Efficiency Optimization of Six-phase Induction Motors by Fuzzy Controller

A. Taheri[1]

[1]Department of Electrical Engineering, Faculty of Engineering, University of Zanjan, University St. IR-313-45195, Zanjan, Iran
taheri@znu.ac.ir

***Abstract*—In this paper efficiency improvement of a Six-phase Induction Machine (6PIM) with fuzzy Anfis method is presented. Six phase induction machine is supplied by SPWM (Sine Pulse Width Modulation). The motor efficiency in low speed or low load conditions (under nominal point) is low. The purpose of this paper is to reduce core losses of six phase induction motor in these conditions. Fuzzy flux search controller is a simple technique and robust against parameter changes that can be easily implemented. Loss minimum point of six phase induction motor is related to stator current, thus by decreasing of current the loss is decreased. Results are presented in the paper to verify the effectiveness of the proposed approach.**

***Index Terms*—Six-phase induction motor, efficiency improvement, fuzzy Anfis method.**

I. INTRODUCTION

Multi-phase motor drives have been studied for more than three decades, but today its application has increased. The Search Control (SC) and Loss Model Control (LMC) of efficiency are two important techniques in loss minimization of electrical drive [1]–[4]. LMC technique depends on loss model of motor and it can be applied in a suitable algorithm to minimize losses and improve efficiency [2]. This is implemented through computing the various loss models by the function of various measurement parameters of machine like currents, flux, and etc. The Loss Model technique produces a certain flux current for which the total loss is minimal for a given speed and torque. The accuracy of LMC depends on the correct modeling and estimation of the motor parameters [5].

The efficiency improvement of a six phase induction motor is proposed in [4]–[8]. In [5], loss variation of six phase induction machine by flux variation is presented. While the six-phase induction motor is controlled and flux reference is in nominal point, the machine loss will be high because of having a high core and cu loss.

By decreasing the flux, when the input power is in minimum point, the efficiency of motor is in maximum point [4]. A proper loss model of a six-phase induction motor is presented in [6].

Flux reduction leads to stator frequency variation that is considered as a new aspect of flux search control in [6]. If the frequency variation is ignored, an error in core loss calculation will occur.

Improvement of switching table of direct torque control of six-phase induction machines for reducing the voltage and current harmonics and the torque pulsation and loss is presented in [7]. A six-phase induction machine has a large zero sequence harmonic currents of the order 6k-1. Decreasing this loss is essential in a six-phase induction machine [7].

A dynamic search algorithm based on fuzzy loss model controller for the online efficiency optimization of induction motor is presented in [9], [10]. A simplified model of the induction motor and the loss function is proposed in [10] to achieve an approximate flux reference for any operating point. In [11], [12], the efficiency optimization by flux control in an IM which is applicable to any machine size without any need to machine parameters is proposed. The efficiency improvement is active in load change and has the possibility of self-tuning of rule base and the system is capable of a permanent operating at optimum efficiency [11]. At the same time, another article introduces a suitable efficiency improvement of FOC of induction motor by decreasing the rotor flux via adjusting the magnetizing current and torque current with fuzzy logic method [12].

In this paper, an Anfis fuzzy search controller reduces stator currents to minimize a six- phase induction motor loss. Simulation results are given in the paper to verify the proposed method. In the next Section, parameters and loss model of a six-phase induction motor is described. In Section III, comparison of minimum losses point and minimum stator current is presented. In the following Section, fuzzy controller for efficiency optimization is presented. Finally simulation results are indicated in Sections V, VI.

