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Torque Ripple Minimization of a Switched Reluctance Motor using Direct Instantaneous Torque Control

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***Abstract*—Torque ripple is one of the major disadvantages of Switched Reluctance Motor (SRM) drives due to its double salient geometry and it is a serious drawback in applications that require smooth torque and high dynamic performances. This paper presents the minimization of torque ripple in SRM using an enhanced direct instantaneous torque control. Linear and non linear modelling is done in SIMULINK. SRM is modelled in ANSYS MAXWELL (FEA method) and the inductance and torque values are obtained. These values have been provided as look up table in MATLAB for obtaining the non linear characteristics of SRM. The switching control rules in each inductance region are then described according to the characteristics of asymmetric power converter. In order to test the method, a SRM drive system is simulated in MATLAB SIMULINK after detailed analysis of linear and non linear models.**

***Index Terms*— Torque ripple, Switched Reluctance Motor, Direct Instantaneous Torque Control.**

I. INTRODUCTION

In recent days the Switched Reluctance Motor (SRM) and its drive system have attracted more attention for its robust structure, flexibility in control, favourable start and fault tolerance ability. Hence the system is regarded as a promising variable speed drive system for numerous industrial applications in the future, such as electric vehicles, aerospace planes and domestic appliances, etc. While the merits are remarkable, the torque ripple is also a problem to be reckoned with resulting from magnetic reluctance property, which is benefit to neither machinery nor environment. Accordingly, it is of great importance to mitigate torque ripple to expand applications and improve performances of SRM. In order to improve performances of SRM, scholars from domestic and foreign have proposed a variety of solutions which in general can be classified into two groups: optimization of machine structure and reasonable control strategy.
Several control strategies have been proposed in recent years, typically including current chopping control (CCC), torque sharing function (TSF) ,voltage space vector control (VSVC) , direct instantaneous torque control (DITC) and others intelligent control algorithms. DITC is proposed on the basis of the relationship between phase inductance and the ideal current and torque. The idea of this method is to control output

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torque directly by generating suitable switching states based on the torque bias between the reference and feedback. In this paper to attain the objective initially the modelling of SRM (linear and non linear) is done and then the DITC strategy is implemented and the simulation results are obtained.

II. Linear Model of SRM

Linear model of SRM implies that the variation of inductance with respect to rotor position is linear. In the actual situation the variation of inductance is not of linear type. It depends on both the position of the rotor and the current in the phase making it a nonlinear one. In order to obtain the linear model a minimum inductance (unaligned inductance) and the maximum inductance (aligned inductance) are considered and the variation with respect to the rotor position is considered to be linear. For different values of current too the inductance

Profile is considered are the same, and the values depend on the position of the rotor.

Mathematical Modeling using the basic equations of SRM was done in MATLAB SIMULINK and the characteristic curves (Inductance, Torque, Current etc.) were analysed.

$$V = R_s i + \frac{d\lambda(\theta,i)}{dt} \quad (1)$$

$$\lambda = L(\theta,i)i \quad (2)$$

$$T_e = \frac{1}{2} i^2 \frac{dL(\theta,i)}{d\theta} \quad (3)$$

$$T_e = J\frac{d\omega}{d\theta} + D\omega + T_L \quad (4)$$

Figure 1 shows the main S1M1LINK block diagram of the linear model. For an 8-6 SRM there are four phases as shown in the model. All the phases are of same type but differ in excitation angles. The instantaneous torque contributions of each phase are added to obtain the total torque of the machine. By using the equation 4, the rotational velocity 'ω' is calculated. The rotor position is obtained by integrating ''ω' and is used to determine the point of excitation of different phases. Figure 2 is the subsystem representing one of the phases of SRM. Other phases are similar to this. There is a current limit that is given using the hysteresis controller. For the hysteresis controller, the difference between the reference and actual current is used.

