International Journal of Power Electronics and Drive Systems (IJPEDS)
Vol. 15, No. 1, March 2024, pp. 136~146
ISSN: 2088-8694, DOI: 10.11591/ijpeds.v15.i1.pp136-146

A simple approach for the computation of magnetic characteristics of 4-phase switched reluctance motor

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Article Info

Article history:

Received May 26, 2023
Revised Sep 2, 2023
Accepted Sep 16, 2023

Keywords:

Flux linkage characteristics
Inductance profile
Magnetic characteristics
Switched reluctance motor
Torque characteristics

ABSTRACT

Switched reluctance motor (SRM) is non-linear in nature due to non-uniform air gap between stator and rotor that is produced from doubly salient poles. To control the operation of non-linear motor, a precise modelling of magnetic characteristic is essential. Traditionally magnetic equivalent circuit, finite element method (FEM) and experimental approaches have been used to derive magnetic characteristics of SRM. These methods involve complex computational steps and numerous assumptions for its calculations. To avoid this complexity, a simple approach is suggested in this paper to compute magnetic characteristics of 4-phase SRM. In this approach, SRM phase inductance is measured directly to identify the location of rotor with respect to stator from unaligned to aligned position. Then, single phase of SRM is excited through asymmetric converter and voltage and currents of corresponding phase is recorded with rotor being blocked using indexing head. Later recorded values are used to compute the magnetic characteristics from unaligned to aligned position. The proposed method is carried out using field programmable gate array (FPGA) controlled 8/6, 4-phase SRM. Further, accuracy of obtained magnetic characteristic is verified using FEM. In addition, fidelity of the magnetic characteristic is also validated by developing a dynamic model of SRM in MATLAB/Simulink

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1. INTRODUCTION

Adoption of switched reluctance motor (SRM) is being increased in recent times in industrial and automotive applications compared to the conventional motors due to advantages such as rugged and robust in construction, wide speed operation, high starting torque, economical, fault tolerant capacity and high torque to weight ratio [1], [2]. However, it is not commercially popular yet due to its non-linear operation resulting in torque ripple. Torque ripple reduces the average torque and hence reduces motor efficiency. To mitigate the torque ripple and control operation of SRM, modifications in the SRM structure and control strategies for SRM have been presented in the literature [3]. Nevertheless, hardware modifications for SRM results in enlarged air gap between stator and rotor that causes minimized average torque. Therefore, control strategies are preferred over hardware modification. SRMs can be designed with 3 phase, 4 phase and even 6 phase supply to use in various applications. For the SRM to be used in automotive applications, 4 phase 8/6 configuration is preferred over other configurations as it has high torque density, low torque ripple and high torque per ampere ratio comparatively [4].

There are various methods reported in the literatures to obtain magnetic characteristics such as magnetic equivalent circuits (MEC), finite element techniques and experimental methods [5], [6]. MEC comprises of sophisticated computational steps and involves approximated assumptions for its calculation [7]–[9]. These assumptions further may lead to deviate from accurate results. Finite element method (FEM) technique requires complete knowledge of motor dimension and its material property to obtain magnetic characteristics [10]–[15]. However, it is difficult to obtain the data that represents property of material as it is not easily available to public [16]. On the other hand, information about machine and material properties are not required to obtain magnetic characteristics through experimental method. It comprises of direct and indirect method of finding magnetic characteristics [17]–[19]. Magnetic sensors are employed in the direct measurement method to measure the magnetic flux linkages. This method is rarely used as it is expensive and is not accurate due to leakage flux [20]. Further, magnetic sensors need to be installed during motor assembly and hence it complicates the motor design. Conversely in indirect method, flux linkages can be estimated indirectly by measuring phase voltage and current at a particular rotor position [16], [17]. The computation of magnetic characteristics of SRM with sinusoidal excitation current of several amplitudes and frequencies ranging from 0.5 to 1000 Hz is reported in [21]. This approach makes the rotor shaft to undergo high stress which results in degradation of rotor laminations. Therefore, this technique is suitable only for SRM having monolithic rotor structure. Magnetic flux is estimated using an AC source as reported in [22]. The accuracy of the measured values is crucially affected by source harmonics and high iron losses. The flux characteristic curves are determined based on discharging of capacitor on motor windings. During discharging process, phase voltage and currents are measured and are utilized in calculation of flux linkage [23]. A novel technique for flux estimation is developed that does not require any rotor locking method and position sensor [24], [25]. However, fidelity of flux estimation is affected by rotor misalignment. Further, this approach requires current sensor and semiconductor devices. This method does not suitable for machines that are highly non-linear. In view of this, the paper presents a simple approach based on rotor-locking method for estimation of magnetic characteristics using field programmable gate array (FPGA) processor.

