International Journal of Power Electronics and Drive System (IJPEDS)
Vol. 8, No. 4, December 2017, pp. 1631~1641
ISSN: 2088-8694, DOI: 10.11591/ijpeds.v8i4.pp1631-1641

Proportional Integral Estimator of the Stator Resistance for Direct Torque Control Induction Motor Drive

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Article Info

Article history:

Received Oct 27, 2017
Revised Nov 8, 2017
Accepted Nov 28, 2017

Keyword:

Compensator
Direct torque control
Induction motor
modulation
Space vector pulse width
Stator resistance PI
voltage source inverter

ABSTRACT

In this paper, an improved proportional integral stator resistance estimation for a direct torque controlled induction motor is proposed. This estimation method is based on an on-line stator resistance correction regarding the variations of the stator current estimation error. In fact, the input variable of the PI estimator is the stator current estimation error. The main idea is to tune accurately the stator resistance value relatively to the evolution of the stator current estimation error gradient to avoid the drive instability and ensure the tracking of the actual value of the stator resistance. But there is an unavoidable steady state error between the filtered stator current modulus and its estimated value from the dq model of the machine which is due to pseudo random commutations of the inverter switches. An offset has been introduced in order to overcome this problem, for different speed command values and load torques. Simulation results show that the proposed estimator was able to successfully track the actual value of the stator resistance for different operating conditions

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1. INTRODUCTION

The first vector control method of induction motor was presented by K. Hasse developed first vector control for IM as Indirect Field Oriented Control (FOC) and F. Blaschke Direct FOC in early of 70s. In FOC motor equations are need to be converted into coordinate system that rotates in synchronism with the rotor flux.After one decade in the middle of 80s I. Takahashi and T. Noguchi developed new control scheme as Direct Torque Control (DTC) which is alternative to conventional vector control, FOC. Thus, DTC can be derived as new vector control scheme of induction motor which minimizes all drawbacks of FOC.As coordinate transformation require in FOC is eliminated in DTC by adopting controllers of hysterias type. Thus with application of power electronics, electric motors and control torque and flux errors can be removed between evaluated and reference value and hence direct torque control scheme is developed for induction motor drives.But DTC is also having drawback of large torque ripples during steady state operation. The stator flux magnitude and torque of IM drive are controlled differently in steady as well as transient state. By controlling stator flux magnitude in steady state optimum efficiency can be achieved. The values of this controlled variable are obtained by processing stator current and inverter DC link voltage by means of IM voltage model. The drive performance degrades with any error in model parameter (stator resistance) or voltage and current transduction.

The value of current and voltage are obtained by transducing the inverter dc link voltage and by manipulating its magnitude according to states of inverter switches. In general, the stator resistance does not match with the motor, and the voltage and current transductions are affected by gain errors and offsets in circuits. Thus all above parameter and transductions causes degradation of drive performance. The various errors and reasons for their occurrence are listed. Various errors causes degradation of DTC IM drives are,

a. Stator Resistance Mismatch;
b. Offsets;
c. Gain error; and
d. Unbalances in gain.

Our main focus is on stator resistance mismatch. To overcome problem of stator resistance mismatch concept of stator resistance PI Compensator is utilized. Due to its simple structure, good dynamic performance, robustness and ability to achieve fast response of flux and torque, the direct torque control strategy has attracted more and more interest in recent years and it has been widely used to overcome the problems of variable switching frequency and high torque ripples at low speeds. However, the stator resistance change can significantly degrade the performance of DTC (direct torque controlled) induction motor since the stator resistance is additionally required for stator flux and torque estimation in the basic configuration of DTC. In fact, one of the main problems of the DTC of induction motor drives is the variation of the stator resistance which is affected mainly by the change in motor temperature. At low speed, this effect is important for a given load torque. And if the value of the stator resistance used in the DTC controller is less than the actual value, the developed flux and torque will be decreased. Moreover, using greater value of the stator resistance in controller than its real value may lead to instability. Elsewhere, an accurate value of the stator resistance is of crucial importance for correct operation of a sensorless drive in the low speed region, since any mismatch between the actual value and the value used within the speed estimator may lead not only to a substantial speed estimation error but to instability as well. As a consequence, numerous online schemes for stator resistance estimation have been proposed in the recent past years. PI (proportional-integral) or I (integral) controllers were used

