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Speed Control of FSTP Inverter Fed Induction Motor Drive with a Neural Network Control

Smita Khanapure[1], Dr. Basavaraj Amarapur[2]
1, 2, Electrical & Electronics Department PDA College of Engineering, Gulbarga, Karnataka.

Abstract: *in this paper, the speed control of an induction motor using Four Switch Three Phase Inverter (FSTPI) and Neural Network is proposed. The proposed work has been carried out by the design and implementation of inverter and control circuit. The four switch three phase inverter is used because of low cost, lesser switching losses and reduced complexity of control algorithm and interfacing circuits. The control circuit was developed by designing a three layered feed forward Neural Network estimator which estimates rotor flux, unit vectors and torque by taking voltage and current reference from machine terminals. Based on the Neural Network output and difference between actual peed and set speed, the digital signal controller (dsPIC30F6012A) generates pulse width modulated (PWM) pulses to the power switches of the inverter. The width and frequency of pulses are adjusted such that to maintain the constant v/f ratio of inverter output voltage to achieve the desired speed. The proposed system has been tested with different loads and different speed. The results are tabulated and corresponding graphs are drawn. From the graphs it is observed that, the constant speed has been achieved with variation of load. The neural network controller provides an accurate and faster speed control.*
Index Terms: *Three phase induction motor, FSTPI, PWM, Neural Network, dsPIC30F6012A*

I. Introduction

Induction motors are widely used in industrial and domestic applications due to their simple construction, low cost, high robustness and higher efficiency. In the earlier days the induction motors are used for constant speed applications. With the revolution of high speed power semiconductor devises and progress in the field of power electronics and microcontroller enable the application of Induction motors for high performance variable speed drive. Variable speed of an Induction Motor is achieved by varying magnitude and frequency of a Supply voltage, which can be obtained by Six Switch Three Phase Inverter (SSTPI). But this inverter has the disadvantages such as losses of the six switches, complexity of control algorithm & interface circuit and increased real time computation. In order to overcome these difficulties of the six switch inverter a Four Switch Three Phase Inverter (FSTPI) are developed for variable speed drives. Which can be used for high performance induction motor drive with reduced cost and size as compared to six switch three phase inverter based motor drive [1]. The achieving of variable speed of an induction motor drive is a challenging task because of non-linear behavior of the motor speed. In order to overcome this, a new method was developed is known as Artificial Neural Network. This is used for non-linear control system because of its ability of modeling a non-linear system without the requirement of mathematical model of a system. It has learning ability and approximation to any arbitrary continuous function because it attempts to imitate the way human brain works rather than using a digital model. The Neural Network can be designed by using input, output and hidden nodes and its connections through weights [6]. Recently neural network have been used in power electronics and motion control applications such as parameter identification and state estimation of an Induction Motor like flux estimation, speed estimation. Evidently Neural Network technique is showing promise as a competitive method of complex signal processing for power electronics applications [2].

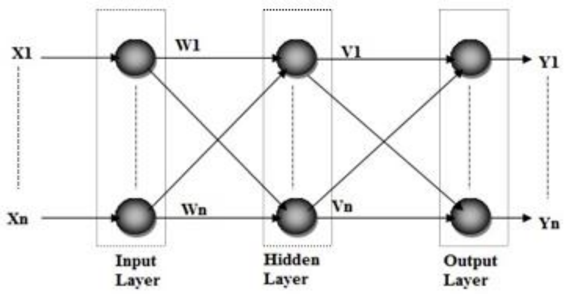

Fig 1 structure of neural network

The Neural Network can be represented by using single or multiple layer Neural Networks. The multilayer Neural Network is as shown in figure 1, consists of input, hidden and output layers which are represented by circles. They are interconnected by lines trough the weights. The weights between input to hidden and hidden to output layers are represented by W_1 to W_n and V_1 to V_n respectively. The desired output of the network is obtained by multiplying the weights to the respective neuron.