In this approach, any one phases of SRM is excited and excited phase's voltage and current values are recorded. This procedure is repeated from unaligned to aligned position at an interval of 5° rotor position with rotor being blocked by indexing head. In every interval of rotor position, the voltage and current readings are recorded using FPGA processor. FPGA is a dominating processor over its competitors such as microprocessors or digital signal processors (DSPs) as it offers numerous benefits such as parallel operation, fast response time, fully customized processor, flexible pin assignment [26], [27]. Later, the recorded values are used to compute flux characterization. The test bench comprises of 4-phase, 8/6 SRM driven through insulated gate bipolar transistor (IGBT) based asymmetric converter powered by 50 V DC supply. The gate signals for IGBT switches in the converter are generated by FPGA processor. In the conventional method, phase inductance was measured by flux linkage characteristic values [28], [29]. As a reason, the accuracy of phase inductance proportional to the fidelity of measured voltage and current readings. A small error in voltage and current reading leads to the inaccurate assessment of inductance that further leads to improper phase excitation. In view of this, a simple procedure is adopted for measurement of phase inductance using inductance capacitance resistance (LCR) meter. This approach helps in locating the accurate rotor position from unaligned to aligned position.

The structure of the paper is as follows: section 2 explains estimation of the magnetic characteristics that comprises of inductance profile measurement, determination of flux linkage and phase torque characteristics. Further, section 3 demonstrates the electromagnetic characteristics using FEM and the dynamic modeling of SRM using MATLAB/Simulink. Finally, the conclusions are depicted in section 4.

2. ESTIMATION OF MAGNETIC CHARACTERISTICS

2.1. Measurement of inductance profile

To estimate the magnetic characteristic, there is a need to derive the inductance profile for all phases of SRM. An LCR meter is used to find the inductance profile of 4-phase 8/6 SRM. The inductance value is measured from unaligned to aligned position of rotor with respect to stator. The measured values of inductance for R-phase are shown in Table 1 and Figure 1 represents the variation of inductance with respect to rotor position. It is observed that, the minimum value of inductance (3.84 mH) obtained at unaligned rotor position (0° rotor position) and maximum value of inductance (13.67 mH) obtained at aligned rotor position (30° rotor position). Therefore, excitation can be done from 0° to 30° rotor position for R-phase. For all other phases, excitation is provided by referring Figure 2. that shows inductance profile for all phases of SRM.

Table 1. Variation of inductance for R – phase

Sl No.	Rotor Position (degrees)	Phase Inductance (mH)
1	0	3.84
2	5	4.09
3	10	6.4
4	15	9.25
5	20	11.14
6	25	12.96
7	30	13.67
8	35	12.62
9	40	10.82
10	45	8.32
11	50	5.73
12	55	4.04
13	60	3.84

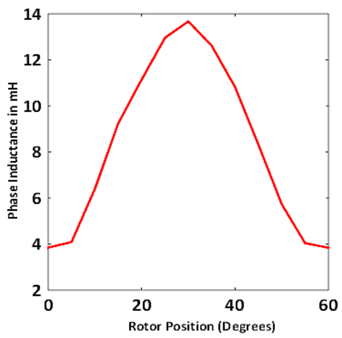


Figure 1. Inductance profile for R-phase

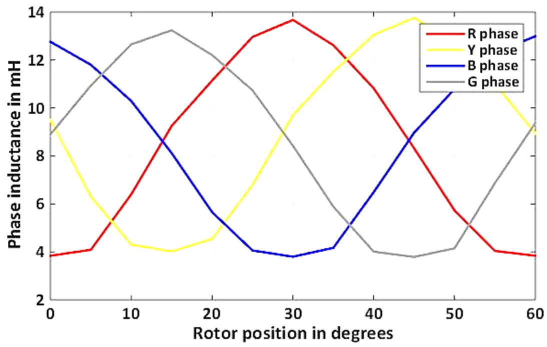


Figure 2. Inductance profile for all phases of SRM

2.2. Estimation of flux linkage characteristics

A locked rotor test is conducted to estimate the flux linkage characteristics of 4 phase 8/6 SRM. In this test, rotor of SRM is locked using indexing head. A DC voltage of 50 V is supplied to one phase of SRM through single leg of asymmetric converter that consists of IGBT switches. FPGA processor is used to generate gate signals for switches. When SRM phase excited, instantaneous voltages and currents in motor phase winding are measured with voltage and current sensors and values are recorded in FPGA processor. This experimental set up is as shown in Figure 3.

