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Realization of Current Controlled Mode for Linear and Non-Linear Model of SRM Along with Torque Ripple Reduction

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***Abstract*-** **The switched reluctance motor is old member of electric machine family. It's simple structure ruggedness and inexpensive manufacturability makes it attractive for industrial application. Mainly switched reluctance motor is beneficial for variable speed applications having comparatively low cost. Torque ripple is a major problem of switched reluctance motor drive, which causes undesirable vibration and acoustic noise. In this paper, simulation of both linear and non-linear model in Matlab is described .Among the three operating modes, first is current controlled mode, which is realized for linear as well as non-linear model. Torque ripple is reduced by using fuzzy controller for both the models.**

Keywords*- *Switched reluctance motor, torque ripple, fuzzy controller.

I. INTRODUCTION

Switched Reluctance Motors(SRM) have advantages such as rotor simplicity, high speed operation, ease of repairing, high degree of independence between phases, short end-turn, and low inertia. SRM drives have been used for aerospace systems, marine propulsion systems, linear drives, mining drives, hand held tools and home utilities applications. The SRM is also suitable for variable speed as well as servo type applications. However, a major disadvantage of SRM is the large torque ripple during lower speeds which produces intensive and undesirable vibration and acoustic noise and limits the application areas of SRM. Nowadays, torque ripple reduction in SRM has become an important and difficult research theme. Especially, at low speed, the torque ripple is very serious, which will cause undesirable vibration and acoustic noise.

II. CURRENT CONTROLLED MODE

First mode is called voltage chopping or current controlled mode to provide adjustable developed torque at shaft for low speed operation of the motor. In this mode stator pole concentrated winding of phase is excited by conducting both devices (MOSFETs) of that particular phase. Figure 1 shows the circuit diagram of converter. The voltage applied to the winding is dc link voltage and current starts building up. When current touches upper limit of current hysteresis controller either upper or lower only one out of two devices, is made off permitting freewheeling of current through winding one diode and other device which is conducting.

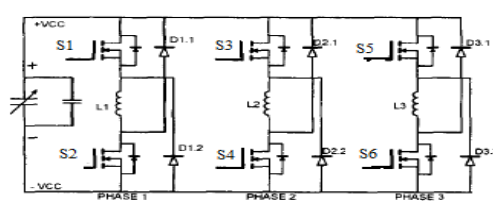


Figure 1 Circuit diagram for converter of SRM

In this control, one device is given continuous gate signal of duration decided by the operating speed and other is fed from hysteresis current controller. When the current in the winding is to be chopped to zero, both the devices are made off either at or before aligned condition of stator and rotor poles. The negative DC link voltage is applied across the winding by conduction of both the diodes and removes the stored energy of magnetic circuit of the machine to the source. Similarly next phase winding is excited by conducting both the devices of the phase to which rotor poles tending to align. In ideal condition the current pulse must be rectangular starting from aligning position with magnitude decided by the load torque. The width of pulses increases with rise in speed. These current pulses must be synchronized with rotor position. This mode continues to be base speed at which the drive may be operated in torque controlled mode to rated valuedecided by the power rating of the motor and rated torque.

III. SIMULATION OF LINEAR MODEL

In the linear model of SRM, saturation and mutual inductance effects are neglected. Here magnetic characteristics of SRM are assumed to be linear. Here hysteresis current controller is applied. In hysteresis control, current is kept within a specified hysteresis band. In this control, depending upon the current error (I_{ref} - I), voltage is applied. The simulation diagram of linear model of SRM with hysteresis current control is given below.

In fig 2 a main layout of simulation diagram is given. A reference current of 20A is applied to all three phases, the second input which is given to individual phases, is rotor position. The output of all four phases is torque, current, inductance and voltage. Individual phase torques are added up resulting in total torque T $= T_1 + T_2 + T_3 + T_4$. Remaining part of simulation diagram is implementation of mechanical equation:

$$J\frac{d\omega}{dt} = T - T_L - D\omega \qquad (3.1)$$

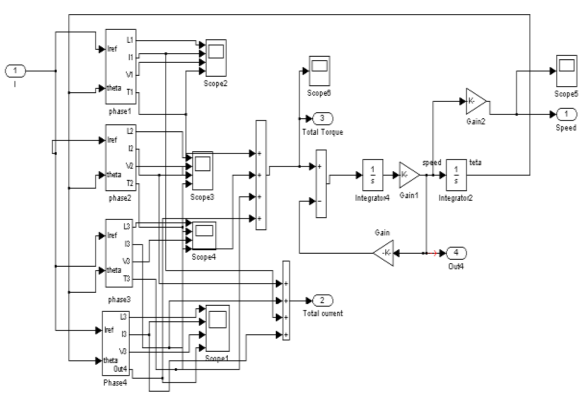


Figure. 2 Linear model of 8/6 Switched Reluctance Motor

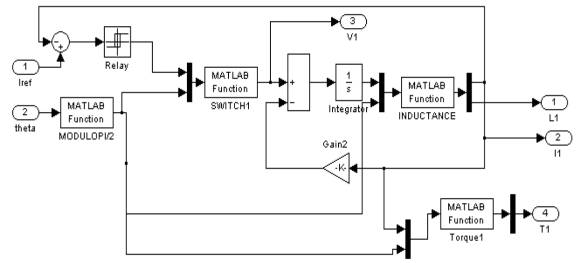


Figure 3 Phase 1 block for linear model of SRM

IV. SIMULATION OF NON-LINEAR MODEL

The non-linear nature of the SRM magnetic characteristics is now taken into consideration for simulation. In linear model of SRM, linear magnetic characteristics have been taken, because of which leads erroneous results. In order to have accurate results non-linearity of magnetic characteristics has to be taken into account.

Most authors proposed analytic solution to take account of non-linearity of the SRM magnetic characteristics.

To represent nonlinear magnetic characteristics we can make use of look up tables. The data required for the look up tables can be obtained by FEM. Rest of the model is similar to linear model of SRM. The simulation diagrams of non-linear model of SRM with hysteresis current control are shown in fig 5

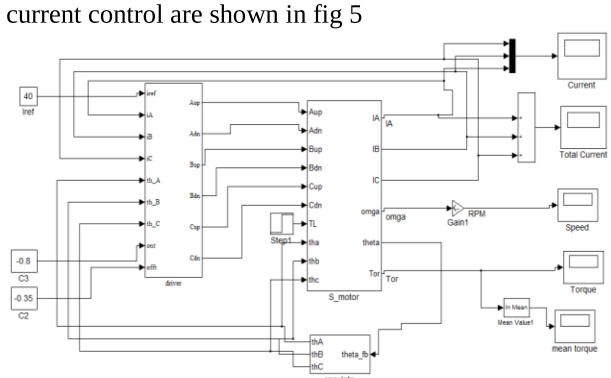


Figure 4 Simulation model of (non-linear) Switched Reluctance Motor with driver circuit.

V. FUZZY CONTROLLER FOR LINEAR AND NONLINEAR MODEL

A Fuzzy+PI compound controller is necessary to overcome the drawbacks existing in the fuzzy logic controller and proportional integral controller. The fuzzy logic controller takes the action during transient states to get fast response [11, 12]. The PI controller is used during steady state to reduce the steady state error of the system. Here, the switch of the fuzzy logic controller and the PI controller is realized by a switching function. By combining fuzzy logic controller with PI controller, a high performance controller can be achieved under both transient and steady states.

The design of fuzzy controller is as follows. There are two inputs for fuzzy controller. First is the current and second is speed. The corresponding linguistic variables of the input fuzzy regions are negative big (NB), Negative medium (NM), negative small (NS), zero (ZE), positive small (PS), positive medium (PM) and positive big (PB).The corresponding linguistic variables of the output fuzzy regions are also same as input . Each region is assigned a fuzzy membership function. In this work, the fuzzy sets are chosen to be of triangular shapes and the center of area (COA) method of de-fuzzification is used. The rules of fuzzy logic controller are formed by experience gained during practical experiments on SRM. The rules table system used in linear model is shown in table 1.

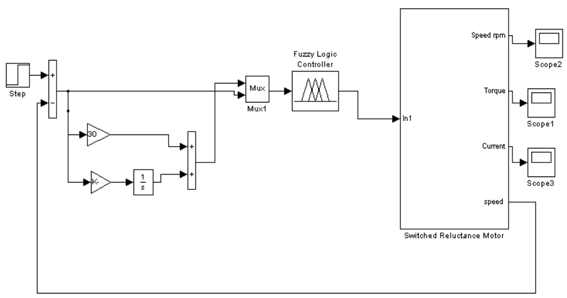


Figure 5. Simulation of linear model of SRM with fuzzy and PI controller

The simple fuzzy controller is designed for nonlinear model, in which single input and single output system is used. In this the feedback from torque is taken. The difference of feedback torque and reference torque gives the error. This error is given as input to fuzzy controller. When torque decreases more than reference value, compensating signal to I_{ref} block of driver circuit is given in increasing direction and vice versa

