi_{qs} + \frac{d\psi_{ds}}{dt} \quad (1)$$

$$V_{qs} = R_s i_{qs} - \omega_s \psi_{ds} + \frac{d\psi_{qs}}{dt} \quad (2)$$

$$V_{dr} = R_r i_{dr} - (\omega_s - \omega_r)\psi_{qr} + \frac{d\psi_{dr}}{dt} \quad (3)$$

$$V_{qr} = R_r i_{qr} - (\omega_s - \omega_r)\psi_{dr} + \frac{d\psi_{qr}}{dt} \quad (4)$$

where V_{ds}, V_{qs}, V_{dr}, V_{qr} are the d- and q-axis of the stator and rotor voltages; I_{ds}, I_{qs},I_{dr},I_{qr} are the d- and q-axis of the stator and rotor currents; $\Psi_{ds,}$ $\Psi_{qs,}$ $\Psi_{dr,}$ Ψ_{qr} are the d- and q-axis of the stator and rotor fluxes; ω_s is the angular velocity of the synchronously rotating reference frame; ω_r is the rotor angular velocity; and R_s,R_r are the stator and rotor resistances[9]. The flux equations of the DFIG are

$$\psi_{ds} = L_s I_{ds} + L_m I_{dr} \quad (5)$$

$$\psi_{qs} = L_s I_{qs} + L_m I_{qr} \quad (6)$$

$$\psi_{dr} = L_m I_{ds} + L_r I_{dr} \quad (7)$$

$$\psi_{qr} = L_m I_{qs} + L_r I_{qr} \quad (8)$$

Where L_s, L_r, and L_m are the stator, rotor, and mutual inductances, respectively. From the flux equations (5)–(8), the current equations can be written as

$$I_{ds} = \frac{1}{\sigma L_s}\psi_{ds} - \frac{L_m}{\sigma L_s L_r}\psi_{dr} \quad (9)$$

$$I_{qs} = \frac{1}{\sigma L_s}\psi_{qs} - \frac{L_m}{\sigma L_s L_r}\psi_{qr} \quad (10)$$

$$I_{dr} = \frac{-L_m}{\sigma L_s L_r}\psi_{ds} + \frac{1}{\sigma L_r}\psi_{dr} \quad (11)$$

$$I_{qr} = \frac{-L_m}{\sigma L_s L_r}\psi_{qs} + \frac{1}{\sigma L_r}\psi_{qr} \quad (12)$$

Where $\sigma = 1 - \frac{L_m^2}{L_s L_r}$ is the leakage coefficient. Neglecting the power losses associated with the stator and rotor resistances, the active and reactive stator and rotor powers are given by

$$P_s = -V_{ds} I_{ds} - V_{qs} I_{qs} \quad (13)$$

$$Q_s = -V_{qs} I_{ds} + V_{ds} \quad (14)$$

$$P_r = -V_{dr} I_{dr} - V_{qr} I_{qr} \quad (15)$$

$$Q_r = -V_{qr} I_{dr} + V_{dr} I_{qr} \quad (16)$$

And the total active and reactive powers of the DFIG are

$$P = P_s + P_r \quad (17)$$

$$Q = Q_s + Q_r \quad (18)$$

Where positive (negative) values of P and Q mean that the DFIG injects power into (draws power from) the grid[9].

The mechanical part of the DFIG is represented by a first-order model

$$J\frac{d\omega_r}{dt} = T_m - T_e - C_f \omega_r \quad (19)$$

where C_f is the friction coefficient, T_m is the mechanical torque generated by the wind turbine, and T_e is the electromagnetic torque given by

$$T_e = \psi_{ds} I_{ds} - \psi_{qs} I_{qs} \quad (20)$$

Where positive (negative) values mean the DFIG acts as a generator (motor) [9].

III. DIRECT TORQUE CONTROL

The Direct Torque Control (DTC) method is basically a performance enhanced scalar control method. The main features of DTC are direct control of flux and torque by the selection of optimum inverter switching vector, indirect control of stator current and voltages, approximately sinusoidal stator flux and stator currents and high dynamic performance even at standstill. The advantages of DTC are minimal torque response time, absence of coordinate transformations which are required in most of vector controlled drive implementation and absence of separate voltage modulation block which is required in vector controlled drives. The disadvantages of DTC are inherent torque and stator flux ripple and requirement for flux and torque estimators implying the consequent parameters identification.

