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Soft starter of an induction motor using adaptive neuro fuzzy inference system and back propagation based feedback estimator

By

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Abstract:

Induction motor is most widely used motor in the industry. It requires sophisticated control of speed, inrush current and pulsations in the electromagnetic torque developed at the starting. This paper presents the neural network based soft starter with feed back estimator to support the on-line training of the network. Thyristor-based controller is used whose firing angles are adjusted by adaptive neuro fuzzy inference system (ANFIS) whose rule base was developed with the experience of the experts and off-line simulation data. A neural network based estimator is designed using back propagation based training algorithms to compute the electromagnetic torque, rotor angles and fluxes fed to ANFIS to adjust the firing angle of the thyristors. Back propagation based neural network was found to be the best among many others because this algorithm requires very small number of neurons. The presented approach can be used with off-line training as well as with on-line training and hence solve the problem of on-line computation of firing angle. Estimator developed was compared in results with the DSP- based estimator and results are shown.

Keywords:

Adaptive neuro fuzzy inference system, artificial neural network, soft starter, induction motor, thyristors, voltage controller, firing angle, inrush current and torque.

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1. Introduction:

Induction motor is the most widely used motor in the industry. Control of speed, torque and inrush current not only enhances the performance of the induction motor but also of the system which contains it. Soft starter by controlling the voltage controls the inrush current, pulsations in the developed torque and speed as well [1]-[2]. Performance of the system depends upon the soft starter which is basically the AC voltage controller and is the part of every modern induction-motor drive. Soft starter provides smooth acceleration reducing the mechanical stresses over the motor due to high torque and increases the life, stability and reliability of not only the motor but also of the equipment connected with the shaft [3]. Electrical stresses over the supply are reduced with controlled voltages and inrush current and brown out conditions are eliminated. Energy conservation is another advantage of the soft starter [4]. By adjusting firing angles of the thyristors i.e., by changing the voltage, start-stop mechanism and speed of the motor can also be controlled [5]-[6]. The firing angle of thyristors is the non-linear function of the speed and torque so their estimation is used to determine the firing angle under different conditions of load torque and speed of induction motor [7]. Proper firing angle reduces pulsations in the developed torque as it is proportional to square of the voltage [8]. The control strategy ensures such a firing angle that first peak of the stator current is not exceeded above the rated current and this is achieved by evaluating firing angle from time dependent functions [9]. The final value of firing angle adjusts the developed torque and speed to the desired value [10]. By keeping the firing angle constant for a while, the motor accelerates with the chosen constant torque [9]-[11].

Number of control techniques has been suggested in different research articles for the soft starting of induction motor. Reference [8] presents a triac-based soft starter with reduced harmonics developed in the system but does not satisfactorily control the pulsations in the torque and inrush current. Reference [6] provides the soft starter with artificial neural network based control to adjust the firing angle but there is no feed back or estimation of the developed torque, speed and other parameters. Adaptive neuro fuzzy inference system (ANFIS) based soft starter combining the capabilities of neural networks and fuzzy logic has reduced the pulsations in the developed torque and inrush current in reference [16] but time taken to achieve the steady state is much higher. This paper presents a soft starter with adaptive neuro fuzzy inference system based firing angle controller and artificial neural network based feed back estimator: working in coordination for a given condition it adjusts the firing angle. The inrush current and pulsations in torque are reduced significantly. The results were compared with DSP-based estimator and were found satisfactory resulting in very low cost as compared to DSP-based system. Performance of the system was evaluated in term of mean squared

error, training time of the network, reduction in inrush current, removal of pulses from the developed torque, hardware complexity and cost of the system and was found much better as compared to available soft starters.

