VOL. X, NO. X, XXXXXXXX ISSN 1819-6608
ARPN Journal of Engineering and Applied Sciences

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ONLINE ADAPTIVE FLUX CONTROL FOR SPACE VECTOR PWM-DTC IM DRIVES TOWARDS OPTIMUM EFFICIENCY DESIGN

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ABSTRACT
An improved Direct Torque Controlled (DTC) Induction Motor (IM) is reported in this paper with the aims to produce an adaptive flux controller design to realize the maximum efficiency in DTC IM drives. The value of reference flux is identified through the artificial intelligent neural network (ANN) algorithm with the input power as the objective function. The description of neural network control system as well as the training procedure is explained in this paper. Consequently, the proposed efficient optimizing controller yields an adaptive reference flux, which ensures a minimum input power that leading to the maximum efficiency of the drives systems is achieved. The proposed schemes have been developed and the performance of the IM Drive under different operating condition has been investigated through simulation and experimentally by using the Simulink/Matlab and digital signal processor of dSPACE. The promising results validate the effectiveness.

Keywords: Efficiency optimization ,Adaptive Flux Control ,Direct Torque Control,Motor Control.

INTRODUCTION

Heretofore, D.C. motors have been used immensely during the last century in applications where variable-speed operation was needed, because its flux and torque can be controlled separately by means of controlling the field and the armature currents respectively, even though d.c motors have several weaknesses. Due to the mechanical commutator and brush assembly, it makes the d.c. motor not only required intermittent maintenance, but also restrict the used in corrosive or explosive environment and under high speed, the commutator capability is limited. These problems can be solved by the applicant of a.c. motors, where the induction motors are robust, reliable, easy and less maintained. Moreover the cost is low, as well as the inertia and the weight. The main drawbacks that make a.c. motor retreats from industry were the control between flux and torque are inherent coupling. However, this advantage was amended by the exits of vector control credit to the latter development in power electronic device that expands the use of a.c. motor instead of d.c. motor (Boulghasoul et al. 2010) (Takahashi & Ohmori 1989). By virtue of the dominance and the positive circumstances, induction motors are replacing d.c. motors in the industrial applications, even in applications where a fast speed and torque response is required, becoming the new horsepower of the industry.

In recent past, an innovative vector control method namely DTC has gained the attraction (Singh, Member, Jain, Mittal, & Gupta, 2006). The use of DTC strategies has become universal and popular for induction motor drives and seems has a very rapid growth in the development of it. DTC can be considered as a simpler alternative to the FOC technique, where both provide an effective control of the flux and torque. However, unlike the traditional Field Oriented Control (FOC), DTC enables both quick and precise torque response excluding the inner current regulation loop and complex field-oriented block, less parameter dependence and increase the precision and the dynamic of flux and torque response (Kaila & Jani, 2011)(Wu, Gao, Zhao, & Lu, 2008). Hence, DTC is much simpler.

DTC abandons the characteristic of FOC which is the stator current philosophy and achieve the torque and flux control by direct modifying the stator voltage in accordance with the torque and flux error. The conventional DTC scheme consists of a pair of hysteresis comparator for torque and flux where the switching condition of the VSI is generating directly from the torque and flux error. Variable switching frequency is the major drawbacks of conventional DTC. Recently a new digital modulation technique known as space vector modulation (SVPWM) has become very prevalent with the vector control concepts and its offer superior performance and control over the others modulation technique. SVPWM refers to a special technique of determining the switching sequence of the upper three power transistors of a three phases VSI. Theoretically, the produced output voltage can reach a maximum value of 1.15 times higher than the conventional sinusoidal modulation. This modulator makes the motor possible for the efficiency improvement with the higher torque when high speeds due to the possibility of the motor can feed by a voltage with a higher value compare with the sub-oscillation modulation method. Due to the prevalent advantages of SVPWM over the others, in this paper, the SVPWM-DTC was implemented by using the torque and flux errors to produce stator reference voltage. On the other hand, a neural network based speed controller of SVPWM-DTC was implemented to replace the conventional PID controller in order to overcome the common problems of conventional DTC such as overshoot during start up and a poor load disturbance rejection in permanent mode(Abdul Halim & Utomo, 2006)(Utomo et al., 2014). ANNs are excellent estimator in nonlinear systems, insensitivity to the distortion of network inexact input data and its simple architecture(Wlas, Krzeminski, Guzin, & Toliyat, 2005).

