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PERFORMANCE ANALYSIS OF DIRECT TORQUE CONTROL OF 3-PHASE INDUCTION MOTOR

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ABSTRACT

The Induction Motors are widely used in industrial applications that require rapid speed and torque response at high performance operation. The Direct Torque Control (DTC) based Induction Motor (IM) with PI controller performance is not appreciable one under load disturbance and transient conditions. To improve the dynamic performance of the IM drive with new method of speed and torque control can be done by Anti-Windup PI controller is proposed and presented in this paper. A complete simulation of DTC based IM drive using Anti-WindUp PI controller is implemented using Matlab/Simulink. In this Anti-Windup PI controller scheme closed loop saturation technique is included between input and output of speed controller. The effectiveness of the proposed systems is verified by simulation process based on Matlab. Therefore, the Anti-Wind Up PI controller has better Performance compared to the conventional PI controller during change of state conditions like load changing will leads to less overshoot percentage, less settling time, speed drop due to change in load with percentage and settling time after load changes done.
Keywords: *Induction Motor (IM), Direct Torque Control (DTC), Anti-Wind Up PI(AWPI)*

1. INTRODUCTION

The induction motor (IM), is having well-known advantages like simple construction, reliability, ruggedness, and low cost, has found very wide industrial applications. At the same time, in contrast to the commutation dc motor, it can be used in an aggressive or volatile environment since there are no problems with spark and corrosion. These advantages, however, are superseded by control problems when using an IM in industrial drives with high performance demands.

IM control methods can be divided into *scalar* and *vector control.* In scalar control, which is based on relationships valid in steady state, only magnitude and frequency (angular speed) of voltage, current, and flux linkage space vectors are controlled. Thus, the scalar control does not act on space vector position during transients. Contrarily, in vector control, which is based on relations valid for dynamic states, not only magnitude and frequency (angular speed) but also instantaneous positions of voltage, current, and flux space vectors are controlled.

In the vector control the motor equations are transformed in a coordinate system that rotates in synchronism with the rotor flux vector. These new coordinates are called *field coordinates*. In field coordinates—under constant rotor flux amplitude—there is a *linear* relationship between control variables and torque.

When, in the mid 1980s, there was a trend toward the standardization of the control systems on the basis of the FOC philosophy, there appeared the innovative studies of Depenbrock [2],[5] and of[6], which depart from the idea of coordinate transformation and the analogy with dc motor control. These innovators proposed to replace the decoupling control with the bang-bang control, which meets very well with on–off operation of the inverter semiconductor power devices. This control strategy is commonly referred to as *direct torque control* (DTC) and since 1985 it has been continuously developed and improved by many other research works.

In the paper the concept of Direct Torque Control and mathematical model of induction motor has to be discussed. Also conventional control using PI and anti-windup PI control of DTC of induction motors analyzed. Mentioned control has be simulated by using MatLab Simulink and comparison between these techniques are presented.

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2. BASIC CONCEPT AND PRINCIPLES OF DTC

The DTC principle was introduced in the late 1980s[3][4]. In contrast to vector control, which became accepted by drive manufacturers after 20 years of extensive research, DTC needed only just over a decade to really take off. A direct torque controlled induction motor drive has been manufactured commercially by ABB since the mid-1990s [7]. In the direct torque controller developed by ABB, the optimum inverter switching pattern is determined in every sampling period (25 ms). The core of the control system in DTC is the sub-system containing torque and flux hysteresis controllers and optimal inverter switching logic. An accurate machine model is also important, since estimation of the stator flux and motor torque is based on the machine model and the measurement of the machine input stator voltages and currents. The measurement of actual speed is not required [7]. A machine model in stationary reference frame is used to develop DTC theory.

