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Performance Analysis of Fuzzy Logic Controlled 8/6 Switched Reluctance Motor for Light Electric Vehicle

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ABSTRACT
Electric Vehicle (EV) is the replacement of conventional Internal Combustion Engine Automobiles. Basic requirement of any vehicle is to have smooth operation and its unique efficient drive train. In Electric vehicles it is very important to analyze the performance characteristics of electric drive. Switched Reluctance Motor (SRM) shows the most favourable characteristics for EVs. In general Permanent Magnet Synchronous Motor (PMSM) and Brush Less DC motor (BLDC) were preferred over other motors for propelling of EVs, because of their performance characteristics. But increasing in cost of permanent magnet and problems related to fast demagnetization, these motors have been difficult in use. Switched reluctance motors (SRMs) had some advantages as high-speed drives because of their simple, robust and rugged structure: they have no windings or permanent magnets (PMs) on the rotor, which contributes to a low rotor inertia and a relatively easy cooling compared to other motor types. The pole and phase number of SRMs play an important role in determining their performance. Speed controlling of SRM is to be done at different speeds with EV application and the performance of SRMs is to be analyzed at different speeds. A new Fuzzy Logic Controller (FLC) technique is employed to achieve desired speed instead of Proportional Integral (PI) Controller, As we know that the SRM is a nonlinear system so that we cannot predict the PI Controller gains directly rather thanTrailand Error method. FLC can be used for Nonlinear systems like SRMs because of its simple control action. In this paper we use FLC for speed controlling of SRM. The complete analysis was simulated by using MATLAB/Simulink Software.
KEYWORDS: SRM, Electric Vehicle, PI Controller, Fuzzy Logic Controller

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I. INTRODUCTION

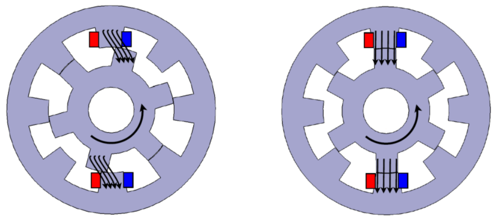
An Automobile will play a key role in our daily life. As population is increasing day by day the demand for Automobiles also increasing drastically, especially during the lockdown in India there is huge spike in sales of automobiles [1]. Globally now we are facing the environment pollution by the emissions of conventional engine Vehicles. It is very important to switchfrom Conventional Internal Combustion Engine (ICE) Vehicles to Electric Vehicles (EVs) to reduce the Pollution. Keeping the pollution problem in view, Government of India also have taken few measures to increase the production and supply of EVs in the National Electric Mobility Mission Plan 2020[NEMMP] [2-3]. As the demand of EVs is increasing, we need to improve its drive train On Road performance. Generally, Permanent Magnet Synchronous Machine (PMSM) or Brush Less DC Motor (BLDC) were used for better performance of EV. But, the problems related to fast demagnetization of permanent magnets and cost of BLDC enables us to look for another Motor Drive. Switched Reluctance Motor (SRM) is better option for EV application, because of its simple, robust and rugged construction and its special features like ability of high speed operation, high reliability, high efficient and less cost.

SRM is an electrical machine which works on the Variable Reluctance principle and runs by reluctance torque.Unlike other normal motor drives, SRMs have no windings or permanent magnets on the rotor, which contributes to a low rotor inertia and a relatively easy cooling compared to other motor types. The pole and phase number of SRMs play an important role in determining their performance.The selection of phase numbers is determined by the self-start capability,rotating direction, reliability, cost, power density, andefficiency [4-8]. The inductances produced in SRM are non-linear so that high electromagnetic torque is generated and it become very hard to control the drive speed. To control the drive-speed we can employ a simple and traditional control technique like Proportional and Integral (PI) Controller which can give good speed response. PI Control technique is widely used for many motor drives but, for non- linear systems like SRM which varies with inductance it is somewhat difficult to calculate the controller gains directly. But for some speeds we can estimate the gains by trail and error method which is not accurate [9-12]. To resolve this issue we need another controller which can deal with uncertain, complex model like SRM. One of the most powerful tool which can translate the linguistic rules into operating mechanism is Fuzzy Logic Controller (FLC). FLC is an adoptive and effective control technique for systems like SRM. Fuzzy Logic Controller can be employed for the systems those are difficult to model mathematically due to its circuit complexity and non – linearity [13-19]. This paper proposes a FLC control technique to improve performance of 8/6 SRM for Light Electric Vehicles and compared with PI Controller.

