Static and Dynamic Characteristics of 8/6, 400W Switched Reluctance Motor

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ABSTRACT
This work describes the main consideration in the design of power converter for a SRM drive with the particular attention to the choice of converter topology, and to study and develop the static and dynamic characteristics of the prototype model of SRM using FEA software (MagNet 6.22). To simulate the power converter switching circuit for prototype model of SRM using MATLAB/Simulink 7.8.0. It is presented by simulation on the 4- phase 8/6 SRM with classic power converter. The converter topology of SRM should eliminate the problem of shoot through faults and makes the control circuitary simple.

Keywords
Switched reluctance motor drives, power converter.

1. INTRODUCTION
Switched reluctance motor (SRM) is a doubly salient machine with independent phase windings on the stator and a solid laminated rotor. The stator windings on diametrically opposite poles are connected in series to form one phase of the motor. Figure 1 shows the four phases 8/6 switched reluctance motor. When a stator phase is energized, the most adjacent rotor pole-pair is attracted towards the energized stator in order to minimize the reluctance of the magnetic path. Therefore, by energizing consecutive phases in succession it is possible to develop constant torque in either direction of rotation.

The SRM is normally operated with shaft-position feedback to synchronize the commutation of the phase currents with precise rotor position. The SRM is an electric machine in which torque is produced by the tendency of its moveable part to move to a position where the inductance of the excited winding is maximized.

SRM drives have been researched in the areas of motor principles, operation, and control, because of their cost advantages and ruggedness. These drives are suitable for high-speed applications.

The torque in a SRM is produced in pulses by the tendency of the rotor to move towards the position where the inductance of the excited stator pole winding is maximized. At low speeds, the torque is limited by the current that is controlled by either voltage-PWM or current regulation and is called 'PWM-control mode'. The stator and rotor configuration of 8/6,400W SRM is shown in figure1.

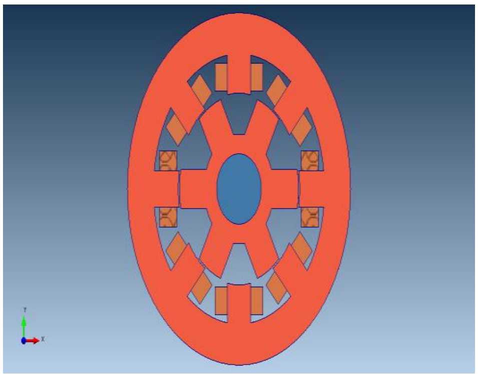

Figure 1. Stator and rotor configuration of 8/6 SRM.

The classic bridge converter for SRM is shown in figure 2. The SRM has two phases (excitation and generation) in one electrifying period, with generation being the primary phase. When the two switches, T1 and T1', are turned on, the windings on the stator are excited by the outer circuit, and the electrical energy provided by exterior circuit is converted into magnetic field energy. When the two switches are turned off and the two diodes, D1 and D1', gets forward biased, hence the magnetic field energy and mechanical energy are converted into electricity energy, feeding back to the source or supplying power to the load.

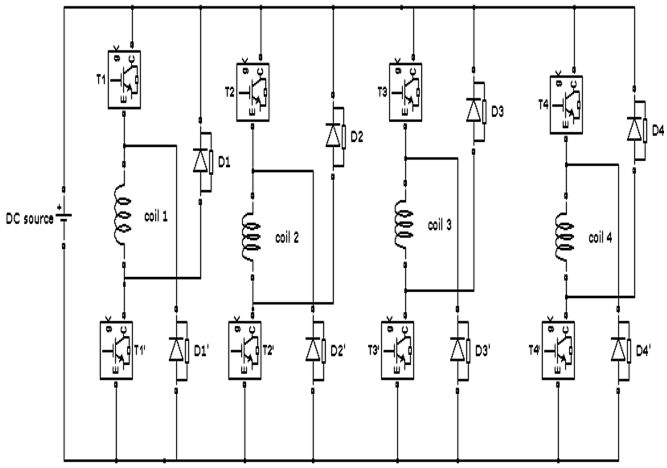

Figure 2. Classic bridge converter for SRM.

The main disadvantages of SR motor drives are the following. High torque ripple. Higher acoustic noise level than other motors. However, advanced motor design techniques and high

Performance algorithms are successfully addressing the above mentioned disadvantages and SR motor drives are becoming more and more suitable for a wide range of applications.

