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Performance Analysis and Speed Regulation Estimation of SR Motor Using FT-ANN Controller with Steady State Stability and Fft Analysis

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Abstract: A closed loop speed regulation estimation of Switched Reluctance (SR) Motor with Fuzzy Tuned Artificial Neural Network (FT-ANN) Controller has been simulated and presented in this paper. The FT-ANN has been used for the closed loop controller and the speed regulation of the SR motor has been estimated with Fuzzy Logic Controller (FLC) and FT_ANN. The comparative results are presents for both static and dynamic conditions. The mathematical model of the SR motor has been developed for steady state stability analysis and simulated using MATLAB. The Harmonic Spectrum (FFT) and steady state error for various speed and load condition have been obtained to validate the role of FT-ANN controller. The FT-ANN based system is expected to give better speed regulation for various load conditions. A prototype 300-W, 50Hz model is designed and built for experimental demonstrations; the transient and steady-state performances for the SR motor are compared from the simulation studies. The result of MATLAB simulation and execution it is clear that the FT-ANN can have better controller compared with Fuzzy Logic Controller (FLC).

Key words: Switched Reluctance Motor · Artificial Neural Network · Fuzzy Logic Controller · Stability analysis · PWM Inverter

INTRODUCTION

The design and developed of SR motor have been focused for variable speed applications with high power density in the recent past. It has been found that these types of special motor have several advantages such as simplicity, less maintenance, robustness, higher torque volume ratio, high starting torque, high efficiency, low manufacturing cost and high speed. The SR motor is highly nonlinear and it operates to steady state region to maximum torque region. This type of special motor having a torque is nonlinear function of rotor position and current. The many researchers has been experimentally demonstrated and reported related to SR motor to solve above problems using different controllers.

Hany M *et al*. [1] have developed the torque ripple minimization of the SR motor with digital controller. The model of SR motor has been presented with torque equation. There is no analysis of the performance of the motor. The speed control of the switched reluctance generator with artificial neural network controller has been presented in. The performance of the generator has been analyzed with variable speed turbine connected in grid. Kioskeridis *et al*. [2] have demonstrated the single pulse controlled SR motor with high efficiency. This control technique is more complicate compare to FT-ANN controller. The dynamic and steady state performance of the motor was not presented.

Yana Zhou *et al*. [3] have developed the torque ripple minimization of the SR motor with sensor less controller using neural network. The neural network structural design was not present. The speed variation with load changes was not present. The speed controller of the SR motor has been developed and presented with adaptive neural network controller in. The dynamic behavior of the motor has been presented. The load disturbance of the motor has been presented with controller performance. Here there is no analysis of the steady state and stability of the motor. Any M *et al*. [4] have demonstrated the speed control of SR motor with adaptive neuro-fuzzy

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controller. The performance of the controller has been described. The analysis of the controller design and dynamic performance of the motor were not present. The stability analysis of the SR motor with fuzzy sliding mode controller was presented in.The speed regulation and load disturbance of the motor performance were not present. The different type of power converter fed SR motor is presented with pulse with modulation technique. The performance of the converter was found for better speed regulation.

P.Kavitha *et al*. [5] have demonstrated the R dumped converter fed SR motor with fuzzy controller. The experimental result of the SR motor was not present. The design procedure of the motor and converter was not present. The performance of the motor speed regulation was present. Gamal M. Hashem *et al*. [6] have described the fuzzy controller for SR motor. The speed regulation of the motor has been presented. The dynamic and transient performance of the motor was not present. M. A. A. Morsy *et al*. [7] have described the speed regulation of the SR motor with fuzzy sliding mode controller. The variable structural control has been developed and presented with comparison of fuzzy sliding mode controller. The static and dynamic analysis of the SR motor was not present.

It is concluded from the literatures that the speed regulation against load and supply voltage fluctuation have important role in the design of high speed drives. The FT-ANN controller is expected to have the speed regulation, high efficiency and better performance in the time of load disturbance. Considering the above facts in view, the FT-ANN controller based SR motor has been designed and the performance is analyzed for estimating various responses. The state space analysis is used for the stability analysis of the motor. The state space equation has been derived from motor model and simulated using MATLAN/Simulink. The FFT analysis of the motor has been present.

Proposed FT-ANN Controller based SR Motor with State Space Analysis: The block diagram of the FT-ANN controller based switch reluctance motor is shown in fig.1. The first stage three phase AC voltages are converting in to DC voltage V_{dc} by using rectifier circuit. The Second stage the inverter is converts in to three phase ac voltage i_a, i_b, i_c.. The motor speed measured by sensor and the signal is given to the error detector unit. A tacho generator (pulse type) is used for sensing the speed. This sensing speed is considered for feedback of the controller. Error detector is used to compare the reference speed and actual speed. The difference error speed is calculated and to generate the error signal which is given to controller block. The Fuzzy tuned Artificial Neural Network Controller gives control signal to the inverter according to the error signal. The speed of the motor is controlled by the inverter through proper excitation of their corresponding windings [8-10].

The FT-ANN controller has been used as two feedback loops. One is outer speed control loop and second one is inner current control loop. The current control loop is used to control the PWM pluses whenever the motor current reached to the maximum value. The speed control loop, the actual speed N is sensed by tacho generator and given to the error detector, the set speed N_{ref} also given to the error detector and the error signal e is obtained by comparing the set speed N_{ref} with the actual speed N. The (Δe) change in error is procured from the (e) present error and pervious error ($e_{previous}$). The (e) error and (Δe) change in error are set as inputs to the FT-ANN controller.