The implementation of proposed work has been carried out in two stages. In the first stage, the design and development of Four Switch Three Phase Inverter using MOSFET to reduces the size and cost of the inverter. In the second stage, design of Neural Network estimator along with a high speed digital signal controller using dsPIC30F6012A. The three layered Neural Network has been designed to estimate the rotor flux, unit vectors and torque by taking reference current and voltage signal from the motor terminals. The estimation mechanism uses continual on-line training to learn unknown stator model dynamics and estimates rotor fluxes of an inverter-fed induction motor. Based on the Neural Network output and speed difference between set speed and actual speed of a motor digital signal controller generates Pulse Width Modulated (PWM) pulses of required width and frequency to the inverter switches to achieve the desired speed.

Neural Network based estimation has the advantages of faster execution speed, distributive associative memory and fault tolerance characteristics and it can easily co-exist as a peripheral chip with a system control [2]. The proposed system is tested for different load and speed. From the experimental results we can observe that the speed remains constant at different loads with the better performance interms of torque and voltage regulation compared to the open loop system

II. Block Diagram Of A Proposed System

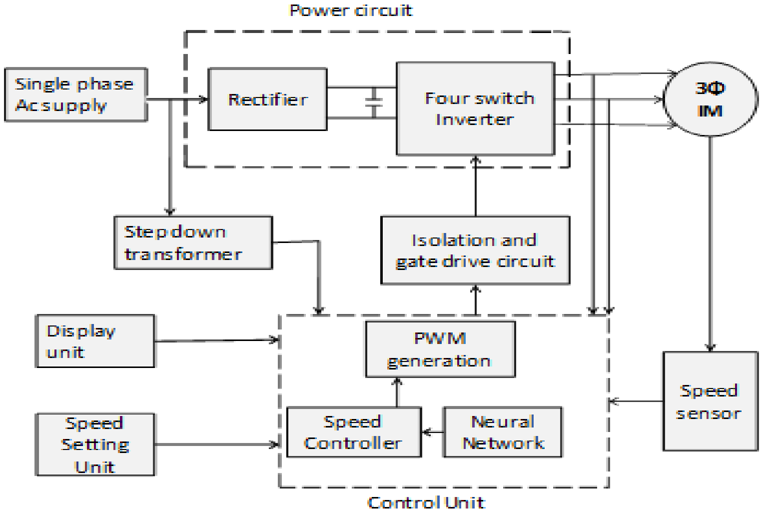

Fig 2 Complete Block Diagram of a System.

Block diagram for the proposed system for speed control of induction motor drive is shown in Fig 2. It consists of power circuit, control circuit, isolation, driver circuit and speed sensing and setting unit. Each unit of the block diagram is discussed in the following subsections.

A Power circuit: The power circuit of the proposed system consists of bridge rectifier and Four Switch Three Phase Inverter. Rectifier converts AC input into a DC output which is smoothened by two series capacitors, the output of bridge rectifies is fed to the MOSFET based four switch three phase inverter. The MOSFET's are used in the inverter circuit is of rating 13A. 500V

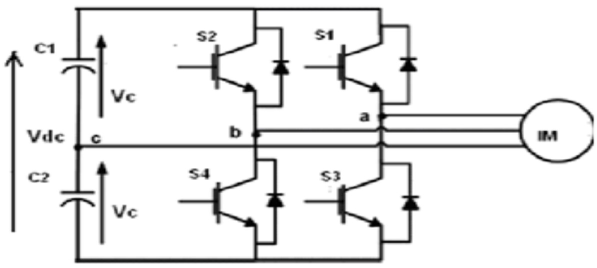

Fig 3. Four Switch Three Phase Inverter.