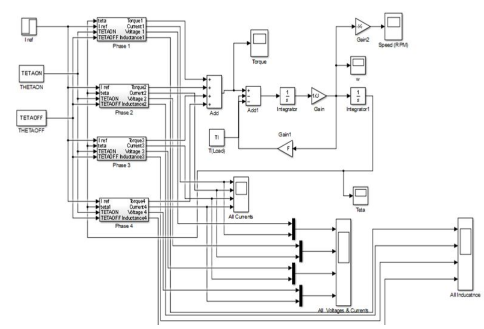

Fig.1. Linear Model of SRM

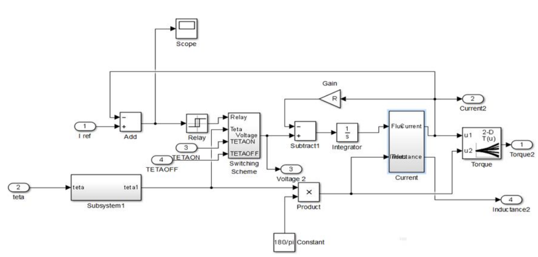

Fig 2. One phase

The output of the hysteresis controller is used for the switching scheme and helps to limit the current. The equations (1) to (3) are used in the implementation of each phase. By using voltage equation (1) flux linkage is obtained. It is clear from the graph that the speed attains steady state value within seconds, as shown in Figure 3. In Figure 4, the current variation of a phase is shown, whenever the voltage is applied, the current rises and then it falls back at the removal of voltage. Figure 5 gives the sequence of voltage application for different phases and the corresponding variation of current in each phase. The linear variation of inductance for different phases is clear and is as seen in Figure 6.

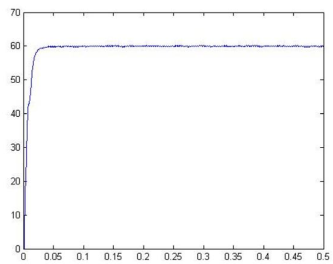

Fig.3. Speed profile

The inductance profile is of trapezoidal nature but the profile shown above is of triangular type without flat top, this is due to the parameters taken for the machine. The total torque output of the machine is given in Figure 7.It is the sum of instantaneous torques produced by different phases.

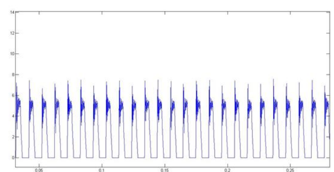

Fig.4. Current profile

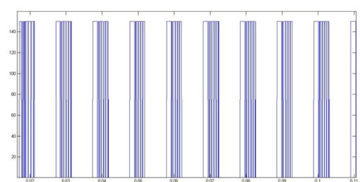

Fig.5. Voltage profile

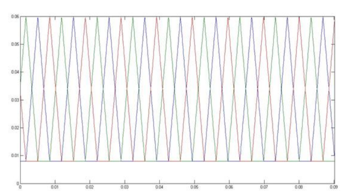

Fig.6. Inductance profile

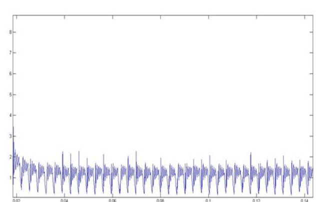

Fig.7. Torque profile

III. NON LINEAR MODELLING OF SRM

From the above discussion it is clear that for the linear model, the inductance variation is considered to be linear. But in actual case it is not true since the inductance variation depends not only on the position of the rotor but also on the current in respective phases. In order to get the non linear characteristics of the machine, MAXWELL software is used. MAXWELL makes use of finite element analysis (FEA) to solve three dimensional electrostatic, magnetostatic, eddy current and transient problems.

SRM is modelled in MAXWELL with stranded conductors. There are two coils for each phase of the machine. The modelled machine is simulated, for different currents and position is varied and the data for inductance profile as well as the torque is obtained. Model of SRM in MAXWELL is shown in Figure 3.1. Using the MAXWELL model, look up tables are created for inductance profile and torque.

