Direct Decoupled Active and Reactive Power Control of Doubly Fed Induction Machine Without Rotor Position Sensors and with Robustness to Saturation and Parameter Variation

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Abstract— **in this paper a new Direct Power Control method of the Doubly Fed Induction Machine without the use of rotor position sensors is presented. The method is based on estimating the stator flux in the rotor reference frame, and then applying the correct rotor voltages to obtain the desired rotor flux and power. Estimation of the rotor position is done by comparing the measured values with the estimated values of the rotor current. For this control method to have minimal sensitivity to parameter inaccuracies, the mutual inductance of the machine is also corrected during the process by an error signal produced by comparing the magnitudes of the measured and estimated rotor current. This will also ensures robustness against machine saturation and can be used to detect saturation in the machine.**

Keywords-component; DFIM; DFIG; DPC; sensorless; MRAS

I. INTRODUCTION

In recent years the interest of using renewable energy sources instead of the fossil fuel sources is increasing rapidly. Knowing the fact that most of the renewable energy sources are coming from the natural events, and natural events mostly have random characteristics. Wind energy is one of the natural renewable energy sources that can be used to generate power through wind turbines connected to an electric generator. Because of the randomness in the wind speed in different areas, a flexible electric generation system is required to counter the randomness in the wind speed and can provide constant frequency voltage and stable power. The doubly fed induction machine is has characteristics which makes it a very good solution for applications such as wind generation. With the ability to operate in variable speeds around the synchronous frequency and using a partially rated back to back converter, this machine satisfies the requirements for a good wind turbine generator. In the most common configuration the stator of the machine is directly connected to the grid and the rotor is fed by a three phase inverter at its rated power. Figure (1) shows the hardware setup of a grid connected DFIG.

The Direct Torque Control method for induction machines was first introduced in 1986 [4] and quickly became a very good alternative to the commonly used Field Oriented Control [5],[6],[7] which is based on controlling the rotor current in order to control the stator power. The DTC strategy has better transient and steady state response compared to the conventional FOC; also it does not need the current control loops or reference frame transformation. However these advantages came at the cost of inconstant switching frequency and torque high ripple. Work has been done by the researchers to address the problems of the DTC by using SVPWM technique instead of switching tables to reduce torque ripple.

The Direct Power Control (DPC) is established upon the principles of the DTC [1],[2] to directly control the machine power instead of the electromagnetic torque and Applicable switching tables to achieve the direct power control was formed. To address the inconstant switching frequency [3], the SVPWM method was used to feed the rotor. For the correct and accurate operation of the control mechanism, the parameters of the machine and the position of the rotor itself and the stator and rotor fluxes are required, which brings up the need to know the exact value of the machine parameters for a good estimation and rotor position sensor to obtain angular position. In this case, both the stator and rotor currents and voltages of DFIM can be measured which is a nice advantage over other types of electrical machines. Having extra measurable parameters will lead to less physical parameters dependent and more accurate estimation process. Also the physical parameters of the machine can be corrected during the control process by comparing a measured value with its estimated one and using the difference to correct the parameter. Finally the fact that a parameter which has both magnitude and angle which in this case is the rotor current can be used to effectively estimate the rotor position without using any rotor positioning sensors. The following sections will first give a quick introduction to the DFIM then, the proposed DPC method will be described and finally the procedure towards sensor less control and parameter correction will be presented.

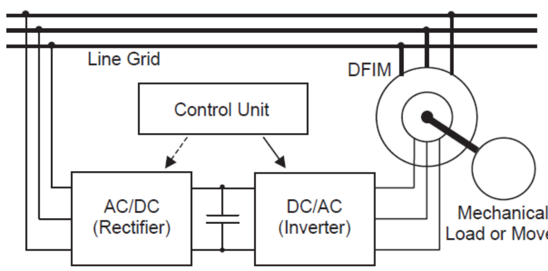

Figure 1. Hardware setup for controling a DFIM

II. DOUBLY FED INDUCTION MACHINE

A. Nomenculture

T_{em}	Electromagnetic Torque
Ψ_s, Ψ_r	Stator and Rotor flux vectors
V_s, V_r	Stator and Rotor Voltages
I_s, I_r	Stator and Rotor currents
ω_r, ω_{slip}	mechanical and slip speeds
R_s, R_r	Stator and Rotor Resistance
$L_{\sigma s}$, $L_{\sigma r}$	Stator and Rotor Leakage Inductance
L_m	Machine Mutual Inductance

B. Model equations

The equivalent circuit of the DFIM in the rotor reference frame is shown in figure (2).