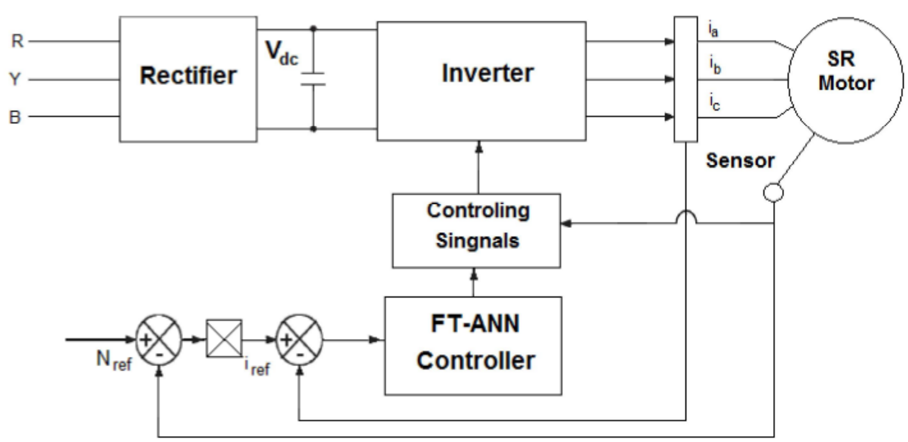

Fig. 1: Block Diagram of the FT-ANN controller based SR motor

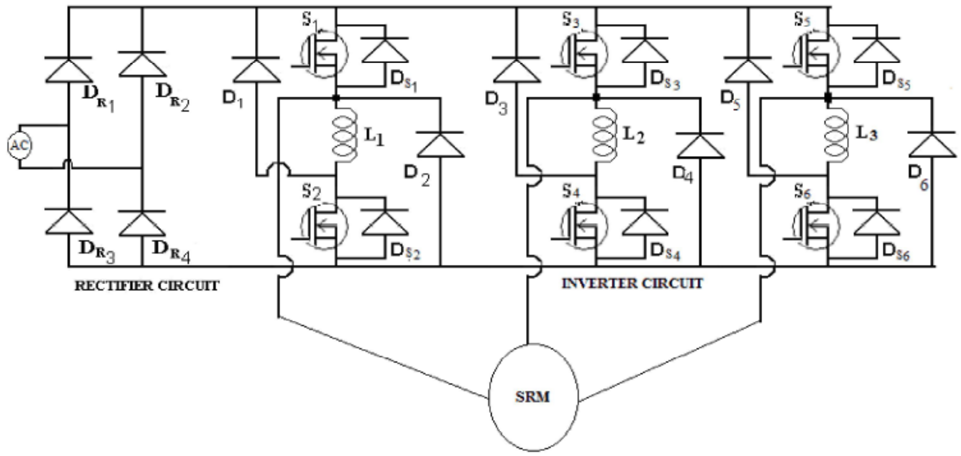

Fig. 2: Structure of Classical Inverter circuit for SR motor

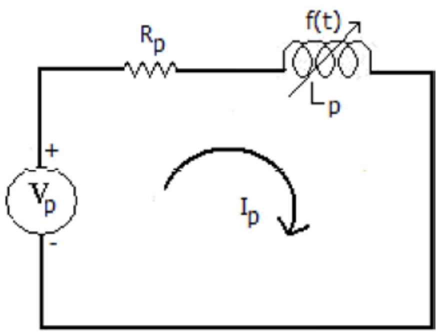

Fig. 3: Equivalent circuit of Single phase SR motor

The output of the controller is PWM Signal. The change in PWM Signal ΔP is given to the inverter and the controller is calculated from the new PWM Signal P(k) and previous PWM Signal p(k-1). The input and output gain of the controller can be estimated by simulation. To obtain the error value is zero by changing the pulse signal which is given to the inverter [11]. The schematic diagram of the proposed system is shown in fig.2.

Mathematical Modeling of the SR motor with Sate Space Analysis: The SR motor is a highly non-linear system, the non-linear system describing the behavior of the motor is developed. A mathematical model can be created based on this construction. The SR motor electromagnetic circuit is characterized by non-linear magnetization. The torque generated by the motor phase is a function of the magnetic flux; therefore, the phase torque is not constant for a constant phase current for different motor positions. This creates torque ripple and noise in the SR motor. The model is based on the electrical diagram of the motor, incorporating phase resistance and phase inductance. The diagram for one phase is shown in fig.3 [11-17].

The applied voltage to a phase is equal to the sum of the resistive voltage drop and the rate of the flux linkages and is given as:

$$V_p(t) = R_p I_p(t) + V_{Lp}(t) \tag{1}$$

$$V_{Lp}(t) = \frac{d\varphi(I_p,\theta_p)}{dt} \tag{2}$$

$$= \frac{d\varphi(I_p,\theta_p)}{dI_p}\cdot\frac{di_p}{dt} + \frac{d\varphi(I_p,\theta_p)}{d\theta_p}\cdot\frac{d\theta_p}{dt} \tag{3}$$

The phase voltage can be expressed as

$$V_p(t) = R_p . I_p(t) + \frac{d\varphi(I_p,\theta_p)}{dI_p}\cdot\frac{di_p}{dt} + \frac{d\varphi(I_p,\theta_p)}{d\theta_p}. N \tag{4}$$

