An 8/6 Two Layers Switched Reluctance Motor: Modeling, Simulation and Experimental Analysis

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ABSTRACT:
Development in power electronic derives, moreover simplicity and robustness of Switched Reluctance Motor (SRM) besides their ability to work in harsh conditions, makes them appealing to industrial applications. Structurally, SRM has ability to conform to different configurations to make it suited for purposed application. In this paper, an 8/6 two layers Switched Reluctance Motor is introduced. This rotor consists of two magnetically dependent sets which each set contains 8 stator poles and 6 rotor poles with windings wrapped around them. The torque ripple reduction is done by a novel introduced method using Rotor Shifting Method (RST). Furthermore, motor operations as SRM are modeled and simulated by 3D Finite Element Method (FEM). Finally, prototype of motor is fabricated and experimental analysis is carried out to confirm validation of modeling and simulation results.

KEYWORDS: Switched Reluctance Motor, Finite Element Method, Rotor Shifting Method.

1. INTODUCTION

Switched Reluctance Motor is robust and simple structure machine because it has no windings or permanent magnets on the rotor, so it can work at high speed applications and harsh conditions. The main advantages of SRM are as follow: high efficiency, simple topology, no starting torque required to start and robustness. Switched Reluctance Motor (SRM) is one of the alternatives for low cost and simple structure motor in variable speed drive applications such as home appliances [1-3].

A two phase motor using common pole E-core structure is introduced in [4]. In this arrangement the E-core stator has three poles with two poles at the ends having windings and the center pole has no copper windings. In [5], a new two phase SRM utilizing a governor for the control of excitation has been presented. Different geometries have been proposed but all of them consist of six stator poles and three rotor poles with different pole arcs and some with variable air gaps in [6]. A detailed analysis of a SRM in which a significant component of the acoustic noise is suppressed or neutralized by means of a flux-switching transition has been discussed in [7]. High speed SRM with magnetic levitated rotor is presented for high speed applications in [8]. The design aspects of SRMs for fan-applications are being pointed out in [9]. It shows there is a trade-off between reduced costs of machine, convertor and control which most likely results in an oversized motor. The new configuration for high starting torque switched reluctance motor is introduced in [10]. This configuration allows more space for coil windings in small size motors with a high number of stator and rotor poles. A new configuration for two phase SRM stepped shape rotor poles is presented in [11]. This motor has an ability to start and run in specified direction without any difficulties and also centrifugal switched is mounted on the motor shaft for a sudden advancement of current-pulses relative to the rotor position after reaching a preset motor speed in order to develop a higher torque at starting.

There are several methods for torque ripple reduction consists of control and improvement of shape geometries in which satisfy torque profile variation approaches. In control strategies for minimizing torque ripple with employing some new methods into drive circuit, output torque ripple is controlled. In [12], the speed ripple and vibration reduction for a Switch Mode Rectifier (SMR) fed Switched Reluctance Motor (SRM) drive via intelligent current is discussed. A single-phase SRM drive system is presented in [13], which includes the realization of a drive circuit for the reduction of torque ripple and PF improvement with a novel switching topology. The proposed drive circuit adds one switch and one diode, which can separate the output of the ac/dc rectifier from the large capacitor and supply power to the SRM alternately. A novel and simple nonlinear logical torque-sharing function (TSF) for a Switched Reluctance Motor (SRM) drive is proposed in [14]. This novel scheme using nonlinear TSF manipulates currents in two adjacent phases during commutation, so that efficiency and torque ripple in an SRM drive can be considerably improved. In [15], a novel control method for the SR motor is derived from analysis of the nonuniform torque characteristics of the motor. The control method applies the philosophy of direct torque control (DTC). As other approach which is more convenient in implementing of drive circuit, but makes the structure of the motor more complicated is strategies in which the shape of motor is changed to gain better torque profile. Reference [16] describes a proposal for a new stator pole face having a nonuniform air-gap and a pole shoe attached to the lateral face of the rotor pole. In [17], a novel method on the basis of genetic algorithm (GA) is proposed to reduce the torque dip, thereby reducing the associated torque ripple, with simultaneous reduction in size with increase in torque output using GA, by maximizing the flux linkage, torque per unit rotor volume and inductance ratio.

2. A NOVEL 8/6 TWO LAYERS MOTOR CONSTRUCTION

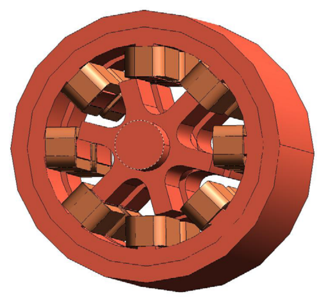
The new motor and structure consists of two magnetically dependent stator and rotor layers, where each stator layer includes eight salient poles having 15º arc length with coils wrapped around them. while, the rotor comprises of six salient poles with different arc lengths (i.e.16 º). This motor includes two stators and rotors layers placed on both sides of the field coil assembly which has the rotor shaft as its main core and two front-end caps plus the motor housing. The two layers are attached exactly symmetrical with respect to a plane vertical to the middle of the motor shaft. The motor construction is shown in Fig 1.

The complete structure of motor with housing is shown in Fig.1 (a). Each rotor in two layers is aligned in each layer and this alignment is shown in Fig.1 (b) and the complete structure of motor without housing is shown in Fig.1 (c).