2. STATIC TORQUE PRODUCTION OF SRM

Consider the primitive reluctance motor as shown in figure 3

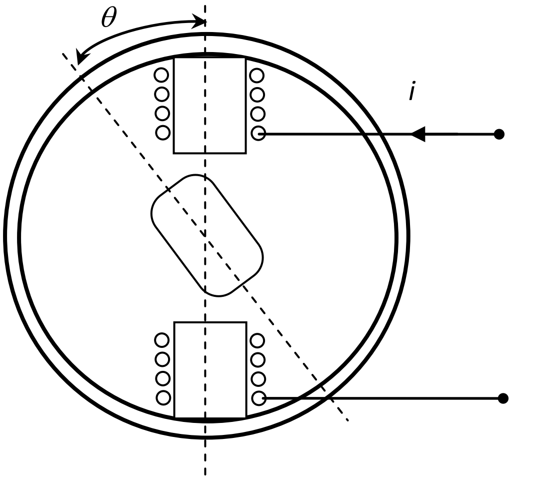

Figure 3. Static Production of SRM

The most general expression for the instantaneous torque is

$$T = \left[\frac{\partial w'}{\partial \theta}\right]_{i=\text{constant}} \tag{1}$$

Where W' = co-energy of the magnetic field.[6]

The Co-energy is defined as

$$w' = \int_0^i \psi di \tag{2}$$

The equivalent expression is given as

$$T = -\left[\frac{\partial w_f}{\partial \theta}\right]_{\psi=\text{constant}} \tag{3}$$

Where w_f is the stored field energy and it is defined as

$$w_f = -\int_0^{\psi} i d\psi \tag{4}$$

If magnetic saturation is negligible, then the relationship between flux linkage & current at the instantaneous rotor position θ is a straight line whose slope is the instantaneous inductance L.

Thus

$$\psi = Li \tag{5}$$

$$w' = w_f = \frac{1}{2} Li^2 \tag{6}$$

$$T = \frac{1}{2} i^2 \frac{dL}{d\theta} \quad \text{(Nm)} \tag{7}$$

If there is magnetic saturation this formula is invalid and the torque should be derived as the derivative of co- energy (or) field energy.

If the rotor and stator pole arcs are different then there will be a small "dwell" at maximum inductance. Similarly if the inter-polar arc of the rotor exceeds the stator pole arc then there will be a small "dwell" at minimum inductance. The Conduction Sequence is shown in figure 4

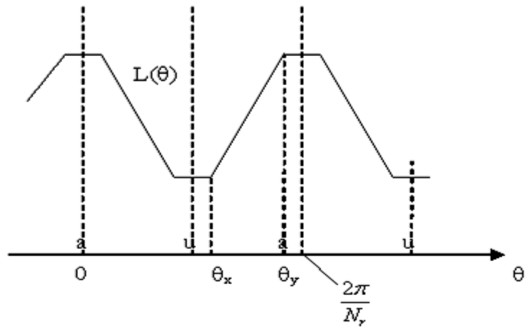

Figure 4. Conduction sequence of SRM

The step angle of the rotor is given by

$$\theta_s = \frac{2\pi}{qR_n} \tag{8}$$

Where 'q' is the number of phases, and 'R_n 'is the no of rotor poles, then for 8/6 SRM the step angle is 30 degree on per-stroke basis [1]. The efficiency can be improved and torque ripple can be reduced by controlling the flux-linkage level of the machine, so that an appropriate balance between the contributions of each phase to the total flux is accomplished. Therefore, high efficiency with reduced torque ripple is achieved by on-line controlling the SRM turn-on and turn-off angles.[2]

The equivalent circuit of SRM consist of resistor R, and an inductor L and it is shown in figure 5

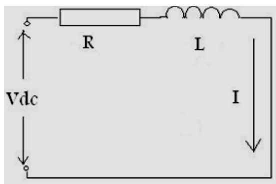

Figure 5: SRM equivalent circuit

The phase voltage equation in Switched reluctance motor can be written as:

$$V = iR + \frac{d\lambda}{dt} \tag{9}$$

Where, V is the dc bus voltage, 'i' is the instantaneous phase current, R is the phase winding resistance and λ is the flux linking the phase coil.

$$V = L(\theta)\frac{di}{dt} + i\frac{dL(\theta)}{d\theta}\omega \tag{10}$$

Where, w is the rotor speed, θ is the rotor angular position, and L (θ) is the instantaneous phase inductance. The rate of flow of energy can be obtained by multiplying the voltage with current and can be written as

$$Vi = Li\frac{di}{dt} + i^2\frac{dL}{d\theta}\omega \tag{11}$$

3.STATIC CHARACTERISTICS OF SRM

To Simulate the power converter switching circuit for the prototype model of SRM using MATLAB/Simulink 7.8.0. The torque profile and the inductance profile is taken from the Finite Element Analysis method using MagNet 6.22.