Where N is the speed of the motor

For 3 phase SR motors Equ.3 can be expanded as follows

$$V_R(t) = R_R . I_R(t) + \frac{d\varphi(I_R,\theta_R)}{dI_R}\cdot\frac{di_R}{dt} + \frac{d\varphi(I_R,\theta_R)}{d\theta_R}. N \tag{5}$$

$$V_Y(t) = R_Y . I_Y(t) + \frac{d\varphi(I_Y,\theta_Y)}{dI_Y}\cdot\frac{di_Y}{dt} + \frac{d\varphi(I_Y,\theta_Y)}{d\theta_Y}. N \tag{6}$$

$$V_B(t) = R_B . I_B(t) + \frac{d\varphi(I_B,\theta_B)}{dI_B}\cdot\frac{di_B}{dt} + \frac{d\varphi(I_B,\theta_B)}{d\theta_B}. N \tag{7}$$

The torque generated by one phase can be expressed as

$$T_p = \int_0^I \frac{d\varphi(I_p,\theta_p)}{d\theta_p} dI_p \tag{8}$$

The mathematical model of an SR motor is represented by a system of equations, describing the conversion of electromechanical energy. Power associated with change in stored energy is$\frac{dW}{dt}$

$$\frac{dW}{dt} = \frac{1}{2} L_p (2i) \frac{dI}{dt} + \frac{1}{2} I^2 \frac{dL_p}{dt} \quad (9)$$

This equation can be written as

$$= L_p i \frac{dI}{dt} + \frac{1}{2} I^2 \omega \frac{dL_p}{d\theta}$$

Where $\omega = \frac{d\theta}{dt}$

The motor Power can be converted into mechanical P_m the developed power equation is

$$P_m = \frac{1}{2} I^2 \omega \frac{dL_p}{d\theta} \quad (10)$$

The SR motor Torque developed equation as

$$T = \frac{P_m}{\omega} = \frac{\frac{1}{2} I^2 \omega \frac{dL_p}{d\theta}}{\omega}$$

$$T = \frac{1}{2} I^2 \frac{dL_p}{d\theta} \text{N-m} \quad (11)$$

The SR motor system model using state space technique can be obtained assuming there is no magnetic saturation, losses and mutual inductance. By using the above basic torque and power equation the vector space equation for the motor can be developed and is given by [11].

$$\frac{dI}{di} = -L^{-1}(\theta) K_i \omega + L^{-1}(\theta) V_p \quad (12)$$

$$\frac{d\omega}{di} = \frac{T}{J} - \frac{T_L}{J} - \frac{B}{J}\omega \quad (13)$$

$$\omega = \frac{d\theta}{dt} \quad (14)$$

The SR motor reference speed (ω^*) and actual speed (ω) taken as a state variables, the state space equation of the motor as

$$x_1 = \omega = \omega^* \quad (15)$$

$$x_2 = \dot{\omega} = -\frac{B}{J}\omega + \frac{T}{J} - \frac{T_L}{J} \quad (16)$$

By taking the inverse Laplace transform from the equation (15 and 16) we get the state space equation of the SR motor is

$$\begin{pmatrix} \dot{x}_1 \\ \dot{x}_2 \end{pmatrix} = \begin{pmatrix} 0 & 1 \\ 0 & -\frac{B}{J} \end{pmatrix} \begin{pmatrix} x_1 \\ x_2 \end{pmatrix} + \begin{pmatrix} 0 \\ \frac{1}{J} \end{pmatrix} \dot{T} \quad (17)$$

Output Equation is

$$y = \begin{pmatrix} 0 & \dot{\omega}^* \\ 0 & \frac{T_L}{J} \end{pmatrix} \begin{pmatrix} x_1 \\ x_2 \end{pmatrix} \quad (18)$$

These state equations can be used to analysis the stability of the system furthermore the equation can be used to estimate the value of parasitic elements.

RESULTS AND DISCUSSIONS

Design of Fuzzy Logic Controller: The Fuzzy Logic Controller (FLC) provides an adaptive control for improved system performance [13]. FLC is intended to give solution for controlling the non-linear processes and to handle ambiguous and uncertain situations. The performance of the Controller is developed with MATLAB/Simulink in terms of speed and load variation. The FLC have three stages namely Fuzzification, Rule-Base and Defuzzification. The fuzzy control is developed using input membership functions for error 'e' and change in error 'Δe' and the output membership function for 'Δu' the duty ratio of inverter. The output of the fuzzy control algorithm is the change in PWM Signal [δd(α)]. The PWM Signald (α), at the α^{th} sampling time, is determined by adding the previous PWM Signal [d (α -1)] to the calculated change in PWM Signal:

$$d(\alpha) = d(\alpha - 1) + \delta d(\alpha)$$

The fuzzy rule variables error 'e', change in eror 'Δe' and output 'Δu' are described by triangular membership functions. The graphical diagram of triangular membership function is shown in fig.4. Seven triangular membership functions are taken for creating the rules. Table 1 present the fuzzy rules. Fuzzy memberships NB, NM,NS, Z, PS, PM,PB are defined as negative big, negative medium, negative small, zero, positive small, positive medium and positive big.