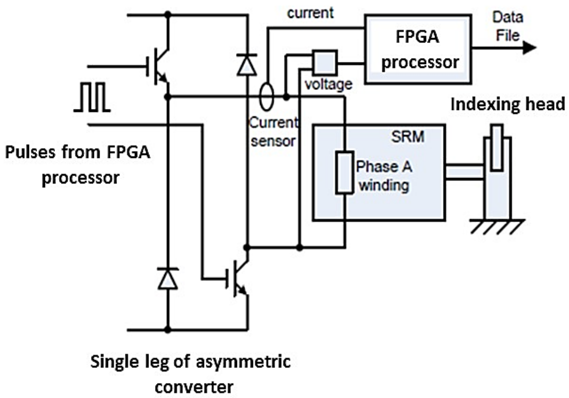


Figure 3. Experimental set up for locked rotor test

This experiment is performed from unaligned to aligned position at an interval of 5° rotor position. The test bench set up in laboratory for carrying out this experiment is as presented in Figure 4. Voltage and current waveforms captured at unaligned position (0° rotor position) is as shown in Figures 5(a) and 5(b). Similarly, Figures 6(a) and 6(b) shows the voltage and currents obtained at aligned position (30° rotor position).

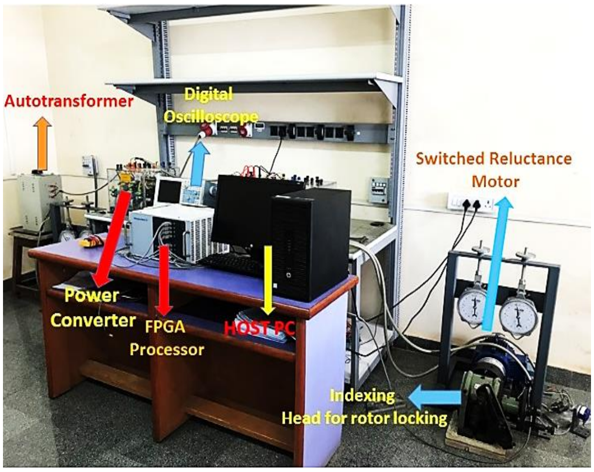
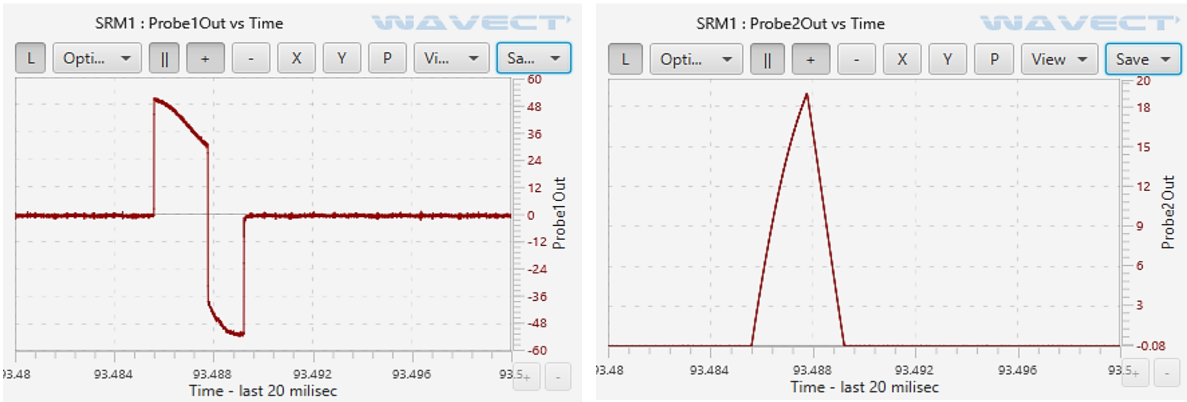
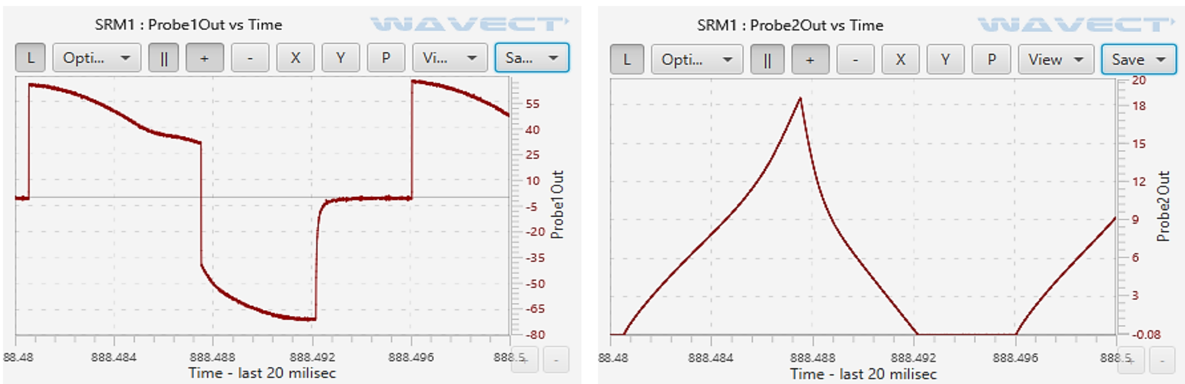


