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Performance Comparison of PI, Sliding Mode and Fuzzy Logic Controllers for DTC of Three Level Inverter Fed Induction Motor

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Abstract

This paper presents direct torque control (DTC) of induction motor fed by a three level inverter employing different speed controllers like PI, Sliding mode controller(SMC) and fuzzy logic controller. Performance of all the three controllers is analyzed in terms of transient, steady state behavior and sensitivity to the parameter variations. It is observed that the PI controller is simple but sensitive to the parameter variation. SMC and fuzzy logic controllers are robust to parameter variations and both can handle nonlinearities in a better way compared with PI controller. To validate this, SIMULINK models have been developed and results have been presented.

Keywords: Direct torque control, sliding mode controller, fuzzy control, Neutral point clamped inverter, space vector.

Introduction

Induction motors has simple and rugged construction. These motors are mostly used for industrial applications. For low performance applications, open loop voltage/frequency control strategies are employed. For high-performance applications, vector control (VC), and Direct Torque Control (DTC) are used. DTC of induction motor is preferred as this technique is based on the space vector approach, where the torque and flux of an induction motor can be directly and independently controlled without any coordinate transformation [1]. The merits of DTC are fast torque response, simple structure and robustness against motor parameter variation [2]–[4]. Multi-level inverters were extensively used especially in high power application areas [5]–[8]. The three-level neutral-point-clamped (NPC) inverter is one of the most commonly used multilevel inverter topologies. Three-level inverter offers superiority in terms of lower voltage distortion, lower stress across the semiconductors, less harmonic content and lower switching frequency when compared with the conventional two level inverters[9]. Speed performance of these drives is poor because of the uncertainties caused by load disturbances. Conventional speed control methods face difficulties like dependency on the accuracy of mathematical model of the system, shows good performance at only one speed etc.,. Advanced speed controllers like Fuzzy logic controllers, sliding mode controllers are employed which improves the speed performance of the system when compared with PI controllers. Fuzzy logic is a technique which incorporates human-like thinking into a control system. SMC tracks the drive response along a predefined trajectory in a phase plane by a switching control algorithm.

This paper presents direct torque control for a three-level inverter-fed induction motor drive which employs SMC and fuzzy logic controllers. A comparative study of the performance of the SMC, fuzzy and PI controllers is presented. Simulation is carried out to validate the effectiveness of the schemes proposed.

Mathematical Modeling of Induction Motor

The induction motor has been modeled by using the following equations.

$$V_{qs} = R_s i_{qs} + \frac{d}{dt}\psi_{qs} \tag{1}$$

$$V_{ds} = R_s i_{ds} + \frac{d}{dt}\psi_{ds} \tag{2}$$

$$R_r i_{qr} + \frac{d}{dt}\psi_{qr} - \omega_r \Psi_{dr} = 0 \tag{3}$$

$$R_r i_{dr} + \frac{d}{dt}\psi_{dr} + \omega_r \Psi_{qr} = 0 \tag{4}$$

$$T_e = \frac{3}{2}\left(\frac{P}{2}\right)\left(\Psi_{ds} i_{qs} - \Psi_{qs} i_{ds}\right) \tag{5}$$

Neutral Point Clamped Inverter

The three level neutral point clamped inverter has many advantages over the conventional two level inverter, such as smoother waveform, less distortion, less switching frequency and low cost [10]. The topology of a three level NPC inverter is shown in figure 1.

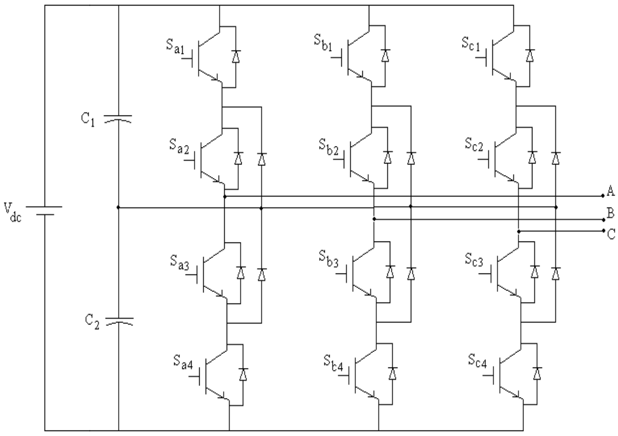


Figure 1: Schematic diagram of NPC three level Inverter

The three level inverter has a total of 27 switching states (3^3). When the upper switches S_{a1}, S_{a2} are in the on state, that corresponds to the state '1'. When the lower switches S_{a3}, S_{a4} are on, that corresponds to state '-1'. When the auxiliary switches S_{a2}, S_{a3} are on, that results in state '0'. The space vector diagram of all the switching states is represented in figure 2. The space vector diagram consists of two hexagons, the inner hexagon and the outer hexagon. A three level inverter has basically 27 switching states out of which three are zero states and the remaining twenty four states are the active states. The zero states produce a zero vector where as the twenty four active states produce eighteen different voltage vectors. These eighteen active vectors are classified as small, medium and large voltage vectors based on their magnitude. This classification is shown in Table 1.