Finite Element method (FEM) is a general technique for numerical solution of the integral or differential equation governing the behavior of the system.

A 4ф-8/6 SRM to modeled and its flux plot in the aligned and unaligned position are obtained and also through parameterization feature flux linkage Vs current graph is to be drawn for the aligned and unaligned position.

Projected Finite Element model of 8/6 Switched Reluctance Motor under study with one phase excited is shown in figure 6 Materials assigned to all parts of the motor. CRGO –stator &rotor ,steel-shaft, copper wire- windings.

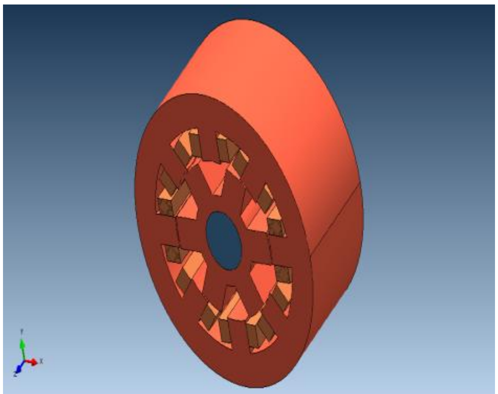

Figure 6: Projected Finite Element model of 8/6 SRM under study with one phase excited

After assigning the materials to all the parts of the machine, the next step is meshing . The meshing is a process in which the entire region should be subdivided into triangles in any desired manner. All iron-air interfaces coincide with triangle sides. Number, shape and size of triangles are not restricted in any way. The meshed finite element model of a 8/6 SRM is shown in figure 7.

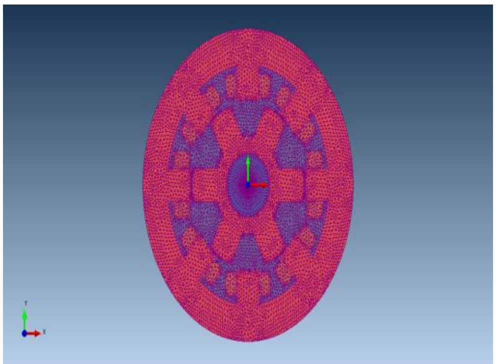

Figure 7. Meshed Finite Element Model of 8/6 SRM

Flux lines plot of 8/6 Switched Reluctance Motor at the unaligned position is shown in figure 8.

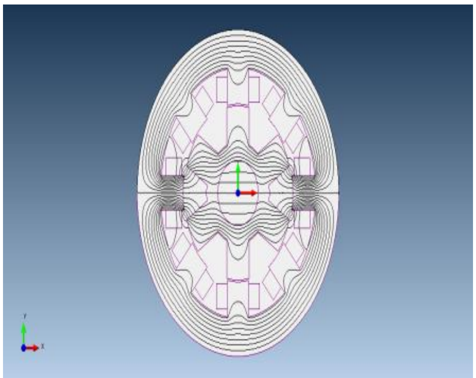

Figure 8: Flux lines plot of 8/6 SRM at the unaligned position

Flux lines plot of 8/6 Switched Reluctance Motor at the aligned position is shown in figure 9

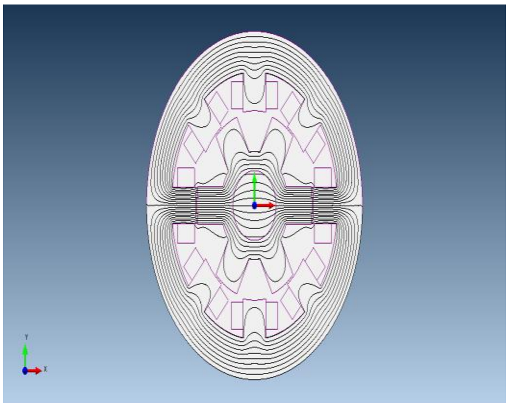

Figure 9: Flux lines plot of 8/6 SRM at the aligned position

3.1 Flux-Linkage Characteristics

The area enclosed between the aligned and unaligned characteristic curves is indicative of the energy conversion possible with this machine. Flux linkage characteristics of 8/6 400W SRM is shown in table 1.

Table 1. Flux linkage characteristics of 8/6 400W SRM

Iph(A)	L (al)	L (un)
0	0	0
1	0.205496	0.039001
2	0.369183	0.078003
3	0.431574	0.117001
4	0.462977	0.155973
5	0.482083	0.194805
6	0.497355	0.23314
7	0.510964	0.270749
8	0.522996	0.307018
9	0.534059	0.340561
10	0.544514	0.370907
11	0.554539	0.398298
12	0.564242	0.421759
13	0.573691	0.440261
14	0.582934	0.455929
15	0.592006	0.469995
16	0.600933	0.483008

The flux-linkage characteristics of the 400W , 8/6 SRM prototype at unaligned and at aligned positions is shown in figure 10.

