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MODELING AND ANALYSIS OF 6/4 SWITCHED RELUCTANCE MOTOR WITH TORQUE RIPPLE REDUCTION

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ABSTRACT: *Switched Reluctance Machines are receiving significant attention from industries, because of its simple structure; inexpensive manufacturability and reliability make it superior to other electric machines. The objective of this paper is to achieve desired speed performance of 6/4 Switched Reluctance Motor (SRM) with reduced torque ripples. To achieve improved speed performance, PI+FUZZY controller was introduced. Double closed loop control system is used for the better speed performance characteristics. In order to minimize the torque ripple, three different strategies are proposed. Simulation results reconfirm the effectiveness in the aspects of better speed performance and torque ripple reduction.*

Keywords: *Current controller, Speed controller, Switched reluctance motor (SRM), Torque ripple.*

I. INTRODUCTION

Switched Reluctance Motors have advantages such as high speed operation, high degree of independence between phases, short end-turn, and low inertia. Switched Reluctance Drive (SRD) is a step less 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 order to obtain high quality control in either torque or speed control applications, it is essential to have an accurate model of the motor that describes the torque characteristics [1, 2].

The SRM's drive performance is strongly dependent on its design and mostly on its control which allows for torque ripple reduction, or for improving the speed control. Therefore, the motor's mathematical model and its accuracy is important [3]. SRM linear and nonlinear model with the voltage and hysteresis current control discussed in [4]. A simplified linear model for closed loop control of SRM with PI controller is presented in [5]. Jin Woo Lee *et al*. [6], proposed a motor with notched teeth but the new motor shapes will affect the average torque value. In [7] the author used an offline current modulation method using a neuro-fuzzy compensation scheme to reduce torque ripple. In [8] Different torque control methods and a torque controller implementation for torque ripple reduction have been explained.

In this paper, mathematical modeling of 6/4 SRM has been developed, speed performance of the motor using PI, PI+FUZZY controllers has been analyzed. And torque ripple reduction methods are proposed without affecting the speed performance characteristics. Remaining part of the paper organized as, section II describes the Dynamic operation of SRM and proposed scheme, section III discusses the Mathematical modeling of SRM and section IV presents the block diagram of the proposed scheme and results.

II. DYNAMIC OPERATION OF SRM

In this paper, double closed loop is considered for the SRM drive system. One is the inner current loop and other is the outer speed loop. The speed signal which is sensed from the motor is given to the speed controller, where the motor speed is compared to the reference speed to generate a current reference signal. The reference current is now given to the chopping current controller which in turn produces an error signal which is used to switch the voltages across the phases of the SRM. Fig 1(a) shows the block diagram representation of double closed loop control of SRM.

In order to get performance oriented Drive, the accurate modeling of a Motor is to be done. The performance of machine can be checked with the help of Mat lab / Simulink. This helps to design the Controller for the motor.

1. Speed performance analysis

1.1. With PI controller

Here first PI controller is adopted to generate the reference current for the corresponding speed error. By varying the k_p, k_I gain values for the PI controller, good results are obtained in terms of response. Since, the magnetic behavior of SRM is highly nonlinear, PI controller cannot be applied with the systems which have a fast change of parameters, because it would require the change of PI constants in the time.

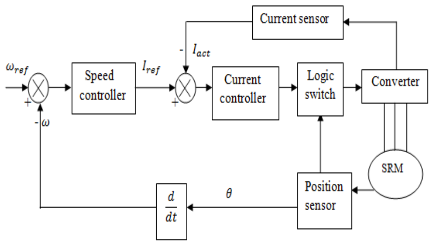


Fig 1(a): Closed loop speed control of SRM

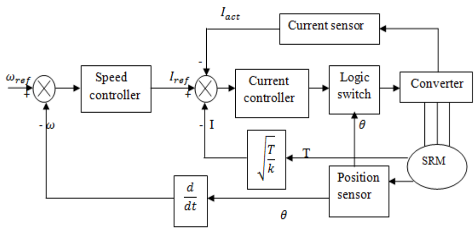


Fig 1(b): Closed loop speed control of SRM With Torque ripple reduction

1.2. With PI+FUZZY controller

It is well known that the Fuzzy Logic Controller is very sensitive to load disturbances or sudden changes, when the parameters are well chosen, the response of the system has very good time domain characteristics. But it has significant steady state error compared with the conventional proportional integral controller. Fuzzy controller has the disadvantage of computing time is much more long that for PI. Hence it will be better to choose the combination of PI and FUZZY. It means that the system can be well controlled by PI which is supervised by a fuzzy system. Rules for the Fuzzy logic controller are tabulated as follows.

