# Modeling of Static Characteristics of Switched Reluctance Motor

ALI ASGHARMEMON*, IMTIAZ HUSSAIN**, AND JAWAID DAUDPOTO***

RECEIVED ON 22.10.2012 ACCEPTED ON 31.12.2012

## ABSTRACT

**To investigate the running characteristics of a switched reluctance motor, the static characteristics and related input data tables are required. The static characteristics comprise of flux linkage, co-energy and static torque characteristics. The co-energy and static torque are calculated once data of magnetization characteristics is available. The data of co-energy is required for the calculation of static torque characteristics. The simulation model includes the data of static characteristics for prediction of the instantaneous and steady state performance of the motor. In this research a computer based procedure of experiments is carried out for measurement of the magnetization characteristics. For every set of measurements, the removal of eddy current is carefully addressed. The experiments are carried out on an existing 8/6 pole rotary switched reluctance motor. Additionally, the instantaneous phase current, instantaneous torque and flux waveforms are produced by using linear, which is by default and spline data interpolation separately. The information obtained from theses simulation results will help in an improved simulation model for predicting the performance of the machine.**

**Key Words:** **Static Characteristics, Magnetization Characteristics, Switched Reluctance Motor, LabVIEW.**

## 1. INTRODUCTION

Switched reluctance motor is widely used in various applications due to its high efficiency over wide range of speed and torque [1]. The stator of the machine carries the windings whereas; rotor is made from steel laminations. This simple structure is an extra advantage. However; acoustic noise and torque ripple are among the shortcomings of the machine. The phases of switched reluctance machine are not dependent on each other. A rectified dc supply via an electronic converter is requirement for running the motor. Magnetic circuit is mainly responsible for complex flux waveforms in different parts of the core of the machine [2]. Due to the trend of magnetization characteristics which is of non-linear and non-sinusoidal, these characteristics are presented by a LUT (Look-Up Table) [2].

The magnetization characteristics often called flux linkage characteristics are much dependent on current and rotor position of the motor. This paper describes the LabVIEW (Laboratory Virtual Instrumentation Engineering Workbench) based measurement of flux linkage characteristics. LabVIEW is a graphical programming

---

* Assistant Professor, Department of Electrical Engineering, Mehran University of Engineering & Technology, Jamshoro.
** Assistant Professor, Department of Electronic Engineering, Mehran University of Engineering & Technology, Jamshoro.
*** Assistant Professor, Department of Mechanical Engineering, Mehran University of Engineering & Technology, Jamshoro.

environment with built-in functions and is an efficient and modern technique of the measurement [3].

## 2. STATIC CHARACTERISTICS OF SWITCHED RELUCTANCE MOTOR

The accurate knowledge of magnetization and static torque characteristics is of importance in modeling the performance of the machine. Static characteristics include flux linkage characteristics, co energy and static torque characteristics. The flux linkage characteristics are experimentally obtained, procedure described in Section 3.1. The static torque characteristics are calculated from co energy that uses the information of data of flux linkage characteristics.

The data of static characteristics is useful to define the magnetic nature and prediction of instantaneous and steady state performance of switched reluctance motor. The literature review reveals that flux linkage characteristics are measured by using ballistic galvanometer [4] and an integrator circuit [5].

Fringing effect and the saturation are responsible for the shape of the flux linkage characteristics [6]. Bulk saturation takes place at the instant when stator and rotor poles of the motor are fully overlapped; whereas, local saturation occurs when the stator and rotor poles are to some extent overlapped [6]. The relationship between flux linkage and current for the given rotor position is not easy due to non-linear trend of the magnetic circuit of the motor [5-8,9].

An easy approach for handling of the data was achieved by integrating the differential voltage equation [2,5] in the form:

$$\frac{d\Psi(\theta,i)}{dt} = V - Ri \tag{1}$$

where $V$ is applied voltage, $R$ represents motor winding resistance, $i$ is used for instantaneous phase current and $d\psi/dt$ is rate of change of flux linking the coil. Equation (1) governs the flow of phase current in the motor windings. The measurement of the characteristics through LabVIEW is documented in [2,3]. The measurement procedure described in [2] is carried out on linear switched reluctance machine. In [10] the DSP (Digital Signal Processor) is used for the measurements of flux linkage characteristics, particularly to capture the data of current and voltage signals. Finite element method is used to analyse the static characteristics of switched reluctance machine [11-13].