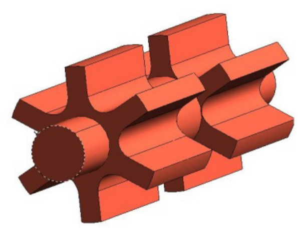
The new motor specifications considered in this study are in Table1:

Table 1. The motor specifications

Stator core outer diameter	72mm
Stator core inner diameter	62mm
Stator pole arc	15°
Air gap	0.25mm
Rotor core outer diameter	41.5mm
Rotor shaft diameter	15mm
Rotor pole arc	16°
Each module thickness	35mm
Number of turns per pole	150



(a)



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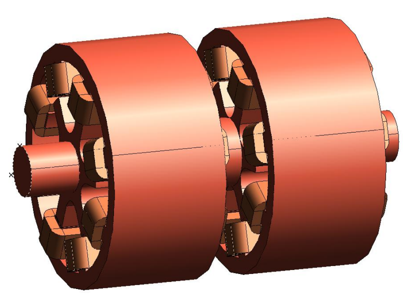


(c)

Fig. 1. The motor construction:
(a) The complete structure of machine with housing
(b) Alignment of rotors in two layers
(c) Structure of motor without housing

3. MATHEMATICAL MODEL FOR MOTOR STATE

In this section, the proposed 8/6 two-layer SRM is going to be considered mathematically in order to extract its theoretical characteristics. To set up a linear magnetic model, inductance variation should be defined at first. The waveform of inductance in this SRM can be represented by Fourier series as follow:

$$L(\theta) = a_0 - \sum_{k=1}^{N} a_k \cos(kp_r\theta) \quad (1)$$

where, θ is the rotor angle and p_r is the rotor poles.

The real value of inductance in general can be obtained by equation (2):

$$L = \frac{N^2}{R} = \frac{\mu.A.N^2}{l} \quad (2)$$

where, R is the reluctance of flux linkage pass, A is the mean area of the cross section of flux path, l is the length of this path in each different part, N is number of turns per pole and μ is magnetic permeability. For each angle, this value will be changed because the flux pass is changed and it can be simply achieved by term of actual reluctance simply.

The reluctance of core consists of flux path should be calculated with respect to its nonlinear behavior as given in equation (3). Due to have better consideration about each prominent value depend on this motor, the inductance formula is assumed to be in general mode as given in Equation (3) and then to get better understanding about each parameter, the simplified model of inductance is taken to show how everything is defined.

$$R = \frac{l}{\mu.A} = \frac{l}{\left(\frac{B}{H}\right).A} = \frac{H.l}{B.A} = \frac{H.l}{\varphi} \quad (3)$$

where, B is flux density, H is magnetic field and φ is flux linkage. With $\lambda(\theta,i) = L(\theta).i$, the flux linkage ($\lambda$) can be obtained by equation (4):

$$\lambda(\theta,i) = \left[a_0 - \sum_{k=1}^{N} a_k \cos(kp_r\theta)\right].i \quad (4)$$

4. NUMERICAL ANALYSIS AND SIMULATION OF PROTOTYPE MOTOR WITH 3-D FEM

The configuration of this novel 8/6 switched reluctance motor imposed the complicated analysis due to complex geometry and material saturation. The performance of the generator has close relation with reluctance variation of the generator. Having knowledge about the flux distribution inside the motor for different excitation currents and rotor positions is inevitable for the estimation of motor performance. This motor even can be highly saturated under some operating conditions. In order to have an accurate evaluation of motor performance a reliable model is required.

The Partial Differential Equation (PDE) for the magnetic vector potential is given by:

$$-\frac{\partial}{\partial x}\left(\gamma\frac{\partial A}{\partial x}\right) - \frac{\partial}{\partial y}\left(\gamma\frac{\partial A}{\partial y}\right) - \frac{\partial}{\partial z}\left(\gamma\frac{\partial A}{\partial z}\right) = J \quad (5)$$

where, A is the magnetic vector potential, j is current density and γ is magnetic constant.

This paper is used Ritz method to find magnetic vector potential. The Ritz method is a direct method to find an approximate solution for boundary value problems. This method is used to achieve this goal. In mathematics, it is exactly the Finite Element Method (FEM) used to compute the eigenvectors and eigenvalues of a Hamiltonian system.

In the Ritz method the solution to (5) obtained by minimizing the following functional:

$$F(A) = \frac{1}{2}\iiint_{\Omega}[\gamma(\frac{\partial A}{\partial x})^2 + \gamma(\frac{\partial A}{\partial y})^2 + \gamma(\frac{\partial A}{\partial z})^2]d\Omega - \iiint_{\Omega} JA d\Omega \quad (6)$$

where, Ω is the problem integration region.