Table 1: Fuzzy Rules for FLC

$\Delta\omega$ / $\Delta\omega'$	**S**	**M/S**	**M**	**M/H**	**H**
S	**S**	**S**	**S**	**S**	**M/S**
M/S	**S**	**S**	**S**	**M/S**	**M/S**
M	**S**	**S**	**M/S**	**M/S**	**M**
M/H	**S**	**M/S**	**M/S**	**M**	**M/H**
H	**M/S**	**M/S**	**M**	**M/H**	**H**

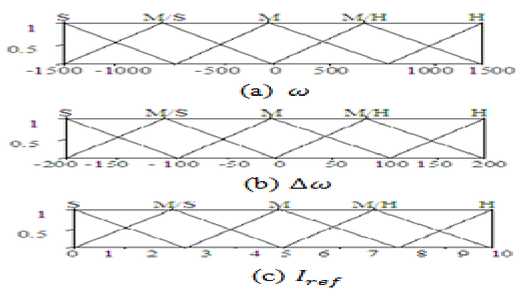


Fig 2: Membership functions for FLC

Fuzzy rules can be explained as follows

Rule 1 if $\Delta\omega$ = S and $\Delta\omega'$ = M/S then I_{ref} =S

Rule 2 if $\Delta\omega$ = M/H and $\Delta\omega'$ = M then I_{ref} =M/S

Rule 3 if $\Delta\omega$ = H and $\Delta\omega'$ =M/H then I_{ref} =M/H

According to the feature of regulating speed system mentioned and time interval of speed sampling, speed error $\Delta\omega$,change of speed error $\Delta\omega'$ and *I ref* are defined to have a range of -1500-1500rpm, -200-200 and 0-10A, respectively. The domains of the input variables are switched to -5 to 5 and are divided into 5 fuzzy regions. The domain of the output variable is 0 to 10 and is also divided into 5 fuzzy regions, that is [0,2.5,5,7.5,10].The corresponding linguistic variables of the input fuzzy regions are Small(S), Medium to Small(M/S), Medium(M), Medium to High(M/H), High(H). Each region is assigned a fuzzy membership function. In this work, the fuzzy sets are chosen to be triangular shapes and the center of area (COA) method of defuzzification is used. The speed response of the SRM with this controller is shown in Fig. 5.

Torque ripple reduction

There are many factors to affect the torque ripple, such as rotor and/or stator shape, air length, commutation strategy, control strategy and so on, but the most important factor is phase current. This paper presents various strategies to reduce torque ripple for a Switched Reluctance Motor. First strategy is to develop the inner torque loop to generate current reference in order to minimize the torque ripple. The electromagnetic torque which is obtained from the motor is taken to get the current reference from the relation T $\propto I^2$. Fig. 1(b) shows the block diagram model for torque ripple reduction and fig. 7 shows the Simulink response of the SRM for torque ripple reduction with and without inner torque loop.

Second one is change in rotor pole arc at the design stage. By changing the rotor pole arc of the SRM also torque ripple has been reduced to certain limit. If the rotor pole arc is greater than that of the stator pole arc, there is no tangible benefit in terms of torque production on the SRM if ideal current turn-off is assumed [8]. Ideal current turn-off is impossible with SRMs, as they have significant inductance. In fact, the largest inductance is encountered at turn-off, where it is most likely at the completely aligned position of the stator and rotor poles where the inductance is at its maximum. Therefore, it becomes necessary to turn off the currents even before they reach the completely aligned position. Hence, to utilize the torque-producing positive inductance slope region completely, it is important that the current be maintained in the region. If the current continues beyond the positive slope region, then a negative torque is produced in SRMs with equal stator and rotor pole arcs, because there is no zero slope inductance region, Due to the negative torque generation, the average *Tav* per stator phase is reduced. Therefore, it becomes necessary to turn off the currents even before they reach the completely aligned position. And it is better to avoid equal pole arcs. To have a better general view of the torque ripple, define the torque ripple coefficient:

$$T_{RIPPLE} = \frac{T_{\max} - T_{\min}}{T_{avg}} \%$$

Where T(max.), T(min.) are the maximal value and minimal value of total torque, Tavg. is the average value of total torque.