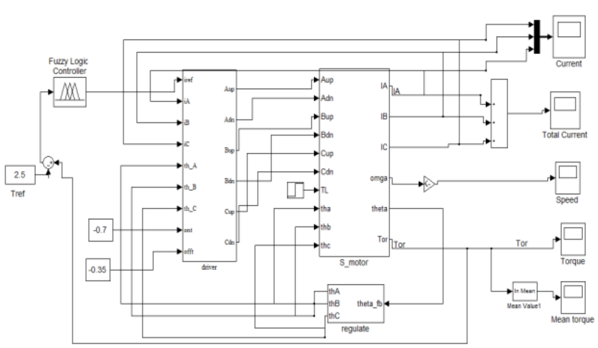
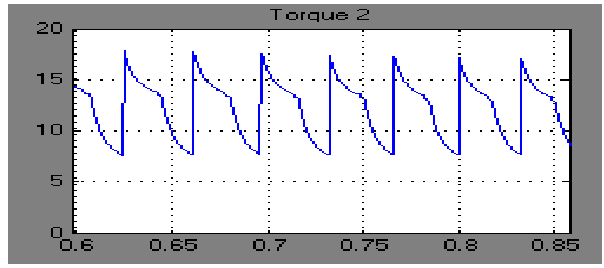


Figure 6 Simulation of non-linear model with fuzzy controller.



VI. RESULTS

A.For Linear Model

For first control mode, the minimum value of switch off angle is found to be 15^0 and maximum value is found to be $\theta_{off} = 23^0$ for linear model. Speed increases from minimum value of θ_{off} to maximum value from 600rpm to 880rpm as shown in fig 8 and 9 respectively.

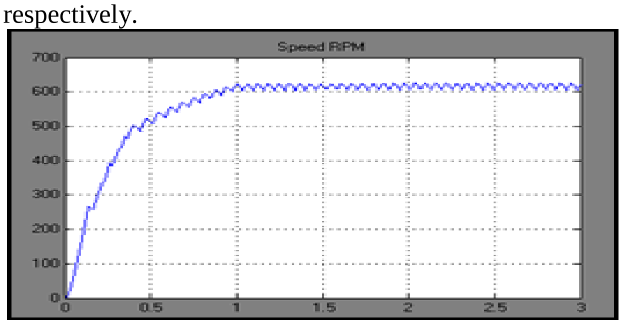


Figure 7. Speed at θ_{off}=15^0

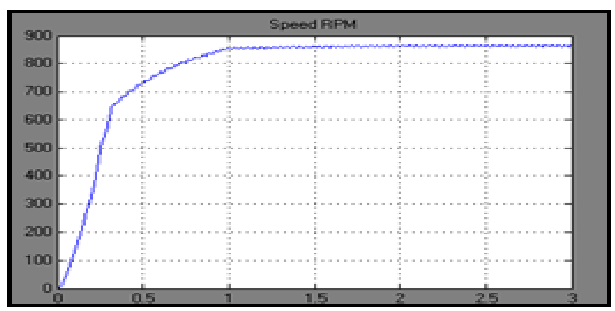


Figure 8. Speed at θ_{off} =23^0

Results of fuzzy controller on torque ripple is shown at θ_{off}=15^0. Percentage of torque ripple can be calculated as

$$\% T_{ripple} = \frac{T_{max} - T_{min}}{T_{max}} * 100 \qquad (6.1)$$

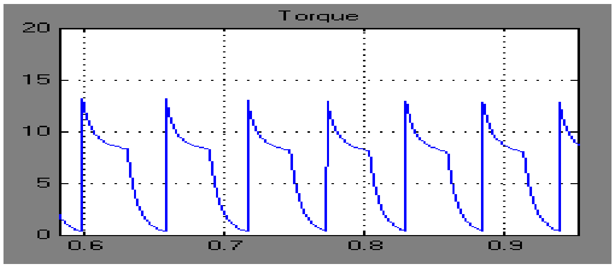


Figure 9. Torque before applying fuzzy controller at θ_{off}=15^0

Figure 10. Torque after applying fuzzy controller at θ_{off}=15^0

B.For Non-Linear Model

For first control mode, the minimum value of switch off angle is found to be 19^0 and maximum value is found to be 45^0 for linear model**.** Speed increases from minimum value of θ_{off} to maximum value from 650rpm to 1600rpm as shown in fig 12 and 13 respectively.