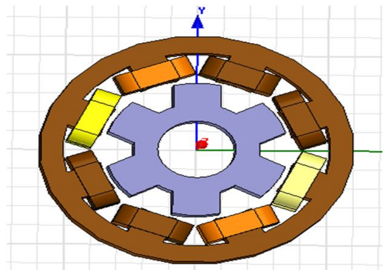

Fig.8. Maxwell model of SRM

The main SIMULINK model for the nonlinear 8-6 stitched reluctance motor is shown in Figure 8. Compared to Figure 1, the linear model of the motor, there is no much difference in the blocks used. The difference in the nonlinear SIMULINK model comes only for the torque calculation and the inductance profile. Instead of going for the linear inductance profile, the look up table obtained from MAXWELL model is used. It is a nonlinear type and varies with respect to both the finding current and the rotor position.

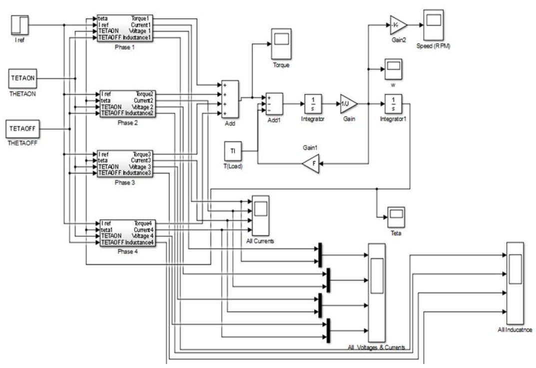

Fig.9. Simulink Diagram of Non linear model of SRM

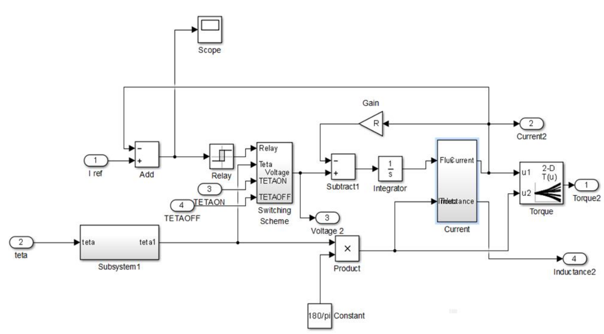

Fig.10. One phase

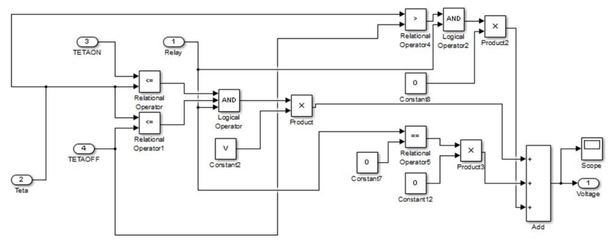

Fig.11. Switching scheme

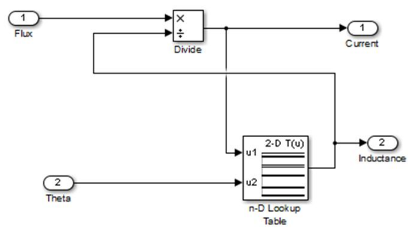

Fig. 12.Current Calculation

Switched reluctance motor's non linear model can be used for design and implementation of the control scheme for efficient speed control. The performance with the control scheme can be evaluated using this model, which makes it is easy and economical. The models obtained can be used for further design of the controller and study of performance optimization of the machine.