The complete system of the Four Switch Three Phase Inverter fed Induction Motor drive is shown in Fig.3. The circuit consists of four switches S_1, S_2, S_3 and S_4 and dc link capacitors C1 and C2. The AC input, which is of fixed frequency, is rectified by the rectifier switches. The 'a' and 'b' phases of the induction motor are connected to the two legs of the inverter, while the third phase 'c' is connected to the center point of the dc-link capacitors, C_1 and C_2. The four power switches are denoted by the binary variables S_1 to S_4, where the binary '1' corresponds to an ON state and the binary '0' corresponds to an OFF state. The states of the upper switches (S_1,S_2) and lower switches (S_3,S_4) of a same leg are complementary that is $S_3 = 1 - S_1$ and $S_4 = 1 - S_2$. The switching states of the switches S_1 to S_4 are controlled in order to generate ac output from the DC bus. The switching states and corresponding phase voltages of the Four Switch Three Phase Inverter are shown in table 1. At any given time two switching pairs (S_1, S_4) and (S_3, S_2) will conduct to generate an AC output to the motor. Since there is no control on the third phase, the middle point of the DC link (point C) is taken as the reference, and phase voltages of the inverter are given by equation (1) to equation (3) [1]

$$\boldsymbol{V_{as}} = \frac{\boldsymbol{V_C}}{\boldsymbol{3}}(\boldsymbol{4S_1} - \boldsymbol{2S_2} - \boldsymbol{1}) \qquad (\boldsymbol{1})$$

$$\boldsymbol{V_{bs}} = \frac{\boldsymbol{V_C}}{\boldsymbol{3}}(-\boldsymbol{2S_1} + \boldsymbol{4S_2} - \boldsymbol{1}) \qquad (\boldsymbol{2})$$

$$\boldsymbol{V_{cs}} = \frac{\boldsymbol{V_C}}{\boldsymbol{3}}(-\boldsymbol{2S_1} - \boldsymbol{2S_2} + \boldsymbol{1}) \qquad (\boldsymbol{3})$$

where V_{as}, V_{bs}, and V_{cs} are the inverter output voltages, V_c is the voltage across the dc link capacitors, V_{dc} is the voltage across the capacitors C_1 and C_2 ($V_c = V_{dc}/2$).

Matrix form the above equations can be written as:

$$\begin{bmatrix} \boldsymbol{V_a} \\ \boldsymbol{V_b} \\ \boldsymbol{V_c} \end{bmatrix} = \frac{V_C}{3}\begin{bmatrix} \boldsymbol{4} & -\boldsymbol{2} \\ -\boldsymbol{2} & \boldsymbol{4} \\ -\boldsymbol{2} & -\boldsymbol{2} \end{bmatrix}\begin{bmatrix} \boldsymbol{S_1} \\ \boldsymbol{S_2} \end{bmatrix} + \frac{V_C}{3}\begin{bmatrix} -\boldsymbol{1} \\ -\boldsymbol{1} \\ \boldsymbol{2} \end{bmatrix} \qquad (\boldsymbol{4})$$

Table 1 Switching states and output phase voltage[1]

Switching states		**Output states**		
S_1	**S_2**	**V_{as}**	**V_{bs}**	**V_{cs}**
0	**0**	**$-V_c/3$**	**$-V_c/3$**	**$2V_c/3$**
0	**1**	**$-V_c$**	**V_c**	**0**
1	**0**	**V_c**	**$-V_c$**	**0**
1	**1**	**$V_c/3$**	**$V_c/3$**	**$-2V_c/3$**

B Isolation and driver circuit

There is a need for electrical isolation between the logic-level control signals and drive circuits. Isolation circuit provides required gate voltage and current to the MOSFET's, it also amplifies control signals to the level required by the power switches and it restricts the flow of any disturbances to the power devices. The pulses available at the output of the logic circuit are applied to the gate of individual MOSFET through separate driver circuit; power supply required for driver circuit is obtained by the regulated dc supply

C Speed sensing and speed setting unit

The inductive type proximity sensor is used in this work to sense the actual speed of the induction motor. Proximity sensor emits an electromagnetic radiation and looks for change in the field or return signal. Whenever metallic target enters the sensing range it generates a pulse based on number of pulses generated per second by the proximity sensor the motor speed in rpm is calculated and displayed by the controller. In the proposed work a pc based speed setting unit is developed through lab view software, which enables the user to enter the desired speed in numerical value through keyboard instead of push buttons. Lab view software is instrument control software which interfaced with controller to feed set speed to controller and displays actual speed and set speed of the induction motor.