II. SWITCHED RELUCTANCE MOTOR

Switched Reluctance Motor is an electrical machine which works on the Variable Reluctance principle. SRM also known as Variable Reluctance Machine. SRM is double salient machine which has the poles on both stator and rotor. Unlike other motors it has no windings on rotor but only on stator. The most attracting feature of SRM towards any application is its simple, rugged and robust construction. The pole and Phase number of SRM determines its performance. The rotor has no magnets orwindings but solid salient-poles which was made up of soft magnetic material mostly laminated steel. Phase windings are connected to stator, to produce flux when connected to supply.

The flux produced by the stator attracts the rotor to get in aligned position, so that it will move towards the stator pole. When one phase winding is aligned with their respective rotor pole, phase winding is disconnected from supply immediately another phase in sequence will excited by the supply to continue the motion of rotor. Fig.1 shows the aligned and unaligned position of SRM.



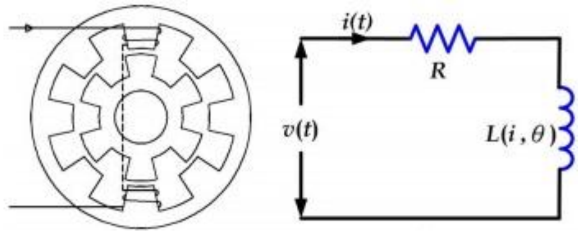


Fig.2 Switched Reluctance Motor and its Equivalent Circuit

(a)SRM – Unaligned (b)SRM – Aligned
Fig.1

The torque in switched reluctance motor is produced byapplying an elementary principle of electromechanical energy conversion in asolenoid. The SRM has doubly salient construction and has winding only on the stator. The rotor of SRM does not have any winding or permanent magnet. The equivalent circuit of a SRM is as shown in figure. SRM has double saliency and non-linear behaviourdue to which the magnetic characteristics vary with respect to rotor position, θ. Fig.2 shows the equivalent circuit.

The instantaneous voltage of an SRM phase winding, is expressed as follows,

$$v(t) = Ri(t) + L(i,\theta)\frac{di}{dt} + i\frac{dL(i,\theta)}{d\theta}\omega \quad ..(1)$$

$$e = i\frac{dL(i,\theta)}{d\theta}\omega \quad ..(2)$$

Where,
V = Instantaneous Phase Voltage
i = Phase Current
L(i, θ) = Phase Inductance
R = Winding Resistance per phase
ω = Rotor Speed
e = emf

The flux linkage of the SRM varies with respect to rotor position θ and current I as,

$$\varphi(\theta,i) = \varphi(0) + \int_0^t \{v(t) - Ri(t)\}\,dt \quad ..(3)$$

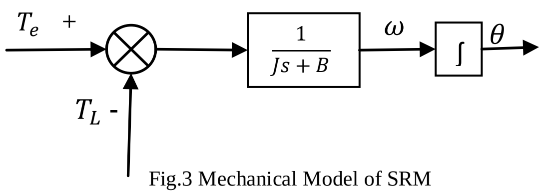


Fig.3 Mechanical Model of SRM

From Fig.3, The Electromagnetic Torque equation is given as,

$$T_e(i,\theta) = T_L + B\omega + J\frac{d\omega}{dt} \quad ..(4)$$

Torque can be derived as below when inductance is varying with the rotor position for a given current,

$$T_e = \frac{i^2}{2}\frac{dL(i,\theta)}{d\theta} \quad ..(5)$$

Where,

$$\frac{dL(i,\theta)}{d\theta} = \frac{L(\theta_2,i) - L(\theta_1,i)}{\theta_2 - \theta_1}$$

