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Implementation of a Sliding Mode Controller Trained ANN for Energy Conservation in Induction Motor

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Abstract

This paper presents a sliding mode controller based Neural Networks for energy conservation in Induction motor. A Multi layer Neural Network trained by back propagation learning algorithm is used to compensate for the system uncertainties and provide energy efficient operation for a wide range of loads. The trained Neural Network controls the stator voltage for optimal efficiency under all operating conditions. Simulations and experimental studies were performed to establish the suggestion made in this paper. The proposed algorithm was simulated using Matlab/Simulink and the results show that the performance of the control scheme is robust, the chattering problem is solved and efficiency improvement is achieved.

Keywords*: Speed Control, Field Oriented Control, Sliding Mode Control and Induction motor, Artificial Neural Network, Adaptive control*

1. Introduction

Energy efficient motor may be a correct choice for new application and re-placement motors. The higher price of these motors is paid back rapidly by their improved efficiency (around 5% more efficiency over premium motors). The population size of rewound motor in textile mills and sugar industries may exceed 50%. Motor efficiency degrades due to rewinding heat treatment applied, to strip old windings. Further, change in air gap will also affect the output torque and power factor. Energy conservation can also be achieved in A.C drives by mitigation of voltage unbalances, since unbalanced voltage supplies results in additional losses. For example a 3 H.P. Machine with proper balanced 3 phase supply consumed a power of 2300 watts. The same machine consummated 2800 watts with 30% voltage drop in Phase ‘A’. The loss associated with voltage unbalanced was higher, compared with balanced supply. Such unbalances results in heating of winding and negative sequence currents, which can be avoided by the addition of an A.C drive.

Although the induction motor model is well documented in literatures real time implementation of controller is tedious, due to nonlinearities. This has created the need for black box modeling methods like ANN (Artificial Neural Networks) and Fuzzy for Field Oriented Control (FOC). The FOC provides decoupling of torque and speed creating operating condition similar to D.C. machine

Motivation of the Research

Various incentives have been promoted worldwide for energy conservation and to reduce green house gas emission levels.

1. Small Machines used in low power application do not carry the detailed test certification during purchase. The Motor Efficiency is generally specified with some levels of tolerance. As per the Indian Standard 325 a tolerance of 15% is allowed for

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machines up to 50KW rating. Operation of machines under different load scenarios requires a drive interface between the power supply and machine for energy conservation and environmental conservation.

2. Exact measurement of stray losses is not feasible even with accurate experimentation.

3. A common task in Industrial machine is rewinding of stator during repair or maintains scheduling; this results in increase of resistance of winding and its associated loss.

4. The soft start feature provided by AC drives helps in smooth, acceleration during starting, thereby reducing the damage to windings and bearings. The proposed methods uses (IPM) Intelligent power modules, which provides reduction in cost and increased reliability, in addition to a significant reduction in physical size. Conventional drive units with re-program features can be modified with this energy conservation scheme.

Prior researchers have investigated various control methods for IM like synchronous control [1], slip control [2], flux control and V/F control [3-6] and Field Oriented Control [7-10]. Optimum control of IM is vital as it is not possible to fabricate a motor with maximum efficiency for every operating point, by optimal design of machine parameters. In many applications involving constant speed operation, induction motor operates under partial load for prolong periods. Application of this sort includes spinning drive in mine hoist load, drill presses, textile industry [11], and wood saw. Both efficiency and Power Factor falls to very low levels at light loads. In operating region, induction motor should operate at reduced flux, to create a balance in between iron loss and copper loss, resulting in efficiency improvement. This can be achieved by means of a loss model Controller (ANN2 as per Figure 2). The role of a loss model controller is to measure the speed, stator current and determines optimal air gap flux by loss model. The inner part of the control algorithm can be vector control method.

The proposed energy conservation module is an add-on to the convention Field Oriented Control based on Sliding Mode Controller (SMC). SMC is one of the efficient methods for controlling electric drive system. It is a robust control, as the high-gain feedback control input eliminates nonlinearities due to parameter variations and external disturbance. It offers a fast dynamic response and enhanced stability [12, 13]. The sampled data obtained from the sliding Mode controller is used to train the Proposed ANN.

This paper is organized as follows. The mathematic model is introduced in section 2. Then, the proposed method is presented and ANN algorithm is presented in section 3. In section 4 the final results of simulation and experimental studies are discussed. Finally, section 5 provides the conclusion of this work.

2. IM Mathematical Model

In order to analyze the system performance various hardware components should be mathematically described. The dynamic model of an A.C machine is complex because the three phase rotor windings move with respect to the stator winding. To achieve simplification the model is represented in by an equivalent two-phase d-q model. The Intelligent Power Module (IPM) based AC-to-AC System is considered to be an ideal, where the DC voltage at the input of the inverter has no AC component, and the output of the inverter has no harmonics. Then, the IM model in the stator reference frame is as follows:

$$\frac{d\omega}{dt} = \frac{M}{JL_{rot}}(\psi_a i_b - \psi_b i_a) - \frac{T_L}{J} \qquad (1)$$

$$\frac{d\psi_a}{dt} = \frac{R_{rot}}{L_{rot}}\psi_a - \omega\psi_b + \frac{R_{rot}}{L_{rot}} M i_a \qquad (2)$$

$$\frac{d\psi_b}{dt} = \frac{R_{rot}}{L_{rot}}\psi_b + \omega\psi_a + \frac{R_{rot}}{L_{rot}}Mi_b \qquad (3)$$