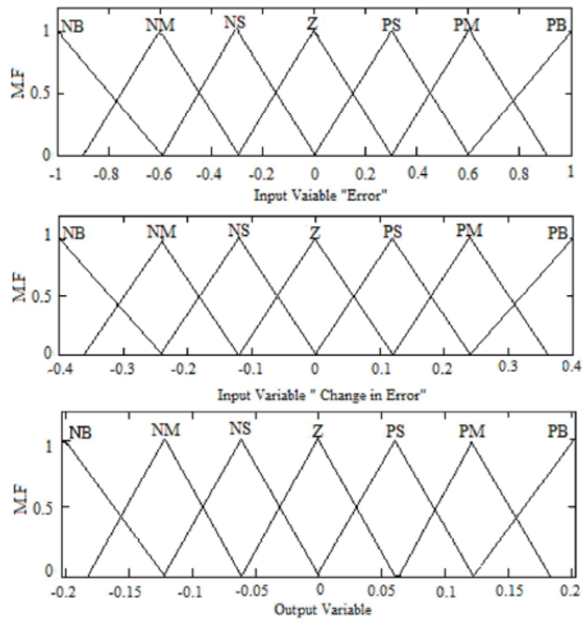

Fig. 4: Fuzzy Membership Function

Table 1: Fuzzy Rules

	NB	NM	NS	Z	PS	PM	PB
NB	NB	NB	NB	NB	NS	PS	Z
NM	NB	NM	NM	NS	NS	Z	NS
NS	NB	NM	NB	NS	Z	NS	PS
Z	NB	NS	NS	Z	PS	NM	PB
PS	NS	NS	Z	PS	PB	NM	PB
PM	NS	Z	PS	PB	PB	NM	PB
PB	Z NS	PS	PB	PB	PB	PB	

Design of Fuzzy Tuned Artificial Neural Network (FT-ANN) Controller: The FT- ANN based control of SR motor is described in reference [9, 12]. Before analyses the results are not attain the prescribed solution, it's desired to be improved further. The performance of SR motor to be improved using the Fuzzy Tuned Artificial Neural Network based controller (FT-ANN). The FLC data is used to design the Artificial Neural Network algorithm (ANN). The proposed controller is working properly due to its well trained algorithm and also it minimize the computational time. The FT-ANN is designed with a small number of neurons and single hidden layer. The feed forward neural network is developed with double neurons in the input layer, thrice in the hidden layer and single in the output layer. The two inputs are taken as error e (α) and change in error Δe(α), these inputs are developed and biased properly. From the FLC the network is designed and trained with the set of inputs and desired outputs.

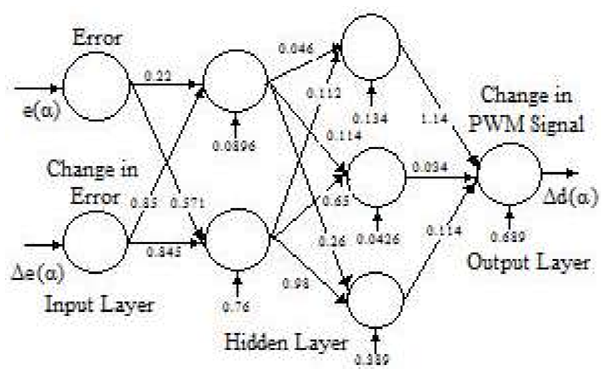

Fig. 5: Configuration of trained Neural Network

A feed forward back propagation neural network-training algorithm is used and it is trained with minimum error. The output of the network is change in PWM Signal Δd(α). The FT-ANN is designed and trained with the error goal value of 0.00596325 at 11 epochs. The complete configuration of the trained network with the weights and bias is shown in figure 5.

The proposed FT-ANN system is simulated using MATLAB software. The simulink model of SR motor is developed with FT-ANN as given in figure 6. The set reference speed and motor actual speed is taken as input. The error and change in error are calculated and then given as input to the FT-ANN. The output of the PWM pulse signal is given as input to the PWM generator of the inverter.

The 100Hz of switching frequency is produced from the PWM unit. Then the current controller receives the pulse signal from the PWM unit. The reference current is equal to the motor current then the current controller permit the PWM signal. The PWM pulse signal is given to the main inverter circuit then the change output voltage changes from variable voltage to fixed voltage. Then the speed of the motor runs with the reference speed. The FT-ANN controller model is shown in fig.7.

Simulation Results of the Proposed System: The simulation of the proposed system is carried out using MATLAB/Simulink software. The FT-ANN controller is used as a closed loop for the SR motor performance estimation. The speed control of the motor has been carried out using fuzzy logic controller and fuzzy tuned artificial neural network controller. The variation of the speed is shown in below fig.8 the expended view also presented. The output of the speed flow the reference with better accuracy, showing a better tracking performance of the controller. Its shows that the FT-ANN controller is settling time and percentage overshoot is very less compare to other controller.