Motor Drive Specifications	
Number of stator poles	8
Number of rotor poles	6
Aligned inductance	23.6e-3 H
Unaligned inductance	0.67e-3 H
Saturated aligned inductance	0.15e-3 H
Stator resistance	0.05 ohms
Inertia	0.05 Kg.m.m
Friction	0.02 N.m.s
voltage	240 v
Maximum current	450 A

III. ELECTRICAL VEHICLE LOAD TORQUE PROFILE

Electric Vehicle is loaded with the total tractive effort which is the sum of rolling resistance force, aerodynamic drag, hill climbing force, linear acceleration forces and angular acceleration force is given by,

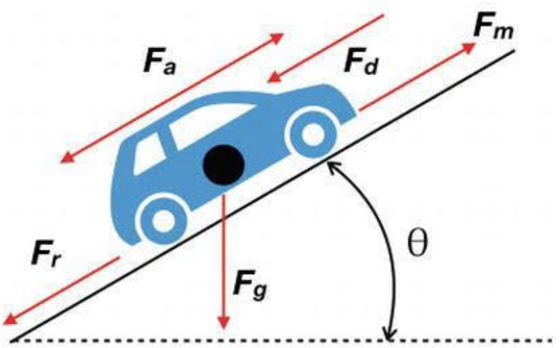


Fig.4 Electrical Vehicle Torque Profile

$$F_{te} = F_r + F_d + F_m + F_a + F_g \quad ..(6)$$

Where, F_{te} is the total tractiveforce.

F_r is the rolling resistance force which is proportional to the weight of the vehicle.

$$F_r = \mu_{rr} mg \quad .. (7)$$

F_d is aerodynamic drag which is caused by vehicle aerodynamic. This force is determined by the shape of the surface of the vehicle (A), coefficient of form (Cd), velocity (v) and air density (ρ). The formula for this component is:

$$F_d = \frac{1}{2}\rho A C v^2 \quad ..(8)$$

F_m is the hill climbing force is the force on the vehicle to move up or move upward with slope.

$$F_m = mg \sin\varphi \quad ..(9)$$

$$F_g = ma \quad ..(10)$$

The vehicle moves with angular speed then the angular acceleration is required. Angular acceleration force is the force required by the wheels to make angular acceleration (F_a), as follows,

$$F_a = I\frac{G^2}{r^2} \quad ..(11)$$

Where Iis the moment of inertia, G is gear ratio and r is radius of tyre.

IV. CONTROL SCHEME

Speed Control is Very important criteria for any motor drive as well as Switched Reluctance Motor and SRM also using for EV application. It should be kept in mind that smooth and dynamic speed control is the basic requirement of any EV. For a non-linear system like SRM drive it is somewhat difficult to design a Controller, to resolve this conflict this paper proposes a Fuzzy Logic Controller which sis extensively used linear or non-linear systems. Fig.5 shows the block diagram of basic control strategy with FLC.

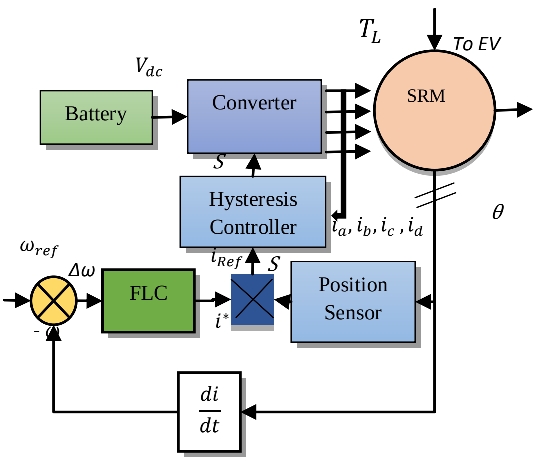


Fig.5BlockDiagram ofControlStrategy

A. Asymmetric Bridge Converter

Asymmetric Bridge Converter (ABC) is preferred over other converters for SRM Drive, because SRM should activate one phase at one instant instead of multiple phases so that it can run smoothly. If not, excitation of multiple phases at same time leads to poor performance of drive. The special feature of ABC is fault tolerant capability.ABC for one phase is as shown in below figure 6.