The complete block diagram of DTC is shown in Figure 2. There are two hysteresis control loops, one for the control of torque and the other for the control of flux. The flux controller controls the machine operating flux to maintain the magnitude of the operating flux at the rated value till the rated speed and at a value decided by the field weakening block for speeds above the rated speeds. Torque control loop maintains the torque value to the torque demand. The output of these controllers together with the instantaneous position of flux vector selects a proper voltage vector. So it is very important to estimate the stator flux and motor torque accurately.

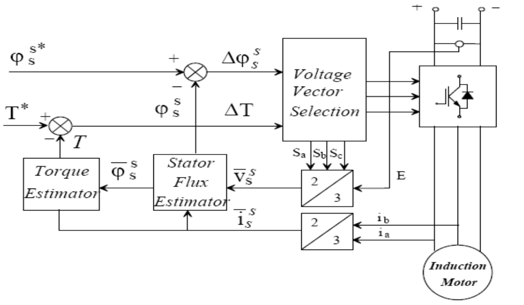

Figure 2: Block diagram of DTC

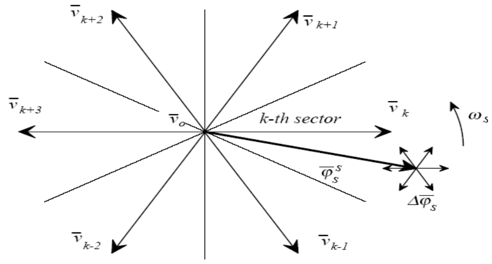

Figure. 3: Inverter output voltages

3.1 Optimal Switching Logic:

Processing of the torque status output and the flux status output is handled by the optimal switching logic. The function of the optimal switching logic is to select the appropriate stator voltage vector that will satisfy both the torque status output and the flux status output. In reality, there are only six active voltage vectors and two zero voltage vectors that a voltage-source inverter can produce [6, 8, 10].These are shown in Figure3.

By using switching functions S_a, S_b and S_c of which value is either 1 or 0, the primary voltage vector v is represented as [8]

$$v = \sqrt{\frac{2}{3}} V_{dc}[S_a + S_b e^{j\frac{2\pi}{3}} + S_c e^{j\frac{4\pi}{3}}] \tag{21}$$

Where V_{dc} is dc link voltage.

IV. DTC OF DFIG IN WECS

4.1 Basic Block Diagram without Rotor Reference Flux

The simulated wind turbine is a 2MW, 690V, Ns/Nr =1/3 and two pair of poles of DFIG. The main objective of this simulation is to show the DFIG behavior when a low depth 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.

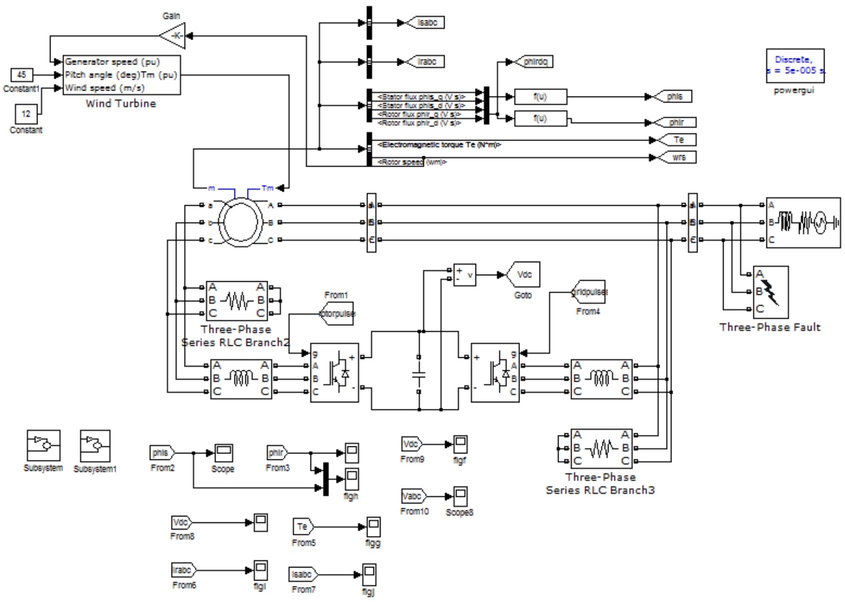

Figure 4 The SIMULINK diagram of direct torque control of DFIG without rotor flux reference.