Figure 4. Test bench set up in the laboratory for carrying out proposed experiment



(a) (b)

Figure 5. Waveforms captured at unaligned rotor position (0° rotor position):
(a) voltage waveform and (b) current waveform



(a) (b)

Figure 6. Waveforms captured at aligned rotor position (30° rotor position):
(a) voltage waveform and (b) current waveform

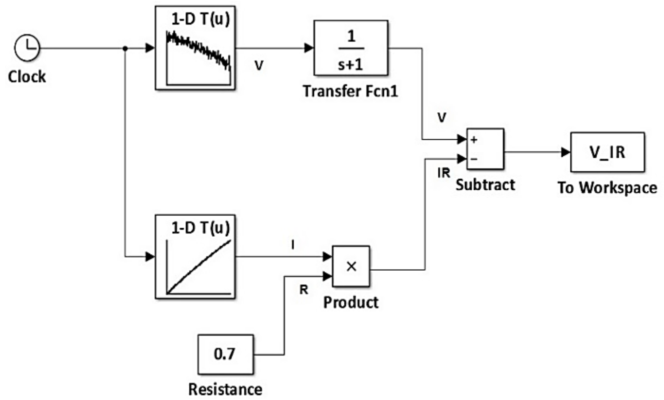
From the Figures 5 and 6, a non-linear change in voltage and current values are observed as rotor moves from unaligned to aligned position. This results in a deep magnetic saturation of motor operation towards aligned position and therefore, SRM is regarded as a non linear motor. The captured voltage and current values of SRM at different rotor position from unaligned to aligned rotor position are used to compute flux characteristics of SRM using in (1) [14].

$$\lambda(i, \theta) = \int_0^t (V - iR)dt + \lambda(0) \quad (1)$$

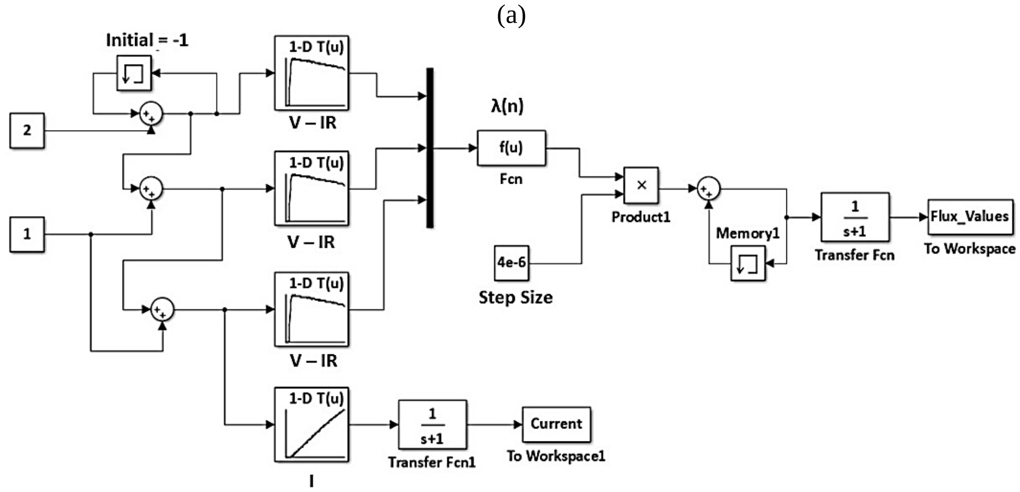
Where, $\lambda(i, \theta)$ is phase flux linkages, 'V' is phase voltage, 'i' is phase current, 'R' is phase resistance and $\lambda(0)$ is initial flux linkage. Since SRM does not have permanent magnets, $\lambda(0)$ is zero. Phase resistance 'R' is measured using LCR meter and is obtained as 0.7 Ω. The numerical integration shown in (1) is simplified by using Simpson's 1/3rd rule whose equation is shown in equation (2) [14]. This equation is solved in MATLAB/Simulink environment by building the model as presented in Figures 7(a) and 7(b).

$$\lambda(n) = \lambda(n-2) + \frac{T_s}{3} \cdot \{[V(n) - Ri(n)] + 4 \cdot [V(n-1) - Ri(n-1)] + [V(n-2) - Ri(n-2)]\} \quad (2)$$

Where, Ts is the sampling period and n is sampling index.