ISSN 1819-6608
ARPN Journal of Engineering and Applied Sciences

Thence, a better performance of transient response by reduce the overshoot and torque ripple is obtained.

The increasing emphasis on energy saving is highlighting the importance of attaining higher motor efficiency under all operating conditions especially for the industrial application. Intentionally, a control algorithm that manage to reduce the losses to maximize the efficiency of the IM drives is highly attractive. It is commonly known that the induction motor have good efficiencies while operating at full load. However, at lighter load, which is a condition that many machines experience for a significant portion of their service life, the efficiency decreases to a large extent. It is, therefore, important to maximize the efficiency of the motor drive system while operating in adjustable speed applications. It is well known that the efficiency of an IM drives can be improved by reducing the flux level when it operates under light load conditions. However, the challenge is to be able to predict the extent to which the flux can be reduced, at any operating point over the complete torque and speed range, which will maximize the efficiency. This paper mainly focus on the determination of the most suitable flux value for a DTC fed IM drives for maximization, especially under part-load operation. An ANN based optimum flux predictor is presented. The speed and load torque are used as inputs for the neural network while the producing optimum flux is taken as neural network output (Bhuvaneswari & Satapathy, 2010)(Abdin, Ghoneem, Diab, & Deraz, n.d.). Simulation and experimental result show a significant improvement in efficiency optimization of drive system while at the same time preserve its excellent system performance.

DIRECT TORQUE CONTROL

Machine Model of Induction Motor

The SVPWM-DTC produces the stator reference voltage vectors by adopt of both torque and flux errors, and then feed to the SVPWM algorithm to modulate. The constant switching frequency signal is then exported to the three-phase inverter(Babu & Poongothai, 2008)as illustrated in Fig. 1.

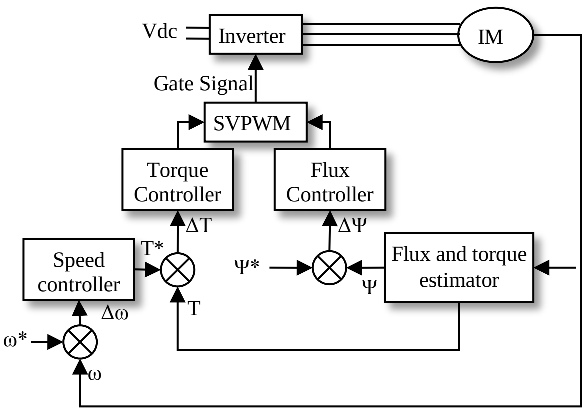

Figure 1: Complete schematic diagram of SVPWM-DTC.

The induction model in the stator fixed d-q reference frame is described by (Choy, Kwon, Choi, Kim, & Kim, 1996).

$$V_s = R_s i_s + \frac{d}{dt}(\Psi_s) \quad (1)$$

$$V_r = 0 = R_r i_r + \frac{d}{dt}(\Psi_r) - j\omega_r \Psi_r \quad (2)$$

$$\Psi_s = L_s i_s + L_m i_r \quad (3)$$

$$\Psi_r = L_r i_r + L_m i_s \quad (4)$$

Whereas the mechanical equation is given as below:

$$\Psi_{ds} = \int (v_{ds} - R_s i_{ds})dt \quad (5)$$

$$\Psi_{qs} = \int (v_{qs} - R_s i_{qs})dt \quad (6)$$

Then, the electromagnetic torque is estimated as

$$T_e = \frac{3}{2}\frac{p}{2}\left(\Psi_{ds} i_{qs} - \Psi_{qs} i_{ds}\right) \quad (7)$$

The parameters for the motor are given as Table 1.