In order to measure actual inductance of the machine, it is required to wipe out the residual magnetism during each step of the measurement. This was achieved by energizing the motor winding from dc voltage source. The same amount of current was allowed through the windings at which previous reading was recorded [2]. The experiments are carried out on an existing linear switched reluctance motor [2]. The removal of eddy current has not been considered in [3,10-13].

Static torque is calculated from the co energy which uses the data of flux linkage characteristics. The LUT for torque is obtained from co energy:

$$T(\theta,i) = \frac{\partial W'(\theta,i)}{\partial\theta} \tag{2}$$

where the co-energy is obtained as:

$$W'(\theta,i) = \int_0^i \Psi(\theta,i)\,di \tag{3}$$

The contribution of this research lies in the LabVIEW based measurement of flux linkage characteristics along with the removal of eddy current. These measurements are performed on 8/6 pole rotary type of the motor for different range of the current and rotor position. The results obtained from the proposed simulation model that uses the static characteristics are helpful for predicting the performance of the machine.

## 3. MATERIALS AND METHOD

### 3.1 Experimental Set-up for the Measurement of Flux Linkage Characteristics

The experimental setup for the measurement of flux linkage characteristics is depicted in Fig. 1. LabVIEW was used to produce a signal to ramp up the current to a desired maximum value for a certain time in seconds [2]. The ramp signal (analogue output for ramping current) was then fed to a programmable dc power supply which was connected to the main phase windings of the machine [2].

The experimental rig consists of an existing prototype SR Machine, D-80, with rated power of 0.75kW at 1500 rpm, with bifilar windings, DC programmable supply, Current transducer, Voltage probes, shunt resistor, data storage oscilloscope and measurement data acquisition card USB 6008.

### 3.2 Experimental Protocol

Following procedure for the experiment was considered:

1. The motor was held locked at certain desired rotor position/range of rotor positions.
2. The motor windings were exited from a dc programmable supply for range of currents.
3. The data of current through the main winding and induced EMF (Electro Motive Force) across the search coil of the motor at different rotor positions was collected using a shunt resistor and a voltage probe.

## 4. RESULTS

The obtained results are listed as:

- Experimentally obtained measured data that is included in the model.
- Simulation results.

### 4.1 Experimentally Obtained Measured Data that is Included in the Model

The captured data of induced EMF was integrated in MATLAB to get flux linkage curve . Fig. 2 shows captured data of induced EMF and flux linkage curve that is obtained by integrating the former quantity for aligned rotor position where inductance is maximized. Fig. 3 shows measured set of flux linkage characteristics at different rotor positions for range of current. The data of measured flux linkage at aligned (0 deg.) and unaligned (-30 deg.) position for range of current is shown in Table 1.

### 4.2 Simulation Results

The simulation results are obtained from the proposed model that uses most of the data obtained through the experiments.