also for online stato resistance identification where an updated stator resistance value is obtained through an adaptive mechanism. This paper is concerned with a relatively simple solution to track the stator resistance so that the performance degradation and a possible instability problem can be avoided. A new robust and simple PI compensator using the measured stator currents is applied. An analytic expression to evaluate the stator current command from the torque and stator flux linkage commands is used and an offset taking into account the speed and the load torque variation is added to compensate the unavoidable steady state error between the filtered stator current modulus and its estimation. The future stator resistance change is developed using the error between the estimated and the actual stator current magnitude by an offset added to the signal of the PI estimator. The performance and robustness of the modified PI are shown and discussed via dynamic simulation studies.

2. DYNAMIC D-Q MODEL OF INDUCTION MOTOR

Dynamic mathematical model of IM is based on the concept of two real axes reference frame theory proposed by park for synchronous machines. After some years Kovacs and Racz described the space complex vector theory, and designed a model for the steady-state analysis of the machine. Using both theory dynamic model of induction machine is obtained. With concept of two axis theory, time varying parameters of motor are mutually perpendicular direct (d) and quadrature (q) axis. This can be done with the help of axis transformation from three phase to two phase. The concept of synchronously rotating reference frame is adopted for modeling of induction motor which is briefly.

2.1. Mathematical modeling using synchronously rotating reference frame- Dynamic Method

For two phase motor, we have to represent both stator and rotor components in synchronously rotating reference frame. Thus the stator circuit Equation can be written as,

$$v_{qs} = R_s i_{qs}^s + \frac{d}{dt}\varphi_{qs}^s \tag{1}$$

$$v_{ds} = R_s i_{ds}^s + \frac{d}{dt}\varphi_{ds}^s \tag{2}$$

φ_{qs}^{s} and φ_{ds}^{s} are q-axis and d-axis stator flux linkages, respectively. The Equation in synchronously rotating frame is given by,

$$v_{qs} = R_s i_{qs} + \frac{d}{dt}\varphi_{qs} + \omega_e \varphi_{ds} \tag{3}$$

$$v_{qs} = R_s i_{ds} + \frac{d}{dt}\varphi_{qs} - \omega_e \varphi_{qs} \tag{4}$$

When motor is not running w_r can be neglected, but in running condition and need to be considered and given by Equation (5-6)

$$v_{qr} = R_{rs} i_{qr} + \frac{d}{dt}\varphi_{qr} + (\omega_e - \omega_r)\varphi_{dr} \tag{5}$$

$$v_{dr} = R_{rs} i_{dr} + \frac{d}{dt}\varphi_{dr} - (\omega_e - \omega_r)\varphi_{qr} \tag{6}$$

The q-axis and d-axis circuits of IM are given in fig below which satisfy above Equations,

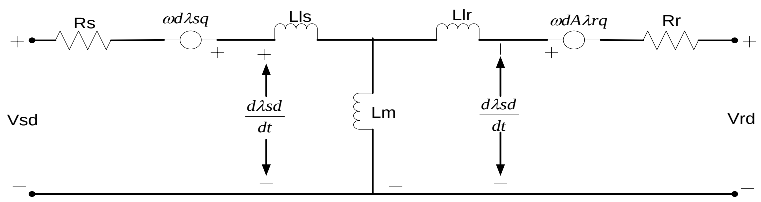

Figure 1. Equivalent circuit representing q[e-] axis of induction machine

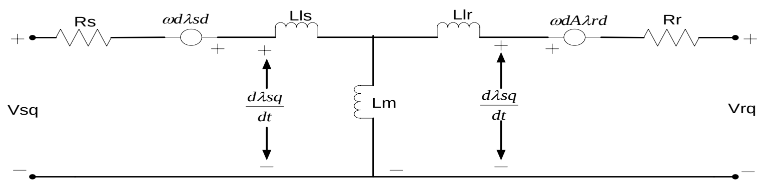

Figure 2. Equivalent circuit representing d[e-]axis of induction machine

The three phase stator voltages under balanced condition are given by,

$$V_a = \sqrt{2}V_{rms}\sin\omega t \tag{7}$$

$$V_b = \sqrt{2}V_{rms}\sin\omega t - \frac{2\Pi}{3} \tag{8}$$

$$V_c = \sqrt{2}V_{rms}\sin\omega t + \frac{2\Pi}{3} \tag{9}$$

By using Clarks and Parks transformation theory this three phase voltages are converted into two phase.