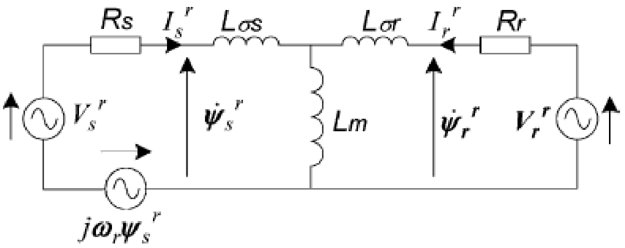

Figure 2. Equivalent Circuit of DFIM

According to figure (2), the stator and rotor flux equations in the rotor reference frame can be written:

$$\overrightarrow{\Psi_s} = L_s \overrightarrow{I_s} + L_m \overrightarrow{I_r} \tag{1}$$

$$\overrightarrow{\Psi_r} = L_m \overrightarrow{I_s} + L_r \overrightarrow{I_r} \tag{2}$$

Where $L_s = L_m + L_{\sigma s}$ and $L_r = L_m + L_{\sigma r}$. For the stator and rotor voltages we have:

$$\overrightarrow{V_s^r} = R_s \overrightarrow{I_s^r} + \frac{d\overrightarrow{\psi_s^r}}{dt} + j\omega_r \overrightarrow{\psi_s^r} \tag{3}$$

$$\overrightarrow{v_r} = R_r \overrightarrow{I_r} + \frac{d\overrightarrow{\Psi_r}}{dt} \tag{4}$$

According to (1) and (2) the stator current can be written as:

$$\overrightarrow{I_s^r} = \frac{L_r \overrightarrow{\psi_s^r} - L_m \overrightarrow{\psi_r^r}}{L_s L_r - L_m^2} = \frac{\overrightarrow{\psi_s^r}}{\sigma L_s} - \frac{L_m \overrightarrow{\psi_r^r}}{\sigma L_s L_r} \tag{5}$$

Where σ is $(L_s L_r - L_m^2)/L_s L_r$. According to (3) and by neglecting the stator resistance, the active power of the stator can be written as:

$$P_s = \frac{3}{2}\overrightarrow{V_s^r} \cdot \overrightarrow{I_s^r} = \frac{3}{2}(\frac{d\overrightarrow{\psi_s^r}}{dt} + j\omega_r \overrightarrow{\psi_s^r}) \cdot \overrightarrow{I_s^r} \tag{6}$$

The same applies for the stator reactive power. So the reactive power equation will be:

$$Q_s = \frac{3}{2} | \overrightarrow{V_s^r} \times \overrightarrow{I_s^r} | = \frac{3}{2} | (\frac{d\overrightarrow{\psi_s^r}}{dt} + j\omega_r \overrightarrow{\psi_s^r}) \times \overrightarrow{I_s^r} | \tag{7}$$

In the power equations (6) and (7) the stator flux in the stationary frame can be obtained using the following equation:

$$\overrightarrow{\Psi_s} = \int (\overrightarrow{v_s} - R_s \overrightarrow{I_s}) \tag{8}$$

Because the resistive voltage drop on the stator windings has minimal effect on the stator flux magnitude we can write the magnitude equation of the stator flux by the following:

$$| \overrightarrow{\Psi_s} | = | \int \overrightarrow{v_s} | = \text{constant} \tag{9}$$

Using (5), (6) and (7) the stator active and reactive power can be rewritten as following

$$P_s = -\frac{3}{2}\frac{L_m}{\sigma L_s L_r}\omega_1 \left|\overrightarrow{\psi_s^r}\right| \left|\overrightarrow{\psi_r^r}\right| \sin\delta_{sr} \tag{10}$$

$$Q_s = \frac{3}{2}\frac{\omega_1}{\sigma L_s}\left|\overrightarrow{\psi_s^r}\right| (\frac{L_m}{L_r}\left|\overrightarrow{\psi_r^r}\right| \cos\delta_{sr} - \left|\overrightarrow{\psi_s^r}\right|) \tag{11}$$

Where δ_{sr} is the angle between the stator and rotor fluxes.

