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An Optimal Fuzzy Logic Control Strategy For Switched Reluctance Motor Drive

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***Abstract*- This paper presents the modeling, simulation, and speed control aspects of a 3-phase 6/4 Switched Reluctance Motor (SRM) drives, using hybrid Artificial Intelligence Fuzzy Logic Controller system. Also a speed control design for Switched Reluctance Motor drive based on fuzzy logic controller is suggested. The fuzzy controller is proposed in this paper as speed controller for SRM. The whole control mechanism consists of a detailed report about the steady state and transient analysis of Switched Reluctance Motor. The control design results are then validated in real-time by Simulink / Matlab software package. The main aim of this project is to control the speed of the Switched Reluctance Motor very effectively using Fuzzy Logic Controller. Though PI controller is more popular and widely used, Fuzzy is something which is more advanced and efficient when compared to other conventional controllers.**

***Keyword* - Switched Reluctance Motor, fuzzy logic, Simulink / Matlab.**

I. INTRODUCTION

A fuzzy control system is a control system based on fuzzy logic—a mathematical system that analyzes analog input values in terms of logical variables that take on continuous values between 0 and 1, in contrast to classical or digital logic, which operates on discrete values of either 1 or 0PV panel with the interconnection system will provide an efficient output as a real time practical system. These add up the advantages in the results delivering the absolute results which can be compared with the hardware prototype models. In this paper, similar model is performed and the results are simulated and the results obtained are tested. The main objective of this project is to control the speed of 6/4- pole, 3-phase Switched Reluctance Motor using Artificial Intelligence say Fuzzy Logic Controller. This project also involves the detailed view on Steady state and also the Transient Analysis of the Switched Reluctance Motor.

Switched reluctance motors (SRMs) are characterized by having salient poles at both the stator and rotor. The rotor is made of stacked steel laminations, or a solid piece of soft iron, and does not require magnets or winding. One of the most common stator configurations consists of pole pairs located facing each other forming electrical phases, such as phases ‘‘a’’, ‘‘b’’, and ‘‘c’’ shown in Fig. 2.1. A SRM is also classified by the ratio of number of stator to rotor poles, Nsp = Nrp.

For example, Fig.1. presents a 6/4 SRM with 6 stator poles and 4 rotor poles. For this 6/4 SRM, the number of phases is equal to half the number of stator poles. When current is applied to a stator phase winding, a magnetic field is created.

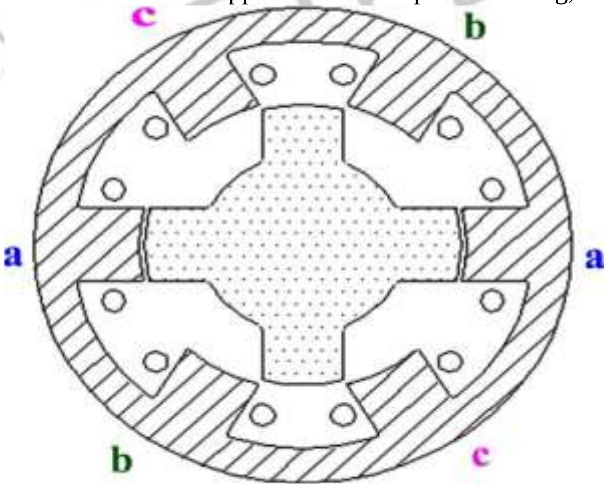

Fig.1. A 6/4 Pole switched reluctance motor with phases ‘‘a’’, ‘‘b’’, and ‘‘c’’

A magnetic flow path appears around the stator, along the active phase poles, across the air gaps, and along the rotor structure. The disposition of rotor poles to align with the poles of the energized stator phase tends to minimize the reluctance in the magnetic circuit. Consequently, clockwise or counterclockwise torque is produced depending on the rotor position and the energized phase. The principle of operation of SRMs is based upon the fact that a piece of magnetic material always tends to align itself in the minimum reluctance position when placed in a magnetic field. For the SRM in

Fig.1. if phase ‘‘a’’ is energized, no torque is created because of the alignment of the rotor and stator poles at that position, which is the minimum reluctance position for phase ‘‘a’’. However, if phase ‘‘b’’ is energized, clockwise torque acts on the rotor; and if phase ‘‘c’’ is energized, counterclockwise torque is generated.