2. Modelling of Induction Motor:

To implement the soft starter, the dynamic model of induction motor was implemented with the real time data in Matlab Simulink using dynamic as well as static frame of references, as given in detail in references [12] and [13]. The transformation equation from d-q axis voltage to d-q axis current used is given as follows:

$$\begin{bmatrix} V_{qs} \\ V_{ds} \\ V_{qr} \\ V_{dr} \end{bmatrix} = \begin{bmatrix} (R_s + sL_s) & \omega_e L_s & sL_m & \omega_e L_m \\ -\omega_e L_s & (R_s + sL_s) & -\omega_e L_m & sL_m \\ sL_m & (\omega_e - \omega_r)L_m & (R_r + sL_r) & (\omega_e - \omega_r)L_r \\ -(\omega_e - \omega_r)L_m & sL_m & -(\omega_e - \omega_r)L_r & (R_r + sL_r) \end{bmatrix} \begin{bmatrix} i_{qs} \\ i_{ds} \\ i_{qr} \\ i_{dr} \end{bmatrix} \quad (1)$$

The induction motor model was tested for a number of different conditions and was found accurate. The motor used in the implementation and simulations results shown later on has the following parameters: three phase, Y-connected, 1 KVA, 400 V, 50 Hz, stator resistance $R_s = 1.115$ ohm, leakage inductance of stator and rotor $L_{ls} = L_{lr} = 0.005974$ H, Rotor resistance referred to stator side $R_r = 1.083$ ohms, Mutual inductance $L_m = 0.2037$ H, Inertia constant $J = 0.02$ kg.m², friction factor $F = 0.005752$ N.m.s and no. of poles $P = 4$.

3. Soft starter:

The soft starter is basically the voltage controller whose output voltage is adjusted by controlling the firing angle of back to back connected thyristors pairs. The thyristor are fired in particular sequence at appropriate time. In our case the firing angle is controlled by adaptive neuro fuzzy inference system in coordination with artificial neural network based feed back estimator which has a defined rule base depending upon different situations. Firing angle is decided for particular condition by consulting the rule base developed by using the experience of the experts of the domain and simulations in Matlab Simulink. The calculated firing angle adjusts the rms value of the voltage to ensure the limited inrush current and reduced torque pulses.

Voltage controller was modeled with the power electronic switches selecting real time operating conditions for simulations. The system showed in Figure 1 gives the block diagram of the system while Figure 2 gives the detailed block diagram of soft starter