III. DIRECT POWER CONTROL OF THE DFIM

A. Control strategy

According to the active and reactive power equations (10) and (11), power can be controlled by controlling the magnitude and relative angle of one of the rotor or stator fluxes. In the common DFIM configuration the stator is directly connected to the grid and its magnitude and angle is defined by the stator voltage and current. Because the grid voltage is normally constant during operations and the effect of the stator resistance can be neglected on the stator flux magnitude, it can be assumed that linear control of the machine power can be achieved by having a correct rotor flux in terms of magnitude and relative angle to the stator flux, which is produced by applying a correct voltage vector to the rotor windings.

Figure (3) shows the vector diagram of the rotor and stator fluxes in the stator and rotor reference frame.

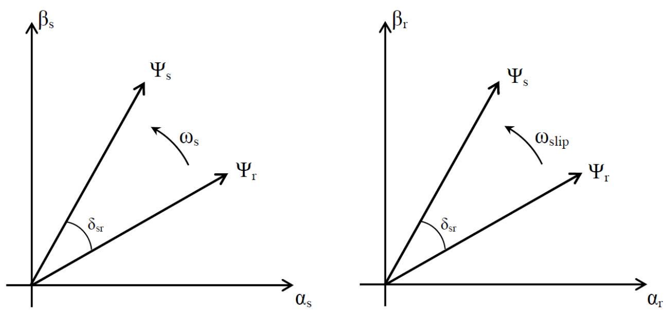

Figure 3. Rotor and stator flux vectors in stator and rotor reference frame

It can be seen from (10) and (11) that controlling the active and reactive power of the machine stator have a direct linear relation with the rotor flux components along the quadrature and direct axis of the stator flux. Therefore it is appropriate to use the stator flux vector as the reference frame for the control process. Also knowing the fact that the rotor voltages and currents are oscillating with slip frequency and controlling the power is done by controlling the rotor flux relative to the stator flux, so it will be appropriate to use the rotor reference frame in order to estimate the required vectors for the control process.

Figure (4) shows the stator and rotor flux vectors in the stator flux reference frame relative to the rotor.

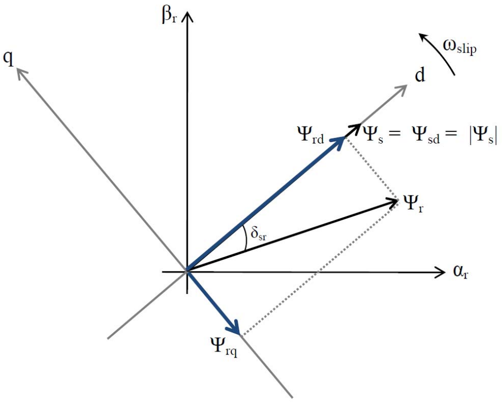

Figure 4. Stator and rotor fluxes in the stator flux reference frame

According to (10), (11), (4) and figure (3) the active and reactive power and rotor voltage equations can be written as the following:

$$P_s = \frac{3}{2}\frac{L_m}{\sigma L_s L_r}\omega_1 \Psi_{sd}\Psi_{rq} \tag{12}$$

$$Q_s = \frac{3}{2}\frac{\omega_1}{\sigma L_s}\Psi_{sd}\left(\frac{L_m}{L_r}\Psi_{rq}\cos\delta_{sr} - \Psi_{sd}\right) \tag{13}$$

$$v_{rd} = R_r i_{rd} + \frac{d\Psi_{rd}}{dt} + \omega_{slip}\Psi_{rq} \tag{14}$$

$$v_{rq} = R_r i_{rq} + \frac{d\Psi_{rq}}{dt} - \omega_{slip}\Psi_{rd} \tag{15}$$

