Vector Controlled Sensorless Estimation and Control of Speed of Induction Motors

Gayatri Gite

Electrical Engineering Department
SSSIST Sehore
Bhopal, India

Prabodh Khampariya

Electrical Engineering Department
SSSIST Sehore
Bhopal, India

---***---

Abstract - *In this paper, speed estimation of vector controlled induction motor drive based on Model Referencing Adaptive Controller (MRAC) is represented. Requirement of no additional sensors makes the drive suitable for retrofit applications. It do not require computation of fluxes and uses both voltage and current in rotating reference frame. MRAC is formed using instantaneous and steady-state values. This makes the drive stable in all four quadrants of operation. This method is simulated in MATLAB/SIMULINK.*

Key Words: **Induction Motor, MRAC, Sensorless Drive, Stator Resistance Estimation, Vector Control, Model reference Adaptive System.**

1. INTRODUCTION

The induction motors are relatively cheap and rugged machines because their construction is realised without slip rings or commutators. Controlling the speed of Induction Motor is far more difficult than controlling the speed of DC motor since there is no linear relationship between the motor current and resulting torque as there is for a DC motor. The control system of the drive calculates the corresponding current component references from the flux and torque references given by the drive's speed control. The technique called Vector Control can be used to vary the speed of an Induction Motor over a wide range. The Vector controlled induction motor (IM) drive is widely used in high performance industrial applications since it is simple and provides fast dynamics. Vector control, also called field-oriented control (FOC), is a variable-frequency drive (VFD) control method in which the stator currents of a three-phase AC electric motor are identified as two orthogonal components that can be visualized with a vector. This control is strongly influenced by the machine parameters variation. In these schemes both torque and rotor flux, are controlled by decomposing the stator current.The implementation of the vector control scheme requires the knowledge of the rotor speed and other machine parameters. In this area, the use of extended Kalman filter is popular due to its robustness and the need of reduced numbers of PI controllers. Finally, a combination of well-known open loop observers, voltage model and current model, is used to estimate the rotor flux and rotor flux angle which are employed in direct field orientation. The motor is initially made to rotate in the clockwise direction and when the speed reversal command is obtained, the control goes into clockwise regeneration mode which brings the rotor to standstill position. Hall Effect sensors are used to obtain the rotor position and from the hall sensor outputs it is determined whether the machine has reversed its direction which is the ideal moment for energizing the stator phase so that machine can start motoring in the counter clockwise direction.
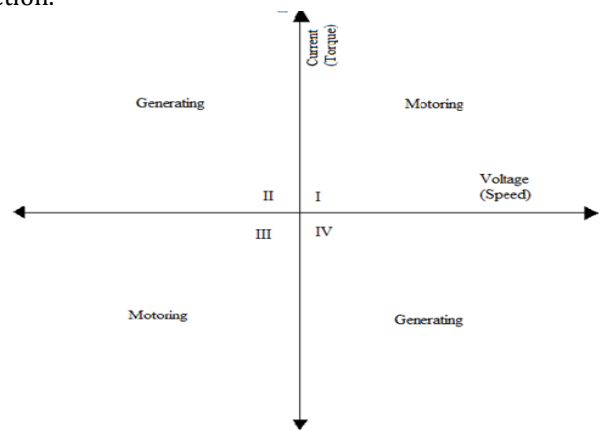

Fig. 1 Four quadrants of operation

Different techniques for estimation of speed for IM drive are available. These are mainly classified as:

 (i) Rotor flux based,
(ii) Frequency signal injection based,
(iii)Artificial Intelligence,
(iv)Observer based,
(v)Artificial Intelligence (AI) based,
(vi) Rotor slot harmonics based, and
(vii)Model Reference Adaptive Controller (MRAC) based.

Among all these methods, MRAC is simple, requires less computation time and has good stability.MRAC is stable in all the four quadrants, operates very well at low speed including zero speed, does not require flux computation and very easy to implement. However, the pure-integrator (which is used in the voltage model of F-MRAC) related problems are the major drawback of the F-MRAC. The pure-integrator is replaced by a low-pass filter (LPF). Back-emf-based MRAC also suffers from the deteriorating performance at low speed due to the presence of derivative operator, which lowers the signal-to-noise ratio. A reactive power-based MRAC overcomes all such problems.

