Self Characterization of Switched Reluctance Machine.

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***Abstract*— In high performance drive systems for Switched Reluctance Machines (SRM), generally it is necessary to know the inductance $\times$ position curve. The used procedures to determine the inductance $\times$ position curve, generally require a experimental setup, beyond being slow. The use of the methods based on the Fourier Series, makes possible to determine the inductance $\times$ position curve more quickly, but its use was only presented for SRM with four phases. In this paper two methods for determination of the inductance $\times$ position curve are presented. The first method adjust the method based on the truncated Fourier series, developed for SRM with four phases, for machines with three phases. In second method, current pulses are applied periodically in one phase of the machine to determine the inductance $\times$ position curve. In both the methods the used experimental setup is the same necessary to drive the machine. Moreover, the methods can be implemented of automatic mode and the time to complete the characterization of the machine is significantly reduced.**

***Keywords*— Switched Reluctance Machine, Fourier Series, Position Estimation, Self Characterization.**

I. INTRODUCTION

In switched reluctance machines it is necessary to known the shaft rotor position for a efficient operation. The position determine the moment of the current commutation among phase windings of the machine. To avoid use of mechanical position sensors, was develops various techniques of position detection. The choice of a appropriate technique depends of the characteristics of the application (machine characteristics, operation conditions, like velocity, torque level, etc).

The rotor position identification techniques can be grouped in two broad categories. The techniques that use the phase voltages and currents and the techniques that apply test signals into the phases. In both groups of techniques it is necessary to know the machine inductance curves for the rotor position identification.

In high performance drive systems the position information is also used to determine instantaneous current profiles. Like this it is possible to minimize the effects of the double saliency, that generate high torque ripple. Various torque ripple minimization techniques [3] use information of the machine characteristics curves: inductance $\times$ position and $dL/d\theta\times$ position. The curves normally are used for instantaneous current profile determination.

To determine the characteristics curves of the Switched Reluctance Machine, that relate variables like flux, current, position and torque, strategies based in flux measures (or estimation) and static torque measures are used. In both cases measures in various angular positions of the machine rotor are made. The wished precision determine the number of repetitions of the machine test procedure, where a larger number of repetitions can require a long time. Some automatic systems to realize the test procedures was proposed. In these systems the position of the switched reluctance machine rotor is determined by a auxiliary high resolution position system [5] or manually [1]. Both methods determine the characteristics curves of the switched reluctance machine with high precision, but both methods require a auxiliary hardware.

In this paper two automatic methods of determination of the curves $L_k(\theta, i) \times \theta$ in the machine phases will be examined. In both methods the system start the identification procedure only with the information of the stator/rotor pole ratio and phases number. The driven system used will be a standard driven system, assembly with one three phase bridge converter and one voltage sensor to measure the DC bus voltage to compensate the ripple effects.

II. IDENTIFICATION METHODS

The identification system of the characteristics curves for Switched Reluctance Machines proposed in this paper can accomplish two strategies of identification.

1) Simplified identification
2) Complete Identification

In the simplified identification method is used the fact of that the inductance of the Switched Reluctance Machines it is a periodic function of the position.

In both methods the Switched Reluctance Machine not use any external system to move its rotor. The movement is generated by currents applied at the phases of the machine.

A. SIMPLIFIED IDENTIFICATION: DETERMINATION OF THE CURVE $L_k(\theta, i) \times \theta$

The characteristic curve $L_k(\theta, i) \times \theta$ is periodic in relation at rotor position, then it is possible to represent the curve $L_k(\theta, i) \times \theta$ using Fourier series. In citefahimi:03 the curve of the self inductance of the Switched Reluctance Machine was represented by a truncating Fourier series given by:

$$L_k(\theta, i) = \sum_{n=0}^{2} L_n(i) \cos(nN_r\theta + \varphi_n) . \quad (1)$$

The coefficients $L_n(i)$ of the truncating Fourier series can be determining using the inductance values in rotor positions:

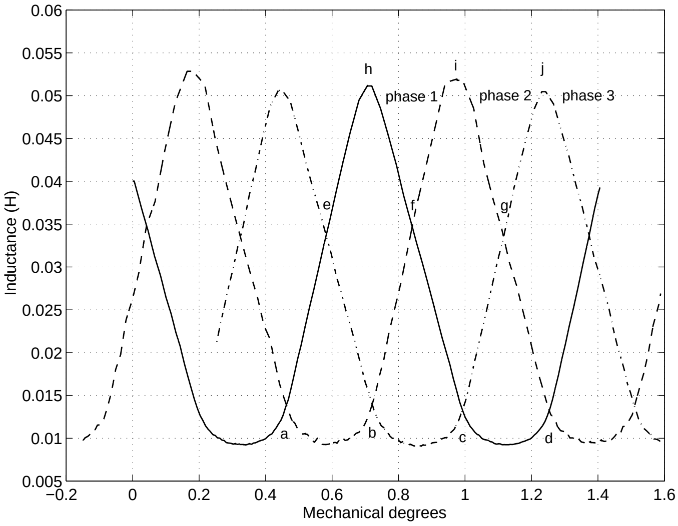

Fig. 1. Inductance profile × Position - Machine used in tests.

aligned, unaligned and intermediate positions. The coefficients are determined by the matrix expression given by:

$$\begin{bmatrix} L_0\,(i) \\ L_1\,(i) \\ L_2\,(i) \end{bmatrix} = \begin{bmatrix} \frac{1}{4} & \frac{1}{2} & \frac{1}{4} \\ \frac{1}{2} & 0 & -\frac{1}{2} \\ \frac{1}{4} & -\frac{1}{2} & \frac{1}{4} \end{bmatrix} \begin{bmatrix} L_a\,(i) \\ L_m\,(i) \\ L_{na}\,(i) \end{bmatrix}, \qquad (2)$$

where $L_a(i)$, $L_m(i)$ and $L_{na}(i)$ are the inductance values in the aligned, unaligned and intermediate positions, respectively. In four phases Switched Reluctance Machines, when the rotor go to the aligned position with the energized phase, the other phases shall be in the unaligned position (one phase) and intermediate position (two phases). In a three phases Switched Reluctance Machines when the rotor is aligned with the energized phase the other phases will not be in the aligned and intermediate positions, respectively. In this case, it is necessary to adapt the procedure to determine the inductances $L_m(i)$ and $L_{na}(i)$.

In three phase machine used in experimental setup (machine 12/8 - 12 stator poles and 8 rotor poles), the self inductance curve repeats to each 45^o mechanical ($360^0/N_r$, where N_r represent the number of rotor poles). The curve $L_k(\theta, i) \times \theta$ of the phases of the machine, shown in Figure1, can be divided in three segments: increase inductance segment, decrease inductance segment and constant inductance segment. The segments has a size of 15 mechanical degrees.

Observing the inductance curve of the phase 2 (see figure 1), the increase inductance segment start in point "b" (intersection of the inductance curves of the phases 2 and 3) and end in the point "i". In this interval the slope of the inductance curve is practically constant, like this, the segment can be approximated by a straight line. The expression of the straight line is given by:

$$L_k(\theta, i) = l_c + ml_m\theta \qquad (3)$$

where:

$$ml_m = \frac{L_a\,(i) - l_c}{15^o} \qquad (4)$$

and the inductance l_c correspond at the inductance in the crossing point of the inductance curves of adjacent phases, "a", "b", "c" and "d" points (see figure 1), while the inductance of the third phase be in the maximum value, ml_m it is the slope coefficient of the inductance curve, given in mechanical degrees. To calculate ml_m it is necessary to know l_c and $L_a\,(i)$. These values are determined through the procedure:

1) One phase of the switched reluctance machine is energized, this way the rotor of the machine tends to align with the stator pole of the energized phase. The machine remain stopped in this position;
2) Current pulses of short duration are applied in the other two phases of the machine;
3) The rise time of the current until to reach a threshold value in the two phases not energized it is measured;
4) The rise time measure in the step 3 it is used to calculate $L_k(\theta, i)$, value in both phases. The time constant of the RL circuit, represented by phase winding of the machine, was used to calculate $L_k(\theta, i)$,;
5) Steps 2, 3 and 4 are repeated to determine the maximum inductance of the phase energized on the step 1.