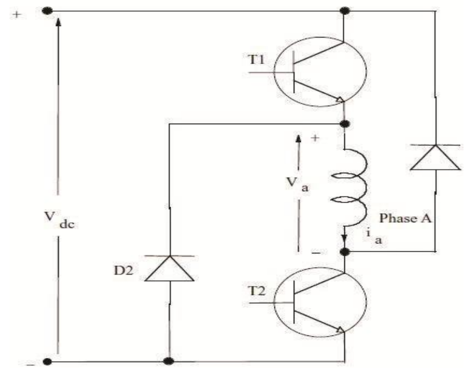


Fig.6 Asymmetric Bridge Converter for One Phase of SRM

If gate pulse is 1, both switches activated to conduct phase winding else pulse is 0, which stops the excitation for phase winding. Soft switching method is used here for current control. IGBT power switches were used for medium speed and highpower operation as the input impedance of IGBT is high.

B. HYSTERESIS CONTROLLER

Hysteresis Current Controller is one of the main controller of this paper, the actual current value given from the product of position sensor signal and Fuzzy Logic Controlled reference current which further subtracted from each phase current. Hysteresis controller is designed to surpass the actual current within a tolerance band of current. Whenever the actual current exceeds or decreases the band value, it will modify the state to bring the current value within band by producing switching pulses. Hysteresis Controller is as shown in below figure 7.

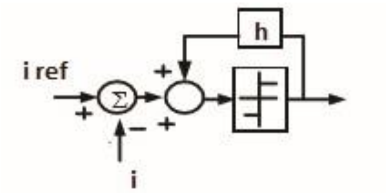


Fig.7 Hysteresis Controller for One Phase of SRM

Switch – On Point:

Actual Current ≥ Hysteresis Band

Switch – Off Point:

Actual Current ≤ Hysteresis Band

C. POSITION SENSOR

Position Sensor plays a key role in speed control of SRM. Position Sensor detects the position angle θ of Rotor by the hall sensor and gives the pulse signal to the controller which decides phase excitation at that instant. The Position Sensor is as shown in below figure 8.

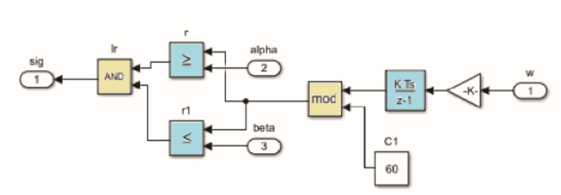


Fig.8 Position Sensor

Speed signal in rad/s is given as the input for the Position sensor, further multiplied by the gain 180/pi to convert in angle θ. Angular speed is fed to Discrete integrator and compared with 60^0 block which was calculated by the formula given by,

$$\frac{360}{No.of\ Rotor\ Poles} \quad ..(12)$$

Angle obtained from modulus block is again compared in between Turn – On and Turn – Off angles to detect whether the rotor is in excitation angle or not. If the given rotor angle is in between Turn – On and Turn – Off angles then Output will be True or binary 1, else the output will be false or binary 0.

D. FUZZY LOGIC CONTROLLER

Fuzzy Logic Controller is widely used for many applications which are linear or non linear in nature. FLC takes the Crisp inputs and gives Crisp outputs to the plant. In this paper, FLC is used for speed controlling of SRM. Fuzzy Logic Controller regulates the speed very close to Reference speed by the predefined Rule base and input/output membership functions. FLC involves in three stages which are Fuzzification, Decision making and Defuzzification. Fuzzification and Defuzzification is depends on Database whereas decision making is depends upon Rule base. Crisp inputs are fuzzified by the membership functions, further passed through rule base to make decision over inputs tp give appropriate output. After decision making crisp output is given to the plant by defuzzification. Block diagram of FLC is as shown in below figure 9.

