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Inverse numerical simulation for the reconstruction of static flux linkage characteristics of switched reluctance motor

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Abstract: Switched reluctance machines (SRMs) are gaining popularity in both AC and DC drives due to their numerous advantages over traditional drive systems. These advantages include a robust design devoid of brushes, having high inertia, and a torque-to-weight ratio that is high, and the absence of rotor windings, all facilitated by a straightforward circuit power converter. SRMs find extensive applications in variable speed and servo drives. However, due to the double saliency structure and the inherent high nonlinearity present in magnetic materials, accurately representing the flux-linkage and static torque characteristics of SRMs presents a significant challenge. This study aims to promote an inverse numerical modeling to reconstruct the data tables and hence the flux linkage for the modeling the static characteristics of SRMs. Specifically, we initiate with the static torque characteristics attained experimentally, which relies on rotor position and phase current, to project a family of simulated flux linkage characteristics. To achieve this, our methodology begins with the utilization of an experimental setup to gather electromagnetic data for SRMs. Subsequently, we employ the inverse numerical integration scheme to construct flux linkage profiles which are then validated through experimental data table of flux linkage for a considered SRM. The results indicate that the proposed model reduces absolute error significantly compared to other state of the art techniques.

Keywords: *Inverse Numerical scheme, Switched Reluctance machine, Flux Linkage, Experimental Validation*

1. Introduction

The concept of switched reluctance motors (SRMs) can be traced back to 1814, but recent decades have witnessed a resurgence in their development and practical application, driven by advancements in electronic power equipment. SRMs are gaining popularity due to their distinct advantages over AC and DC drives. These advantages include a straightforward and sturdy construction, brushless operation, high efficiency, a favorable torque-to-inertia ratio, a high torque-to-weight ratio, and the absence of conductors and permanent magnets in the rotor, making them cost-effective.

Qiao et. al in [1] presented a thorough review of the literature on the state of research on the optimization methods and techniques utilized for SRMS. They covered the theory of the design of such optimizers, modeling methods tending to both thermal and electromagnetic aspects, the topologies used as well as the most recent suggested. They finished their discussion with elucidating on the different classifications of optimization techniques used to increase optimization efficiency and their effects as well.

Thirumalasetty and Narayanan in [2] also presented another review of the literature focusing on the enhancement of the torque density for SRMs by making modifications to the magnetic structure of the machine. It was found that this could be achieved by making changes in terms of different configurations of the poles, modifying their geometry such as the adding teeth to stator poles, addition of tapering to both the rotor and stator poles, replacing the uniform air gap present with a non-uniform air gap, adding barriers to the flux present in the poles. Moreover, they also studied segmental rotors in the SRM. Lan et. al in [3] argued that in order to achieve a reduction in torque ripples while increasing power factor and torque density, one could make use of multi-stack switched reluctance motors with a segmental rotor (MSSRM-SR) and multi-stack conventional switched reluctance motors (MSCSRM). Azer et. al in [4] presented a review of the literature on the operation concept, configurations of the windings and the poles and the current based control methods used in MCSRMs. They also provide a comparison of the performance of the different configurations used in MCSRMs, the modeling methods used as well as provide future directions for improving the performance of MCSRM for different applications. Husain et. al in [5] recommended a single controller for switching reluctance vehicles for high-speed applications.

