A New Model Reference Adaptive Formulation to Estimate Stator Resistance in Field Oriented Induction Motor Drive

Saptarshi Basak[1], Chandan Chakraborty[1], *Senior Member IEEE* and Yoichi Hori[2], *Fellow IEEE*
1 Department of Electrical Engineering, Indian Institute of Technology Kharagpur, India
2 Department of Advanced Energy, Graduate School of Frontier Sciences, University of Tokyo, Japan

***Abstract*— A novel model reference adaptive system based stator resistance estimation algorithm has been proposed in this paper. A new functional candidate has been introduced which is positive definite and does not depend on speed information for resistance estimation. This makes the formulation very effective for X-MRAS based speed sensorless drive as the tuning for speed and stator resistance may now be done in a decoupled manner. Extensive simulation using MATLAB/SIMULINK has confirmed the effectiveness of the proposed technique.**

Keywords—Stator Resistance Estimation, MRAS, Sensorless Drive, Induction Motor, Vector Control

List of Symbols:

$\bar{v}_s$	Stator voltage space vector
$\bar{\imath}_s$	Stator current space vector
v_{sd}, v_{sq}	d-axis and q-axis component of stator voltage
i_{sd},i_{sq}	d-axis and q-axis component of stator current
ψ_{rd}, ψ_{rq}	d-axis and q-axis component of rotor flux
ω_e	Speed of rotating reference frame
ω_{sl}	Slip speed
ω_m	Rotor Speed in mech. rad/s.
L_s,L_r	Stator and Rotor Self Inductance Per Phase.
R_s,R_r	Stator and Rotor Resistance Per Phase.
σ	Leakage Factor
L_m	Magnetizing Inductance

I. INTRODUCTION

Field Oriented Control has become a standard technique for the control of a symmetrical AC Machine. The major advantage of a vector-controlled drive is to provide fast dynamics in terms of the torque response as the independent control of flux and torque can be achieved. However, the major bottleneck of a vector controlled drive is the requirement of a flux observer. In case of direct or feedback vector controlled drive, the control is dependent on stator resistance [1]. Therefore, for perfect decoupling of flux and torque, estimation and compensation for these parameter variations is necessary as shown in [2]. Also, for certain speed sensor-less drives, the estimation technique is dependent on plant parameters. In such cases, compensation for variation of these parameters is an absolute necessity. Not only for control or estimation in drives, non-invasive methods of winding temperature estimation using stator resistance identification has been found to be very reliable [3].

Various methods for stator resistance estimation are available in literature. The estimation algorithms can be broadly classified into model-based, stochastic observer based, Artificial Intelligent (AI) (like ANN, Quasi Fuzzy, PSO) based methods are available in literature [4-5]. These techniques are computationally intensive. AI based methods require training and consideration of a rule base.

Compared to all other methods, Model Reference Adaptive Systems (MRAS) based estimation is computationally less intensive and is simple to implement. If we consider stator resistance estimation techniques based on MRAS, several methods are also proposed in literature. The authors use rotor flux as a functional candidate for stator resistance estimation in [6]. 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. As a result, other methods based on active power and fictitious quantity 'X' have been proposed to identify stator resistance [7-8]. All the stator resistance estimation algorithm proposed so far require speed information. In this paper, a novel functional candidate is introduced which requires only voltage and current information for R_s estimation.