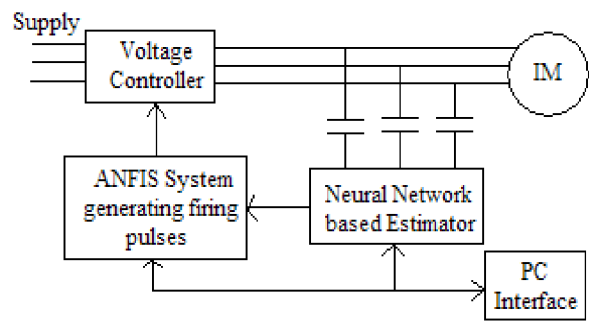


Figure (1): Block diagram of system

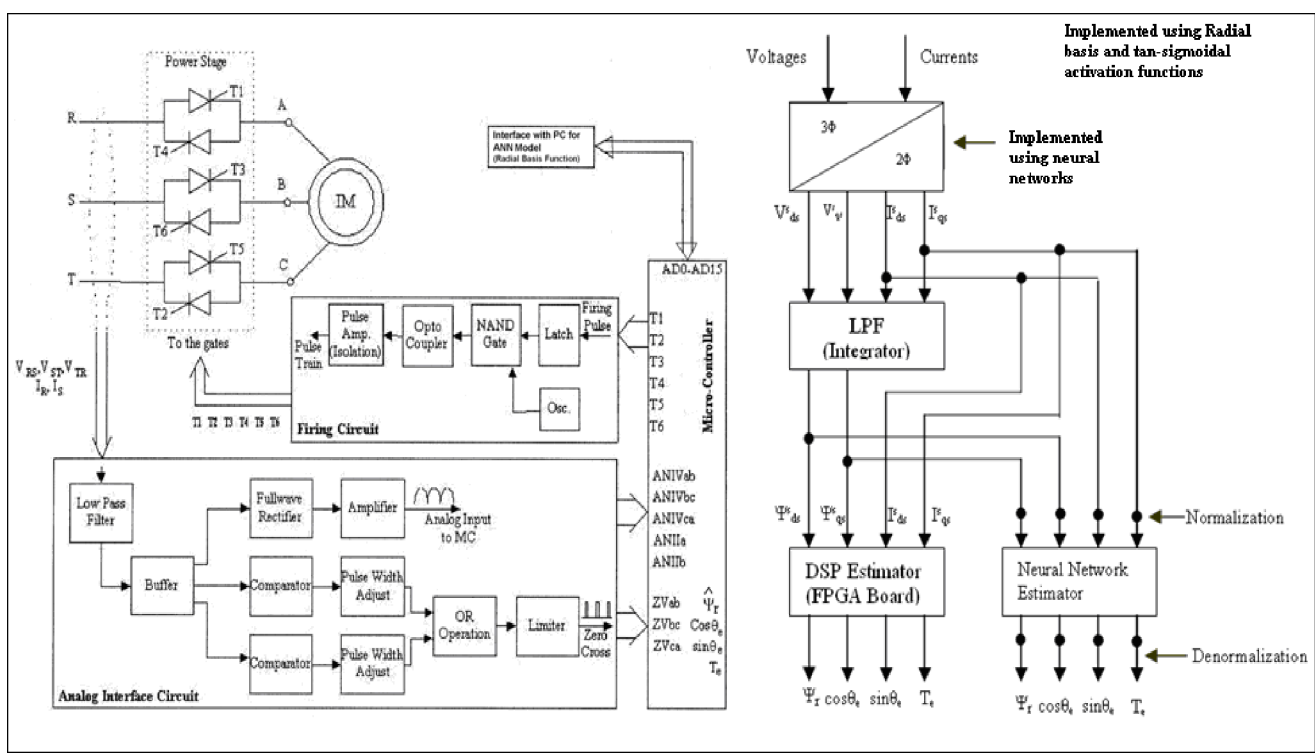


Figure (2): Detailed block diagram for the system containing voltage controller, isolator circuit, estimation network, DSP based network implementation for the comparison of results, microcontroller based link between the ANFIS and neural networks and voltage controller and PC interfacing for the training of neural networks and updating of rules in ANFIS.

that was completely modeled in Simulink and tested for about 25 different conditions with different types of motors and showed the satisfactory results as the starting torque and current were very close to the desired values. The inrush current, voltage dips in the system, speed and torque pulsations were recorded for each condition. It was found that the inrush current reduced remarkably to just the 1.3 times of rated value as compared to six to eight times of rated current in conventional starting techniques discussed in

reference [2].

The proposed system can modify itself as the weights of the neural networks can be recalculated for any induction machine and can be updated through the PC interface so it's the 'intelligent control' as the ANFIS can decide under any conditions according the rule base of system.

4. Adaptive Neuro Fuzzy Inference System

The adaptive neuro fuzzy inference system used is based upon Takagi and Sugeno's fuzzy if-the rule and can be used for classification, modelling and controlling of different problems [1],[14]-[15]. The designed ANFIS takes torque and speed as the inputs while decides the firing angle using inputs and defined rule base to adjust the voltage.

The architecture of ANFIS as shown in Figure 3 consists of five layers. The first layer is fuzzification layer which decides the membership value for each input. Second layer calculates the firing strength of each rule using the product inference and termed as rule inference layer. The third layer normalizes the firing strength and consequent function is determined in the fourth layer. The fifth layer calculates the weighted sum consequent function and the output from this layer is the firing angle. The selected ANFIS was implemented using PIC microcontroller and PC interface, as the database of the rules was stored on the PC because of limited memory available in the controller.