2.1 Torque Production in a Direct Torque Controlled Drive

In a direct torque controlled induction motor drive supplied by a voltage source inverter, it is possible to directly control the stator flux linkage and the electromagnetic torque by the Direct Torque Control of AC Machines by the selection of the optimum stator voltage space vectors in the inverter. The selection of the most appropriate voltage vector is done in such a way that the flux and torque errors are restricted within the respective flux and torque hysteresis bands, fast torque response is obtained, and the inverter switching frequency is kept at the lowest possible level. In the case of rotor flux oriented control of an induction motor, the electromagnetic torque developed by the motor is described by

$$T_e = (3/2)P(L_m/L_r)\psi_r i_{qs} \qquad (1)$$

where the stator q-axis current is the imaginary component of the stator current space vector in the co-ordinate system fixed to the rotor flux space vector. The torque equation (1) can be written in terms of the amplitude and phase of the stator current space vector with respect to the d-axis of the reference frame as

$$T_e = K\psi_r |\underline{i}_s| \sin\lambda \qquad (2)$$

Instantaneous change of the torque requires, according to equation (2), change in the amplitude and phase of the stator current space vector, such that the d-axis current component remains the same (so that rotor flux is constant), while the torque is stepped to the new appropriate value by the change in the stator q-axis current component. An alternative expression for the torque uses the stator flux space vector and stator current space vector. Regardless of the applied method of control, the torque developed by the motor can be written as

$$T_e = \frac{3}{2}P\left|\underline{\psi}_s\right|\left|\underline{i}_s\right|\sin\alpha \qquad (3)$$

where the angle α is the instantaneous value of the angle between the stator current and stator flux space vectors[10].

3. MATHEMATICAL MODEL OF THREE-PHASE INDUCTION MOTOR

An induction machine with a perfectly smoothed air gap is considered. The phase windings of the machine are assumed to be physically 120 degrees apart for both stator and rotor. Winding resistances and leakage inductances are assumed to be constant. All the parasitic phenomena, such as iron loss and main flux saturation, are ignored at this stage. The induction machine under consideration is therefore an ideal smooth air-gap machine with a sinusoidal distribution of windings, and all the effects of MMF harmonics are neglected.

A schematic representation of the machine is shown in Figure 1.

The notations in the figure below are:

ω_r : angular rotor speed;

ω_s : angular speed of stator flux space vector;

θ : instantaneous rotor angular position with respect to phase a magnetic axis of stator;

θ_s : instantaneous angular position of common rotating reference frame with respect to phase a magnetic axis of stator.

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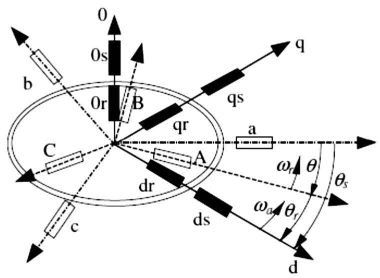

Figure 1: Schematic Representation Of Induction Machine With Reference Frames In Three-Phase Domain And Common Rotating D-Q Reference Frame.

θ_r : instantaneous angular position of common rotating reference frame with respect to phase a magnetic axis of rotor.

After the transformation from a three-phase domain to a common rotating reference frame with an arbitrary angular speed, the stator and rotor voltage equations of the induction machine are

$$v_{ds} = R_s i_{ds} + \frac{d\psi_{ds}}{dt} - \omega_a \psi_{qs}$$
$$v_{qs} = R_s i_{qs} + \frac{d\psi_{qs}}{dt} - \omega_a \psi_{ds} \quad (4)$$

$$v_{dr} = R_r i_{dr} + \frac{d\psi_{dr}}{dt} - (\omega_a - \omega_r)\psi_{qr}$$
$$v_{qr} = R_r i_{qr} + \frac{d\psi_{qr}}{dt} - (\omega_a - \omega_r)\psi_{dr} \quad (5)$$

The flux linkages are

$$\psi_{ds} = L_s i_{ds} + L_m i_{dr}$$
$$\psi_{qs} = L_s i_{qs} + L_m i_{qr} \quad (6)$$

$$\psi_{dr} = L_r i_{dr} + L_m i_{ds}$$
$$\psi_{qr} = L_r i_{qr} + L_m i_{qs} \quad (7)$$

symbols L_s , L_r denote stator and rotor self-inductance respectively; while Lm is the magnetizing inductance.