D Control circuit

Control unit of the proposed system has been designed using digital signal controller DSPIC30F6012A, in which neural network estimator and speed controller is implemented. The control unit generates PWM pulses to the Power MOSFET's of the inverter based on the speed error and neural network output. The input and output signals required to train the neural network are calculated from the equations (5) to equation (18) by receiving motor terminal voltage and current feedback.

$$V_{ds}^{s} = \frac{2}{3}V_a - \frac{1}{3}V_b - \frac{1}{3}V_C \qquad (5)$$

$$V_{qs}^{s} = -\frac{\sqrt{3}}{2}\ (V_b\ \ + V_c) \qquad (6)$$

$$i_{ds}^{s} = \frac{2}{3}i_a - \frac{1}{3}i_b - \frac{1}{3}i_c \qquad (7)$$

$$i_{qs}^{s} = -\frac{\sqrt{3}}{2}\ (i_a + i_c) \qquad (8)$$

$$\psi_{ds}^{s} = \int(V_{ds} - R_s i_{ds})\, dt \qquad (9)$$

$$\psi_{qs}^{s} = \int(V_{qs} - R_S\, i_{qs})\, dt \qquad (10)$$

$$\psi_{dm}^{s} = \psi_{ds}^{s} - L_s i_{ds} \qquad (11)$$

$$\psi_{qm}^{s} = \psi_{qs}^{s} - L_S i_{qs} \qquad (12)$$

$$\psi_{qr} = \left(\frac{L_R}{L_M}\right)\psi_{qm} - L_r i_{qs} \qquad (13)$$

$$\psi_{dr} = \left(\frac{Lr}{Lm}\right)\psi_{dm} - L_R i_{ds} \qquad (14)$$

$$\psi_r = \sqrt{(\psi_{dr})^2 + (\psi_{qr})^2} \qquad (15)$$

$$\cos\theta = \left(\frac{\psi_{dr}}{\psi_r}\right) \qquad (16)$$

$$\sin\theta = \left(\frac{\psi_{qr}}{\psi_r}\right) \qquad (17)$$

$$T_e = \left(\frac{3P}{4}\right)(\psi_{ds} i_{ds} - \psi_{qs} i_{qs}) \qquad (18)$$

where

v^s_{ds} (v^s_{qs}) stator voltage in d-axis (q-axis),
i^s_{ds} (i^s_{qs}) stator current in d-axis (q-axis)
Ψ^s_{ds}(Ψ^s_{qs}) stator flux linkage in d-axis (q-axis),
Ψ^s_{dm} (Ψ^s_{qm}) air gap flux linkage in d-axis (y-axis)
Ψ^s_{dr} (Ψ^s_{qr}) rotor flux linkage in d-axis (q-axis)
Ψ_r rotor
R_s stator resistance,
L_{ls} stator leakage inductance,
L_{lr} rotor leakage inductance,
L_m magnetizing inductance
L_r rotor inductance, and
p no of poles
T*e* Torque in NM

All the signals with superscript -s indicate that they are in stationary reference frame. Neural network receive the variable frequency variable magnitude signal waves Ψ^s_{ds}, Ψ^s_{qs}, i^s_{ds} and i^s_{qs} and then compute through equations (15) to equation (18) to estimate rotor flux, torque and unit vectors [2][3] [5]

