Vector Control of a Cost Effective FSTP Inverter Fed Synchronous Reluctance Motor Drive Based on Recurrent Neural Network

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ABSTRACT

This paper proposes a position sensorless vector control methodology for Synchronous Reluctance Motor (SynRM) drive. In this control scheme, instead of a conventional Six Switch Three Phase (SSTP) inverter a Four Switch Three Phase (FSTP) inverter is used. The reduction of the number of power switches from six to four improves the cost-effectiveness, volume-compactness and reliability of the three phase inverters. The control system estimates the motor stator flux and its position using a Recurrent Neural Network (RNN). A simulation model of the drive system is developed and analyzed in order to validate the proposed approach. The robustness of the drive system is tested for different operating conditions. Simulation results show that the proposed drive system provides a fast speed response and good disturbance rejection capability.

(Keywords: Four switch three phase inverter, flux estimation, recurrent neural network, sensorless control, and synchronous reluctance motor)

INTRODUCTION

Synchronous reluctance motors have recently been attracted a number of researchers due to their inherent advantages such as low cost, mechanical simplicity and robust structure. A SynRM is superior to an Induction Motor (IM) due to the absence of rotor copper losses, to brushless motor due to economical rotor structure, and to a switched reluctance motor because of low torque ripple. Thus these motors are gaining increasing interest as a possible alternative of the other ac motor drives [1-4]. SynRMs have salient poles without any winding or permanent magnet on the rotor. The flux linkage of the SynRM is directly proportional to the stator currents as the rotor circuit of the motor is opened. Thus, the torque of a SynRM can be controlled by controlling the stator currents [3]. Besides, the motors operate at synchronous speed so they need simple controller than any other AC machines [4].

Driving a SynRM requires the rotor position information to control the motor torque which is generally detected by position sensors such as an encoder or a resolver. But these position sensors not only increase the cost of the drives but also decrease the system reliability. Therefore, many papers on position sensorless drive of SynRM have been published.

In [1] an Adaptive Input–Output Feedback-Linearization (AIOFL) controller has been designed for maximum rate of change of torque control of an encoderless three phase SynRM drive. Variable structure control strategy using the sliding mode technique has been the focus of many studies for sensorless SynRM control. The application of sliding mode controller was proposed in [4] for robust speed control of SynRM drive. A sliding mode controller based on Gaussian radial basis function neural network was utilized for SynRM system robust stabilization and disturbance rejection in [5]. Heath Hofmann et al. [6], in their paper developed a refined design of a high-speed SynRM drive with minimized eddy-current losses in the rotor. The authors also proposed position sensorless vector control strategy based on stator flux estimation [7].

In recent years, many research and development projects have been also developed to reduce the cost of the power converter. The conventional SSTP inverter was popular since the last few decades. But these inverters have some disadvantages such as losses in the six switches, complexity of the control algorithms and generating six PWM logic signals [8-12]. So researchers are working to find a substitute of the SSTP inverter. In [8] an ac to ac converter with least amount hardware was proposed for three phase IM drive. A cost effective FSTP inverter was proposed for IM drive in [9]. The authors showed a performance comparison of the FSTP inverter fed drive with SSTP inverter fed drive in terms of speed response and total harmonic distortion of the stator current. The same authors proposed fuzzy logic controller based control scheme for FSTP fed interior permanent magnet (IPM) synchronous motor drive [10]. A vector control technique for IM using FSTP inverter was presented for high performance industrial drive systems in [11]. The authors verified the complete vector control scheme by simulation and experimentation in a DSP environment. A RNN based stator flux and position estimator was proposed in [12] for sensorless control of FSTP fed IPM synchronous motor drive. The authors showed that with the RNN, accurate estimation is possible both under transient and steady-state conditions.

This paper considers two ideas to reduce the cost of the SynRM drive system; the first one is to reduce the inverter size and the other is to eliminate the need for position sensor. The performance of the proposed cost effective position sensorless SynRM drive has been investigated through simulation studies. The close loop vector control scheme of the drive system has been simulated in C++ environment. The hysteresis controller is used to control the motor current so that it can follow the command current as close as possible to the sinusoidal reference. The performances of the drive system have also been studied for sudden change of load torque, sudden change of command speed, parameter variation, and speed reversal conditions.