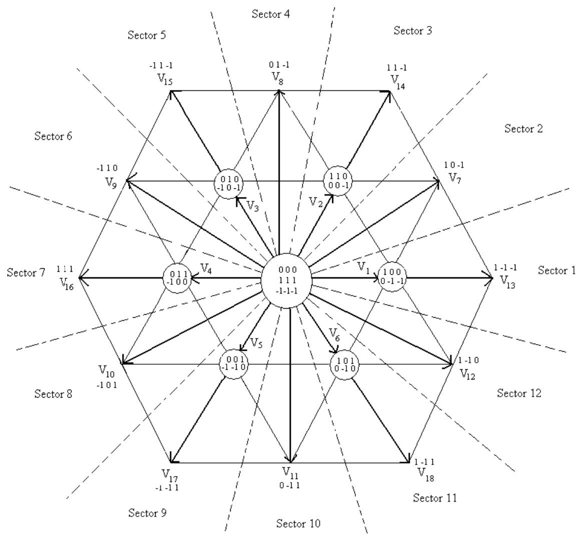


Figure 2: Space vector diagram

Table I: Classification of Voltage Vectors

Type	Vector numbers	Magnitude
Small	$V_1, V_2, V_3, V_4, V_5, V_6$	$0.5\ V_d$
Medium	$V_7, V_8, V_9, V_{10}, V_{11}, V_{12}$	$0.866\ V_d$
Large	$V_{13}, V_{14}, V_{15}, V_{16}, V_{17}, V_{18}$	V_d

PI Control for DTC of Induction Motor

The electromagnetic torque of 3-phase induction motor is given by,

$$T_e = \frac{3}{2}\frac{P}{2}\frac{L_m}{\sigma L_s L_r}|\psi_r||\psi_s|\sin\eta \tag{6}$$

Where ψ_r and ψ_s are the rotor and stator flux linkages and η is the angle between the fluxes and σ is the leakage coefficient. The direct torque control of induction motor fed by a three level NPC inverter is as shown in figure 3.

According to this block diagram, the scheme includes two hysteresis controllers. They are the torque hysteresis and the flux hysteresis controllers. The adaptive motor controller block provides the information related to the actual torque, speed, flux and the angle to the hysteresis torque and flux controllers and the sector estimator blocks.

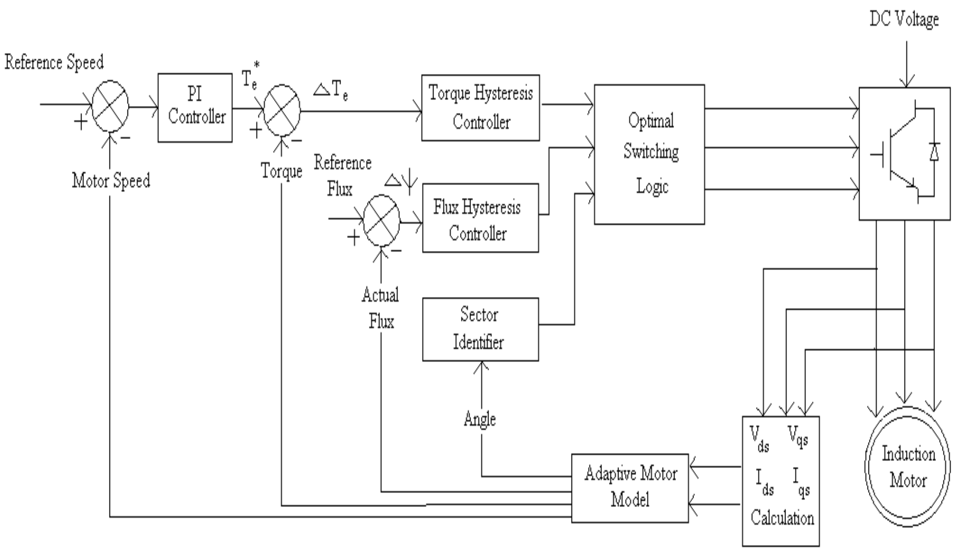


Figure 3: DTC of Induction Motor fed by a three level Inverter

The PI controller employed in the system results in the torque command signal. The optimal switching logic block generates the control signals S_a, S_b, S_c to the three level inverter. The modulation strategy of the three level NPC inverter is implemented as in [11].