Table 1. Motor Parameter

Motor Parameter	Value
Frequency, f	50 Hz
Pole, p	4
Stator Resistance, R_s	8Ω
Rotor Resistances, R_r	5.8
Stator Self Inductances, L_s	0.215H
Rotor Self Inductances, L_r	0.215H
Mutual inductances, L_m	0.198H

OPTIMUM ADAPTIVE FLUX DETERMINATION

Control Strategy

Basically, this method uses the input power of drive system as the objective function and minimizes it. Fig. 2 shows the proposed optimum flux controller imposed on the SVPWM DTC scheme. To apply the ANN based optimum flux predictor, the input power of motor has been calculated by Eq. 8.

$$P_{in} = V_d I_d + V_q I_q \quad (8)$$

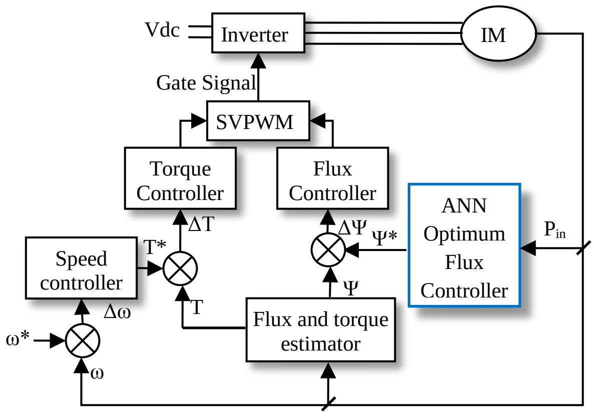

Figure 2: Schematic representation of efficiency optimization algorithm

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ARPN Journal of Engineering and Applied Sciences

Proposed Optimum Flux Controller Based On ANN Algorithm

The basic concept is a must in order to design a successful neural network. The input number of the NN structure is designed based on the number of applicable input signal of the system. Furthermore, the required training accurateness and complexity of the system will determine the total neuron that implemented and the number of hidden layer that requested. In view of the type of the task to be performed, a multilayer perceptrons neural network control is developed to implement speed controller of an induction motor drive, the structure of the proposed NN DTC (Utomo et al., 2014) is as shown in Fig.3.

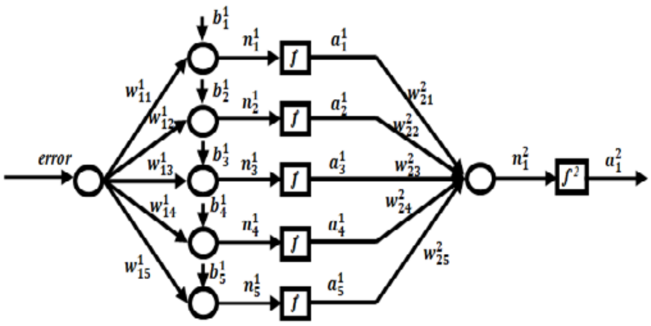

Figure 3: Block diagram of NN speed control for DTC induction motor drive.

The proposed NN speed controller consists of 3 layers namely the input layer, hidden layer and output layer. A 1-5-1 network structure is defined based on the number of neuron in each layer. The first neuron of the output layer is used as a torque reference signal ***($a^2_1=m_f$).*** The connections weight parameter between j^{th} and i^{th} neuron at m^{th} layer is given by w^m_{ij}, while bias parameter of this layer at i^{th} neuron is given by b^m_i. Transfer function of the network at i^{th} neuron in m^{th} layer is defined by:

$$n_i^m = \sum_{j=1}^{S^{m-1}} w_{ij}^m a_j^{m-1} + b_i^m \qquad (9)$$

The output function of neuron at m^{th} layer is given by:

$$a_i^m = f^m(n_i^m) \qquad (10)$$

Where f is activation function of the neuron. In this design the activation function of the output layer is unity and for the hidden layer is a tangent hyperbolic function given by:

$$f^m(n_i^m) = \frac{2}{1+e^{-2n_i^m}} - 1$$

(11)