F Control method

The control scheme for closed loop speed control of an induction motor includes speed controller and neural network estimator. The speed controller takes actual speed of the induction motor from proximity sensor and setting of the speed from PC based speed setting mechanism using labview software and estimates the error between them. Mean time the controller receives the current and voltage signals from the phase a and b of the machine terminals, then these three phase variables are converted into two phase variables v^s_{ds} , v^s_{qs} and i^s_{ds}, i^s_{qs} by using equations (5) to equation (8) these two phase variables are then converted to fluxes Ψ^s_{ds}, Ψ^s_{qs} by using equations (9) and equation (10). Currents i^s_{ds}, i^s_{qs} and fluxes Ψ^s_{ds}, Ψ^s_{qs} are applied to the Neural Network estimator as inputs to estimate rotor flux, unit vectors and torque at the output. The estimation mechanism uses continual on-line training to learn unknown stator model dynamics. The output of the neural network estimator and speed controller are used to generate the PWM pulses of required width and frequency to the inverter switches to achieve desired speed. The Induction motor speed is directly proportional to the supply frequency. If the supply frequency is reduced keeping the voltage constant, the air gap flux will saturate, to avoid flux saturation. The supply voltage is also reduced so that the v/f ratio of the induction motor supply remains constant with the changing load and speed references. By maintaining constant v/f ratio maximum torque developed is maintained constant, where as speed can be varied to a desired value at any load conditions

III. Proposed Multilayered Neural Network

The designed three layered feed forward neural network is shown in fig 4.Which has input layer, hidden layer and output layer. The number of neurons in the input and output layer are four as the input and output variables are also four. The number of hidden layer neurons is determined by trial and error method which is found to be 9.

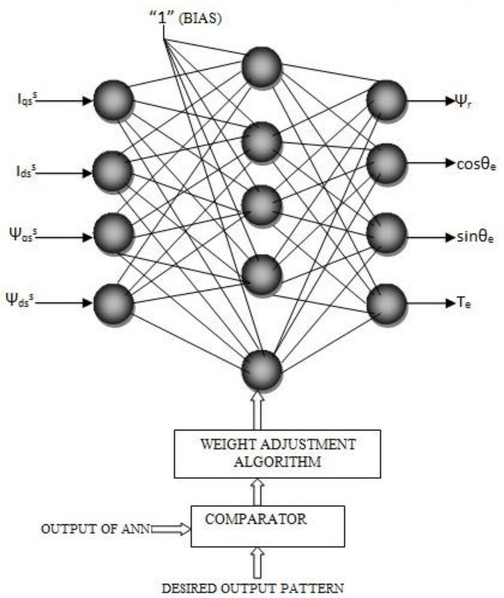

Fig. 4 Topology of Neural Network.

The input to the neural network are Ψ^s_{ds} ,Ψ^s_{qs}, i^s_{ds} and i^s_{qs} which are calculated by equation (7) to (10) and outputs are namely rotor flux, torque and unit vectors. The network is fully connected and a constant bias signal is coupled to all the neurons of the hidden and output layers through a weight. The input layer neurons have linear transfer characteristics where as the hidden layer and output layer neurons have hyperbolic-tan type nonlinear transfer function. The training was carried out by adjustment of the connection weights so that the predetermined input-output representation is established. The objective of the training process is to minimize a performance index defined in terms of output error. Back propagation algorithm is used to train the neural network. For the training of the neural network 200 samples are collected by changing input voltage and load of the motor out of them 50 samples are kept aside for the testing purpose.

IV. Experimental Results

The proposed control system was implemented by a DSC (dsPIC30F6012) based PWM inverter. C language is used to develop the control software. The device is programmed using MPLAB Integrated Development Environment (IDE) tool. In this work 440V, 50Hz, 1.5A, 3-phase 1HP Induction motor is used. The experiment has been carried out on the proposed system for open loop as well as closed loop system. In an open loop system the load is varied from 0 to 2 kg in steps of 0.5 kg and the corresponding speed, voltage and current readings are tabulated in table 2. Similarly for the closed loop systems two sets of reading were taken in two condition namely (i) at constant speed and (ii) at constant load

(i) For constant speed operation, at particular set speed of 1300 RPM the load on the induction motor was varied from 0 to 2 kg in steps of 0.5 kg the corresponding readings of speed, voltage and current were tabulated in the table 3. In the table 3 and 4 the torque and regulation were calculated by using equation (18) and equation (20).