$$\begin{bmatrix} V\alpha \\ V\beta \end{bmatrix} = \frac{2}{3}\begin{bmatrix} 1 & -\frac{1}{2} & -\frac{1}{2} \\ 0 & \frac{\sqrt{3}}{2} & \frac{-\sqrt{3}}{2} \end{bmatrix}\begin{bmatrix} Va \\ Vb \\ Vc \end{bmatrix} \tag{10}$$

The instantaneous values of the stator and rotor currents in three-phase system are ultimately calculated by using the following transformation,

$$\begin{bmatrix} ia \\ ib \\ ic \end{bmatrix} = \frac{2}{3}\begin{bmatrix} 1 & 0 \\ -\frac{1}{2} & \frac{\sqrt{3}}{2} \\ -\frac{1}{2} & \frac{-\sqrt{3}}{2} \end{bmatrix}\begin{bmatrix} i\alpha \\ i\beta \end{bmatrix} \tag{11}$$

Based on the above Equations, the torque and rotor speed of induction machine can be determined as follows,

$$Te = 3/2*(P/2)*(\psi_{ds}i_{qs}-\psi_{qs}i_{ds})/\ \omega_b \tag{12}$$

$$\omega_r = \int(P/2*J)(Te-Tl) \tag{13}$$

By using all above Equations mathematical modelling of induction motor is done.The sinusoidally distributed flux density cut the rotor conductors and generates a voltage in conductor. Hence sinusoidally distributed currents generates in the short-circuited rotor bars. Because of the low resistance of these shorted bars, only flux wave and the mechanical angular velocity ω of the two-pole rotor is required to produce the necessary rotor current. The relative angular velocity (ω_r), is called the slip velocity. The interaction of the sinuSsoidally distributed air gap flux density and induced rotor currents produces a torque on the rotor.

3. BASIC DTC SCHEME

The basic concept behind the DTC of AC drive with its conventional block diagram given in Figure 3, as its name states, is to control the electromagnetic torque and flux linkage directly and independently by the use of six or eight voltage space vectors found in lookup Tables.

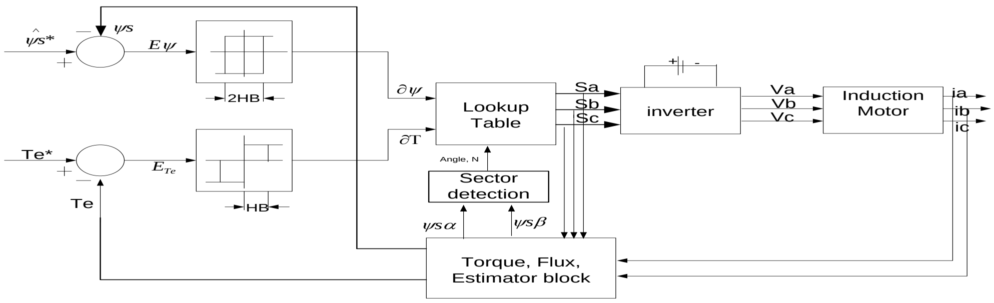

Figure 3. Conventional DTC block diagram.

The classical DTC consist of two hysteresis controllers, one is torque hysteresis controllers and one for flux hysteresis controllers. The hysteresis flux controller causes the stator flux to rotate in a circular manner along the reference trajectory. Thus whole control technique with its basic scheme principle of operation is given in next section.