The suggested controller provides negligible output torque ripple at low and medium speeds and operates in a single-pulse mode at high speeds. Control is applied to overlapping parts between phases. This simplifies torque sharing during commutation and reduces torque ripple caused by poor cutting-edge tracking and mutual torque. Sah et. al [6] presented a simple control law for managing the speed of a switching reluctance motor. Chopping is used to manage phase currents in the low-speed area. The reference current used for current chopping is generated by the Proportional Integral (PI) controller. The turn-on angle is constant, while the turn-off angle is reduced as the speed increases. A generalized equation governs turn-off angles in both low and high-speed zones. Memon and Shaikh [7] proposed direct numerical method on computed data of SRM by LabVIEW. In this method they have applied direct numerical method in measured data of flux by LabVIEW and then with the help of simulation they obtained the co-

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energy and static torque. After those results they measured simulated and computed data. Results are measured by both methods, simulation and experimental, to find the accuracy in measured data. Mahar et. al [8] suggested an efficient numerical scheme for static torque profiling of switched reluctance machine with experimental validation. In this method they have enhanced the existing direct numerical method of static torque. With the help of experimental data which is already computed they had profiling of static torque and obtained better results than existing method of direct numerical simulation.

This research primarily concentrates on computing and enhancing data tables by inverse numerical method starting from the experimental torque, co-energy $W'(\theta, i)$ then flux linkage for SRMs. Among these, Experimental torque data is acquired from experiments conducted on an existing machine using software. Static torque data is extracted from experiments through the locked rotor test on the same machine. An inverse mathematical model is proposed for co-energy calculations based on the experimental torque table, and static flux is approximated using finite difference approximation. Hence, we get the data tables with the help of inverse mathematical model. Simulations are executed in MATLAB, and the proposed model is compared with an already present model, with results being validated by conducting error analysis and also checking accuracy checks against the data from the experiments.

2. Methodology

In this section, we describe the experimental setup and the mathematical model of SRM along with the suggested inverse numerical modelling to get the flux linkage profile. To determine the SRMs phase current i, the basic simulation model used by many researchers including [10] is described by the following equations.

Equation (1) relates the applied voltage v to the winding resistance R and the flux linkage ψ, with respect to time t:

$$v = Ri + d(\psi) / dt \qquad (1)$$

We can express Equation (1) differently by using the relationship between flux linkage and current, which is:

$$\psi = Li \qquad (2)$$

Now, Equation (1) can be written as:

$$v = Ri + Ldi/dt + idL/dt \qquad (3)$$

If we introduce rotor position θ and angular speed $\omega = d\theta/dt$ into Equation (3), we get:

$$v = Ri + Ldi/\mathrm{dt} + idL/\mathrm{dt} * \omega \qquad (4)$$

Where ω represents angular speed in radians per second.

Equation (4) shows that the applied voltage is the sum of resistive voltage drop, inductive voltage drop, and the induced EMF. To analyze the power components, we multiply Equation (4) by phase current i:

$$vi = Ri^2 + i^2 + i^2 dL/dt * \omega \qquad (5)$$

Equation (5) demonstrates that the total power consists of power loss, the rate increase of the magnetic energy stored and also the converted power between electrical and mechanical energy. Once the data of induced electromotive force is available across the winding of the machine, we can obtain the flux linkage ψ using Equation (6):

$$\int EMF\, dt = \psi \qquad (6)$$

Having obtained the flux linkage from Equation (6), we can use the relationship from Equation (2) to calculate the inductance profile of the machine. Equation (7) can be used to related the co-energy represented by W' and the profile of the flux within the SRM with respect to the current represented by i and the position represented by θ.

$$W'(\theta, i) = \int i\, \Psi(\theta, u)\, du \qquad (7)$$

The co-energy profile obtained from Equation (7) can be utilized to compute the static torque (θ, i) of the machine, as described in Equation (8):

$$T(\theta, i) = \partial W(\theta, i) / \partial\theta \qquad (8)$$

Equation (8) represents how the co-energy profile is used to calculate the static torque based on the position and current.

The foundation of our investigation in this study relies on the collection and measurement of experimental data, a crucial step that is executed using the methodologies outlined in [7-8]. Specifically, we have meticulously documented the data tables pertaining to the induced electromotive force (EMF) within the search coil of an existing switched reluctance prototype.