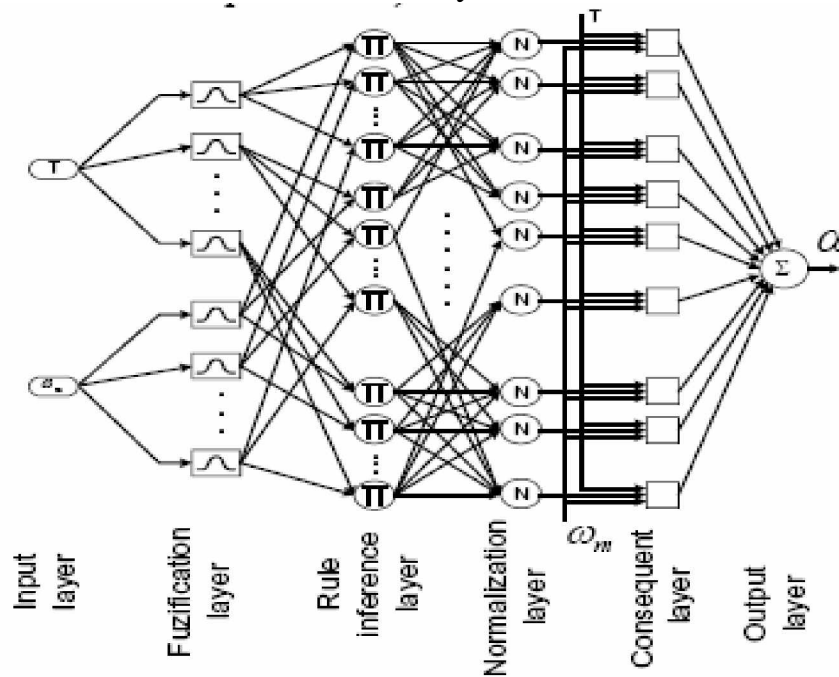
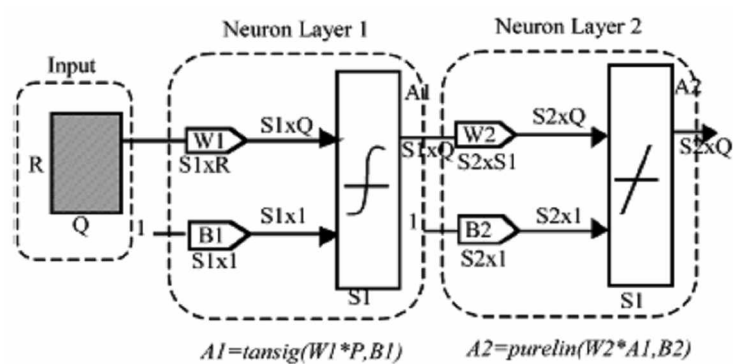


Figure (3): Structure of Adaptive Neuro Fuzzy Inference System

5. Artificial neural network model

The inputs of ANFIS are provided by artificial neural network based estimator which uses tan-sigmoidal activation function in the hidden layer while the linear activation function in the output layer. The architecture of neural network used is shown in Figure 4. The number of neurons in hidden layer depends upon the complexity of problem under consideration and is chosen arbitrarily. The network was trained with the data given in Table 1. The input-output samples for the training were selected from the simulations in Matlab Simulink under different conditions. Different parameters for training ANN used are shown in Table 1 while performance curve is given in Figure 5.



R= 4 inputs Q=156 samples S1=20: hidden layer neurons
 S2=4: output layer neurons A2=output of network

Figure (4): Architecture of neural network used with tansigmoidal activation function