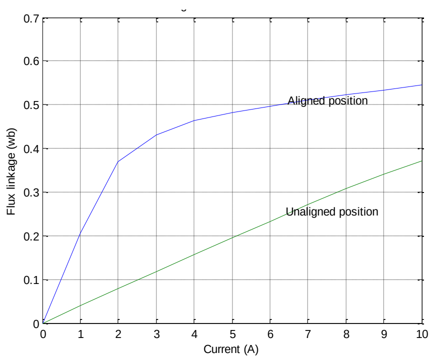

Figure 10: Flux linkage characteristics of 8/6, SRM

3.2 Inductance Profile

From the flux-linkage characteristics computed at different rotor positions from unaligned to aligned position along the air-gap, the inductance profile of the SRM can be plotted as shown in Figure11. By considering the non-linear relationship between flux-linkage (ψ) and inductance (*L*). It is given in table 2.

Table 2. Inductance profile of 8/6,400W SRM

θ \ I	0	1	2	3	4	5	6	7	8	9
0	0	0.039	0.039	0.039	0.038	0.038	0.038	0.038	0.038	0.037
5	0	0.045	0.045	0.045	0.044	0.044	0.043	0.042	0.041	0.040
10	0	0.075	0.073	0.067	0.062	0.058	0.054	0.051	0.048	0.046
15	0	0.112	0.109	0.095	0.082	0.073	0.066	0.060	0.055	0.051
20	0	0.149	0.143	0.121	0.100	0.086	0.075	0.067	0.060	0.055
25	0	0.183	0.172	0.138	0.112	0.094	0.081	0.071	0.064	0.058
30	0	0.205	0.184	0.143	0.115	0.096	0.082	0.072	0.065	0.059
35	0	0.183	0.172	0.138	0.112	0.094	0.081	0.071	0.064	0.058
40	0	0.149	0.143	0.121	0.100	0.086	0.075	0.067	0.060	0.055
45	0	0.112	0.109	0.095	0.082	0.073	0.066	0.060	0.055	0.051
50	0	0.075	0.073	0.067	0.062	0.058	0.054	0.051	0.048	0.046
55	0	0.045	0.045	0.045	0.044	0.044	0.043	0.042	0.041	0.040
60	0	0.039	0.039	0.039	0.038	0.038	0.038	0.038	0.038	0.037

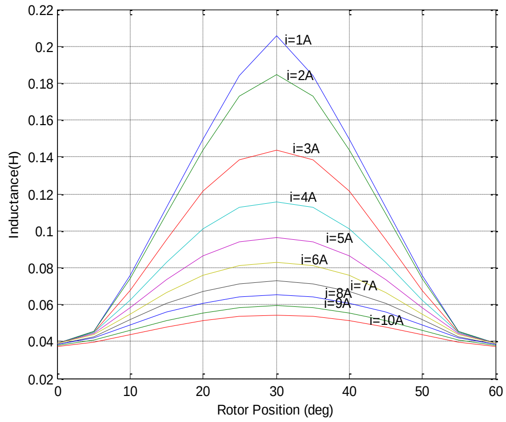

Figure 11: Inductance profile of 8/6,400W SRM

3.3 Instantaneous Torque Profile

The torque data obtained (i.e. from direct solving method) is from the instances when the rotor position is changing in time steps. The torque characteristics of the 8/6 SRM is shown in figure 12, which indicates that the torque developed by the machine is also a non-linear function of stator current and rotor position. It is listed in Table 3.

Table 3. Torque profile of 8/6,400W SRM

T / θ	0	1	2	3	4	5	6	7	8	9
5	0	0.087	0.348	0.771	1.309	1.909	2.534	3.155	3.741	4.273
10	0	0.213	0.844	1.730	2.659	3.574	4.443	5.236	5.963	6.614
15	0	0.212	0.842	1.753	2.703	3.581	4.389	5.107	5.704	6.194
20	0	0.208	0.816	1.599	2.350	3.017	3.557	4.001	4.400	4.771
25	0	0.187	0.692	1.121	1.478	1.774	2.041	2.288	2.522	2.746
30	0	0.003	0.001	0.004	0.001	0.001	0.001	0.001	0.002	0.002
35	0	0.187	0.692	1.121	1.478	1.774	2.041	2.288	2.522	2.746
40	0	0.208	0.816	1.599	2.350	3.017	3.557	4.001	4.400	4.771
45	0	0.212	0.842	1.753	2.703	3.581	4.389	5.107	5.704	6.194
50	0	0.213	0.844	1.730	2.659	3.574	4.443	5.236	5.963	6.614
55	0	0.087	0.348	0.771	1.309	1.909	2.534	3.155	3.741	4.273