To create continuous rotor motion, the firing sequence of the electrical phases must take place at the correct mechanical angles, also called firing angles, which are determined from the motor’s geometry and operating conditions. To control torque production, the current magnitudes at the active phases have to be controlled in relation to rotor position as well as in relation to the torque generated by other SRM phases. Since torque and current are related in a non-linear way, performing control actions to obtain constant phase current would still generate torque variations. Therefore, undesired vibration and acoustic noise may be generated. In theory, by knowing the relationship between torque–current–rotor position, T (i, θ), it is possible to control the current magnitude in a way such that constant torque is produced .

II. CIRCUIT DIAGRAM DESCRIPTION

SRM POWER CONVERTER

A power converter is required to activate and commutate the SRM phases, and the classic asymmetric half-bridge inverter is in general used, requiring two switching devices and two power diodes per phase. Another important SRM inverter has a single high-side switching device shared with all phases and it has a low-side switching device per phase for commutation purposes . This is a simple, practical, an economical power converter, derived from the classic converter and it holds similar characteristics to it, but with only one high-side switching device (Tc) and one low-side free-wheeling power diode (Dc), as presented in

The power converter in or a similar option, is crucial to reduce the number of switching devices, diodes, floating transistor gate drives, and motor connections It is a requirement to use a current sensor for protection and safety purposes, to avoid excessive current through the windings when the motor is controlled with any method that does not use current feedback like when using voltage PWM methods. This power converter in Fig.3. was constructed for the 1.5 kW, 1500 rpm, 6/4 SRM used to drive a centrifugal pump in this project. A disadvantage of this power converter with respect to the classic SRM power converter is that phase demagnetization is affected at particularly high speed due to shorter time available for commutation.

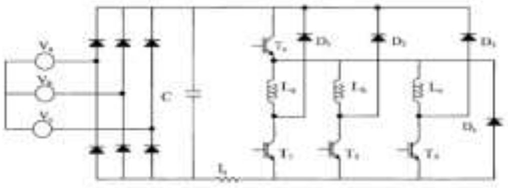

Fig.2. Inverter for three-phase SRMs with single high-side transistor and single low-side free-wheeling power diode.

The situation is made even more critical at high speed because during commutation the off-going phase requires that the shared high-side transistor be turned off to speed up its demagnetization stage and, at the same time, the incoming phase requires it turned on for its magnetization and to produce the required torque. However, the particular application in this research of a SRM driving a centrifugal pump required operation for a large number of hours at medium and low speeds, like in central system ground-source heat pump or similar applications. Hence, the limitation of such power converter at high speed was not considered a problem in such specific application.

III. MATHEMATICAL MODEL FOR SRM SYSTEM:

It is widely known in the literature that the following Eqs. (1) – (4), apply to each SRM phase electromagnetic circuit [1, 2]:

$$V_{bus} D = R_i + \frac{d\lambda(i,\theta)}{dt} \qquad (1)$$

Where Vbus is the DC-link voltage, D is the duty cycle of the switching devices, R is the Electrical resistance and k is the flux linkage. Flux linkage is related to the inductance and current in the electromagnetic circuit of a SRM phase by Eq. (2)

$$\lambda(i,\theta) = L(i,\theta).i \qquad (2)$$

Hence, substituting Eq. (2) in Eq. (1) generates Eq. (3).

$$V_{bus} D = R_i + i\omega \frac{dL}{d\theta} + L(i,\theta)\frac{di}{dt} \qquad (3)$$

The middle term on the right hand side of Eq. (3) is called back electromotive force (Back-EMF) as defined in Eq. (4).

