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Implementation of Switched Reluctance Motor, Measurement of Flux Linkage, and Inductance Characteristics

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ABSTRACT

Magnetization characteristics play an important role in design, implementation and performance for switched reluctance motors SRMs. The first objective in modelling of SRM is to provide a good accuracy and robust operation over the entire speed and torque range. This paper introduces physical phenomenon that need to be included in actual model of the SRM drive. The introduced methodology is applied on SRM that may be used in aerospace, military, and medical applications for measurement of flux linkage and inductance characteristics. Experimental results are well accurate for modelling and performance analysis of implemented SRM. The cost is lowered in measurement of flux linkage, and inductance characteristic, where the experimental instruments used in this method are common, and the test bench is easy to build, as the SRM has been built. The test indicates the measuring process is simple to implement, and the results are satisfactory, and accurate.

Key words: Implementation, Inductance, Flux Linkage, Simpson's rule, SRM.

1. INTRODUCTION

In the last few years SRM drives, which are electrically, and mechanically rugged have gained more interest, become more popular and have raised many analysis, design and measurement issues than other electrical drives.

One of the important aspects in modelling of SRM drives is the measurement of motor parameters used for the analysis and design of the converter, prediction of the performance of drive etc. SRM has advantages over AC & DC motors like simple and robust construction, no brushes, low inertia and high torque to weight ratio, no rotor windings, no commutator, consequently low maintenance cost, and simple power converter circuit. But the most important advantage is it has fault tolerant capability all of the above and more make it an ideal candidate for use in industrial and domestic applications.

The knowledge of real flux linkage characteristic is the key to design, control, and performance analysis of SRM drive [1], [2]. The flux linkage and inductance profile of the SRM depend on the rotor position and phase current.

The measurement of flux linkage curves may be carried out in many different ways:

- From static interaction torque measurement and a known flux linkage value at an arbitrary position [14].
- Using a DC power supply and measuring the transient current response during the energizing or the de-energizing period [15], [16].
- Without a search coil fitted, applying an AC power supply, and measuring the RMS values of the voltage, and current.
- Supplying an AC voltage superimposed on a DC voltage to the winding and measuring the RMS values of the AC voltage and AC current.
- Supplying AC power to the winding with a search coil fitted, measuring the instantaneous current in the excitation coil and the voltage induced in the search coil.
- Using an AC power supply and no search coil, measuring the instantaneous current and voltage in the motor phase winding.

This paper presents an overview of previous reported measurement methods, and demonstration of the applied method which means using a DC power supply and measuring the transient current, and voltage response during the energizing period. The DC flux linkage measurement method are based on the fact that the flux linkage is equal to the integral of the terminal voltage minus the stator resistive voltage drop [15], [16].

For this study, a SRM has been implemented as a part of the test bench member. This paper presents building up, and implementation procedure of 3-phases 6/4 SRM and the measurement method for obtaining the flux linkage, and inductance characteristics of SRM. For different rotor positions the family of the flux linkage characteristics would be computed as accurately as possible [3].

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2. OPERATION PRINCIPLE

In SRM both the stator and the rotor are salient poles Fig.1, shows he cross section of 6/4 SRM. The stator winding consists of a set of concentrated coils, each of which is wound on one pole, then every two diametrically opposite poles windings connected in series, or parallel as designed to correctly set magnetic poles (north, and south) up as these windings are energized with appropriate power [4].

The reluctance of the flux path between the two diametrically opposite stator poles varies as a pair of rotor poles rotates in and out of alignment. Since inductance is inversely proportional to reluctance, the inductance of a phase winding has to distinct positions [5] characterized by the properties summarized in Table I:

Figure 1. Cross section of One Lamination 6/4 SRM

- Aligned position (maximum inductance): when any pair of rotor poles is exactly aligned with the stator poles of the excited phase, that phase is said to be in aligned position.
- Unaligned position (minimum inductance): when the interpolar axis of the rotor is aligned with the poles of the excited phase, that phase is said to be in unaligned position.

TABLE I. ALIGNED AND UNALIGNED POSITIONS PROPERTIES

	Aligned Position	**Unaligned Position**
Relative Position Between Rotor and Stator Axes	0°, or 180°	±90°
Inductance	Maximum	Minimum
Magnetic Circuit	Liable to saturation	Unlikely to saturate
Torque-Stability	Zero-Stable equilibrium	Zero-Unstable equilibrium

With successively energizing phases, the rotor can rotate in any direction according to energizing sequence of phases. The production of torque of the SRM depends upon the stator current magnitude not of the direction Fig.2. If current flows in a phase winding the inductance of that phase winding will get increase, and result in pulse of positive torque.