The SIMULINK diagram of the above wind energy conversion system consists of five main important blocks. They are constant pitch and variable speed wind turbine, induction generator, DTC controller, back-to-back converter, three phase fault. The following subsections will explain each block.

4.1.1 Wind Turbine Block

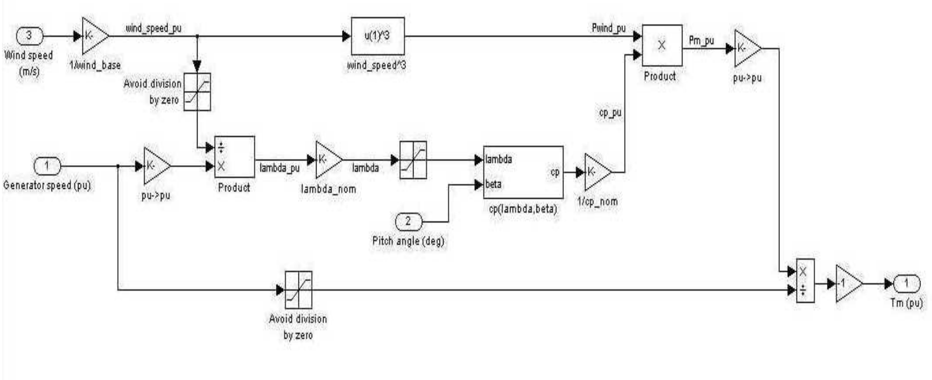

Figure 5: Wind turbine Block

This block is required as it converts wind energy which is an input to the machine.
The inputs to the block are generator speed, pitch angle, wind speed, Lambda(tip-speed ratio).These values are substituted in the mathematical modeling equations of turbine which are implemented as blocks and the output 'T_m' is obtained. Based on the output obtained T_t, T_l and T_e are also obtained.
Turbine acts as a prime mover to the induction generator. Wind turbine pitch angle is 45 degrees (constant) and wind velocity is varied between 0 to 20 m/sec randomly. The torque developed by wind turbine is applied as load on induction generator. The aerodynamic torque(T_m) and mechanical power (P_o) generated by a wind turbine is given by Equation (22) and Equation (23) respectively.

$$T_m = C_t(\lambda)\left[\,0.5\frac{\rho\pi R_r^3}{\eta_{gear}}\right]V_w^2 \tag{22}$$

$$P_m = \frac{1}{2}C_p\rho A_r V_w^3 \tag{23}$$

Where P_m is the power in watts, ρ is the air density in g/m^3,C_P a dimensionless factor called power Coefficient, A_r the turbine rotor area in m^2 ($Ar = \pi R_r^2$, where R_r is the rotor blade radius), η_{gear} is and V_w the wind speed in m/s. The power coefficient is related to the tip speed ratio (*λ)* and rotor blade pitch angle $\boldsymbol{\beta}$ according to Equation (26)

$$\mathrm{Cp} = 0.73\left(\frac{151}{\lambda i} - 0.58\beta - 0.002\beta^{2.14} - 13.2\right)e^{\frac{-18.4}{\lambda i}} \tag{24}$$

$$\text{Where}\boldsymbol{\lambda_i} = \frac{\mathbf{1}}{\frac{\mathbf{1}}{\boldsymbol{\lambda}-\mathbf{0.02\beta}}-\frac{\mathbf{0.003}}{\boldsymbol{\beta^3}+\mathbf{1}}} \tag{25}$$

$$\text{And } \boldsymbol{\lambda} = \frac{\boldsymbol{\omega_r R_r}}{\boldsymbol{V_w}} \tag{26}$$

$$C_t = \frac{C_p}{\lambda} \tag{27}$$

In equation (6.5), ω_r is the angular speed of the turbine shaft. The theoretical limit for C_P is 0.59 according to Betz's Law but its practical range of variation is 0.2-0.4.

4.1.2 DTC block

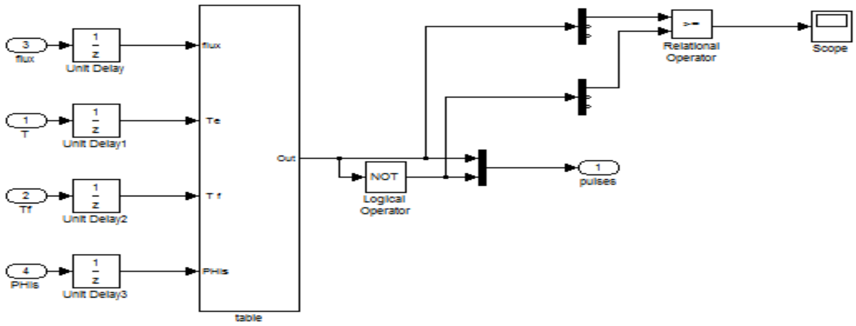

Figure 7. DTC block without reference.

