A SIMPLE IDENTIFICATION PROCESS OF THE VRM INDUCTANCE × POSITION PROFILE.

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Abstract: **This work proposes a simplified approach to the determination of $L(\theta) \times \theta$ curves for the three-phase variable reluctance machines. The $L(\theta) \times \theta$ characteristics are segmented into three parts: constant, growing and decreasing inductances, respectively. The growing and decreasing segments are approximated by straight-lines, which have their sloping coefficients obtained from $l_{\max}$ and l_c, where this parameter corresponds to the value in which the two crossing phases inductances are not in the maximun inductance position. It will be noted that the sloping coefficients change according with the machine operational current level, which defines if it is saturated. Experimental results are given taking into account the saturation effect on the $L(\theta) \times \theta$ curves, which are obtained from the proposed approach. Further, the driving system performance is shown making use of the $L(\theta) \times \theta$ curves.**

I. INTRODUCTION

In the driving of the reluctance machines, the angular position information of their shaft should be periodically determined to allow the commutation of the current between the phases of the machine. The required performance depends on the precision of the characteristic curves $L(\theta) \times \theta$ and $dL/d\theta \times \theta$. The former is utilized to identify the commutation instants of current between two phases of the machine, while the latter is used to define the possible current profiles which should be imposed to the phases, so that they could result in the reduction of the ripple torque [1–4].

The utilization of a sensor to determine this position has been eliminated due to the additional cost, volume and weight of the driving systems. Further, it represents an extra item that could cause system fault. Several works deal with the problem of finding suitable angular position identification strategies. Basically, all of them require the knowledge of the $L(\theta) \times \theta$ characteristic curve which is obtained in advance [5–10].

The most commonly strategies used to characterize the variable reluctance machine are the method based on the flux [11], in which the current and voltage are measured in the phase of the machine and subsequently they are utilized to determine the flux, and the method based on the measurement of the static torque [11]. In both cases, these measurements are accomplished in several angular positions, being the machine kept on standstill in these positions. The angular resolution used in these tests defines the number of repetitions of the procedure concerning the benchmark of the machine, which could demand a considerable time. Some systems applying automatic characterization of the machine have been proposed, in which the variable reluctance motor has been driving from a high resolution stepper motor [12] or manually [13]. Both systems accomplish a necessary characterization of the machine with a relatively simple experimental structure, however they still demand a manual manipulation or external resources for their implementations.

This work tackle this problem by proposing a method to determine the $L(\theta) \times \theta$ characteristic curve based on a linear identification approach in the area of interest for production of torque, which takes in consideration the effects of the saturation and neglects any additional apparatus needed for driving the variable reluctance machine. The method allows for characterizing and operating it starting from basic information, i.e.:

- geometric machine configuration;
- number of phases;
- rated current;
- rated voltage

In spite of its simplicity, the strategy allows for a correct operation of the machine, which is accomplished from the method of flux × current, using a linear expression to calculate the inductance in the area of interest (positive slope) as a function of the angular position, which is determined according to the proposed method, concerning the calculation of the reference flux; i.e, for a given current value, this flux will give an indication of the commutation instant. Thus, the developed method avoids using look-up tables of Flux/Current/Position. For current control, a predictive controller was adopted, that despite its simple implementation, it provided to be quite robust to parametric mismatches. The diagram of the implemented system is shown in Figure 1.

II. VARIABLE RELUCTANCE MACHINE: CONTINUOUS MODEL

The variable reluctance machine model can be written as follows.

$$v_j = r_s i_j + \frac{d\lambda_j(\theta, i)}{dt} \quad (1)$$

$$\frac{dw}{dt} = \frac{T_{em} - T_l}{J} \quad (2)$$

$$\frac{d\theta}{dt} = w \quad (3)$$

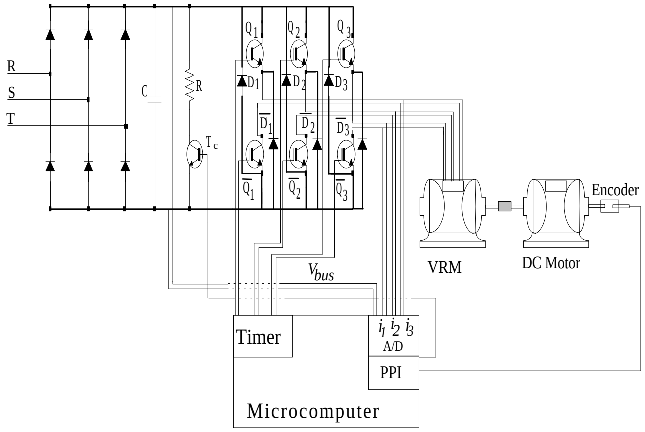

Figure 1: VRM driving system.

where: v_j voltage in the j-th phase;
i_j current in the j-th phase;
$\lambda_j(\theta, i)$ total flux in the j-th coil;
r_s phase resistance;
w electrical angular speed;
θ angular position;
T_{em} electromagnetic torque;
T_l load torque.