By Neglecting the rotor resistance in (14) and (15), we will have:

$$\frac{d\psi_{rd}}{dt} = -v_{rd} - \omega_{slip}\Psi_{rq} \tag{16}$$

$$\frac{d\psi_{rq}}{dt} = -v_{rq} + \omega_{slip}\Psi_{rd} \tag{17}$$

It can be seen that controlling the active and reactive power can be achieved by having the correct rotor flux along the q and d axis respectively. From (16) and (17) it can also be seen that controlling the rotor flux along the dq axis can be done by applying the correct rotor voltages in the corresponding axis. It should be noted that because of the rotational voltage caused by the slip frequency in the rotor windings, the motion induced rotor voltages are feed forwarded so the flux can be controlled decoupled. Also we can see from (16) and (17) that the actual rotor flux is calculated by integrating the applied voltage so there is an integrator in the machine control loop from rotor voltage to rotor flux, there for the rotor flux controller does not need a PI controller as a simple proportional controller can achieve good results. A small integral gain is used in the controller to handle the effect of the rotor resistance and inaccuracies in machine parameters. The rotor flux control loop is shown in figure (5).

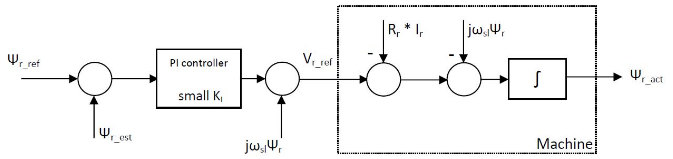

Figure 5. Rotor Flux controller

B. *Obtaining the slip and rotor angle without using rotor position sensors*

Slip and rotor angle estimation are based on having a same parameter in two different reference frames, which in this case is rotor current. The rotor current in the rotor reference frame can be obtained by directly measuring the current at the rotor terminals, knowing that the rotor current is oscillating with the slip frequency, the angle of the measured current in its own reference frame is a good estimation of the slip angle. At the other hand, the rotor current in the synchronous reference frame is calculated using the machine voltage and flux equations; which is oscillating with the synchronous frequency. The difference between the rotor current angles in the rotor and synchronous reference frame will result in the rotor angle which can be used to transform any parameter from the synchronous frame to rotor frame and vice versa. Therefor by knowing the difference between the rotor current and the stator flux in the synchronous frame we can calculate the stator flux angle which is the d axis in the rotor frame.

Figure (6) shows the stator flux vector and rotor current vector in the rotor, stator and stator flux synchronous reference frames.

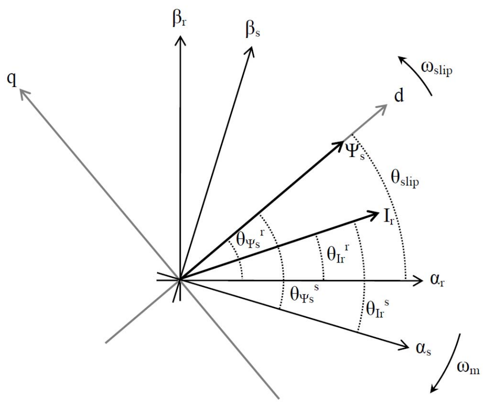

Figure 6. Rotor current and Stator flux in both the stator and rotor reference frame

The equations regarding the calculation of the slip and rotor angles are as follows:

$$\theta_{slip} = \theta^r_{\Psi s} = \theta^s_{\Psi s} - (\theta^s_{Ir} - \theta^r_{Ir}) \tag{18}$$

In (18) the angle of the stator flux in the stator frame $\theta_{\psi s}{}^s$ can be calculated by the estimation of the stator flux in (8). Therefore we have:

$$\theta^s_{\Psi s} = \tan^{-1}\left(\frac{\int V_s^{\beta s} - R_s I_s^{\beta s}}{\int V_s^{\alpha s} - R_s I_s^{\alpha s}}\right) \tag{19}$$

Also, the angle of the rotor current in the stator reference frame is calculated by using the estimated rotor current in the following equation:

$$\theta^s_{Ir} = \tan^{-1}\left(\frac{(\int V_s^{\beta s} - R_s I_s^{\beta s}) - L_s I_s^{\beta s}}{(\int V_s^{\alpha s} - R_s I_s^{\alpha s}) - L_s I_s^{\alpha s}}\right) \tag{20}$$

Finally, the angle of the rotor current in the rotor frame can be directly calculated from the measured rotor currents.

$$\theta^r_{Ir} = \tan^{-1}\frac{I_r^{\beta r}}{I_r^{\alpha r}} \tag{21}$$

C. Parameter Correction and robustness to saturation

Knowing the fact that for this sensor less method to obtain the rotor and slip angles correctly relies on a correct value of machine parameters used in estimation equations. So preparation should be made to counter inaccuracies in machine parameters. Knowing that the most important parameter in the machine parameter estimation is the mutual inductance between the rotor and stator windings, and inaccuracies in that particular parameter will lead to wrong estimation of the rotor current and therefore, wrong estimation of rotor and slip angles.