Where,

ω ....Actual rotor speed
ψ_a, ψ_b.........Rotor fluxes
M..............Mutual Inductance
i_a, i_b ....Stator currents
L_{rot}............Rotor Inductance
L_{sta}............Stator Inductance

$$\frac{di_a}{dt} = \frac{MR_{rot}}{(L_{rot}L_{sta}-M^2)L_{rot}}\psi_a + \frac{M}{L_{rot}L_{sta}-M^2}\omega\psi_b - \frac{M^2R_{rot}+L_{rot}{}^2R_{sta}}{(L_{rot}L_{sta}-M^2)L_{rot}}i_a + \frac{L_{rot}}{L_{rot}L_{sta}-M^2}u_a \qquad (4)$$

Where,

L_{sta}.........Stator Inductance
R_{rot}........Resistance of Rotor
R_{sta}........Resistance of Stator

$$\frac{di_b}{dt} = \frac{MR_{rot}}{(L_{rot}L_{sta}-M^2)L_{rot}}\psi_b + \frac{M}{L_{rot}L_{sta}-M^2}\omega\psi_a - \frac{M^2R_{rot}+L_{rot}{}^2R_{sta}}{(L_{rot}L_{sta}-M^2)L_{rot}}i_b + \frac{L_{rot}}{L_{rot}L_{sta}-M^2}u_b \qquad (5)$$

Two Phase stationary (α, β) to Two Phase rotating (d, q) conversion was done using the Park Transformation and the outputs forms a two co-ordinate time invariant system (Proposed by Robeter H. Park). Such a time invariant system is very useful in control application as the complexity of the differential equation is reduced by the time invariance. The same transformations apply for flux linkages and phase voltages. The variables in the d-q reference frame are given as follows:

$$\begin{bmatrix}\psi_d\\ \psi_q\end{bmatrix} = \begin{bmatrix}\cos\varphi & \sin\varphi\\ -\sin\varphi & \cos\varphi\end{bmatrix}\begin{bmatrix}\psi_a\\ \psi_b\end{bmatrix} \qquad (6)$$

$$\begin{bmatrix}i_d\\ i_q\end{bmatrix} = \begin{bmatrix}\cos\varphi & \sin\varphi\\ -\sin\varphi & \cos\varphi\end{bmatrix}\begin{bmatrix}i_a\\ i_b\end{bmatrix} \qquad (7)$$

$$\begin{bmatrix}u_d\\ u_q\end{bmatrix} = \begin{bmatrix}\cos\varphi & \sin\varphi\\ -\sin\varphi & \cos\varphi\end{bmatrix}\begin{bmatrix}u_a\\ u_b\end{bmatrix} \qquad (8)$$

ψ_d, ψ_q ....Rotor fluxes in the d-q frame
i_d, i_q ....Stator currents in the d-q frame
u_d, u_q...........Stator Voltage in the d-q frame

$$\frac{d\omega}{dt} = \frac{M}{JL_{rot}}(\psi_a i_b - \psi_b i_a) - \frac{T_L}{J} \qquad (9)$$

$$\frac{d\psi_d}{dt} = \frac{R_{rot}M}{L_{rot}}i_d - \frac{R_{rot}}{L_{rot}}\psi_d + (\omega_e - \omega)\psi_q \qquad (10)$$

$$\frac{d\psi_q}{dt} = \frac{R_{rot}M}{L_{rot}}i_q - \frac{R_{rot}}{L_{rot}}\psi_q + (\omega_e - \omega)\psi_d \qquad (11)$$

$$\frac{di_d}{dt} = -\left(\frac{L_{rot}R_{sta}}{L_{rot}L_{sta}-M^2}\psi_a + \frac{M^2R_{rot}}{(L_{rot}L_{sta}-M^2)L_{rot}}\right)i_d + \omega_e i_q + \frac{MR_{rot}}{(L_{rot}L_{sta}-M^2)L_{rot}}\psi_d + \frac{M}{L_{rot}L_{sta}-M^2}\omega\psi_d + \frac{L_{rot}}{L_{rot}L_{sta}-M^2}u_d \qquad (12)$$

$$\frac{di_q}{dt} = -\left(\frac{L_{rot}R_{sta}}{L_{rot}L_{sta}-M^2} + \frac{M^2R_{rot}}{(L_{rot}L_{sta}-M^2)L_{rot}}\right)i_q - \omega_e i_d + \frac{MR_{rot}}{(L_{rot}L_{sta}-M^2)L_{rot}}\psi_q + \frac{M}{L_{rot}L_{sta}-M^2}\omega\psi_q + \frac{L_{rot}}{L_{rot}L_{sta}-M^2}u_q \qquad (13)$$

For the case of a current-controlled PWM the model is reduced into a third-order system [14-15].

$$\frac{d\omega}{dt} = \frac{M}{JL_r}\left(\psi_d i_q - \psi_q i_d\right) - \frac{T_L}{J} \qquad (14)$$

$$\frac{d\psi_d}{dt} = \frac{R_r M}{L_r} i_d - \frac{R_r}{L_r}\psi_d + (\omega_e - \omega)\psi_q \qquad (15)$$

$$\frac{d\psi_q}{dt} = \frac{R_r M}{L_r} i_q - \frac{R_r}{L_r}\psi_q + (\omega_e - \omega)\psi_d \qquad (16)$$