II. LOSS MODEL OF SIX-PHASE INDUCTION MOTOR

This motor has defined phase voltages, currents and flux linkages as [13], [14]:

$$V^{s}_{abcdef} = [v_{as} \quad v_{bs} \quad v_{cs} \quad v_{ds} \quad v_{es} \quad v_{fs}]^{T}, \quad (1)$$

$$I^{S}_{abcdef} = [i_{as} \quad i_{bs} \quad i_{cs} \quad i_{ds} \quad i_{es} \quad i_{fs}]^{T}. \quad (2)$$

By applying Clarke and Park rotational transformation, the six-phase induction motor model will be as:

Manuscript received January 30, 2013; accepted August 22, 2013.
This research was funded by Zanjan University power electronics Lab.

$$V_{ds} = R_s i_{ds} - \omega_e \psi_{qs} + \frac{d\psi_{ds}}{dt}, \tag{3}$$

$$V_{qs} = R_s i_{qs} + \omega_e \psi_{ds} + \frac{d\psi_{qs}}{dt}, \tag{4}$$

$$V_{xs} = R_s i_{xs} + \frac{d\psi_{xs}}{dt}, \tag{5}$$

$$V_{ys} = R_s i_{ys} + \frac{d\psi_{ys}}{dt}, \tag{6}$$

$$V_{o+s} = 0, \tag{7}$$

$$V_{o-s} = 0. \tag{8}$$

Rotor voltage equations are formulated as follows:

$$V_{dr} = 0 = R_r i_{dr} - (\omega_e - \omega_r)\psi_{qr} + \frac{d\psi_{dr}}{dt}, \tag{9}$$

$$V_{qr} = 0 = R_r i_{qr} - (\omega_e - \omega_r)\psi_{dr} + \frac{d\psi_{qr}}{dt}. \tag{10}$$

Flux linkage equations of motor with respect to stator and rotor currents are:

$$\psi_{ds} = (L_{ls} + L_m) i_{ds} + L_m i_{dr}, \tag{11}$$

$$\psi_{qs} = (L_{ls} + L_m) i_{qs} + L_m i_{qr}. \tag{12}$$

Motor electromechanical torque is as below

$$T_e = \frac{3}{4} P L_m [i_{dr} i_{qs} - i_{ds} i_{qr}]. \tag{13}$$

The total loss of 6PIM includes stator and rotor copper losse (P_{cu}), copper losses in (x-y) subspace (P_{cu_x}) core losses (P_{core}) and mechanical losses (P_m):

$$\mathrm{P_{loss}} = P_{hyst} + P_{eddy} + P_{ex} + P_{cu} + P_m, \tag{14}$$

$$P_{hyst} = P_{eddy} = k_h \omega_e |\Psi_s|^2, \tag{15}$$

$$P_{ex} = k_{ex} (\omega_e |\Psi_s|)^{1.5}, \tag{16}$$

where k_h, k_e, k_{ex} are hysteresis, eddy current, and excess loss coefficients respectively. The core losses include eddy current losses and hysteresis losses. Mechanical loss is dependent on mechanical speed and it is given as

$$P_m = k_m \omega_r^2, \tag{17}$$

k_m is mechanical loss coefficient. In a steady state, from (14) to (17), we can get the expression for total motor losses as bellow

$$P_{loss} = \frac{3}{2}[R_s(i_{ds}^2 + i_{qs}^2) + R_r(i_{dr}^2 + i_{qr}^2) + R_s(i_{xs}^2 + i_{ys}^2) + $$
$$+ R_r(i_{xr}^2 + i_{yr}^2)] + k_h \omega_e \psi_m^2 + k_e \omega_e^2 \psi_m^2 + k_m \omega_r^2. \tag{18}$$

We can modify (18) as below

$$P_{loss} = \frac{3}{2}\left[A i_{ds}^2 + \frac{B T_e^2}{K^2} \frac{1}{i_{ds}^2} \right] + k_m \omega_r^2 + \frac{3}{2} R_S \left(i_{xs}^2 + i_{ys}^2 \right), \tag{19}$$

where

$$A = R_s + (k_h \omega_e + k_e \omega_e^2) L_m^2 + k_{ex} \omega_e^{1.5} L_m^{1.5}, \tag{20}$$

$$B = R_s + R_r \frac{L_m^2}{L_r^2} (k_h \omega_e + k_e \omega_e^2) \frac{L_{\sigma r}^2 L_m^2}{L_r^2} + $$
$$+ R_r \frac{L_m^2}{L_r^2} k_{ex} \omega_e^{1.5} \frac{L_{\sigma r}^2 L_m^{1.5}}{L_r^2}. \tag{21}$$