The influence of noise characteristic, the absence of criteria for tuning, and the computational burden of this stochastic observer are major limitations for wide acceptability. The use of LPF introduces gain and phase angle error in the flux estimation below cutoff frequency of the filter. The major drawback of using rotor flux as functional candidate is the presence of integrator which makes it unattractive for operation at near zero speeds. The speed estimation algorithm (i.e., speed estimating MRAS) depends on stator resistance making it sensitive to stator resistance variation. This is compensated by another MRAC making the speed estimation algorithm independent of stator resistance. The proposed method is simulated in MATLAB/SIMULINK and simulation results are obtained.

1.1 Speed Estimation

The structure of such MRAC for speed estimation is shown in Fig. 1. Selection of _$v \times i$_ is a major success in the sense that the proposed system is now stable in all the four quadrants modes of operation. This cross product is denoted by X, which is neither active power nor reactive power. It can be clearly seen that at no-load condition i.e. when isq=0, X-MRAS becomes independent of stator resistance. Therefore, injecting only a small amount of d-axis current is not sufficient for speed estimation; a sufficient amount of q-axis current is required for estimation of stator resistance.
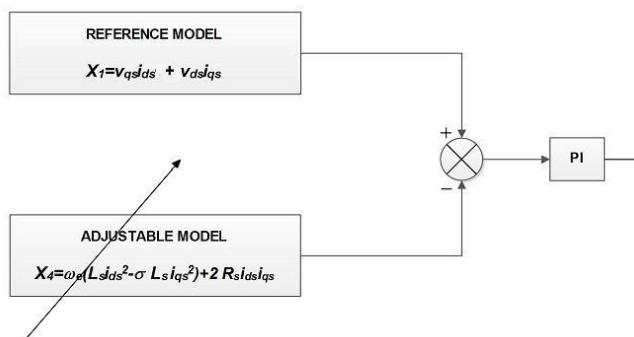

Fig. 2 Speed Estimation Based on MRAC

Instantaneous value of X (i.e.,_$v \times i$_) is known as,

$$X_1 = vsq*isd + vsd*isq \qquad \text{……….…………} (1)$$

The stator voltages of induction motor in the synchronously rotating reference frame are,

$$Vsq = Rsisq + \omega e \sigma Lsisd + p\sigma Lsisq + Lm/Lr(\omega e\psi rd + p\psi rq) \tag{2}$$

$$Vsd = Rsis\, d - \omega e \sigma Lsisq + p\sigma Lsisd - Lm/Lr(\omega e\psi rq - p\psi rd) \tag{3}$$

Inserting Eq^n (2) & (3) in Eq^n (1), we get X as,

$$X2 = [Rsisq + \omega e\sigma Lsisd + p\sigma Lsisq + Lm/Lr (\omega e\psi rd + p\psi rq)] isd + [Rsisd - \omega e\sigma Lsisq + p\sigma Lsisd. - Lm/Lr (\omega e\psi rq - p\psi rd)] isq \tag{4}$$

At Steady state it becomes,

$$X3 = [Rsisq + \omega e\sigma Lsisd + Lm/Lr (\omega e\psi rd)] isd + [Rsisd - \omega e\sigma Lsisq - Lm/Lr (\omega e\psi rq)]isq \tag{5}$$

For a rotor flux-oriented drive, substituting $\psi rd = Lmisd$, and $\psi rq = 0$, the simplified expression of X becomes X_4 , i.e.,

$$X4 = \omega e\, [Lsi^2sd - \sigma Lsi^2sq] + 2R_si_{sd}i_{sq} \tag{6}$$

The expression of X_1 is selected as a reference model and od X_4 is selected as a adjustable model as it does not involve flux estimation and any derivative operations but it is dependent on rotor speed unlike X_1.