In this method, electric vector potential shown as T and Ω is defined by;

$$J = \nabla \times T \quad (7)$$

From Maxwell's equation we have;

$$\nabla \times H = J = \nabla \times T \quad (8)$$

Then;

$$\nabla \times (H - T) = 0 \quad (9)$$

where, the vector (H-T) can be expressed as the gradient of a scalar. This expression is defined in (9).

$$H = T - \nabla\Omega \quad (10)$$

This gives a magnetic scalar potential. Since:

$$\nabla \times E = -\frac{\partial B}{\partial t} \quad (11)$$

where, B is the flux density. Then;

$$\nabla \times E = \nabla \times \left[\left(\frac{1}{\sigma}\right)\nabla \times T\right] = -\frac{\partial B}{\partial t} = -\mu_0\mu_r\left(\frac{\partial}{\partial t}\right)(T - \nabla\Omega) = -\mu_0\mu_r\left(\frac{\partial T}{\partial t}\right) - \nabla\left(\frac{\partial \Omega}{\partial t}\right) \quad (12)$$

That is finally reduced to the following two scalar equations as shown as follow;

$$\nabla^2 T - \mu\sigma\left(\frac{\partial T}{\partial t}\right) = -\mu\sigma\nabla\left(\frac{\partial \Omega}{\partial t}\right) \quad (13)$$

$$\nabla^2 \Omega = 0 \quad (14)$$

T and Ω are given from (13), (14) equations, these values are used for calculation of A and E. Three dimensional magnetic field vectors can be obtained by A and E.

The field analysis has been performed using Magnet CAD package [16], is based on the variation energy minimization technique to solve for the magnetic vector potential. Magnet CAD finds the magneto static field in and around specified current distributions in the presence of magnetic materials that may be linear or non-linear, and isotropic or anisotropic. The schemes of magnetic flux density and its directions for three important rotor positions respect to stator, i.e. the beginning of alignment, the half aligned and fully aligned cases with 1A current flows through the one phase in each set and each coil has 150 turns wrapped winding are considered.

3D simulated magnetic flux density for the beginning of alignment, the half aligned and fully aligned states are shown in Fig.2 (a),(b) and (c).

In order to have motors characteristics, inductance variations and torque curve per rotor position is required. The inductance can be calculated as the ration of each phase flux linkage to the phase current (λ / I). Variations of inductance per rotor position for one phase are presented in Fig.3.

There is not overlap between rotor and stator poles then inductance profile has not death zone in aligned position. Hence positive torque is obtained from -15° to 0° which -15° is for the beginning of alignment mode, 0° correspond to the fully aligned mode and +15° for the ending of alignment. In Fig.4 static torque curve with respect to the rotor position from -15 to +15 degrees is presented for a phase current 1A from the beginning of alignment to the ending of alignment position.

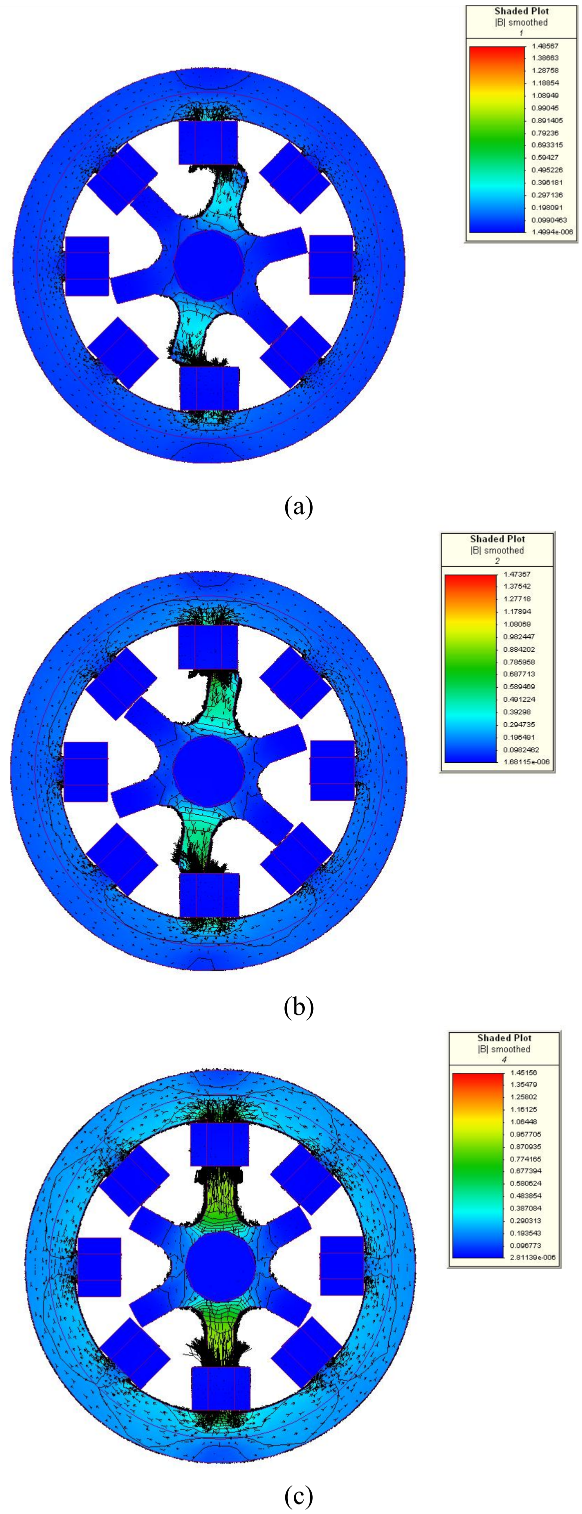


Fig. 2. 3D simulated magnetic flux density:
(a) The beginning of alignment
(b) Half aligned mode
(c) Fully aligned mode

