# An Improved Method for Measuring the Inductance Profile of a Switched Reluctance Motor


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***Abstract*— This paper aims to develop an improved method for experimentally measuring the phase inductance profile of a Switched Reluctance Motor (SRM) based on the current saturation method. Simulation results of the Finite Element Method (FEM) for determining the inductance profile of a three-phase, type 12/8, SRM (LZA-48V/60V1200W) and experimentally obtained results are presented.**



***Keywords—switched reluctance motor, inductance profile, measurement, flux linkage, FEM***


## I. Introduction

The Switched Reluctance Motor (SRM) has enjoyed great interest in various industrial applications, including wind power systems and electric vehicles, due to its straightforward and resilient design, high torque capacity, extensive speed range, and exceptional energy efficiency [1].

The measurement of the phase inductance profile of SRMs is essential for their effective modeling, control, and optimization. SRMs are characterized by highly nonlinear magnetic properties, where phase inductance varies significantly depending on rotor position and winding current.

Due to the highly non-linear nature of the inductance profile of this motor type and its absence in the manufacturing specifications, it is essential that the inductance be measured accurately for a single electrical period and at different phase currents. The accuracy of determining phase inductance is also critical for predicting the electromagnetic torque, which depends on the inductance gradient with respect to the rotor's angular position.

Various methods exist for measuring the phase inductance of SRM [2]. Some of these methods are characterized by complex experimental setups, the availability of specific devices, significant computational resources, and time, and result in large relative errors [3].

This paper aims to develop an improved method for experimentally measuring the phase inductance profile of a Switched Reluctance Motor (SRM) based on the current saturation method. Simulation results of the Finite Element Method (FEM) for determining the inductance profile of a three-phase, type 12/8, SRM (LZA-48V/60V1200W) and experimentally obtained results are presented.

## II. An Inductance Profile Measurement Techniques

The primary SRM parameters, including the phase inductance profile and the electromagnetic torque, are determined by the magnetization characteristics $\Psi_{ph}(\theta_{ph}, i_{ph})$ obtained at varying rotor positions and phase current magnitudes.

### *A. Current saturation method for an SRM inductance profile measurement*

A current saturation method for an SRM inductance profile measurement proposed in [4,5] represents a determination of the inductance profile with DC current when switching a single transistor (with a frequency of 1Hz). A DC voltage source delivers electrical energy to the SRM phase under investigation, with the rotor maintained in a fixed position.

The functional generator controls a single MOSFET transistor to turn the inductive voltage ON and OFF. The phase current is calculated after measuring the voltage drop over the shunt resistor with an appropriate value. In parallel with the phase winding and shunt resistor, a freewheeling diode is connected, and its forward current is the demagnetization phase winding current during the OFF period of the switching MOSFET. The digital oscilloscope is applied for direct measurement of the voltage throughout the phase winding and the voltage of the shunt resistor to calculate the phase current.

Saturation of the phase inductance is achieved by adjusting the on-time ton and off-time toff of the transistor. The switching frequency is set to 1 Hz to minimize the error caused by iron losses. A capacitor is also connected in parallel to the power source, thereby ensuring that the phase current will continue to increase until it reaches the inductance saturation region. The switching MOSFET is controlled by a functional generator, which determines the transistor's on and off periods. The ton must be much shorter than the toff, ensuring full charging of the bulk capacitor before the next switching cycle.

After each successive change of rotor position, the function generator must be fine-tuned to maintain the peak current value in the phase inductance saturation zone. The measurement is repeated for different rotor positions, and the inductance profile can be calculated in accordance with equation (1) and the measured values of the phase voltage and current [4].

$$L_{ph}(\theta_{ph}, i_{ph}) = \frac{1}{2\pi f}\sqrt{\left(\frac{V_{ph}}{i_{ph}}\right)^2 - \left(R_{ph}\right)^2} \tag{1}$$

where $V_{ph}$ and $i_{ph}$ are the phase voltage and current, respectively; $R_{ph}$ is the phase active resistance, and $f$ is the switching frequency. In view of the motor rotor's high magnetic saturation, the maximum and minimum values of the measured results must be taken into account.

One limitation of the proposed method is that when measuring under saturation conditions, a phase current that can reach up to three times the nominal current is operated. This phenomenon is accompanied by the heating of the stator windings and a concomitant change in active and resistance $R_{ph}$.