1.2 MRAC Based Speed Estimation using MATLAB Simulation

Estimation is carried out using the terminal voltages and currents which are readily available using sensors. Sensor less vector control induction motor drive essentially means vector control without any speed sensor. A classical rotor-flux-based MRAC estimator is sensitive to motor parameter changes due to the high sensitivity of rotor flux current and voltage models used for rotor flux vector estimation. If speed signal is available from speed encoder, the X-MRAC can also be used for stator resistance estimation. The stator currents are sensed and then transformed from abc to synchronously rotating frame quantities (d-q),ids and iqs, which are the feedback stator currents to current controllers. Using these voltages and currents in synchronously rotating frame rotor speed is estimated and stator resistance, Rs is updated each time during estimation of rotor speed The X-MRAC can also be used for stator resistance estimation, if speed signal is available from speed encoder. To replace the sensor the information on the rotor speed is extracted from measured stator voltages and currents at the motor terminals. The complete system shown in Fig.3 is simulated in Matlab/Simulink and this section presents the simulation
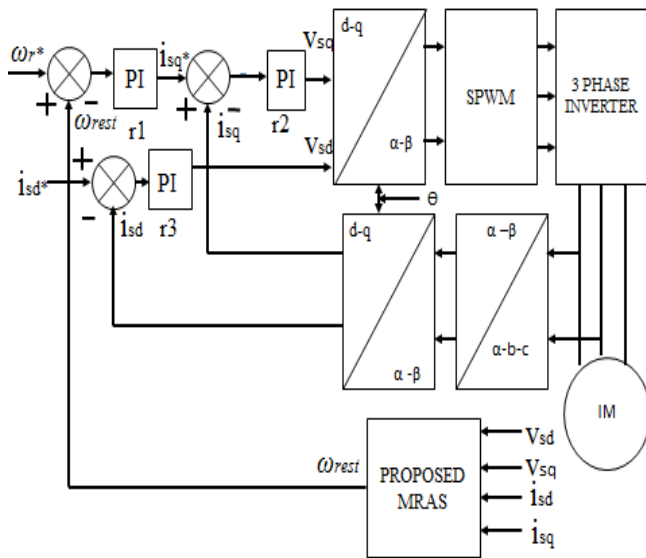
results.

Fig.3 Vector Control Drive with the proposed X-MRAC

The algorithms have been found to be stable in all the four quadrants of operation. The vector controlled induction motor drives are easily adoptable to algorithm. The X-MRAC can also be used for stator resistance estimation, if speed signal is available from speed encoder. For the stability analysis, the investigation is carried out around a nominal speed, and the dynamics for the mechanical equations for a perturbation of $\Delta\omega r$ is neglected as the mechanical time constant is much larger than the electrical time constant. Ensuring the ablity of the system to reach or cross the chosen sliding line is the next stage of a control algorithm. With the correct value of rotor speed, the fluxes determined from the two models should match. The simulation of sensorless speed control of Induction Motor is done by using MATLAB/SIMULINK. we can get the expressions of $\Delta isd/\Delta\omega r$ and $\Delta isq/\Delta\omega r$. The X-MRAC error ε is given by,

$\varepsilon = X1 - X4$ ....(7)

$\varepsilon = vsqisd + vsdisq - \omega e[Lsi2sd - \sigma Lsi2sq] - 2Rsisdisq$......(8)

Considering the perturbed signals, $\Delta\varepsilon$ can be expressed as,

$\Delta\varepsilon = K2\Delta isd + K3\Delta isq + k4\Delta\omega sl + k5\Delta\hat{\omega}r$ ....(9)

where

$K2 = vsqisq0 - 2Rsisq0 - 2Ls\omega e0isd0 - r3isq0$

$K3 = vsdisd0 - 2Rsisd0 + 2\sigma Ls\omega e0isq0 - r2isd0,$

$K4 = (\sigma Lsi2sq0 - Lsi2sd0)$

$K5 = \sigma Lsi2sq0 - Lsi2sd0 - r1r2isd0.$

Any small increase in the estimated rotor speed ($\hat{\omega}r + \Delta\hat{\omega}r$) leads to decrease of the slip speed ($\omega sl - \Delta\omega sl$). If it

is assumed that the speed of the rotor flux (i.e., ωe) remains the same after the perturbation, then