3.1. Estimation of Flux

The estimation of torque is depending upon load angle, here estimation of flux is done with the help of proper selection of voltage vector. Thus the different voltage vectors with variation of flux linkage. With stator voltage stator flux linkage, Ψ_s position and amplitude can be changed incrementally for small time period T_s. The stator flux linkage of a IM that is revolving in the stationary reference frame is given as,

$$\Psi_s = \int (V_s - R_sI_s)\ dt \tag{14}$$

During the sampling interval $T_s$out of t, the above Equation can be rewrite as,

$$\Psi_s = V_st-R_s\int i_sdt + \Psi_{st}=0 \tag{15}$$

Where Ψ_{st} =0, is stator flux linkage at the time of switching, $V_{s,}$ is the calculated stator voltage, Isis the calculated stator current, and R_s, is the evaluated stator resistance. As stator flux is revolve in direction of applied voltage Vs by neglecting stator quantity of flux given by Figure 4.

$$\Delta\Psi_s = V_s\Delta t \quad (16)$$

The value of amplitude of stator flux linkage is controlled by voltage vectors in d-q plane.

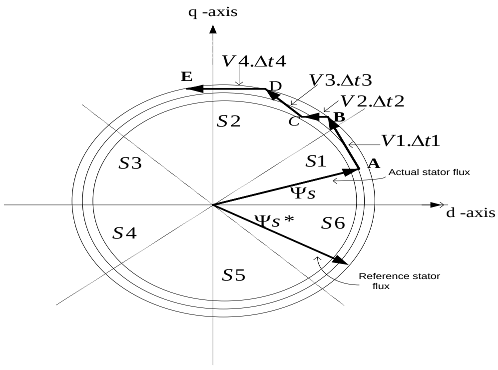

Figure 4. Trajectory of stator flux vector in DTC control

3.2. Control strategy of DTC

The commands of stator flux $\boldsymbol{\psi_s^*}$ and torque T_e^* magnitudes are compared with respective estimated values, and the errors are proceeded through hysteresis-band controllers, as shown. The flux hysteresis controller has two level digital outputs and torque hysteresis controller has three level digital outputs. Where, 2= HBψ, total hysteresis bandwidth of controller.

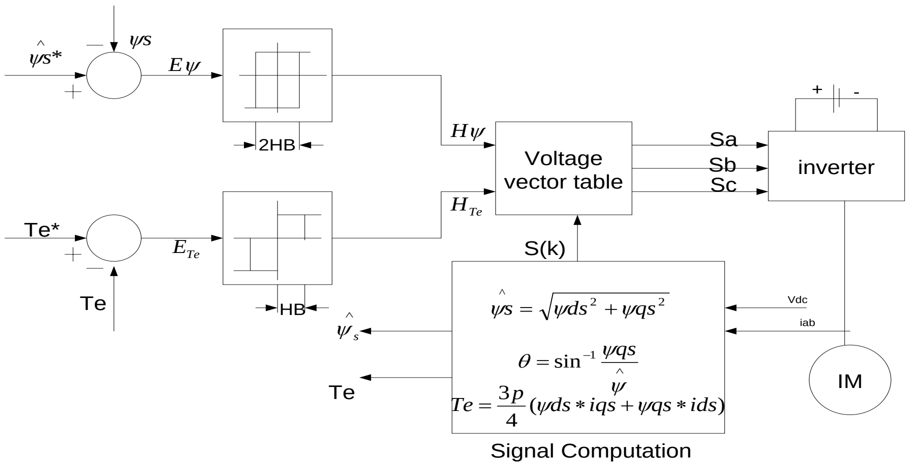

Figure 5. DTC control scheme

3.3. Flux Estimator

Now that the current, $i_{\alpha\beta,}$ is known, the signal continues into the flux estimator. Into this block also enters the VSI voltage vector transformed to the αβ –stationary reference fram. The dq-voltage Equation with zero components left is,

$$Vdq = Rs\ idq + \omega r \begin{pmatrix} -\Psi q \\ \Psi d \end{pmatrix} + \frac{d}{dt}\Psi dq \quad (17)$$

One can directly obtain a mean for stator flux estimation by noting that w_r= 0 and rearranging the terms,

$$\Psi\alpha\beta = \int(v\alpha\beta - Rs\ i\alpha\beta)dt \tag{18}$$

This formula is the foundation of implementing the flux estimator.