$$e_{back} = i\omega \frac{dL}{d\theta} \qquad (4)$$

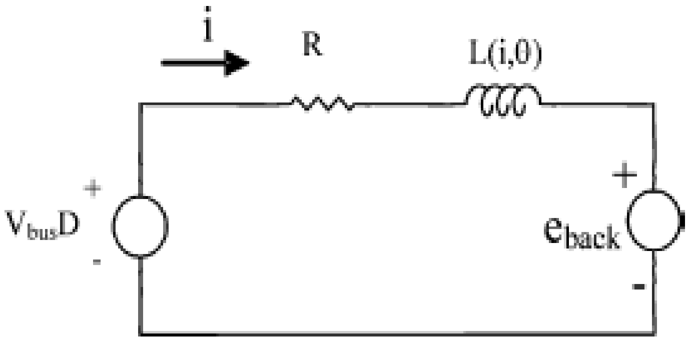

Fig.3. Electrical circuit of a SRM phase winding

An equivalent electrical circuit of one of the phases of a SRM is presented in Fig.2. Notice that the inductance is a function of both current through the winding and rotor position. The modeling of the SRM–load mechanical elements is presented in Eq. (5).

$$J\omega + b\omega = T - T_L \qquad (5)$$

Where J is the inertia of the rotating part of the SRM–load system, b is the viscous friction, x is the angular speed, T is the torque generated by the motor, and TL is the load torque. The input to the system is the voltage across the phase winding, which when a controller is added to the system, becomes a function of the error of the parameter to be controlled, such as rotor position, speed, torque, current, or other. One common approach found in the literature to solve the mathematical model formed by the coupled equations (1) and (5) is to determine the magnetic characteristics of the SRM by experimental tests or using finite element analysis (FEA) techniques. Usually the flux linkage,$\lambda(i,\theta)$, is determined as a function of current through the phase winding and rotor position . The information is stored in look-up tables, or it is curving fitted to generate a flux–current–position analytic expression. The co-energy in the magnetic circuit is determined using Eq. (6), and the magnetic torque generated by the SRM is obtained using Eq. (7).

$$W_{c(i,\theta)} = \int_0^i \lambda(i,\theta)\,di \qquad (6)$$

$$T = \frac{\partial W_c(i,\theta)}{\partial\theta} \qquad (7)$$

To simulate and control the SRM–load system, the electromagnetic torque produced by the motor has to be estimated at all times. In several approaches found in the literature the experimentally obtained flux–current–position relationship is either manipulated to obtain an explicit expression of torque as a function of current and rotor position [8], or the required integral and derivative in Eqs. (6) And (7) are numerically computed using information from look-up tables along the simulation or control process.

As a final step in simulation and control of SRMs and since Eq. (3) applies to every phase of the motor, a commutation strategy based on the geometry of the SRM and its operating conditions is required. The latter way to determine the rotor position is called sensor-less control, meaning that a mechanical device is not required for that task.

The above-explained procedure to model and solve the mathematical model for the SRM–load system requires extensive, specialized, and complex work, which might be difficult to simulate and implement. By following such procedure, it seems that potential SRM users would have to almost redesign the motor in order to model, simulate, and design its controller.

SRMs might have lost or might lose attractiveness to potential users because of this fact. Among the options to solve such problem would be that the SRM designer provided the motor's electromagnetic and mechanical information when selling the motor, or maybe in a less revealing way, to sell a customized SRM and its controller as a whole unit for specific applications. It seems that the ideal situation would be that the SRM designer, manufacturer, and control system designer be the same one, or be integrated so that the entire system could be developed for a particular application. Such situation presents several limitations and drawbacks for the practical utilization of SRMs compared to conventional motors.

One alternative to such approaches for SRM modeling and simulation would be to model, simulate, and control SRMs in a way such that magnetic saturation is taken into account, but little or no magnetization information be required; instead, only the motor geometry, and easily measurable electrical and mechanical properties would be required. However, this is possible only in some SRM applications where a highly accurate SRM model is not indispensable. Instead, a reasonable approximation of the SRM model is sufficient and adequate, like when a SRM is used to drive a centrifugal pump to achieve a desired speed in a single rotating direction.

IV. CONVENTIONAL METHOD

The concept of the switched reluctance machine is actually very old, going back to the 19th century inventions called electromagnetic engines", which were the forerunners of modern stepper motors. These years, power transistors, GTOs, IGBTs, and power MOSFETs have been developed in the power ranges required for SRM control. Switched reluctance Motor (SRM) have been found to offer important advantages over conventional AC machines in generating/breaking as well as motoring operations and has proved to be the potential candidate for many industrial applications.