SYNCHRONOUS RELUCTANCE MOTOR MODEL

A mathematical model of the SynRM is required for proper simulation of the system. The dynamic model which describes the behavior of the SynRM in the synchronously rotating d-q reference frame can be expressed as follows [4]:

$$v_d = R_s i_d + L_d \frac{di_d}{dt} - \omega_r L_q i_q \qquad \textbf{(1)}$$

$$v_q = R_s i_q + L_q \frac{di_q}{dt} + \omega_r L_d i_d \qquad \textbf{(2)}$$

Where the v_d and v_q are *d*- and *q*- axis terminal voltages, respectively. The i_d and i_q are, respectively, *d*- axis and *q*- axis torque producing currents. The L_d and L_q are the *d*- and *q*- axis magnetizing inductances, respectively. The R_s is the stator resistance and ω_r is the angular speed of the rotor.

The developed electromagnetic torque is given as:

$$T_e = \frac{3P_p}{2}(L_d - L_q) i_d i_q \qquad \textbf{(3)}$$

The mechanical motion of the SynRM can be expressed as:

$$T_e = T_L + J_m \frac{d\omega_m}{dt} + B_m \omega_m \qquad \textbf{(4)}$$

and

$$\omega_r = p_p \cdot \omega_m \qquad \textbf{(5)}$$

Where P_p, T_L, J_m, ω_m, and B_m are the number of pole pairs, the load torque, the moment of inertia of rotor, the mechanical speed of rotor, and the viscous friction coefficient, respectively.

FOUR SWITCH THREE PHASE INVERTER MODEL

Fig. 1 shows the power circuit of four switch inverter fed SynRM drive. A three phase system is obtained by connecting the phase 'c' terminal of the stator windings directly to the centre tap of the dc link capacitors. The single phase ac supply is rectified by the front-end rectifier. The capacitors are used to level the output dc voltage. If V_{dc} is the maximum voltage across the dc link capacitors, and S_a, S_b are the states of power switches for each phase, then three phase voltages of the SynRM can be expressed as follows [9]:

$$V_a = \frac{V_{dc}}{3}\left[4S_a - 2S_b - 1\right] \qquad \textbf{(6)}$$

$$V_b = \frac{V_{dc}}{3}\left[4S_b - 2S_a - 1\right] \qquad \textbf{(7)}$$

$$V_c = \frac{2V_{dc}}{3}\left[-S_a - S_b + 1\right] \qquad \textbf{(8)}$$

If S_a =1 then T_1 is on and T_2 is off;
If S_a =0 then T_1 is off and T_2 is on;
If S_b =1 then T_3 is on and T_4 is off;
If S_b =0 then T_3 is off and T_2 is on.

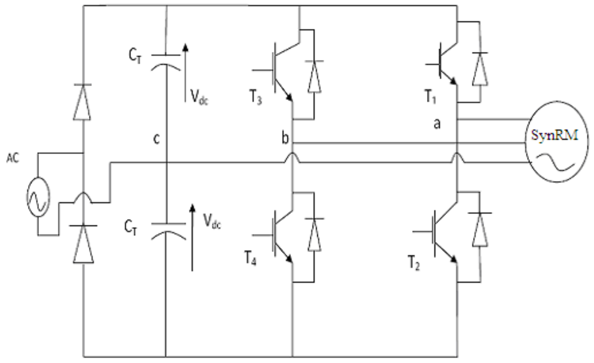


Figure 1: Power circuit of the drive system.

PROPOSED CONTROL SCHEME

The proposed control scheme of the drive system is shown in Fig. 2. The high performance control strategy is implemented in closed loop using PI controller. This requires speed error to be processed in closed loop to generate the torque producing component of the stator current, i_q^*. The magnetizing component of the stator currents i_d^* along with i_q^* are used to generate the reference currents i_a^*, i_b^*, and i_c^*. Two independent hysteresis current controller with a suitable hysteresis band are used to command the motor currents i_a, and i_b to follow the reference currents. The hysteresis controllers also generate four switching signals which fire the power semiconductor devices of the three phase inverter to produce the actual voltages to the motor.