$\Delta\hat{\omega}r = -\Delta\omega sl$ ....(10)

Substituting Eqn (10) in Eqn(9)

$\Delta\varepsilon = K2\Delta isd + K3\Delta isq + (k5 - k4)\Delta\hat{\omega}r$

Dividing both sides by $\Delta\hat{\omega}r$

$\Delta\varepsilon/\Delta\hat{\omega}r = K2\Delta isd/\Delta\omega r + K3\Delta isq/\Delta\omega r + (k5 - k4) = G(s)$ ....(11)

Using Eqn (11), the stability is checked for many operating points in the speed-torque domain. The parameters of the machine are given in the Table I :

INDUCTION MACHINE RATINGS AND PARAMETERS		
Symbol	**Meaning**	**Value**
-	Rated Shaft Power	1.3 kW
-	Line to Line Voltage	400 V
-	Rated Speed	1430rpm
P	Pole Pair	2
Ls	Stator Self Inductance	0.6848 H
Lr	Rotor Self Inductance	0.6848 H
Lm	Magnetising Inductance	0.6705 H
Rs	Stator Resistance	5.71Ω
Rr	Rotor Resistance	4.0859Ω
J	Machine Inertia	0.011Kg-m2

2. RESULTS

The simulation of sensorless speed control of Induction Motor is done by using MATLAB/SIMULINK. The usefulness of the proposed algorithms has been confirmed through stabilitystudy (small signal analysis in state space m domain), simulation (in MATLAB/SIMULINK), and experiments. The proposed MRAC-based speed estimation algorithm is experimentally verified using a laboratory developed prototype, built around a dSPACE-1104 controller. The results for different cases are given below.
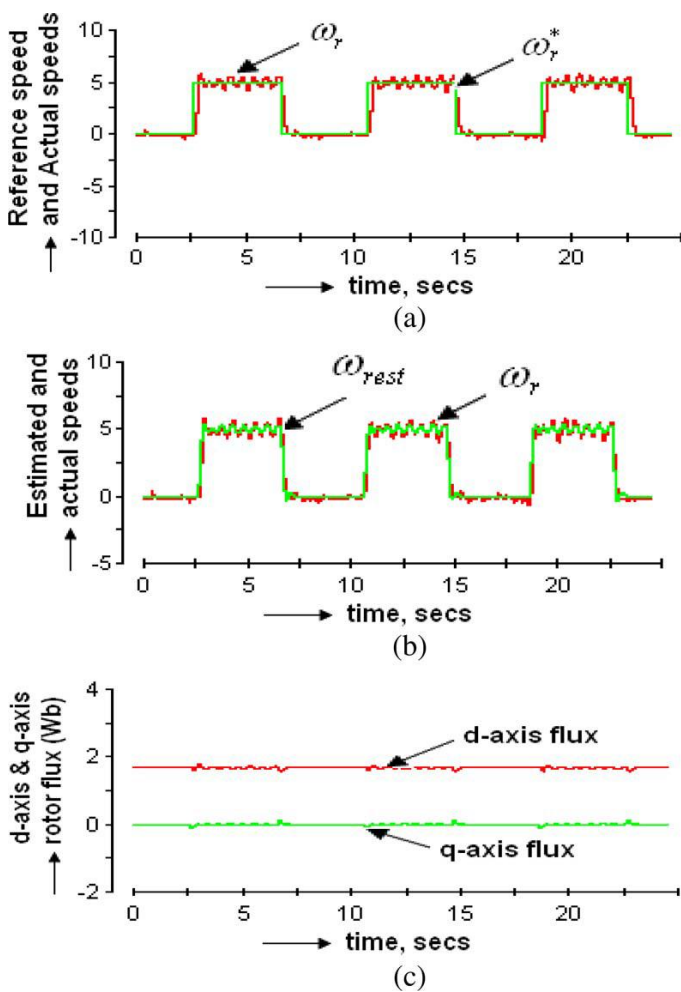
Fig. 4. (a) Reference speed and actual speed [rad/s] versus time [s].