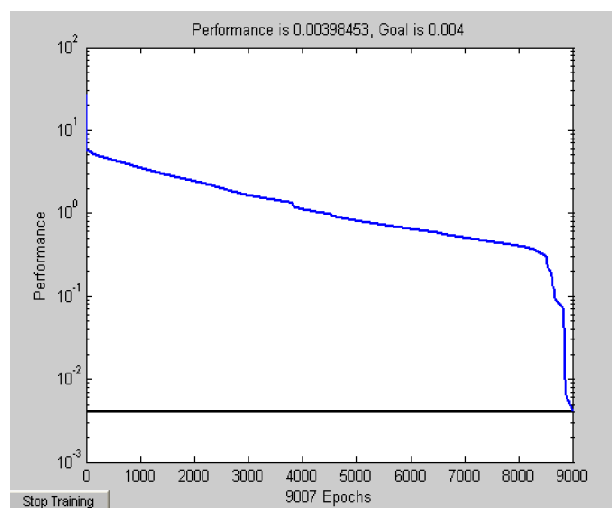


Figure (5): Performance curve of artificial neural network training

Table (1): Artificial neural network training parameters

Inputs	q- and d- axes currents and flux linkages of stator side
Outputs	Developed torque, rotor angles and rotor flux
Maximum Input value	[0.9471 0.9455 34.9946 33.7451]
Minimum Input value	[-0.9426 -0.9471 -28.8112 -32.2498]
Maximum output value	[34.0943 1.0767 1.0607 1.1246]
Minimum output value	[-18.1001 -1.0146 -1.2494 -0.0985]
Activation functions	Tan-sigmoidal and Linear
No. of hidden layers	1
No. of hidden nodes	20
No. of samples	156 samples of inputs and outputs
Iterations(epochs)	9007
Mean squared error	0.004
Training Algorithm	Levenberg-Marquard Back Propagation

The training algorithm selected provides very fast response as compare to other training algorithms and provides minimum mean squared error

6. Simulations and results of ANN Model and overall soft starter:

The presented soft starter with adaptive neuro fuzzy inference system and artificial neural network based estimator and voltage controller was completely simulated in Matlab Simulink as shown in Figure 6. The weights and biases used are those, obtained in training the neural network. ANN estimator estimates developed torque, rotor angles and rotor flux with d-q axis stator current and flux linkages as the input. The inputs of the ANFIS are the developed torque and reference speed, which using the defined rule base adjust the value of the firing angle of the thyristors to limit the current at the start and to eliminate the pulses from the torque. Load was varied from 0 to 2 Nm during the simulations and response of the controller and motor was recorded. The system was tested with rising ramp of reference speed to ensure the reduction in the electrical stress over the supply and mechanical stresses on the drive system during the starting period of the motor. To compare the results of the ANN model DSP-based estimator was implemented and comparison results are shown in Figure 7. The results were found highly satisfactory with minimum error. To check the performance of the overall system and to illustrate the benefit of the soft starter using ANN based technique the direct on line simulations were also carried out which are shown in the Figure 8.

