Measurement of Inductance in Switch-Reluctance(SR) Motor

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Abstract—**This paper presents the measurement of inductances in two phases 4/6 pole switched-reluctance (SR) motor. This project is mainly focused in laboratory measurement and data analysis to measure the inductance. The current and voltage waveform need to be measured in lab in order to do the integration of flux by using MATLAB software. Then the unsaturated inductance for rotor position can be obtained by the slope of linear part of the flux linkage versus current curve. Finally, the laboratory experiment results will be compared with finite element analysis that can be obtained by using the 2D Finite Element Method Magnetic (FEMM) program.**

Keywords-SR motor, inductance, flux linkage, FEA

I. Introduction

Switch reluctance (SR) motors are the simplest electric motors in construction which has salient pole in both rotor and stator. Thus, it is referred as a doubly salient motor. There is wound field coil of a dc motor at the stator and no coils on the rotor. They have a highly nonlinear magnetic characteristic which is related to the change of their inductances depending on the current and its position[1]. The basic assumptions of SR motor are there is no mutual flux linkage between phase windings which means one phase is excited at a time and the ferromagnetic materials in the motor have a linear characteristic. Therefore, the flux linkage of a winding can be described by an inductance[2]. To measure the flux linked of SR motor, the rotor is locked at certain positions[3]. The measurement can be obtained by repeating the different rotor positions and it will present the flux curve for a variety of phase currents in one period time. The unsaturated inductance for the different rotor position involved is the slope of linear part of the flux-linkage versus current curve. The core losses need to be taken care in this experiment because the area of flux linkage versus current loop under locked rotor represents the core losses. The suitable value of resistor will minimize the flux linkage curve loop area.

From the previous literature, finite element analysis (FEA) is a computer simulation which is widely used for SR motor magnetization characteristic and performance analysis [3-4]. FEA can be used to measure flux linkage and inductance at variable value of currents and different rotor positions. To do the FEA, the measurements of exact geometrical parameters need to be taken from the actual motor to get accurate result.

II. Methodology

A. Experiment Setup for measurement

The simple power MOSFET controller is construct to excite a phase winding at a particular instant. The MOSFET works as a switch to control the motor. In order to construct the controller, the high speed dual MOSFET driver is used for applications that require low current digital signals to drive large inductive load. The input from signal generator has transistor-transistor logic (TTL) compatible in order to generate the square wave that can be triggered by MOSFET. The parallel resistor and capacitor is to provide suitable circuit of turn-on and turn- off times. The capacitor increases the drive to the base at switch ON and the voltage stored in the capacitor, drive the base negative at switch OFF. The fast recovery freewheeling diode is connected to parallel with the SR motor as a protection mechanism to dissipate any back electromagnetic force (EMF) generated by the motor when the MOSFET turns it "OFF" and clamps the drain terminal of the device to the output voltage represent by the 12V battery[5] [6]. The capacitor is functioning as a dc voltage to give supply to the SR motor phase winding. When the rotor is locked mechanically at desired position, a dc voltage is applied to the test phase winding, thus the phase current increases. The power is switched off and the current is diverted when the current reaches the steady state. The experimental setup for measurement of inductance is shown in figure 1.

The laboratory equipments that had been used to measure the inductance are:

1) Digital oscilloscope
2) Function generator with TTL compatible
3) DC power supply with maximum range of current until 1A
4) Dual tracking DC power supply with maximum range of current until 5A
5) Differential probe to measure phase voltage

6) Current probe to measure phase current

The performance measurement of inductance is obtained by applying the digital oscilloscope with USB interface which allows the data of voltage and current waveform of the SR motor in excel file to be saved. The application of differential probe is used to obtain the voltage waveform and the application of current probe is used to obtain the current waveform. The voltage and current waveform is taken at difference rotor position in order to see the variable of inductance at different position starting from unaligned position until reached the aligned position.