The relationship between the stator, rotor, and magnetizing inductances and the three-phase model self and mutual inductances are

$$L_s = L_{\sigma s} + L_m \quad (8)$$
$$L_r = L_{\sigma r} + L_m$$

where $L_{\sigma s}$, $L_{\sigma r}$ are stator and rotor leakage inductances, respectively. The equation of mechanical motion remains as

$$T_e - T_L = \frac{J}{P}\frac{d\omega_r}{dt} \quad (9)$$

where, T_e is electromagnetic torque; T_L *is* load torque*;* J is inertia of the induction machine; and P is the number of pole pairs.

Electromagnetic torque can be expressed in terms of d-q components of stator flux and stator current as

$$T_e = \frac{3}{2}p(\psi_{ds} i_{qs} - \psi_{qs} i_{ds}) \quad (10)$$

The per phase equivalent circuit of the ideal constant parameter machine mode in the d-q rotating reference frame is shown in Figure 2.

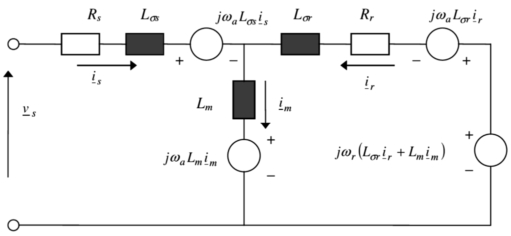

Figure 2: Dynamic Equivalent Circuit Of An IM In An Arbitrary Rotating Common Reference Frame

The induction machine model that will be used later in this chapter for simulation purposes is the machine model in the stationary reference frame. Components of stator current, rotor current and angular electrical speed ω_r are used as state-space variables in the fifth-order differential equation system. The stator and rotor voltage equations with stator current ,rotor current, and rotor angular speed as state-space variables are obtained by using equations (4)–(7), and (9) as

$$v_{\alpha s} = R_s i_{\alpha s} + L_s \frac{di_{\alpha s}}{dt} + L_m \frac{di_{\alpha r}}{dt}$$
$$v_{\beta s} = R_s i_{\beta s} + L_s \frac{di_{\beta s}}{dt} + L_m \frac{di_{\beta r}}{dt} \quad (11)$$

$$0 = L_m \frac{di_{\alpha s}}{dt} + \omega_r L_m i_{\beta s} + R_r i_{\alpha r} + L_r \frac{di_{\alpha r}}{dt} + \omega_r L_r i_{\beta r}$$
$$0 = -\omega_r L_m i_{\alpha s} + L_m \frac{di_{\beta s}}{dt} - \omega_r L_r i_{\alpha r} + R_r i_{\beta r} + L_r \frac{di_{\beta r}}{dt} \quad (12)$$

$$\frac{J}{P}\frac{d\omega_r}{dt} = \frac{3}{2}P\left[i_{\beta s}(L_s i_{\alpha s} + L_m i_{\alpha r}) - i_{\alpha s}(L_s i_{\beta s} + L_m i_{\beta r})\right] - T_L \quad (13)$$

4. BASIC CONTROL SCHEME OF DIRECT TORQUE CONTROLLED INDUCTION MOTOR

Since $\Delta \underline{\psi}_s = \underline{v}\Delta t$, then the stator flux space vector will move fast if non-zero voltage vectors are applied to the motor. It will almost stop if zero voltage vectors are applied. In DTC drives, at every sampling period the stator voltage vectors

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are selected on the basis of keeping the stator flux amplitude error and torque error within the prescribed hysteresis bands. The size of the hysteresis bands will significantly affect the inverter switching frequency. In general, the larger the hysteresis band, the lower the switching frequency and the poorer the response of the drive to change in reference. Because the stator flux space vector is the integral of the stator voltage vector, it will move in the direction of the stator voltage space vector for as long as this voltage vector is applied to the motor.