4.2 Basic Block Diagram With Rotor Reference Flux

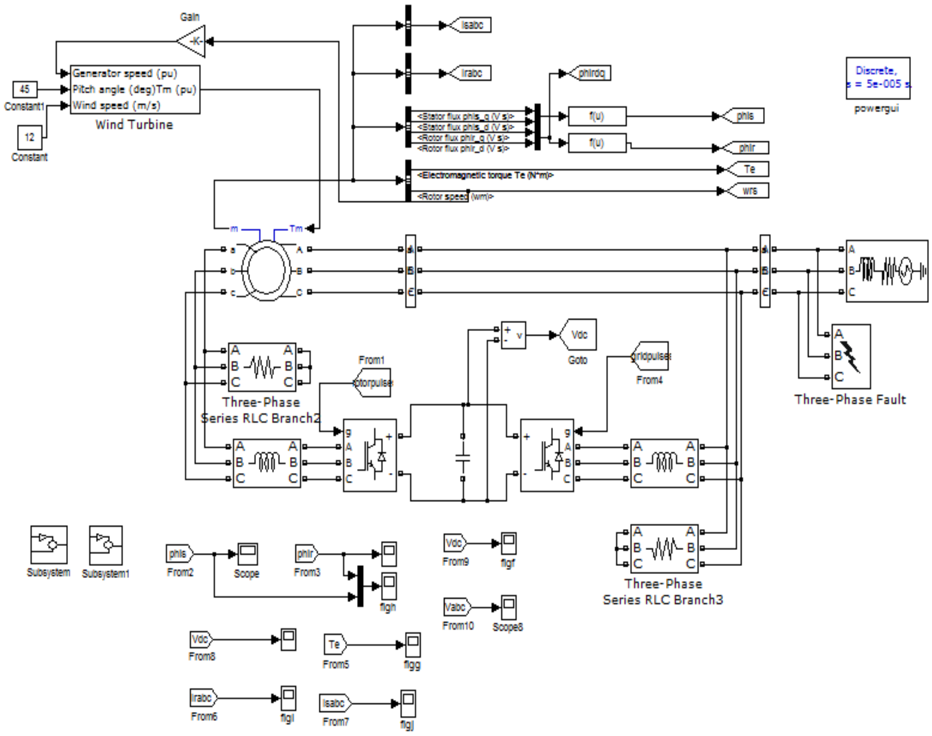

Figure 8. Simulink diagram of direct torque control of DFIG with rotor flux reference.

4.2.1 DTC Block

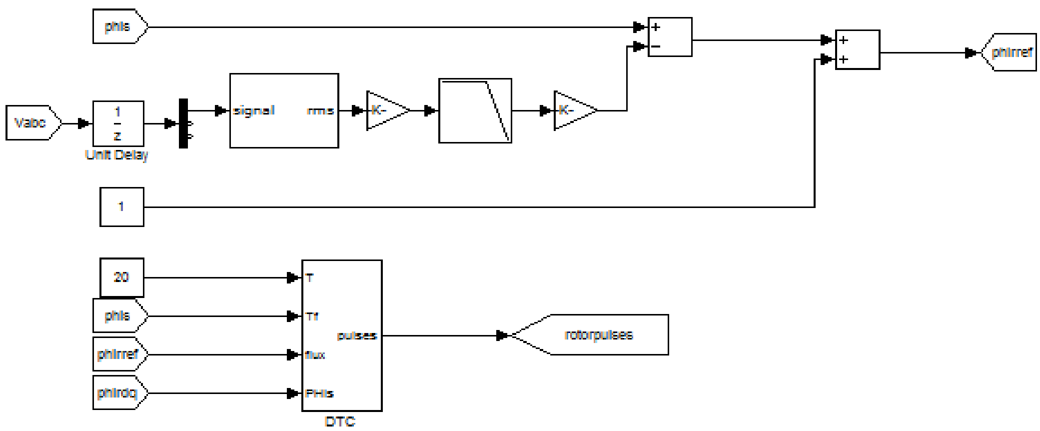

Figure 9. DTC Block with rotor flux reference.