(a)



(b)

Figure 7. Modeling of flux linkages in MATLAB/Simulink: (a) calculation of differential voltage V – iR and (b) computation of flux linkage values using Simpson's 1/3rd rule

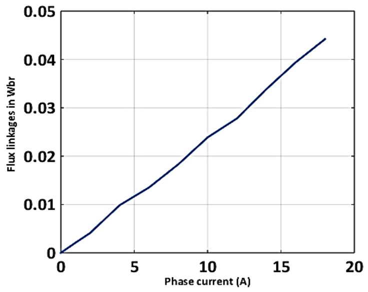
3. RESULTS OF MAGNETIC CHARACTERISTICS

The experimental methodology mentioned in the above section is utilized to derive the magnetic characteristics such as phase flux and torque characteristics of 8/6 SRM. Such characteristics are computed from unaligned to aligned rotor position at an interval of 5° rotor position. These helps in accurate modeling of machine. The results of computed magnetic characteristics are illustrated in below sections.

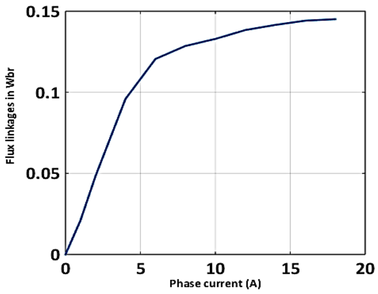
3.1. Calculation of phase flux characteristics

The voltage and current values captured at unaligned and aligned positions as shown in Figure 5 and Figure 6 are employed to compute flux values using in (1) and (2). These values are plotted against phase currents as presented in Figures 8(a) and 8(b). respectively. The complete flux characteristic of SRM computed from unaligned to aligned position with an increment of 5° rotor position is as shown in Figure 9. It is inferred from Figure 9. that, the saturation level of SRM depends on the rotor position. At the unaligned position of rotor, reluctance for magnetic flux is more and hence it results in linear characteristic of flux linkage with phase currents.

On the other hand, reluctance for magnetic flux is minimum at the aligned position of rotor poles and hence magnetic circuit saturates significantly. Therefore, as the rotor poles moves from unaligned to aligned position, the motor flux characteristic subjected to deep saturation and results in non-linear operation of machine.



(a)



(b)

Figure 8. Computed flux linkage values plotted against phase current at (a) unaligned rotor position (0°) and (b) aligned rotor position (30°)

3.2. Calculation of phase torque characteristics

Phase torque of the SRM is computed by obtaining co-energy of the motor. Co-energy is the area under flux linkage curve from an origin to a particular point as shown by marked area in Figure 10 [10]. In Figure 10 W_f is the energy stored in the magnetic field and Wc is co-energy of the motor. Co-energy is calculated by integrating the area under flux linkage using in (3) [16].

$$W_c = \int_0^i \lambda \cdot di \tag{3}$$

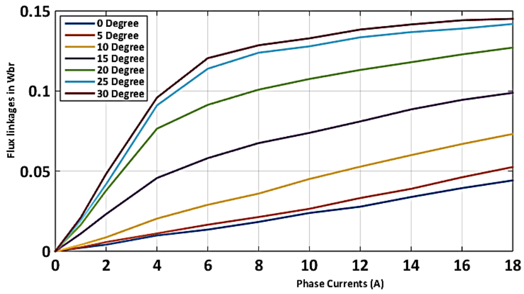


Figure 9. Computed flux linkage characteristic from unaligned (0°) to aligned position (30°)

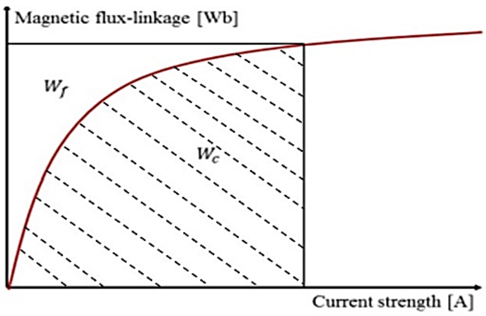


Figure 10. Co-energy of SRM

The phase torque is obtained at a constant current using equation (4) and is modeled using Matlab/Simulink as shown in Figure 11 [17]. The computed phase torque of SRM at constant current from 0° to 60° rotor position is as shown in Figure 12. Torque curves are computed for different current levels from 1A to 18A from 0° to 60° rotor position. It is observed from the torque curve that switched reluctance machine operates as motor from 0° to 30° and operates as generator from 30° to 60° rotor position

$$T_{ph} = \frac{\partial W_c}{\partial \theta} \tag{4}$$

3.3. Comparison between conventional methods and proposed method

Magnetic characteristics can be estimated conventionally by magnetic equivalent circuit method, finite element method and experimental approach. The comparison between conventional methods and proposed method is tabulated in detail in Table 2. This makes the proposed methodology very simple to derive magnetic characteristics of 8/6 SRM compare to other methods exist in the literature.