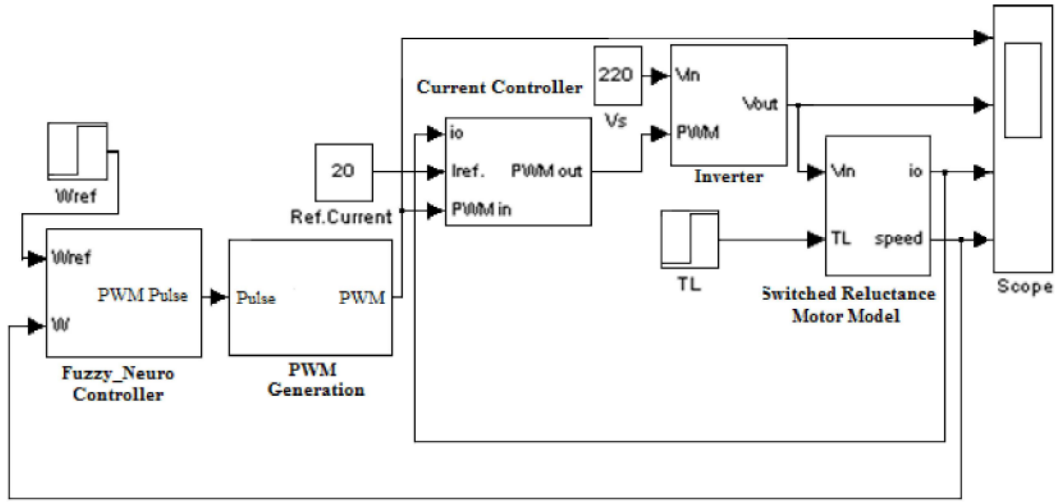

Fig. 6: MATLAB/Simulink Model of the proposed system

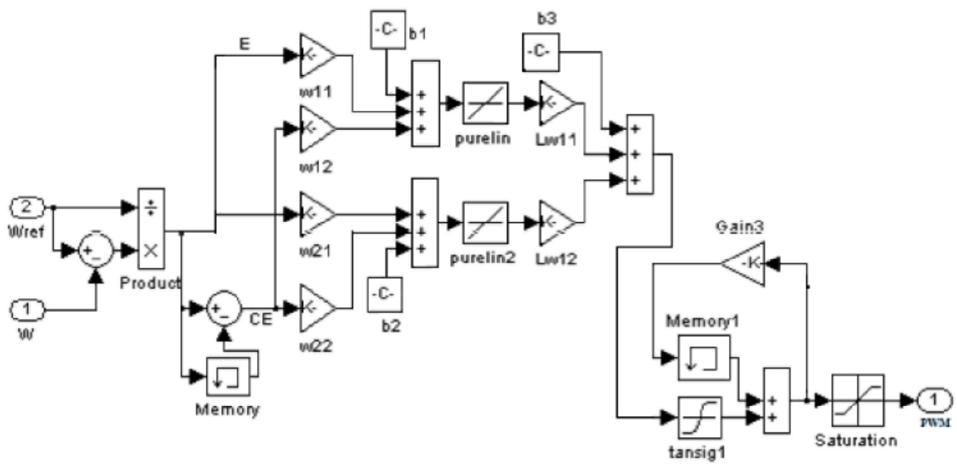

Fig. 7: Simulink Model of FT-ANN Controller

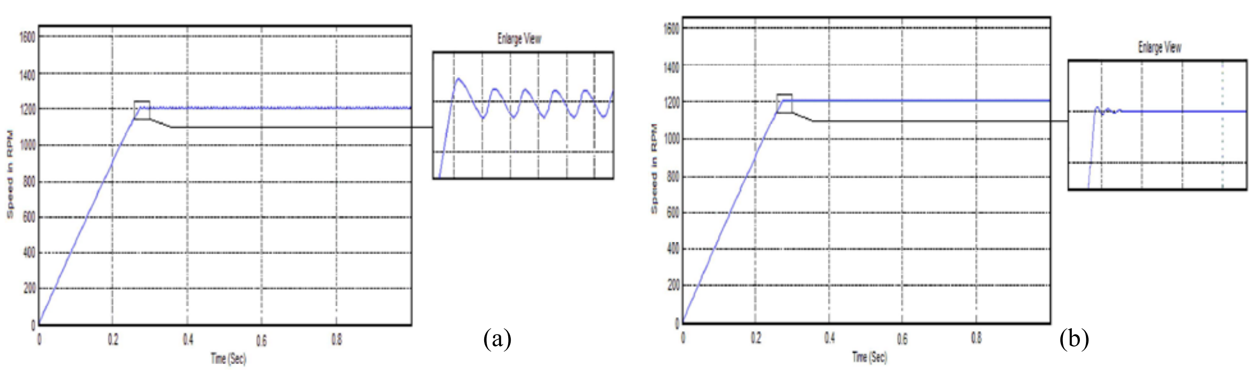

Fig. 8: SR motor Speed (a) using FLC (b) using FT-ANN controller

The maximum overshoot and percentage error is very small and it tends to zero as shown in fig.8 (b) the rise time and settling is near to 0.01 sec its very less compare to FLC. The expended view diagram shows that the steady state error is near equal to 0.001sec. It is clear that the FT-ANN controller eliminating the rise time, overshoot and suppers the harmonics.