The DTC block is used to generate the rotor pulses by using the torque and rotor flux reference. The inputs to the block are torque, reference torque, flux. This block consists of switching table, torque and flux hysteresis blocks.

V. SIMULATION RESULTS

The results show the variation in torques during the fault at the instant between 0.8 to 0.9using with and without rotor flux reference.

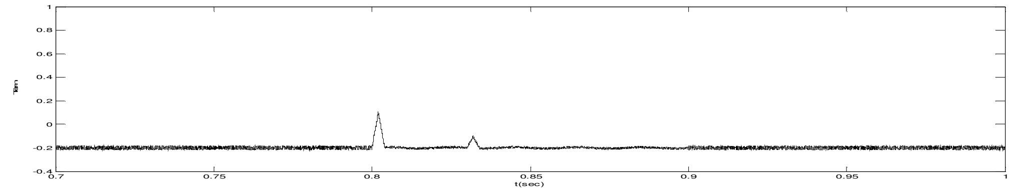

Figure 9. Torque without rotor flux reference.

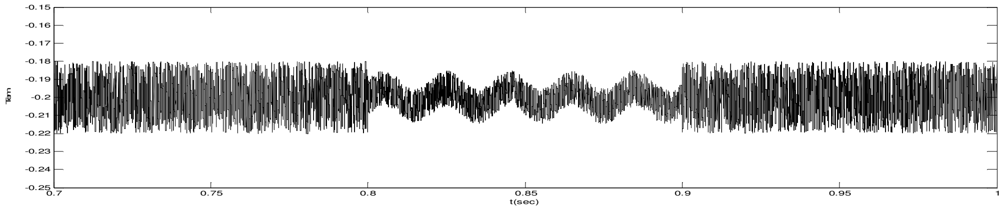

Figure 10. Torque with rotor flux reference.

The results show the variation in stator and rotor fluxes during the fault at the instant between 0.8 to 0.9 using with and without rotor flux reference.

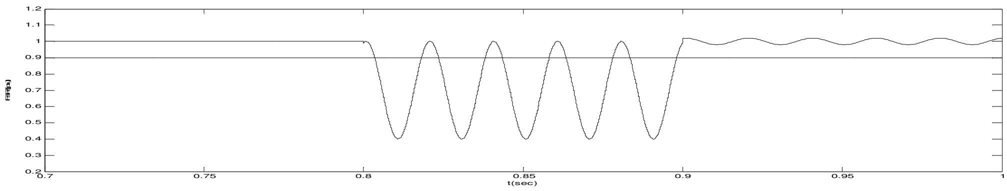

Figure 11. Stator and Rotor fluxes without rotor flux reference.

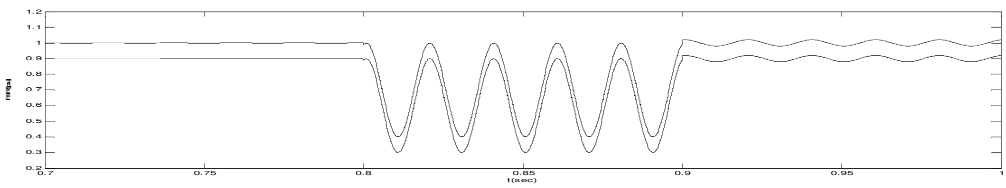

Figure 12. Stator and Rotor fluxes with rotor flux reference.

The results show the variation in rotor currents during the fault at the instant between 0.8 to 0.9 using with and without rotor flux reference.

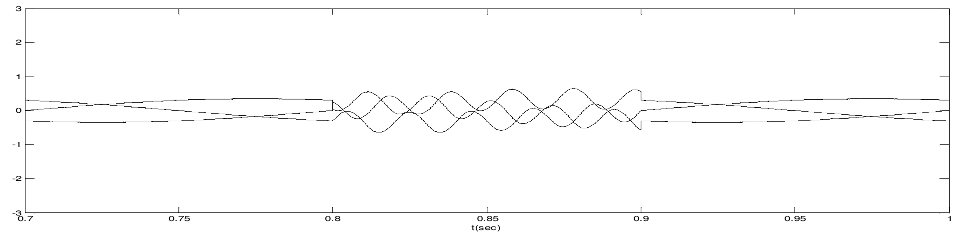

Figure 13. Rotor Currents without rotor flux reference.