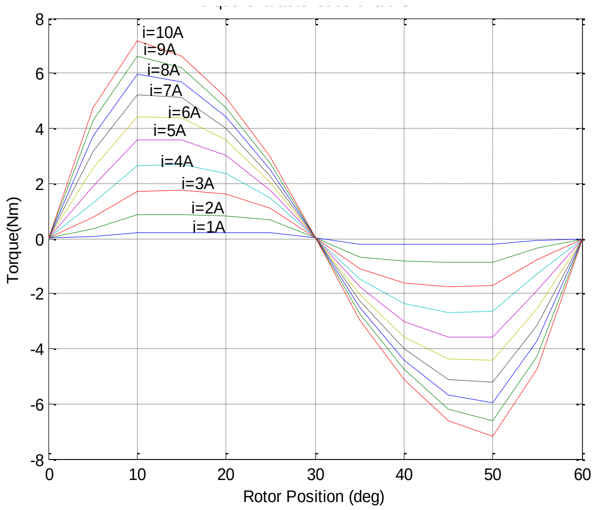

Figure 12: Torque characteristics of 8/6, 400W, SRM

4. DYNAMIC CHARACTERISTICS OF SRM

To Simulate the power converter switching circuit for the prototype model of SRM using MATLAB/Simulink 7.8.0. The torque profile and the inductance profile is obtained from the Finite Element Analysis method. The internal diagram for one phase of 8/6 SRM is shown in figure 13

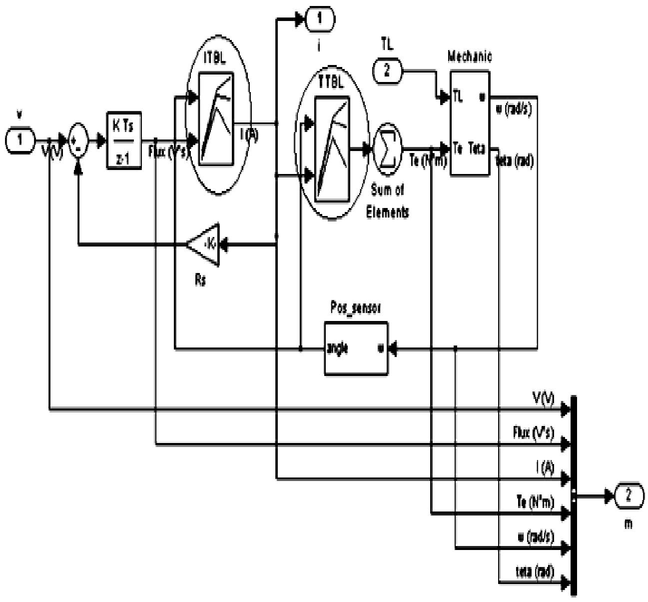

Figure 13: Internal diagram for one phase of 8/6 SRM

The performance of the controller is experimentally verified through a 8/6 four-phase SRM designed for a 400 W. Figure 14 shows the block diagram of the classic converter for SRM drives.

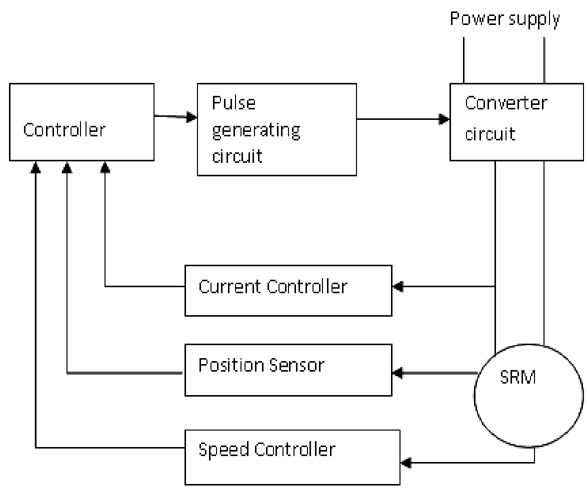

Figure 14: Block diagram of Classic converter for SRM drives

Simulation model of 8/6 SRM using MATLAB/Simulink 7.8.0. software is shown in figure 15