After to determine r_s, l_c, $L_a\,(i)$ and ml_m values the expression (3) can be used to determine the inductance value, $L_k\,(\theta, i)$, in all positions on the rise and falling segments of the inductance × position curve.

The θ value that will be used in the expression (3) to calculate the inductance on the intermediate position of the inductance × position curve is given by: $\theta = 11,25^o - 7,5^o$, where $11,25^o$ correspond the half distance among the maximum inductance position (aligned position) and minimum inductance position (totally not aligned position). The value $7,5^o$correspond at distance in degrees among the position of minimum inductance of one phase and the position where the inductances of the other phases are the same.

B. DETERMINATION OF THE RESISTANCE OF THE WINDING PHASE OF THE MACHINE: r_s

The $L_a(i)$ e l_c values are calculate using the time constant expression of the RL circuit or using the information of the flux × current curve. In both cases it is necessary to know r_s value, then it is necessary implement methods for its determination. To calculate r_s value, every machine phase is energized which current constant. The voltage between terminals of each energized phase is measure and the r_s is calculate using the ratio $r_s = voltage/current$. The constant current cancel the inductance effect and since the machine remain stopped it is eliminate the emf effect, then the voltage measure in phase terminals correspond only the resistive voltage. The constant current is generated using the itself machine driven system. The current is generate using a PWM signal with duty cycle constant, where the duty cycle value is determined by expression (5):

$$\tau = T\frac{(v_{k\_dc} + e_{sw})}{(E_{dc} - e_{sw} + e_{swd})} \qquad (5)$$

where: v_{k_dc} DC voltage that will be applied in the k^{th} phase of the machine;

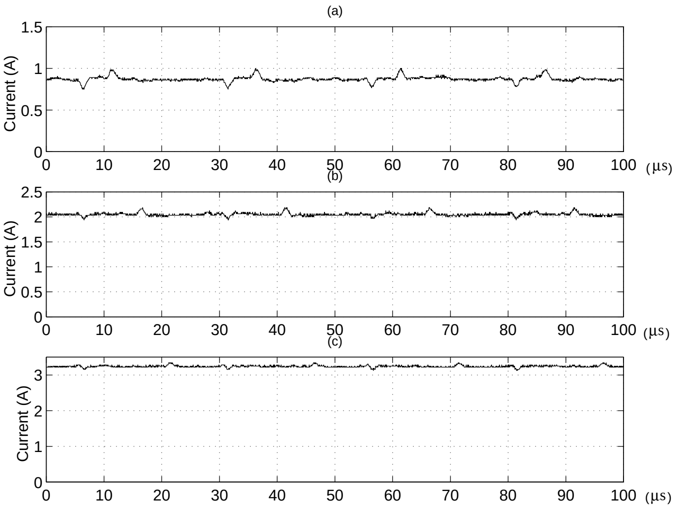

Fig. 2. Current curves for determination of r_s.