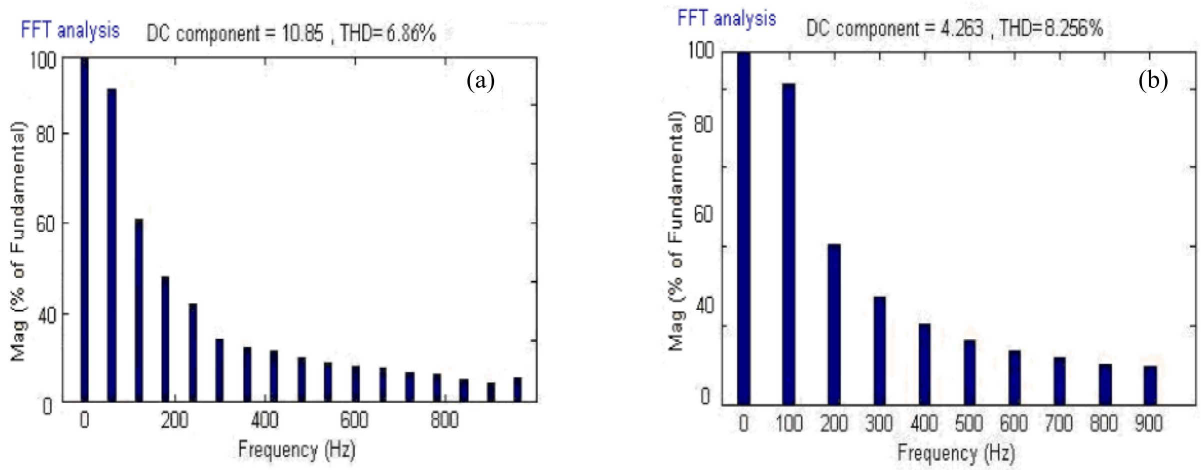

Fig. 9: FFT analysis (a) FT-ANN (b) FLC

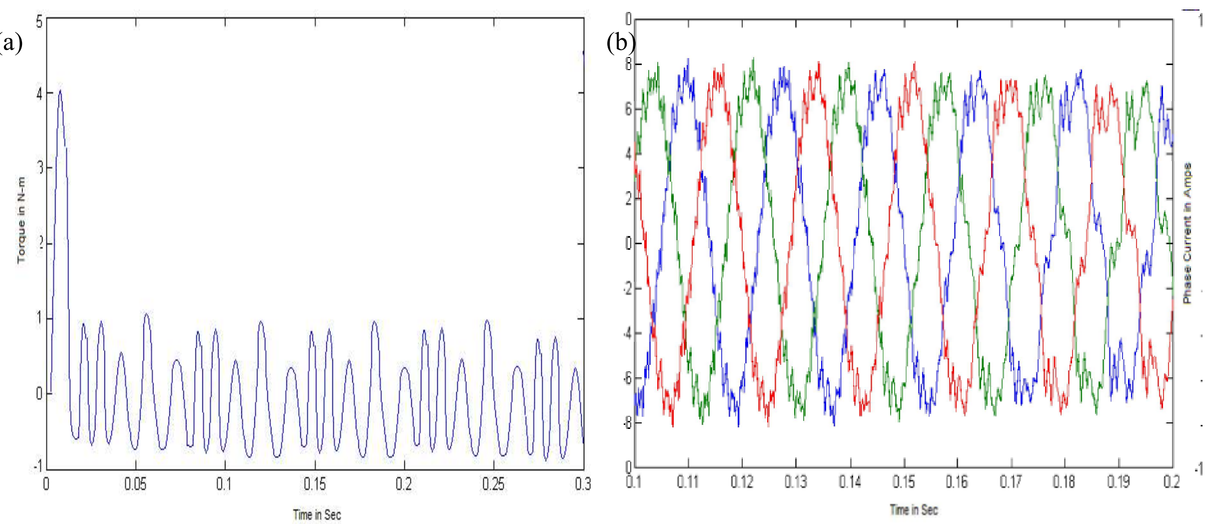

Fig. 10: (a) Torque Response (b) Phase current

Table 2: Comparative analysis of transient and steady state performance for different controllers

Controller	% Overshoot	Rise time in Sec	Steady state error	Settling Time in Sec.	THD in %
FLC	0.36	0.85	0.04	1	8.25
FT-ANN	nil	0.52	0.001	0.68	6.8

The FFT analysis of the SR motor for the output voltage as shown fig.9. The Total Harmonics distraction (THD) is calculated from the inverter side. It's found from the above FFT analysis clearly shows that the controller tracking performance is good and THD values are less compared to fuzzy controller. The developed torque performance of the SR motor as shown in fig.10 (a) and the phase current of the motor are present in fig.10(b)

The performance of the controller response for SR motor speed control has been estimated and provided in table.2. It is seen that the FLC/FT-ANN closed loop controllers give the better settling time. This ensures that the controller provide the effective feedback. It is concluded from the above table 2 the FT-ANN controller has improved the transient and dynamic performance of the SR motor. The harmonics spectrum analysis of the motor speed can be estimated and provided in table.2.

In further to analysis the performance of the SR motor controller the simulation is carried out different set speed changes it is shown in fig.11 and 12 respectively. The set speed changes from 500 rpm to 1000 rpm and 1000 rpm to 1600 rpm. The fuzzy controller shows a comparatively

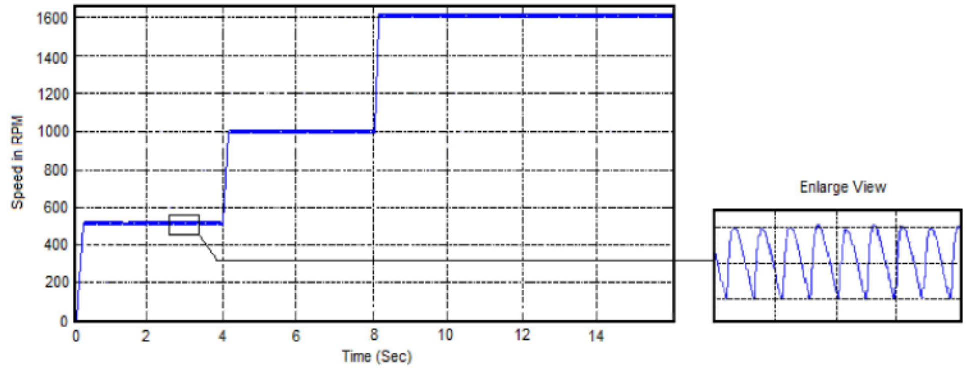

Fig. 11: Speed control from 500 RPM to 1000 RPM, 1000 RPM to 1600 RPM at 4 sec and 8sec respectively (using FLC)