The reference currents are formulated as follows:

$$i_a^* = i_d^* \cos\theta - i_q^* \sin\theta \tag{9}$$

$$i_b^* = i_d^* \cos(\theta - 120^0) - i_q^* \sin(\theta - 120^0) \tag{10}$$

$$i_c^* = i_d^* \cos(\theta + 120^0) - i_q^* \sin(\theta + 120^0) \tag{11}$$

The stationary 3-axes (*a*-, *b*-, *c*-) to stationary 2-axes (*α*-, *β*-) transformation is given by

$$x_{\alpha s} = x_a - 0.5\, x_b - 0.5\, x_c \tag{12}$$

$$x_{\beta s} = \frac{\sqrt{3}}{2}(i_b - i_c) \tag{13}$$

Where, *x* is either voltage or current vector.

RECURRENT NEURAL NETWORK BASED STATOR FLUX ESTIMATION

The recurrent neural network is a single layer neural network with input and output nodes. The output nodes act as summing nodes and in this study the two output variables, i.e., *α*- and *β*-components of stator flux linkage are fed to the input with unit delay operator. The value of activation function at the output node is taken unity. The common inputs for both the outputs are α- and *β*- components of stator voltage and current which results in the following matrix equation:

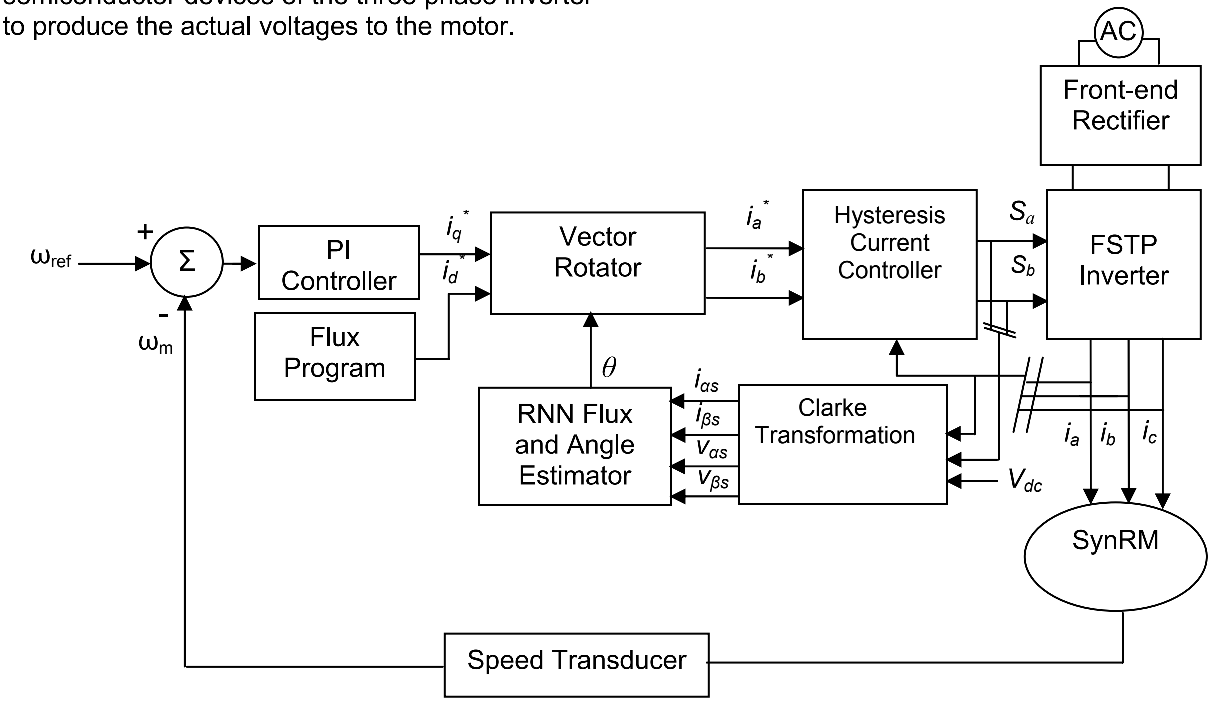


Figure 2: Proposed Control Scheme of the SynRM.