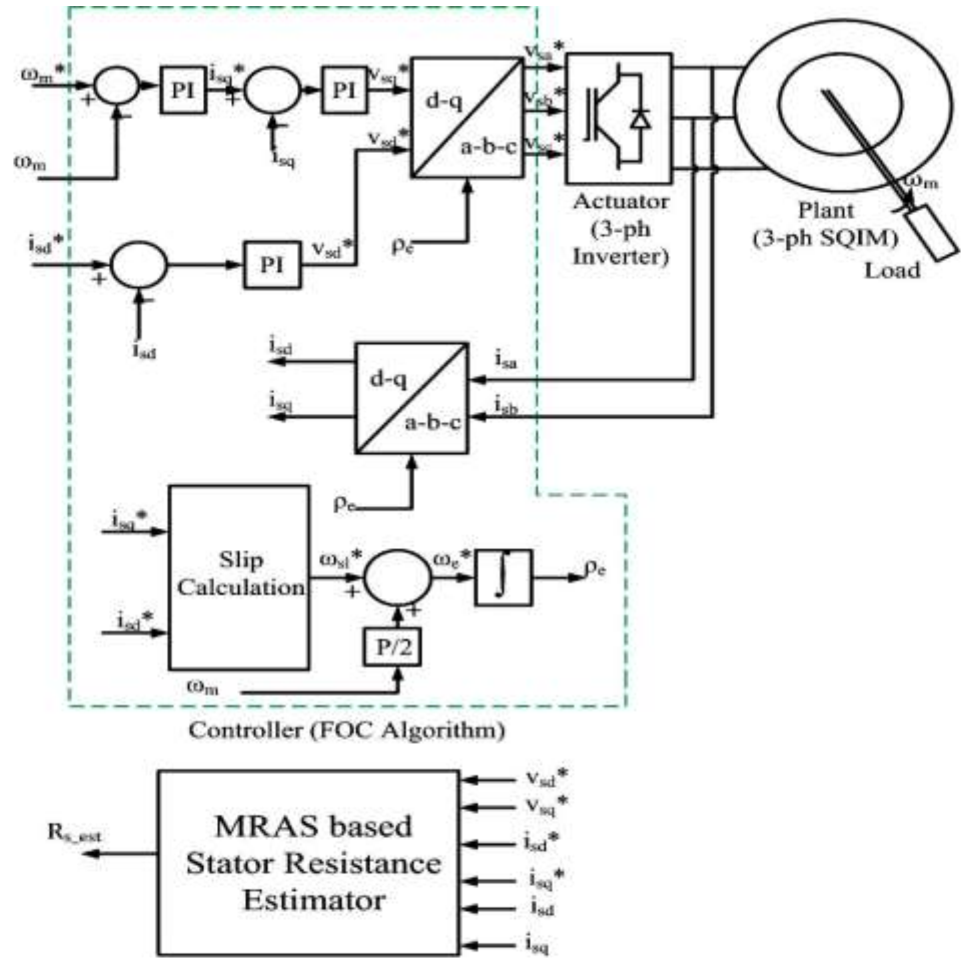

Fig.1: Basic Block Diagram of the Overall Indirect Vector-Controlled System along with Stator Resistance Estimator

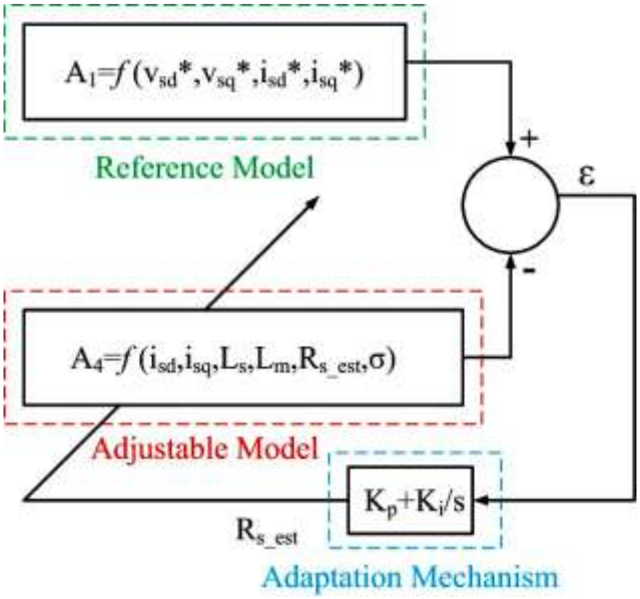

Fig.2: MRAS based Stator Resistance Estimation

The paper is organized into six sections. Section II deals with the theoretical background necessary for the development of the proposed stator resistance algorithm. The formulation of a new functional candidate for MRAS is provided in section III. Section IV deals with the performance of the proposed stator resistance estimation technique when X-MRAS based speed sensor-less drive is used. Simulation results are presented in section V. Section VI concludes the work.

II. THEORETICAL BACKGROUND

The control block diagram is shown in Fig.1. Let us consider stator voltage space vector as $\bar{v}_s = v_{sd} + jv_{sq}$ and stator line current space vector $\bar{\imath}_s = i_{sd} + ji_{sq}$ .The complex power or apparent power 'S' can be expressed as $\overline{S} = \overline{v}_s\,(\overline{i}_s)^* = P + jQ$ Here, P is the instantaneous active power; Q is the instantaneous reactive power. Also, $\bar{v}_s\,\bar{\imath}_s = -Y + j\,X$ .Here X and Y are neither active power nor reactive power. They are some fictitious quantity having no physical significance.