The researches on this machine had been focused on the motoring operation over a long period of time. Since the machine has the good reversibility characteristics and the SRG can run as good as SRM, fewer scholars took notice on the generating mode of SRM. This led to the increased interest in researchers of electrical community as this machine is an attractive solution for worldwide increasing demand of electrical energyThe inherent simplicity, ruggedness, and low cost of SRM make it possess strong competition in many adjustable speed and servo-type applications. Switched Reluctance Drive (SRD) is a steepless speed regulation system, which is composed of SRM, converter and controller. However, control strategy, converter's topology and optimization design of SRM have crucial influence on performance of SRD.

Thus, dynamic simulation of the whole SRD has become very important in this paper, a whole simulation model for SRM double closed loop compound control system is presented. In order to describe the characteristic of SRM exactly, a nonlinear model of SRM is adopted. With the help of MATLAB/SIMULINK, various subsystems, such as motor model block, speed controller block, current control block etc, have been modeled and the actual implementation of the models are explained in detail. Simulation results are presented to verify the effectiveness of the model, which lays the foundation for the study of the dynamic performance of switched reluctance motor drives with different control methods and shows that it can be easily generalized to the modeling and simulation research of SRD with arbitrary phase numbers.

V. HISTORY, DESIGN AND APPLICATION DEVELOPMENTS OF SWITCHED RELUCTANCE GENERATOR

The switched reluctance machine as a motor has been known for over 150 years. The generating mode of this machine SRG has created considerable interest during past few years in machine systems which either generate or regenerate. Although it is one of the earliest discovered machines, special power requirements limited the earlier investigation and application. Development of power electronic components and the advent of cheap microcomputers renewed the research interest in SRG.

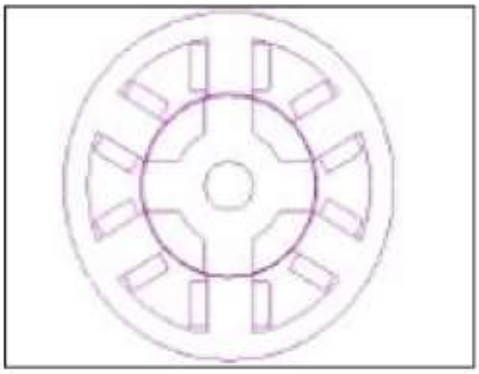

Fig 4.*Cross section of the Switched Reluctance Machine*

The inherent simple construction, ruggedness, wide speed range of operation, low cost, fault tolerant capability, easy cooling simple excitation, requirement of simple converter circuit, high torque volume ratio, high efficiency and suitability under harsh environments are some of the important advantageous features of switched reluctance machine. The simple construction of the doubly salient, singly excited switched reluctance machine is shown in fig 3.1 The physical appearance of a Switched Reluctance motor is similar to that of other rotating motors (AC and DC) Induction Motor, DC motor etc. The construction of SRM is shown in figure. It has doubly salient construction. Usually the number of stator and rotor poles is even.

The windings of Switched Reluctance Motor are simpler than those of other types of motor. There is winding only on stator poles, simply wound on it and no winding on rotor poles. The winding of opposite poles is connected in series or in parallel forming no of phases exactly half of the number of stator poles.The stampings are made preferably of silicon steel, especially in higher efficiency applications. For aerospace application the rotor is operating at very high speed, for that cobalt, iron and variants are used. The air gap is kept as minimum as possible, especially 0.1 to 0.3mm. The rotor and stator pole arc should be approximately the same. If the rotor pole arc is larger than the stator pole arc it is more advantageous.

The recent research shows that the SRG is inherently completely passive and has no self excitation capability. To overcome this problem some researchers used a slot of permanent magnet on the edge of the stator pole to create a magnetic field that run through the rotor to both sides of the stator; the rotation of the rotor will change the permanent magnetic flux which induces alternating voltage in the stator winding.