$$\begin{bmatrix}\lambda_{\alpha s}(k+1)\\ \lambda_{\beta s}(k+1)\end{bmatrix}=\begin{bmatrix}W_{11} & W_{12}\\ W_{21} & W_{22}\end{bmatrix}\begin{bmatrix}\lambda_{\alpha s}(k)\\ \lambda_{\beta s}(k)\end{bmatrix}+\begin{bmatrix}W_{13} & W_{14}\\ W_{23} & W_{24}\end{bmatrix}\begin{bmatrix}v_{\alpha s}\\ v_{\beta s}\end{bmatrix}+\begin{bmatrix}W_{15} & W_{16}\\ W_{25} & W_{26}\end{bmatrix}\begin{bmatrix}i_{\alpha s}\\ i_{\beta s}\end{bmatrix} \qquad \textbf{(14)}$$

The inputs are connected to the output node through the weights W_{11}, W_{12}, W_{21}, W_{22} etc. as indicated by the line segments and shown in Fig. 3. Each output node is also connected to the corresponding recurrent input node through weights. The weights indicated by the different line segments are adjusted by training the neural network.

Estimated angle of reference pole,

$$\theta=\tan^{-1}\left(\frac{\lambda_{\beta s}}{\lambda_{\alpha s}}\right) \qquad \textbf{(15)}$$

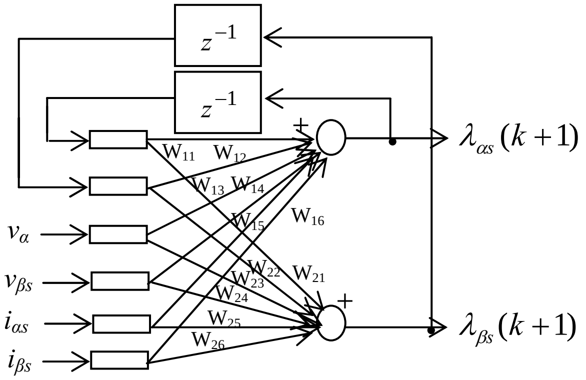


Figure 3: Stationary *α*- and *β*- axis stator flux estimation by recurrent neural network

SIMULATION RESULTS

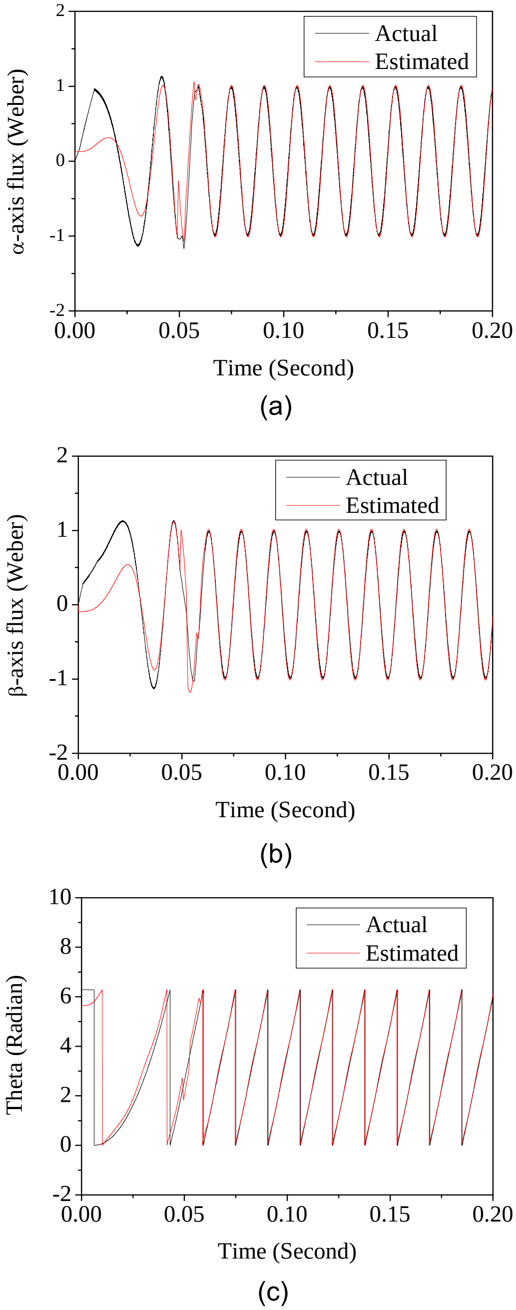
The objective of computer simulation is to verify the control strategy proposed in this study for different operating situations. The prototype 0.37 kW SynRM used in this drive system is a three phase machine, the parameters of which are reported in Table 1.