3.4. Torque Estimator

The torque in the induction motor drive reference frame is given by,

$$T_e = (3/4)\ P\ (\Psi_d i_q - \Psi_q i_d) \tag{19}$$

This is true for all dq-reference frames. The torque in induction motor is estimated from the calculated currents and fluxes in the stationary αβ reference frame. To calculate torque one only has to substitute the corresponding already calculated fluxes and currents. Torque calculation is thus a simple operation.

3.5. Voltage Vector Selection in DTC IM Drive

In a DTC scheme it is possible to reconstruct those voltages from the DC-link voltage, V_{dc}, and the switching states ($S_a\ S_b S_c$) of a six-step voltage source inverter (VSI) rather than monitoring them from the motor terminals. The primary voltage vector, V_s, is defined by the following equation,

$$\overline{Vs} = \frac{2}{3}Vdc\ (Sa + Sb\ e^{j\frac{2\pi}{3}} + Sc\ e^{j\frac{4\pi}{3}}) \tag{20}$$

Where $V_{a,}$ V_b and V_c are the instantaneous values of the primary line-to-neutral voltages The values of voltages are find out with ON and OFF of switches.

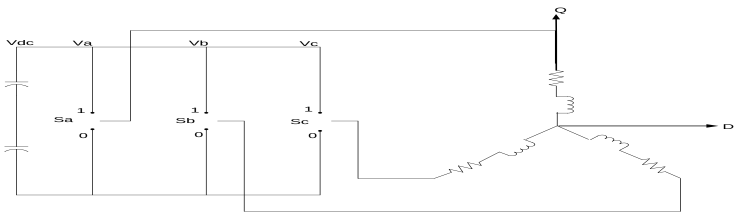

Figure 6. Voltage source inverter connected to RL load

The ψ and τ are signals from hysteresis controllers for flux and torque, respectively, and θ(1)–θ(6) are the sectors. Flux controller and torque controller are of two level and three level respectively. If ψ = τ= 1, that mean it is smaller than its reference value and or vice versa. If ψ = τ= 0, its actual value is greater than reference. Thus with the help of states of switches and flux and torque command voltage vector is selected by Table 1.

Table 1. Switching table for inverter voltage vector

HΨ	Hτ	Sector					
		θ(1)	θ(2)	θ(3)	θ(4)	θ(5)	θ(6)
Ψ=1	1	V_2(110)	V_3(010)	V_4(011)	V_5(001)	V_6(101)	V_3(010)
	0	V_7(111)	V_0(000)	V_7(111)	V_0(000)	V_7(111)	V_0(000)
	-1	V_6(101)	V_1(100)	V_2(110)	V_3(010)	V_4(011)	V_5(001)
Ψ=0	1	V_3(010)	V_4(011)	V_5(001)	V_6(101)	V_1(100)	V_2(110)
	0	V_7(111)	V_0(000)	V_7(111)	V_0(000)	V_7(111)	V_0(000)
	-1	V_5(001)	V_6(101)	V_1(100)	V_2(110)	V_3(010)	V_4(011)

4. STEADY STATE PERFORMANCE DEGRADATION OF DTC IM DRIVE

With DTC, the stator flux magnitude and torque of IM drive are controlled differently in steady as well as transient state. The drive performance degrades with any error in model parameter (stator resistance) or voltage and current transduction. Various errors causes degradation of DTC IM drives are, Stator Resistance Mismatch, Offsets, Gain error and Unbalances in gain.

Mismatch in the stator resistance is essentially due to the resistance variations during IM operation because of the motor heating. As continuous operation of motor means variation in temperature and frequency of stator. Resulting error in estimated values of stator flux and torque of motor. Our main focus is on stator resistance mismatch due to heating of motor. Stator resistance PI compensator scheme is adopted and briefly given in next section.