(ii) For the constant load operation, for the load of 2 kg the set speed was varied from 1400 RPM to 1100 RPM in steps of 50 RPM the corresponding slip and torque were calculated using equations (18) and equation (20) and is tabulated in table 4 and the speed versus torque curve is drawn in Fig 8.From the table 3 and 4 it is observed that as the load changes the speed also changes in open loop system. But in the proposed closed loop system the speed will remain constant as the load increases. The comparison of the open loop and closed loop system has been made and the corresponding graphs are shown in figure 5 to figure 7, open loop graph is indicated by light color line & closed loop graph is indicated by dark color line. From the graph it is observed that a constant speed, higher torque and reduced voltage regulation has been achieved from closed loop as compared to open loop system. The gate pulses at set speed of 1200RPM, 1300 RPM and 1400 RPM are shown in Fig 9, Fig 10 and Fig 11 respectively.

$$\mathbf{Torque}_{\mathbf{EM}} = \mathbf{P_m} \times \mathbf{W_r}\ \mathbf{NM} \qquad (18)$$

$$\text{Regulation } (\%) = \frac{V_i - V_o}{V_i} \times 100 \qquad (19)$$

$$\mathbf{slip}(\%) = \frac{N_s - N_r}{N_s} \times 100 \qquad (20)$$

Table 3 Experimental Results for open loop system.

S no	Load in kg	Speed (RPM)	Voltage (V)	Current (A)	$Torque_{em}$ (NM)	Regulation
1	0	1300	230	0.96	1.07	0.06
2	0.5	1296	230	1.1	1.16	0.08
3	1	1290	230	1.21	1.27	0.1
4	1.5	1284	230	1.37	1.36	0.12
5	2	1280	230	1.45	1.45	0.14

Table 4 Experimental Results for closed loop system

S no	Load in kg	Speed (RPM)	Voltage (V)	Current (A)	$Torque_{em}$ (NM)	Regulation
1	0	1300	230	0.95	1.1	0.03
2	0.5	1300	230	1.1	1.2	0.05
3	1	1300	230	1.2	1.3	0.07
4	1.5	1300	230	1.34	1.41	0.09
5	2	1300	230	1.42	1.51	0.11

Table 5 Experimental results at 1.5 kg load

S no	Set Speed (RPM)	Slip (%)	$Torque_{em}$ (NM)
1	1400	6.6	1.12
2	1350	10	1.29
3	1300	13.3	1.41
4	1250	16.6	1.38
5	1200	20	1.34
6	1150	23.3	1.3
7	1100	26.6	1.27

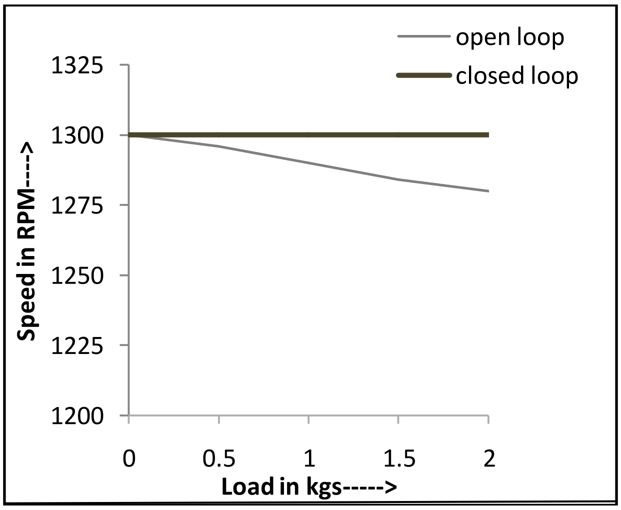

Fig 5. Speed versus Load curve.