This prototype boasts a distinctive pole structure and is equipped with an asymmetrical converter featuring 4-phase connections for the switched reluctance motor (SRM), as elaborated in [7-8]. LabVIEW was used to collected data from the flux of a SRM. The considered SRM had an RPM of 1500, a power of 0.75 kW and a configuration of D-80. These gathered flux linkage characteristics, corresponding to various rotor positions and current levels, are visually depicted in Figure 1, offering a comprehensive 3D representation. Furthermore, the acquisition of experimental data for static torque involved the use of a dynamometer, employing a locked rotor test to facilitate the flow of current through the motor winding. The experimental torque profile will be elaborated upon in the results section and will play a pivotal role in validating the outcomes of our simulations. Figure 2 shows the experimental toque for various values of current and lines for positions.

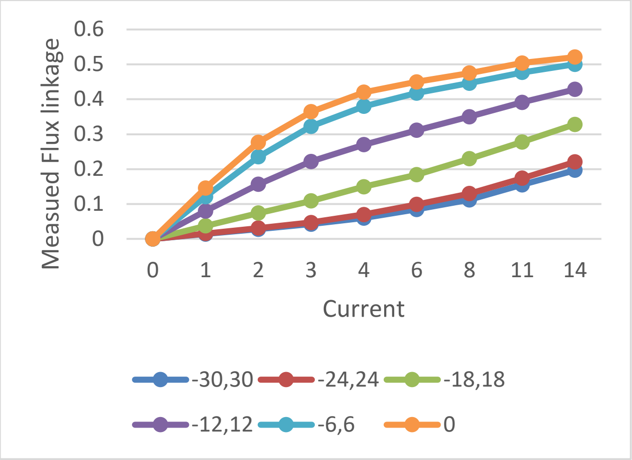

Figure 1. Measured flux linkage data table

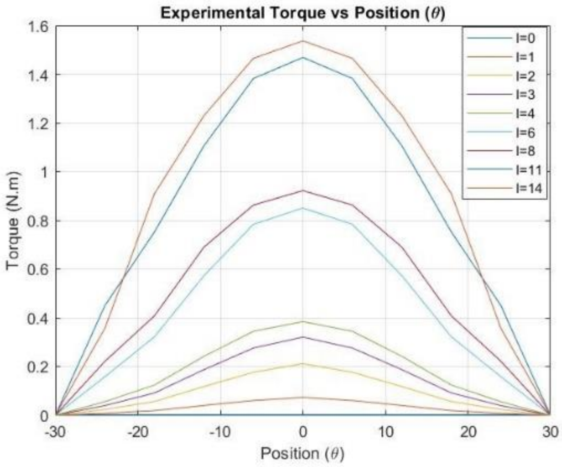

Figure 2. Measured static torque

The proposed inverse simulation protocol comprises of the following steps:

1. Initially input the experimental torque data $T\ (\theta, i)$.
2. Then, numerically inverse integrate the experimental torque $T\ (\theta, i)$to get the Co-Energy $W'(\theta, i)$ by using trapezoidal rule.

$$\omega'\ (\theta, i)\ =\ \int_0^{\theta} \tau\ (\theta, i)\ \partial\theta \qquad (9)$$

3. By using finite derivative approximation on $W'(\theta, i)$, we get the simulated/computed Flux as:

$$\varphi\ (\theta_{j,} i_k) = \frac{\delta}{\delta i}\ \omega'(\theta_{j,} i_k) \qquad (10)$$

4. The simulated flux profile can be validated with the experimental flux as in Fig. 2.

Thus the flux can be calculated by performing inverse numerical integration on the experimental torque data, specifically integrating T(θ, i), followed by numerical differentiation of $W'(\theta, i)$. The Trapezoidal scheme has been adopted for numerical integration in (9) [8], whereas the finite difference approximation of forward step is suggested for the differentiation in (10) [8].