4.1. Effect of Variation in Stator Resistance on DTC

In DTC IM system continuous operation of motor leads to motor heating. As if motor temperature increases, it results in two influences happen to change the division of the given d-axis voltage,

a. With the presence of rotor circuit coupling increases in the rotor resistance do not reproducing theslipofthe machine increases q-axis stator flux. Increases and
b. Greater the stator resistance results in increasing the resistive voltage drop. Both add to disquieting the flux current (id).

In general, variation in stator resistance during induction motor operation is,

$$\widetilde{Rs} = Rs - \Delta Rs \tag{21}$$

Where,$\widetilde{Rs}$ the stator resistance of the model, ΔRs is error and Rs is actual value. Stability can be achieved by using smaller value of the stator resistance in controller than its real value. The parameter mismatch between the controller and machine also results in a nonlinear linearity between torque and its reference. Therefore motor resistance adaptation is necessary to avoid instability and to give security of getting a linear torque amplifier in the direct torque controlled drive. To eliminate this stator resistance PI compensator scheme is adopted and given in next section.

4.2. Stator Resistance PI Compensator scheme

In DTC of induction motor, it is shown that if stator flux and motor torque be equal to their reference values, the magnitude of the stator current vector is a constant value that can be calculated with these reference values and motor parameters by using dynamic model and its equations as,

$$\overline{\iota s^*} = \sqrt{((ids^*) + (\lambda qs^{*2}))} \tag{22}$$

The stator feedback current phasor magnitude obtained from the q and d axis measured currents as,

$$is = \sqrt{iqs^2} + \sqrt{ids^2} \tag{23}$$

The variations of the stator resistance change the flux and torque of the motor which leads to variations of the stator current vector magnitude.

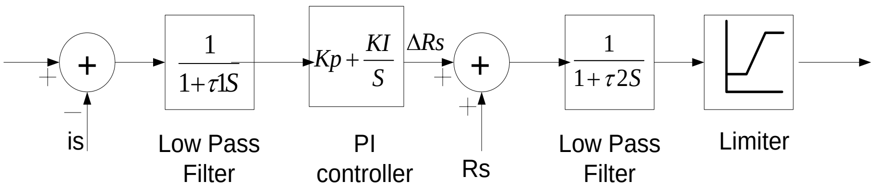

Figure 7. Stator Resistance PI Compensator

This method is based on the theory that the error between the calculated stator feedback current phasor magnitudes i_s and its command i is proportional to the stator resistance change which is results of variation in motor temperature and to a quite amount by the varying stator frequency. The incremental value of stator resistance for improvement is found out through a PIcontroller and limiter. With low pass filter adaption of stator resistance is simple with consideration, is that the filter time constant value must be smaller than that of the adaptation time constant.This stator resistance variation, ΔR_S, continuously is added to the previous estimated resistance value R_{so}. The final estimated value, R_s, is obtained as the output of another low pass filter and limiter.