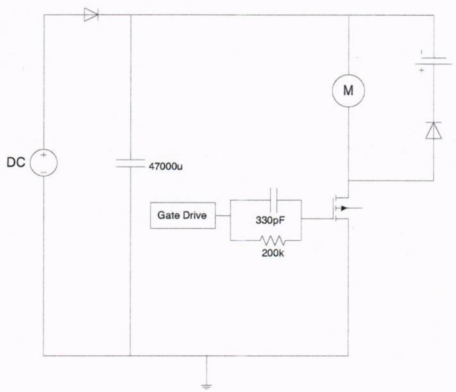

Figure 1. Experiment setup

B. *Data analysis*

In order to do the data analysis from voltage and current waveform, MATLAB software is suitable to do the integration and plotting the graph to get the flux linkage curve. The ratio from differential probe and current probe need to give attention to get the accurate value while doing the integration. A simple integration program is written by using the trapezoidal rule to get the flux linkage curve. The integration of flux linkages, $\lambda(t)$ is given for one rotor position:

$$\lambda(t) = \int_0^t v(t) - i(t)R_p \, dt \qquad (1)$$

Where:

- v is the voltage across the phase winding
- i is the phase current
- R is the resistance of the phase winding

The resistance in the function represents the resistance per phase from which the inductance is obtained. Through the experiment, there is core loss in the SR motor. When the flux linkage versus current loop is plotting, the area of the curve represents the core loss. To isolate the core loss from the SR motor by using the calculation, the value of resistor need to change repeatedly until the appropriate resistor is acquire.

III. EXPERIMENTAL AND DATA ANALYSIS RESULTS

A. *Experiment results*

The maximum current from dc supply is applied to the circuit. Then the voltage is increased from the dc supply until the current and voltage waveform can be analyzed. During the experiment, it was difficult to get a nice waveform of current and voltage. The capacitor of 56000μF was installed into the circuit to get nice waveform of voltage. The signal generator functioned at 100Hz and the time ON and time OFF at 0.001s. The rotor position started from unaligned at 0° until aligned position at 30° because the one electric period of the motor is 30°. The data was taken for one phases of stator pole and will be recorded by using digital oscilloscope with USB interface.

Figure 2 shows the voltage and current waveform for the aligned position at 0° by using excel. For other rotor position is almost the same waveform but have different value of inductance.

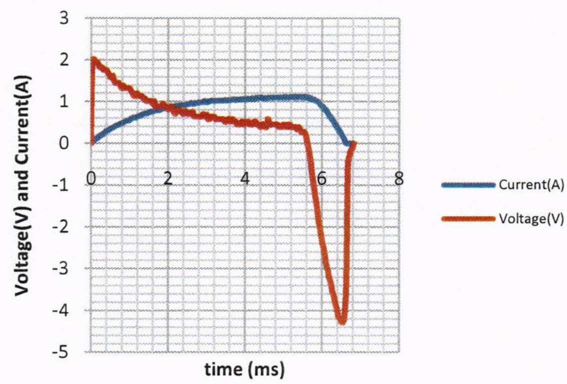

Figure 2. Measured voltage and current waveforms at unaligned position.

The flux linkage curve is obtained from integration function of flux from (1). By assuming the phase winding, R_p, is the sum of actual phase winding, R, and the resistance error, ΔR, the equation of R_p can represent as [7]:

$$R_p = R + \Delta R \qquad (2)$$

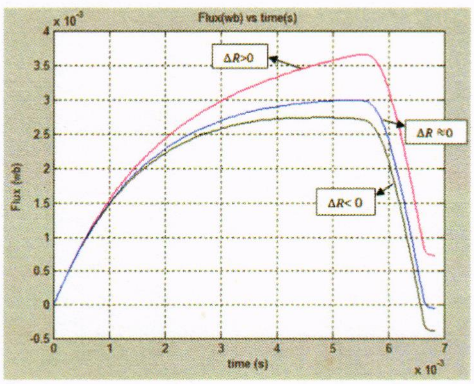

Figure 3. Flux linkage curve with different value of resistance

To obtain the curve of zero loop area from flux linkage versus current curve, the flux linkage curve must returns to zero as voltage waveform is returns to zero. From the figure 3, the flux linkage curve is almost returns to zero after adjusting the value of phase resistance. After the appropriate value of resistor is measure, the flux linkage curves versus current need to be plotting in order to calculate the unsaturated inductance from the slope of linear part of the curve. The result from adjusting the value of resistor will contribute to the area of flux linkage versus current loop under locked rotor which is representing the core losses. If the core losses are attributed to the appropriate resistor, the final flux linkage curve has almost zero loop area.

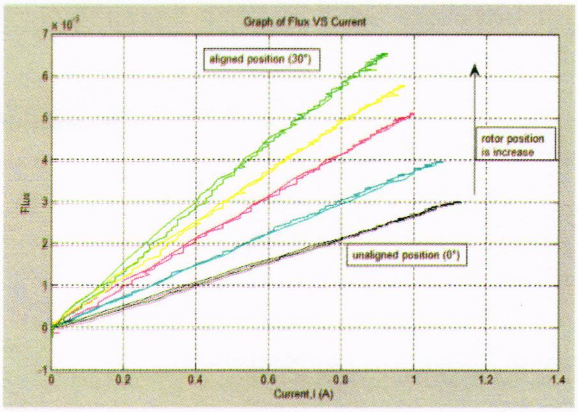

Figure 4. Flux linkage versus current

Figure 4 shows the graph of flux linkage curves versus current with different rotor positions. The measured position started from unaligned position 0°, 10°,15°,20° and lastly at aligned position which is 30°. From the graph, the value of unsaturated inductance can be calculated from the slope of linear part of flux linkage curve. The equation of inductance is [2]

$$L = \frac{\lambda}{i} \qquad (2)$$

Table 1 shows the value of calculated inductance at variable rotor positions.

TABLE 1. Value of calculated inductance

Rotor Position	Inductance(mH)
0°	2.65
10°	3.70
15°	5.00
20°	6.00
30°	7.50

By referring to table 1, the value of inductance is increased depending on the change of rotor position. At aligned position, the maximum inductance occurs and at unaligned position the inductance is minimum.

B. Finate Element Analysis (FEA)

The geometry of real SR motor can be draw using FEMM software. FEA method will be used to compare the value of inductance that has been measured during experiment. Due to the difficulty of modeling nonlinear SR motor, the FEA results are commonly acceptable [3]. The flux distribution using FEMM is showed in figure 6 and figure 7. In FEMM, the rotor in SR motor used the M19 steel block type. The 1010 steel block type was used for the shaft of SR motor. The dimension of SR motor is given in table 2.

From the previous final year project, it was found that the most significant parameter that affects the end-winding inductance is the distance that separate the two phase winding blocks. To measure the inductance using FEMM software, the simulation of SR motor at different rotor position and the end winding inductance simulation need to be measured to get the accurate value of inductance. This is because the FEMM is the 2D program that cannot measure the inductance with end winding inductance at one time. While doing the FEA, the end winding inductance is measured and will be add up with the inductance that had been measured with different rotor position to get the accurate value of inductance. The value of end winding inductance was 1.19mH. Tables 3 show the measurement of inductance before and after add up with the end winding of inductance. Figure 5 shows the flux distribution of end winding inductance using FEA method.