The total flux can be expressed by:

$$\lambda_j(\theta, i) = \sum_{n=1}^{N} L_{jn}(\theta, i_n) i_n \tag{4}$$

where N is the number of phases. It is common considering negligible the mutual inductance between the phases [14], in this manner, the equation(4) can be simplified accordingly to the following equation:

$$\lambda_j(\theta, i) = L_j(\theta, i_j) i_j \tag{5}$$

and (1) can be written as:

$$\begin{aligned} v_j &= r_s i_j + \left(L_j(\theta, i_j) + i_j \frac{\partial L_j(\theta, i_j)}{\partial i_j} \right) \frac{di_j}{dt} \\ &\quad + w i_j \frac{\partial L_j(\theta, i_j)}{\partial \theta} \end{aligned} \tag{6}$$

The phase voltage consists of three terms: "ri", "Ldi/dt" and a term of movement (or back emf) $wi_j \partial L_j(\theta, i_j)/\partial\theta$. If we ignore the effect of the magnetic saturation, the expression (6) can be rewritten as:

$$v_j = r_s i_j + L_j(\theta) \frac{di_j}{dt} + w i_j \frac{\partial L_j(\theta)}{\partial \theta} \tag{7}$$

III. DETERMINATION OF THE $L(\theta) \times \theta$ CURVE: SIMPLIFIED METHOD

The characteristic curve $L(\theta) \times \theta$ of a variable reluctance machine is periodic in relation to θ. For the considered machine with geometry 12/8 (stator/rotor poles), which has been used during the experimental tests, the inductance of each phase repeats periodically at the intervals of 45^o mechanical ($360^0/p_r$, where p_r = number of rotor poles), therefore, the inductance curve shown in Figure 2 could be divided in three segments: rising, constant and falling inductances. Each segment represents 15^o (mechanical).

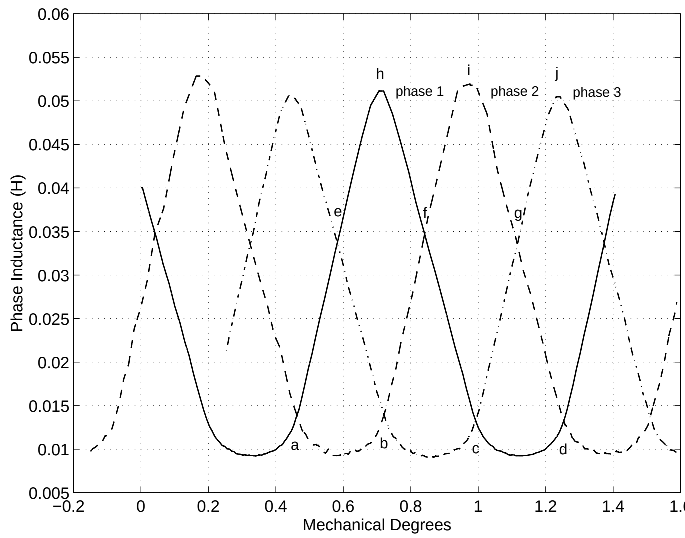

Figure 2: Inductance $\times$ Position profile of the used machine.

Considering phase 2, the rising segment of the inductance extends from point "b" (intersection of phases 3 and 2) to point "i". The choice of the axis origin, θ (position), is arbitrary, thus, the selection of this origin is based on the position of maximum inductance of phase 1, i.e. point "b" or $\theta = 0^o$. During the motor operation, the region of interest for producing positive torque will be the one that is going from $\theta = 0^o$ to $\theta = 15^o$ (maximum inductance), in this interval, the slope of the inductance curve is practically constant, in this manner, it could be approximated by a straight line.

$$L_j(\theta) = l_{c_j} + ml_e\theta_e \text{ ou} \tag{8}$$
$$L_j(\theta) = l_{c_j} + ml_m\theta_m \tag{9}$$

where:

$$ml_m = \frac{l_{\max} - l_c}{15^o}, ml_e = \frac{l_{\max} - l_c}{120^o} \tag{10}$$