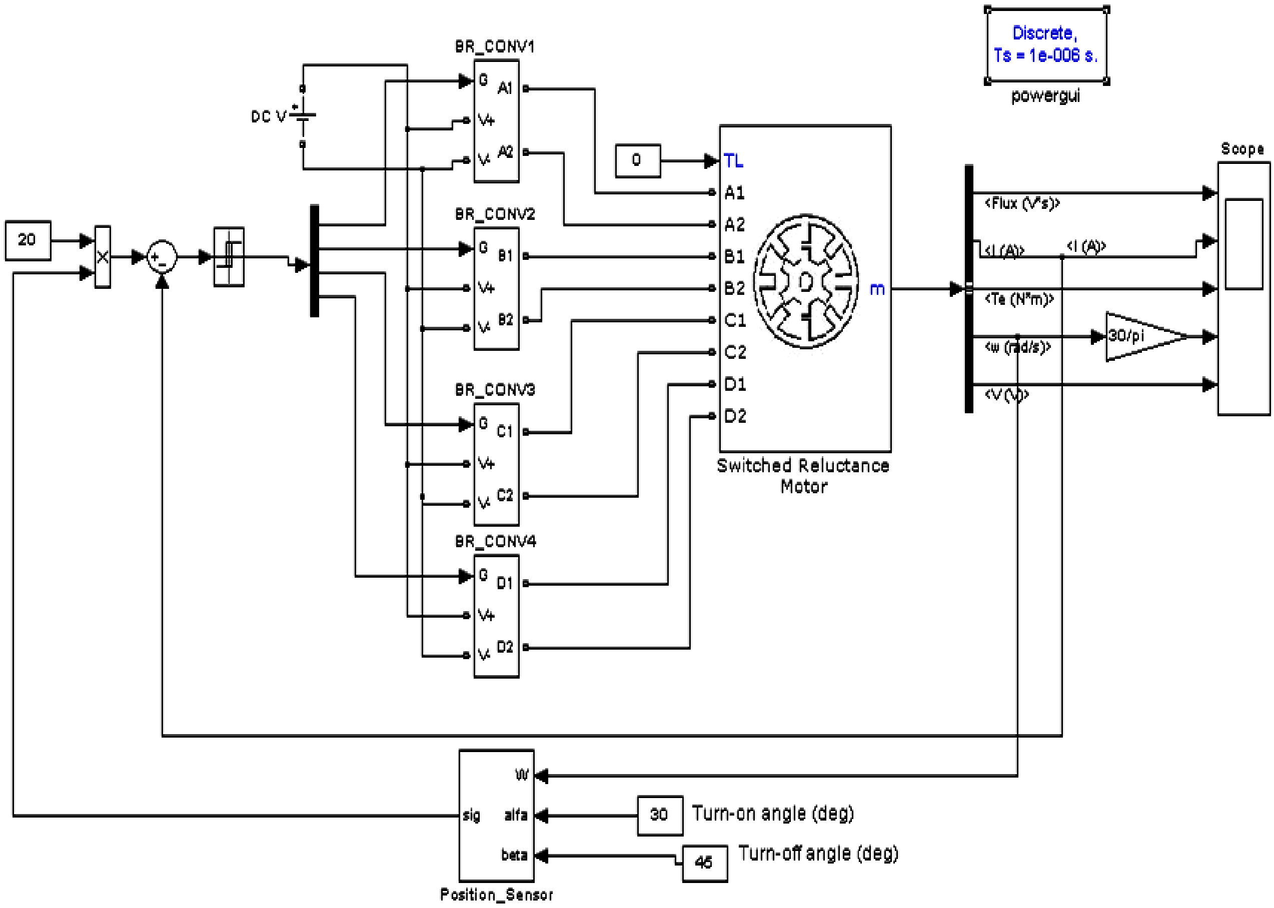

Figure 15: Simulation model of SRM

The basic requirements of converter is to demagnetize the phase before it steps into the generating region if the machine is operating as a motor and should be able to excite the phase before it steps into the motoring region if operated as a generator. Single leg of classic converter block is shown in figure 16.

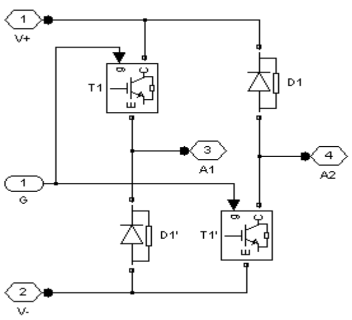

Figure 16: Single leg of classic converter block

The position sensor block is used to sense the position of the rotor. The speed is sensed and it is compared with the operating region of the motor, pulse is generated which is given to the converter circuit. The position sensor block is shown in figure 4.5.

