

Analytical and Experimental Investigation of the Phase Inductance Profile of a Three-Phase 12/8 SRM

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Abstract—The paper presents a comparison between methods for analytical and experimental investigation of the phase inductance profile of switched reluctance motors. Since this type of motors have highly nonlinear phase inductance characteristics and most often only the maximum and minimum inductance values are given in the specification, which in many cases the specification is not available, they must be measured very precisely for one electrical period. The obtained results are used to structure an accurate mathematical model for a simulation study of the performance of the SRM. For this reason, the purpose of this paper is to investigate and compare analytical and different experimental methods, using as a reference frame for comparison the simulation results obtained by the Finite Element Analysis method to determine the inductance profile of a three-phase type 12/8 SRM (H55PWBKM-1844). From the analysis performed, the relative error between the individual methods was calculated and the most accurate one was proposed to be used to measure the static characteristics of the SRM phase inductance and guarantee the most reliable results.

Keywords— *inductance, switched reluctance motor, modeling, nonlinear characteristics*

I. INTRODUCTION

The growing interest in the switched reluctance motor (SRM) in recent years is associated with a number of difficulties in the analysis, measurement and design of propulsion systems realized through them [1]. One of the most important things in the research is the measurement of the motor parameters to be used in the mathematical modeling of the motor drive. For this reason, it is necessary to develop a precise mathematical model of the relevant switched reluctance motor.

The inductance profile is a very important parameter in drive design and operation. Due to its highly nonlinear characteristic, it is necessary to obtain an accurate profile of the inductance for one electrical period, which in turn is not an easy task when measuring this parameter [1].

The purpose of the performed analytical and experimental studies is to determine the exact characteristics of magnetization of the corresponding SRM. As a result, the inductance profile will be determined in order to achieve higher efficiency in the design of the converter controlling the motor, as well in the synthesis of a simulation nonlinear mathematical model as close as possible to the real one.

II. METHODS FOR DETERMINING THE INDUCTANCE PROFILE OF THE SRM

The electromagnetic torque and inductance profile can be determined from the magnetization curves of the corresponding SRM at different rotor positions and applied phase currents. The results of the magnetization curves can be obtained from experimental studies or calculated using the Finite Element Analysis method for the corresponding SRM. Another method of obtaining the inductance profile is its analytical calculation.

The purpose of the research done is to analyze and compare different methods for measuring the phase inductance profile and to choose the most accurate one in order to achieve higher efficiency in the design of the converter driving the motor, as well as to synthesize a simulation mathematical model, as close as possible to the real one.

A. Analytical determination of the inductance profile

One method of determining the inductance profile of a SRM is doing it analytically, neglecting magnetization. The physical parameters of the machine are used. The value of the maximum phase inductance is calculated when the rotor position is aligned with the stator of one of the phases. The phase inductance of the investigated three-phase type 12/8 SRM (H55PWBKM-1844) consists of four pole sections connected by means of the 2-parallel, 2-series method, from which it follows that the total phase inductance consists of two series-connected windings or the following equation can be written down [2,3]:

$$L_{ph} = L_{ph1} + L_{ph2} = 2L_{ph1}, \quad (1)$$

from where L_{ph1} is equal to:

$$\frac{1}{L_{ph1}} = \frac{1}{L_1} + \frac{1}{L_4}. \quad (2)$$

For L_{ph2} it can be written:

$$\frac{1}{L_{ph2}} = \frac{1}{L_2} + \frac{1}{L_3}. \quad (3)$$

The equation for determining the maximum inductance value is [2,3]:

$$L_{ph} = 2 \frac{\mu_0 S_m w^2}{(x_{a1} + x_{a2})}, \quad (4)$$

where in $\mu_0 = 4\pi \cdot 10^{-7}$ μ_0 is the magnetic constant (the magnetic permeability in a vacuum), S_m is the section of the magnetic core in the case of the SRM pole, w is the number of windings on the stator pole, and x_{a1} and x_{a2} is the air gap between the stator and the rotor tooth in an aligned position [2,3].

To calculate the section of the magnetic core, the following formula is used:

$$S_m = L_{stk} b_{zs}, \quad (5)$$

where L_{stk} and b_{zs} are, respectively, the length and width of the sides of the magnetic core (in this case, the stator tooth).

B. Alternating current method for determining the inductance profile

There are various experimental methods to determine the inductance profile of the SRM at different current and rotor position. One of them is the alternating current method. The magnitude of the inductance is determined by the measured current and voltage. An alternating voltage is applied to one of the phases of the SRM by means of an autotransformer, as shown in Fig.1.