Table 1: SynRM specifications [3]

Number of pole pair: P_P	1
Stator resistance: R_s	4.2 Ω
d-axis inductance: L_d	0.328 H
q-axis inductance: L_q	0.181 H
Motor inertia: J_m	0.00076 Kg-m^2
Friction coefficient: B_m	0.00012 N-m /rad /sec

Performance of Flux and Angle Estimator

The effectiveness of the proposed flux estimator along α- and β- axis needs to be verified before implementing it in the drive system. Real flux components calculated from exact values of motor variables are computed and compared with the estimated flux components and rotor angle.



(a)

(b)

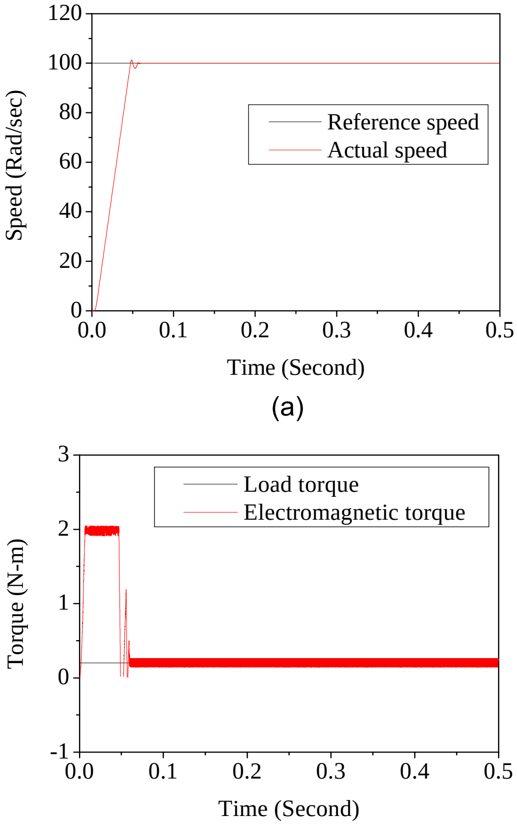
(c)

Figure 4: (a) α-axis components of estimated and actual flux, (b) β-axis components of estimated and actual flux, and (c) Estimated and actual rotor angle for the SynRM drive.

Fig. 4 (a) & (b) show the estimated α- and β- axis stator flux respectively. It can be visualized that accurate estimation is possible by the proposed recurrent neural network. A complete matching of the variables is indicated in the figures. These figures illustrate the performance of RNN based flux and rotor angle estimator. Fig.4 (c) shows the estimated angle which follows very closely the actual angle deduced from machine model.

Starting Performance of the SynRM Drive

From standstill condition, the motor was started with a command speed of 100 rad/sec and load torque of 0.2 N-m. The motor reaches to the command speed at 0.06 second. Fig. 5 (a) shows the speed response of the SynRM drive. The motor follows the command speed accurately without any steady-state error and oscillations. Fig. 5 (b) shows the developed electromagnetic torque of the drive under starting condition. It is observed that higher electromagnetic torque is generated during the motor acceleration.