III. COMPARISON OF MINIMUM LOSSES POINT AND MINIMUM STATOR CURRENT POINT

The optimal flux or input power is achieved by minimum of stator current or minimum of i_{ds}. As seen in (18), the motor loss is function of current and mechanical speed $(i_{ds}, i_{xs,ys}, \omega_r)$. If output power is constant, the ω_r term and thus mechanical loss will be constant. Also, $i_{xs,ys}$ currents and thus cu loss in (x-y) subspace are independent from motor flux and are almost fixed.

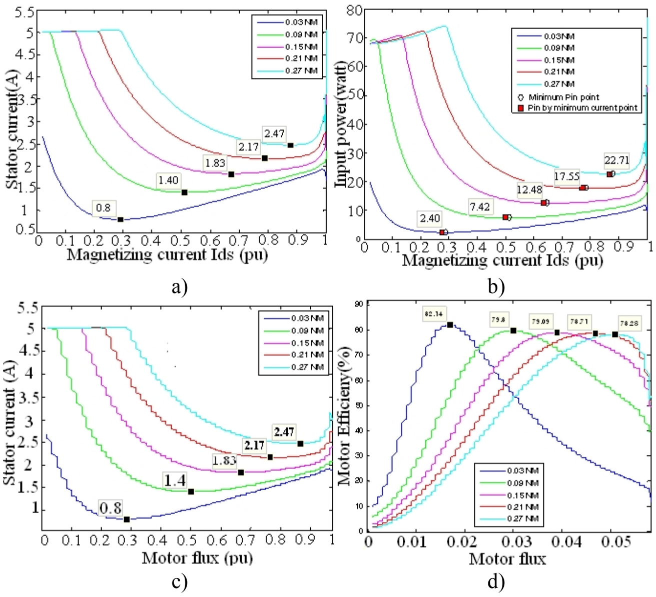


Fig. 1. Variation of stator current and input power via i_{ds} (a, b); variation of stator current and efficiency via motor flux (c, d).

If output power is fixed, the input power in terms of current change is as Fig. 1. In addition, in Fig. 1, variation of loss minimization via stator current variation is shown. The real minimum of loss occurs in the point approaching to stator current minimum point. The motor efficiency via motor flux and magnetizing current at different torques are presented in Fig. 1. Table I shows parameters of motor applied in simulation.

IV. FUZZY CONTROLLER FOR EFFICIENCY OPTIMIZATION

The proposed control system dedicates a motor regulation at the steady state by means of a continuous search for the point of minimum electrical losses.

Because of a noisy data in the Anfis method, mean value of every ten values is selected in the input. The principle of efficiency optimization by controlling stator current is shown in Fig. 2. The fuzzy Anfis program explores the minimum stator current by adjusting the magnetizing current in an appropriate point. The usual SC technique depends on gradual increase or decrease of stator or rotor flux until the measured input power reaches to a minimum point. In SC method, input power is selected as objective function and minimized by adjusting the flux value. If the rotor flux is reduced, the iron loss and copper loss decrease at the same time. If the flux reduction is less than the stator frequency increment, the core loss increases [6]. A fuzzy Anfis improvement of efficiency considers these conditions in a simple model of loss. With considering various parameters change in an Anfis fuzzy rule, the results have a good performance.

TABLE I. MOTOR PARAMETERS.

Rated Power	90 W	**Stator Resistance**	1.04
Rated Torque	0.3 Nm	**Stator Leakage**	0.30 mH
VSI DC bus	42 V	**Rotor resistance**	0.64
Number of poles	2	**Rotor Leakage**	0.65 mH
Mutual inductance	30.9 mH	**J**	0.000095

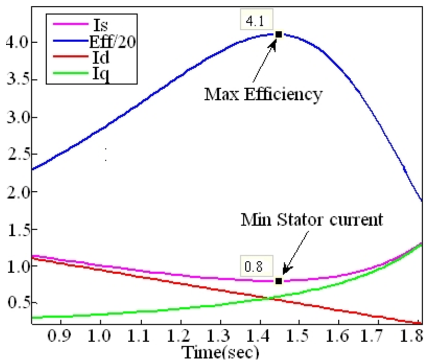


Fig. 2. Maximum of motor efficiency by control of stator current.