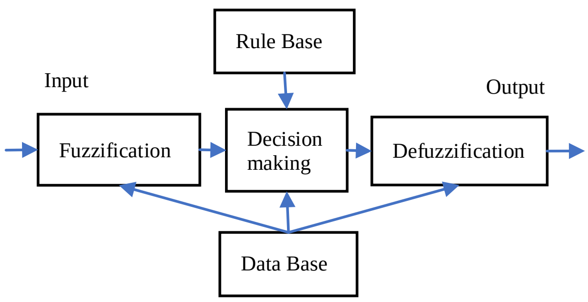


Fig.9 Fuzzy Logic Controller

FLC is designed with two inputs and one output membership functions for SRM. The Input Variables are Speed Error (e), Change in Speed

Error (Δe) and Output Variable is Reference Current (i^*).

$$e = \omega^*(K) - \omega(K) \quad ..(13)$$

$$\Delta e = \Delta\omega(K) - \Delta\omega(K-1) \quad ..(14)$$

$$i^*(K) = i^*(K-1) + \Delta i^*(K) \quad ..(15)$$

Where, Δe is Change in Speed Error and $\Delta\omega$(K), $\Delta\omega$(K-1) are Speed Errors at (K) and (K-1) sampling instants.i(K) and i(K-1) are the currents at (K) and (K-1) sampling instants.

Range of Membership functions is (-1, 1), trapezoidal and triangular functions were used to get optimum results. Membership functions of input and output variables are given in below figure. Rule base for the Given variables is given in below table.

NM-Negative Medium
NS-Negative Small
ZO-Zero

V. SIMULATION

A Four Phase, 75KW 8/6 Switched Reluctance Motor is Used for the Simulation of Fuzzy Logic Controlled SRM for Light Electric Vehicle. Four Phase Asymmetric Bridge Converter is used for better performance of drive. Reference Speed is given by the Drive Cycle Block in Simulink, drive speed is measured by the hall sensor. Measured speed is compared with reference speed to obtain Speed Error which will given to the Fuzzy