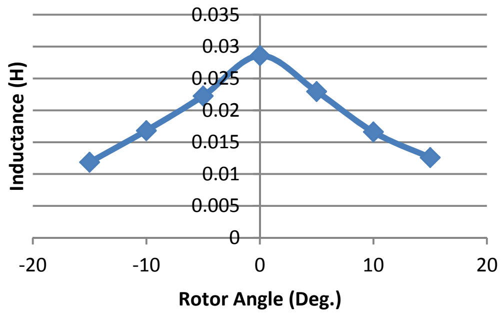


Fig.3. variations of inductance per rotor position for one phase

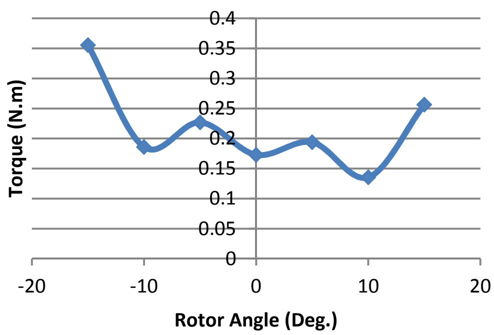


Fig.4. Static torque versus rotor positions

5. ROTOR SHIFTING TECHNIQUE (RST) FOR 8/6 TWO LAYER SRM FOR REDUCTION TORQUE RIPPLE

5.1. Rotor Shifting Technique (RST)

RST is based on the shifting the angle of rotor of one layer respect to other layer in switched reluctance motor to obtain smooth and monotonous torque curve. To study this technique, analytical equation of SRM, which p_r is the number of rotor poles, is considered. The waveform of inductance of SRM employing RST can be presented by Fourier series as following equation (15):

$$L_m(\theta) = a_0 - \sum_{k=1}^{N} a_k \cos(kp_r(\theta + \theta_{shift})) \qquad (15)$$

where, θ is the rotor angle. With $\lambda(\theta, i) = L(\theta).i$, which i is the current of SRM phase, the flux linkage can be obtained by equation (16):

$$\lambda_m(\theta, i) = \left[a_0 - \sum_{k=1}^{N} a_k \cos\left(kp_r(\theta + \theta_{shift})\right)\right] \qquad (16)$$

To obtain the relation of the produced torque with respect to the rotor angle, first the co-energy equation should be determined. Equation (17) shows the co-energy relation.

$$W'(\theta, i) = \int_0^i \lambda(\theta, i)di \quad , when\ \theta = constant$$
$$W'_m(\theta, i) = \frac{1}{2} i^2 \left[a_0 - \sum_{k=1}^{N} a_k \cos\left(kp_r(\theta + \theta_{shift})\right)\right] \qquad (17)$$

Then the produced torque of the motor can be evaluated by equation (18):

$$T(\theta, i) = \frac{dW'(\theta, i)}{d\theta} \xrightarrow{i=constant}$$
$$T_m = \frac{1}{2} i^2 \frac{dL}{d\theta} = \frac{1}{2} i^2 \left(kp_r \sum_{k=1}^{N} a_k \sin\left(kp_r(\theta + \theta_{shift})\right)\right) \qquad (18)$$

The total torque which is produced with M layers motor is obtained by equation (19).

$$T_{total} = \sum_{m=1}^{M} T_m \qquad (19)$$

5.2. Employing Of RST in 8/6 Two-Layer SRM

This technique has special constraints according to the motor construction. These constraints should be considered for this motor to gain desirable outcomes. The constraints of this motor are brought in (20).

$$-10 < \theta_{shift} < +10 \qquad (20)$$

To achieve preferred response the trade-off between torque ripple reduction and maximum torque value should be done. To reach maximum monotonous profile, $\theta_{shift}$is chosen$+10°$. Fig.5 shows comparison between rotors with RST and without RST in 8/6 two layer SRM.

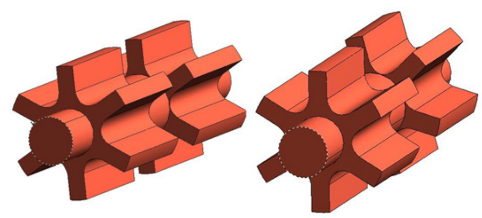


Fig.5. comparison between rotors with RST and without RST in 8/6 two layer SRM

The construction of 8/6 two-layer SRM with +10 degrees shifting in rotor can be seen in Fig.6.