Fuzzy Speed Control for DTC of Induction Motor

Fuzzy logic control is an adaptive and nonlinear control which gives robust performance with parameter variation. These controllers can handle complicated non linear systems which have a degree of uncertainty [12]. It does not require exact system modeling and parameters which makes the controller suitable for the motor control [13],[14]. The fuzzy logic controller has two inputs (1) speed error 'E' (2) derivative of the speed error 'CE'. The block diagram of a fuzzy PI controller is shown in figure 4 [15].

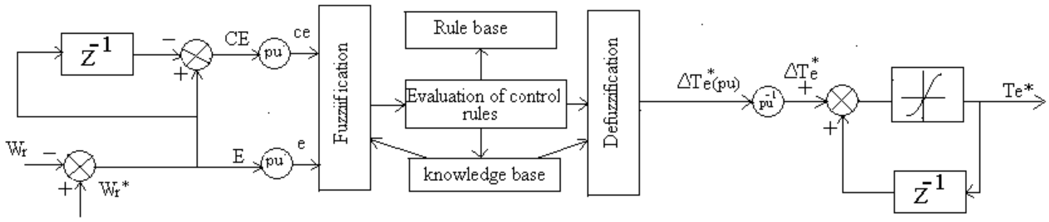


Figure 4: Block diagram of fuzzy PI controller

The rule base of a fuzzy system is IF – THEN statement. The execution of the rules goes like this: IF there exists a case, THEN a particular condition has to be executed. For example,

IF e(PU) = PS AND ce(PU) = NM, THEN dT_e*(PU) = NVS.

The membership functions of the input and output variables are as shown in figures 5,6.

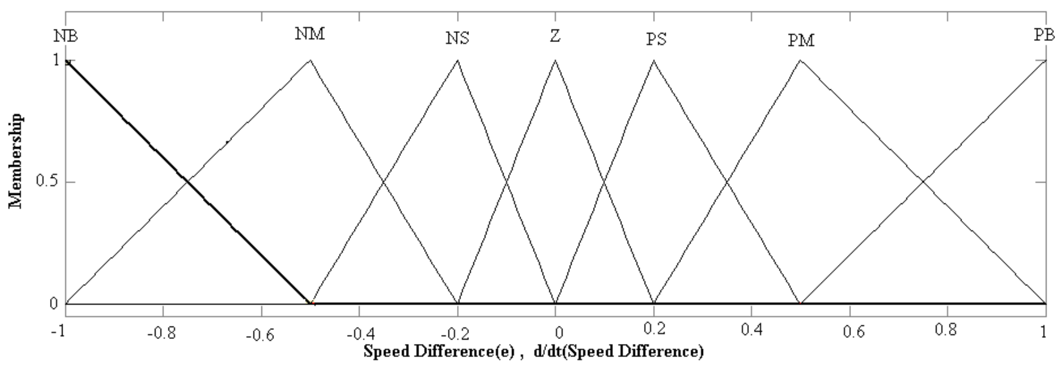


Figure 5: Membership functions of the input variables (a) speed error (e) (b) change in speed error (de)

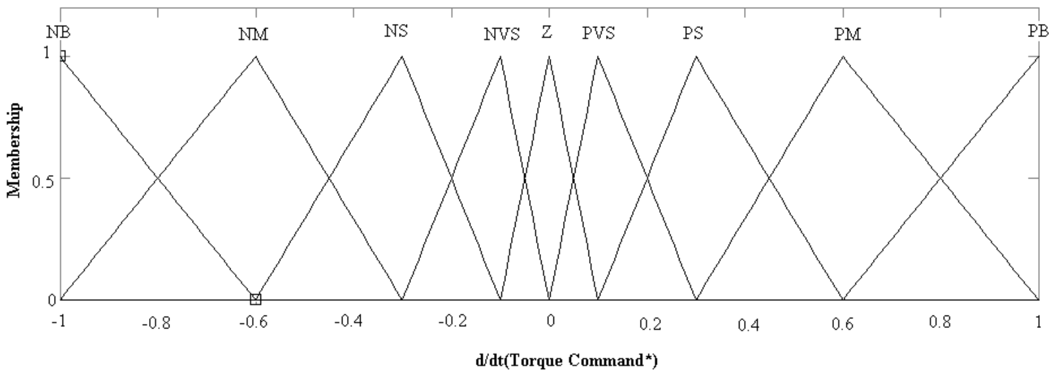


Figure 6: Membership functions of the output variable change in torque command(dT_e*)

The number of input variables chosen is 7 and hence the possible number of fuzzy rules is 7X7 = 49. All these rules are shown in table 2.