Excitation Methods

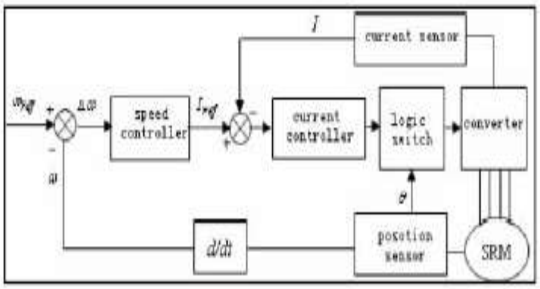

Fig 5.Double closed loop compound controlled SRM drive system

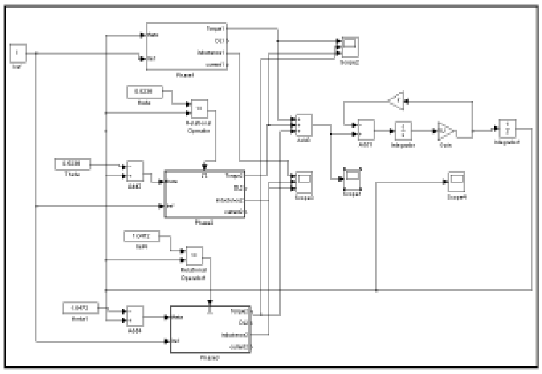

Fig 6.MATLAB / Simulink model of the SRM drive system.

The others have chosen an external power source to help in self excitation for this SRG like using a battery or capacitor to create a magnetic field around the stator winding for a set time and then this magnetic field will be used to create electricity when the rotor moves . The concept of attaching rectangular pieces to each pole of the machine phase for self excitation has been presented and implemented the same in three different means. The Permanent magnet material used is Samarium Cobalt.

In the first option of magnet placement, the stator core was cut around the teeth of one phase from top surface towards bottom of the core. Several lamination layers of each tooth were removed and room for the permanent magnets was provided. The second option that has been implemented comprises only permanent magnets fastened to the stator poles without cutting the stator core. The last option for a self excited SR Generator design was the same as the first case except that only two instead of four permanent magnet pieces were fastened on each phase tooth on only one side of the stator core

VI. INPUT AND OUTPUT SPACES:

- A proper choice of process state variables and control variables is essential to characterization of the operation of a fuzzy logic control system (FLCS).
- Expert experience and engineering knowledge play an important role during this state variables and control variables selection process.
- Typically, the input variables in a FLC are the state, state error, state error derivative, state error integral, and so on.
- The input vector x and the output state vector y can be defined, respectively, as

$$x = \{(x_i, U_i, \{T_{X_i}^1, T_{X_i}^2, \dots, T_{X_i}^{k_i}\}, \{\mu_{X_i}^1, \mu_{X_i}^2, \dots, \mu_{X_i}^{k_i}\}) | i = 1, \dots, n\}$$

$$y = \{y_i, V_i, \{T_{Y_i}^1, T_{Y_i}^2, \dots T_{Y_i}^{l_i}\}, \{\mu_{Y_i}^1, \mu_{Y_i}^2, \dots, \mu_{Y_i}^{l_i}\}) | i = 1, \dots, m$$

}

where the input linguistic variables X_i form a fuzzy input space U=U1 ×U2…×Un and the output linguistic variables Y_i form a fuzzy output space V=V1 ×V2 …Vm.

- ❖ An input linguistic variable, variable xi , is associated with a term set

$$T(X_i) = \{T_{X_i}^1, T_{X_i}^2, \dots, T_{X_i}^{k_i}\}.$$

- ❖ The size (or cardinality) of a term set, $|T(X_i)| = K_i$, is called the fuzzy partition number of X_i.
- ❖ Diagrammatic representation of a fuzzy partition