To tackle that problem, a simple form of the model reference (MRAS) is used, which is based on comparing a measured value with the estimated value of a same parameter of the system and use the error signal to correct specific parameters in the model. In this case, we have both the measured and estimated value of the rotor current. The difference between the angles of these two values is used to estimate the rotor angle; but according to (19), the amplitude of the rotor current is a good indication of a machine mutual inductance, therefore the difference between the amplitude of the measured and estimated value of the rotor current will be used to correct the value of L_m. Figure (7) shows the diagram of the described method.

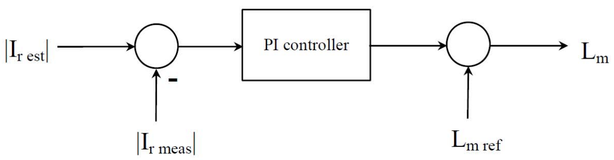

Figure 7. The MRAS loop for correcting the mutul inductance

It should be noted that to prevent the control algorithm from being affected by the parameter correction loop dynamics, the applied PI controller has a very small proportional gain and is mostly operating as an integrator.

D. The complete DPC block digram

The complete block diagram of the proposed method is shown in figure (8).

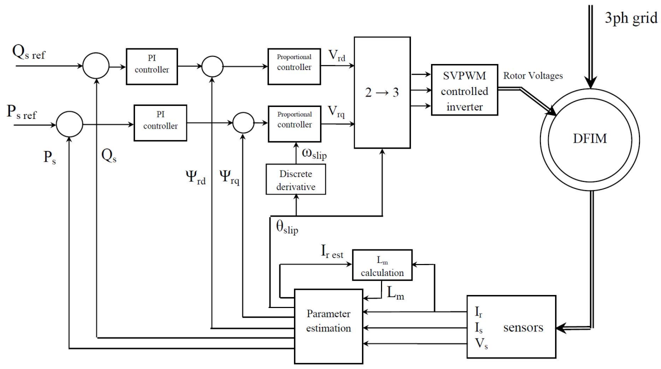

Figure 8. The control digram

IV. SIMULATION RESULTS

The proposed method has been simulated on a 4KW DFIM. The rotor windings are fed with a SVPWM inverter, operating with the switching frequency of 10 KHz. The DC link voltage has been set on 200V and is kept constant by a grid connected converter during the process. The machine parameters used in the simulation are given in table (I).

TABLE I. MACHINE PARAMETERS

Machine parameters	Parameter value
Nominal Power (W)	4000 W
Nominal speed (rpm)	1440 rpm
Mutual inductance (H)	0.1722 H
Stator leakage inductance (H)	0.005839 H
Rotor leakage inductance (H)	0.005839 H
Stator resistance (Ω)	1 Ω
Rotor resistance (Ω)	0.2 Ω
Pole Pairs	2

In the proposed simulation, first the parameter correction loop starts and estimates the correct mutual inductance of the machine. The simulation results are shown from t = 0.2 to t = 2. The power controllers' constants are $K_p = 6$ And $K_I = 2$. The proportional gain of the used flux controller is $K_p = 50$.

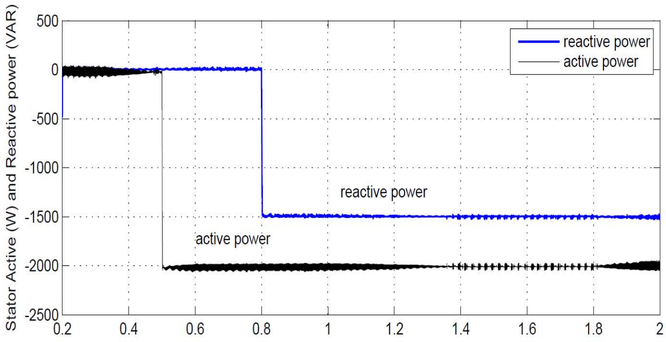

Figure 9. stator active (W) and reactive power (Var)