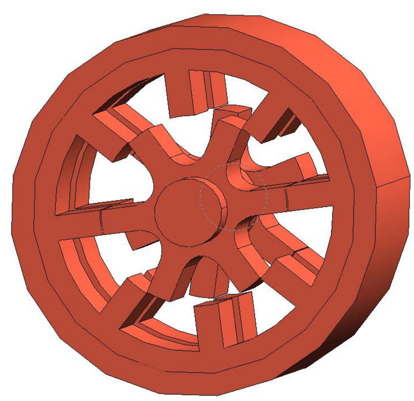
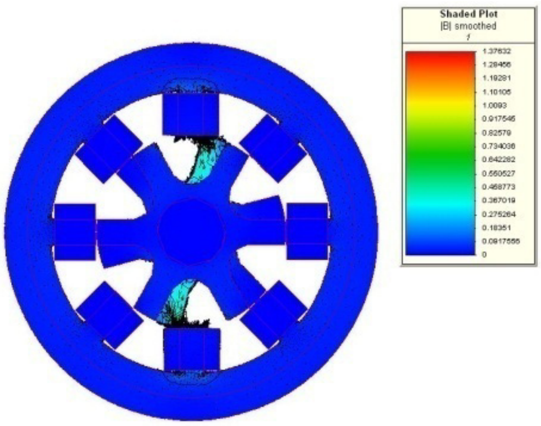


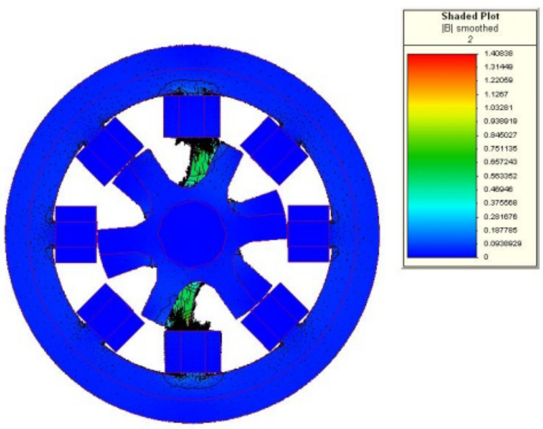
Fig. 6. Construction of 8/6 two-layer of SRM with +10 degrees shifting in rotor

5.3. Simulation Analysis with RST

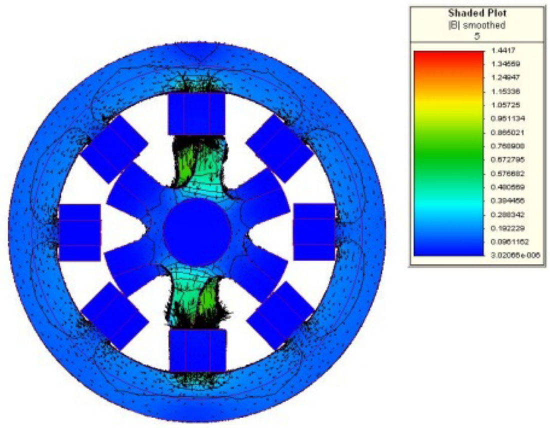
To extract motor characteristics, simulation analysis is carried out using 3D Finite Element Method (FEM). Fig.7 shows the flux linkage through the motor with RST in different position of the rotor. The rotation in each stage is five degree and simulation analysis is performed from -15 to 30 rotor degrees.



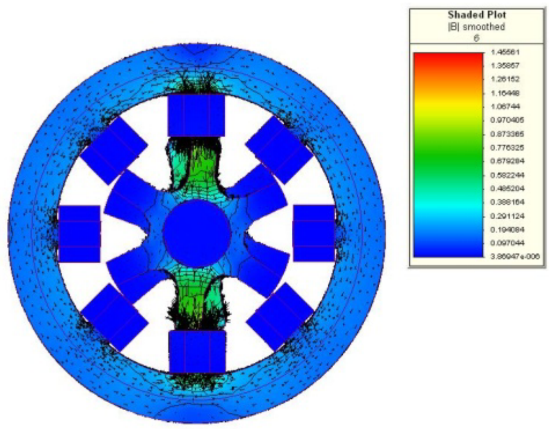
Stage 1



Stage 2



Stage 3



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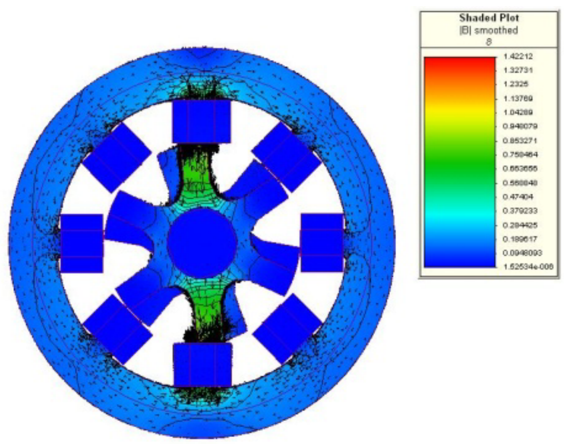

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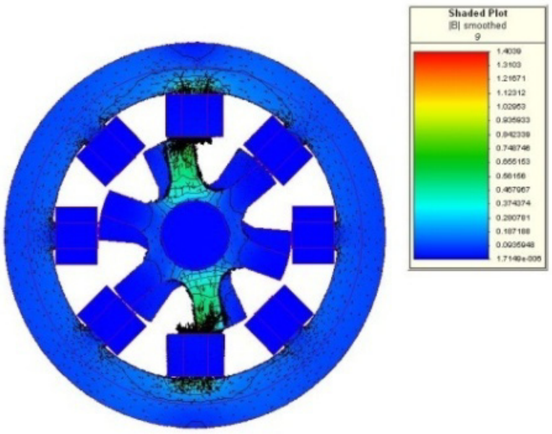
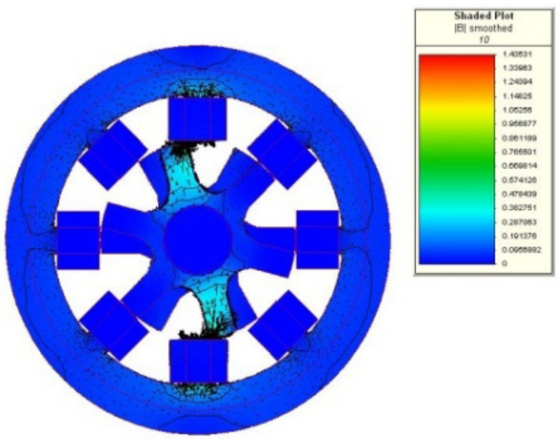