Updating of the connection weight and bias parameters are given by:

$$w_{ij}^m(k+1) = w_{ij}^m(k) - \alpha \frac{\partial F(k)}{\partial w_{ij}^m} \qquad (12)$$

$$b_i^m(k+1) = b_i^m(k) - \alpha \frac{\partial F(k)}{\partial b_i^m} \qquad (13)$$

where k is an iteration, α is learning rate and F performance index function of the network.

Learning Scheme of the Proposed ANN Optimum Flux Controller

After the neural network architecture is modeled, the learning model is determined in next stage to update network parameters. By this learning capability, it makes the ANN suitable to be implemented for the system with motor parameters which are difficult to define and vary against with environment. The training process minimizes the error output of the network through an optimization method. Generally, in learning mode of the neural network controller a sufficient training data input-output mapping data of a plant is required. Since the motor parameters of the induction motor drive vary with temperature and magnetic saturation, the online learning Back propagation algorithm is developed.

Based on first order optimization scheme, updating of the network parameters are determined. The performance index sum of square error is given by:

$$F(k) = \frac{1}{2}\sum_i e_i^2(k) \qquad (14)$$

$$e_i(k) = t_i(k) - a_i(k) \qquad (15)$$

where t_i is target signal and a_i output signal on last layer.

The gradient descent of the performance index against to the connection weight is given by:

$$\frac{\partial F}{\partial w_{ij}^m} = \frac{\partial F}{\partial n_i^m}\frac{\partial n_i^m}{\partial w_{ij}^m} \qquad (16)$$

The sensitivity parameter of the network is defined as:

$$s_i^m = \frac{\partial F}{\partial n_i^m} \qquad (17)$$

$$s_i^m = \frac{\partial F}{\partial a_i^m}\frac{\partial a_i^m}{\partial n_i^m} \qquad (18)$$

Gradient the transfer function again to the connection weight parameter is given by:

$$\frac{\partial n_i^m}{\partial w_{ij}^m} = a_i^{m-1}$$

(19)

From substitution equation (17) and (19) into (12) the updating connection parameter is given by:

$$w_{ij}^{m-1}(k+1) = w_i^{m-i}(k) - \alpha s_i^m(k) a_i^{m-1}(k) \qquad (21)$$

With the same technique the updating bias parameter is given by:

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$$b_i^{m-1}(k+1) = b_i^{m-i}(k) - \alpha s_i^m(k) \qquad (22)$$

RESULTS AND DISCUSSION

The proposed model has been developed by Matlab/Simulink. The simulation block diagram for the proposed IM drives is shown in Fig. 4. To verify the simulation result in real time, the proposed control method has been applied to an experiment setup for real time testing. The experiment setup, shown in Fig. 5 consists a three phases insulated gate bipolar transistor (IGBT) based inverter to fed the induction motor and controlled through the dSPACE DS1103 Real-time Digital Signal Controller. The entired control system is programmed in C language by the Matlab 2013 and interfaced by the ControlDesk 5.1. The digital control unit and current sensor is used to measure the feedback signal.

In this point, a new control strategy that combines the technique mentioned above is proposed. Where in the first instance includes modification of SVPWM control technique instead of the conventional hysteresis controller to obtaining a better performance with a constant switching frequency and higher output voltage. After, an intelligent speed controller is included for better transient response to reduce the overshoot during start up response. Lastly, the proposed adaptive optimum flux is adopted before the DTC system in order to generate the appropriate flux reference according to a different speed and torque level instead of the conventional constant flux value.