The rotor flux is aligned with the *d* axis and kept constant.

$$\psi_q = \psi_q = 0 \qquad (17)$$

$$\psi_d = \psi_r = \text{const} \qquad (18)$$

Equation (15) and (16) can be modified using (17) and (18) as below,

$$\omega_s = \omega_e - \omega = \frac{R_r M}{L_r \psi^*} i_q = \frac{M}{L_r \psi^*} i_q \qquad (19)$$

$$i_d = \frac{\psi^*}{M} \qquad (20)$$

Where,

ω_s……. Slip frequency

i_d …….. Flux component of current in steady state

The aim of the vector control method shown above is to ensure that the actual speed ω follows the reference speed ω* with a better transient response.

$$\tau \frac{di_q}{dt} + i_q = u \qquad (21)$$

$$\frac{dx_1}{dt} = x_2 \qquad (22)$$

$$\frac{dx_2}{dt} = -a_1(t)x_2 - a_1(t)x_1 - b(t)u \qquad (23)$$

$$u = \varphi x_1 \qquad (24)$$

$$\varphi = \begin{cases} \alpha, -x_1\delta > 0, \\ \beta, -x_1\delta < 0 \end{cases} \qquad (25)$$

3. Proposed Method

Induction Motors (IM) are preferred for industrial application worldwide, due to their rugged structure and maintenance free operation. IM operate at maximum efficiency at rated torque and speed (Full load condition). However, under partially loaded conditions IM efficiency reduces due to the imbalances between the variable losses (Copper Loss) and fixed losses (Core Loss). This has lead to the development of several efficiency improvement methods based on scalar and vector control methods [16-20].

The Proposed system consists of AC to D.C front end converter followed by a D.C to A.C converter as shown in Figure 1. The D.C to A.C converter was fabricated using Powerex Intellimod PM50L1A120. The device features built –in gate drive, IGBTS, Free-wheel diode and protection circuits. The D.C link Voltage was maintained at 700V D.C any apparent increase in this level can be controlled by means of the braking IGBT. The Experimental Setup used for this study is shown in Figure 2. The gating pulses were derived from a SPARTAN3 FPGA. Current sensing was done externally using LEM current sensors. Excess current drawn during startup is limited by the use of soft start principle, wherein the pulse width is increased gradually from Ton =0.

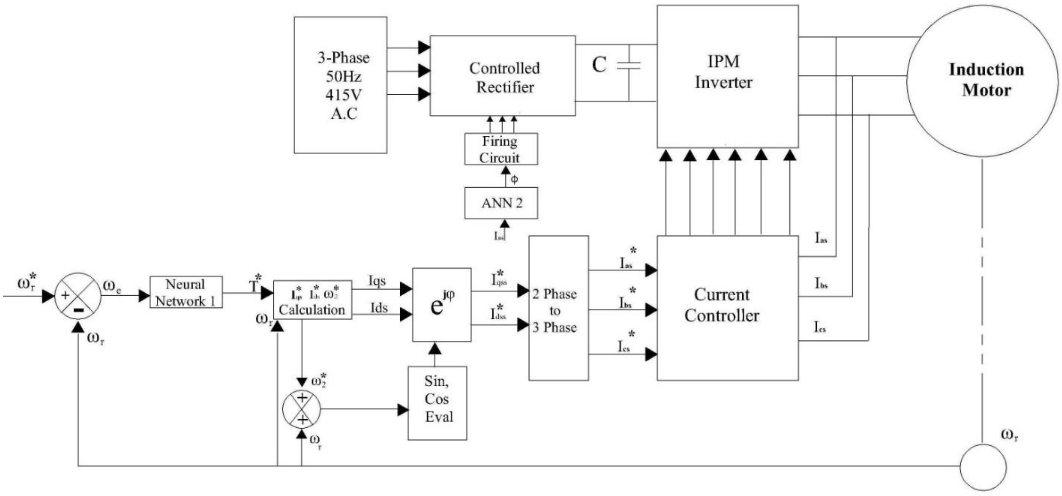

Figure 1. Block Diagram of Proposed Systems

The ANN1 Controller is a SMC trained network which receives a sampled vector of speed error to evaluate the reference torque. The job of ANN 1 is system identification performed on the SMC based conventional FOC [10]. The ANN 1 controller was tuned for have several important functions: they provide feedback; they need to eliminate steady state error. The use of ANN controller for torque control of induction motor drives is to overcome an overshoot during startup and to minimize steady state error.

In general, the working of ANN2 can be considered as voltage reduction circuit. The voltage reduction is proportional to the load. The 3Φ IM is like rotating transformer wherein the induced E.M.F is given by

$$E=4.44\Phi K.T.f \tag{26}$$

Where,

E ………Induced Voltage
Φ……….Flux
K……….Winding Constant
T……….Number of turns per phase
f………..Frequency

From (26) it can be inferred that the flux reduces with induced voltage. Through practical experimentation it was found that with partially loaded terminal voltage reduction up to 350V can be permitted.