### *B. An improved current saturation method for SRM inductance profile measurement*

The proposed advanced method for measuring the inductance profile of the considered SRM is presented in Fig. 1. The current and voltage of the corresponding phase (in this case, phase ***A***) are measured directly using a digital oscilloscope, and the voltage and current probes are connected to it. The square pulse, generated by the control logic, determines the conduction time of the switched MOSFET transistor. The switching of this transistor is initiated manually, and the duration of this switching can be set to within 0.1mS. Consequently, the motor winding is disconnected from the power source. Notably, significant phase currents do not flow through the motor winding while recording and processing the captured data and subsequent settings. As a result, phase winding heating and copper losses are reduced.

Fig. 2 presents the oscillograms from the experimental measurements obtained under a phase current 55A and a commutation angle of 18 mechanical degrees.


Fig. 2. Phase current (blue) and phase voltage (yellow).

The current during phase conduction is represented in blue, while the applied phase voltage is in yellow.

To calculate the magnetization, using the following [4,5]:

$$\psi_{ph}\left(\theta_{ph}, i_{ph}\right) = \int \left(V_{ph} - i_{ph} R_{ph}\right) dt, \tag{2}$$

where $V_{ph}$ represents the applied pulse voltage on the phase winding, $R_{ph}$ represents the active winding resistance, and $i_{ph}$ represents the measured phase current. The precise measurement of the active resistance of the phase winding $R_{ph}$ is essential to the accuracy of the results obtained. Two independent methods were utilized for this study, and the results obtained from these methods were sufficiently approximate in value.

The first method involves directly measuring $R_{ph}$ using a precision multimeter (FLUKE 8842A) and applying the four-wire technique. The second method involves the construction of an A-V (ammeter-voltmeter) circuit, where a sufficiently powerful external source passes a constant current through the phase winding. This current generates a voltage drop, and the precise measurement of $i_{ph}$ and $V_{ph}$ guarantees an accurate value of the observed active resistance, which is calculated using Ohm's law.

This method enables the acquisition of readings over an extended time interval while ensuring minimal heating of the phase winding. Consequently, the error in $R_{ph}$ calculations is minimized.

To calculate the flux linkage $\Psi_{ph}$ is used, Simpson's 1/3rd rule [6,7] according to the established methodology, each continuous quantity is represented as a set of points at equal intervals on the abscissa axis, lying on a parabola tangent. This paper divides the time interval into eight subintervals ($n$ = 8) for more accurate results. The following system of equations calculates the flux linkage:

$$\psi_{ph} = h/3\{f(X_0)+4f(X_1)+2f(X_2)+...2f(X_{n-2})+4f(X_{n-1})+f(X_n)\} \tag{3}$$

$$f(X_n) = (V_{phn} - i_{phn} R_{phn}), \tag{4}$$

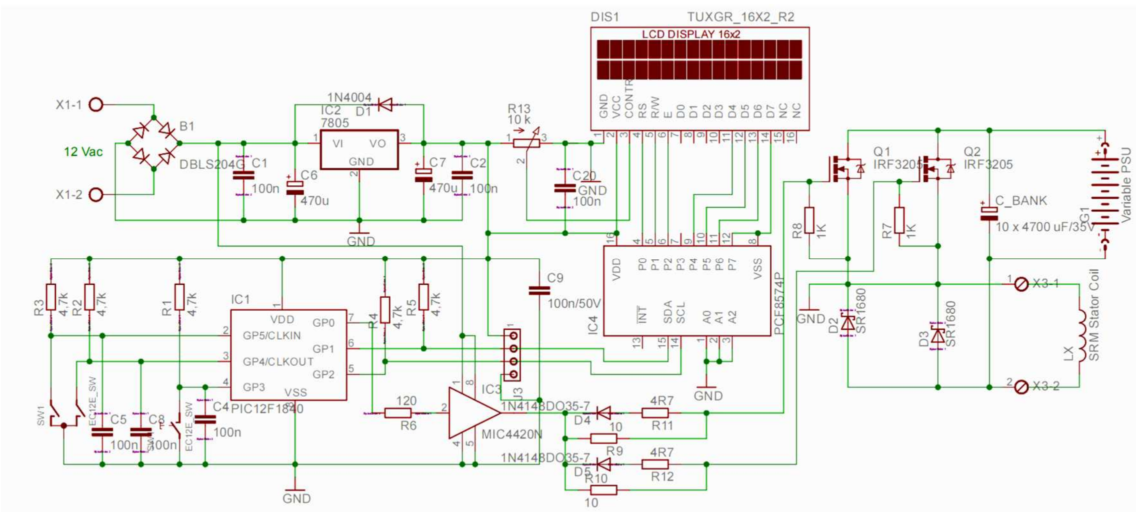


Fig.1. Operation circuit of the proposed SRM inductance profile measurement.