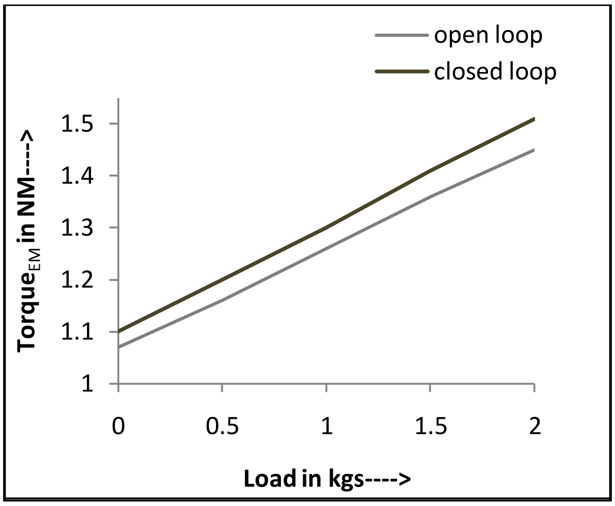

Fig 6 Torque versus Load curve

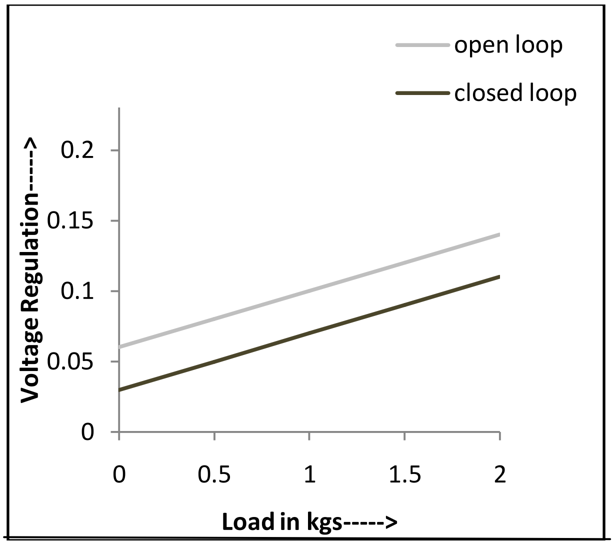

Fig 7 Voltage Regulation versus Load curve.