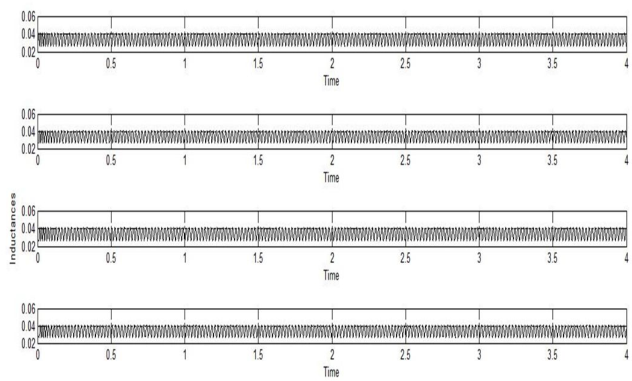

Fig.13. Inductances

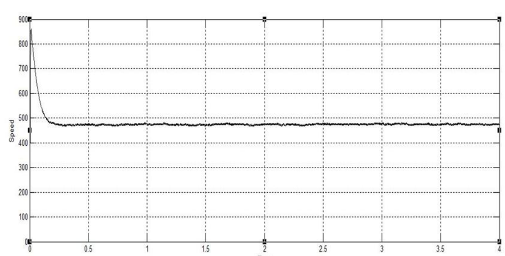

Fig.14. Speed

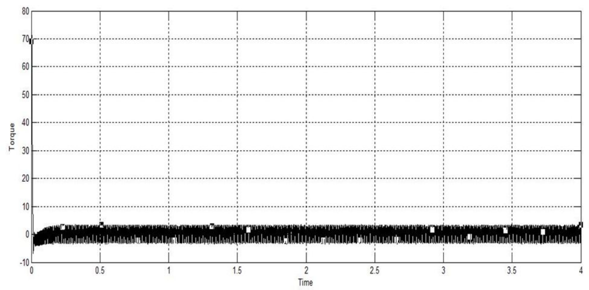

Fig.15. Torque

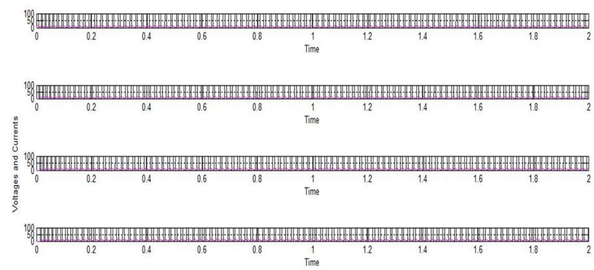

Fig.16. Voltages and Currents

IV. DITC Principle

At a particular rotor position the torque of an SRM is a function of current and inductance. The ideal current and torque curves are as shown in Figure 17 in order to output a constant torque. There are three voltage states in each phase for output current two switches working independently and they are defined to positive, zero and negative in Figure 18 and respectively marked by 1, 0 and -1. The winding will absorb energies from the source and the magnetic field is then established when the phase circuit works as state 1,that is, a pair of switches Q_{AH} and Q_{AL} is simultaneously turned on. As a result, the torque of this phase will increase in the period of the phase inductance rising. The circuit works in freewheeling mode when only Q_{AH} or Q_{AL} is solely turned on, and the self-regulating phase torque will maintain a constant total torque by stopping it from continuing to increase or decrease in the situation. The phase torque will decrease when a pair of switches Q_{AH} and Q_{AL} is simultaneously turned off because the energy stored in windings return to the source.

The three states must be coordinated with the inductance regions of adjacent phase windings for achieving a minimum torque ripple.