Table 2: Fuzzy Rules

e(pu) ce(pu)	NB	NM	NS	Z	PS	PM	PB
NB	NB	NB	NB	NM	NS	NVS	Z
NM	NB	NB	NM	NS	NVS	Z	PVS
NS	NB	NM	NS	NVS	Z	PVS	PS
Z	NM	NS	NVS	Z	PVS	PS	PM
PS	NS	NVS	Z	PVS	PS	PM	PB
PM	NVS	Z	PVS	PS	PM	PB	PB
PB	Z	PVS	PS	PM	PB	PB	PB

Where NB=Negative Big, NM=Negative Medium, NS=Negative Small, Z=Zero, PS=Positive Small, PM=Positive Medium, PB=Positive Big, NVS=Negative Very Small, PVS=Positive Very Small.

The mapping relationship between the input variables and output variables is shown in figure 7.

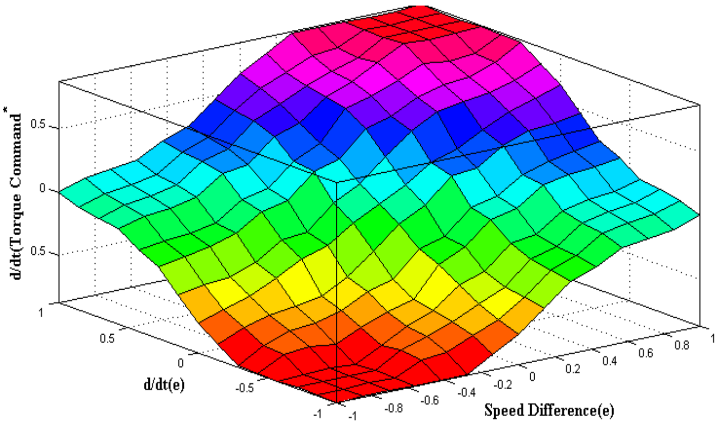


Figure 7: Control surface of the fuzzy logic controller

SMC for DTC of induction motor

A SMC with a variable structure control(VSC) is an adaptive control technique that gives robust performance of a drive with parameter variation and load torque disturbances. This can be applied to a linear or nonlinear plant. In the SMC, the drive response is forced to track along a predefined trajectory in a phase plane by a switching control algorithm, irrespective of the plant's parameter variation and load disturbance. SMC based speed controller is tested for various load torque disturbances.

The design and implementation of SMC is simpler. SMC can be applied to induction motors for applications such as robot drives, machine tool control, etc. A novel variable structure control law with an integral sliding mode surface for speed control is presented to compensate the uncertainties that are present in the system. The block diagram of SMC based CDTC drive is as shown in [16].

The electromechanical equation of an induction motor is described as shown in (7).

$$T_e = J\frac{d\omega_m}{dt} + B\omega_m + T_L \tag{7}$$

Where *J* and *B* are the inertia constant and the viscous friction coefficient of the induction motor system respectively, *TL* is load torque, *Te* is the electromagnetic torque of induction motor and ω_m is the rotor mechanical speed. The electromechanical equation can be modified further as shown in (8).

$$\dot{\omega}_m + a\omega_m + d = bT_e \tag{8}$$

Where a= B/J, b = 1/J, d = T_l/J.

Consider the electromechanical equation (9) with uncertainties as shown below.

$$\dot{\omega}_m = -(a+\Delta a)\omega_m - (d+\Delta d) + (b+\Delta b)T_e \tag{9}$$

Δa , Δb and Δd represents the uncertainties of the terms *a*, *b* and *d* respectively introduced by system parameters *J* and *B*. Consider the tracking speed error as given in (10).

$$e(t) = \omega_m(t) - \overset{*}{\omega}_m(t) \tag{10}$$

The sliding variable with integral component can be defined as (11)

$$S(t) = e(t) - \int_0^t (h-a)e(\tau)d\tau \tag{11}$$

Where h is a constant gain. The *h* must be chosen so that the term (*h*-*a*) is strictly negative and hence *h<0*. Based on the switching surface, a switching control that guarantees the existence of sliding surface, a speed controller is defined as [17]-[19],

$$f(t) = he(t) - \beta\,\mathrm{sgn}(S(t)) \tag{12}$$

where β is the switching gain and sgn(.) is the sign function defined as

$$\begin{aligned} \mathrm{sgn}(S(t)) &= +1 --- if, S(t) > 0 \\ \mathrm{sgn}(S(t)) &= -1 --- if, S(t) < 0 \end{aligned} \tag{13}$$

The gain β must be chosen so that β ≥ x (t) for all the times Where x(t) is the lumped uncertainty defined as

$$x(t) = -\Delta a\omega_m(t) - \Delta d(t) + \Delta b T_e(t) \tag{14}$$

Consider the Lyapunov function given in (15)

$$V(t) = 1/2(S(t))^2 \tag{15}$$

As per the the Lyapunov's direct method, it is found that *V* (*t*) is clearly positive definite, derivative of *V* (*t*) is negative definite and *V* (*t*) tends to infinity as *S*(*t*) tends to infinity, and then the equilibrium at the origin *S*(*t*) = 0 is globally asymptotically stable. Now *S* (*t)* tends to zero as the time *t* tends to infinity. All trajectories starting off the sliding surface S=0 must reach it in finite time and then will remain on this surface. This system's behavior on the sliding surface is usually called sliding mode. When the sliding mode occurs on the sliding surface, then, *S* (*t*) = d*S*(*t*) = 0 and the tracking error *e(t)* converges to zero exponentially. Finally, the reference torque command $\overset{*}{T}_e$ can be obtained as given below.