III. MATHEMATICAL MODELING OF SRM

The instantaneous voltage across the terminals of a phase of an SR motor winding is related to the flux linked in the winding is obtained by Faraday's law. Because of the double salience construction of the SR motor and the magnetic saturation effects, the flux linked in an SRM phase varies as a function of rotor position θ and the phase current and is obtained as:

$$V_j = RI_j + \frac{\partial \psi_j(i,\theta)}{\partial i}\frac{di}{dt} + \frac{\partial \psi_j(i,\theta)}{\partial \theta}\frac{d\theta}{dt} \qquad \text{With } j = 1 \ldots 3 \qquad (1)$$

In which: $\omega = \frac{\partial \theta}{\partial t}$ (2)

while excluding saturation and mutual inductance effects, the flux in each phase is given by the linear equation

$$\psi_j(\theta, i_j) = L(\theta) i_j \qquad (3)$$

It can be written as

$$V_j = RI_j + L(\theta)\frac{\partial i}{\partial t} + i\frac{\partial L(\theta)}{\partial \theta}\omega \qquad (4)$$

The total energy associated with the three phases (*n* = 3) is given by

$$W_{total}=\frac{1}{2}\sum_{j=1}^{3}L\left(\theta+(n-j-1)\theta_s\right)I_j^2 \tag{5}$$

Each phase inductance displaced by an angle θ_s. and the motor total torque by

$$T_e=\frac{\partial W_{total}}{\partial\theta}=\frac{1}{2}\sum_{j=1}^{3}\frac{\partial L\left(\theta+(n-j-1)\theta_s\right)}{\partial\theta}I_j^2 \tag{6}$$

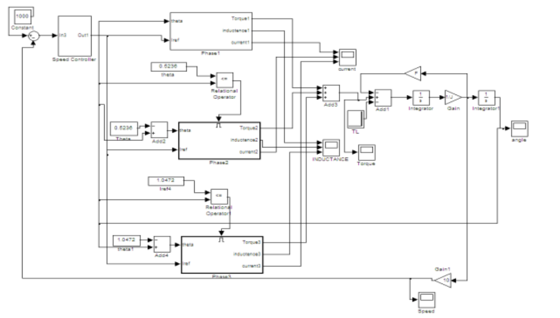
The mechanical equations are

$$J\frac{\partial\omega}{\partial t}=T_e-T_l-f\omega \tag{7}$$

Where *V* - the terminal voltage, *I* - the phase current, *R* - the phase winding resistance, φ - the flux linked by the winding, *J* - the moment of inertia, *f* - the friction coefficient, $L(\theta)$ - the instantaneous inductance, *Nr* number of rotor poles, *Ns* number of stator poles, T_l is the torque load and *Te* is the total torque.

IV. SIMULATION RESULTS

The SRM drive is simulated with PI controller alone and with PI+FUZZY controller using MATLAB/SIMULINK. And the results obtained are shown in fig. 5. A load disturbance of T_L=2N-M is injected at time 0.15 sec. From the figure we can clearly observe the steady state and transient response of the model. By using PI+FUZZY controller, the steady response of the system is increased nearly from 0.08sec to 0.06sec with the PI controller, because Fuzzy controller is more robust to sudden change of load disturbances. But it has significant steady state error which can be reduced by PI controller. Hence by using a combination of these controllers, the response of the model increases to certain extent.



