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Modeling of Switched Reluctance Machine Based on Variable Input Data

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***Abstract* — The modeling of switched reluctance machine (SRM) is challenging particularly when variable data points are concerned. This paper aims to the development of a simulation model in MATLAB/Simulink environment based on more and less data. In this paper, first the procedure of data necessary for simulation is presented. This data is included in the model with less and more data that is available from experiments and simulations. The impact of the variable data is analyzed based on the obtained results.**

***Index Terms*— Interpolation, lookup data, mathematical modeling, single pulse mode, switched reluctance machine**

I. INTRODUCTION

Switched Reluctance Machines (SRMs) is an attractive machine for its application and performance. having simple and rugged construction. SRM produce torque due to magnetic attraction when energized opposite poles. Owing to its advantages over other machines i.e. simple construction makes it robust, absence of rotor windings allows high speed operation and absence of permanent magnets and brushless operation makes it an ideal candidate for variable speed drives in commercial and industrial applications such as electric vehicles and starter/alternator etc [1],[2]. SRMs cannot be directly operated as other motors with ordinary supply but rather it inherently requires electronic converter for its operation [1]. Pole structure of 8/6 poles 4-phase SRM is shown in Fig. 1. SRM however suffer from few disadvantages as well, including high torque ripple, high noise & vibrations being significant drawbacks [3], [4].

SRM has dual salient structure of poles (i.e. projected poles) of both stator as well as rotor as shown in fig.1 and operation in magnetic saturation which makes the electromagnetic characteristics i.e., (flux linkage, inductance & static torque) highly nonlinear resulting difficulty in modelling and simulation, where simulation model depends on these characteristics, therefore for real-time simulations, analysing. Different operating conditions and its dynamic control necessitates accurate electromagnetic characteristics data [4]-[6]. There are number of approaches available for modelling SRM [7]-[12], however obtaining static characteristics of SRM is very critical due to the fact model accuracy depends on it. Methods such as finite element analysis [7]-[9] for these accuracy heavily depends on exact geometrical dimensions by the manufacturer which are sometimes difficult to procure and their accuracy is compromised by nonuniform iron properties thereby inevitably requiring experimental verification. Experimental measurements [10]-[12] on the other hand are carried out on actual machine mainly by indirect measurement of emf as compared to direct measurement methods which requires costly sensors and complex installation [12]. However experimental measurements are complicated and time consuming for complete characterization of static characteristics therefore most adopted methods are to take few measurements with respect to current at different rotor positions and the complete characterization is achieved using numerical computations and artificial intelligence techniques [13]-[19].

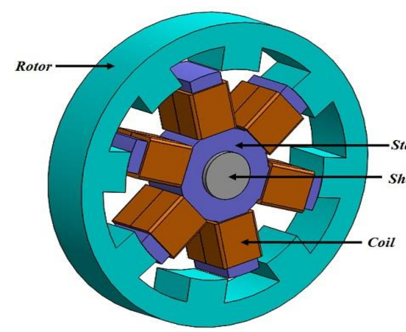

Fig. 1. A 4-phase, 8/6-pole SRM.

In recent studies among several proposed flux linkage modelling techniques lookup data tables-based technique has been employed [13]-[15], which is simple and mostly relies on fewer accurate data directly obtained from an existing machine. In [10] a comprehensive analysis of static properties was given using search tables to assess the inductance & torque profiles based on measured flux linkage characteristics. A mathematical model was proposed in [14] that computes other static characteristics from measured flux linkages for dissimilar operating modes using lookup data tables in MATLAB/Simulink environment. Similar approach was employed in [15] where flux linkages were measured while the static torque characteristics were derived numerically using finite difference approximations and numerical integration and were compared with measured static torque data to see the accuracy moreover a relational study was carried to measure the difference. In [17] two-dimensional B-spline neural network (BSNN) was proposed which was designed to learn the nonlinear-flux-linkage characteristic of an SRM online and in real-time within a trained current range and for low to medium motor speed while its torque, inductance, and back-emf were derived from the BSNN after training. A further brief study is reported in [20] which compares advantages and limitations of each method based on complexity & accuracy of different modelling methods.

Lookup data model SRM used in this study relying on interpolation and extrapolation techniques as fewer test data samples for different rotor positions and currents are available, since the accuracy of the model depends on the number of samples measured [16]. In addition, limitation of large experimental data which may introduce precision error when closely data is measured due to rotor misalignment and instrument handling which alters measurements. Above studies conclude that models based on computed static characteristics provide acceptable agreements, but a compromise is made between number of input data samples against accuracy and complexity of the method. This study aims to investigate machines behaviour by considering variable input data of static torque.