Referring to Fig. 2, the quantity 'A' is the functional candidate for the MRAS. 'A' can be active power, fictitious quantity 'X' and 'Y' i.e. $A \in \{P, X, Y\}$. Reactive Power is independent of stator resistance and therefore it is not considered here. The formulations of P, X, Y MRAS based stator resistance estimation technique are explained in the next page.

A. Active Power MRAS (P-MRAS)

As derived in [8], P-MRAS based stator resistance estimation is formulated as follows:

$$P_1 = v_{sd}^* i_{sd}^* + v_{sq}^* i_{sq}^* \tag{1}$$

$$P_4 = R_s\left(i_{sd}^2 + i_{sq}^2\right) + \omega_e \frac{L_m^2}{L_r} i_{sd}\, i_{sq} \tag{2}$$

A closer look in (2) will reveal that the first term in the right hand side i.e. $R_s\ (i_{sd}^2+i_{sq}^2)$ represents the Copper Loss in the stator winding and the other term represents air gap power. Also, it important to note that over the whole torque-speed plane, the coefficient of R_s is always positive and will never become zero as in case of a vector controlled drive d-axis stator current reference is set according to the value of rated flux. Therefore, in all points of torque-speed plane, P-MRAS will be able to estimate stator resistance successfully. There are no points in the torque-speed where P-MRAS becomes independent of stator resistance.

B. X-MRAS

In similar manner, X-MRAS based stator resistance algorithm can be formed.

$$X_1 = v_{sq}^* i_{sd}^* + v_{sd}^* i_{sq}^* \tag{3}$$

$$X_4 = 2R_s i_{sd}\, i_{sq} + \omega_e\left(L_s i_{sd}^2 - \sigma L_s i_{sq}^2\right) \tag{4}$$

From (4), it can be clearly seen that at no-load condition i.e. when i_{sq}=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.

C. Y-MRAS

Y-MRAS based stator resistance estimation algorithm is not found in literature. But in a similar way as done for P-MRAS and X-MRAS, Y-MRAS can be formulated in the following manner:

$$Y_1 = v_{sq}^* i_{sq}^* - v_{sd}^* i_{sd}^* \tag{5}$$

$$Y_4 = R_s\left(i_{sq}^2 - i_{sd}^2\right) + \omega_e i_{sd}\, i_{sq}\left(2\sigma L_s + \frac{L_m^2}{L_r}\right) \tag{6}$$

When i_{sq}=i_{sd}, the quantity 'Y' becomes independent of stator resistance. Therefore, in this case also, there are singularity points. Therefore, so far, we can conclude that active power based MRAS is the most suitable functional candidate for Rs estimation. But the requirement of speed information is a major drawback and this may result in failure of Rs estimation when the rotor speed has to be estimated and stator resistance has to be simultaneously compensated for.

III. PROPOSED STATOR RESISTANCE ESTIMATOR

In this section, a novel MRAS based speed estimator is proposed. All the MRAS based speed estimation algorithm proposed so far are dependent on speed. Therefore, for estimation of stator resistance, information of speed from speed encoder or from speed observer is an absolute necessity. The major advantage of the proposed stator resistance estimator is that stator resistance is independent of speed.

The formulation of the MRAS is as described as follows. Since the new functional candidate has been derived from the quantities P and Y, the functional candidate is named as 'PY'. Multiplying (5) by the constant k_1 and subtracting from (1), we obtain

$$PY_1 = P_1 - k_1\, Y_1 \tag{7}$$

$$or, PY_1 = \left(v_{sd}^* i_{sd}^* + v_{sq}^* i_{sq}^*\right) - k_1\left(v_{sq}^* i_{sq}^* - v_{sd}^* i_{sd}^*\right) \tag{8}$$

$$\text{where, } k_1 = \frac{L_m^2}{(2\sigma L_s L_r + L_m^2)}, 0 < k_1 < 1 \tag{9}$$

Similarly, multiplying (6) by k_1 and subtracting from (2) and simplification, we obtain

$$PY_4 = R_s\left\{i_{sd}^2(k_2) + i_{sq}^2(k_3)\right\} \tag{10}$$

Where,

$$k_2 = 1 + k_1 \tag{11}$$

$$k_3 = 1 - k_1 \tag{12}$$

A MRAS can thereby be formed using (8) and (10) where (8) forms the reference model and (10) forms the adjustable model. The structure of the MRAS is a parallel MRAS and is in form as shown in Fig.2. The quantity 'A' in this case refers to the functional candidate 'PY'.