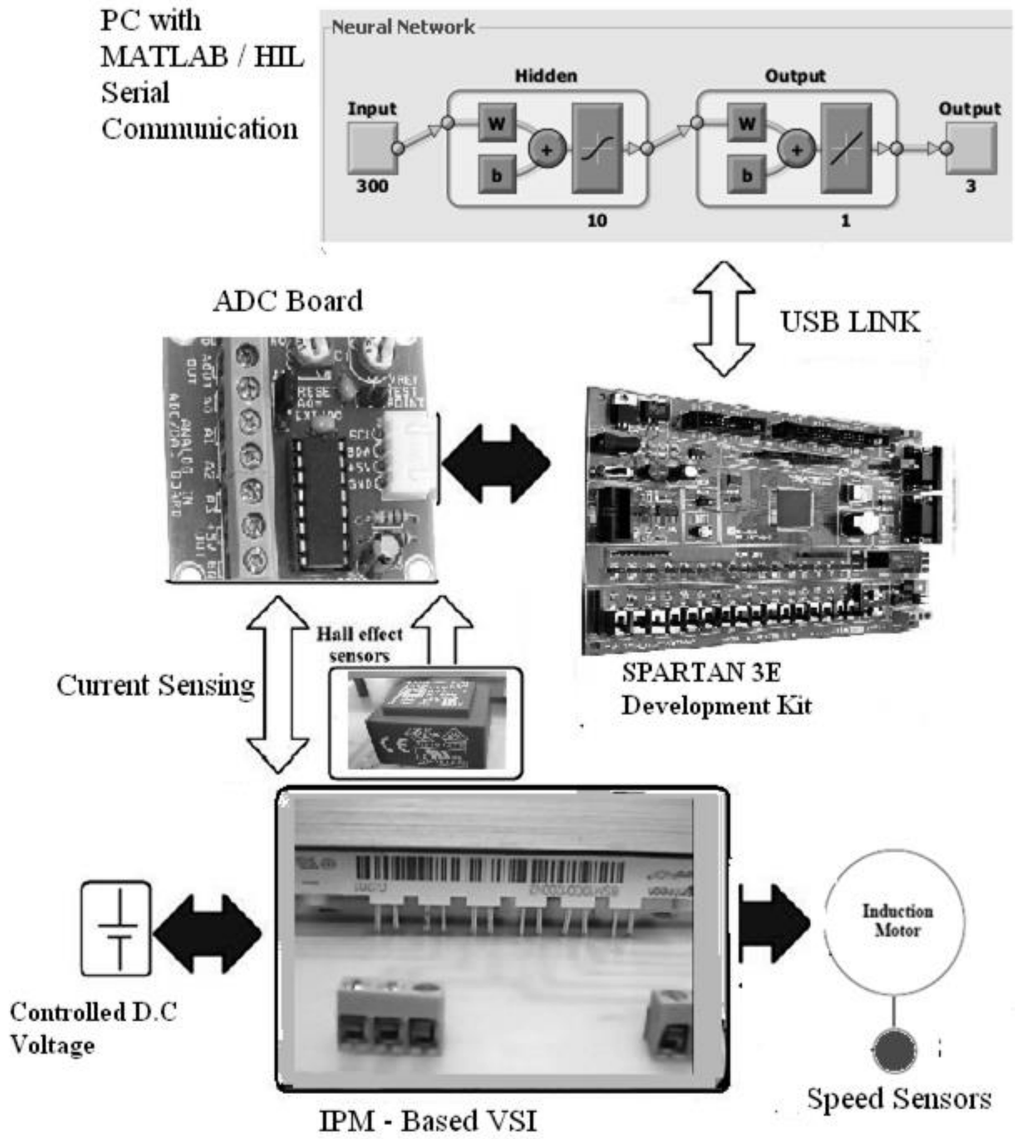

Figure 2. Hardware Implementation

3.1. Variable Structure Control

In Nonlinear plant simplification commonly involves order reduction to facilitate easy computation. Non-linear systems imprecision's arises due to actual uncertainty of the plant and due to simplified representation of the plant models. Actual uncertainty of plant can be solved by the use of robust controllers (system with less parameter variations and disturbances). Amongst these Sliding Mode Control (SMC) has served as an important tool for non- linear systems, where modeling inaccuracies, parameter variations and disturbances are present. The SMC is a form of variable structure controller developed by Russian scientists during 1950. It is composed of several different continuous functions which can map the plant state to a control surface. The final trajectory is not limited to one control structure; instead it slides along the boundaries of the control structure.

3.2. Practical Limitation of SMC

The implementation of SMC involves fast switching of control signals, which leads to chattering. Chattering refers to the unwanted fast oscillations of the system trajectories around the sliding surface. Sampling process of digital circuits also creates chattering problem. This is due to fact that the plant acts as an open loop system between any two sampling instants. In this case black box modeling methods like Fuzzy and ANN can be opted.

3.3. Artificial Neural Networks

Artificial Neural Networks (ANN) refers to computer programs developed to mimic the working of human brain. Two Neural Controllers namely ANN1 and ANN2 were developed using the HIL (Hardware in Loop) feature of MATLAB. The job of the ANN2 would be to adjust the stator Voltage to an optimal level so that the variable loss is reduced and the efficiency is improved under various load scenarios. Similarly, the job of ANN1 is to model the sliding mode controller found in conventional vector control schemes. The various steps involved in implementation of ANN are as follows,

1. Collect ANN training data through field experimentation using the conventional SMC based FOC. The training set for ANN1 comprises of ω_c as input and T^* as the output. Similarly, the load current, losses and efficiency serve as the training data for the second ANN (ANN2). These data is scaled in the range of 0 to 1.
2. Create a feed-forward neural network structure consisting of input layer, hidden layer and output layer. Initialize the weights and select a learning rate.
3. Perform Training on the network until goal is reached (Training refers to the weight adjustment process).
4. Validate the trained network using testing data (about 25% of the samples collected were used for testing).