II. Mathematical Model of SRM

General equations used for modelling by most researchers [22] are given as follows as voltage equations which control the flow of the stator current:

$$v = Ri + \frac{d\psi}{dt} \tag{1}$$

Provided that $\psi = Li$, (1) can be written as follows:

$$= Ri + L\frac{di}{dt} + i\frac{dL}{d\theta}\omega \tag{2}$$

Where the first terms represent, a resistive voltage drop, second term is an inductive voltage drop, and induced EMF, respectively; ω (omega) denotes the rotational speed (rad/sec). The energy flow is given by the following expression:

$$vi = Ri^2 + \frac{d}{dt}(\frac{Li^2}{2}) + \frac{i^2}{2}\frac{dL}{d\theta}\omega \tag{3}$$

where the three terms on the right-hand side represent the power loss in winding, rate of increase of stored magnetic energy, and power converted from electrical energy to mechanical output power.

$$Torque = \tau = \frac{i^2}{2}\frac{dL}{d\theta} \tag{4}$$

III. INPUT DATA TABLES

The proposed SRM model uses data of flux, inverted data of flux, co-energy and static torque. Several sensor-less position detection methods use prestored information such as input data of flux linkage $\psi(\theta, i)$ or inductance $L(\theta, i)$ in the form of 2-D table, as a function of phase current and rotor position [13]–[15]. Obtaining the flux linkage characteristics are important because other data such as co-energy which is essential for calculating static torque. Lookup data tables of inverted flux linkage, and static torque characteristics are used for calculation of machine electromagnetic torque and phase current, are dependent on these data tables.

Using the method described in [21] data of flux linkage were obtained by the search coil method the rotor of a prototype was placed in a well-defined position, and a pulsed *dc* voltage was applied to the machine windings; the current was allowed to flow through machine windings. The data of induced EMF were captured from a bifilar winding of the machine that acted as the secondary winding of a transformer as shown in Fig. 4 with one phase representation of a 4-phase machine. These EMF data were useful for calculating flux linkage via integration as indicated by (5). The set of measured flux linkage characteristics is shown in Fig. 5.

$$Flux\ (\psi) = \int EMF\ dt \tag{5}$$

Also, the data of static torque were obtained from a locked rotor test performed on an existing machine. The SRM was locked, and a certain amount of current was allowed to flow at different voltage levels. The data of the machine static torque were captured with the help of dynamometer (a spring balance with the load dynamometer, accuracy class of 1% when measurements of torque were taken between 1 -10 Nm). SRM (A bifilar wound 4-phase, 0.75 kW, 1500 rpm) was used as a prototype for experimental measurements. The experimental data of flux and static torque are given in Table 1 and Table 2. The data tables are requirement of the model for determining the running performance of the machine in different operating modes such as, single pulse mode in this study. For this, instantaneous current (phase current through machine winding) and instantaneous torque are the required profiles. Steady sate and transient performance of the machine are only possible once we have instantaneous current and instantaneous torque profiles.

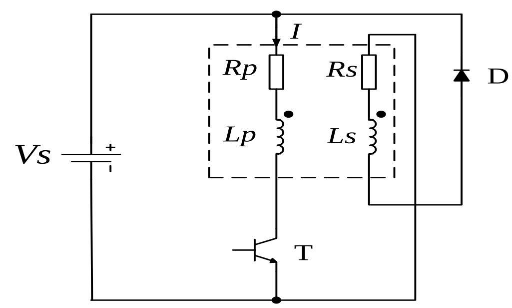

Fig.4. Bifilar winding connection for capturing data of EMF

TABLE I: Experimental data of current versus flux at different rotor positions.

θ = -30 [degrees]					
Current (I)[A]	0	2	4	8	14
Flux (Ψ)[Wb]	0	0.02	0.05	0.11	0.19
θ = -15[degrees]					
Current (I)[A]	0	2	4	8	14
Flux (Ψ)[Wb]	0	0.11	0.20	0.29	0.38

TABLE II: Experimental data of torque at different rotor position and different fixed currents.