Table 2. Comparison between conventional and proposed method of deriving magnetic characteristics

Sl. No.	Method of obtaining Magnetic Characteristics	Comparison of conventional methods with the proposed methodology
1	Magnetic Equivalent Circuit Method	This method involves complex mathematical modelling and requires considerable computation time for solving mathematical modelling. It involves numerous assumptions in modelling which may deviate from actual results. As modelling involves more assumptions, its accuracy is low compared to other methodologies.
2	Finite Element Method	It is required to the know the dimension and material property of each parts of machine. Manufacturers do not disclose the material properties and steel data easily. As this method completely depends on the machine dimensions, the results may not be accurate and needs experimental verification.
3	Experimental method	It requires high resolution position sensors to identify unaligned and aligned position of rotor with respect to stator for stator phase excitation. High resolution position sensors are costly and hence this methodology is not economical.
4	Proposed Method	As this method is based on rotor locking method, it does not involve complex mathematical modelling and no need to solve any time consuming mathematical equations. This method also does not require any information of machine dimension and material properties. LCR meter is used to estimate the phase inductance of SRM that helps to locate the aligned and unaligned position of stator with respect to rotor without using high resolution position sensors. This makes it more economical to estimate the magnetic characteristics.

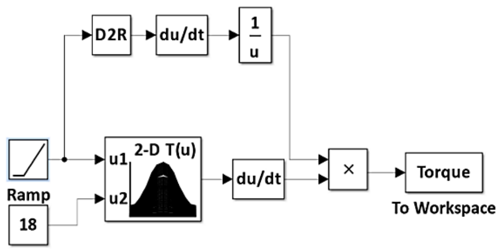


Figure 11. Computation of phase torque using MATLAB/Simulink

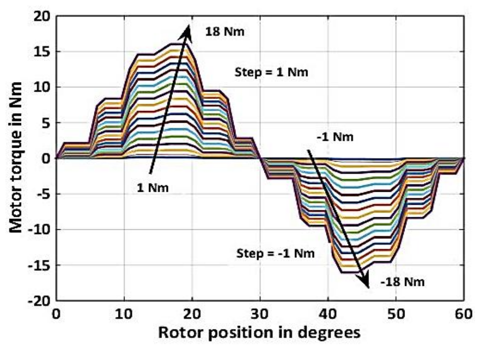


Figure 12. Calculated phase torque from 0° to 60° rotor position

4. VALIDATION OF MAGNETIC CHARACTERISTICS

The accuracy of magnetic characteristics of 4-phase 8/6 SRM obtained through proposed method is validated by using numerical technique such as finite element method (FEM). It gives the accurate results or analysis based on flux distribution. Further, the accuracy is also validated by constructing the dynamic model of 8/6 SRM in MATLAB/Simulink. The dynamic model is constructed to test the variation of phase current, torque and speed of SRM.

4.1. Validation of magnetic characteristics by FEM

Magnetic characteristics of 4-phase 8/6 SRM can also derived through FEM approach. Traditionally, ANSYS finite element software package is used to obtain the magnetic characteristics of SRM [11]–[14]. However, it is time consuming, difficult to solve low frequency electromagnetic problems on 2-D domains and is less accurate in solving the linear or non-linear magneto static problems [11]. To overcome these problems, a finite element method magnetics (FEMM) software package based FEM is used in this paper to obtain the characteristics of SRM. It provides solution to the drawbacks of ANSYS based FEM [30]. This approach requires the comprehensive information on the dimension of machine parts and properties of material to analyze motor [13]. The complete geometrical details of 8/6 SRM considered to obtain magnetic characterization is as shown in Table 3. With geometrical dimensions as shown in Table 3, the cross section of motor is drawn using FEMM software as shown in Figure 13.

Table 3. Geometrical details of 8/6 SRM

Parameter	Values	Parameter	Values
Number of stator/rotor poles	8/6	Number of Stator/Rotor poles	8/6
Output power (kW)	4	Output power (kW)	4
Rated voltage (V)	240	Rated voltage (V)	240
Rated current (A)	11	Height of stator pole (mm)	29.3
Turns per pole	88	Air gap length (mm)	0.4
Phase resistance (Ω)	0.7	Rotor pole arc	21.50
Shaft diameters (mm)	36	Stator pole arc	20.450
Bore diameter (mm)	96.7	Stack length (mm)	151
Stator outside diameter (mm)	179.5	Rated Speed (rpm)	3000
Height of rotor pole (mm)	18.1		