The major advantage of this stator resistance estimation technique is that only voltage and current information is sufficient for successful estimation, as compared to P, X and Y based MRAS. Also, we can find that functional candidate is a positive definite function. The elimination of speed term gives us a definite advantage of a degree of freedom achieved when the tuning the PY-MRAS for speed sensor-less control using stator resistance compensation as done in [7]. The simulation results are presented in the section to validate the proposed claim.

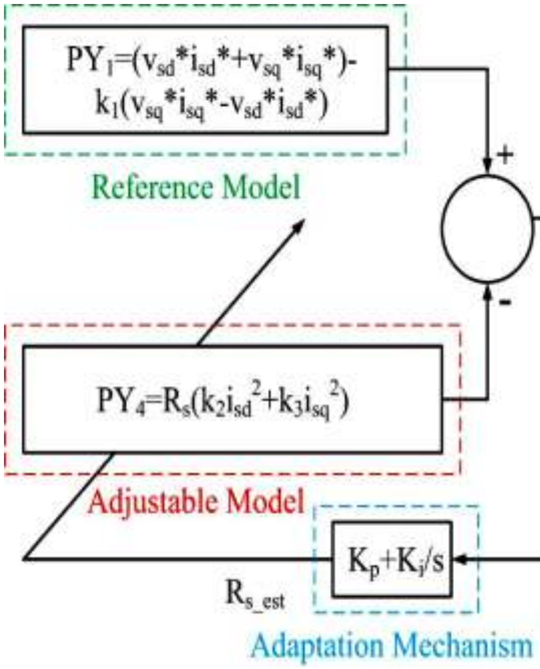

Fig. 3: Proposed PY-MRAS for Stator Resistance Estimation

IV. APPLICATION OF PROPOSED COMPENSATION TECHNIQUE FOR SPEED SENSORLESS DRIVE

The performance of the PY-MRAS for stator resistance compensation in speed sensor-less algorithm is studied. 'X' is considered to be the functional candidate for speed estimation and 'PY' is used for stator resistance estimation. The major reason for choosing 'X' as the functional candidate for speed estimation is that it is stable in all four quadrants as shown in [7] and there are no derivative or integral terms. The only drawback of 'X-MRAS' is the dependency on the stator resistance which needs to compensated for. The block diagram for the system is shown in Fig. 4.

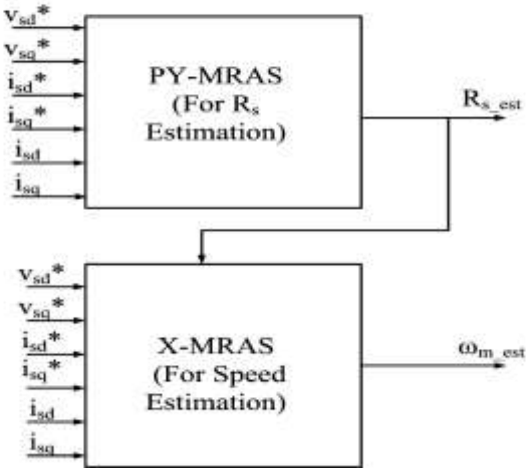

Fig .4: Simultaneous Speed and Rs estimation

TABLE I. INDUCTION MACHINE RATINGS AND PARAMETERS

Symbol	Meaning	Value
P_r	Rated Shaft Power	1.8 kW
$V_{L\text{-}L(rated)}$	Rated Line-to-Line Voltage	400 V
I_{rated}	Rated Line Current	4.4 A
P	No. of Pole Pairs	2
L_s	Stator Self Inductance	321.2 mH
L_r	Rotor Self Inductance	321.2 mH
L_m	Magnetizing Inductance	304.8 mH
R_s	Stator Resistance	3.96 Ω
R_r	Rotor Resistance	2.24 Ω
J	Shaft Inertia	0.0851 kg-m^2
B	Viscous Frictional Coefficient	0.00015

V.SIMULATION RESULTS

To validate the proposed speed sensor-less based vector control scheme, some simulation studies has been performed in MATLAB/SIMULINK environment. This section will illustrate some of the simulation results.

A. Four Quadrant Operation

In this case, the performance of the PY-MRAS is investigated in all four quadrants of operation and at also, zero speed and zero torque condition. The speed reference is set to 20 rad /s from t=5 to 20 sec. and then changed to -20 rad/s. for t>20 sec. The performance of the speed estimator in all four quadrants of torque-speed plane is found to be satisfactory as shown in Fig. 5 (c). Note that, under no load-condition, the functional candidate X becomes independent of stator resistance and Y fails to estimate stator resistance.