$$\overset{*}{T}_e(t) = \frac{1}{b}\left[(he) - \beta\,\mathrm{sgn}(S) + a\,\overset{*}{\omega}_m + \dot{\overset{*}{\omega}}_m + d\right] \tag{16}$$

Results and Discussion

To validate the effectiveness of these controllers, simulation of the three level DTC of induction motor with PI, SMC and fuzzy logic controllers is done.

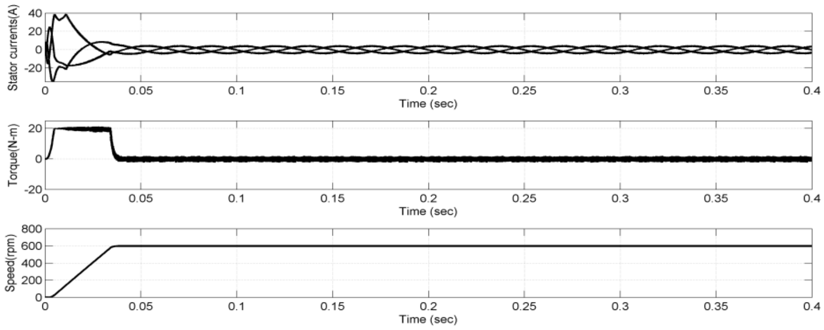
Parameters of the induction motor used in this paper are as shown below.

Stator resistance = 1.57 Ohms, Rotor resistance = 1.21 Ohms, Magnetizing inductance = 0.165H, Stator leakage inductance = 0.17H, Rotor leakage inductance = 0.17H, Number of pole pairs = 4

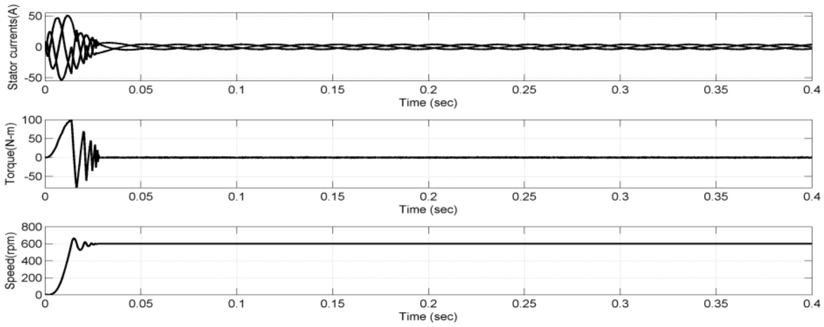
J = 0.089 Kg-m^2.

For simulation, the reference flux is taken as 1wb.

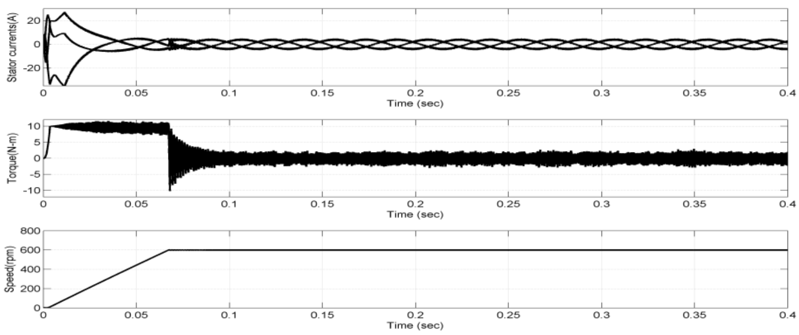
The no load stator currents, torque and the speed of the motor employing the three controllers during the transient and steady state period are as shown below. The transient behavior of the motor when the reference speed is set as 600 rpm is as shown in figure 8.