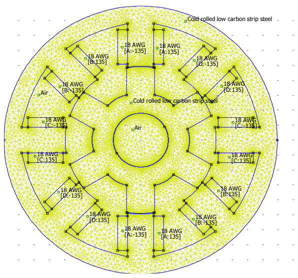
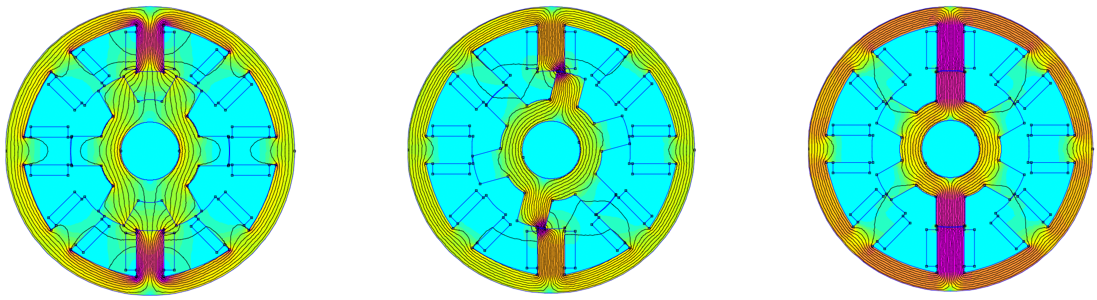


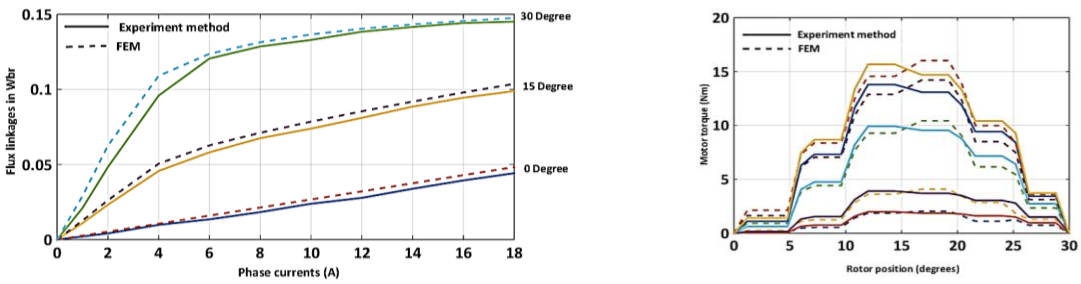
Figure 13. Cross section of 8/6 SRM

This model is then analyzed for flux distribution from unaligned to aligned position of rotor. For instance, Figures 14 (a)-14(c) shows the flux density distribution obtained at 0°, 15° and 30° rotor position for phase R respectively. Flux linkage values are obtained from flux density distribution from unaligned to aligned position and are compared with experimental values at 0°, 15° and 30° rotor position as depicted in Figure 15 (a). Further, Figure 15 (b). represents the torque characteristic comparison obtained through FEM and experimental method. From the comparison, nearly 8% to 10% error between experimental values and FEM results is observed. It is due to inevitable measurement errors and errors during numerical computation process.



(a) (b) (c)

Figure 14. Flux density distribution plot obtained at (a) unaligned rotor position (0°), (b) Intermediate rotor position (15°), and (c) aligned rotor position (30°)



(a) (b)

Figure 15. Magnetic characteristics comparison (a) flux characteristics and (b) torque characteristics

4.2. Validation of magnetic characteristics by dynamic modeling of SRM

The obtained flux linkages and phase torque characteristics by experimental method are further validated by testing the performance of SRM through its dynamic model. Figure 16. shows the dynamic model of SRM using MATLAB/Simulink environment. The model is validated for supply voltage of 200 V, system inertia of 0.00890 kg-m^2, turn on/off angles as 10° and 25° respectively. The performance of motor is observed in terms of current, torque and speed as represented in Figures 17, 18 and 19 respectively. Generally, SRM has high starting current due to its low phase resistance and low back e.m.f value. However, when speed develops to its rated value, back e.m.f increases and therefore phase current reduces gradually. In this model, starting current is limited to 50 A by adding hysteresis controller. Thus, starting phase current limits at 50 A and gradually reduces as back e.m.f develops with increase in motor speed as shown in Figure 17. As starting torque of motor is proportional to the square of the current, SRM always produce high starting torque in spite of limited starting current. Later, torque reduces with increase in motor speed as shown in Figure 18. Motor speed slowly increases with increase in back e.m.f and reaches its rated speed 1600 rpm at 0.25 seconds as shown in Figure 19. and remains at same level unless there is a disturbance in loading or supply voltage.