$$
\begin{aligned}
f(X_0) &= (V_{ph0} - i_{ph0}R_{ph0}) \\
f(X_1) &= (V_{ph1} - i_{ph1}R_{ph1}) \\
f(X_2) &= (V_{ph2} - i_{ph2}R_{ph2}) \\
&. \\
&. \\
&. \\
f(X_8) &= (V_{ph8} - i_{ph8}R_{ph8})
\end{aligned}
\tag{5}
$$

The flux values $\Psi_{ph}$ thus obtained are calculated for angles with a step of 1 degree for a whole electrical period. After the acquisition of the magnetization values for one electrical period and the various phase currents, the phase inductance is calculated using the following equation:

$$
L_{ph}(\theta_{ph}, i_{ph}) = \frac{\Psi_{ph}}{(i_{phn} - i_{ph0})} \tag{6}
$$

## III. Simulation and Experimental Results

This section presents some of the simulation and experimental results obtained from the study.

Furthermore, a FEM model is structured in the Infolytica MotorSolve software simulator, with the following input parameters: a rotor position changes from 0° to 45° mechanical degrees through 1°, and a phase winding excitation current from 0A to 60A through 1A. Fig. 3 illustrates the FEM simulation results of the magnetization characteristics $\Psi_{ph}(\theta_{ph}, i_{ph})$ at varying magnitudes of phase currents and switching angles.

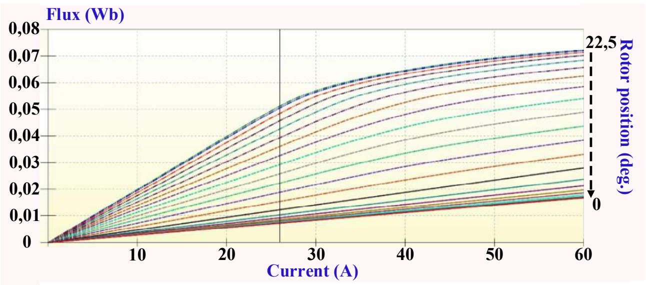


Fig. 3. FEM results of flux linkage characteristics $\Psi_{ph}(\theta_{ph}, i_{ph})$.

As illustrated in Fig. 4, the FEM simulation results obtained for the phase inductance are presented $L_{ph}(\theta_{ph}, i_{ph})$ as the rotor position is changed and the phase winding excitation current is increased.

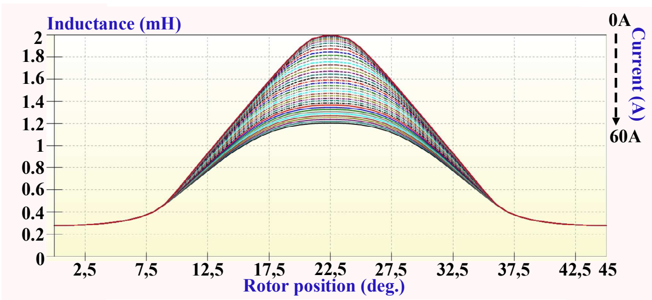


Fig. 4. Two-dimensional plot of the inductance profile – FEM results.

Using the improved direct current method with a single transistor switch, we obtained the magnetization and phase inductance values experimentally for different rotor positions ranging from 0° to 45° in 1° increments, as well as for phase winding excitation currents ranging from 1 A to 60 A in 1 A increments.

Fig. 5 and Fig. 6 present two-dimensional graphs of magnetization $\Psi_{ph}(\theta_{ph}, i_{ph})$ and inductance $L_{ph}(\theta_{ph}, i_{ph})$, respectively, showing some of the experimental results. The characteristics of both parameters are shown in different colors depending on the magnitude of the excitation currents and the commutation angles. It is evident that the graphs reflect the symmetrical structure of the investigated SRM.