PI Controller



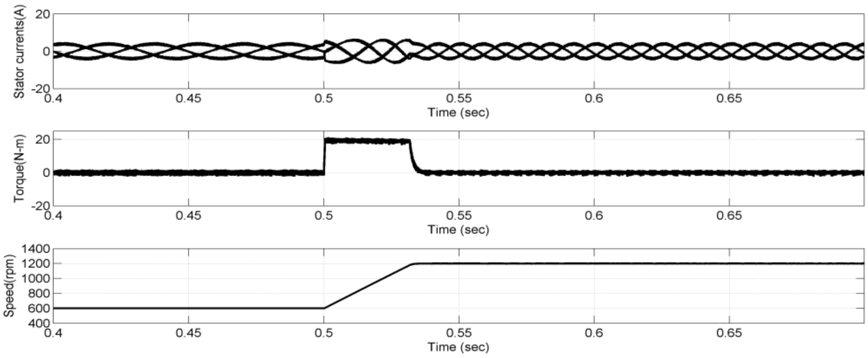
Sliding mode controller



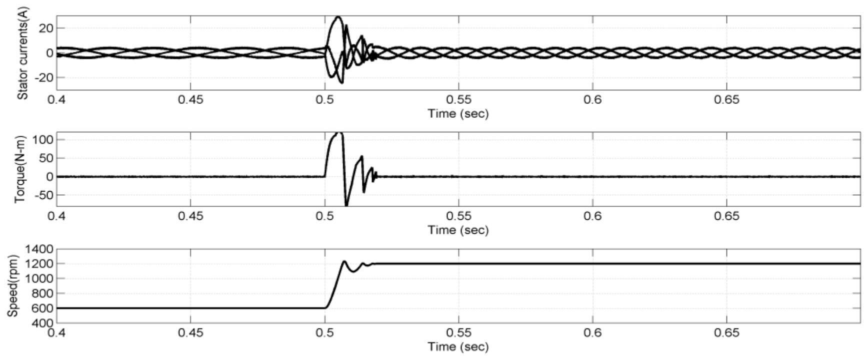
Fuzzy logic controller

Figure 8: Starting transients with the reference speed as 600 rpm.

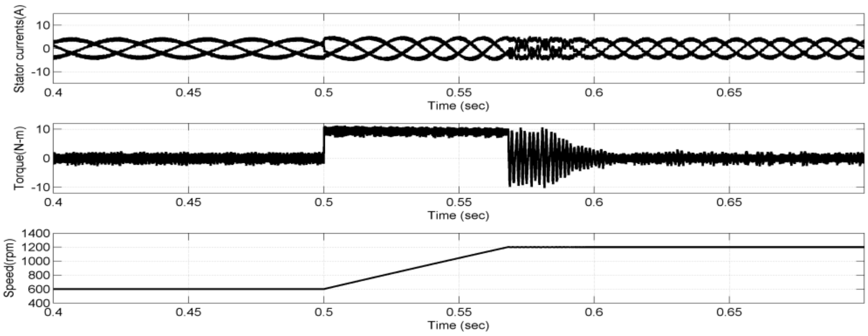
It is observed that, using SMC controller the motor reaches the steady state speed of 600 rpm quickly compared with the PI and fuzzy controllers. The ascending order of the time taken by the controllers to reach steady state speed is SMC, PI and fuzzy controller. It is also observed that starting currents drawn by the motor in SMC is more compared with PI and fuzzy controllers. The ascending order of magnitude of the starting currents drawn by the motor is fuzzy controller, PI and SMC.The transient behavior of the motor when the speed is changed from 600 rpm to 1200 rpm is as shown in figure 9.



PI Controller



Sliding mode controller

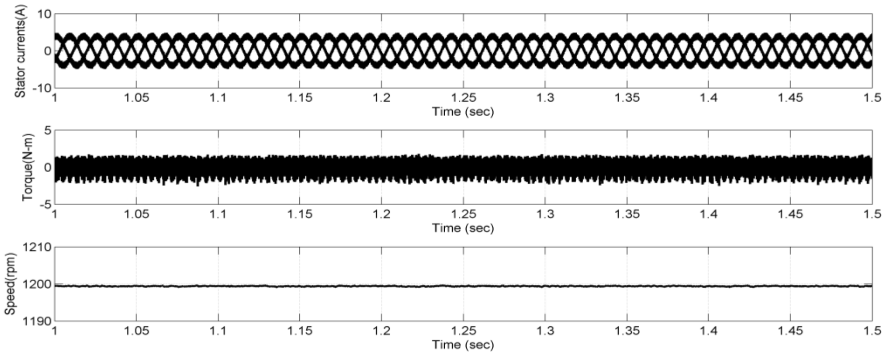


Fuzzy logic controller

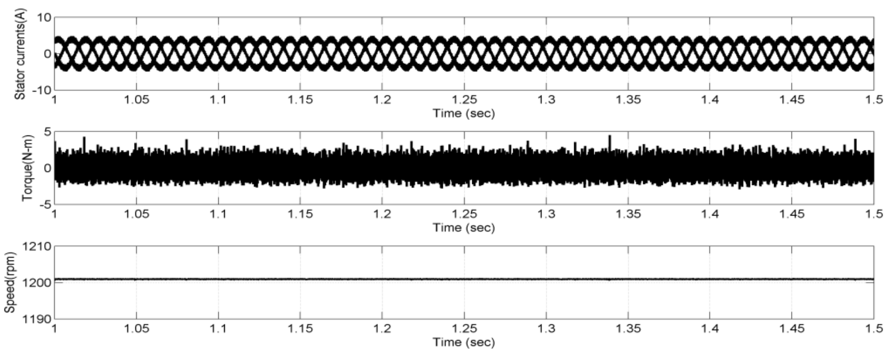
Figure 9: Transients during speed change from 600 rpm to 1200 rpm