A negative torque contribution is avoided if the current is reduced to zero before the inductance starts to decrease again. The rotor speed can be controlled by controlling the switching frequency of the phase current pulses while synchronism with the rotor position has been retained [3], [4].

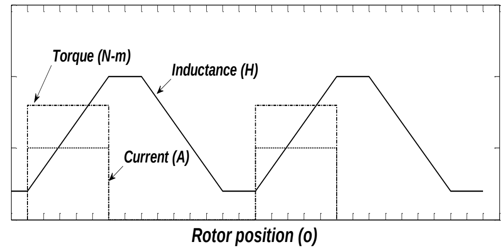

Figure 2. Idealized Inductance, Current, and Torque versus Rotor position

3. MATHMATICAL MODEL OF SRM

System simulation Complexity is the significant feature of SRM drive much more than DC & AC motor drives because its operational region nonlinearity. The nonlinearity is produced due to the three factors [6], [7]. First, nonlinearity of B-H characteristics of the magnetic material. Second phase flux linkages dependence on both the current magnitude, and rotor position while in other machine it is dependent only on current magnitude. Third the single source of excitation.

There are numerous methods for modelling the SRM, such as magnetic equivalent circuit analysis, lookup table techniques, finite element analysis FEA [8], [9], and cubic-spline interpolations.

Magnetic equivalent-circuit analysis and FEA are computationally intense. The cubic-spline interpolations and lookup table techniques require numerous flux-linkage versus current versus position data, which are obtained either through FEA or making experiments, which are time-consuming and tedious.

SRM model obtained using analytic methods have been presented [4]. Magnetic equivalent-circuit analysis characterized by easier analysis of the machine, as they offer insight into its working, in formulating control strategies and in implementing high accuracy in performance computations, where integration, and differentiation are easier to perform.

By applying the presented method, zero speed consequently no influence on a deviation of the current Slope. The deviation of the current slope is only related to DC input voltage and self-inductance of motor. As a result, by sensing current slope the self-inductance of the motor can be precisely estimated.

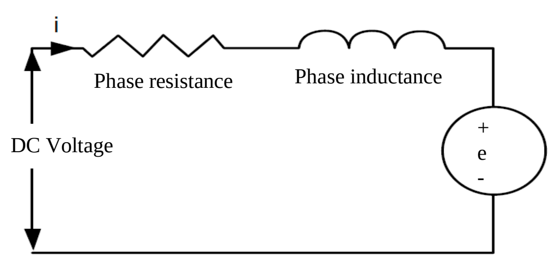

Figure 3. The electrical circuit for one energized phase of SRM

SRM model is basically consisted of three parts: the electrical model, torque characteristics and mechanical model. The electrical circuit for one energized phase of SRM is shown in Fig. 3.

Applying Kirchhoff's voltage law thus voltage given by (1)

$$v = ir + \frac{d\lambda(i.\vartheta)}{dt}. \qquad (1)$$

where v is the phase voltage, i is the phase current, r is the phase resistance and $\lambda(i.\vartheta)$ is the magnetic flux linkage that is given by (2).

$$\lambda(i.\vartheta) = L(i.\vartheta)i. \qquad (2)$$

where ω is the angular velocity, and $L(i.\vartheta)$ is the phase inductance, which varies as a function of phase current (due to magnetic saturation), and rotor position (due to varying reluctance).

Applying variable separation to solve (1), and calculate magnetic flux linkage at various phase currents, and rotor positions from measured stator voltages, currents and resistance as given in (3).

$$\lambda(i.\vartheta) = \int (v - ir)dt. \qquad (3)$$

The electrical model of SRM can be compared with DC motor by substituting (2) in (1) as follows

$$v = ir + \frac{d(L(i.\vartheta)i)}{dt}$$

$$v = ir + L(i.\vartheta)\frac{di}{dt} + i\frac{dL(i.\vartheta)}{dt}$$

$$v = ir + L(i.\vartheta)\frac{di}{dt} + i\frac{d\vartheta}{dt}\frac{dL(i.\vartheta)}{d\vartheta}$$

$$v = ir + L(i.\vartheta)\frac{di}{dt} + i\omega\frac{dL(i.\vartheta)}{d\vartheta}. \qquad (4)$$

According stand still operation (4) may be rewritten as

$$v = ir + L(i.\vartheta)\frac{di}{dt} \qquad (5)$$

so flux linkage, and inductance can be calculated at different rotor positions using numerical integration.