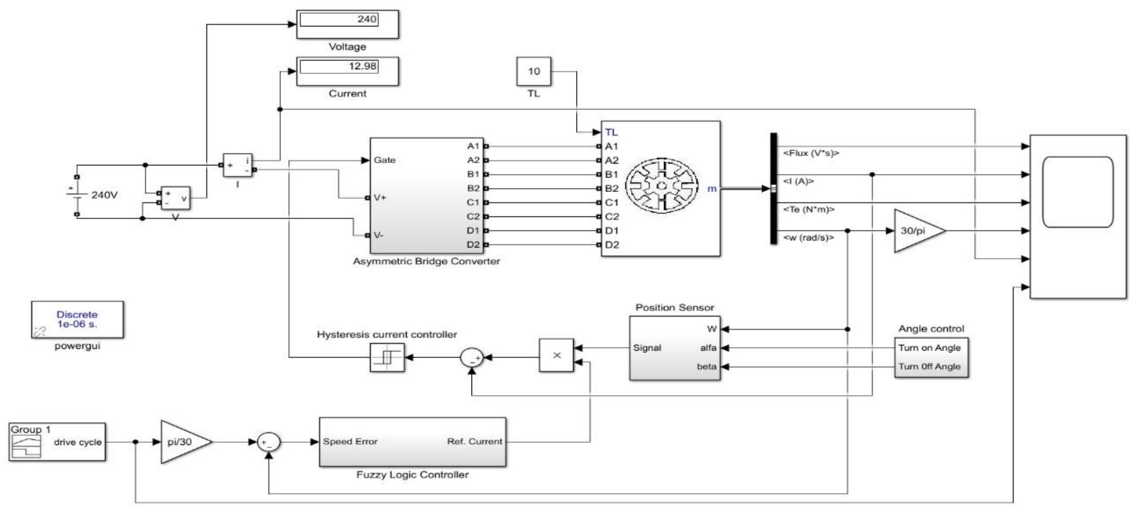


Fig.11 Simulink Model of SRM Drive

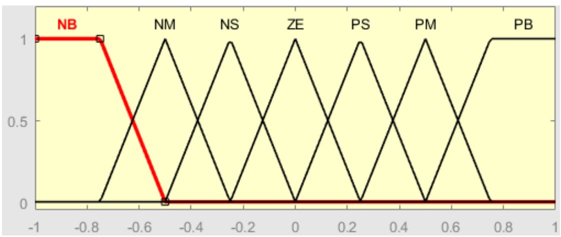


Fig.10 Membership Functions of Speed Error, Change in Speed Error and Reference Current

Table 1: Rule based table

E/CE	NB	NM	NS	ZO	PS	PS	PB
NB	NB	NB	NB	NB	NM	NS	ZO
NM	NB	NB	NB	NM	NS	ZO	PS
NS	NB	NB	NM	NS	ZO	PS	PM
ZO	NB	NM	NS	ZO	PS	PM	PB
PS	NM	NS	ZO	PS	PM	PB	PB
PM	NS	ZO	PS	PM	PB	PB	PB
PB	ZO	PS	PM	PB	PB	PB	PB

Where,
SPB-Positive Big
PM-Positive Medium
PS-Positive Small
NB-Negative Big

Logic Controller for speed controlling of SRM Drive. FLC has two inputs one is speed error and another one is change in Speed Error. By using these two inputs FLC gives appropriate Output as Reference Current. Controller output is further multiplied by signal obtained by the position sensor. Position Sensor takes the radian speed as input further converts into angular speed to compare with the angle 60^0 and also with the Turn – On and Turn – Off angles to detect whether the Rotor has to be Excited or not. Turn - On angle is 37.5^0 and Turn – Off Angle is 52.5^0 taken for better results. Reference current which is multiplied by controller output and signal obtained by position sensor is again compared with the Actual phase currents and given to the Hysteresis Controller bring phase currents near to the reference current and produces the gate pulse for the Asymmetric Bridge Converter.

The 75KW, 8/6 Switched Reluctance Motor Drive model is taken from MATLAB/Simscape/SimPowerSystems/Specialized Technology/Machines as inbuilt block. The overall system is built in MATLAB/ Simulink environment as shown in fig.11.

VI. RESULTS

Switched Reluctance Motor is fed with 240 V DC supply from Battery, Reference speed is given by the Drive cycle. Figure shows the starting performance of SRM drive. Initially speed is set to 500 RPM, motor started at t = 0.005s and attains its reference speed at t = 0.008s. Torque, Phase Current and flux are high at starting which are desirable for better starting performance of a drive.

Figure 13 shows that once drive is achieved its reference speed of 500 RPM, Drive parameters like Torque, Current and Flux as well as Speed settles at t = 0.01s and runs the drive smoothly in steady state and Hence, Drive speed is almost equals to reference speed.

After few seconds drive speed is changed from 500 RPM to 800 RPM, speed change command is initialized at t= 0.4s, within 0.04s drive reached its reference speed as shown in figure 14. Torque, current and flux values again raised for few seconds which is desirable for better performance of drive.

Figure 15 shows that the speed of drive is settled again after reaching speed to 800 RPM from 500 RPM. Drive is running smoothly after few seconds in steady state with desired torque, current and flux values.

It is clearly shows that the drive speed is closely following reference speed. Electromagnetic Torque is settled at 10Nm with less ripples. Electrical braking is applied to Drive at t = 0.7s, within 0.062s speed is reached to 0 RPM at t = 0.762s and torque, current and flux also reached to zero which shows that drive is stopped and is in stalling position in fig.16.