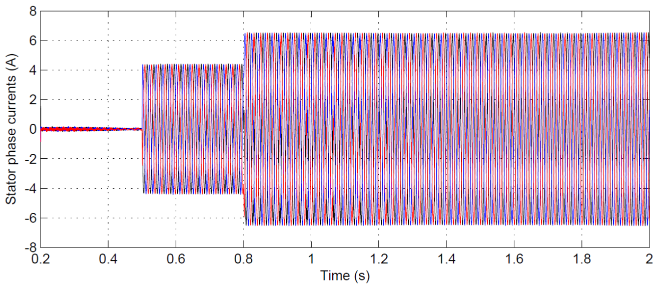

Figure 10. Stator three phase currents (A)

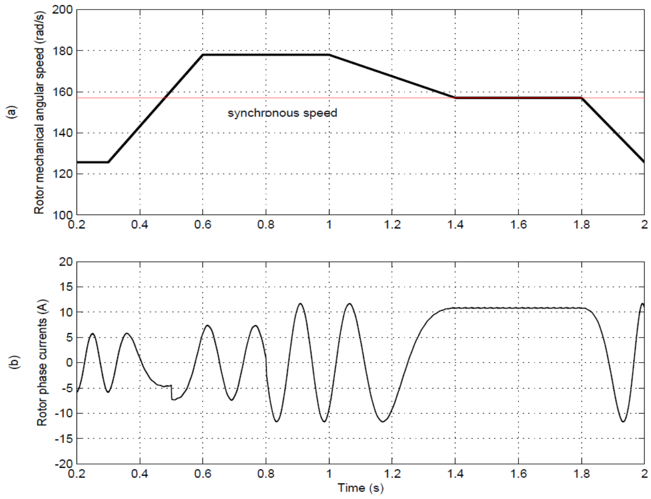

Figure 11. (a). Rotor mechanical speed (rad/s) (b). rotor phase current (A)

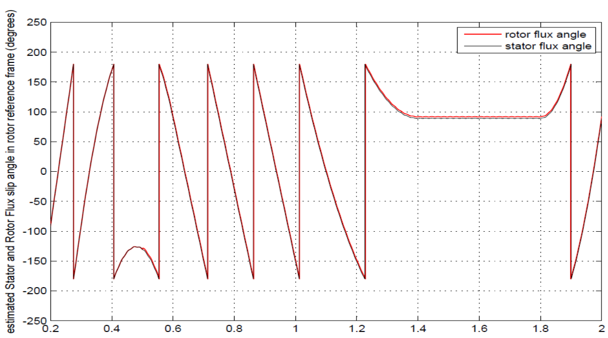

Figure 12. Stator and Rotor flux angles (degrees)

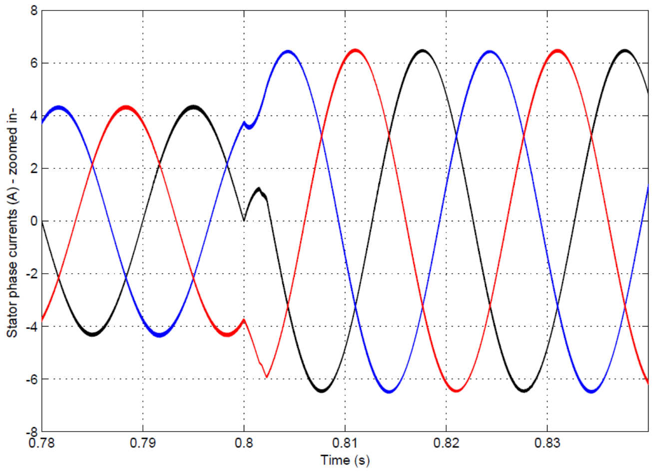

Figure 13. Stator phase currents(A) –zoomed in-

Figure (12) shows that the proposed sensor less strategy is able to accurately estimate the slip angle, ensuring the correct performance of the DPC