4. POWER CONVERTER OF SRM DRIVE

Since the direction of the torque does not depend on the sign or the value of current or flux linkage, but only controlled by $dL/d\vartheta$. Accordingly, the current and the flux linkage may be unipolar not alternating, and phase independence, so a great feature have been achieved.

The controller must be supply, and regulate the magnitude, and the shape of unipolar current pulses, to fulfil speed, and torque control requirements, and ensure safe operation of power transistor and, the motor.

For each rotor stroke, the power electronic converter for a SRM is required to first increase the flux in the phase winding by providing a positive voltage loop. Second, if the desired current level is reached it must have the ability to reduce the applied voltage. Third, it must apply a negative voltage at turn off, also referred to as a negative voltage loop [10].

Classification of power converters of SRM drives, where q is the number of phases is shown below in Fig. 4.

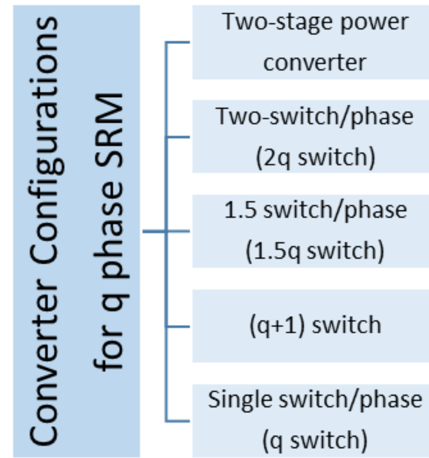

Figure 4. Classification of Power converters of SRM Drive

5. METHODOLOGY

The rotor position and the energized stator phase current are factors which controlling the flux linkage characteristics, consequently phase inductance of SRM. The ideal flux linkage characteristics of SRM are plotted in Fig. 5.

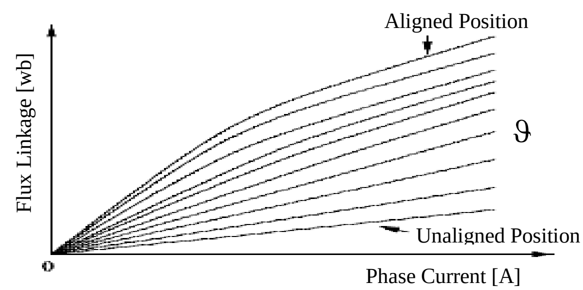

Figure 5. Ideal Flux Linkage Characteristic of SRM

The flux linkage characteristics at aligned, unaligned, and intermediate positions are represented [5].

While the phase winding is excited with the appropriate DC current. The measurement of phase voltage and current with knowing phase resistance, so the flux linkages, and phase inductance can be estimated in two approaches. First measuring the rising current profile by supplying a constant voltage to phase windings. Second measuring the decaying current profile when the circuit is de-energized, by establishing a steady state DC current in the winding and then de-energized. A simplified measurement circuit for SRM flux linkage characteristics is shown in Fig. 6.

While all phases are open except the phase under test the voltage given by (1) when a voltage pulse applied to that phase of the SRM.

From (3), estimation of flux linkage could be achieved using any numerical integration technique, so (3) is integrated by using Simpson's 1/3rd rule.

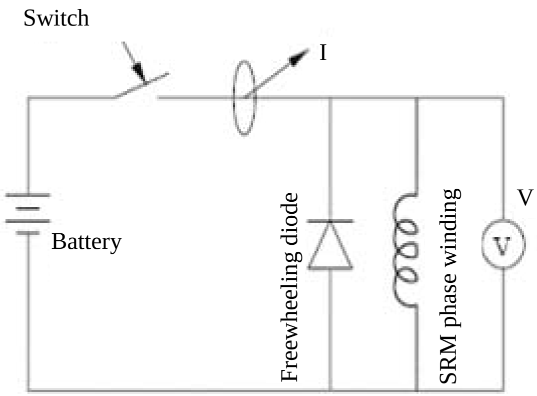

Figure 6. Circuit Diagram for Estimating Flux Linkage

Simpson's 1/3rd rule (6) is one of the popular methods of numerical integration [11], and it is used for the calculation of definite integrals

$$\int_b^a f(x) = \frac{h}{3}[f_0 + 4f_1 + 2f_2 + \cdots$$

$$+4f_{n-2} + 4f_{n-1} + f_n]. \quad (6)$$

$$h = \frac{a-b}{n}. \quad (7)$$

where a, and b are the lower and upper limits of integration, and n the number of subdivisions must be even.