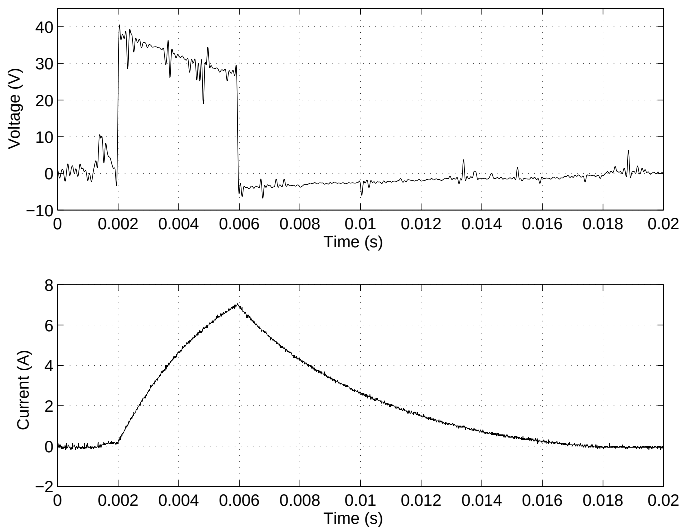

Fig. 3. Voltage and current for determination of l_c.

E_{dc} DC bus voltage;
e_{sw} Voltage when the power switch is on;
e_{swd} Total voltage in a power switch and a flywheel diode;
τ Duty Cycle value of the PWM signal;
T PWM signal period.

The use of the expression (5) demands to know the voltages on the power switches. The determination of those voltages can be made using information of the datasheets of the switch or characterizing the three phase bridge converter. In this paper the second option was adopted. The knowledge of the converter characteristics allows to calculate the average voltage applied to the windings of the machine (see expression (5)), this way it isn't necessary to use sensors for measurement of the voltage on the machine phases.

In Figures 2(a), 2(b) and 2(c) the curves of generated current are shown. There is a small ripple at the moments of the commutation.

The values of the resistance, r_s, calculated using the described method above, are presented in table 1. In the same table the values of e_{sw} and e_{swd} in function of the current are presented.

$\tau(\mu s)$	$I\ (A)$	$e_{sw}(V)$	$e_{swd}(V)$	$r_s(\Omega)$
5.0	0.9175	2.39	1.88	2.3646
10.0	1.9952	3.53	3.28	2.1151
15.0	3.2164	3.99	3.44	2.1455

TABLE I
RESISTANCE OF THE PHASE WINDINGS

The nominal value of the phase winding resistance is 2.2Ω.

C. DETERMINATION OF THE INDUCTANCE $L_a(i)$ e l_c

In Figure 3 the curve of the test signal used to determine the inductance l_c is shown. The value l_c is used in sequence to determine the coefficient ml_m.

It can be observed that it has a small negative voltage when the current falls. This negative voltage must be considered when the value of the time constant (l_c/r_s) will be calculated. Analyzing the curve of the Figure 3, a time constant of $5.64ms$ was determined. The same procedure was used to determine the inductance in the aligned position, however, to verify the saturation effect the procedure was repeated using some values of current, where the used values are shown in the table II. The time constant $(L_a(i)/r_s)$ found was $23.73ms$.

$I\ (A)$	$l_c\ (H)$	$L_a\ (H)$	$ml_m \times 10^{-3}$
2.0	0.0134	0.0524	2.600
3.0	0.0130	0.0498	2.453
4.0	0.0129	0.0458	2.193
5.0	0.0127	0.0387	1.733
6.0	0.0130	0.0244	0.760

TABLE II
INDUCTANCE CURVE COEFFICIENTS

The measured value of the inductance in the half position of alignment was of approximately

The calculate values of l_c and ml_m was respectively $l_c = 12.41mH$ and $ml_m = 2.6233 \times 10^{-3}$. Then, $L_m(i) = L_k(3.75, i) = l_c + 3.75ml_m = 22.24mH$. The measured value of the inductance in the half position of alignment was approximately 23mH. In Figure 4 the inductance curves determined using the truncated Fourier series are shown. The nominal curve was obtained using the nominal data of the machine ($L_a(i) = 52mH$, $L_m(i) = 22.5mH$ e $L_{na}(i) = 8mH$). The estimated curve was obtained through the inductances ($L_a(i) = 52.4mH$, $L_m(i) = 22.41mH$ and $L_{na}(i) = 12.41mH$). The difference in the value of the minimum inductance was caused by substitution of $L_{na}(i)$ by l_c.