(b) Actual speed and estimated speed [rad/s] versus time [s].

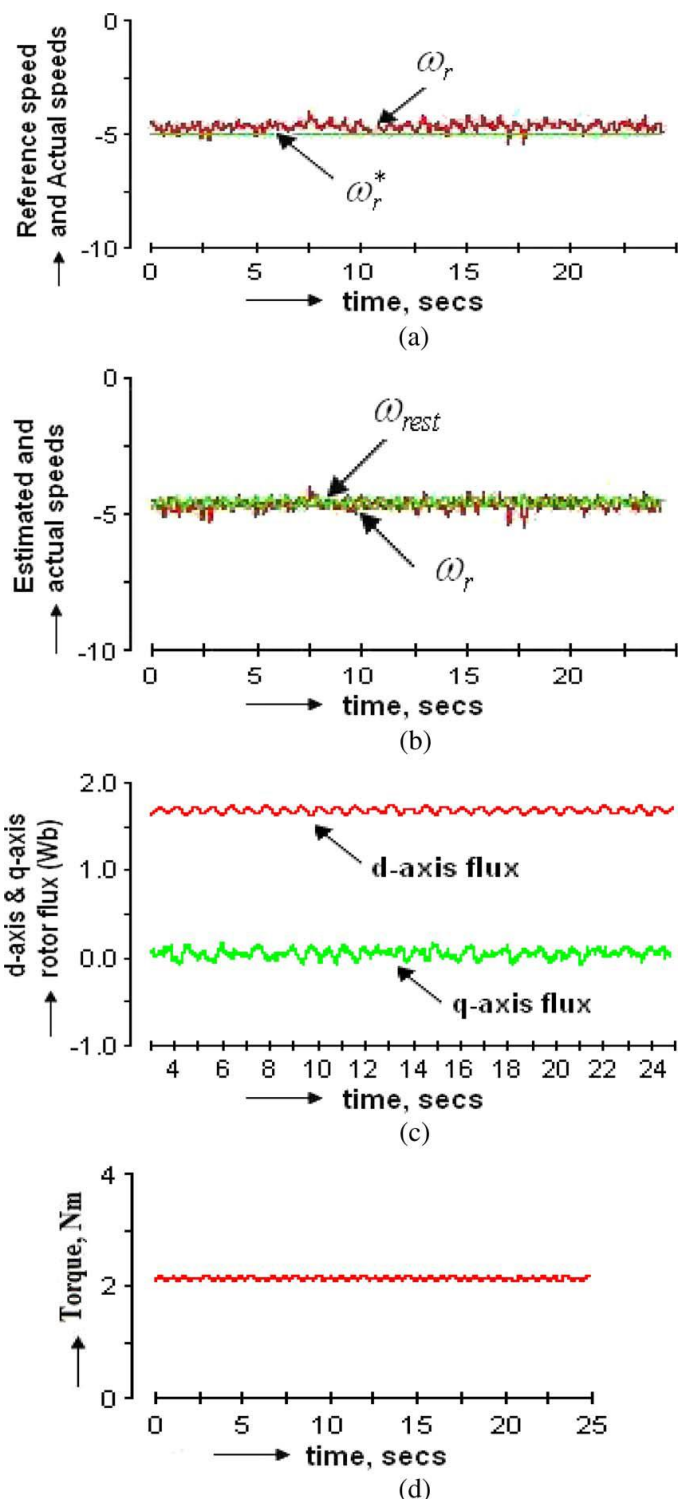(c) d-axis and q-axis rotor flux [Wb] versus time [s].

Fig. 5. (a) Reference speed and actual speed [rad/s] versus time [s].

(b) Actual speed and estimated speed [rad/s] versus time [s].

(c) d-axis and q-axis rotor flux [Wb] versus time [s].