6. EXPERIMENTAL SETUP

6.1.Implementation and Building up of SRM

The selected motor was designed and manufactured by Danfoss A/S in 1992 and the motor has also been tested at Aalborg University [4]. The main design parameters for a 0.55 kW, 6/4, 3-phase, 80 volts, and 2500 rpm. Design parameters somewhat altered according to available materials, and workshop abilities, and summarized in Table II.

TABLE II. MAIN PARAMETERS OF THE IMPLEMENTED SRM

Main Dimensions	Design
Number of Phases	3
Number of Stator poles	6
Number of Rotor poles	4
Rotor diameter (D)	0.052 (m)
Axial length (l)	0.065 (m)
Internal rotor diameter (D_{ri})	0.038 (m)
Airgap length (l_g)	0.3 (mm)
Stator internal diameter (D_{si})	0.090 (m)
Outer diameter (D_0)	0.110 (m)
Shaft diameter (d_{sh})	0.014 (m)
Stator pole angle	29°
Rotor pole angle	45°
Number of turns (N_{ph})	96
Wire diameter	1.5 (mm)

The Electrical silicone steel sheets with designation of M 800-50A [12], [13] comply with regulation of DIN EN 010106 part 1 1996 have been bought from Shubra Engineering Industries Company (27th military factory), and cut by a high accuracy laser cutting machine in Qaluib city, (Egypt) to cutting lamination shown in Fig. 1 with mentioned above dimensions.

Figure 7. Implemented SRM

Since all laminations have ready to assembled, exactly 130 laminations, forming stator, and rotor cores, using a pressure holding tool indeed. After preparing of shaft, searching a suitable yoke, preparing windings, and making some modifications all may be assembled as shown in Fig. 7.

6.2.Measurement of Flux Linkage, and Inductance Characteristics

The presented method has been tested using the implemented SRM, which is designed for electric lift truck application. The DC resistance of phase winding is measured using Voltmeter- Ammeter method, and corrected to be AC resistance of 0.3276 Ω [5]. A test platform composed of:

- SRM (implemented)
- 12 V, 65 A Battery
- Potentiometer- implemented
- GW-INSTEK GDS-1062, 60 MHz, 250 M Sam/sec, 2-channels digital storage oscilloscope DSO
- Dividing head (implemented)
- Freewheeling diode
- Allegro ACS770LCB-050B-PFF-T hall effect current sensor
- Laptop

The experimental setup is shown in Fig. 8. The potentiometer, and switch are used as a switching device to energize the phase winding of SRM under test.

Freewheeling diode is connected across the phase winding for dissipates the stored energy at de-energizing mode.

While short duration of a voltage pulse applied by turning on the switch, then the voltage and current waveforms are acquired using DSO.

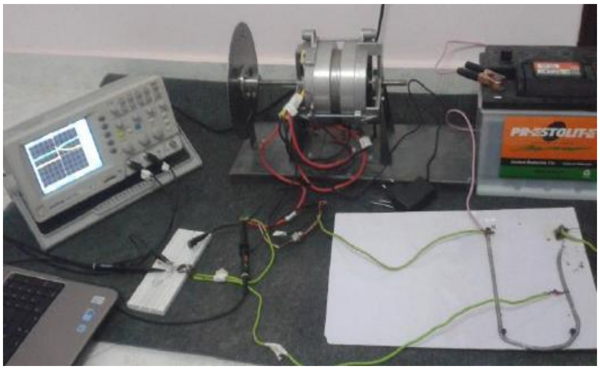

Figure 8. Measurement Test Platform

Whereas high torque produced during the experiment current a dividing, or indexing head is built to hold the rotor with even division of 2° mechanical, so the full unalignment position 44° has selected instead of 45° ideal unalignment position. While all phases windings are open except the one under test is connected to DC supply. The current and voltage waveforms across the phase winding under test are acquired using DSO as shown in Fig. 9.