It can be observed that, using SMC controller the motor response to the speed change command from 600 rpm to 1200 rpm is quick when compared with the PI and fuzzy controllers. The increasing order of the time taken by the controllers to reach steady state speed is SMC, PI and fuzzy controller. It is also observed that currents drawn by the motor during step change in speed in SMC is more compared with PI and fuzzy controllers.

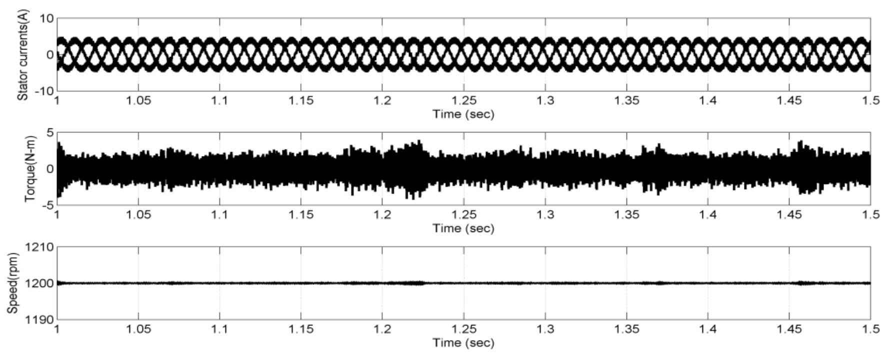
Steady state plots of the stator currents, torque and speed at 1200 rpm is as shown in figure 10.



PI controller



Sliding mode controller



Fuzzy logic controller

Figure 10: Steady state waveforms at 1200 rpm

The controllers are tested by considering different load torque disturbances. Figure 11 shows the external load torque disturbance. The behavior of the motor with PI, SMC and fuzzy logic controller is as shown in figure 12. The reference speed command is set at 1200 rpm.

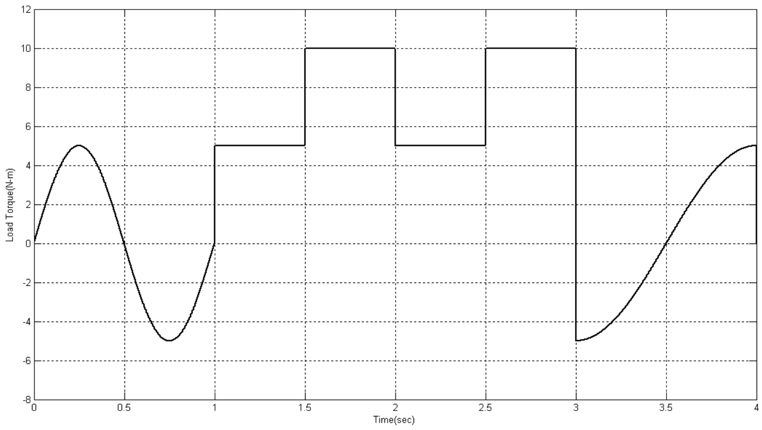
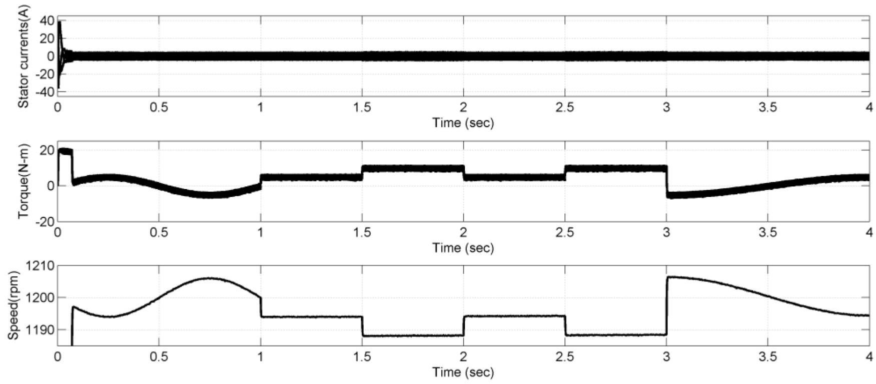
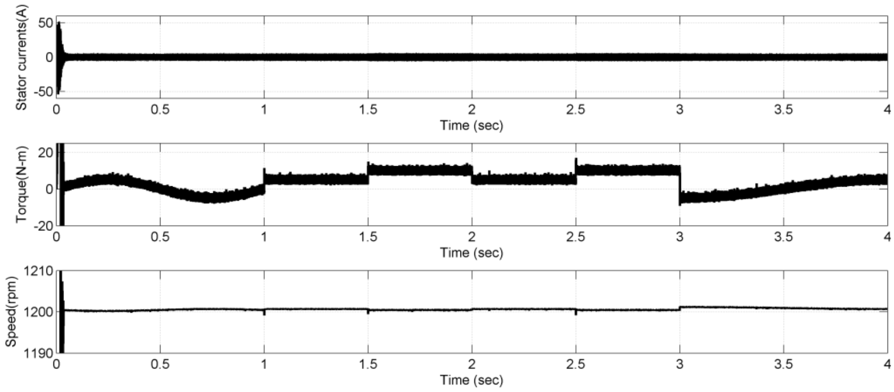