Table 1 represents the ANN parameters used for controller 1 and controller 2. The number of input and output layer was selected based on the size of input and output training vector. The hidden layer size as selected by trial and error to achieve best training characteristics. The goal of Mean square Error (MSE) =10 E-4 was arrived at 19 Epochs for ANN1 and at 13 Epochs for ANN2

Levenberg-Marquardt algorithm an effective training algorithms for the feed-forward neural networks is used to modify the weights in accordance with the training vector. For the weight connecting a node in layer k to a node in layer j the change in weight of the n^{th} epoch is given by,

$$\Delta W_{kj}(n)=\alpha\delta_j y_k + \mu\Delta W_{kj}(n-1)$$

Where,

α ……..Learning rate [0,1];
y_k …….Activation of the node in layer k;
μ ……..is the momentum [0,1];
δ_j …….. Error factor

Table 1. ANN Parameters

Parameter	**Value ANN1**	**Value ANN2**
Number of Neurons in hidden layer	30	40
Number of Neurons in Input Layer	10	10
Number of Neurons in Output layer	1	1
Network structure	FFNN	FFNN
Training Algorithm	Levenberg-Marquardt	Levenberg-Marquardt
Algorithm Termination Conditions - Mean square Error (MSE) - Epochs	 10E-4 100	 10E-4 100

The error term for output layer is given by,

$$\delta_j= (t_j-y_j) *y_j * (1-y_j);$$

Similarly the error term for output layer is given by,

$$\delta_j = \sum_{i \in Ij} \delta_j * w_{ji} * y_j * (1-y_j);$$

From the above equation it's obvious that calculation of error term for a hidden layer requires the error term from nodes in the subsequent layer (*i.e.* downstream), and so on unto output layer. Thus, computation of error term propagates backward, beginning with output layer and terminating with the first hidden layer (hence called Error Back Propagation).

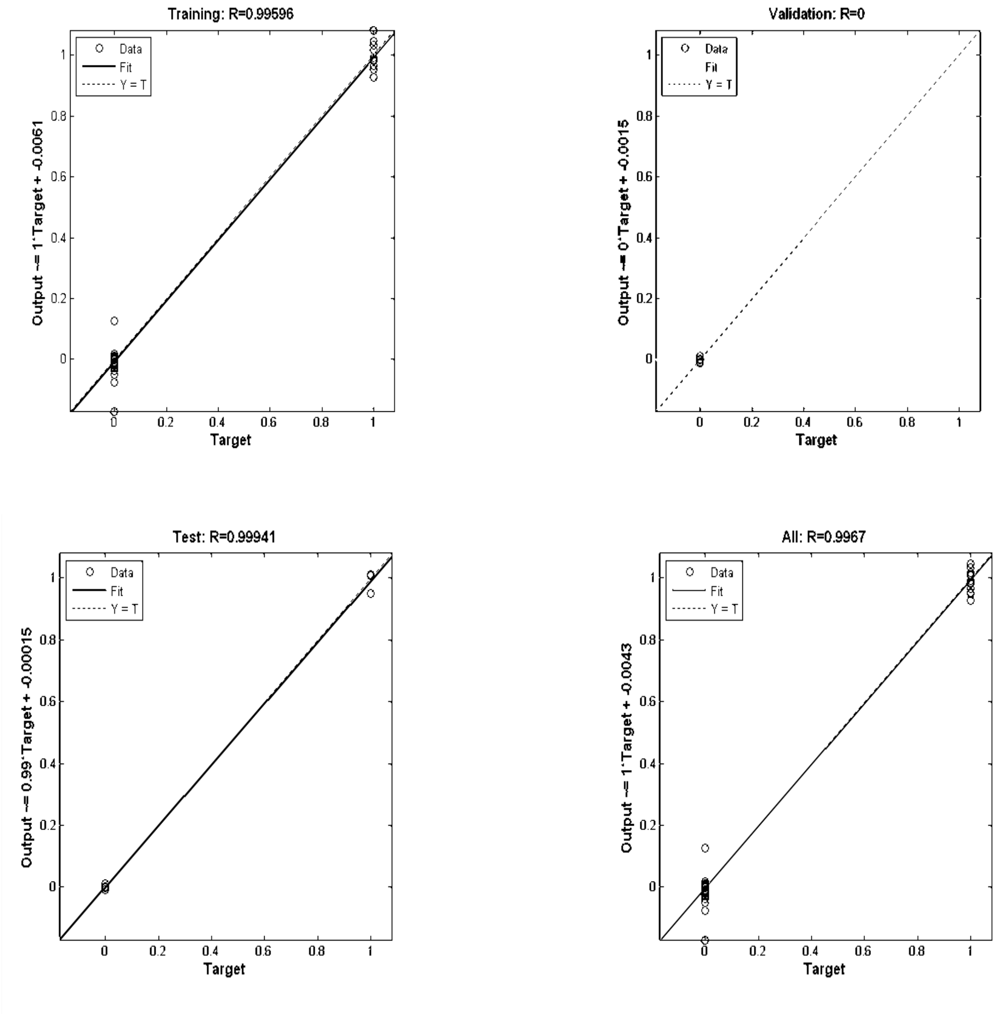

Figure 3. Training, Validation and Test Performance of ANN1.