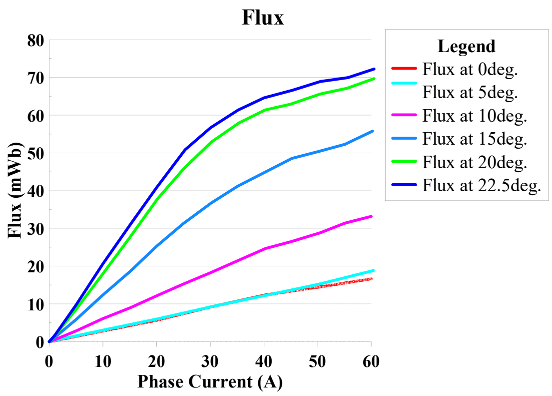


Fig. 5. Experimental results of flux linkage characteristics $\Psi_{ph}(\theta_{ph}, i_{ph})$.

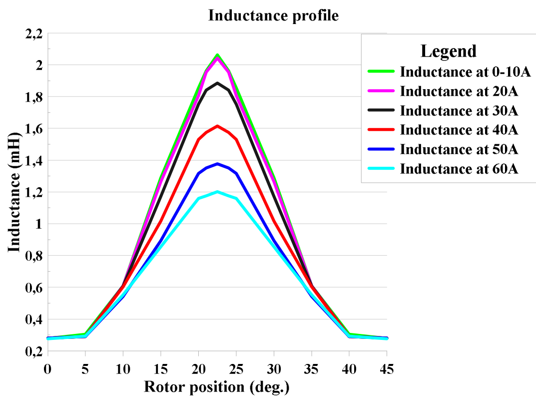


Fig. 6. Two-dimensional plot of the inductance profile – experimental results.

As can be seen from the graphical results presented here, the shapes and values of the magnetization and phase inductance are close to each other in experimental measurements and simulations. However, a more detailed analysis was conducted by comparing the phase inductance profile $L_{ph}(\theta_{ph}, i_{ph})$ results of the SRM under study and compiling a table of relative errors and a two-dimensional graph. Table 1 presents a summary analysis for two rotor positions (aligned and unaligned, respectively) and a phase excitation current of 30 A, using the simulation study results as a reference frame.

TABLE I. EXPERIMENTAL AND SIMULATION RESULTS OF SRM (LZA-48V/60V1200W) INDUCTANCE PROFILE

| Methods | Inductance (mH)at aligned position | Inductance (mH)at unaligned position | Aligned position - relative error δ % | Unaligned position – relative error δ % |
|---|---|---|---|---|
| **FEM** | 1,8992 | 0,2793 | - | - |
| **Method [4]** | 2,05 | 0,299 | 7,94 | 7,05 |
| **Proposed method** | 1,8851 | 0,2796 | 0,74 | 0,107 |

Fig. 7 presents a summary comparison between the different rotor positions and a phase current of 30 A. In order to perform a comprehensive comparative analysis of the proposed method, inductance values obtained by simulation study of the motor by the finite element method (FEM) are used as a reference frame.

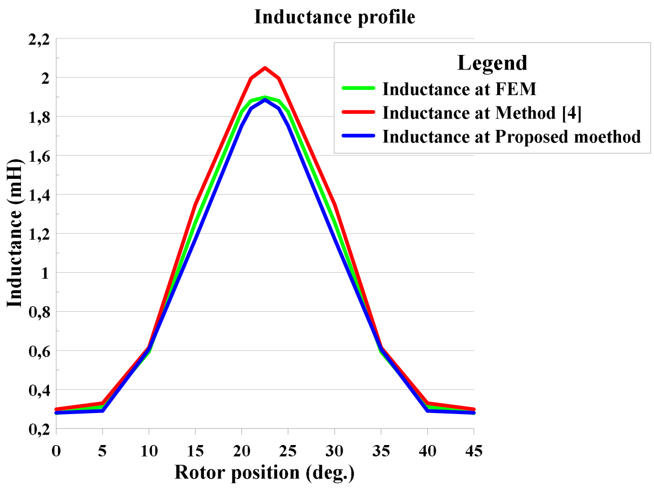


Fig. 7. Comparison of the results obtained for the inductance profile using different methods.

As shown in Fig. 7, the error between the experimental results obtained from the proposed method and the simulation results is minimal, if not negligible. This is in contrast to the method discussed in [4], where the error is much larger. Therefore, it can be concluded that the proposed experimental method yields accurate results.

## IV. CONCLUSION

This paper presents an enhancement to a method for experimental determination of the phase inductance profile of SRM. The proposed method is characterized by reduced losses in motor steel due to the use of non-repeatable pulses. Additionally, this results in reduced copper losses due to lowered coil heating. Precision measurements are also accomplished, as the relative error to the FEM analysis is below 1%. The findings will be instrumental in developing a model of the examined SRM within the MATLAB/Simulink environment.

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