III. COMPLETE IDENTIFICATION: DETERMINATION OF THE CURVE $L_k(\theta, i) \times \theta$

The procedures to determine the characteristics curves ($L_k(\theta, i) \times \theta$ e $\frac{dL_k(\theta,i)}{d\theta} \times \theta$) with high precision generally need a long time and specific structures [2], [5], [1]. In these structures the switched reluctance machine remains stopped in various positions that change during the characterization process.

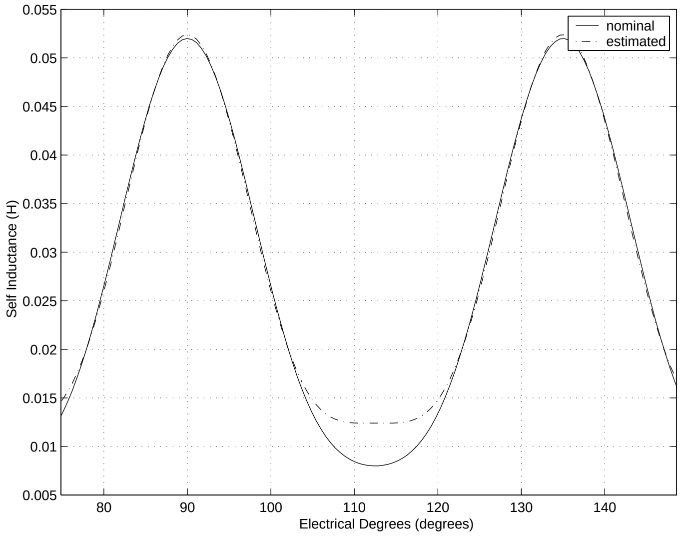

Fig. 4. Inductance curves obtained through of the truncated Fourier series.

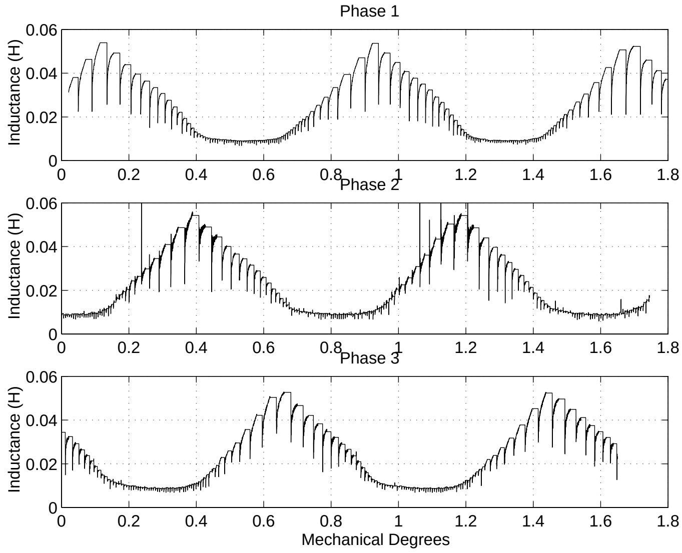

Fig. 5. Inductance curves without cover.

In the technique based on the flux $\times$ current curve the voltage and current in the terminals of the machine are used for calculate the flux. The flux is determined integrating the term $(v_k - ri_k)$ during the application of the test pulse. With the estimated flux and measured current the curves $L_k(\theta, i)$ $\times$ θ and $\frac{dL_k(\theta,i)}{d\theta} \times \theta$ are obtained.

The use of the technique based on the flux $\times$ current continues valid when the machine rotor is in movement to a very low speed, however, it is necessary to establish a correlation between the estimated inductances and the rotor position. The machine geometry defines the angular displacement of the inductance curves, then, defining a reference position as the position where the rotor position is equal the zero, $\theta = 0$, all the other positions will be defined. Taking as example the machine used in the experimental setup, the position of maximum inductance of phase 1 can be selected as the origin position. This position can be identified of only form since the inductance of the proper phase reaches the maximum value and the inductance of the two other phases presents equal values.