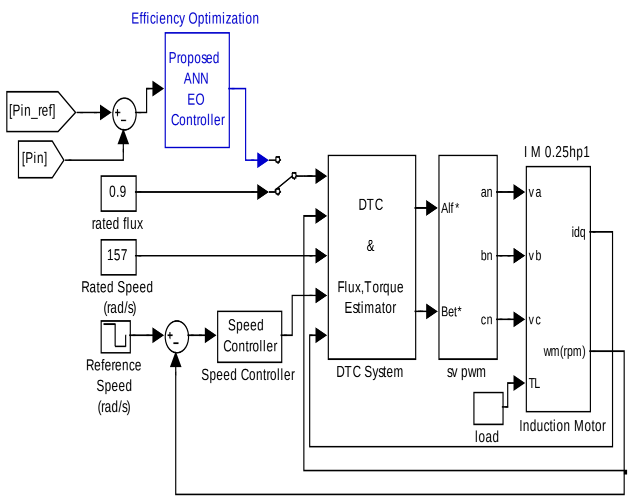

Figure 4: The Simulink block diagram of the proposed LM SVPWM-DTC.

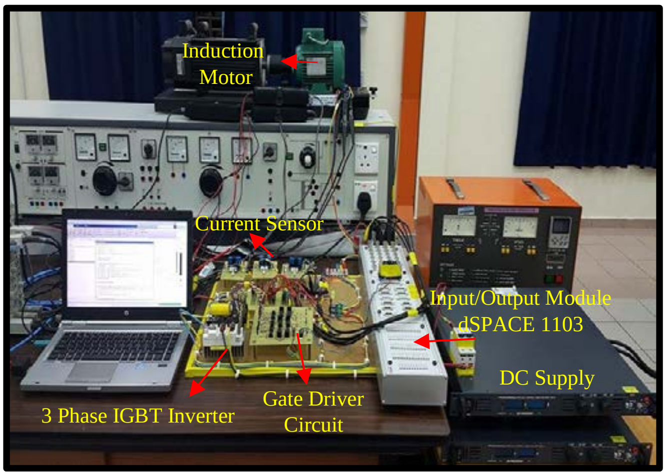

Figure 5: Hardware prototype of the proposed of the proposed EO SVPWM-DTC.

In order to verify the validity of the proposed ANNEO DTC, the efficiency is obtained with and without the ANNEO controller for a variety of speed and torque. Different operating speed is tested, which is 150 rad/s, 120 rad/s, 90 rad/s and 60 rad/s. Corresponding to each speed, different torque value will be tested, which is 0.2 Nm, 0.4 Nm, 0.7 Nm and 0.9 Nm, where the rated torque is 1 Nm for this testing three phase's induction motor. The reference flux value is switched from the conventional constant flux value to the adaptive optimum flux reference generated by the proposed ANNEO controller at the time, t=10 second.

The ANNEO controller is expected to be adaptive and produce the optimal flux level corresponding to variance speed under difference torque in order to attain its maximum efficiency, specifically at low speed and low torque operation. Fig. 6 and Fig. 7 shows the experimental results with the motor speed set as 150 rad/s and 90rad/s while the torque is set as 0.7 Nm and 0.2 Nm corresponding. Both Fig. 6 and Fig. 7, from top to bottom represent the motor speed (rad/s), optimal flux (Wb) and the input power (W) respectively. The optimal flux level determined by the ANNEO was injected to the system at the time of 5s. One can see that the proposed optimum flux controller able to preserve the good dynamic response of the drive systems. The stator flux rapidly decreased from the rated value, 0.9 to its corresponding optimal value, thus, minimize the input power. As a result, a significant amount of efficiency improvement has been achieved at the same time.