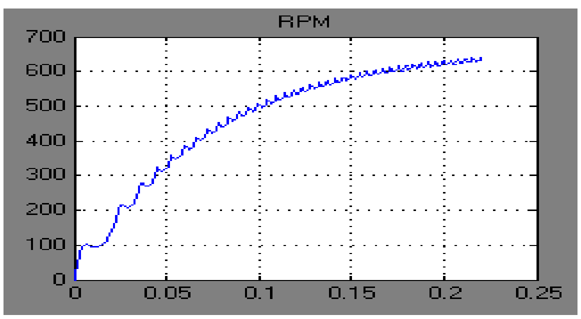


Figure 11. Speed at θ_{off}=19^0

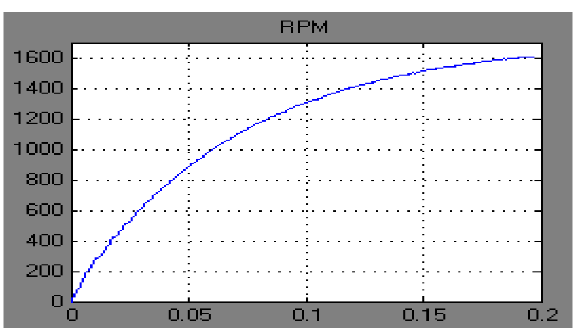


Figure 12. Speed at θ_{off}=45^0

Effect of fuzzy controller on torque ripple for non-linear model at θ_{off}=32^0 is shown in fig14 and 15.

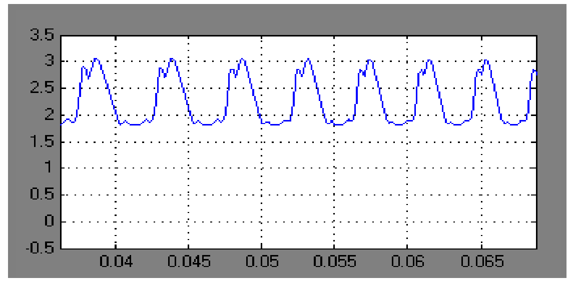


Figure 13. Torque before applying fuzzy controller at θ_{off}=32^0

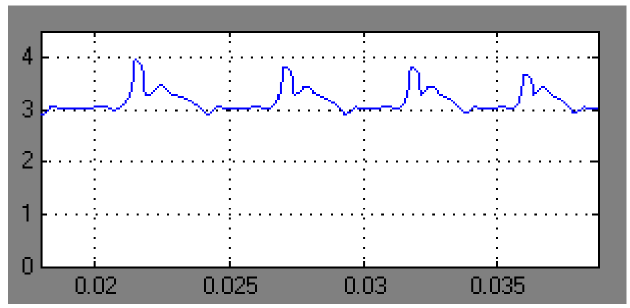


Figure 14. Torque after applying fuzzy controller at θ_{off}=32^0

VII CONCLUSIONS

First control mode (current controlled mode) of operation is realized for both linear and nonlinear models. In this mode speed increases as value of θ_{off} increases, and at particular value of θ_{off} speed becomes constant. At minimum value of θ_{off}, phase torques are not superimposed so T_{min} is 0 Nm, hence torque ripple is maximum. As value of θ_{off} increases, phase torque starts to superimpose which increases value of T_{min} and torque ripple is reduced. Minimum and maximum values of θ_{off} for linear model are found to be 15^0 and 22^0 respectively. In this case, speed increases from 600 rpm and become constant at 880 rpm. For non-linear model, minimum and maximum value of θ_{off} is 19^0 and 45^0 respectively. In this case, speed increases from 650 rpm to 1600 rpm.

Control of SRM is very complicated due non-linear magnetic characteristics. Fuzzy logic control is good for controlling non-linear systems. Hence fuzzy controller is designed to reduce torque ripple. Depending on error in torque, fuzzy controller generates compensating signal which is given to Iref of driver block. Effect of fuzzy controller on both linear and non-linear models is determined. Minimum value of torque ripple reduction is 20% and maximum value is 54%. Because of fuzzy controller, speed and total torque of motor are increased.

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VII. APPENDICES

Specification of the switched reluctance motors used in simulation.

A. For linear Model

No. of stator poles	Ns	= 8;
No. of rotor poles	Nr	= 6;
Voltage	V	= 150 V;
Current	I_{ref}	= 20 A;
Phase Resistance	R	= 1ohm;
Minimum inductance	L_{min}	= 0.01H
Maximum inductance	L_{max}	= 0.04 H;
Stator pole arc	β_s	= 22;
Rotor pole arc	β_r	= 24;
Moment of inertia	J	= 0.0013 Kg-m^2;
Friction coefficient	D	= 0.0183

B. For non-linear Model

No. of phases	P	= 3;
No. of stator poles	Ns	= 6;
No. of rotor poles	Nr	= 4;
Voltage	V	= 150 V;
Current	I_{ref}	= 40 A;
Phase Resistance	R	= 1ohm;
Moment of inertia	J	= 0.0013 Kg-m^2;
Friction coefficient	D	= 0.0183