4. Results and Discussion

We utilized equation (9)-(10) to implement inverse numerical simulation techniques starting with the measured torque profile (depicted in Figure 2) across a range of constant currents spanning from 0A to 14A, while also considering different machine positions within the -30 to 30 degree range. This simulation was conducted using MATLAB. The data derived from the experimental torque profile using (9) to get co-energy of the machine is shown in Fig. 3 and 4 across the entire range of machine positions (-30 to 30 degrees) and various constant current levels (0 to 14A). Fig. 3 shows co-energy versus position and Fig. 4 show the same versus current.

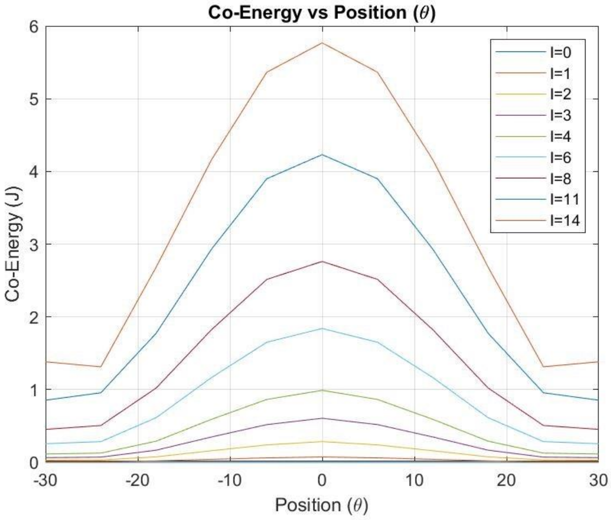

Figure 3. Computed Co-energy versus position using (9)

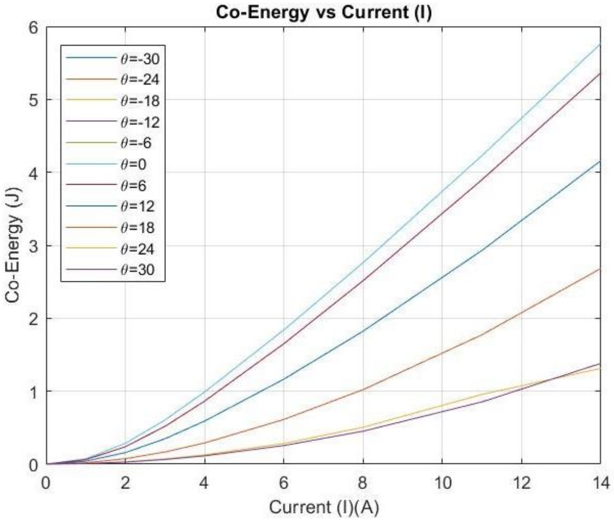

Figure 4. Computed Co-energy w.r.t current using (9)

After obtaining the approximate co-energy profiles of SRM through inverse mathematical model, we proceed to calculate static flux profiles using equation (10). This is done to facilitate the application of the finite difference formula for approximating the partial derivative of co-energy with respect to position, as depicted in the implementation. The static flux profiles computed using (10) are illustrated in Fig. 5 and 6, Fig. 5 as flux versus rotor position and in Fig. 6 as flux versus current.