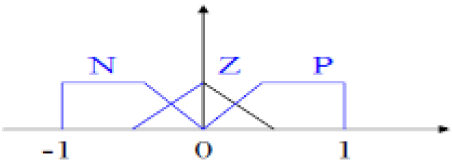

Fig 7..*Fuzzy Partition (1)*

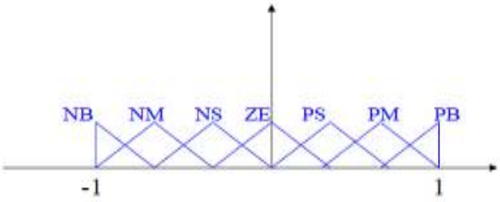

Fig.8.*Fuzzy Partition (2)*

Torque Calculation Block

The simulation model of torque calculation , where In1 is the A phase current (the output of current calculation block) and In2 is the rotor position angle. Then we can get the torque. Besides, just as Fig.2 mentioned, according to, we can get total torque of switched reluctance motor with sum module of MATLAB/SIMULINK. Angle velocity may be obtained from and rotor position angle can be easily gained by integrating angle velocity. As a result, the complete model of SRM may be established.

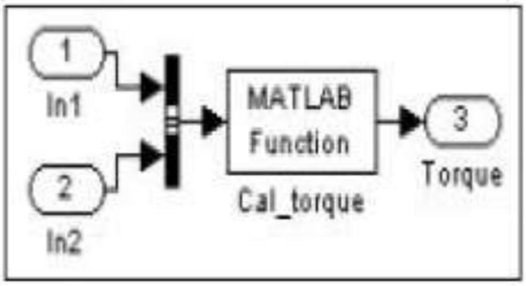

Fig 9. *The model of torque calculation block*

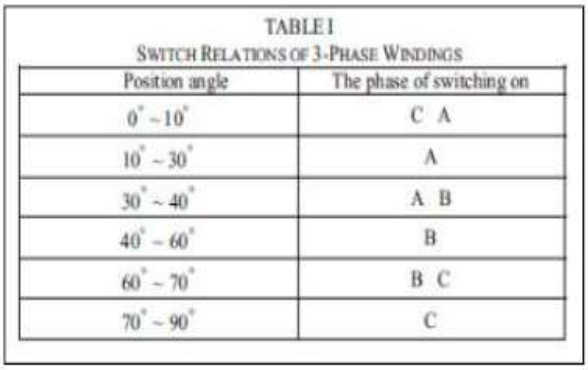

TABLE I

SWITCH RELATIONS OF 3-PHASE WINDINGS

Position angle	The phase of switching on
0°~10°	C A
10°~30°	A
30°~40°	A B
40°~60°	B
60°~70°	B C
70°~90°	C

Table 1. *Switch relations of 3-phase Windings*

Fuzzy Logic Controller

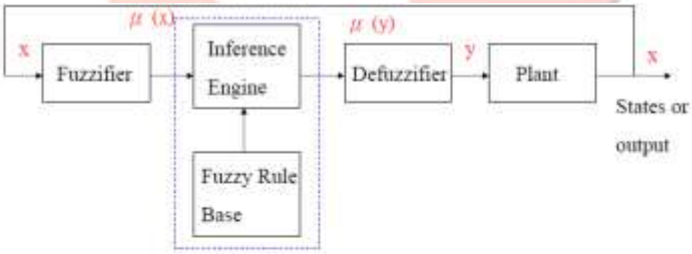

Fig 10.Fuzzy Logic Controller

Fuzzy Rules

- For a two-input FLC, the fuzzy input space is divided into many overlapping grids
- Grid-type partition:

N: Negative
Z: Zero
P: Positive
L: Large
S: Small
M: Medium

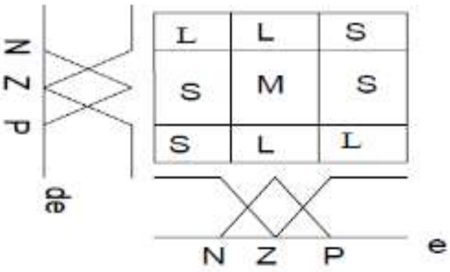

Fig. 11. *Grid Type Partition*

Rule set. R1: IF e is N And de is N Then u is L
R2: IF e is Z And de is N Then u is L
R3: IF e is P And de is N Then u is S
R4: IF e is N And de is Z Then u is S
R5: IF e is Z And de is Z Then u is M
R6: IF e is P And de is Z Then u is S
R7: IF e is N And de is P Then u is S
R8: IF e is Z And de is P Then u is L
R9: IF e is P And de is P Then u is L