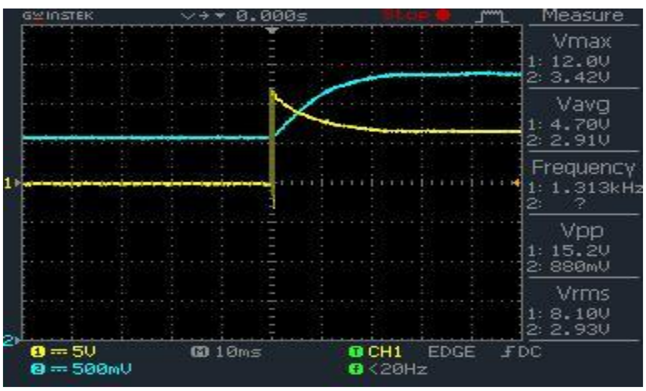

Figure 9. Acquired Current, and Voltage Waveform Using DSO

With different rotor positions, at every rotor position the digitally stored voltage and current waveform are handled in (3), (6) to estimate the flux linkage at different current levels of the phase winding under test. The flux linkage values at equally spaced rotor positions versus different current levels from unaligned to aligned position are recorded in Table III.

7. RESULTS AND DISCUSSION

The experimental results were obtained on the basis of captured voltage and current waveform at different rotor position, the flux linkage is estimated using Simpson's 1/3rd rule (6). On the basis of digitally acquired current, and voltage waveform at different rotor positions, the experimental results were obtained are recorded in Table III.

The results are compared with [17], that obtained from FEA method. Comparison showed slight difference in flux linkage, and inductance curves, due to using different cross sectional area of winding conductor, silicon steel type.

The flux linkage profile of the SRM based on experiments is shown in Fig. 10.

TABLE III. ESTIMATED FLUX LINKAGE CHARACTERISTICS OF THE IMPLEMENTED SRM

Phase Current [A]	Flux Linkage [mWb]								
	44°	*40°*	*36°*	*32°*	*16°*	*12°*	*8°*	*4°*	*0°*
0	0	0	0	0	0	0	0	0	0
1	1.9	2.7	4.3	6.7	15.3	16.0	17.3	18.0	18.9
1.75	3.3	4.9	7.3	10.5	24.9	26.7	28.6	30.5	32.3
3	5.7	7.8	11.9	17.0	40.8	43.5	47.0	50.2	53.0
4	7.6	10.1	14.4	20.9	51.7	54.9	59.9	64.2	68.1
4.75	8.7	11.2	15.8	23.5	58.7	63.1	67.8	73.4	78.5
5.75	10.8	13.8	17.1	26.0	68.1	73.6	79.2	85.4	91.5
7	13.2	16.2	19.4	29.7	80.9	86.9	92.2	99.0	105.9
8.25	16.2	19.0	21.7	31.4	91.9	97.6	104.2	112.2	118.2
9.25	17.1	20.5	22.4	32.3	97.4	103.5	112.3	120.7	126.1
10.25	19.0	21.6	23.7	31.1	102.3	109.3	119.9	126.1	131.8
11	20.5	23.3	25.3	31.1	105.2	111.7	123.0	130.0	135.9
13	24.2	27.4	29.6	35.3	113.7	120.5	131.8	138.8	145.1
13.5	24.0	27.1	29.6	34.2	113.2	120.9	130.6	139.8	146.1
14.75	26.7	28.3	31.0	36.7	117.1	123.6	134.2	143.4	149.7
15.5	27.6	29.6	31.1	36.8	116.9	122.4	133.7	140.6	149.5
16.75	29.4	31.4	32.2	37.8	116.9	126.9	136.7	143.1	150.5
17	30.2	32.4	33.5	37.6	113.5	123.7	133.6	140.1	148.7
18.5	32.5	33.6	35.2	36.1	112.5	123.5	134.3	141.4	150.7
19.5	34.6	35.3	36.7	37.2	111.7	123.3	134.8	142.2	152.1