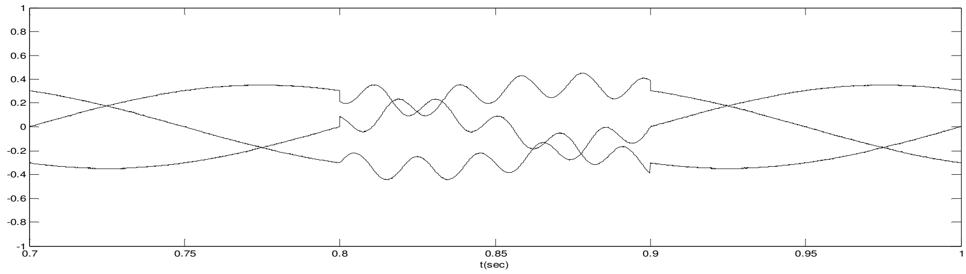

Figure14. Rotor Currents with rotor flux reference.

The results show the variation in stator currents during the fault at the instant between 0.8 to 0.9 using with and without rotor flux reference.

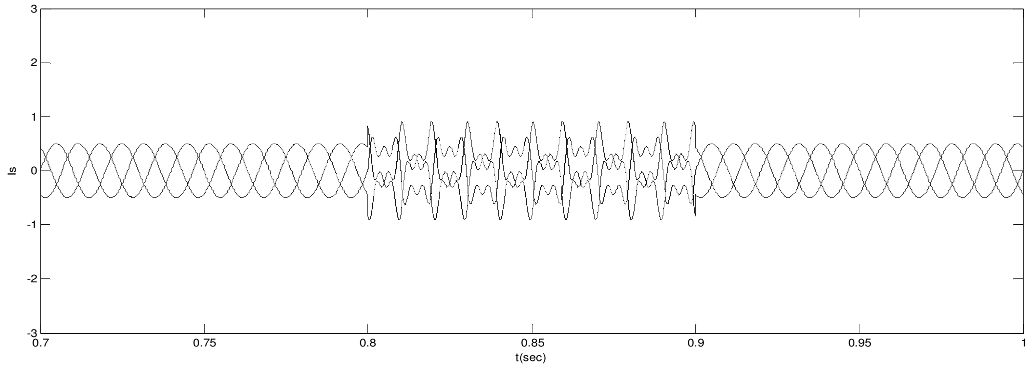

Figure 15. Stator currents without rotor flux reference.

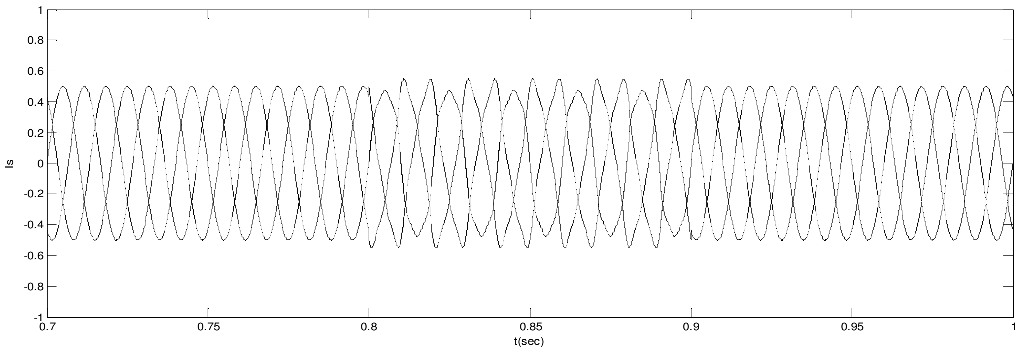

Figure 16. Stator currents with rotor flux reference.

The results show the variation in DC bus voltage during the fault at the instant between 0.8 to 0.9 using with and without rotor flux reference.