Fuzzy Table

TABLE II
FUZZY RULES OF FUZZY LOGIC CONTROLLER

$\Delta\omega$ $\Delta\omega$	NB	NM	NS	ZE	PS	PM	PB
NB	EB	EB	EB	VB	VB	M	M
NM	FR	FR	FR	VR	R	M	M
NS	VB	VB	B	M	S	S	VS
ZE	VB	B	M	S	S	VS	VS
PS	B	M	S	VS	VS	VS	VS
PM	M	S	VS	VS	ZE	ZE	ZE
PB	S	VS	VS	ZE	ZE	ZE	ZE

Table 2: *Fuzzy Rules of Fuzzy Logic Controller*

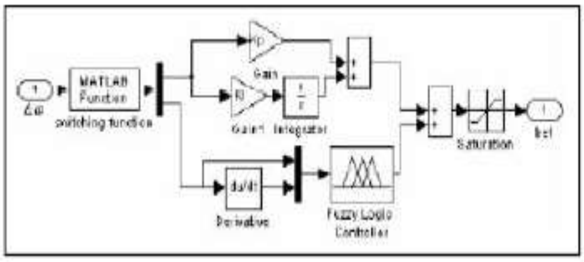

Fig.12. *Conventional simulation diagram.*

VII.PROPOSED METHOD

Open Loop Mode

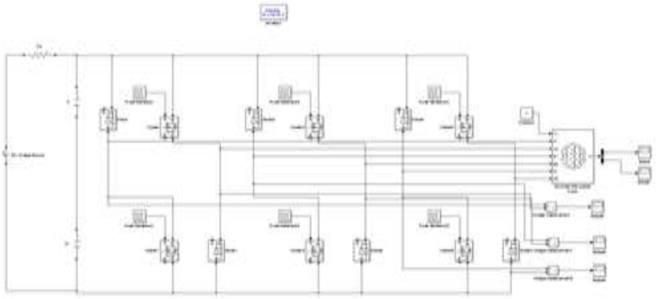

Fig 13. *Open loop simulation diagram*

Torque Result

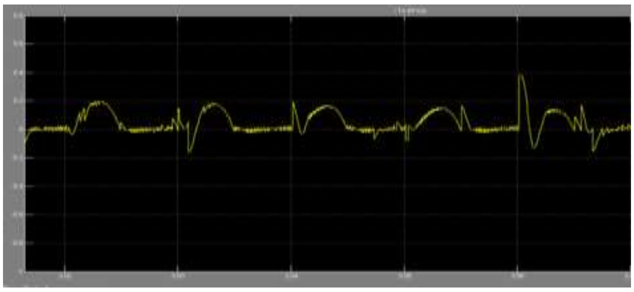

Fig.14. *Open loop torque characteristics graph*
Scale: X-axis represents Time
Y-axis represents Torque