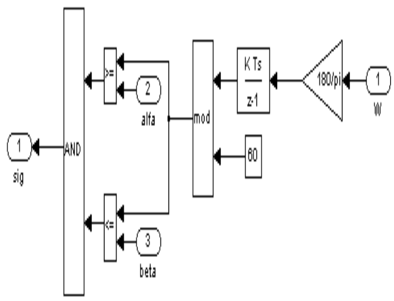

Fig16: Position sensor block

5. SIMULATION RESULTS

The SRM torque characteristic can be optimized by applying appropriated pre-calculated turn-on and turn-off angles in function of the machine current and speed. The optimum values of optimum angles can be stored in a 2-D lookup table. The SRM waveforms (phase voltages, magnetic flux, windings currents, torque, and speed) are displayed on the scopes.

The output flux waveform of 8/6 400W SRM is shown in figure 17

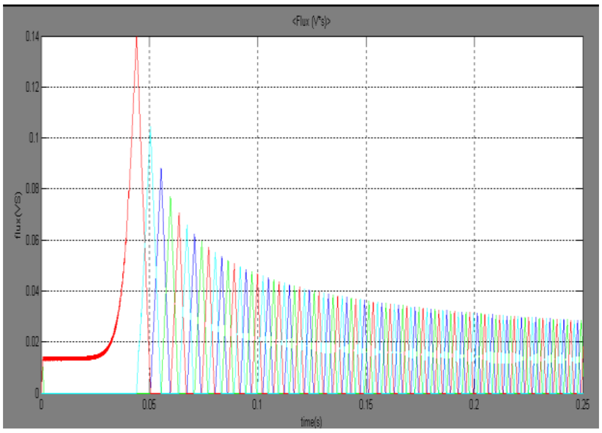

Figure 17: Flux under each phases of 8/6 SRM

The voltage waveform for 8/6, 400W SRM is shown in figure 18.The voltage shown under for each phase is 20V

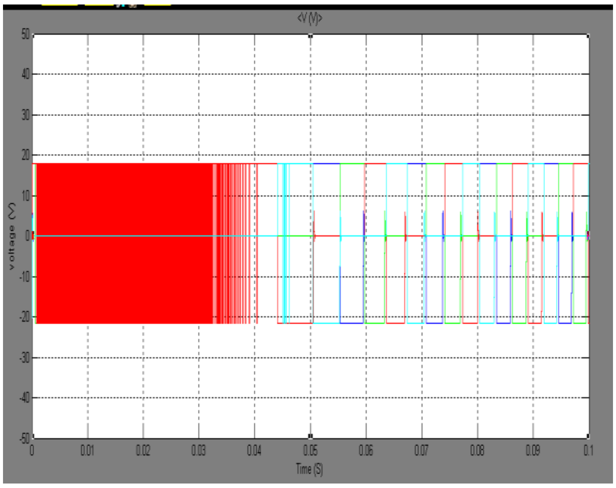

Fig 18: Voltage response of each phase of 8/6SRM

The output current waveform for 8/6,400W SRM is shown in figure 19.

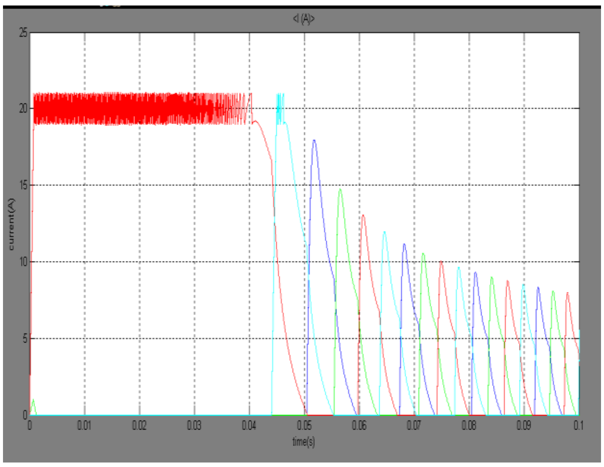

Figure 18: Phase Current under each phase of 8/6 SRM

The output torque waveform for 8/6,400W SRM is shown in figure 20. The torque ripple reduces to 4.05 Nm