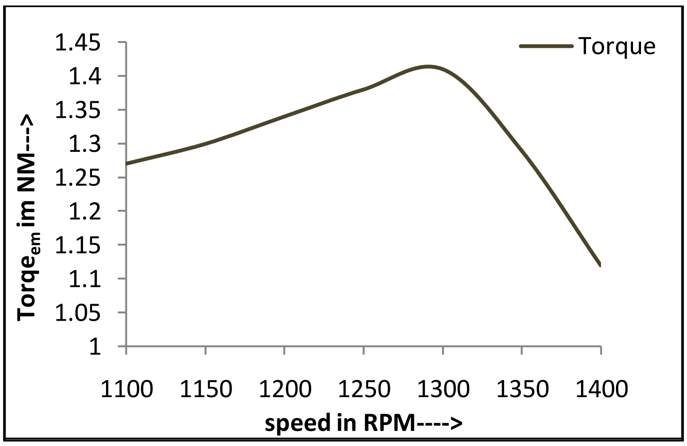

Fig 8. Speed versus Torque

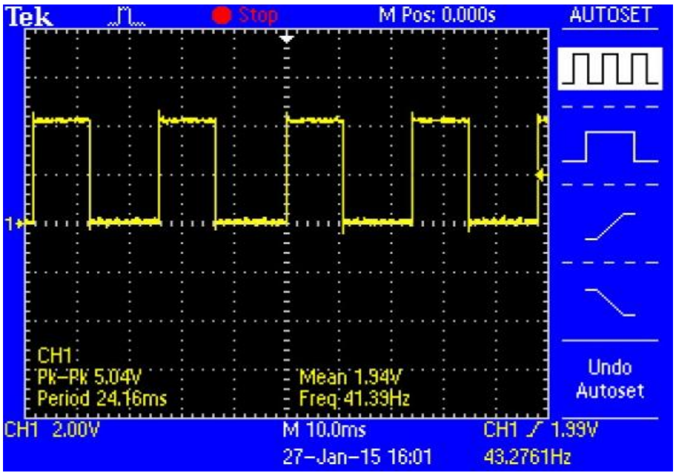

Fig 9. Gate Pulses at 1200 RPM.

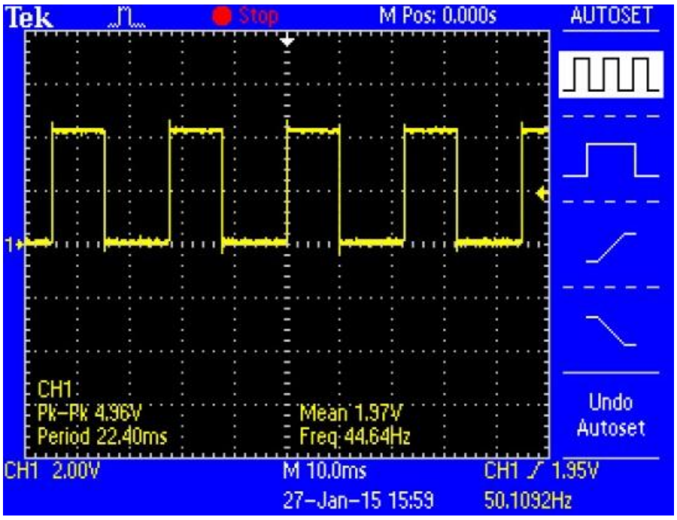

Fig 10. Gate pulses at 1300 RPM

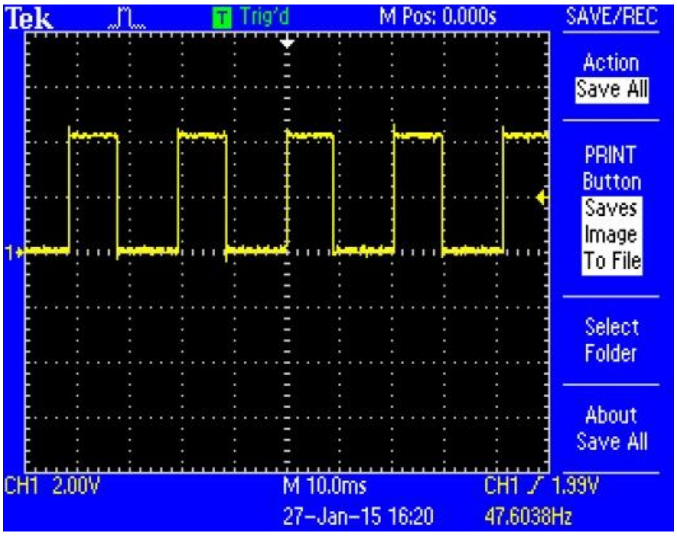

Fig 11 Gate Pulses at 1400 RPM

V. Conclusion

The Four Switch Three Phase Inverter (FSTPI) fed Induction Motor Drive for closed loop speed control using Neural Network estimator is implemented. The proposed topology reduces the cost, switching losses and complexity of control algorithm compared to conventional six switch three phase inverter drive also the neural network estimator used in this paper provides faster and accurate speed control with a variable load and at different set speed. From the experimental results it is observed that in the open loop system the speed decreases as load increases where as in the closed loop system using proposed topology the speed remains constant with the varying load. The electromagnetic torque developed increases by 4% and voltage regulation decreases by 3% compared to open loop system.

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