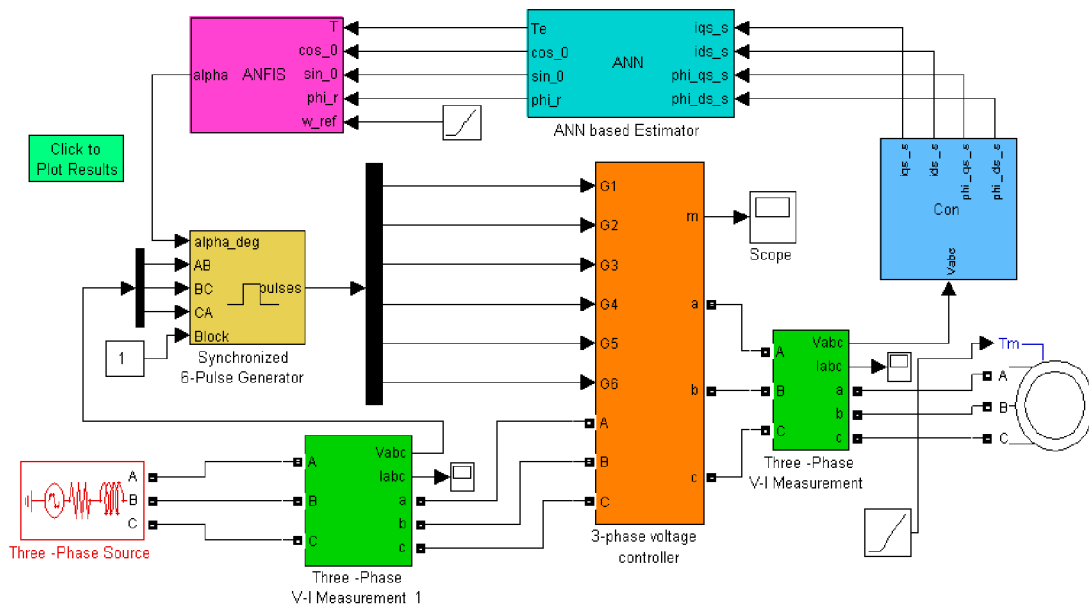


Figure (6): Matlab Simulink block for the system implemented

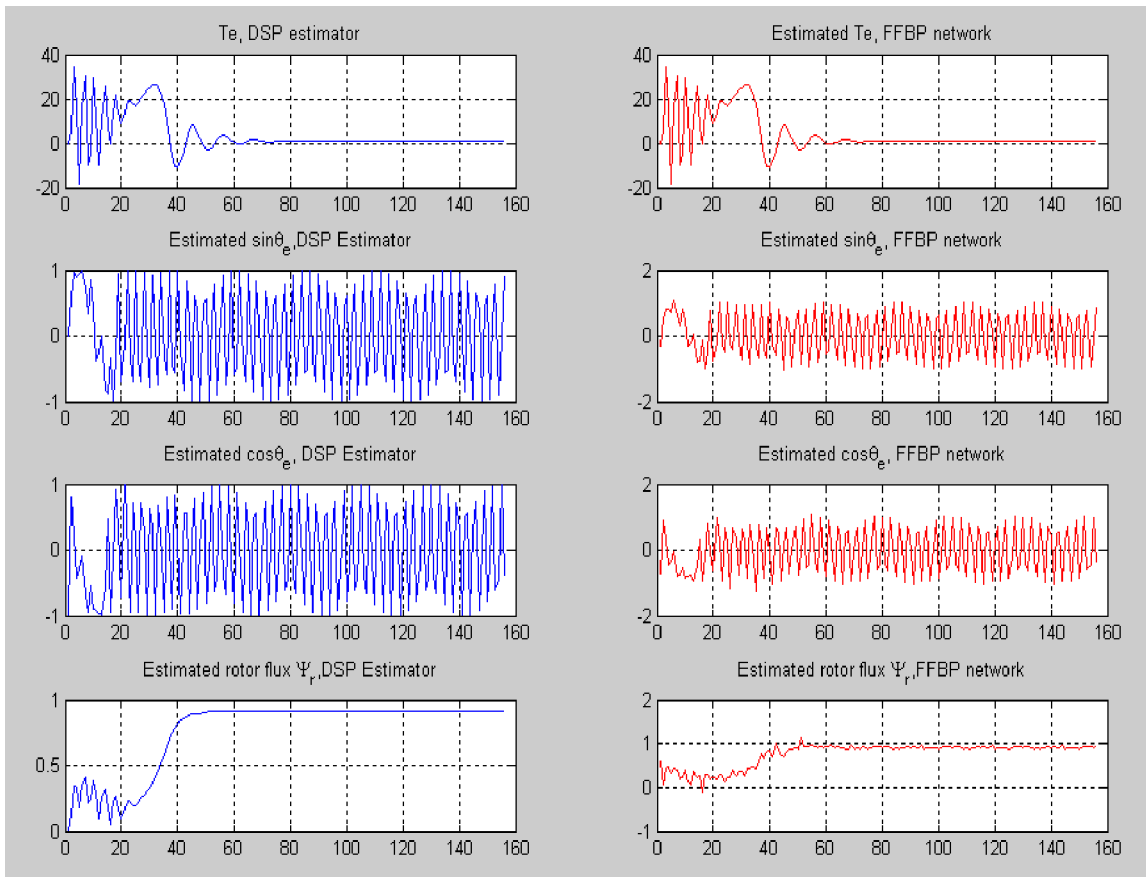


Figure (7): Matlab Simulink block for the system implemented

It can be clearly seen from the figure that current at start is very high in DOL starting i.e., about the five times of the rated current but with the help of ANN based soft starter it is reduced to just the 1.3 times rated current as shown in Figure 9 and hence the electrical stresses over the supply are reduced in starting. It can be observed that in DOL starting the developed torque pulsates till the steady state is achieved while in the case of ANN based soft starter the torque raises gradually without any pulses which reduces the mechanical stresses over the drive system.