B. Performance under Step Change

The performance of the stator resistance estimator under step change in stator resistance is studied. At t=10s, there is a step change in resistance from nominal value to twice its nominal value. At t=20 s, the resistance is stepped down from twice its nominal value to its nominal value. The performance is found to be satisfactory as shown in Fig. 6(c). Though step change in stator resistance is not practical, the test has been done to investigate the performance under worst possible condition. A ramp command in speed is given to test the performance of the estimator under varying speed conditions.

C. Performance under Slow Change

In this case, the performance of the stator resistance estimator under a gradual change is resistance is studied via simulation. This situation replicates a practical case when this estimator can be used a non-invasive method for winding temperature measurement. The stator resistance is gradually increased from its nominal value to twice its nominal value. The performance is found to be satisfactory as can been viewed from Fig. 7(c).

D. Stator Resistance Compensation for X-MRAS

The performance under low speed is studied. At t=5 s a step change in speed reference is applied and at t=10 s, a load torque disturbance of 5 N-m (0.4 p .u.) is applied to the system. PY-MRAS is successfully able to compensate for change in stator resistance and the rotor speed is held constant as can be seen from Fig. 8 (a). The flux orientation is found to be satisfactory as shown in Fig. 8 (b). Slow variation in stator resistance is considered to emulate the practical situation where the stator resistance in the winding increases due to temperature rise within the machine. The stator resistance estimation and further compensation using PY-MRAS is successful as evident from Fig. 8(c).

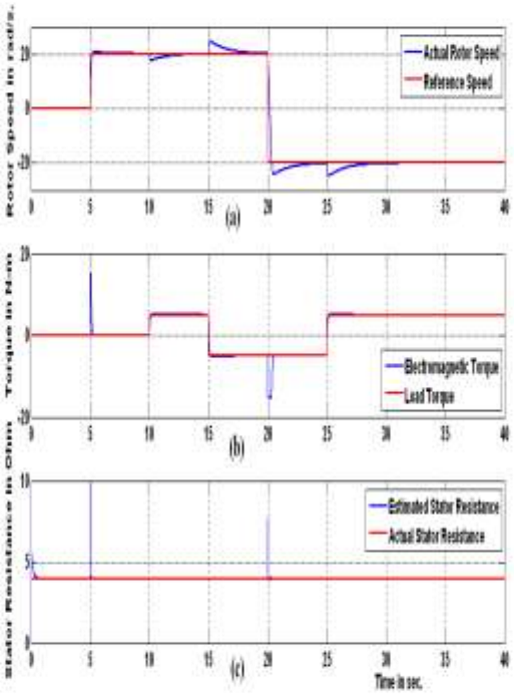

Fig.5 (a) Speed Response (b) Torque Response (c) Performance of Stator Resistance Estimator in all quadrants of operation

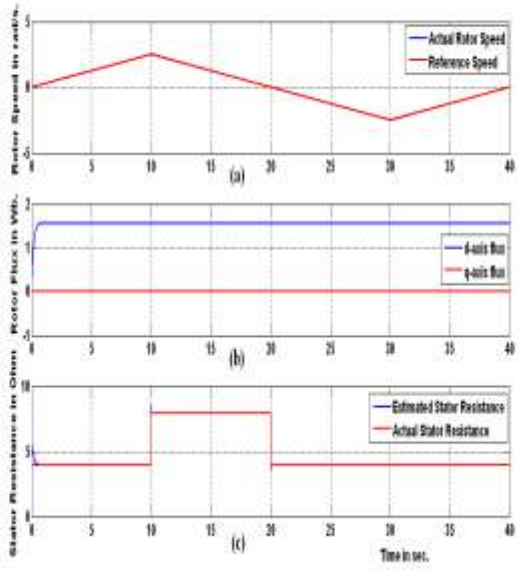

Fig.6 (a) Speed Response (b) Rotor Flux (c) Performance of Stator Resistance Estimator for sudden variation in stator resistance