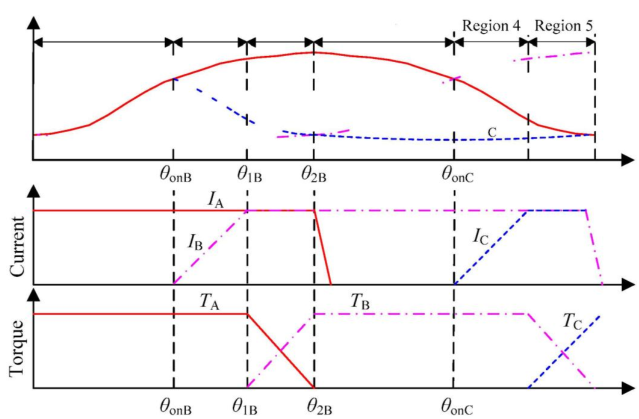

Fig. 17. Six regions of phase inductance, ideal current and torque

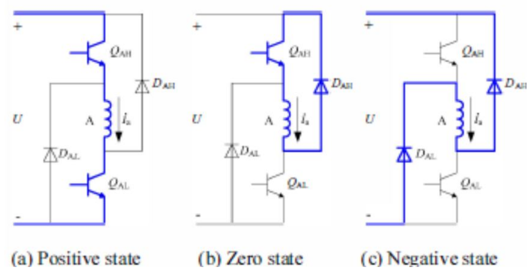

Fig. 18. Switch states of one phase in asymmetric power converter

V. SIMULATION RESULTS FOR DITC BASED SRM

A DITC based controller was implemented to the non linear model of SRM along with a PID controller for the better control of the torque ripple in an SRM. A drastic reduction n torque ripples has been observed and the torque waveforms have become smoother with minimised ripples. The Simulink model of the DITC+PID controlled SRM is as shown in Figure 19. The torque waveform is obtained in Figure 20 and comparing it with Figure 15 it is clear that the ripples in the torque waveform have reduced drastically. The ripple peak has reduced and the negative ripples have also been reduced after the application of the controller. Hence torque ripple minimisation is clearly obtained using this controller.

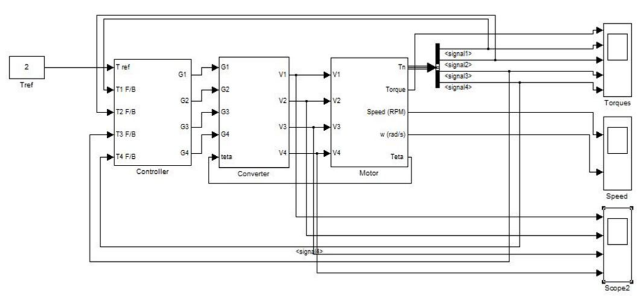

Fig.19 Simulink diagram of SRM with DITC controller

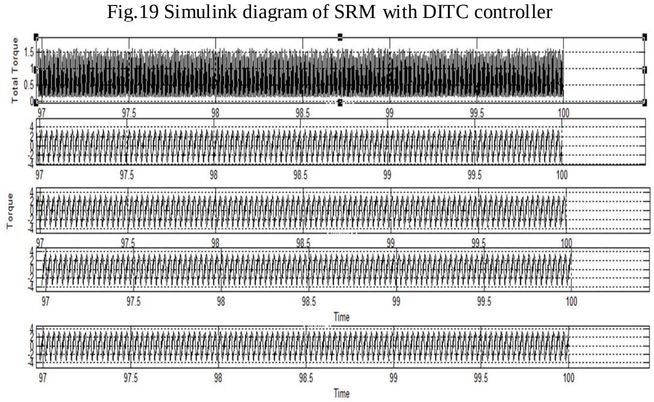

Fig 20 Torque Output Waveform

VI. FUTURE WORK

As a future step, I plan to develop the hardware model of the above controller and demonstrate the switching of the four phases of the SRM.

VII. CONCLUSION

Initially, the linear model of SRM was analysed in MATLAB SIMULINK and the torque and speed waveforms were analysed. But in actual case it is not true since the inductance variation depends not only on the position of the rotor but also on the current in respective phases. In order to get the non linear characteristics of the machine, look up table of inductance and torque obtained from MAXWELL software is used. Torque ripple is the major problem faced by non linear SRM. Torque ripple can be minimised using DITC principle and the controller can be designed to provide the appropriate switching so that SRM runs with reduced torque ripple. This has been verified by simulating the non linear model of SRM with a DITC controller and the results have been analysed. As a future work, the controller can be designed and implemented a real time SRM.

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