$l_{\max}$ is the maximum per-phase self-inductance of the machine, l_c is the crossing inductance between two phases, when the third is in its maximum value; ml_m is the slope coefficient of the inductance curve, expressed in mechanical degrees, and ml_e is its reciprocal, in electrical degrees. The computation of ml_m and ml_e requires the knowledge of l_c and $l_{\max}$, which are obtained from the following procedure:

1. One of the phases of the variable reluctance machine is energized, so that it could be brought to the position of maximum inductance, and in addition kept on energized;
2. Following, a current pulse, of short duration, is applied in the other two phases;

3. The extinction time of the current pulse is measured (time between the maximum peakk of the current pulse and the instant in which the current goes to zero);
4. The value of $L(\theta)$, of both phases, is calculated using an equivalent time, namely the RL circuit (l_c/r_s) time constant, and the per-phase resistance value;
5. The steps 2, 3 and 4 are repeated to determine the maximum inductance of the phase, which has been energized in step 1.

Using the equations (8) or (9) results the value of the inductance in the desired position. Substituting it in equation (5), the expected flux is calculated for a certain value of current i_j. This methodology provides a larger flexibility with respect to the choice of the commutation angle, since for each angular position there are several ordered (flux,current) pairs.

The values of the crossing inductance and maximum inductance (l_c and $l_{\max}$, respectively), are affected in a different way by the saturation effect. The former doesn't suffer the saturation effect, because l_c corresponds to an inductance where the relative position between stator and rotor poles are mismatched. The value of the latter , however, suffers a strong influence of the saturation effect, since this inductance reflects the total alignment between stator and rotor poles. The curves of flux $\times$ current are shown in Figure 3, which puts in evidence the effect of the saturation in the alignment position and the non-influence of the saturation in the unalignment positions, where the relationship flux $\times$ current stays linear and constant. The saturation effect tends to reduce the

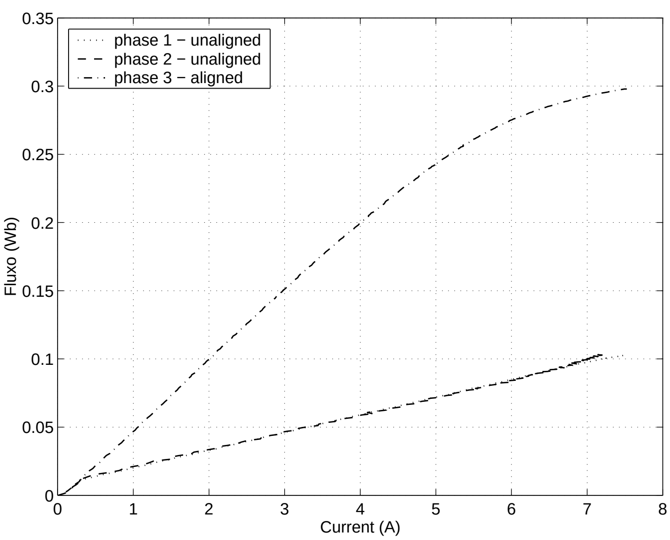

Figure 3: Saturation effect: Flux $\times$ Current.

value of the maximum inductance, and proportionally the value of the inductances in the region of its influence. The inductance reduction, due to the saturation, requires that the value $l_{\max}$ be determined for the level of demanded current. Once it is determined, the coefficients ml_m and ml_e could be calculated for this operational point. The l_c determination can be implemented as described above, however, given the variation of $l_{\max}$ as a function of the current, in the saturation zone, its value will be determined using a procedure for the determination of the flux for a given current value, starting with the relationship flux $\times$ current. In the curves shown in Figures 4 and 5 the inductance values are presented as a function of the current in the aligned/unaligned positions, respectively. As mentioned above, a reduction is observed in the value of $L(\theta)$ when the axis of the machine is aligned with the stator and for higher currents up to 6.0A.

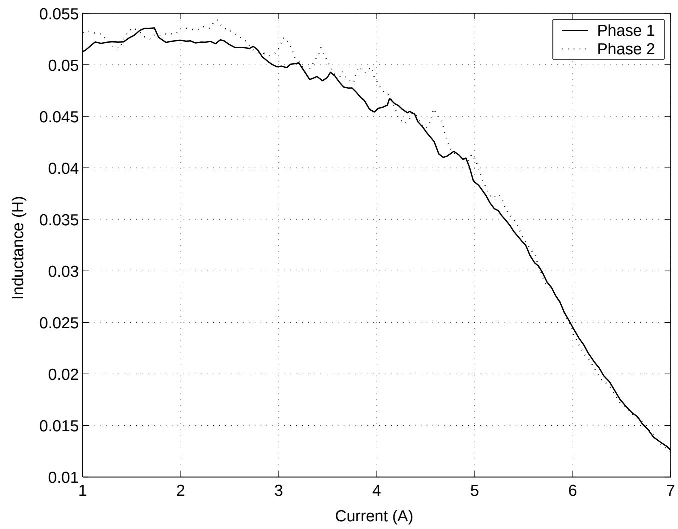

Figure 4: Saturation effect in the inductance values in the alignment position.