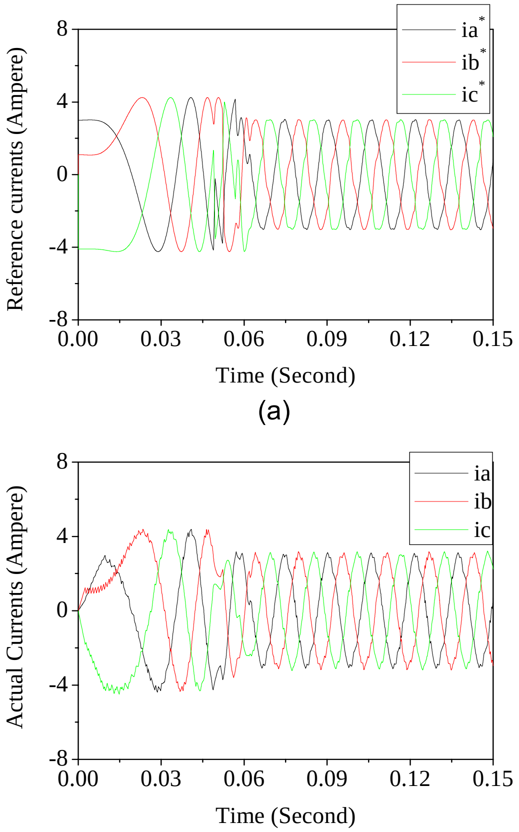


(a)

(b)

Figure 5: (a) Simulated speed response, and (b) Developed electromagnetic torque under transient and steady-state condition.

Some oscillations in electromagnetic torque is noticed which is due to switching of the devices with hysteresis controller. Difference between developed and load torques is due to viscous damping torque of the drive system. Fig. 6 (a) and (b) show the command currents and actual currents of the three phases respectively.



(a)

(b)

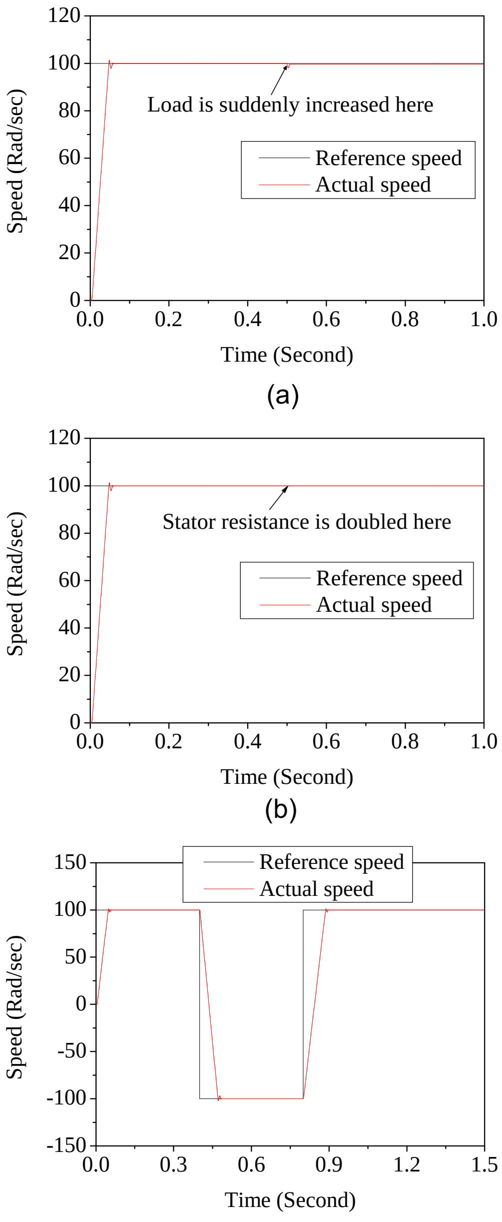
Figure 6: Three phase (a) command currents, and (b) actual currents under transient and steady-state condition.

Performance under Different Operating Conditions

To verify the robustness of the proposed drive system, the performance of the SynRM drive was also investigated under different operating conditions. The load torque of the motor was suddenly increased from 0.2 N-m to 1.2 N-m at 0.5 second. The corresponding speed response of the drive is shown in Fig. 7 (a). The speed slightly falls but no oscillation in speed is noticed due to this load torque disturbance.

To observe the effect of parameter variation, the motor stator resistance was doubled at 0.5

second. Fig. 7 (b) shows that the speed does not drop at all due to change of stator resistance. To examine the performance of the drive system under speed reversal condition, the command speed was reversed from 100 rad/sec to -100 rad/sec at 0.4 second and again to 100 rad/sec at 0.8 second. Fig. 7 (c) shows the corresponding speed response which confirms the robustness of the drive system.