I = 2A					
Rotor Position[deg.] (θ)	0	-4	-18	-26	-30
Torque[Nm] (T)	0	0.68	0.81	0.04	0
I = 6A					
Rotor Position[deg.] (θ)	0	-7	-18	-22.2	-30
Torque[Nm] (T)	0	4.9	5.57	1.42	0

IV. COMPUTATION OF FLUX LINKAGE & STATIC TORQUE

Flux linkage data were used to generate the data for co-energy. The static torque can be found from the corresponding current and angle through a co-energy lookup table. Co-energy and flux linkage are expressed according to (6) whereas. (7) describes the static torque. Instantaneous current and torque are computed using the data of inverted flux $i(\theta, \Psi)$ and static torque $T(\theta, i)$. To determine the instantaneous current and torque for all four phases of the motor, it is important to define the rotor position relative to its stator reference [13].

$$W'(\theta,i)_{(\theta=constant)} = \int_0^i \psi(\theta,i)di \tag{6}$$

$$T(\theta,i) = \frac{\partial W'(\theta,i)}{\partial \theta} \Big|_{(current=constant)} \tag{7}$$

Using the same model based on the available experimental data samples limited data of flux linkage characteristics $\varphi(\theta,i)$ at different rotor positions and current values were extended based on available data of flux using lookup table. Co-energy $W'(\theta,i)$ derived is input to the second data table for deriving static torque $T(\theta,i)$ from the primary data of flux linkages.

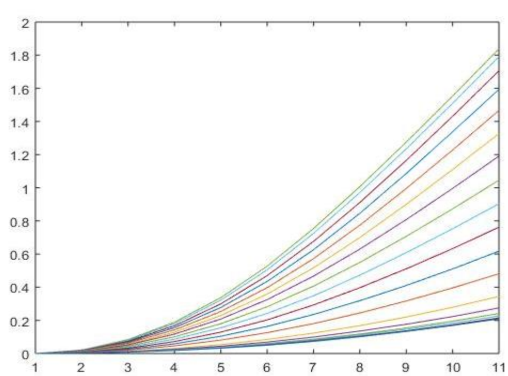

Fig. 5. Computed co-energy profile $W'(\theta,i)$

Primary data of flux linkage is used to derive co-energy profile using the relation in (6). Rotor position (θ) and current (i) are the inputs to the lookup table. At first rotor position θ_1 is kept constant and current is increased from *0 to* I_{max} therefore computing the co-energy at that rotor position. Similarly, at rotor position θ_2, same process is repeated, keeping the θ_2 constant current is increased from *0 to* I_{max} and so on. Fig. 5 shows obtained co-energy profile. Similarly, static torque $T(\theta,i)$ characteristics are computed using the relation described by (7), differentiating calculated co-energy $W'(\theta,i)$ w.r.t rotor position at constant current, therefore for different current values static torque is computed shown in Fig. 6.

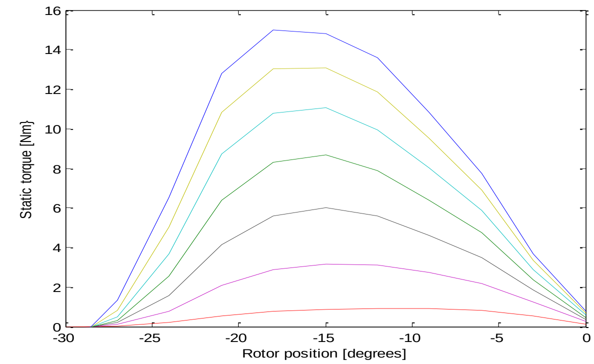

Fig. 6. Computed static torque profile $T(\theta,i)$

V. SIMULATION MODEL

Fig. 7 & 8 shows the mathematical lookup table model [23] for computation of co-energy and thus calculating static torque as described in previous section. This model is based on the relations in (6) and (7). Available flux data is input to the lookup data block in Fig. 7 against rotor position and current. For calculation of co-energy rotor position is kept constant for the range of current from minimum to maximum thus the co-energy is calculated for that particular rotor position. Completing one cycle from minimum to maximum current the process is repeated to calculate co-energy at all rotor positions. In this study the co-energy is calculated at interval of 22.5° degrees (electrical). However, this process is repeated for several rotor positions and started again to avoid accumulation error over time. Similarly, in Fig. 8 shows similar model for calculating static torque. Calculated co-energy is here input to the lookup table against rotor position and current where static torque is measured for constant current against 0° to 360° degree (electrical) thus deriving simulated static torque using co-energy calculations.

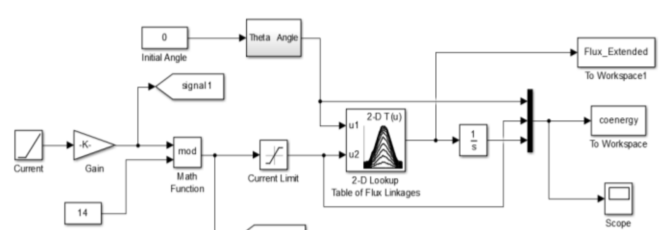

Fig.7. Lookup Table Based Computation of Co-energy $W'(\theta,i)$

SRM mathematical model represented by equations in the previous section is used that describes the SRM performance depends on basic voltage and current equations of SRM. This model takes two inputs one for inverted flux linkage $i(\theta, \Psi)$ for calculating phase current and other for instantaneous phase torque computation for set of operating conditions mentioned in Table 3.