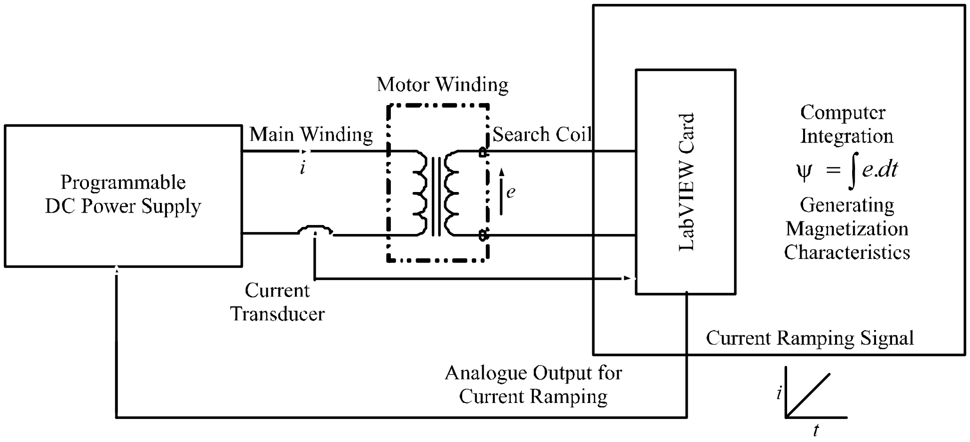

FIG. 1. EXPERIMENTAL RIG FOR THE MEASUREMENT OF FLUX LINKAGE CHARACTERISTICS [2]

## 5. PROPOSED SIMULATION MODEL

The phase current of the motor winding can be expressed by the Equation (1) that can be re-written as:

$$\upsilon = Ri + L\frac{di}{dt} + i\frac{dL}{dt} \qquad \text{Since } \Psi = \text{Li} \tag{4}$$

$$\upsilon = Ri + L\frac{di}{dt} + i\left(\frac{dL}{d\theta}\right)\frac{d\theta}{dt} \tag{5}$$

$$\upsilon = Ri + L\frac{di}{dt} + i\frac{dL}{d\theta}\omega \tag{6}$$

where 1st term on right hand side of Equation (6) represents resistive voltage drop, 2nd is inductive voltage drop and 3rd term is induced emf. While ω represents the rotational speed in rad /s. The rate of flow of the energy is given by:

$$\upsilon i = Ri^2 + \frac{d}{dt}\left(\frac{Li^2}{2}\right) + \frac{i^2}{2}\frac{dL}{d\theta}\omega \tag{7}$$

where the first term on right hand side of the Equation (7) indicates the power loss in coil due to its resistance, second term is rate of increase of stored magnetic energy and the last term is the power converted from electrical energy to mechanical output power. Torque can be expressed by:

$$\tau = \frac{i^2}{2} \times \frac{dL}{d\theta} \tag{8}$$

The developed model uses the data of $\psi(\theta,i)$ that is obtained experimentally as discussed. The new obtained look-up data table $i(\theta,\psi)$ is obtained by inversion of $\psi(\theta,i)$ [7,8]. The data tables of $i(\theta,\psi)$ and $T(\theta,i)$ are useful for the computation of instantaneous and steady state current and torque waveforms.

The required input data tables obtained from static characteristics are included in the simulation model to predict the instantaneous and steady state performance of the motor. Fig. 4 shows 3-D reflection of flux linkage versus rotor position for range of currents. Fig. 5 shows 3-D presentation of co-energy characteristics $W'(\theta,i)$. The calculated static torque characteristics are shown in Fig. 6. The static characteristics produced using spline data interpolation technique are shown in the Figs. 3-6.

For the purpose of the illustrations, the examples shown in Figs. 7-8 are produced under operating conditions given as follow with spline and linear data interpolations.