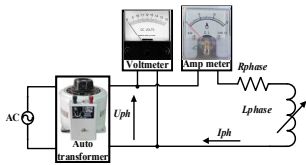


Fig. 1. Schematic circuit diagram for determining the inductance profile of the SRM by means of alternating current method.

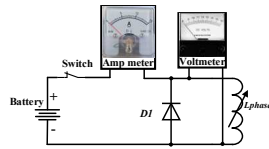


Fig. 2. Schematic circuit diagram for determining the inductance profile of the SRM by means of the direct current method.

With the help of a voltmeter and an ammeter, the effective values (rms) of the applied phase voltage V_{ph} and current i_{ph} are measured when the rotor is blocked relative to the stator. The measurements were repeated for different positions of the rotor and magnitude of the phase currents. The phase inductance is calculated using equation (6) at a constant phase resistance R_{ph} and the network frequency f [3,4,5].

For the phase inductance, the following dependence is valid:

$$L_{ph}(\theta_{ph}, i_{ph}) = \frac{1}{2\pi f} \sqrt{\left(\frac{V_{ph}}{i_{ph}}\right)^2 - (R_{ph})^2} \quad (6)$$

where the measurement of the value of R_{ph} is performed in advance by means of an Ohmmeter.

C. Direct current method for determining the inductance profile

Another method by means of which the phase inductance of the SRM is determined is the so-called direct current method. With it, in an analogous way to the previous method, the values of the applied voltage and the current flowing through the motor winding are measured with the

help of an ammeter and a voltmeter. The measurements are repeated for the different rotor positions and magnitude of the phase current. Unlike the previous method, this one applies a constant voltage to the corresponding phase of the SRM. The phase voltage is determined by the dependence:

$$V_{ph} = i_{ph} R_{ph} + \frac{d\psi_{ph}(\theta_{ph}, i_{ph})}{dt}, \quad (7)$$

from where for flux linkage it can be written:

$$\psi_{ph}(\theta_{ph}, i_{ph}) = \int (V_{ph} - i_{ph} R_{ph}) dt, \quad (8)$$

where Ψ_{ph} is the phase flux linkage.

By calculating the flux linkage by means of equation (7) and performed calculations, (8) is transformed and the equation for the phase inductance $L_{ph}(\theta_{ph}, i_{ph})$ is derived which has the form [3,5]:

$$L_{ph}(\theta_{ph}, i_{ph}) = \frac{\psi_{ph}(\theta_{ph}, i_{ph})}{i_{ph}}. \quad (9)$$

Using equation (8) and (9), the phase inductance is calculated for the different rotor positions and magnitude of the current through the phase. Fig.2 shows the schematic diagram used in measuring the phase inductance characteristics this method [3,4,5,6].

D. Method for directly determining the DC inductance profile of two transistors switching

In this method, the rotor is locked in a fixed position, but unlike the previous two methods, a pulsed voltage is applied to its phase. As in the previous methods, the phase resistance (R_{ph}) is measured in advance, after which the inductance can be calculated with equation (6) using the measured current and voltage. In this method, as in the alternating current method, the calculation of the magnetic flux is not necessary [3,5,6]. The basic electrical circuit comprises a single-phase inverter, consisting of two MOS transistors and two diodes, shown in Fig.3.

A voltmeter and an ammeter are used connected in parallel and in series on the respective phase. With the help of a signal generator, the control signals for the operation of the MOSFET transistors are provided. For different rotor positions, the experiment is repeated to obtain the current characteristic, then using equation (6) and the directly measured current and voltage values, the inductance profile is calculated [3,5].

For the *rms* value of the current, the following dependence is valid:

$$i_{ph} = \frac{V_{ph}}{R_{ph}} \left(1 - e^{-\frac{R_{ph} t}{L_{ph}}} \right). \quad (10)$$

Inductance L_{ph} is determined by expression (6), where f in this case is the switching frequency of the transistors. In view of the high magnetic saturation of the motor rotor, the peak and minimum values of the measured results must be taken into account. A disadvantage of the method is that the values for the inductance are calculated by means of the *rms*

current values and cannot be used accurately to represent the instantaneous values of the inductance [3,5,6].

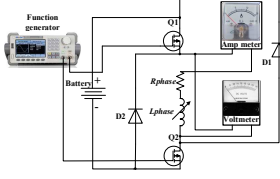


Fig. 3. Schematic circuit diagram for determining the inductance profile of the SRM using the method of direct determination with DC when switching two transistors.