The fuzzy controller uses $i_{ds}(k), i_{xs}, i_{ys}, i_{ds}(k-1), i_s(k)$ as inputs and Ids_ref(k) as output. Figure 3 shows the fuzzy Anfis method input and output in loss minimization.

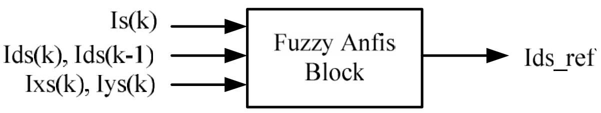


Fig. 3. Block diagram of fuzzy Anfis section.

As in Fig. 3, fuzzy Anfis block produces Ids reference which is applied in FOC method. This technique has less response time against the SC technique. Algorithm of this method in loss minimization of fuzzy Anfis technique and FOC of six-phase induction motor is presented in Fig. 4.

V. Simulation Results

By modeling of loss minimization of the motor, simulation results at constant speed (600 rpm), different load torques and decreased stator current are presented. The simulation results consist of six-phase induction motor power loss, power efficiency, stator current of q-axis and d-axis. Decreasing Ids causes motor losses decrease and increase of efficiency. As presented in Fig. 5, the efficiency maximum point is very near to minimum point of current. As (9), (10) motor flux is related to d-axis current and decreasing this current results in flux reduction.

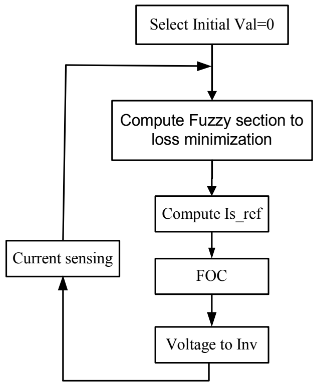


Fig. 4. Loss minimization and control algorithm.

According to (16), (18) reduction of Ids or flux causes loss decreased. The motor rated load is 0.03 N.m and 10 % of this load is 0.003 N.m. If motor load is less than rated value, the motor efficiency will be lower than rated condition. In this condition, suitable loss minimization technique can improve motor efficiency.

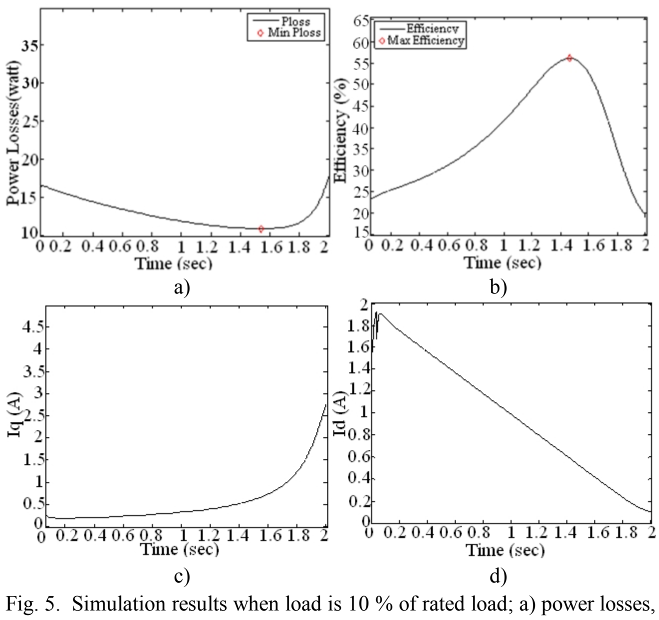


Fig. 5. Simulation results when load is 10 % of rated load; a) power losses, b) power efficiency, c) stator current of q-axis, d) stator current of d-axis.