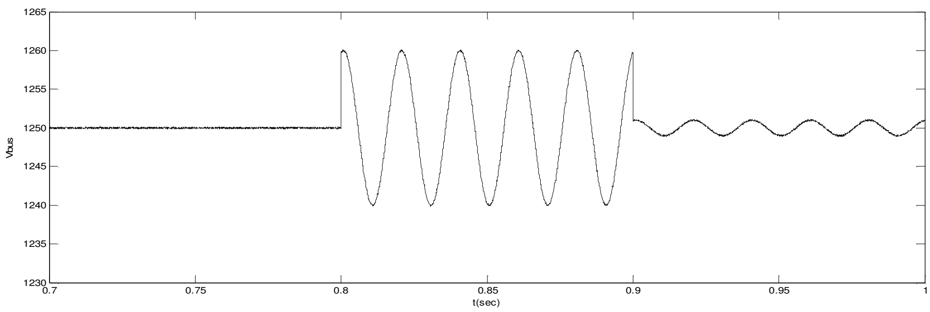

Figure 17. DC bus voltage without rotor flux reference.

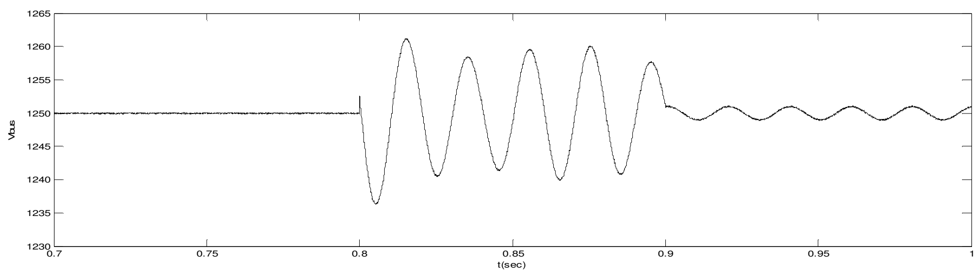

Figure 18. DC bus voltage with rotor flux reference.

The results show the variation in stator voltage during the fault at the instant between 0.8 to 0.9 using without rotor flux reference.

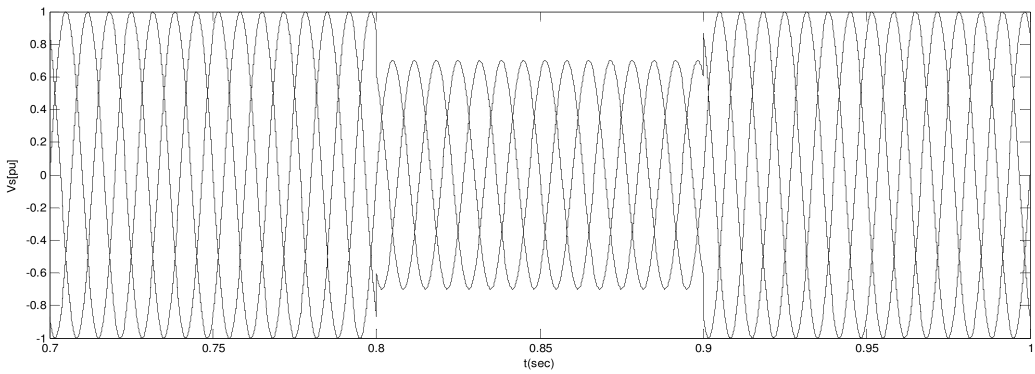

Figure 19. Stator voltage without rotor flux reference.

VI. CONCLUSION

The direct torque control of doubly fed induction machine is used to generate the required rotor pulses using the rotor flux reference generation strategy. The proposed control strategy is used during the low depth voltage dips for higher voltage dips it is necessary to use crowbar protection. The DC bus voltage available in the back-to-back converter determines the voltage dips depth that can be kept under control.

The direct torque control combines the benefits of vector control and direct self-control into a sensor-less variable-frequency drive that does not require a PWM modulator. In steady state there is a ripple in the torque. This ripple depends on the switching frequency of the inverter which is determined by the torque and flux band. At the time of starting DTC draws high current. The switching frequency of the inverter varies over a wide range because of using hysteresis controllers. The magnitude of the stator flux can be maintained constant and several bright spots show the points where stator flux halts. In the transient state, the highest torque response can be obtained by selecting the fastest accelerating voltage vector to produce the maximum slip frequency. In steady state, by selecting the acceleration vector and the zero voltage vectors alternatively, the torque can be maintained constant. Since the flux ripples are relatively small and minor loops are not observed in the locus, harmonic losses and acoustic noise of the machine may be effectively decreased. The transient response of the drive is fast with independent control of flux and the torque.

Thus the DTC offers excellent dynamic performance and gives good torque response than the field-oriented control. It may be predicted that the DTC will be the most preferred control algorithm for A.C. drives in future because of its simplicity in control logic.

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