Stage 6

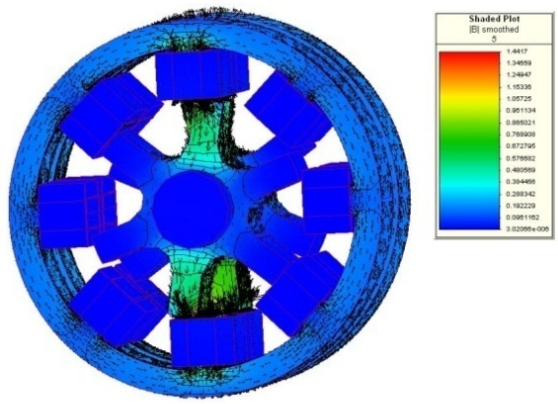


Stage 7

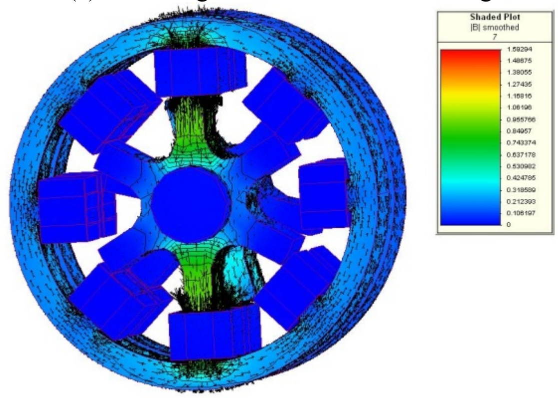
Fig. 7. Flux linkages through the motor in different the rotor position

3D view of flux linkage with flux orientations is shown in Fig.8, (a), (b) critical positions of rotor without housing and (c) the fully aligned mode with housing.

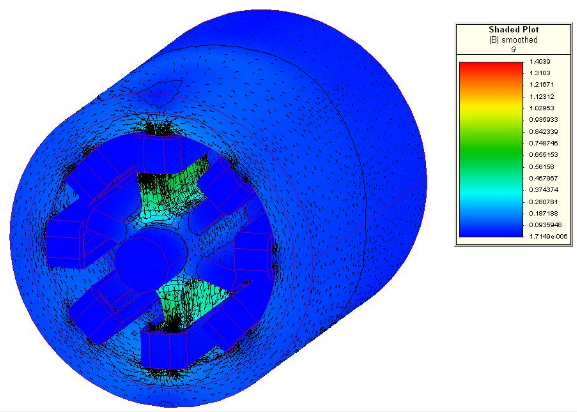
The main parameters of the motor which should be evaluated is flux linkage variation and torque profile. To compare the effect of RST on 8/6 two layers SRM with same motor without rotor shifting, two-curve for each parameter are presented. One belongs for motor with RST and other without RST. The flux linkage profile of this motor with RST and without RST is shown in Fig.9.