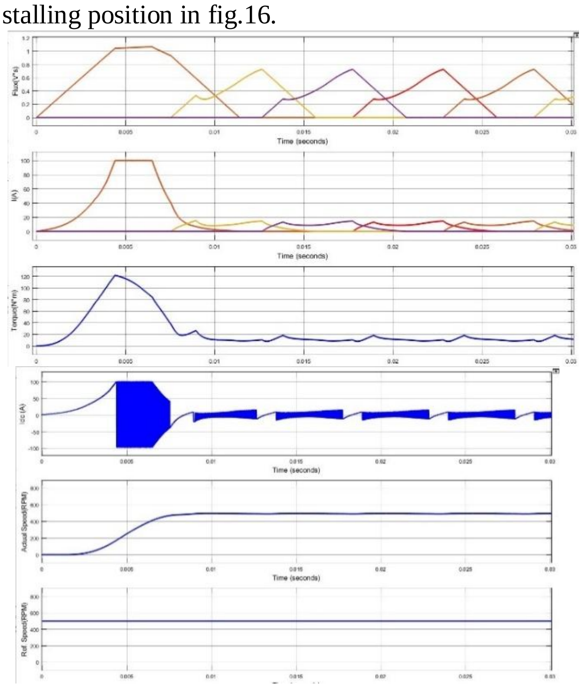


Fig.12 Starting performance of SRM Drive

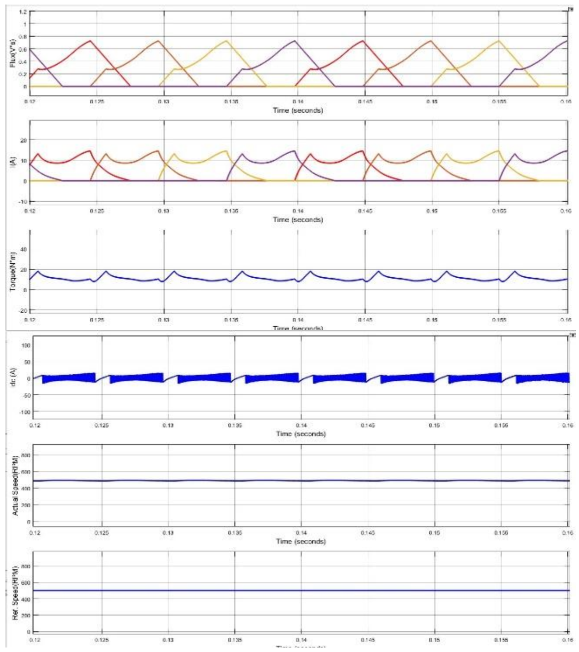


Fig.13 Steady state performance of SRM Drive at 500 RPM

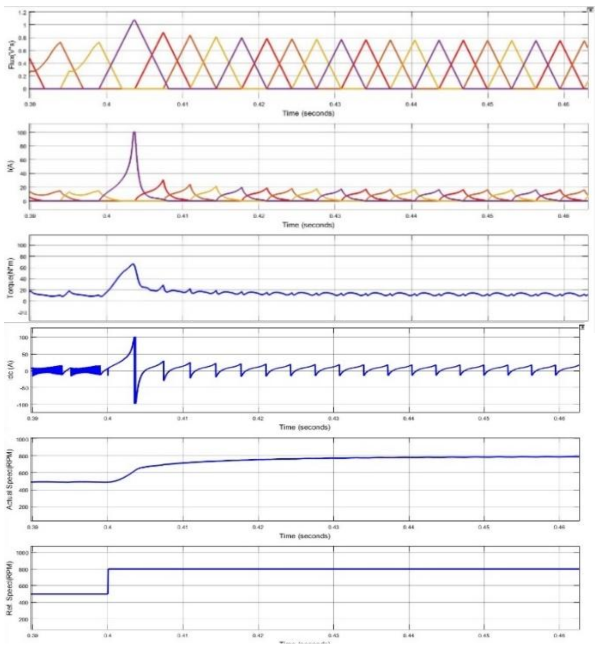


Fig.14 Performance of SRM Drive At 500 – 800 RPM

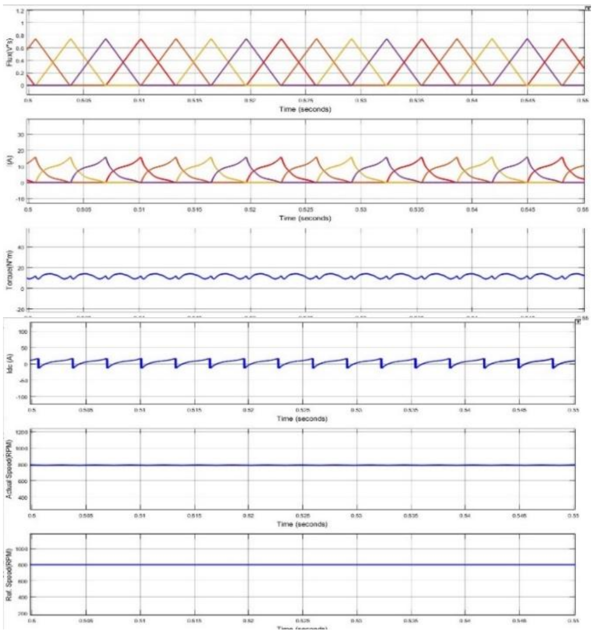


Fig.15 Steady state performance of SRM Drive at 800 RPM

Comparison Table.2

Parameter	PI	FLC
Delay Time	0.0058s	0.005s
Rise Time	0.008s	0.0075s
Peak Time	0.011s	0.0095s
Settling Time	0.016s	0.0105s
Braking Time	0.068s	0.062s
SteadyState Error	0.5 rad/s	0.3 rad/s

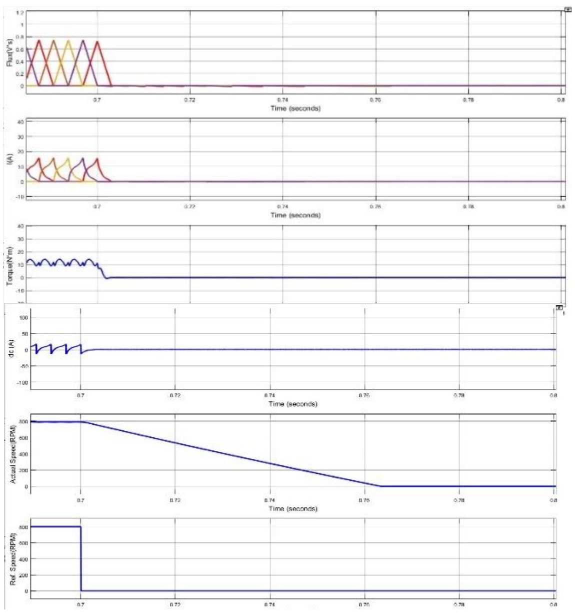


Fig.16 Performance of SRM Drive at 800 - 0 RPM

VII. CONCLUSION

This paper work presented here focuses mainly on the control of switched reluctance motor with FLC. It also highlights SRM's the necessity, advantages, applications and main issues. A literature survey is done for the detailed study of SRM drives, and design, simulation and control of SRM drive is observed through modelling, simulation and control of 4 phase, 8/6 240 V Switched Reluctance Motor used for Light electric vehicle is carried out. Use of asymmetric bridge converter is preferred here because of its extremely high fault tolerant capability of asymmetric bridge converter recommended for electric vehicle inspite of high cost of power devices, its advantages like high controllability which allows overlap and fault tolerance, compensates its drawbacks. FLC is used here to improve performance of SRM Drive for Electric Vehicle applications. Comparison table is given above to show that the FLC has better results than PI controller

Switched reluctance motor drives inherently have favourable speed-torque characteristics for traction application. In this paper, it is clearly observed that electric vehicle loading conditions are obtained using Light Electric Vehicle specifications and shown in results that the speed of the vehicle is maintained at desired values. The simulation results are presented to demonstrate the FLC is much better control scheme than PI Controller for switched reluctance motor drive system.

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