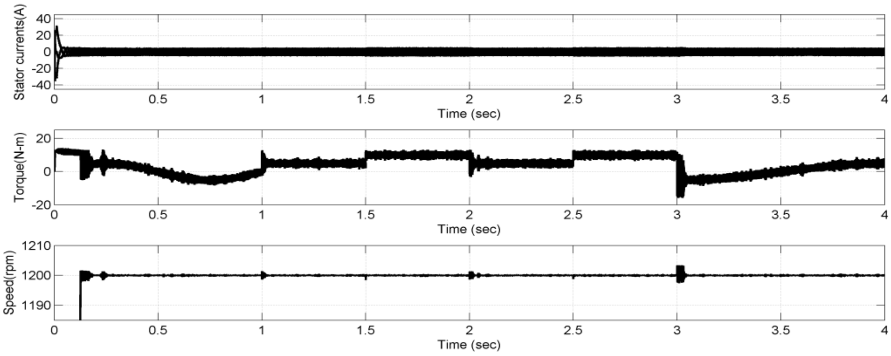
Figure 11: External load torque disturbance



PI controller



SMC Controller



Fuzzy logic controller

Figure 12: Response to external load torque disturbance

Speed comparison of the motor with PI, SMC and fuzzy controllers is shown in figure 13.

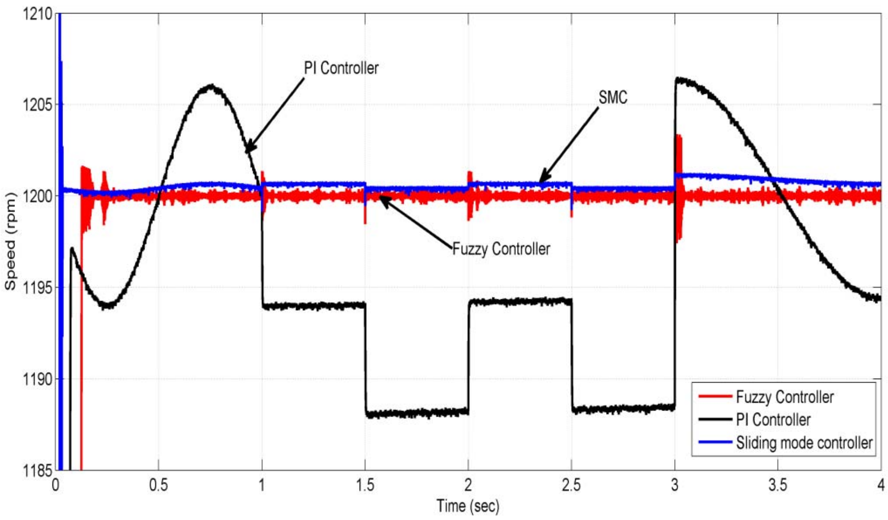


Figure 13: Speed comparison of PI, SMC and fuzzy controller

It can be observed from the speed comparison figure that for an external load disturbance the speed response of the motor is better with both SMC and fuzzy controllers when compared with PI. Conclusion can be made after the clear observation of the comparison waveform. Motor with fuzzy controller results in almost constant speed of 1200 rpm with slight ripples at the instant of the step changes in load.

Conclusions

Performance of DTC of induction motor fed by a three level inverter employing different speed controllers like PI, SMC and fuzzy logic controllers is presented. Behavior of all the three controllers is analyzed in terms of transient, steady state and sensitivity to the parameter variations. It can be concluded that the fuzzy logic controller's performance is excellent in comparison with that of PI and SMC in terms of the steady-state accuracy, robustness to load disturbance and parameters variations. The dynamic performance of SMC is found to be the best out of the three controllers. PI is very simple to implement, but its dynamic performance and steady-state accuracy are not very satisfactory. Its robustness to load disturbances and parameter variations are also relatively poor.

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