(d) d-axis and q-axis rotor flux [Wb] versus time [s].

A. Step Change of Rotor Speed and Zero Speed Operation

The response of the induction motor for step change and zero speed operation are shown in Fig. 4. A step change in speed of 5 rad/s is applied every 4 s from 0 rad/s and the actual speed is found to track the reference speed [Fig. 4(a)] satisfactorily. The estimated speed is very close to the actual rotor speed [Fig. 4(b)]. Flux orientation is well maintained as depicted in Fig. 4(c). The load applied to the motor is through a DC generator as detailed in simulation.

B. Regenerative Mode Operation

Simulation (Section IV) and stability study (Section III) have confirmed that the drive is stable in all the four quadrant modes of operation. Here, the same is verified through experiments for an operating point, which is located in the second quadrant. Load torque is applied through a DC motor which drives the induction machine. The torque generated by the induction machine is shown in Fig. 5(d). A reference speed of –5 rad/s is applied to the machine [Fig. 5(a)]. Hence, the induction machine is now running in second quadrant (regenerating mode). The estimated and actual speeds of the machine are observed in Fig. 5(b) which shows that the proposed MRAC can estimate the rotor speed satisfactorily even in the regenerating mode of operation. The flux orientation is available in Fig. 5(c).
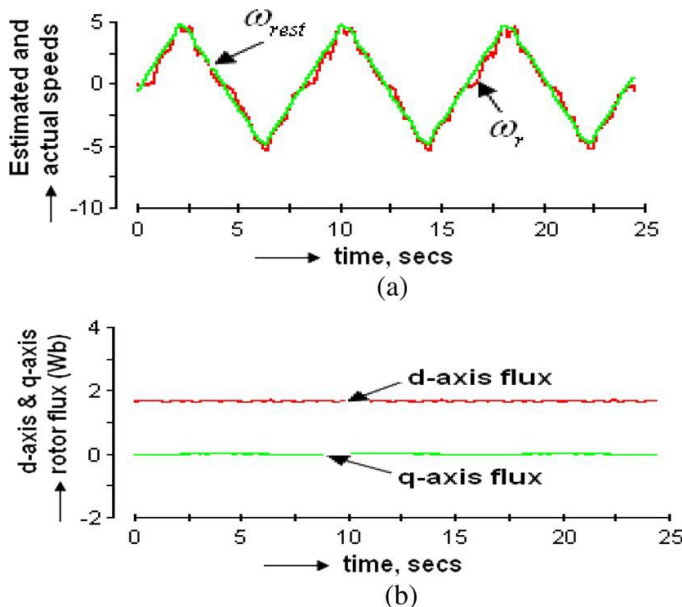

(a)

(b)

Fig. 6. (a) Actual speed and estimated speed [rad/s] versus time [s].

(b) d-axis and q-axis rotor flux [Wb] versus time [s].

C. Response to Ramp Command in Speed

The performance of the algorithm for a ramp command in speed reference is shown in Fig. 6. The estimated speed is matching with the actual speed, as shown in Fig. 6(a). The flux orientation is not disturbed, as observed in Fig. 6(b).