Speed Result

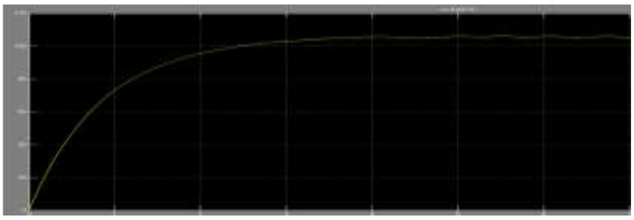

Fig.15. *Open loop speed characteristics graph*

Scale: X-axis represents Time
Y-axis represents Speed

Closed Loop Mode

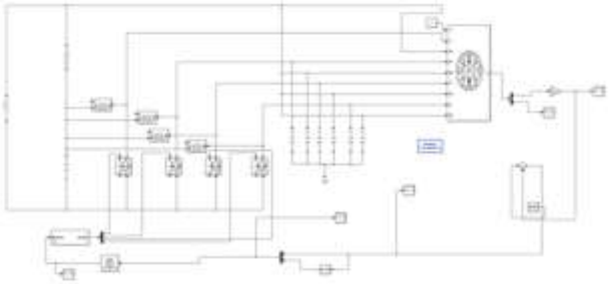

Fig.16. *Closed loop simulation diagram*

Torque Result

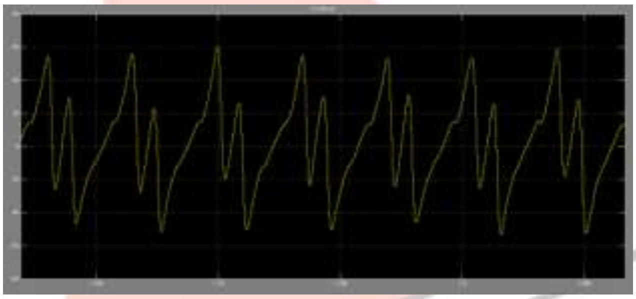

Fig.17. *closed loop torque characteristics graph*
Scale: X-axis represents Time
Y-axis represents Torque

Speed Result

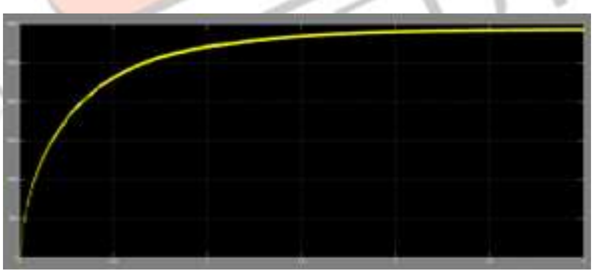

Fig.18. *closed loop speed characteristics graph*
Scale: X-axis represents Time
Y-axis represents Speed

Fuzzy Output

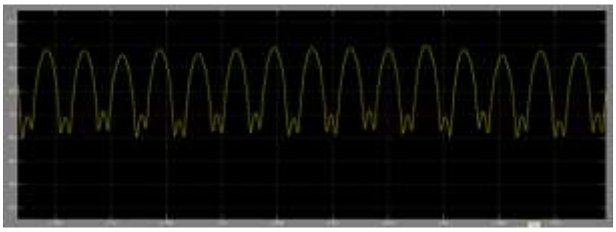

Fig.19. *Fuzzy output graph*
Scale: X-axis represents Time
Y-axis represents Fuzzy Result

Open Loop Mode

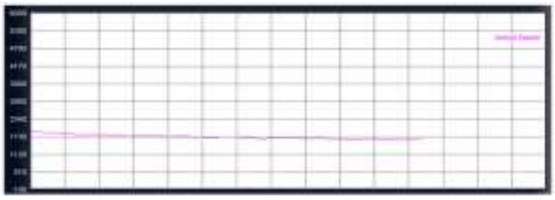

Fig.20. *Open loop result*
Set Speed=800rpm
Actual Speed=1666rpm

In the above graph it clearly shows that the actual speed cannot be changed which proves that the speed cannot be controlled in this mode of operation.

Closed Loop Mode

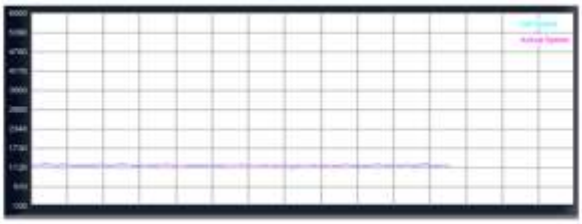

Fig.21. *Closed loop result*
Set Speed=1204rpm
Actual Speed=1198rpm

In the above graph it clearly shows that the actual speed can be changed which proves that the speed can be controlled in this mode of operation.

***Application of SRM*:**

- Analog electric meters.
- Some washing machine designs.
- Control rod drive mechanisms of nuclear reactors.
- Hard disk drive motor.

VIII. CONCLUSION

After studying the whole setup of speed control mechanism in SWITCHED RELUCTANCE MOTOR using fuzzy logic controller, it is clear that the output obtained from the simulation results from various conditions shows good response when compared to conventional method. The transients of motor are analyzed and its harmonic is reduced. As fuzzy is used to set values from time intervals between 1 and 0, it is very efficient than conventional method. So finally it's clear that artificial intelligence is more advanced and efficient than conventional method.

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