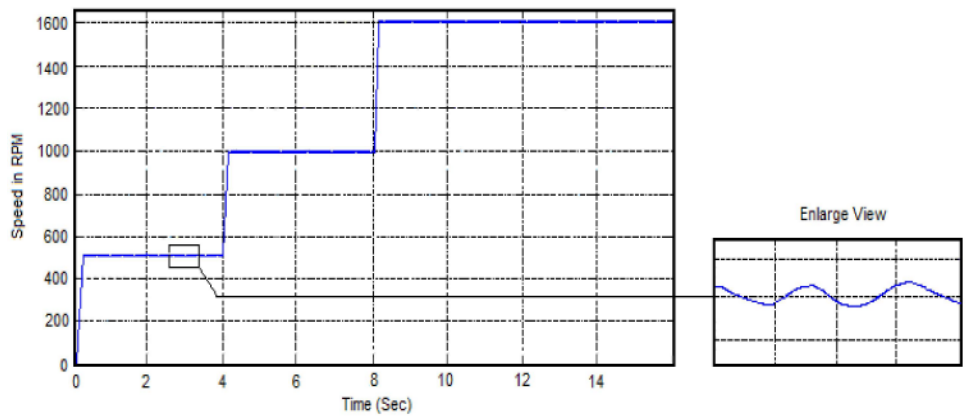

Fig. 12: Speed control from 500 RPM to 1000 RPM,1000 RPM to 1600 RPM at 4 Sec and 8sec respectively

Table 3: Transient response of the controllers in with reference speed changes

	Change in speed from 0 to 500 RPM		Change in speed from 500 to 1000 RPM		Change in speed from 1000 to 1600 RPM	
Controllers	% over Shoot	Settling time in Sec.	% over Shoot	Settling time in Sec.	% over Shoot	Settling time in Sec.
FLC	0.2	0.35	0.29	0.295	0.3	0.39
FT-ANN	0.001	0.15	0.001	0.18	0.001	0.19

maximum percentage overshoot and more time to settle, there is no steady-state error as shown in fig.11. It's clearly found that the FT-ANN controller gives the least amount of overshoot and zero steady state error and the rise time and settling time is near to 0.001 as shown in fig.12.

From the above figure we found that the transient and dynamic performance is more in fuzzy logic controller due to more oscillation and its very minimum in FT-ANN controller. While the motor is running to the rated speed the variation is very minimum at both speed changes. The transient performance of the different controllers with speed changes as provided in table.3. It is clear from the table 3 that the transient performance is under control limit in FT-ANN controller compared to FLC. It is learn that the steady state error is very less in the proposed controller.

Stability Analysis of the Proposed System: The plot has drawn for SR motor basic equation with torque equation from the state space model equations (17and 18). It is clear that the proposed system is stable for the system speed changes. It is concluded that the -0.5+j0 point is encircled in the all direction in single time. Hence overall encirclement is zero. Also the open loop system has no poles at the right half of s-plan. So the proposed system is stable.The nyquist plot as shown in figure 13.

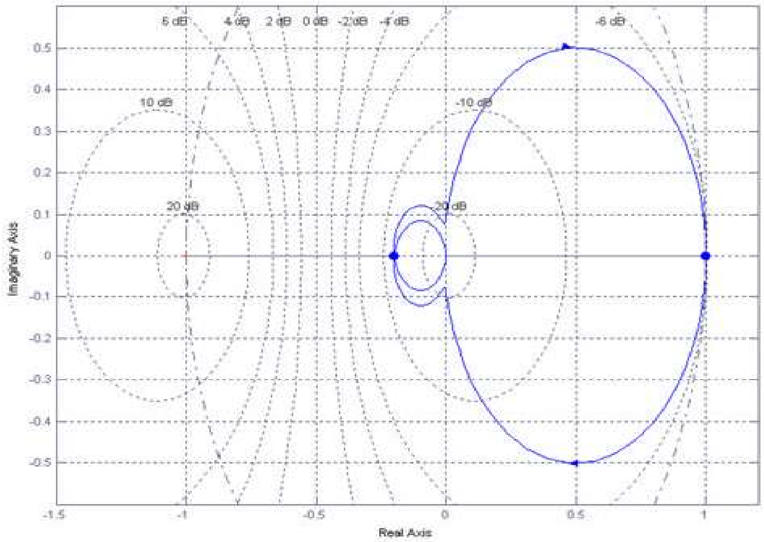

Fig. 13: Stability analysis using nyquist plot for SR motor

(a)
(b)
(c)
(d)