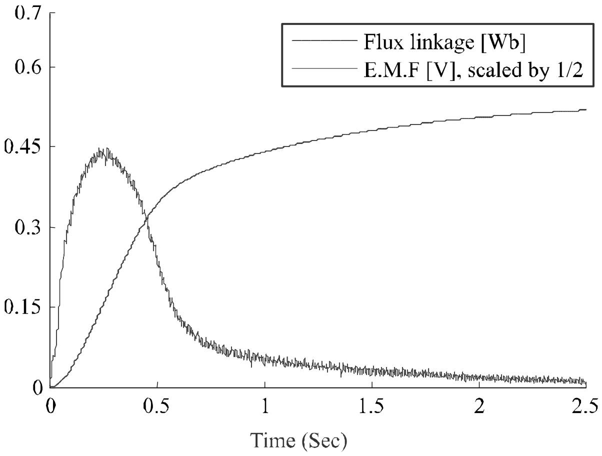

*FIG. 2. MEASURED DATA OF E.M.F AND CALCULATED FLUX LINKAGE AT ALIGNED POSITION*

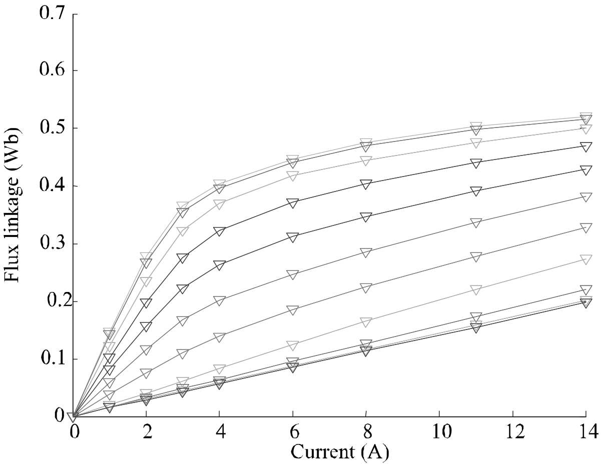

*FIG. 3. MEASURED FLUX LINKAGE CHACTERISTICS AT DIFFERENT ROTOR POSITION FOR RANGE OF CURRENT*

**TABLE 1. MEASURED DATA OF FLUX LINKAGE AT UNALIGNED AND ALIGNED POSITIONS.**

| 0 [deg.] | 1 A | 2 A | 3 A | 4 A | 6 A | 8 A | 11 A | 14 A |
|---|---|---|---|---|---|---|---|---|
| -30 | 0.0144 | 0.0282 | 0.0428 | 0.0567 | 0.0847 | 0.1125 | 0.1552 | 0.1968 |
| 0 | 0.1461 | 0.2768 | 0.3645 | 0.4038 | 0.4468 | 0.4752 | 0.5039 | 0.5207 |

| | |
|---|---|
| Resistance of Motor Winding | 2.7 (Ohms) |
| Number of Rotor Poles | 6 |
| Number of Motor Phases | 4 |
| Supply Voltage | 150 V |
| Speed of Motor | 1500 rev/minute |
| Switch-on angle | -30 deg. |
| Switch-off angle | 0 deg. |