Basic control schemes of a DTC induction motor drive are shown in Fig. 3 and 4 for torque mode and speed mode of operation, respectively. In each figure there are two parallel branches, one for stator flux amplitude and the other for the torque control. The torque reference is either an independent input (for a torque-controlled drive, Figure. 3) or the output of the speed controller (in a speed-controlled drive, Fig. 4). Both the stator flux and the torque controllers are of the hysteresis type. The drive requires appropriate measurements that will enable the estimation of the stator flux and torque for closed loop control of these two quantities. Stator currents and measured or reconstructed stator voltage are used for the estimation, as given by the equations (11) and (12):

$$\psi_{\alpha s} = \int (v_{\alpha s} - R_s i_{\alpha s})dt$$
$$\psi_{\beta s} = \int (v_{\beta s} - R_s i_{\beta s})dt \qquad (14)$$
$$\psi_s = \sqrt{\psi_{\alpha s}^2 + \psi_{\beta s}^2} \quad \cos\phi_s = \psi_{\alpha s}/\psi_s \quad \sin\phi_s = \psi_{\beta s}/\psi$$

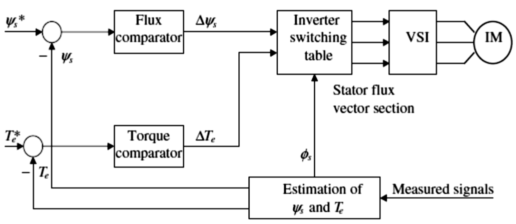

Figure 3 Control Scheme Of A DTC Induction Motor Drive For Torque Mode Of Operation

$$T_e = \frac{3}{2}P(\psi_{\alpha s} i_{\beta s} - \psi_{\beta s} i_{\alpha s}) \qquad (15)$$

In addition, an estimate of the speed of rotation is required for closed loop speed control in sensor-less DTC drives. Note that the DTC induction motor drive inherently lends itself to sensor-less operation, since no co-ordinate transformation is involved and a speed signal is only needed for closing the speed loop.

4.1 Stator Flux and Torque Estimation

From the considerations of the previous sub-section, it follows that for successful operation of a DTC scheme, it is necessary to have accurate estimates of the stator flux amplitude and the electromagnetic torque. In addition, it is necessary to estimate in which sector of the complex plane the stator flux space vector is situated. As already shown in the sub-section above, the stator flux amplitude and torque can be obtained in a straight forward manner if stator currents are measured and stator voltages are reconstructed (or measured) according to equations (11) and (12).

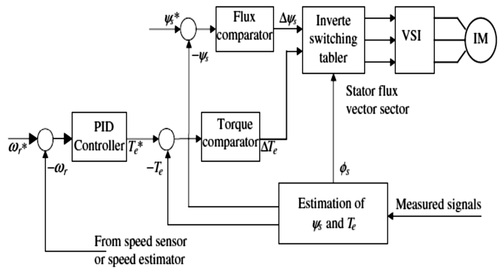

Figure 4: Control Scheme Of DTC Induction Motor Drive For Speed Mode Of Operation With Or Without Speed Sensor

The two problems encountered in the process of stator flux and torque estimation are the requirement for the pure integration and temperature related variation in stator resistance in equation (11). Stator resistance related voltage drop is significant at low speed of operation. The accuracy of the estimation at low frequency depends on the accuracy of stator resistance value.

An open loop stator flux estimator can work well down to 1–2 Hz, but not below this frequency. Equation (11) can also be used to find the location of the stator flux space vector in the complex plane:

$$\phi_s^e = \tan^{-1}(\psi_{\beta s}/\psi_{\alpha s}) \qquad (16)$$

The exact position of the stator flux space vector is not needed in DTC induction motor drives. It is only necessary to know in which sector (out of six possible ones) of the complex plane the vector is located. Equation (13) will be used in the simulations for determining the sector containing the stator flux space vector. The determination of the sector of the complex plane containing the stator flux space vector can be done by using the algebraic signs of the stator flux α-β components obtained from equation (11) and the sign of the

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phase *'b'* stator flux, which is obtained by using $\psi_{bs} = -0.5\psi_{\alpha s} + 0.5\sqrt{3}\psi_{\beta s}$.