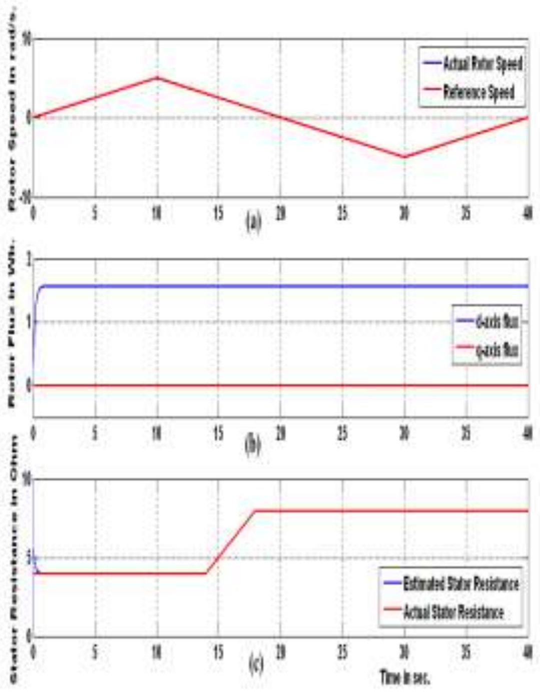

Fig.7 (a) Speed Response (b) Rotor Flux (c) Performance of Stator Resistance Estimator for smooth variation in stator resistance

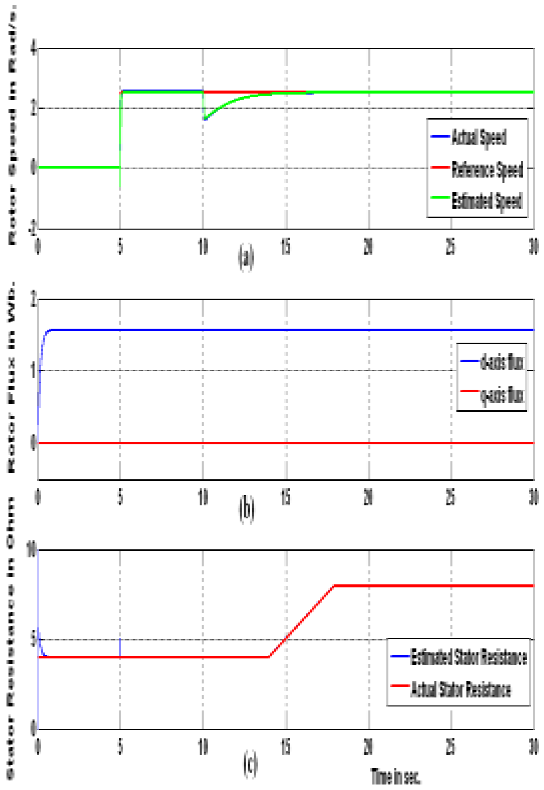

Fig.8 (a) Speed Response for the speed sensor-less drive (b) Rotor Flux (c) Performance of Stator Resistance Estimator for smooth variation in stator resistance

VI. CONCLUSION

This paper has investigated different formulation of the MRAS to develop a new functional candidate for R_s estimation that does not require speed information. Therefore, R_s can be estimated accurately for speed sensorless drive, particularly at low speed. Moreover, for speed sensorless drive that requires stator resistance information, can offer better performance with the inclusion of proposed Rs estimation technique. This is confirmed for an X-MRAS based speed sensorless drive. Extensive simulation in MATLAB/SIMULINK is carried out to validate the proposed technique.

REFERENCES

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

[2] L. Umanand and S. Bhat, "Online estimation of stator resistance of an induction motor for speed control applications," *IEE Proc. Electr. Power Appl*., vol. 142, pp. 97–103, Mar. 1995.

[3] 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

[4] B.K. Bose, and N. R. Patel; "Quasi-Fuzzy Estimation of Stator Resistance of Induction Motor"; *IEEE Transactions on Power Electronics*, Vol. 13, No. 3, pp. 401-409, May 1998.

[5]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.

[6]V.Vasic, S.N.Vukosavic, and Emil Levi; "A Stator Resistance Estimation Scheme for Speed Sensorless Rotor Flux Oriented Induction Motor Drives"; *IEEE Transactions On Energy Conversion*, Vol. 18, No. 4, Pp. 476-483, December 2003.

[7] A. V. Ravi Teja, C. Chakraborty, S. Maiti, and Y. Hori; "A New Model Reference Adaptive Controller for Four Quadrant Vector Controlled Induction Motor Drives"; *IEEE Transactions on Industrial Electronics*, Vol. 59, No. 10, pp. 3757-3767, October 2012.

[8] C. Chakraborty, A.V. Ravi Teja, S.Maiti, Y. Hori; "A VxI based adaptive speed sensorless four quadrant vector controlled induction motor drive"; *International Power Electronics Conference (IPEC) 2010*; pp. 3041-3048; June 2010.