5. MATLAB Implementation & Results

5.1. Modeling of Stator Resistance PI Compensator:

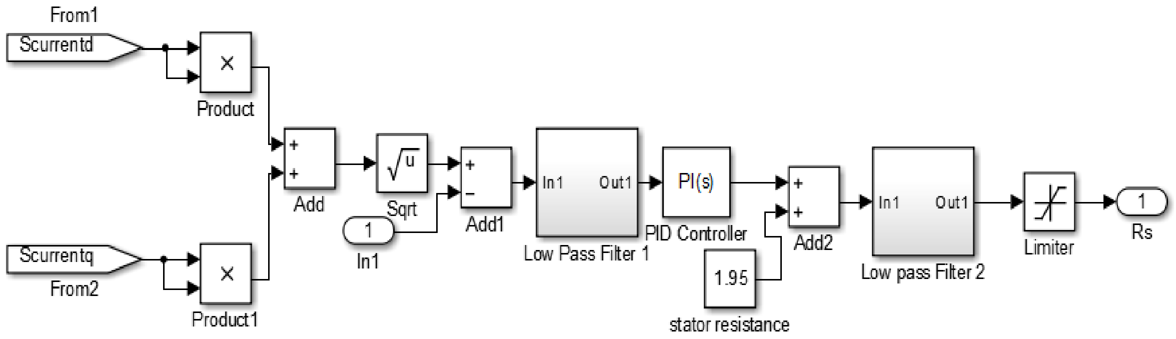

Figure 8. Implementation of stator resistance PI compensator

5.2. Modeling of DTC-SVM for Induction Motor With PI compensator

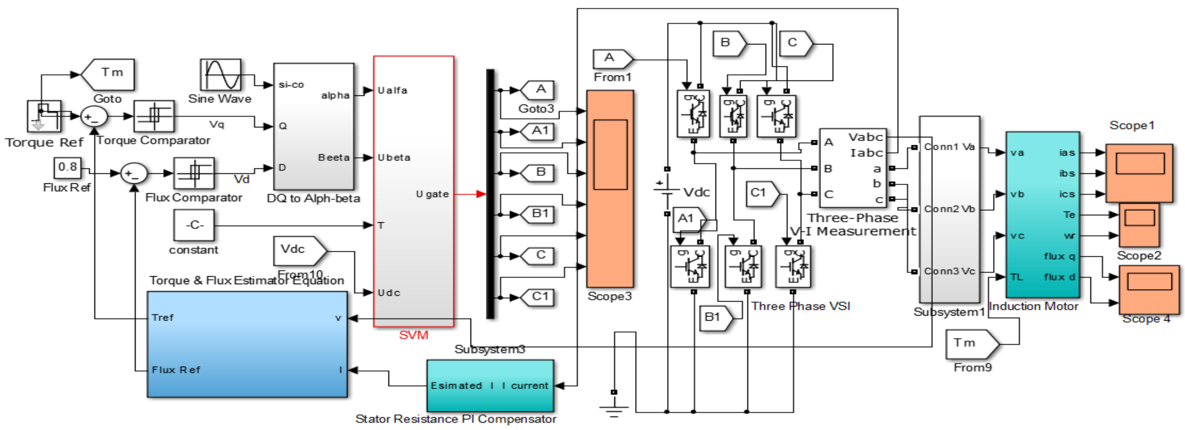

Figure 9. Simulink model of DTC IM Drive with stator resistance PI compensator

5.3. Simulation results of IM Drive fed with inverter using PWM

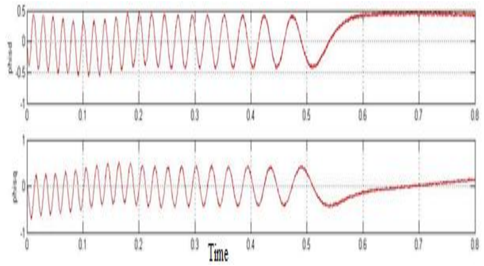

Figure 10. Stator flux of DTC IM drive with PWM

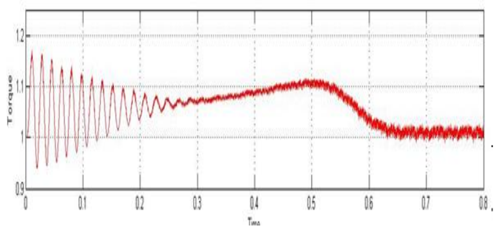

Figure11. Electromagnetic Torque (N-m) of DTC IM drive with PWM

5.4. Simulation results of DTC IM drive without stator resistance PI compensator

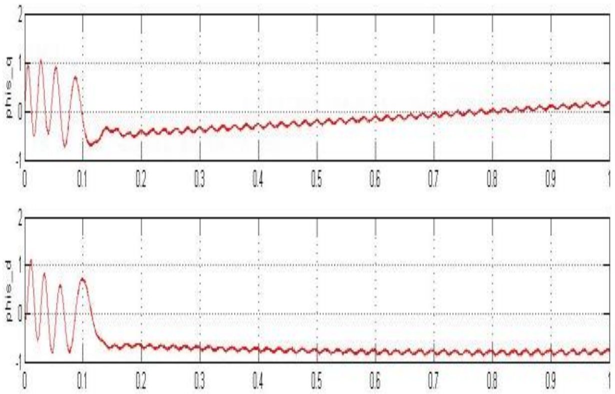

Figure 12. Stator flux of DTC IM drive without PI

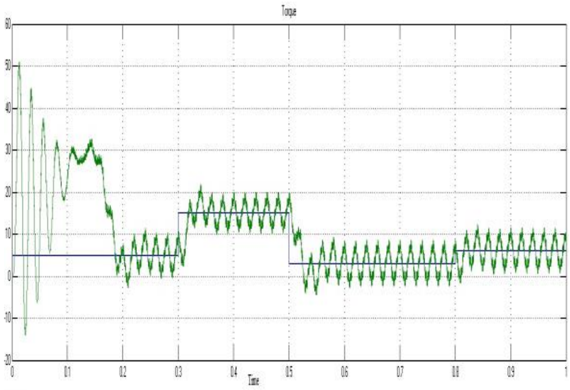

Figure 13. Electromagnetic Torque (N-m) (For variable load) of DTC IM drive without PI

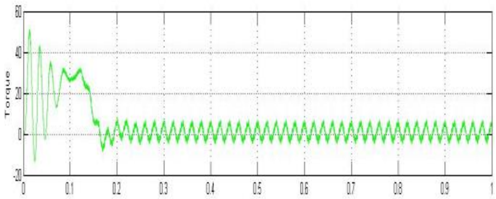

Figure14. Electromagnetic Torque (N-m) (For constant load) of DTC IM drive without PI

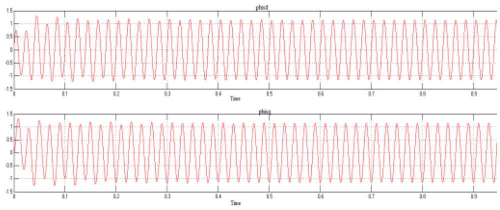

Figure 15. Stator flux of DTC IM Drive with PI

5.5. Simulation Results of DTC IM drive with stator resistance PI compensator

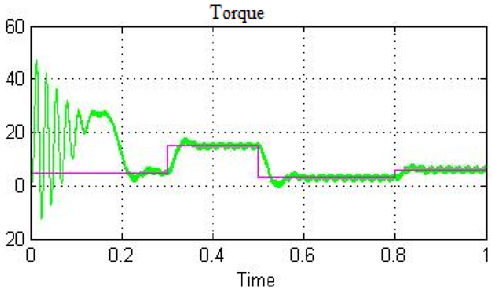

Figure 16. Electromagnetic Torque (N-m) (for variable load) of DTC IM Drive with PI

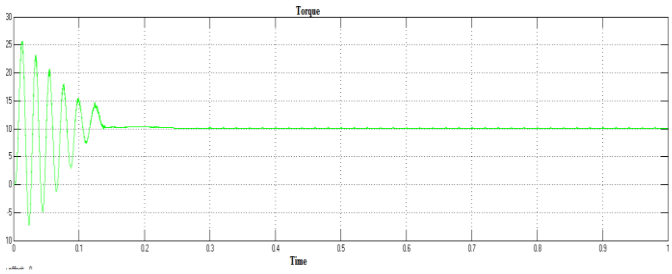

Figure 17. Electromagnetic Torque (N-m) (for constant load) of DTC IM Drive with PI

6. CONCLUSION

In this paper, the stator resistance variation issue of the DTC induction motor drive system has been examined. The unstable operation due to the stator resistance over-estimation has also been observed. An improved PI stator resistance estimator for a DTC induction motor drive has been proposed. In fact, simulation results show that there is an error between the filtered stator current magnitude and its estimated value from the dq model of the induction motor, which decreases the performance of the stator resistance estimation by a conventional PI controller.So, an offset has been introduced in order to overcome this situation and improve accuracy of the PI estimator. The effectiveness of the proposed PI stator resistance estimator was shown and simulation results proved its excellent tracking capability, in both cases of increase and decrease of the actual stator resistance. This accuracy improvement of the stator resistance estimation will be important in the case of high power DTC drives with high levels of voltage and current and low switching frequency of the PWM inverter.

ACKNOWLEDGEMENTS

The athors would like to thanks G. H. Raisoni College of Engineering, Nagpur for their kind co-operation and providing lab facility for doing research work in Electrical Drives & Control area.

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