The value R is a relation indicator between the actual outputs and the targets. Our aim was to attain R=1 thereby creating a perfect match between the output and target. With reference to Figure 3 it can be seen that R=0.9 for all the three cases, conveying that ANN1 structure represents the speed controller absolutely.

4. Results and Discussions

These section explain the system behavior under different operating conditions. To test the proposed system a 3 H.P. and 30 H.P I.M. was selected and the controller performance was carefully examined. The Parameters of the Electrical machine used for hardware prototype and simulation studies are given in Table 2 and Table 3 respectively. Different test conditions investigated are shown in Figures 4-7.

Table 2. Induction Machine used in the Prototype

Induction Motor Ratings	3 H.P., 415 V, 50 Hz
Number of Poles	4
Rated Current	4.5A
Ambient Temperature	45 Degree C
Stator Resistance	2 Ohms
Rotor Resistance	3.68
Stator Inductance	0.23 H
No load Speed,	1440 RPM
Full load speed	1430 RPM
Stator Slots	36
Air gap Length	1 mm

Table 3. Induction Machine Normal Ratings – MATLAB Simulation

Parameter Name	Normal Values	For Robustness Test
Machine type	Squirrel Cage, Three phase, 50 Hz	Squirrel Cage, Three phase, 50 Hz
Power	30 HP	30 HP
Speed	1440rpm	1440rpm
Stator Resistance R_s	0.248 Ohms	0.31 Ohms
Rotor resistance R_r	0.25 Ohms	0.31 Ohms
Stator Reactance X_{Ls}	0.43 Ohms	0.537 Ohms
Rotor Reactance X_{Lr}	0.43 Ohms	0.537 Ohms
Number of Poles P	4	4
Mutual Inductance M	0.06	0.06
Moment of Inertia J	0.305 Kg-m^2	0.305 Kg-m^2

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4.1. Starting Performance and Step change in Load Torque

At time t = 0 the 30 H.P IM machine is started to track a reference speed of 120rad. The machine takes 0.8 seconds to reach steady state as shown in Figure 4. At time t = 1.8 seconds the load torque is change from 5 to 148 N.m. The machine accelerates to the rated torque within 0.3 seconds. From the speed tracking response it can be seen that the ANN1 provides a good tracking with less overshoots and static error. The results show that it is possible to train an ANN from sliding mode control topology to implement FOC. This approach reduced the tuning problem of conventional speed controllers.

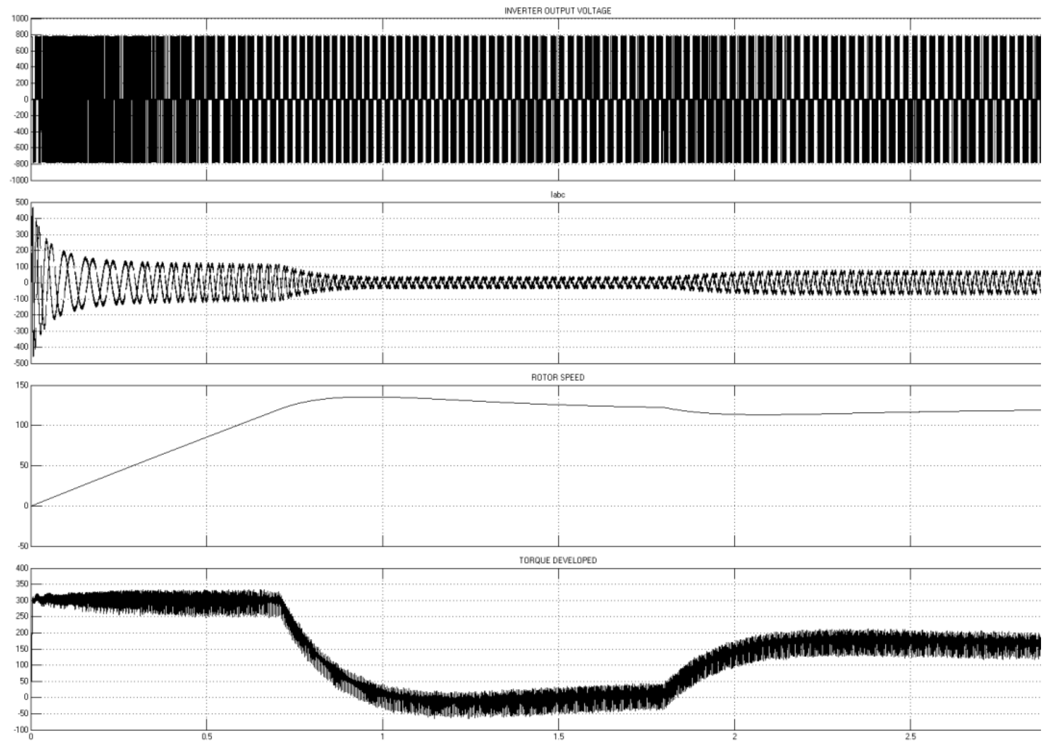
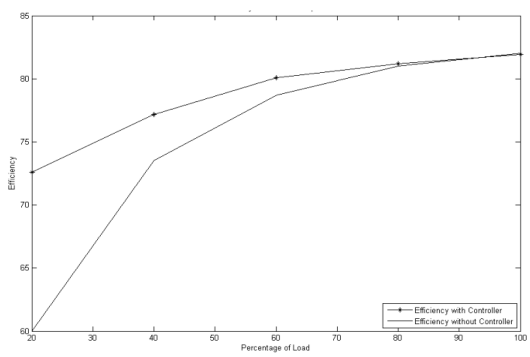