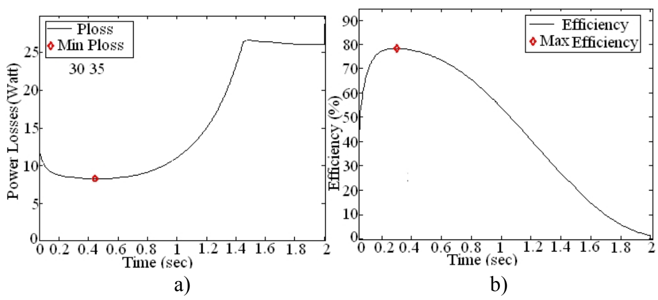
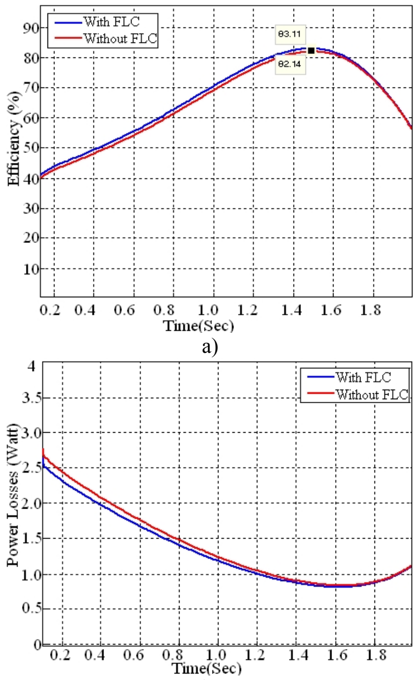


Fig. 6. Simulation results when load = 0.7 pu; a) power losses, b) efficiency.

Figure 6 shows motor efficiency improvement results while the motor d-axis current is decreasing and motor works in 70 % of rated load. Comparing Fig. 5 and Fig. 6 indicates that motor efficiency improvement is better in proposed technique in fewer loads. From simulation results, we can say that motor efficiency improvement in the 10 % of rated load is near to 100 %.

VI. SIMULATION RESULTS FOR FUZZY-ANFIS EFFICIENCY OPTIMIZATION

The simulation results of fuzzy Anfis technique are presented in Fig. 7 and Fig. 8. Figure 7 shows the efficiency and power loss variation at a certain load toque and speed (Tl = 0.015 N.m & speed = 600 rpm).



a)

b)

Fig. 7. a) Power losses, b) stator current with and without controller.

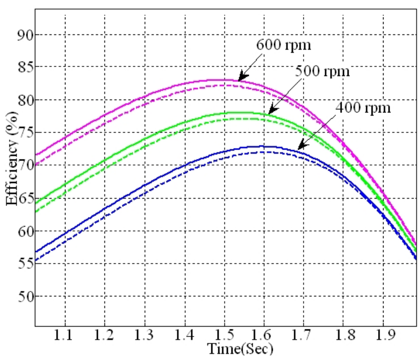


Fig. 8. Comparison of efficiency curves at different motor speed with and without fuzzy optimization.

Figure 8 shows that the stator current and motor losses decrease until the controller reaches steady state (almost minimum point). The efficiency variation is also shown in Fig. 8, which it depends on three cases of speed (600, 500, 400 rpm) with and without fuzzy optimization.

VII. CONCLUSIONS

In order to improve efficiency of the FOC of six-phase induction motor in full load range, the stator current is generally reduced to improve efficiency of motor. Results indicate that the current minimization controller finds the minimum loss value rapidly and selected point doesn't have any ripple in steady state. By varying the load, the proposed method is active and suitable efficiency is achieved. In proposed technique, motor efficiency improvement is much better in fewer loads. Even changing the motor parameters fuzzy Anfis technique shows a good performance. Simulation results show a relationship between stator current minimization and motor loss minimization in the six phase induction motor vector control system. Furthermore, it is concluded that the motor loss minimization can be achieved by an appropriate fuzzy stator current minimization and it does not need extra hardware to implement.