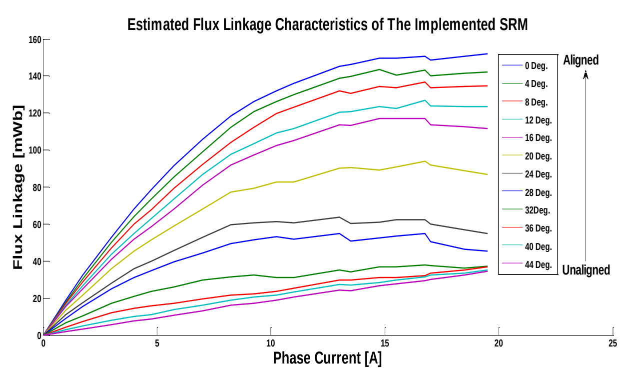

Figure 10. Estimated Flux Linkage Characteristics of The Implemented SRM

As the flux linkage characteristics of the SRM is estimated at specified rotor positions against different current levels for the phase under test, the inductance of the motor can be easily calculated according (2). Table IV presents the obtained results that are plotted as shown in Fig. 11.

TABLE IV. INDUCTANCE CHARACTERISTICS OF THE IMPLEMENTED SRM

Phase Current [A]	Inductance [mH]								
	44°	*40°*	*36°*	*32°*	*16°*	*12°*	*8°*	*4°*	*0°*
0	1.9	2.7	4.3	6.7	15.3	16.0	17.3	18.0	18.9
1	1.9	2.8	4.2	6.0	14.2	15.2	16.4	17.4	18.4
1.75	1.9	2.6	4.0	5.7	13.6	14.5	15.7	16.7	17.7
3	1.9	2.5	3.6	5.2	12.9	13.7	15.0	16.0	17.0
4	1.8	2.3	3.3	4.9	12.4	13.3	14.3	15.5	16.5
4.75	1.9	2.4	3.0	4.5	11.9	12.8	13.8	14.9	15.9
5.75	1.9	2.3	2.8	4.2	11.6	12.4	13.2	14.1	15.1
7	2.0	2.3	2.6	3.8	11.1	11.8	12.6	13.6	14.3
8.25	1.8	2.2	2.4	3.5	10.5	11.2	12.1	13.0	13.6
9.25	1.9	2.1	2.3	3.0	10.0	10.7	11.7	12.3	12.9
10.25	1.9	2.1	2.3	2.8	9.6	10.2	11.2	11.8	12.4
11	1.9	2.1	2.3	2.7	8.7	9.3	10.1	10.7	11.2
13	1.8	2.0	2.2	2.5	8.4	9.0	9.7	10.4	10.8
13.5	1.8	1.9	2.1	2.5	7.9	8.4	9.1	9.7	10.1
14.75	1.8	1.9	2.0	2.4	7.5	7.9	8.6	9.1	9.6
15.5	1.8	1.9	1.9	2.3	7.0	7.6	8.2	8.5	9.0
16.75	1.8	1.9	2.0	2.2	6.7	7.3	7.9	8.2	8.7
17	1.8	1.8	1.9	1.9	6.1	6.7	7.3	7.6	8.1
18.5	1.8	1.8	1.9	1.9	5.7	6.3	6.9	7.3	7.8
19.5	1.9	2.7	4.3	6.7	15.3	16.0	17.3	18.0	18.9

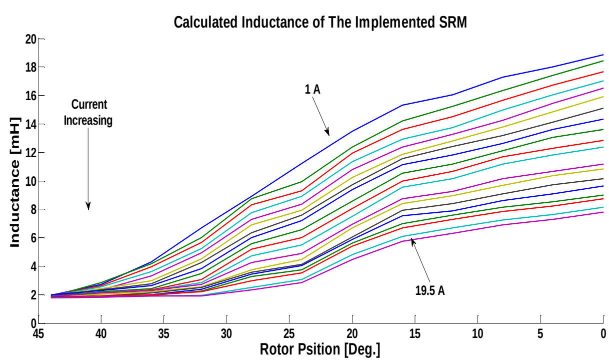

Figure 11. Calculated Inductance of The Implemented SRM

8. CONCLUSION

The paper has presented an experimental method to estimating the magnetization parameters of the SRM with simple test bench implementation, and low cost. characteristics, and inductance of the implemented SRM has been developed.

The experimental test performed on a 0.55-kW 3-phase 6/4-pole SRM gives satisfactory results and shows the effectiveness of the measurement system, and low cost platform. The flux linkage characteristics, and inductance obtained in this measurement system are very important in predicting the performance of the SRM, and can be used to derive precise analytical model and consequently utilized to develop advanced control strategies.

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