4.2 Speed and Torque Control with DTC

The general speed control scheme is shown in Figure 4. A PID controller is used as a speed controller whose input is the error between the speed command and feedback speed. Feedback speed can be from the speed sensor or speed estimator. A PI controller is commonly used instead of a PID controller. For better performance of speed responses (lower overshoot, faster time response, reduced or zero steady state-error), a PI controller with anti-wind up is used as a speed controller. Figure 6 shows the structure of a PID controller with anti-wind up in MATLAB/Simulink.

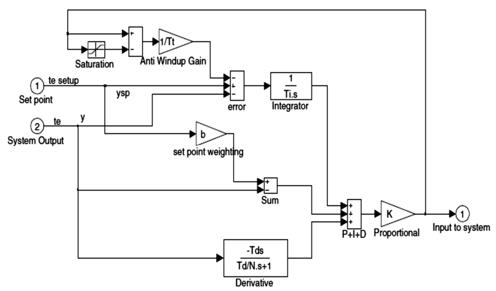

Figure 6: PI Controller With Anti-Wind Up

Simulation of the performance of the DTC of the induction motor using MATLAB/Simulink will be discussed in the next sub-section. The discussion will focus on both the torque control mode and the speed control mode.

5. SIMULATION RESULTS

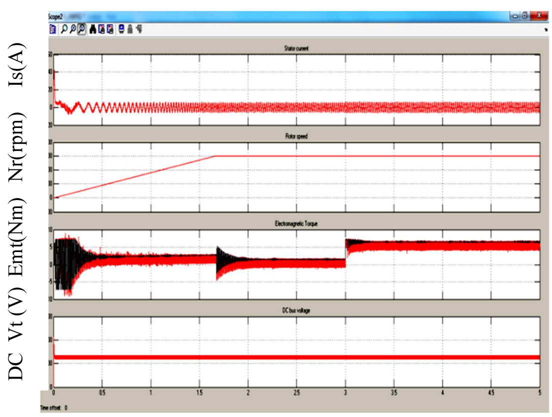

Figure 7: Output Response Of DTC Of IM Using PI And AWPI Control Technique

time (sec)

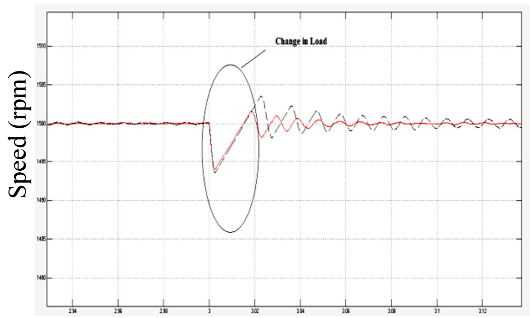

Figure 8: Change In Speed Response For Given Time

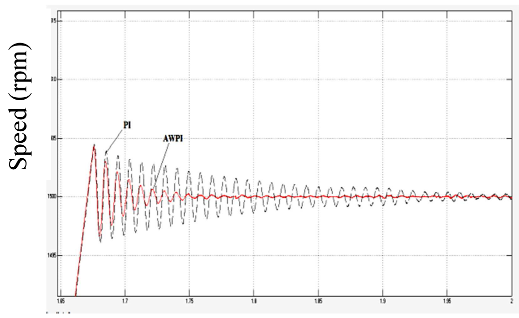

Figure 9: Speed Comparison Between PI And AWPI Control Technique

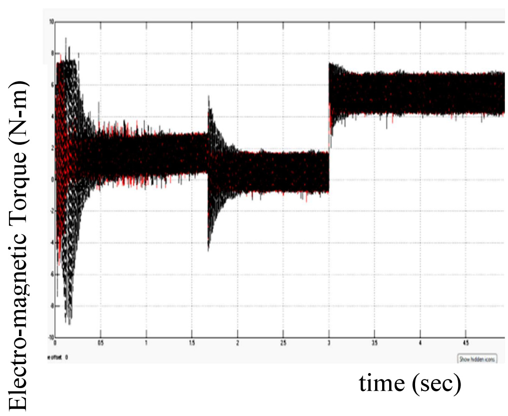

Figure 10: Electro-Magnetic Torque Developed In PI And AWPI Control Technique

From Figure 7 the stator current response is similar to sinusoidal signal hence the drive system develops the rotational magnetic flux. Also electromagnetic torque response with disturbance of load difference is shown.