(a) Half aligned mode without housing

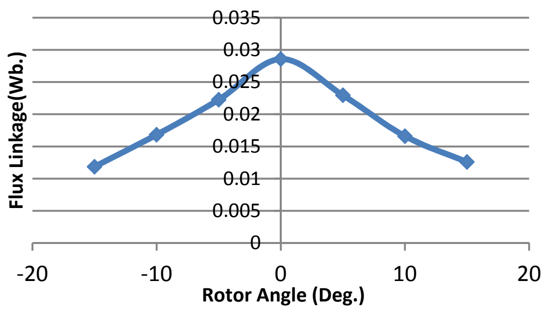


(b) Fully aligned mode without housing

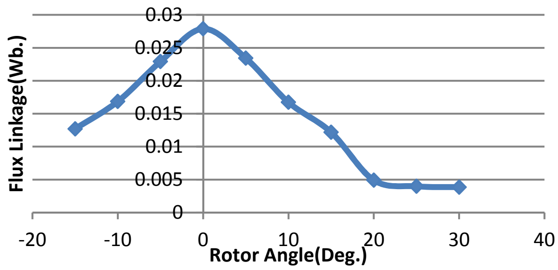


(c) Fully aligned mode with housing

Fig. 8. 3D view of flux linkage with flux orientations



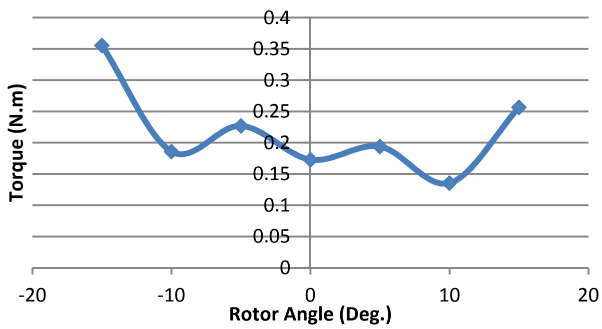
(a) Without RST



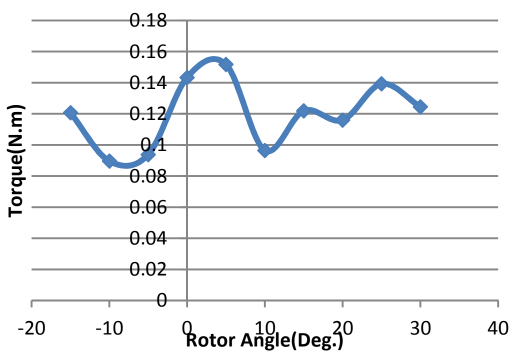
(b) With RST

Fig. 9. Flux linkage profile of 8/6 two-layer SRM without (a) and with (b) RST

The Torque curve variation also is illustrated in Fig.10 as well as the flux linkage.



(a) Without RST



(b) With RST

Fig.10. Torque profile of 8/6 two-layer SRM without (a) and with (b) RST

Consider of Fig.10a and Fig.10b show not only the torque specification but also ripple torque with RST are more than without using RST.

6. EXPERIMENTAL RESULT FOR NOVEL 8/6 TWO LAYERS SRM IN MOTOR ESTATE

The motor has been fabricated and tested for performance and functionality in the laboratory. The novel two layers 8/6 switched reluctance motor fabricated in the laboratory is shown in Fig.11.

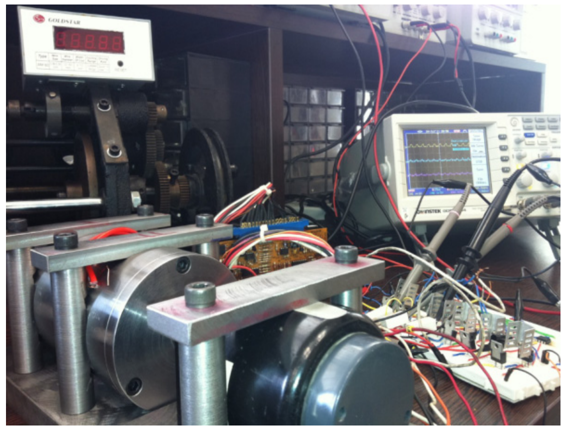


Fig.11. Fabricated two layers 8/6 SRM

To achieve static torque of motor, the motor is blocked at different angles. The average static torque for a rated current of 1A has been measured to be about 0.55 N.m over the stator pole from zero to 15 degrees arc.

When, the start of stator complete overlap, the torque profile suddenly went to zero. The dynamic torques versus speed for the novel motor has been measured by loading the motors and using torque meter. Fig.12 illustrates the torque speed characteristics of the motor. The polynomial curve fitting has been used for the data points. As shown in Fig.12 the torque speed characteristic of the motor is similar to a series dc motor.

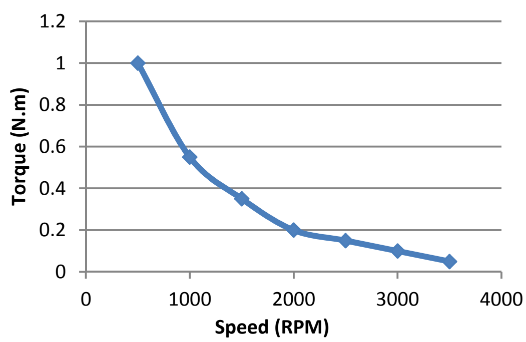


Fig.12. Torque versus speed

The torque versus current under different loads is depicted in Fig.13. As shown in Fig.13, the torque is proportional to the square of the motor current.

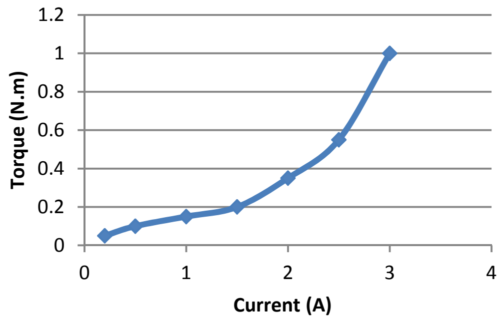


Fig.13. Torque versus current

As show Fig.13 with increase the input current, the torque exponentially grows up.

To drive Switched Reluctance Motor need a control board for starting and rotating at constant speed. The drive circuit motor includes three asymmetric half bridges to drive motor with PWM signals. Each asymmetric half bridge is used to drive one phase. In Fig.14 is shown a complete drive with all connections.