REFERENCES

[1] M. Uddin, S. Nam, "Development new online Loss minimization based control of an induction motor drives", *IEEE Trans. Power Electron.,* vol. 23, no. 2, pp. 926–933, Mar. 2008. [Online]. Available: http://dx.doi.org/10.1109/TPEL.2007.915029

[2] V. Bleizgys, A. Baskys, T. Lipinskis, "Induction Motor Voltage Amplitude Control Technique based on the Motor Efficiency Observation", *Elektronika ir Elektrotechnika (Electronics and Electrical Engineering)*, no. 3, pp. 89–92, 2011.

[3] I. Kioskeridis, N. Margaris, "Loss minimization in induction motor adjustable speed drives", *IEEE Trans. Ind. Electron*., vol. 43, pp. 226–231, Feb. 1996. [Online]. Available: http://dx.doi.org/ 10.1109/41.481429

[4] A. Taheri, A. Rahmati, S. Kaboli, "Flux Search Control of Field Oriented Control of Six-Phase Induction Motor supplied by SVPWM", *Przegląd Elektrotechniczny (Electrical Review),* vol. 87, no. 8, 2011.

[5] A. Taheri, A. Rahmati, S. Kaboli, "Energy optimization of field oriented six-phase induction motor drive", *Advances in Electrical and Computer Engineering*, vol. 11, no. 2, pp. 107–112, 2011. [Online]. Available: http://dx.doi.org/10.4316/aece.2011.02017

[6] A. Taheri, A. Rahmati, S. Kaboli, "Efficiency improvement in DTC of Six-phase induction machine by adaptive gradient descent of flux", *IEEE Trans. Power Electronics*, vol. 27, no. 3, pp. 1552–1562, Mar. 2012. [Online]. Available: http://dx.doi.org/10.1109/TPEL. 2011.2163420

[7] A. Taheri, A. Rahmati, S. Kaboli, "Comparison of efficiency for different switching tables in six-phase induction motor DTC drive", *Jounal of Power Elec. (JPE)*, vol. 12, no. 1, pp. 128–135, Mar. 2012. [Online]. Available: http://dx.doi.org/10.6113/JPE.2012.12.1.128

[8] A. Taheri, "EKF modeling of field oriented control of six-phase induction motor", *IEICE Electron. Express*, vol. 9, no. 7, pp. 642–647, 2012. [Online]. Available: http://dx.doi.org/10.1587/elex.9.642

[9] R. Yanamshetti, S. S. Bharatkar, D. Chatterjee, A. K. Ganguli, "A hybrid fuzzy based loss minimization technique for fast efficiency optimization for variable speed induction machine", *IEEE Conf.* 2009.

[10] D. A. Souza, W. C. P. A. Filho, G. C. Drumond Sousa, "Adaptive fuzzy controller for efficiency optimization of induction motors", *IEEE Trans. Industrial Elec*., vol. 54, no. 4, pp. 2157–2164. Aug. 2007. [Online]. Available: http://dx.doi.org/10.1109/TIE. 2007.895138

[11] Z. Rouabah, F. Zidani, B. Abdelhadi, "Efficiency optimization of induction motor drive using fuzzy logic and genetic algorithms", *IEEE Conf.*, 2008, pp. 737–742.

[12] J. Li, L. Xu, Z. Zhang, "A new efficiency optimization method on vector control of induction motors", *IEEE Conf.*, 2005, pp. 1995–2001.

[13] Y. Zhao, T. A. Lipo, "Space vector PWM control of dual three-phase induction machine using vector space decomposition", *IEEE Trans. Ind. App*., vol. 31, no. 5, pp. 1369–1379, 1995.

[14] R. Bojoi, M. Lazzari, F. Profumo, A. Tenconi, "Digital field-oriented control for dual three-phase induction motor drives", *IEEE Trans. Ind. App*., vol. 39, no. 3, pp. 1243–1254, May/Jun. 2003. [Online]. Available: http://dx.doi.org/10.1109/TIA.2003.811790