The efficiency improvement by the optimum flux instead of the constant 0.9 as the reference for different operating mode is shown in Table 2. The efficiency for each speed, resultant by different torque condition is shown in Fig. 8. A reasonable amount or efficiency has been increased specially at light load. At the low load operation, in both high speed and low speed, the efficiency varies from 52% to 65 % and 30 % to 42% accordingly when the suitable flux value implemented as a reference value yields by the proposed ANNEO controller.

ISSN 1819-6608
ARPN Journal of Engineering and Applied Sciences

Table 2: Efficiency of the DTC with and without EO corresponding to different speed and Torque.

Torque (Nm)	Efficiency, η (%) 0.2		0.4		0.7		0.9	
Speed (rad/s)	**Without EO Controller**	**With EO Controller**	**Without EO Controller**	**With EO Controller**	**Without EO Controller**	**With EO Controller**	**Without EO Controller**	**With EO Controller**
150	51.91	65.31	66.73	73.74	74.64	77.22	76.55	76.98
120	48.33	58.26	63.48	68.89	71.80	73.16	72.33	73.28
90	39.31	50.97	54.61	62.46	63.80	67.12	66.18	67.24
60	30.15	41.61	44.51	52.89	54.02	57.57	56.60	57.80

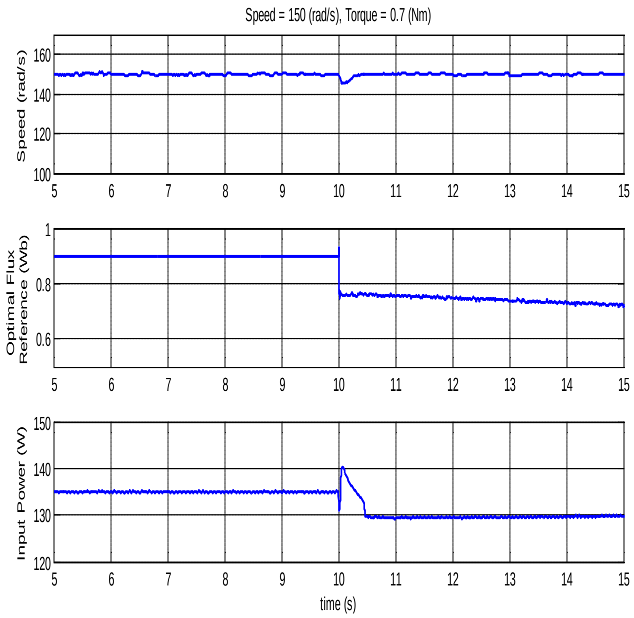

Figure 6: Experimental results of SVPWM-DTC with efficiency optimization applied at the time t=10(s) for the speed of 150 rad/s and a 0.7NM load torque applied.

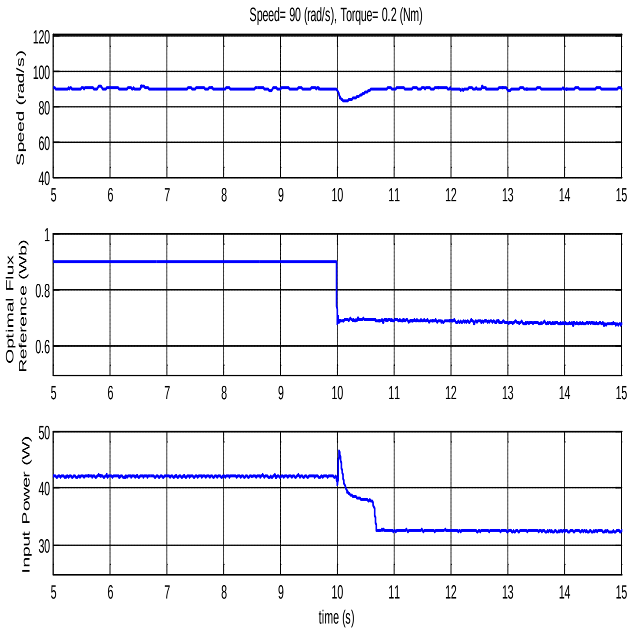

Figure 7: Experimental results of SVPWM-DTC with efficiency optimization applied at the time t=10(s) for the speed of 90 rad/s and a 0.2NM load torque applied.