The angular resolution obtained using the technique of characterization with the rotor machine in movement is determined by the relation of the frequency of the test pulses and the turn speed of the rotor. In low speed velocity the angular displacement of the machine rotor during the test pulse period does not affect in the inductance calculation, because for each position it has an only relation between the values of the inductance, current and flux.

A. PROCEDURE OF IDENTIFICATION

In switched reluctance machines the rotor displacement is synchronized with the current commutation in the phases of the machine. Thus, knowing the frequency of the current commutation between the phases and the machine geometry (relation between mechanical cycles and electrical cycles) it is possible determine the turn speed of the rotor of the machine. With the speed information it is possible to calculate the angular displacement during the period of characterization of the machine.

With the rotor in movement, each phase of the machine is characterized individually with the application of the total voltage of the DC bus until the current reaches the reference value. When the current reach the reference value the power switch turn off and the current fall. The generated current pulse was called ”test pulse”. When the current falls at the zero the voltage of the DC bus is applied again to the phase. During the test pulses the flux is determined through the integration of the term $(v_k - ri_k)$. In each sampling period the inductance is determined through the relation $L_k(\theta, i) = \frac{\lambda(\theta,i)}{i_k}$, and the last calculated value is stored. This procedure gives to the inductance curve one forms cut, as can be seen in Figure 5. The inductance curves in Figure 7 are the coverings of its respective curves in Figure 5. The steps of the inductance in Figure 5 are connected by straight lines that give form to the covering commented in the last paragraph. To move the rotor without external resources the other phases of the machine that are not being characterized are energized to produce torque, as it can be observed in Figure 6. Thus, the rotor of the machine tends to turn in the commutation frequency of the current in phases of the machine. The curves in Figure 5 denote that phase 1 is under test, while phases 2 and 3 generate torque.

The average current in phase 1, when the other phases are energized, must be lesser of what the average current in other phases, mainly in phase 2, that is energized after phase 1. If this is not respected, the opposed torque generated by the phase 1 will annul the motor torque generated by the two other phases.

The current wave form on the phases used to generate torque can be divided in three segments: rise ramp, sinusoidal segment and descent ramp. The disturbance caused by current, growing in ramp shape, on the other phases (mutual coupling), is minimized if compared to the case when the current grow in step shape. In this way, the test pulses are not affected. The sinusoidal segment allows to get a bigger average current during the period where the phases, that generate torque, are energized. This is obtained

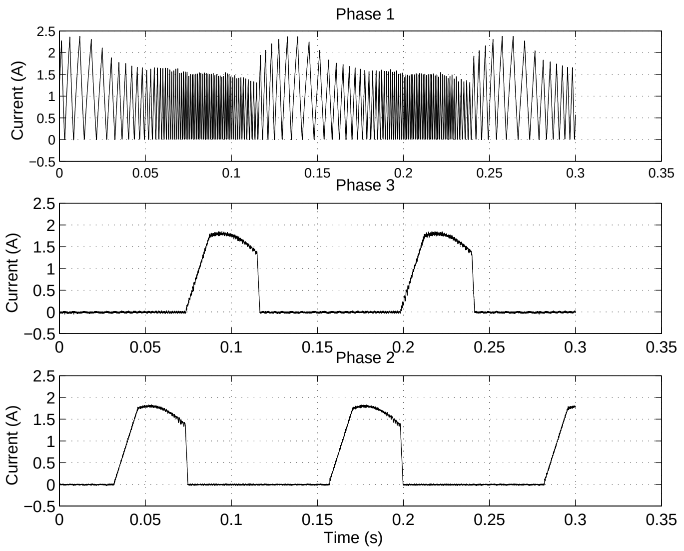

Fig. 6. Phase currents to estimation of the inductance with self-driven.