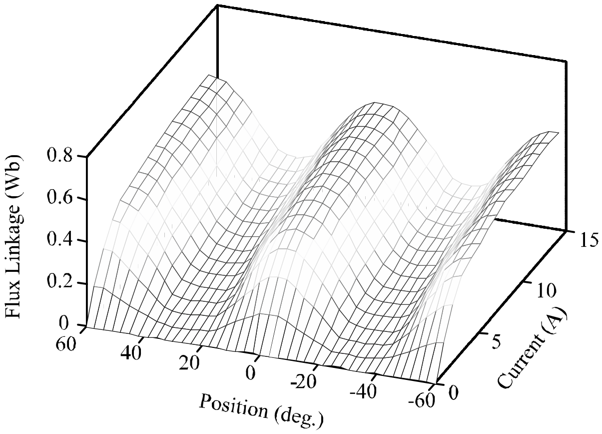

FIG. 4. 3-D PRESENTATION OF CHARACTERISTICS OF FLUX LINKAGE $\psi(\theta,i)$

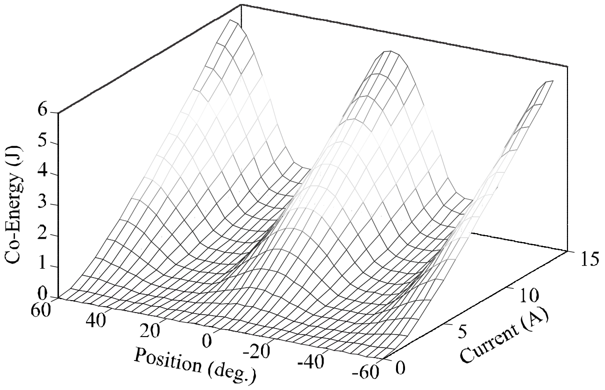

FIG. 5. 3-D PRESENTATION OF CHARACTERISTICS OF CO-ENERGY CHARACTERISTICS $W'(\theta,i)$

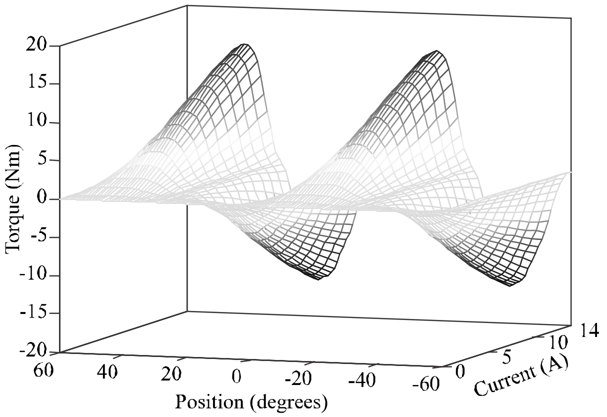

FIG. 6. 3-D PRESENTATION OF STATIC TORQUE CHARACTERISTICS $T(\theta,i)$

Figs.6-7 represent the instantaneous current, instantaneous torque and flux waveforms of the motor under single pulse mode of the operation. When voltage pulse is applied across the motor windings, the phase current starts increasing. It decays due to motional EMF and increasing inductance until switches are opened [6]. The instantaneous torque is positive when inductance is increasing Flux is always maximized at switch off instant.

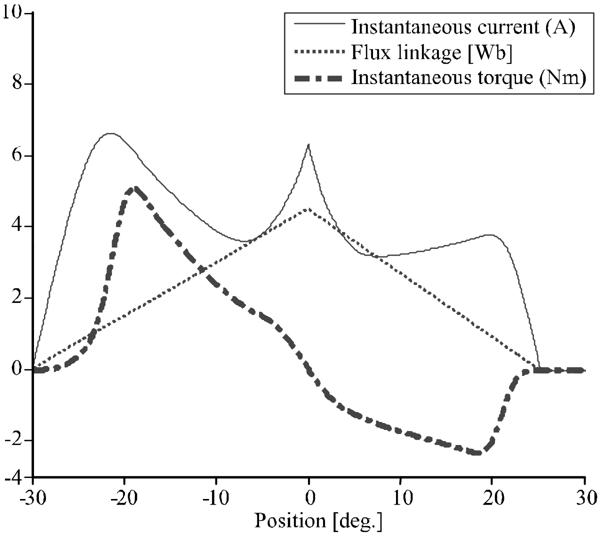

FIG. 7. INSTANTANEOUS CURRENT, TORQUE AND FLUX WAVEFORMS VERSUS POSITION USING PIECEWISE SPLINE DATA INTERPOLATION

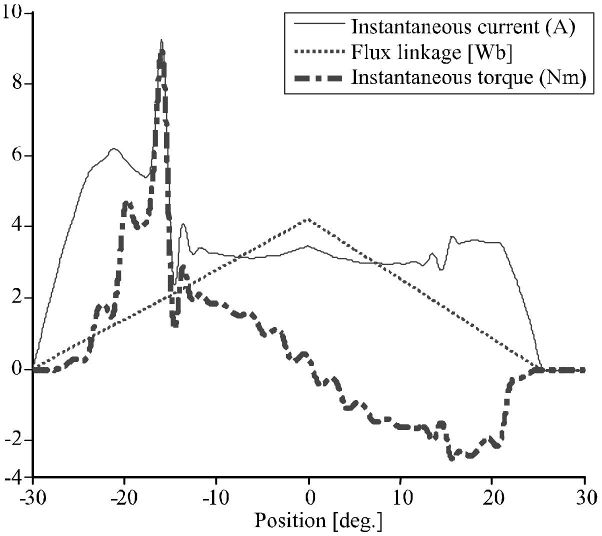

FIG. 8. INSTANTANEOUS CURRENT, TORQUE AND FLUX WAVEFORMS VERSUS POSITION USING PIECEWISE LINEAR DATA INTERPOLATION TECHNIQUE

## 6. CONCLUSTION

In this paper the existing literature, procedure of the measurement and modelling the static characteristics have been discussed. The measurement of the characteristics has been performed with consideration for the eddy current in LabVIEW. The static characteristics have been shown in 3-D mirror image for the purpose of clear variation of different quantities. Finally a very appealing difference has been observed from the simulation results if the input data tables were presented in two forms of interpolation techniques. The difference in the waveforms under same operating conditions is useful and will help in proper selection of best fit to get improved prediction of the performance of the motor.