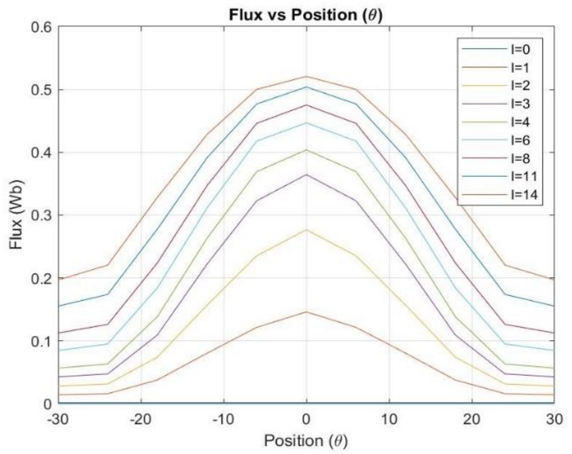

Figure 5. Computed Static Flux w.r.t rotor position

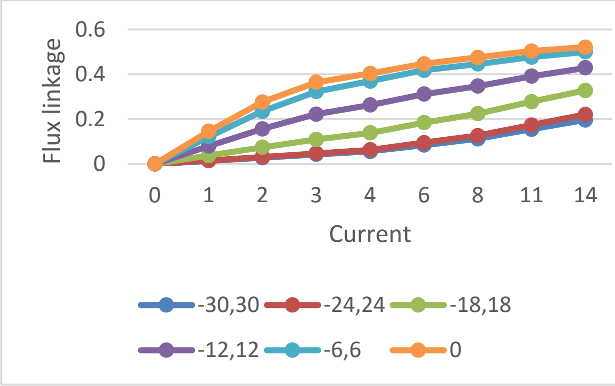

Figure 6. Computed Static Flux w.r.t current

For analysis of errors and accuracy, we compute absolute errors in the computed flux data as shown in Figure 4 with the experimental flux data as in Figure 1. The absolute errors are shown in Figure 7. Figure 7 shows that the simulated flux agrees well with the experimental flux for starting and ending current nodes, whereas there are slight deviations in the numerically computed profiles for the current nodes at 4A, 6A and 8A. These variations correspond to the rotor positions in the range -30 to 30 degrees. The deviations are no more than 0.0162 which occurs at the intersecting nodal point for current 4A and at rotor positions of -6 and 6 degrees. All other deviations are smaller than this, which is in good agreement with the direct profiling of these profiles as discussed in [7-8].

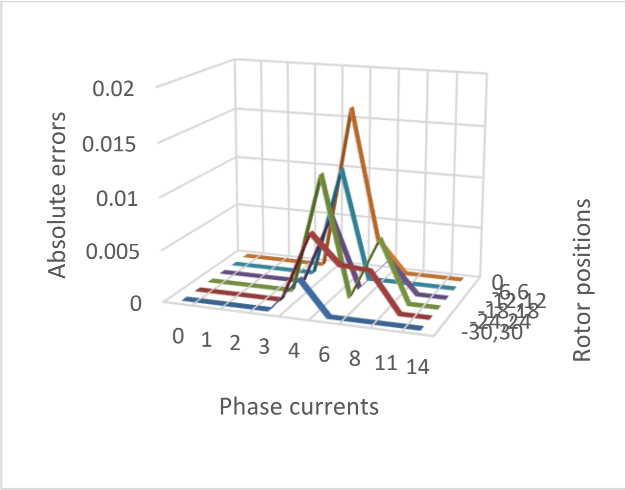

Figure 5: 3D plot of absolute error distributions in the simulated versus the experimental flux for different phase currents and rotor positions

5. Conclusion

A highly efficient inverse numerical simulation protocol has been proposed to more accurately simulate the static flux linkage characteristics of Switched Reluctance Motors (SRMs), surpassing the precision of an existing direct simulation scheme which relies on experimental validation of flux linkage. The methodology commences by utilizing experimental input data depicting the experimental torque profile of the SRM. Subsequently, an inverse protocol based on numerical integration technique is employed to generate a comprehensive co-energy table without relying on flux linkage data. Lastly, flux linkage characteristics are computed using a finite difference approach from the co-energy profiles. To assess the accuracy, the static flux profiles produced by the proposed model are compared using experimental data as the reference benchmark. The analysis of error distributions and the comparison of static flux linkage profiles reveal that the proposed inverse numerical scheme exhibits acceptable accuracy, with fewer errors and increased efficiency compared to the direct simulation results. This comparison is grounded in the experimentally obtained static flux linkage profiles of the SRM, confirming the successful validation of the proposed inverse numerical method.

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