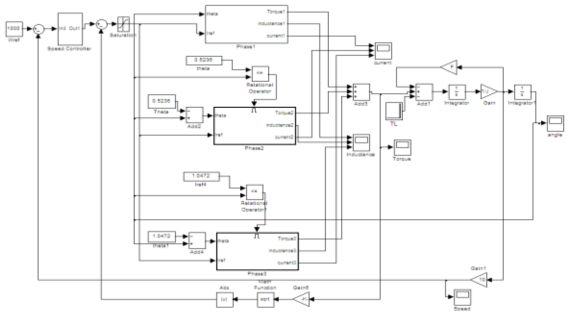


Fig 3(a): Simulink model of closed loop SRM

Fig 3(b): Simulink model of closed loop SRM with Torque ripple reduction

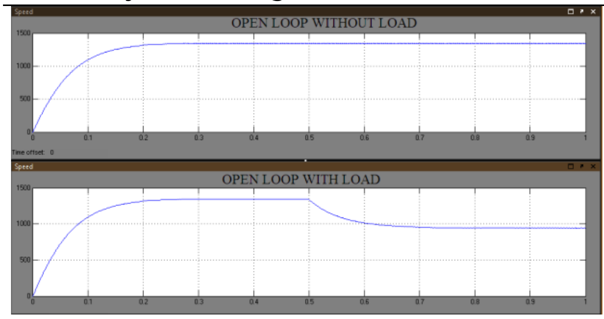


Fig 4: Speed response of open loop SRM model with and without load

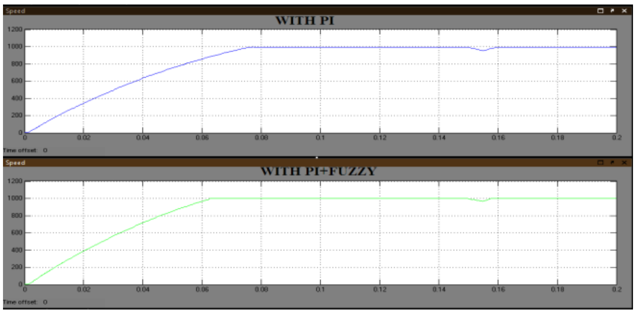


Fig 5: Speed response of the SRM model with PI and PI+FUZZY controller with a load disturbance of 2N-M

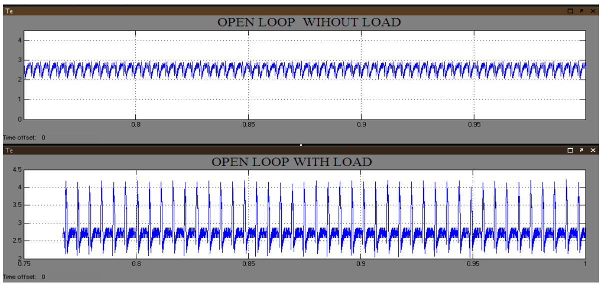


Fig 6: Total Torque produced by open loop with and with without load

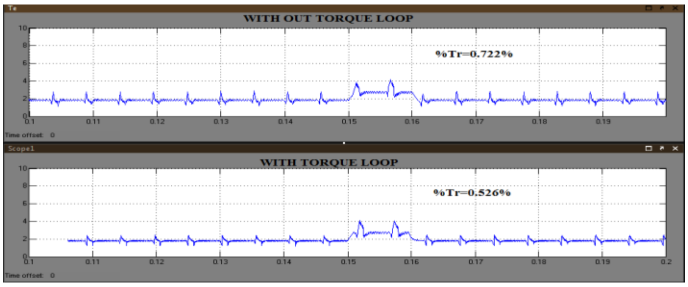


Fig 7: Torque ripple reduction of the SRM model and without inner torque loop

In this paper, three methods are discussed for Torque ripple reduction of the SRM. First one is by taking inner torque loop for the SRM model as shown in fig. 1(b). With this the torque ripple has been further reduced to 0.564% as shown in fig. 7. Further reduction is possible only with the second method, i.e. Taking rotor pole arc, β_r greater than the stator pole arc β_s, T_{min} increases thereby T_{avg} and therefore $\%T_r$ decreases. Further increase of rotor pole arc generates negative torque; it will increase the torque ripple and main drawback is any changes in the pole arcs are possible at the design stage only. And the third method is changing the turn on, turn off angle for the reduction of torque ripple. A set of combinations with change in these angles are considered. By decreasing values of θ_{on} , θ_{0ff} the torque ripple is reduced.

V. CONCLUSION

In this paper, an effective dynamic model for simulating adjustable speed performance of a SRM drive has been described in detail. SRM modeling, speed performance analysis with PI and PI+FUZZY controller has been presented. With the PI+FUZZY controller the steady state and transient response is improved. Along with this, Torque ripple reduction of SRM using three different methods is discussed. Torque ripple is calculated by taking inner torque loop, with which ripple has been reduced to considerable amount. By applying the remaining two methods, we can get reduced torque ripple for different applications. This model is an ideal tool to validate the performance of the different control algorithms during steady state and transient state of an SRM drive for any kind of applications.

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