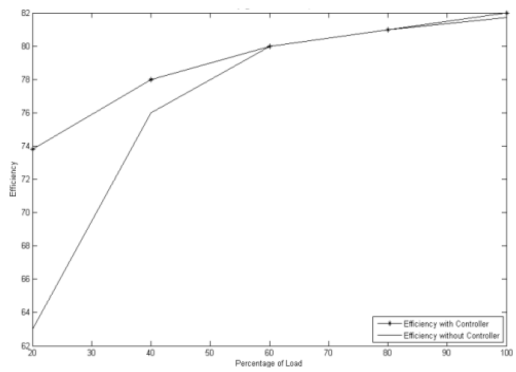
Figure 4. Starting Performance and Loading Effect

4.2. Energy Conservation under Partial Load

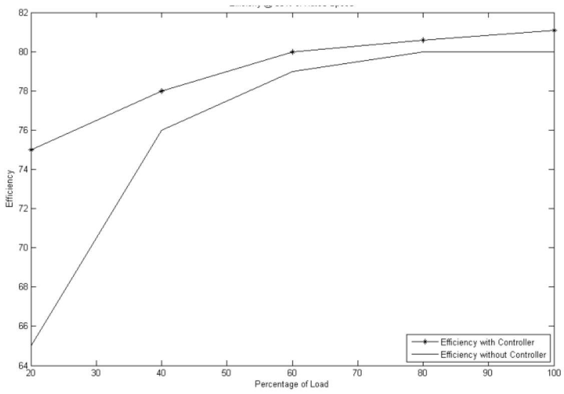
Induction machines Efficiency can be evaluated by two standard methods; a) IEC 34-2, b) IEEE 112. The IEC methods used in this research is relatively easier, but for smaller machines (<10 KW) it overestimates efficiencies by upto 2%. In this test the machine is made to drive a load of 75N.m (50 % loading) at time t=2 Seconds. As shown in Figure 6 the Energy Controller (Sampled every 3 Seconds) comes to action at t=3 reducing the terminal voltage to 360V at t= 3.1 sec. Energy Conservation controller characteristics obtain by experimentation for various ranges of speed and load conditions are displayed in Figure 5(a- d).

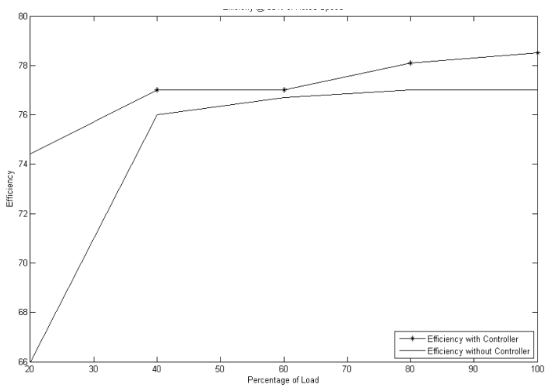


(a)

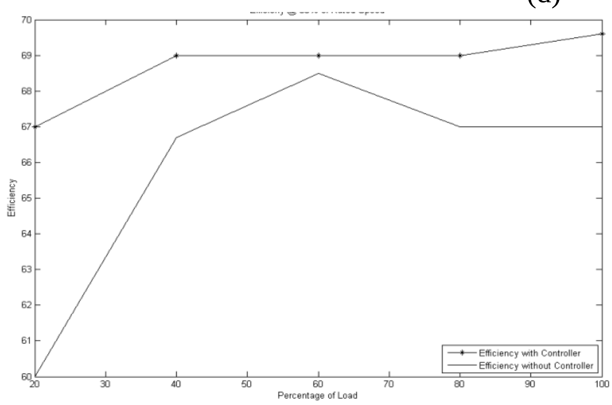


(b)





(c) (d)



(e)

Figure 5. Efficiency under Different Load Scenarios (a) Rated Speed (b) 80% of Rated Speed (c) 60% of Rated Speed (d) 40% of Rated Speed (e) 20% of Rated Speed

The performance of the Energy conservation controller is good for machine running at speed upto 60% of the rated speed. Further it's obvious that the effect of energy conservation controller is not significant when the machine operates at rated speed and full load.