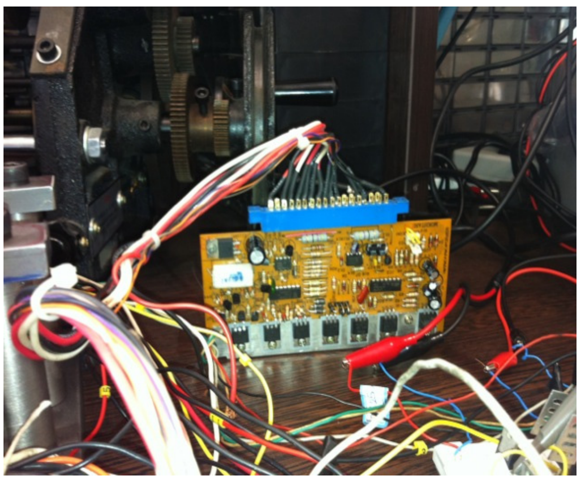


Fig. 14. The control board

To detect rotor position and tune the switching phase time, a photo interrupters is used on the back of the motor. Fig.15 is illustrated a photo interrupter sensor position on the set up. There are three sensors for three phases of the motor.

The output signal comes from one of the photo interrupters mounted on the back of the motor is shown in Fig.16.

In Fig.17 shows the three phase sequences to excitation of motor phases.

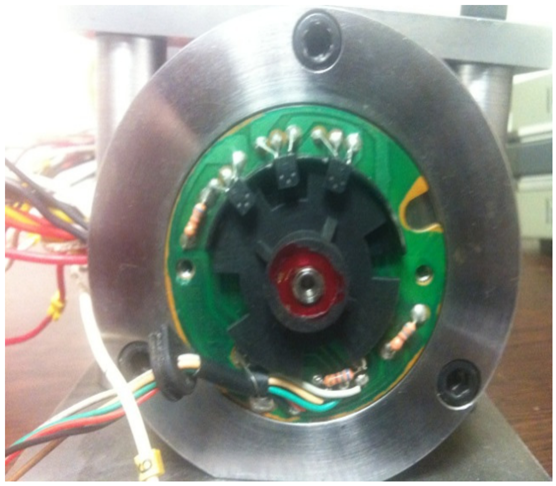


Fig.15. photo interrupter sensor position

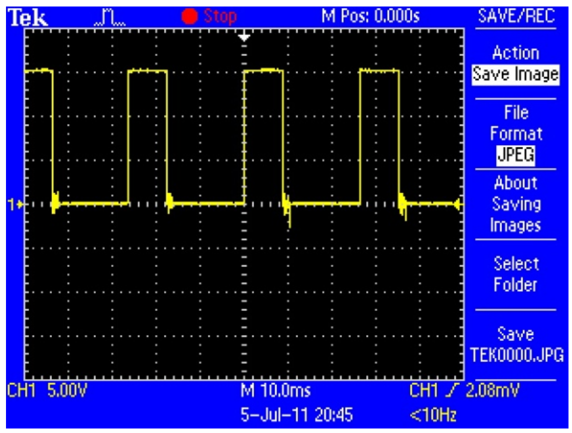


Fig. 16. the output signal from the photo interrupter

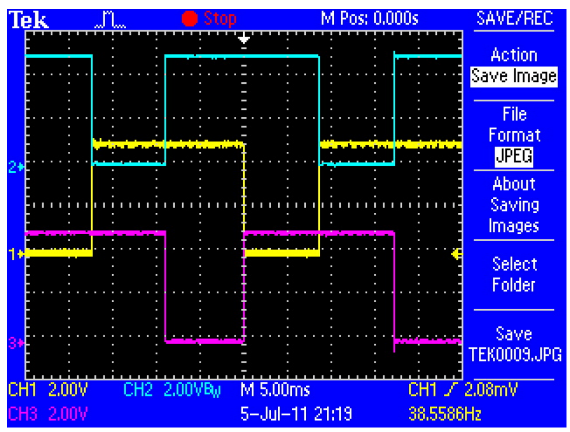


Fig.17. The three phase sequences

Fig.18 shows one phase current of the novel motor at 2000rpm as show below the current increase when the phase switch is turn on.

During excitation the reluctance of phase has been changed.

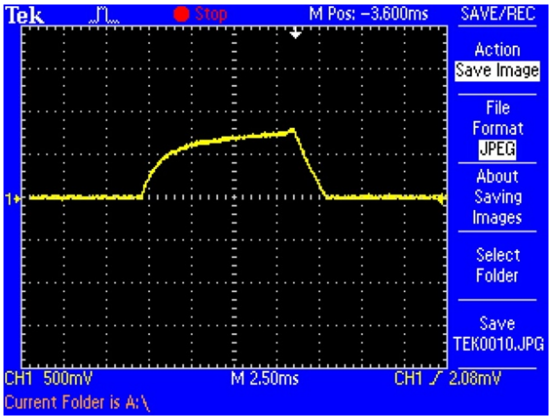


Fig. 18. One phase current of the developed motor at 2000rpm

7. CONCLUSIONS

This paper studied the two layers 8/6 switched reluctance motor. This motor consists of two dependent 8 by 6 layers. The mathematical modeling of the motor has been investigated. The novel Rotor Shifting Technique (RST) was proposed to reduce torque ripple of the motor. This technique was well suited to this motor because the motor structure. To find out the motor characteristics, numerical and simulation analysis were performed and torque profile with and without RST as well as inductance was extracted. Finally, the prototype of motor has been fabricated and experimental analysis was carried out to fulfill the results. This motor can reach desire profile, since it will be promising for servo applications and many other industries.

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