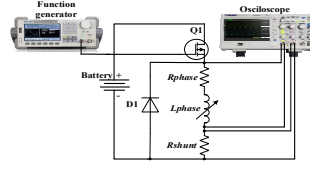


Fig. 4. Schematic circuit diagram for determining the profile of the inductance of the SRM using DC when switching one transistor.

E. Method of directly determining the DC inductance profile of a single transistor switching

In the literature, there are other methods for measuring the inductance of a SRM. Their experimental setups are much more complex and require highly specific devices, huge costs and time. The presented method is much simpler and accurate for magnetic phase saturation using a simple experimental setup to achieve precise results [3,5].

The method uses a DC voltage applied to the corresponding SRM phase winding with the rotor locked in a fixed position. Unlike the previous method, the two MOS transistors used are replaced by one similarly connected to a function generator. In order to calculate the phase current, a shunt resistor with low resistance and high power connected in series to the phase under study was used. A diode is connected in parallel to the motor phase and the shunt resistor to allow current to flow in the reverse direction when the MOS transistor is off. Using an oscilloscope, the phase voltage and the current through the phase are measured by means of the voltage drop across the shunt resistor. The schematic diagram of the experimental setup is shown in Fig.4.

The saturation of the phase inductance is adjusted by changing the on t_{on} and off t_{off} times of the transistor. The switching frequency of the transistor is chosen to be 1Hz to minimize the error from steel losses. The function generator used serves to generate the control pulses of the transistor and ensures shorter on time than off time to fully charge the capacitor. Since only the increasing part of the current curve is calculated, the use of a classical asymmetric bridge converter is not necessary. When changing the rotor position, it is necessary to readjust the function generator to maintain the peak value of the current in the saturation zone of the phase inductance [3,5].

III. ANALYTICAL AND EXPERIMENTAL RESULTS

This section presents the results obtained using the methods described above.

First method: Analytical determination of the inductance profile.

Using expression (5), the stator tooth width ($b_{zs}=1.27\text{cm}$), the magnetic core cross section is equal to $S_m=5,97 \cdot 10^{-4}\text{m}^2$.

The number of turns on one of the poles is experimentally determined to be $w=150$. The air gaps between the stator and rotor teeth are the same in the aligned

position and the measured physical dimensions are equal to: $x_{a1}=x_{a2}=0,46\text{mm}=4,6 \cdot 10^{-4}\text{m}$.

After investigation and determination of the unknown values from (4), the maximum value of the phase inductance in the aligned position is equal to $L_{ph}=36,69 \cdot 10^{-3}$.

To calculate the values of the phase inductance when the rotor is in the unaligned position and the magnetic saturation is neglected, the shape of the rotor is assumed to be circular. The perimeter is used to calculate the air gap length per degree. The rotor circumference is equal to:

$$P = \pi \cdot d = 3,14 \cdot 8,3\text{cm} = 26,062\text{cm} = 26,062 \cdot 10^{-4}\text{m}. \quad (11)$$

To calculate the length per degree L_{deg} , the circumference of the rotor is divided by 360 degrees. The result of the calculation is:

$$L_{deg} = \frac{P}{360} = \frac{26,062}{360} = 0,072394\text{cm} = 0,072394 \cdot 10^{-4}\text{m}. \quad (12)$$

The equation for calculating the different values of phase inductance in the unaligned position is as follows:

$$L_{ph} = 2 \frac{\mu_0 S_m w^2}{(x_{a1} + x_{a2} + x_{La1} + x_{La2})}, \quad (13)$$

where x_{La1} and x_{La2} are the length of the air gap depending on the position of the rotor relative to the stator. To calculate the x_{La1} and x_{La2} air gaps, the corresponding degree of offset from the aligned rotor position is multiplied by the length per degree of rotor circumference L_{deg} .

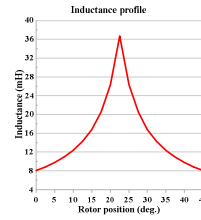


Fig. 5. Phase inductance profile from analytical calculation.

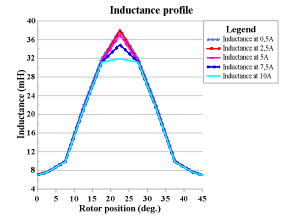


Fig. 6. Phase inductance profile obtained using the second method.

After the mathematical calculations, the phase inductance values at different angles of the rotor with respect to the stator are graphically presented in Fig.5.

Second method: Alternating current method for determining the inductance profile

The alternating current method was used to experimentally determine the phase inductance values at different rotor positions and excitation currents up to 10A. Fig.6 shows the corresponding two-dimensional (2D) plot of the inductance profile obtained from the experiments and analytical calculations. The investigations were carried out by varying the rotor position from 0° to 45° and the phase current from 0A to 10A. The phase inductance characteristics at different excitation current values are shown in different colors.