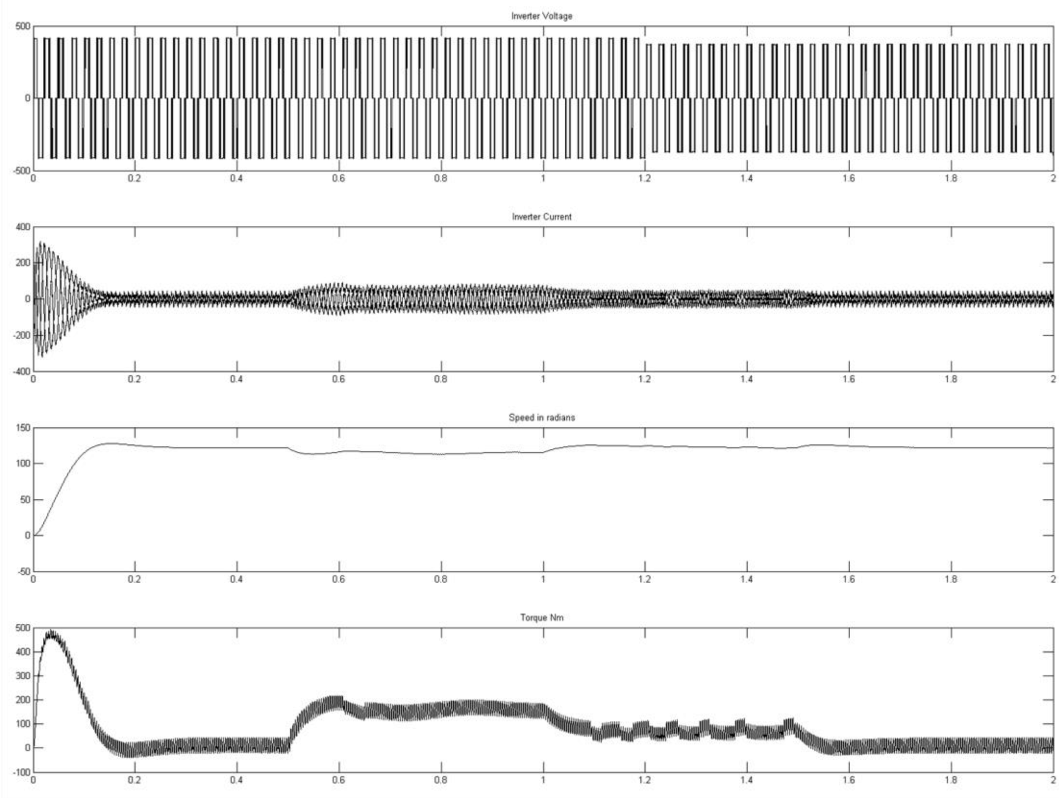


Figure 6. Efficiency Improvements under Partial Load

The efficiency improvement under partially loaded condition is shown in Figure 5. The machine load was reduce from the full value of 148 N.m to 70N.m at time T= 1 sec. The energy conservation loop samples the system load changes every 2 seconds. The voltage regulation action is carried by the neural controller at time t=1.2 and it can be seen through the drop in inverter output voltage.

4.3. Robustness Test

The robustness test was performed by varying the resistances and inductances of stator and rotor (as given in Table 1). This would represent a practical situation of overheating due to continuous operation under high ambient temperature. A loading sequence similar to that of case 1 was applied and the simulation results are presented in Figure 7. It can be the observed that the speed remains robust even with changes in parameters.

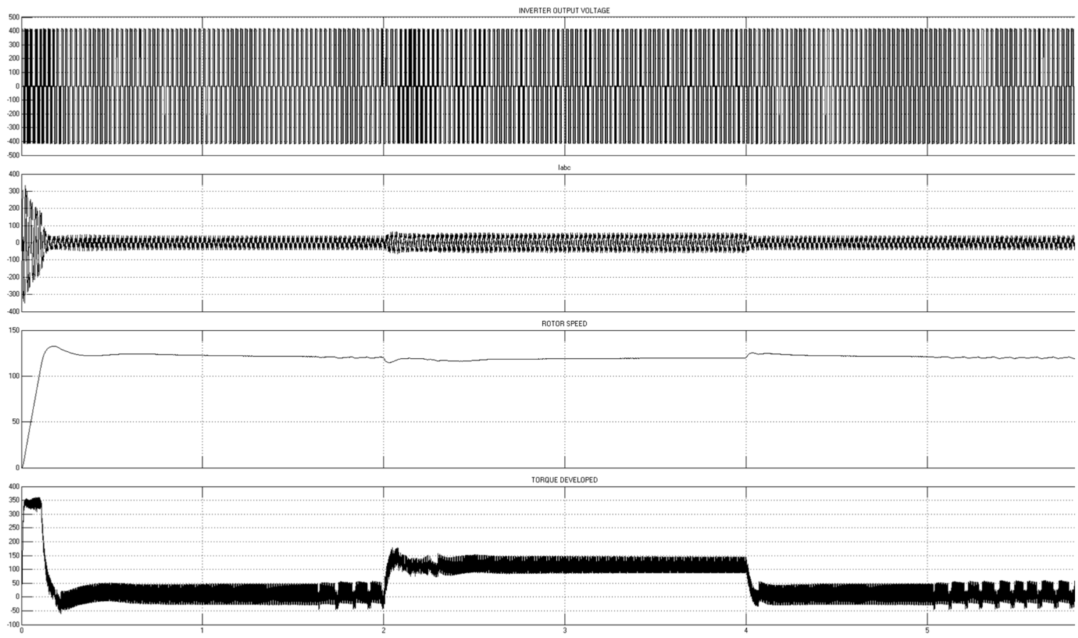


Figure 7. Motor performance with Parameter Variation

5. Conclusion

This paper reported an ANN based controller to operate the machine with maximum efficiency, under partially loaded conditions. The proposed scheme can provide energy savings in applications like pump drives and hoist. The major high light of the proposed method is that the computation burden of Tuning conventional PI or PID controllers is completely eliminated. The on-line training feature demonstrated in this work can be used to adopt the controller for different sized IM. Efficiency of partially loaded machines can be improved by 7 to 10 % without any major disturbance in torque.

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