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Table 1: Comparison Table Between PI Control And AWPI Control.

Control Variable	Over-shoot	Sett-ling time	Steady State error	Speed drop with load	Settling time after change in load
Control Tech-niques	(%)	(sec)	(%)	(%)	(sec)
PI	**0.33**	**2.15**	**0.033**	**0.43**	**0.16**
AWPI	**0.27**	**1.8**	**0.02**	**0.4**	**0.08**

6. CONCLUSION

In this paper a new approach of controller to improving performance in DTC based IM using Anti-wind up PI controller is proposed and simulated. The Anti-wind up PI controller and conventional PI controllers are used in speed – torque waveforms and the performance are analysis and compared with change if load and load setting. The performance improvement from the conventional method with Anti-wind up PI controller with to less overshoot percentage, less settling time, speed drop due to change in load with percentage and settling time after load changes. Control parameter of the anti-windup scheme must select properly to achieve better results in outputs.

Further research in this field is to introduce any well known optimization techniques in order to obtain superior performance in the torque control and speed control at any load disturbance.

Im Simulation Design Parameters

Nominal Power/ Horse Power	4 kW / 5.4 hP
Line-to-Line Voltage, V_{LL}	400 V
Speed, N	1430 rpm
Stator Resistance, R_s	1.405 Ω
Rotor Resistance, R_r	1.395 Ω
Stator Inductance, L_s	0.5839 m H
Rotor Inductance, L_r	0.5839 mH
Mutual Inductance, L_m	0.1722 m H
Moment of Inertia, J	0.0131 kg·m^2
No. of Phase	3
No. of Pole Pairs	2

REFERENCES

[1] Antonio Flores T., “Antiwindup Control Scheme”,2008., pp-1-10
[2] Baader,U., M. Depenbrock, and G. Gierse, “Direct self control (DSC) of inverter-fed-induction machine—A basis for speed control without speed measurement,” *IEEE Trans. Ind. Applicat.*, vol. 28, pp. 581–588 May/June 1992
[3] Casadei, D., Grandi, G., Serra, G., and Tani, A. (1994) Switching strategies in direct torque control of induction machines. Int. Conf. Elect. Mach. ICEM’94. Paris, pp. 204–209.
[4] Casadei, D., Grandi, G., Serra, G., and Tani, A. (1998a) “The use of matrix converters in direct torque control of induction machines. IEEE Ann. Mtg. Ind. Elect. Soc., IECON’98. Aachen, Germany, pp. 744–749.
[5] M. Depenbrock, “Direct self control of inverter-fed induction machines,”*IEEE Trans. Power Electron.*, vol. 3, pp. 420–429, Oct. 1988.
[6] I. Takahashi and T. Noguchi, “A new quick-response and high efficiency control strategy of an induction machine,” *IEEE Trans. Ind. Applicat.*,vol. IA-22, pp. 820–827, Sept./Oct. 1986.
[7] Tiitinen, P., Pohjalainen, P., and Lalu, J. (1995) The next generation motor control method: Direct torque control (DTC). Europ. Power Elect. J., 5(1), 14–18.
[8] Truc Phamdinh,” High Performance Control of AC Drives with MATLAB/Simulink Models”, First Edition, John Wiley & Sons, Ltd, 2012.
[9] Vas, P. (1992) Electrical Machines and Drives: A Space-vector Theory Approach. Oxford, Clarendon Press.
[10] Vas, P., (1998) Sensorless Vector and Direct Torque Control. Oxford University Press, New York.