Third method: Direct current method for determining the inductance profile

The phase inductance values were measured at different rotor angles and phase excitation currents. Fig.7 shows the phase inductance characteristics obtained by means of the

direct current method as a function of rotor position and phase current magnitude. The range of the rotor position over which the investigations were carried out was the same as for the previous method, from 0° to 45°, and the phase winding excitation current was 0A to 10A.

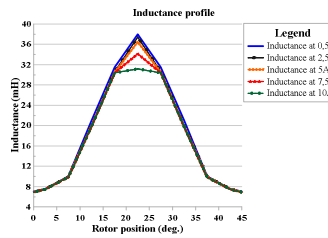


Fig. 7. Phase inductance profile obtained using the third method.

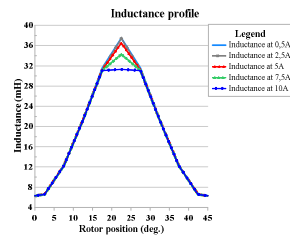


Fig. 8. Phase inductance profile obtained using the fourth method.

Fourth method: Method for directly determining the DC inductance profile of two transistors switching

Determination of the phase inductance characteristics using a constant supply voltage and two transistors switching. Fig.8 shows the characteristics of the inductance profile based on the numerical results. The data are obtained for different values of the current flowing through the phase from 0A to 10A for the rotor displacement range from 0° to 45°.

Fifth method: Method of directly determining the DC inductance profile of a single transistor switching

Determination of the phase inductance by applying a constant voltage and switching only one transistor. As with the previous methods, similar values for the magnitude of the phase inductance are obtained. Fig.9 shows a graphical representation of the inductance profile based on the measured and calculated values. The phase inductance values are shown at different current levels from 0A to 10A. The range of rotor position change is from 0° to 45°.

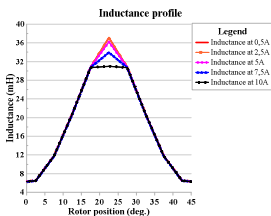


Fig. 9. Phase inductance profile obtained using the fifth method.

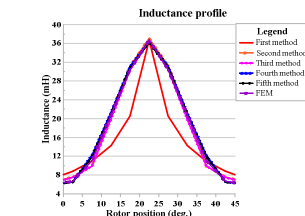


Fig. 10. Comparison of the results obtained for the inductance profile of the different methods.

TABLE I. NUMERICAL VALUES AND RELATIVE ERROR BETWEEN ANALYTICAL, EXPERIMENTAL AND SIMULATION STUDY OF PHASE INDUCTANCE OF THE STUDIED 12/8 THREE-PHASE SRM

Methods	Inductance (mH) at align. pos.	Inductance (mH) at unalign. pos.	Aligned position – error %	Unaligned position – error %
FEM	36,73	6,40		
First	36,70	8,08	-0,08	26,30
Second	37,10	7,06	1,02	10,32
Third	36,46	6,92	-0,71	8,14
Fourth	36,51	6,31	-0,58	-1,40
Fifth	36,20	6,34	-1,42	-0,84

In Fig.10, are shown in different colors the values of the inductance profile for the different methods at different rotor positions and 5A phase inductance excitation current of its determination. It can be concluded that the relative error

between experimentally measured and calculated phase inductance results is minimal with respect to the reference frame, finite element analysis method. Table 1 shows the relative error in determining the inductance profile through FEM analysis and the values obtained using analytical and experimental methods. The error is calculated for the aligned rotor position at maximum inductance and the unaligned position at minimum inductance at either 22.5° and 0° or 45°.

From the results presented in Table 1, it can be concluded that the most suitable method for the experimental determination of the inductance profile is the direct current method using two transistors (fourth method).

IV. CONCLUSION

The paper presents methods for analytical and experimental determination of the phase inductance profile of a SRM. After literature research, several methods were chosen for determining it both analytically and experimentally. Unlike the analytical approach for calculating the inductance presented in the literature review, which calculates the inductance only for an aligned position of the rotor relative to the stator, the analytical approach proposed in this paper makes it possible to determine the phase inductance profile at different positions of the rotor.

On the basis of the research a table was produced to show how the different methods for determining the profile of the phase inductance compare. From the results shown and the obtained relative errors between the individual methods for measuring the phase inductance in comparison with the the Finite Element Analysis method it can be concluded that of all the methods, the direct current method with two transistors is the most suitable one and has the smallest error thus being as close as possible to the reference inductance values.

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