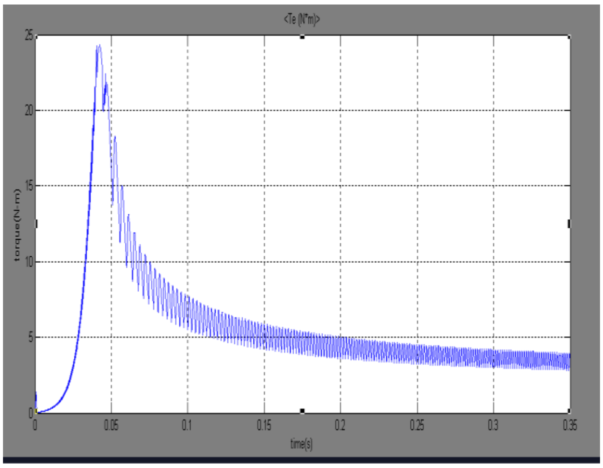

Figure 19:Torque response of of 8/6 SRM

The output speed waveform for 8/6,400W SRM is shown in figure 21. The motor attains a constant speed at 1800 rpm.

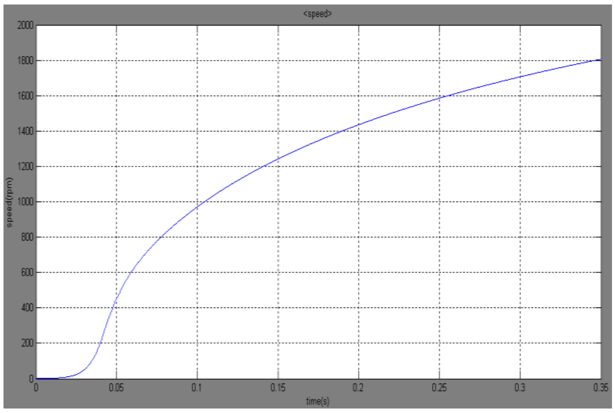

Figure 21: Speed response of the 8/6 SRM

6. CONCLUSION

Thus the static and dynamic characteristics of 8/6, 400W SRM were studied and the torque and flux linkage characteristics were obtained by using FEA software (MagNet 6.22). The developed flux linkage and torque characteristics were used to develop the torque and inductance block of MATLAB/Simulink 7.8, in building the simulation circuit for the SRM prototype model and the motor runs upto 1800 rpm at no load condition. Static magnetic characteristics as obtained from finite element analysis have been explained. The mathematical model of the SRM was obtained through MATLAB / SIMULINK simulation

7. REFERENCES

[1] Martin Lipt´ak, Val´eria Hrabovcov´a, Pavol Rafajdus, Equivalent circuit of switched reluctance generator based on dc series generator. Journal of electrical engineering, vol. 59, no. 1, 2008.

[2] Ahmed Khalil, Iqbal Husain, Syed A. Hossain Suresh Gopalakrishnan, Avoki M. Omekanda, Bruno Lequesne, and Harald Klode (2005) 'A Hybrid Sensorless SRM Drive With Eight- and Six-Switch Converter Topologies' IEEE Transactions on Industry Applications, vol. 41, no. 6, pp 1647-1655

[3] Amit Kumar Jain and Ned Mohan (2005) 'SRM Power Converter for operation with High Demagnetization Voltage' IEEE Transactions on Industry Application, vol. 41, no. 5, pp 1224-1231.

[4] Natalia S. Gameiro and Antonio J. Marques Cardoso (2012) 'A New Method for Power Converter Fault Diagnosis in SRM Drive' IEEE Transactions on Industry Applications, vol. 48, no. 2, pp 653-662.

[5] Staley A.M. and Krishnan R. (2005) 'Single Controlloble Switch Power Converter for SRM Drive Systems' Industrial Electronics Society.

[6] Miller T J E 'Electronic control of Switched Reluctance Machine' Newnes power engineering series.

[7] T.W.Ching,K.T.Chau,C.C.Chan, "A New Zero-Voltage-Transition converter for Switched Reluctance Motor Drives" IEEE Proceedings 1998. pp 1295-1301.

[8] Mehrdad Ehsani, Iqbal Husain,K.R.Ramani And James H.Galloway ,"Dual-Decay Converter for Switched Relutance Motor Drives in Low-Voltage Applications" IEEE transactions on industrial electronics, vol. 8, no. 2,pp 224-230 April 1993.

APPENDIX-I

SWITCHED RELUCTANCE MACHINE MODEL PARAMETERS

1. Power : 400 W
2. Voltage : 20 volts
3. Current : 20 Amperes
4. Stator outer diameter : 90 mm
6. Stator core length :40 mm
7. Shaft diameter : 18 mm
8. Stator poles : 8
9. Rotor poles : 6
10. No of Turns/Poles : 55
11. Cross section of the Conductor : 1.7 sq.mm
12. Stator pole arc : 22°
13. Stator pole height : 10 mm
14. Rotor pole arc : 24°
15. Rotor pole height : 15 mm