(a)

(b)

(c)

Figure 7: Simulated speed response for (a) sudden change of load, (b) sudden increase of stator resistance, (c) speed reversal condition.

CONCLUSION

In this paper, a position sensorless vector control scheme using RNN for FSTP fed SynRM drive has been presented. The weights of the RNN are obtained by offline training method. The results obtained and presented in this work indicate that the proposed control scheme produces very fast response of the SynRM drive. The drive also shows good performance in speed operation under the effect of load disturbances, parameter variation, and reversal of speed. The proposed RNN based SynRM drive provides the advantages of simple structure, robustness, and accurate tracking performance. Thus this cost effective drive system fulfills the demand of present industry applications.

REFERENCES

1. Hossein Abootorabi Zarchi, Jafar Soltani, and Gholamreza Arab Markadeh. 2010. “Adaptive Input–Output Feedback-Linearization-Based Torque Control of Synchronous Reluctance Motor without Mechanical Sensor”. *IEEE Transactions on Industrial Electronics*. 57(1): 375-384

2. B. V. Litvinov and O. B. Davydenko. 2010. “Synchronous Reluctance Motors with Lowered Magnetic Conductivity along Transverse Axis”. *Russian Electrical Engineering.* 81(3): 121-125.

3. Huann-Keng Chiang, Chih-Huang Tseng, and Wei-Lun Hsu. 2003. “Implementation of a Sliding Mode Controller for Synchronous Reluctance Motor Drive Considering Core Losses”. *Journal of the Chinese Institute of Engineers.* 26(1): 81-86.

4. Mostafa. A. Fellani and Dawo. E. Abaid. 2009. “Sliding-Mode Control of Synchronous Reluctance Motor”. *International Journal of Electronics, Circuits and Systems*. 3(2): pp. 91-95.

5. Chien-An Chen, Huann-Keng Chiang, Wen-Bin Lin, and Chih-Huang Tseng. 2009. “Synchronous Reluctance Motor Speed Drive Using Sliding Mode Controller Based on Gaussian Radial Basis Function Neural Network”. *Artificial Life and Robotics*. 14: 53–57.

6. Heath Hofmann and Seth R. Sanders. 2000. “High-Speed Synchronous Reluctance Machine with Minimized Rotor Losses”. *IEEE Transactions on Industry Applications*. 36(2): 531-539.

7. Heath F. Hofmann, Seth R. Sanders, and Ahmed EL-Antably. 2004. “Stator-Flux-Oriented Vector Control of Synchronous Reluctance Machines with

Maximized Efficiency". *IEEE Transactions on Industrial Electronics*. 51(5):1066-1072.

8. S. Saravanasundaram and K. Thanushkodi. 2008. "Compound Active Clamping Boost Converter-Three Phase Four Switch Inverter Fed Induction Motor". *International Journal of Computer Science and Network Security*. 8(8):358-361.

9. M. N. Uddin, T. S. Radwan, and M. A. Rahman. 2006. "Performance Analysis of a Cost Effective 4-Switch, 3-Phase Inverter Fed IM Drive*". Iranian Journal of Electrical and Computer Engineering*. 5(2):97-102.

10. M. N. Uddin, T. S. Radwan, and M. A. Rahman. 2006. "Fuzzy-Logic-Controller-Based Cost Effective Four-Switch Three-Phase Inverter-Fed IPM Synchronous Motor Drive System". *IEEE Transactions on Industry Applications*. 42(1):21-30.

11. Phan Quoc Dzung, Le Minh Phuong, Tran Cong Binh, and Nguyen Minh Hoang. 2007. "A Complete Implementation of Vector Control for a Four-Switch Three-Phase Inverter Fed IM Drive". *International Symposium on Electrical & Electronics Engineering*. HCM City, Vietnam.

12. Kalyan Kumar Halder and B. C. Ghosh. 2010. "Vector Control of Four Switch Three Phase Inverter Fed Interior Permanent Magnet Synchronous Motor Drive without Position Sensor". *Journal of Electrical Engineering*, 10(2):67-74.

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