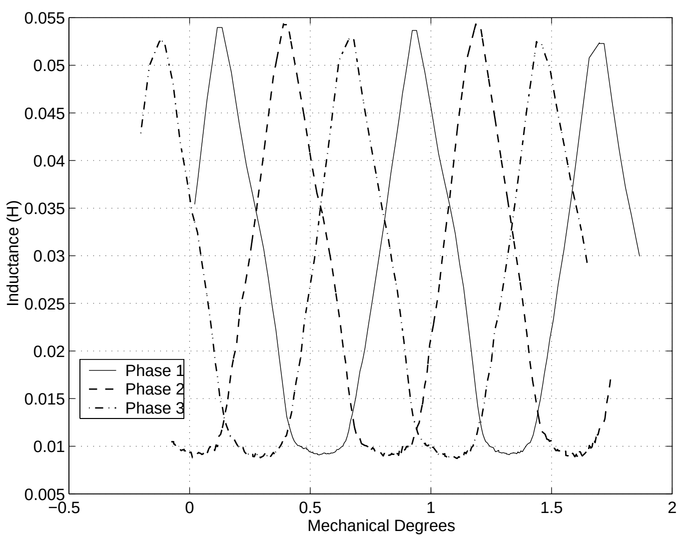

Fig. 7. Self inductance of the machine phases.

without increasing the maximum current level on the begin of the current pulse. The use of the descent ramp also prevent disturbances for mutual coupling.

In table III the maximum and minimum inductance values, obtained for each phase, and errors compared to the nominal parameters of the machine are presented.

Phase	L_{na}	L_a	error - L_{na}	error - L_a
1	9.1	54.0	-1.1	-2.0
2	8.7	54.3	-0.7	-2.3
3	8.8	52.8	-0.8	-0.8

TABLE III
MAXIMUM AND MINIMUM VALUES OF THE SELF INDUCTANCES OF THE MACHINE PHASES

In figure 7 a soft asymmetry in the inductance curve can be observed between the interval where increase the inductance and the interval where diminishes the inductance. That asymmetry is caused by mutual coupling between phases. However, the disturbance is small and more evident in interval where the inductance diminishes, then, to eliminate the disturbance the machine can be driving with the rotor turning in the opposing direction. In the opposing direction the previous interval where the inductance diminishes will be the interval where the same increases. As it can be observed in figure 7, in this interval does not have the effect of the mutual coupling because the phase under test is only energized.

IV. CONCLUSIONS

In this paper the procedures to determine the $L_k(\theta, i) \times \theta$ curve of a Switched Reluctance Machine were discussed. In the simplified procedure the inductance curve was obtained through of the truncated Fourier series. In this method the inductances $L_a(i)$, $L_m(i)$ and $L_{na}(i)$ (that it was substituted by the l_c value) are used in equation 2 to determine inductance $L_n(i)$ of the ”n” phases of the machine. In the simplified method $L_a(i)$ and l_c were determined using the equation of the time constant and the $L_m(i)$ value was determined using the linear expression of the curve of the inductance in the interval where the inductance increases. The inductance curve obtained with the simplified method presents a distinction significative when compared with the inductance curve generated with the nominal parameters of the machine, however, the difference happens in the interval where the inductance in both the curves is constant, not used interval to generate torque, thus, this difference does not compromise the use of the curve in Switched Reluctance Machine drive systems.

In complete method, the inductance curve is determined using a current pulses sequence. Because of the mutual coupling between phases and currents in the other phases, energized to generate torque, the inductance curves show a soft disturbance. However, besides the disturbance to be soft is possible to eliminate the same, driving the machine in both the directions (Counter-clockwise and clockwise direction).

In both the methods, simplified and complete, no external resource to drive the machine is used.

V. ACKNOWLEDGEMENT

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APPENDIX

Data of the SRM used experimentally

- Model: H55BMBJL
- r_s: 2.2 Ω
- L_s(inductance in the aligned position): 52 mH
- L_s(inductance in the totally not aligned position): 8 mH
- J (rotor inertia): 1.07×10^{-3} kgm^2
- nominal current: 2.5A
- nominal voltage: 120 V (DC)
- Number of stator poles: 12
- Number of rotor poles: 8
- Number of stator phases: 3

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