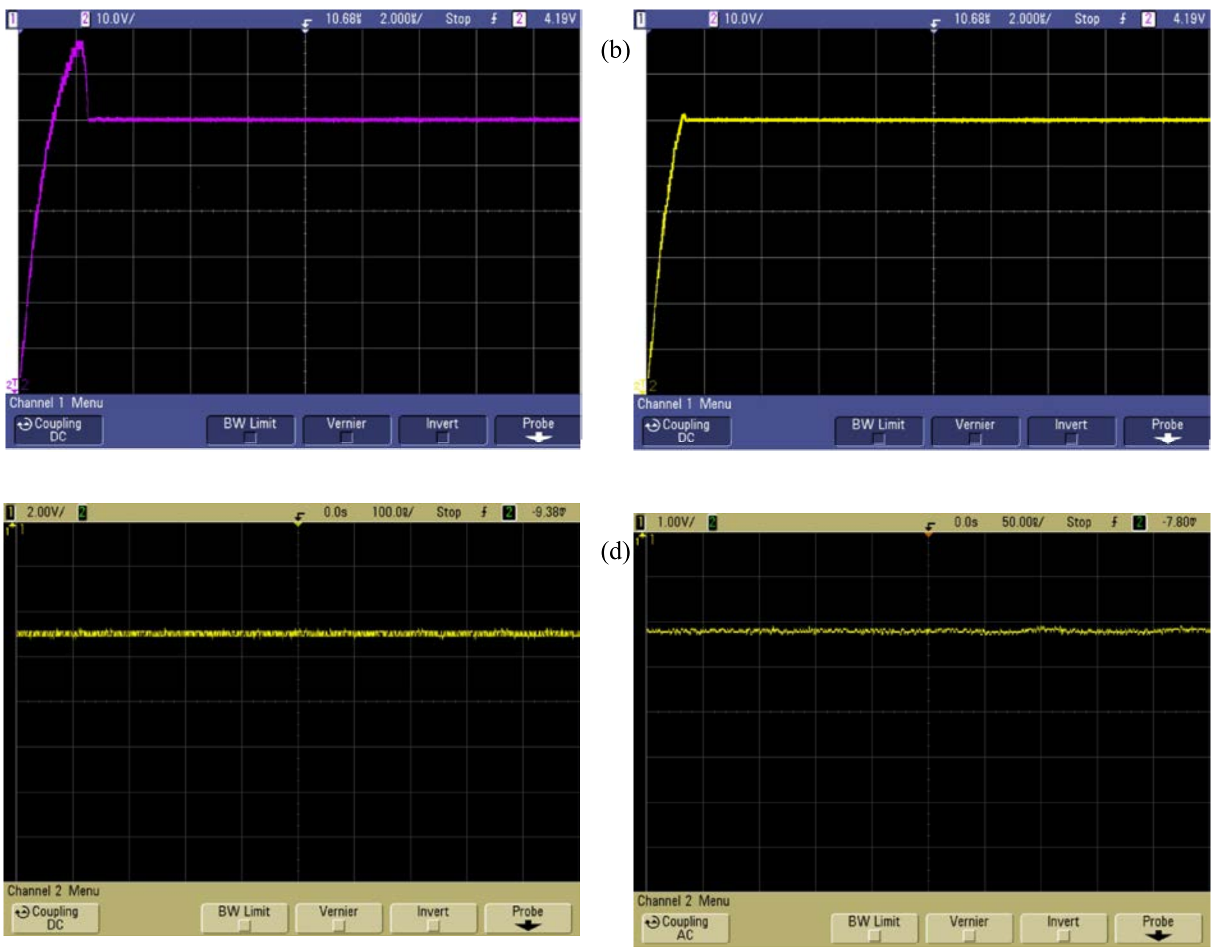

Fig. 14: Experimental waveform of SR motor speed (a) with FLC (b) with FT-ANN controller (c) Steady state error voltage for FLC (d) (c) Steady state error voltage for FT-ANN

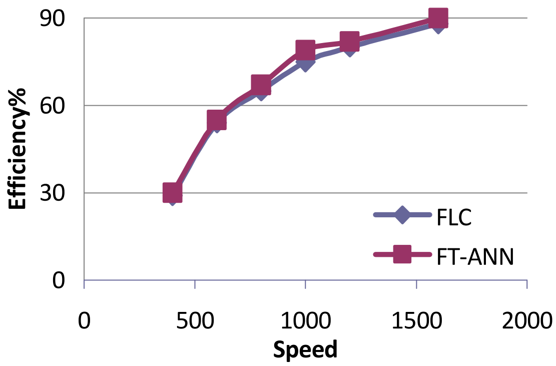

Fig. 15: Speed Vs Efficiency of the SR motor

Experimental Results: The SR motor model is fabricated and performance is tested. A prototype SR motor with FT-ANN controller is operating 300W, 50Hz is designed. The P89V51RD2BN microcontroller is used for generating the driving pulses and IRFP840 MOSFET used as switches in the inverter bridge circuit.MUR4100 diodes used in the rectifier circuit. The frequency level of the generated PWM is 10 KHz. the open collector optocoupler CYN 17-1 is generate the PWM signal from the microcontroller through isolator and IR2110 driver IC. The speed of the motor can be controlled from inverter output. The motor speed is sensed by a digital type pulse sensor GP1L53V. The PWM pulse signal is given to a LM2907 voltage converter IC and feedback signal is given to the microcontroller through an ADC IC ADC0808CCN.

Figure 14 (a) shows the speed voltage waveform with reference speed of 1500 rpm using FLC, it is clearly shows that 4 seconds of time to settle the reference speed. It seen that the oscillations is present due to delay of pulse generation of the controller. Figurer 14 (b) it is observed that there is a minimum steady state error, less percentage overshoot and the minimum settling time at 2.5 seconds. Fig 14(c and d) shows the output voltage of the motor. The steady state error is very minimum compare to FLC. Based on the fig.(14 b,d),. It's clearly seen that FT-ANN based controller having the better transient and steady state performance. The comparison chart is shown in fig.15. The motor speed with efficiency is plotted, it is observed that the proposed controller has high efficiency with step change speed. It is seen form this plot the SR motor have a better efficiency while using FT-ANN controller.

CONCLUSION

The steady state stability analysis of the SR motor has been developed and simulated for estimating the performance for various speed changes using MATLAB/simulink. It has been found from the analysis that the FT-ANN controller provides better efficiency and speed regulation. The comparison results were presented for both controllers. It's found from that FT-ANN controller performs better than fuzzy controller. The proposed controller provides a good speed tracking without overshoot. The proto type model was design and the experimental results are closely agreed with simulation results.

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