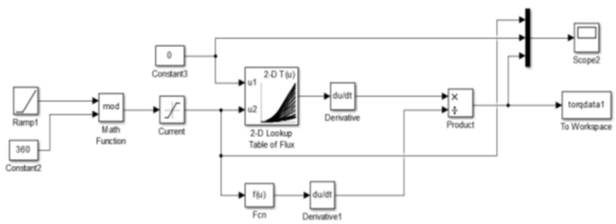

Fig. 8. Lookup Table Based Computation of Static Torque $T(\theta, i)$

VI. SIMULATION RESULTS & DISCUSSIONS

For simulation of the SRM under single-pulse mode of operation, mathematical model of SRM uses lookup tables that functions as input data to the model based on extended data of flux linkage characteristics and static torque depending on more data samples and less data samples the simulation was carried out. Two different cases are discusses below depending on different number of data samples.

Case 1: With More Samples of Flux Data & Static Torque Data

Flux linkage characteristics and static torque characteristics functions as the input to the model obtained using lookup tables that based on interpolation were included in the mathematical model, and simulation results under single-pulse mode operation was carried out (switches are turned on and off during one switching cycle) together with operation conditions as mentioned in Table 3, with data samples of torque = 31 x 11 (rotor position and current), and $\psi(\theta, i)$ = 11 x 53 (rotor position and flux data).

TABLE.III Operating conditions of SRM model

System Parameter	Value
Switch on angle	-36°
Switch off angle	-6°
Winding resistance	3.2 Ω
Source voltage	100V
Speed	315 rpm

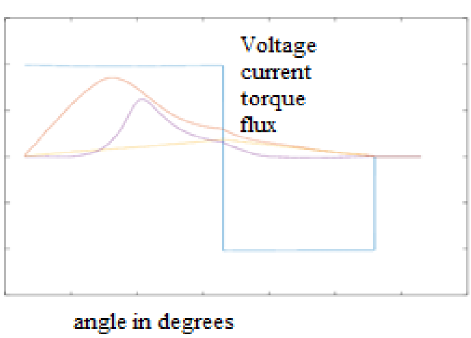

Fig. 8. Simulation results of current, torque, and flux profile of one phase.

Performance of the machine under single-pulse operation mode comprehended by that in the above-mentioned conditions in Table.3 are shown in Fig. 8. The current, torque, applied voltage, and flux waveforms of the machine are scaled for the sake of a clear presentation.

Case 2: With Reduced Samples of Computed Static Torque Data

In this case, the data of $\psi(\theta, i)$ were kept unchanged, and only the data of $T(\theta, i)$ were reduced to the order (11 x 11) i.e., 11 rotor position values and 11 current values. Under the new reduced data, same operating conditions, simulations were carried out for current, torque, flux waveforms, shown in Fig. 11.

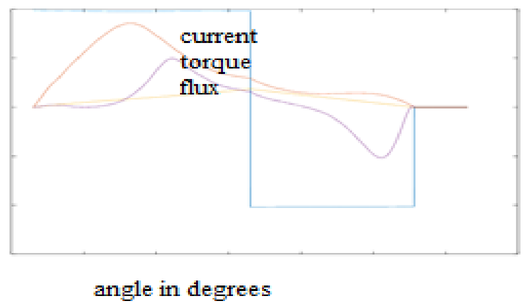

Fig. 11. Simulation results of current, torque, and flux profile of one phase with reduced data of $T(\theta, i)$.

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VII. CONCLUSION

Accurate mathematical modelling is very important for nonlinear characteristics of SRMs for analyzing performance of SRM based on air gap inductance varying with rotor position and current. Obtaining the data tables of flux linkage and static torque is very critical. These data tables were used as lookup tables in the mathematical model of SRM equations. The effective use and explanation of simulated and measured data tables and the impact of variation of the data samples on performance of the machine under single-pulse mode was addressed. The comparison results show that the proposed model with extended data provides higher accuracy than the model with less data. The experimental data confines due to error that accounts for precision in the measurements when close data is measured. The outcomes of this study can be applied to further explorations under different operating conditions, such as steady state and transient performance of SRM.

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