It is noted that, significant ripples are observed in torque as shown in Figure 18. owing to the presence of doubly salient poles and discrete excitation of stator phases. This torque ripples further contributes ripples in motor speed and causes vibration and noise in motor operation that limits the penetration of SRM into industrial and automobile application. This drawback needs to be reduced effectively to employ SRM at its full potential.

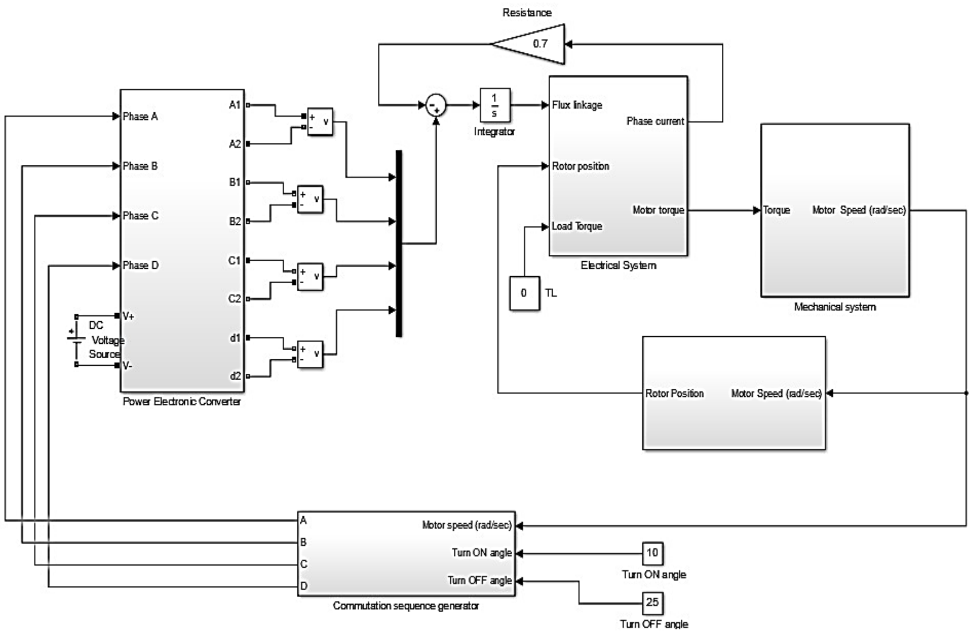


Figure 16. Dynamic model of 8/6 SRM

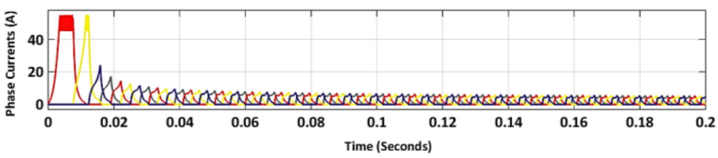


Figure 17. Phase current in A

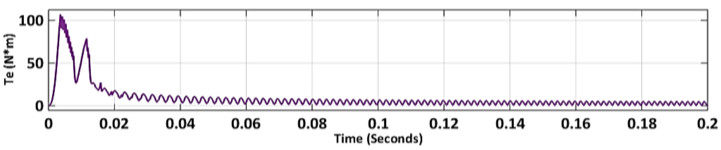


Figure 18. Motor torque in Nm

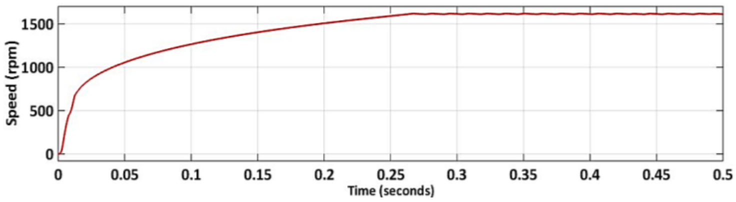


Figure 19. Motor speed in rpm

5. CONCLUSION

A simple approach for the estimation of magnetic characteristics of 4-phase 8/6 SRM is presented in this paper. The simplicity of this paper is to identify the location of rotor with respect to stator by measuring the phase inductance using LCR meter. This resulted in precise estimation of flux and torque characteristics from unaligned to aligned position. The accuracy of the estimated characteristics is validated using FEM by FEMM software tool. Nearly 8% to 10% error between experimental values and FEM results is noticed owing to inevitable measurement errors and errors during numerical computation process. Further, the derived flux and torque characteristics are employed to test the operation of SRM in terms of phase current, torque and speed by building its dynamic model in MATLAB/Simulink. The simulation results show the smooth operation of SRM with high starting torque and significant torque ripple that further causes the acoustic noise and vibration. In view of this, computed flux and torque characteristics from the proposed methodology is helpful in developing the sophisticated control algorithms to mitigate the torque ripple of SRM.

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