This validates the proposed speed estimation algorithm experimentally making it suitable for low speed applications.
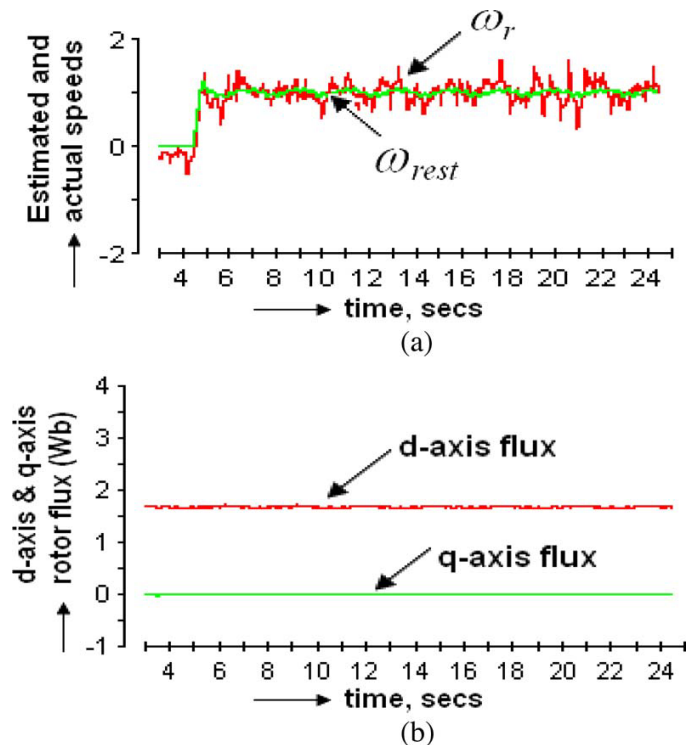

(a)

(b)

Fig. 7. (a) Actual speed and estimated speed [rad/s] versus time [s].

(b) d-axis and q-axis rotor flux [Wb] versus time [s].

D. Low Speed Operation

The hardware result corresponding to the operation of the proposed controller at 1 rad/s reference can be seen from Fig.7(a) which shows that the estimated speed matches with the actual speed satisfactorily. The flux is oriented as seen from Fig. 7(b).

3. CONCLUSIONS

The principle of Sensorless control of induction motor is given elaborately. This paper has presented X-MRAC based speed estimation with stator resistance updation.The X-MRAC based speed estimation technique is stable in all four quadrants of operation suitable for low speed and zero speed operation. This is confirmed for an X-MRAS based speed sensorless drive. Extensive simulation in MATLAB/SIMULINK is carried out to validate the proposed technique. Computation of flux is no longer required.

References

[1] A.V Ravi Theja. C.Chakraborty, Suman Maita, and Y.Hori, "A New *V* x *I.* Adaptive Speed Sensorless four quadrant vector controlled induction motor drive,"*IEEE International Power Electronics Conference*2010.

[2] R. Verma, V. Verma, and C. Chakraborty, "Ann based sensorless vector controlled induction motor drive suitable for four quadrant operation", *in Students' Technology Symposium (TechSym*), IEEE, 2014, pp. 182-187.

[3] B..Karanayil, M.F.Rahman, and C. Grantham; "Online Stator and Rotor Resistance Estimation Scheme Using Artificial Neural Networks for Vector Controlled Speed Sensorless Induction Motor Drive"; *IEEE Transactions on Industrial Electronics*, Vol. 54, No. 1, pp. 167-176,February 2007.

[4] Orłowska-Kowalska T., Dybkowski M., *Stator Current-based MRAS Estimator for Wide Range Speed-Sensorless Induction Motor Drive*, IEEE Trans. on Industrial Electronics, 2010, Vol. 57, No. 4, pp. 1296–1308.

[5] L. Zheng, J. E. Fletcher, B.W.Williams, and X. He, "A novel direct torque control scheme for a sensorless five-phase induction motor drive," *IEEE Trans. Ind. Electron.*, vol. 58, no. 2, pp. 503–513, Feb. 2011.

[6] B. K. Bose, "*Modern Power Electronics and AC Drives*."; Englewood Cliffs, NJ: Prentice-Hall, 2002.

[7] E. Levi, M. Wang, "Impact of parameter variations on speed estimation in sensorless rotor flux oriented induction machines,"

[8]S.MaitiandC.Chakraborty,"Anewinstantaneousreactivepo werbasedMRASforsensorlessinductionmotordrive,"*Simul.Mo dell.Pract.Theory*,vol.18,no.9,pp.1314–1326,Oct.2010J.

[9] P.Zhang, Bin Lu, and T.G. Habetler; "A Remote and Sensorless Stator Winding Resistance Estimation Method for Thermal Protection of Soft-Starter-Connected Induction Machines"; *IEEE Transactions on Industrial Electronics*, Vol. 55, No. 10, Pp. 3611-3618, October 2008