## ACKNOWLEDGEMENTS

The work presented in this paper is part of the first authors' Ph.D. work. The author is also thankful to Dr. J. Corda, University of Leeds, UK, for his scholarly guidance.

## REFERENCES

[1] Ray, W.F., Lawrenson, P.J., Davis, R.M., Stephenson, J.M., Fulton, N.N., and Blake, R.J., "High-Performance Switched Reluctance Brushless Drives", IEEE Transactions on Industry Applications, Volume IA-22, No. 4, pp. 722-730, July, 1986.

[2] Corda, J., Jamil, S.H., "Experimental Determination of Equivalent-Circuit Parameters of a Tabular Switched Reluctance Machiune with Solid Steel Magnetic Core", IEEE Transactions on Industrial Electronics, Volume 57, No. 1, pp. 304-310, January, 2010.

[3] Cheok, A.D., and Ertugrul, N., "Computer-Based Automated Test Measurement System for Determining Magnetization Characteristics of Switched Reluctance Motors", IEEE Transactions on Instrumentation and Measurement, Volume 50, No. 3, pp. 690-696, June, 2001.

[4] Jones, C.V., "The Unified Theory of Electrical Machines", London, Butterworths, 1967.

[5] Corda, J., "Switched Reluctance Machine as a Variable-Speed Drive", Ph.D. Thesis, School of Electronic and Electrical Engineering, University of Leeds, Leeds, UK, 1979.

[6] Lawrenson, P.J., Stephenson, J.M., Fulton, N.N., Blenkinsop, P.T., and Corda, J., "Variable-Speed Switched Reluctance Motors", IEE Proceedings of Electric Power Applications, Volume 127, No. 4, pp. 253-265, July, 1980.

[7] Stephenson, J.M., and Corda, J., "Computation of Torque and Current in Doubly Salient Reluctance Motors from Nonlinear Magnetisation Data", IEE Proceeding, Volume 126, No. 5, pp. 393-396, May, 1979.

[8] Corda, J., Stephenson, J.M., "Analytical Estimation of Minimum and Maximum Inductances of a Double-Salient Motor", Proceedings of International Conference on Stepping Motors and Systems, pp. 50-59, Leeds, UK, September, 1979.

[9] Corda, J., Masic, S., and Stephenson, J.M., "Computation and Experimental Determination of Running Torque Waveforms in Switched-Reluctance Motors", IEE Proceedings of Electric Power Applications, Volume 140, No. 6, pp. 387-392, November, 1993.

[10] Chancharoensook, P., and Rahman, M.F., "Magnetization and Static Torque Characterization of a Four-Phase Switched Reluctance Motor: Experimental Investigations", Proceedings 4th IEEE International Conference on Power Electronics and Drive Systems, Volume 2, pp. 456-460, October, 2001.

[11] Xiaoyuan, W., Chuan, W., and Zhi, G., "The Static Characteristics of DSPM under Different Armature Current and Different PM Thickness", 18th International Conference on Electrical Machines, pp. 1-4, 6-9 September, 2008.

[12] Masic, S., Smaka, S., Salihbegovic, I., and Cosovic, M., "The Effects of Magnetic Circuit Geometry on Characteristics of Switched Reluctance Motors", IEEE International Conference on Electric Machines & Drive, pp. 1427-1432, 15-18 May, 2011.

[13] Kacenka, V., Rafajdus, P., Makys, P., Vavrus, V., and Szabo, L., "Static and Dynamic Fault Analysis of Switched Reluctance Motor", ELEKTRO, pp. 206-211, 21-22 May, 2012.