TABLE 2. Dimension of SR Motor

Number of stator poles	4
Number of rotor poles	6
Stator pole diameter (outer)	85mm
Rotor diameter (bore)	35mm
Shaft diameter	8mm
Number of turns/phase	110
Estimated end winding length	31mm
Stack length	10mm
Air gap	0.6mm

TABLE 3. Value of inductance at different rotor position using FEA before and after add with the end winding inductance

Rotor Position	Inductance(mH)	Inductance with end winding inductance (mH)
0°	1.50	2.69
10°	2.58	3.77
15°	3.68	4.87
20°	4.68	5.87
30°	6.09	7.28

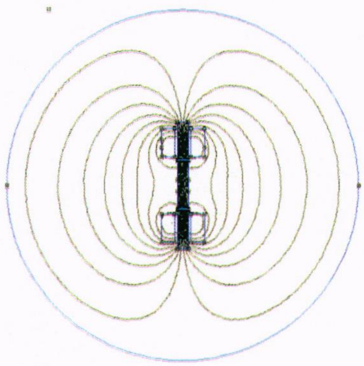

Figure 5. Flux distribution for end winding inductance

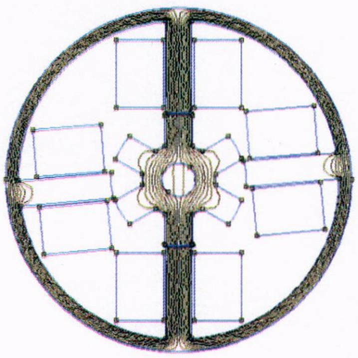

Figure 6. Flux distribution during fully aligned position

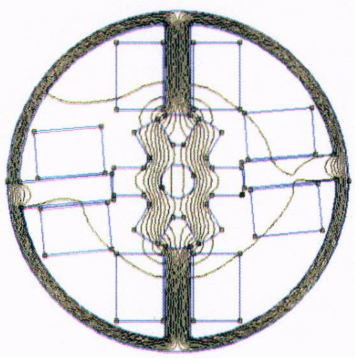

Figure 7. Flux distribution during unaligned position

C. Comparison between the experimental results and FEA

The experimental results is measured using the digital oscilloscope that can be recorded the waveform of voltage and current. The flux curves for both experimental and FEA results were plotted using MATLAB software. From figure 8, it shows the comparison of flux curve between experiment and FEA. FEA results act as the reference to prove the efficiency of the experimental results.

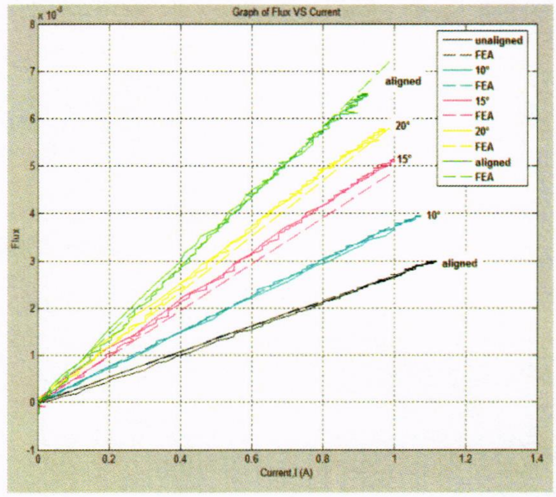

Figure 8. Comparison of flux between experimental and FEA

As given clearly in table 4, the values of inductance between FEA and measurement results from experiment are not much difference. All the percentage difference between the FEA and experiment is less than 10%. Thus, the proposed experiment setup is efficient to obtain the inductance profile.

TABLE 4. Values of Inductance using experiment and FEA

Rotor Position	**Measurement (mH)**	**Finite Element Analysis(mH)**	**Percentage differences (%)**
Unaligned	2.65	2.69	1.49
10°	3.70	3.77	1.86
15°	5.00	4.87	2.67
20°	6.00	5.87	2.22
30°	7.50	7.27	3.16

IV. CONCLUSION

As a conclusion, the inductance profile of short stack two-phase 4/6 poles SR motor had been measured using laboratory measurement. The result that was obtained in experiment had been compared with the estimated value of inductance profile using finite element analysis. From the results, it is observed that the experimental measurement of inductance can be accepted because of lower percentage difference.

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