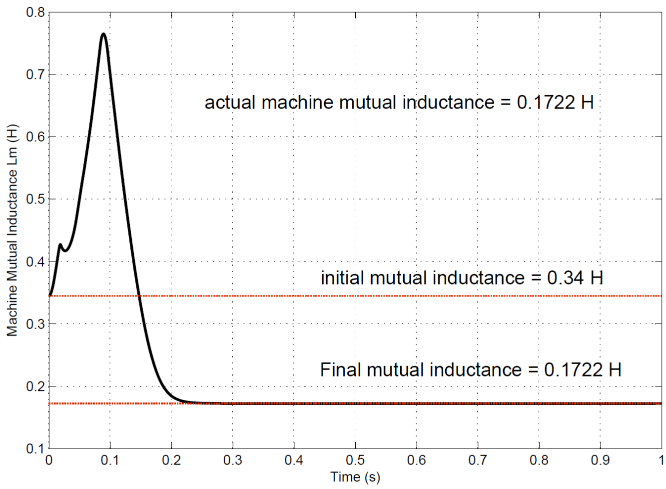

Figure 14. Estimated mutual inductance of the machine during operation (H)

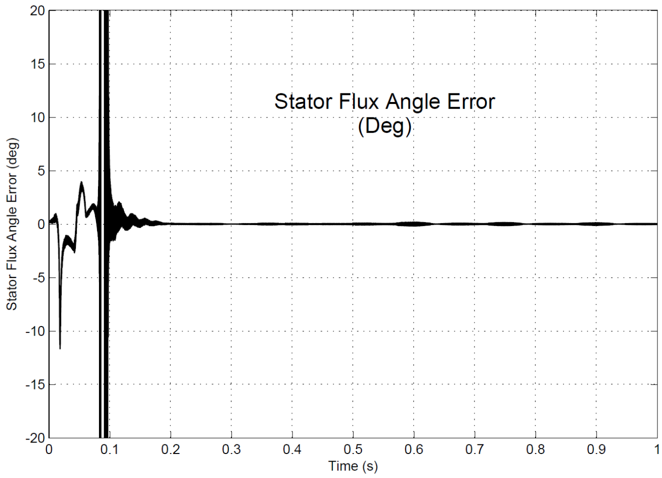

Figure 15. Stator flux angle error during operation (deg)

Figures (14) and (15) show that the proposed parameter correction loop is able to effectively compensate large machine parameter errors. Also because of the slow operation of the controller used in the loop, it has minimal effect on the power control dynamics.

V. CONCLUSION

In this paper a method for the direct power control of a DFIM through rotor flux control and without using rotor position sensor is proposed. Simulation results show that the proposed method for acquiring the slip and rotor angle can accurately estimate the angles needed for the DPC control. SVPWM controlled inverter of the rotor side will maintain the switching frequency constant and will minimize the power ripple. Also saturation detection and robustness to the variation of the machine mutual inductance L_m are countered by the use of a simple MRAS method.

REFERENCES

[1] Rajib Datta and V. T. Ranganathan, "Direct Power Control of Grid-Connected Wound Rotor Induction Machine Without Rotor Position Sensors" IEEE transactions on power electronics, vol. 16, no. 3, May 2001.

[2] Lie Xu and Phillip Cartwright, "Direct Active and Reactive Power Control of DFIG for Wind Energy Generation," IEEE transactions on energy conversion, vol. 21, no. 3, september 2006.

[3] Dawei Zhi and Lie Xu, "Direct Power Control of DFIG With Constant Switching Frequency and Improved Transient Performance," IEEE transactions on energy conversion, vol. 22, no. 1, March 2007.

[4] I. Takahashi and T. Noguchi, "A new quick-response and high-efficiency control strategy of an induction motor," *IEEE Trans. Ind. Appl.*, vol. IA- 22, no. 5, pp. 820–827, Sep.–Oct. 1986.

[5] R. Pena, J. C. Clare, and G. M. Asher, "Doubly fed induction generator using back-to-back PWM converters and its application to variable-speed wind-energy generation," Inst. Elect. Eng. Proc. Elect. Power Appl., vol. 143, no. 3, pp. 231–241, May 1996.

[6] H.Akagi andH. Sato, "Control and performance of a doubly-fed induction machine intended for a flywheel energy storage system," IEEE Trans. Power Electron., vol. 17, no. 1, pp. 109–116, Jan. 2002.

[7] R. W. De Doncker, S. Muller, and M. Deicke, "Doubly fed induction generator systems for wind turbines," IEEE Ind. Appl. Mag., vol. 8, no. 3, pp. 26–33, May/Jun. 2002.