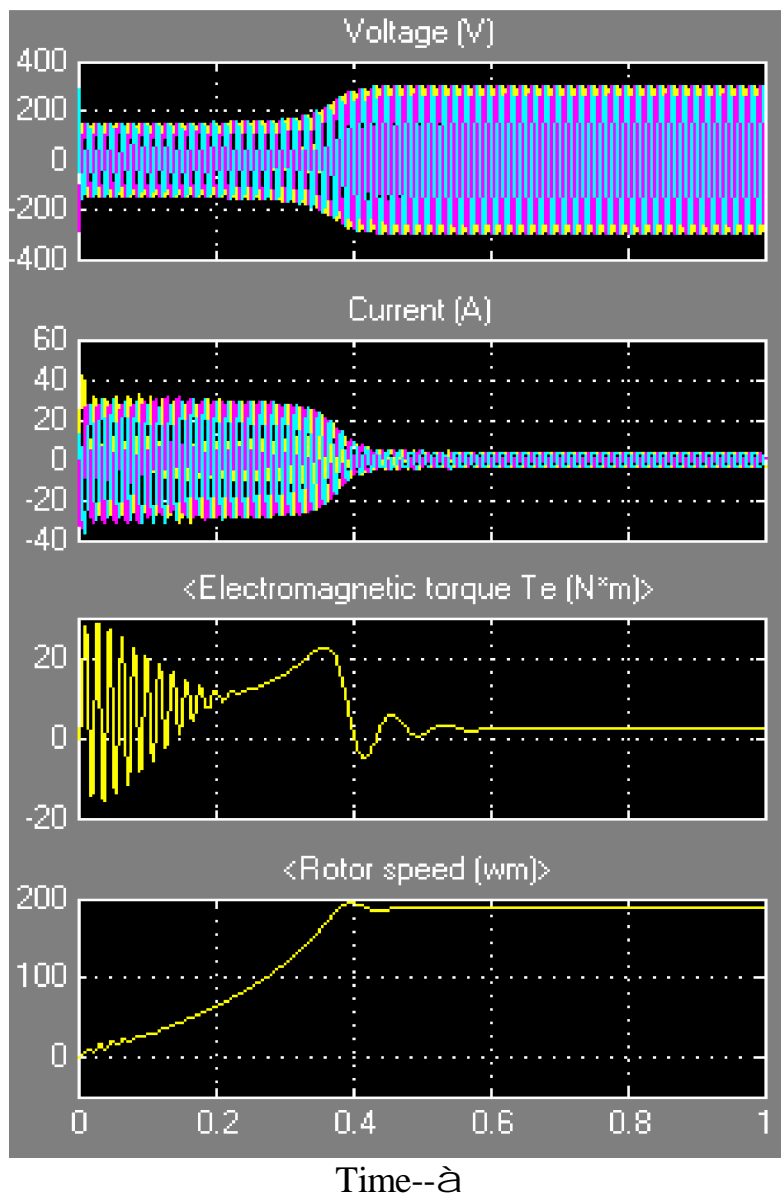


Figure (8): Simulation results for DOL starting

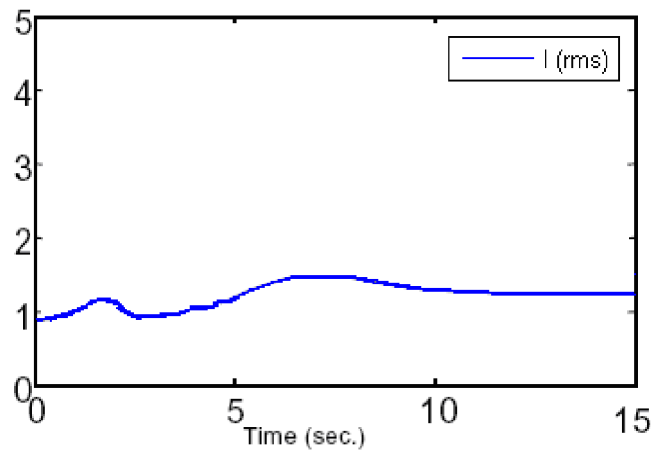


Figure (9): Simulation results for rms value of current

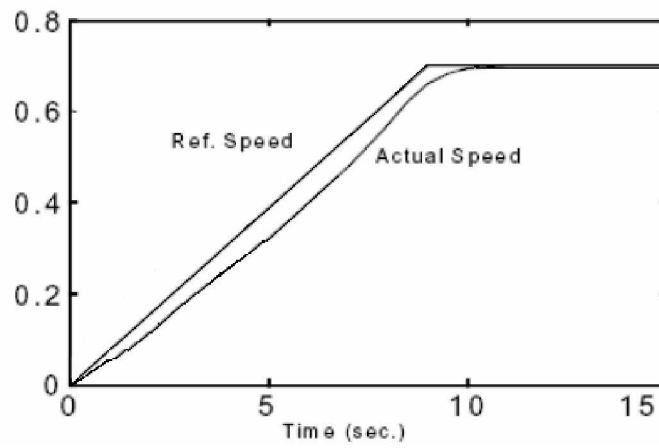


Figure (10): Simulation results for speed of induction motor

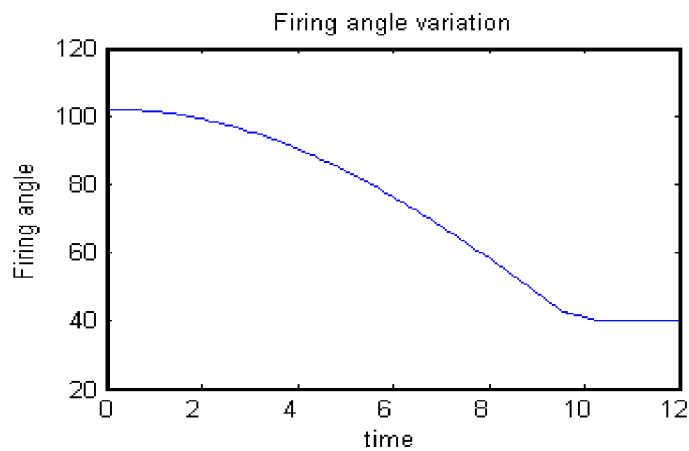


Figure (11): Simulation results for firing angle variation

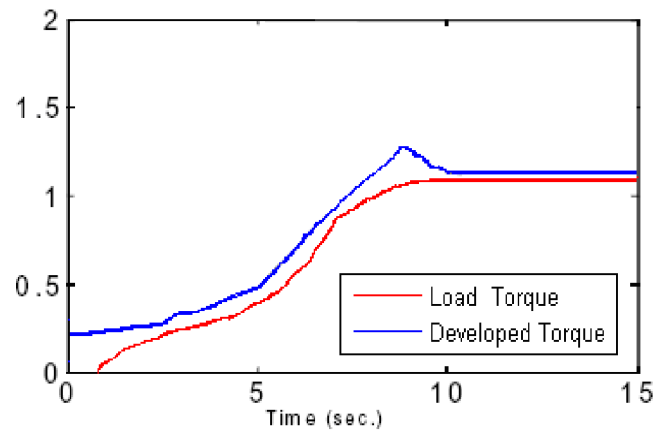


Figure (12): Simulation results for developed and load torque with soft starting

Figures 9-12 show the current, speed, firing angle variation and developed torque with the presented soft starter.

7. Conclusion

The soft starter presented with the artificial neural network and adaptive neuro fuzzy inference system has shown the highly satisfactory results as the inrush current is controlled and reduced significantly - maximum to 1.3 times of the rated current - and pulsations in the developed torque were eliminated resulting in reduced mechanical stresses. The presented soft starter was implemented using DSP and with neural networks tools and were compared in performance. The ANN based performance is highly satisfactory and can be implemented using microcontrollers as compared to DSP boards hence provides the low cost solution. The presented method for the inrush current and torque control adjusts the firing angle of the thyristors. ANNs can be trained off-line or on-line, providing the solution for on-line determination of the firing angle of thyristors.

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