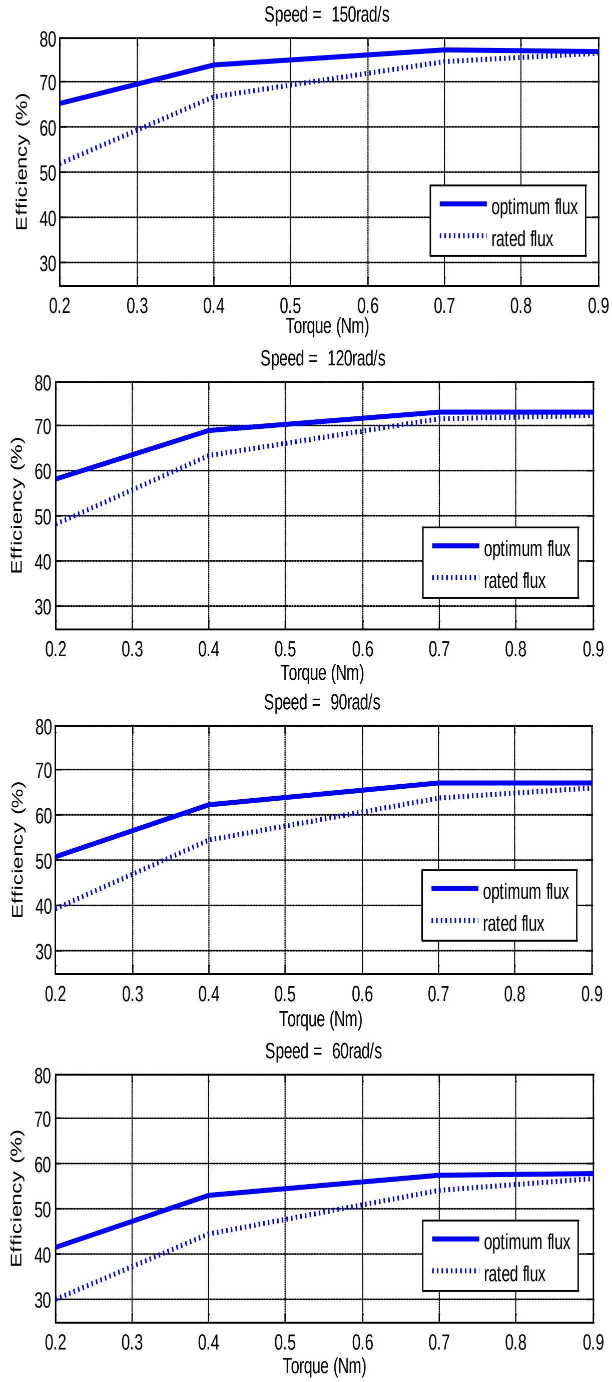

Figure 8: The efficiency for constant flux value and optimal flux value for the speed of 150 rad/s, 120 rad/s, 90 rad/s and 60 rad/s corresponding with different torque value.

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CONCLUSION

An efficiency optimization controller based on the artificial neural network for a three phase induction motor drive system is presented. The proposed controller employs a multilayer perception with a 1-5-1 structure neural network algorithm. The output of the controller is aiming to produce an adaptive flux reference which is suitable for different operating mode instead of the constant flux to maximize the overall drive system efficiency. The proposed controller is a nonlinear controller which can be employed without required any motor parameter data and is proven to be particularly effective at light load and in a steady state of the drive. The experiment shows a significant improvement in the system efficiency with the proposed ANN EO controller, especially at the low torque and low speed operation. In a nutshell, by adjusting the flux level to the suitable value can result in a significant efficiency improvement, thus, the proposed adaptive flux EO controller is significant.

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