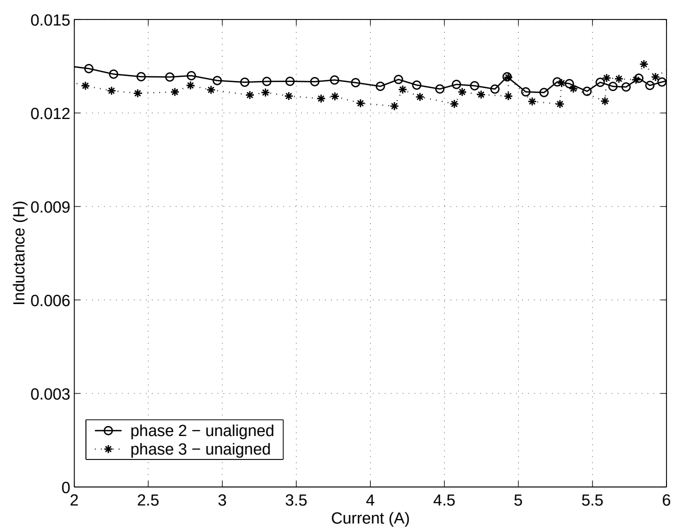

Figure 5: Saturation effect in the inductance values in the unalignment position.

A. DETERMINATION OF THE r_s

According to the proposed method, the determination of the inductances $l_{\max}$ and l_c has been done from the circuit RL time constant concerning each phase of the machine and/or from the flux $\times$ current curve. In both cases, the knowledge of r_s is necessary; in this way, its determination is implemented inside the proposed strategy. To obtain the value of r_s, a constant current is applied to the machine, which results in the elimination of inductance effect. In this manner, the measured voltage drop will be only given due to the machine winding resistance. To generate a constant current, using the machine driving system, a pulse sequence with fixed duration, whose value depends on the DC bus voltage and the one which is intended to be applied, which is calculated by the expression

$$\tau = T\frac{(v_{j\_dc} + e_{sw})}{(E_d - e_{sw} + e_{swd})} \tag{11}$$

where: v_{j_dc} is the desired j-th DC phase voltage;
E_d the DC bus voltage;
e_{sw} is the voltage drop of the two switches arranged in series with the machine windings in an asymmetric half-wave bridge inverter;
e_{swd} is the voltage drop of the switches and freewheeling diodes;
τ is the pulse width;
T is the PWM period.

From the expression (11) it can be seen how important is the knowledge of the inverter utilized in the drive system, mainly with relation to the voltage drops of the switches and the freewheeling diodes. The knowledge of the inverter characteristics, allows for the calculation of the average voltage applied to the machine in each switching period, from the expression (11), which avoids the use of a voltage sensor. In Figures 6 and 7 are shown the

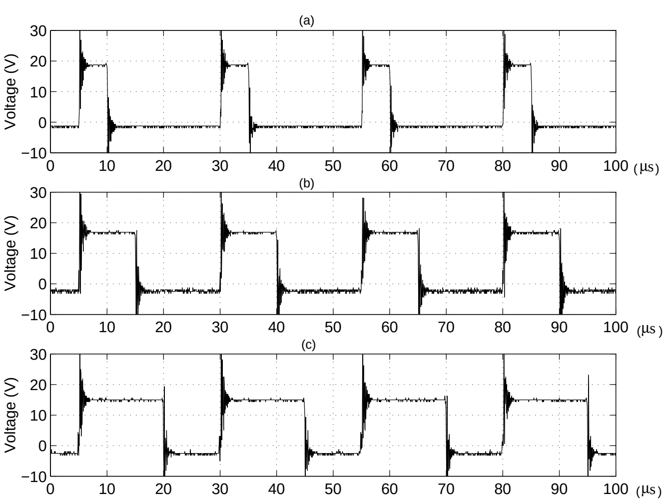

Figure 6: Voltage curves for r_s determination.

voltage and current waveforms applied to the machine to obtain the winding resistances. In Figures 6(a), 6(b) and 6(c) are shown the voltage signals, with pulse widths of $5\mu s$, $10\mu s$ and $15\mu s$, respectively. In Figures 7(a), 7(b) and 7(c) are shown the respective produced current signals. Note that, the current waveforms are nearly constants, with some slight perturbations in the commutation

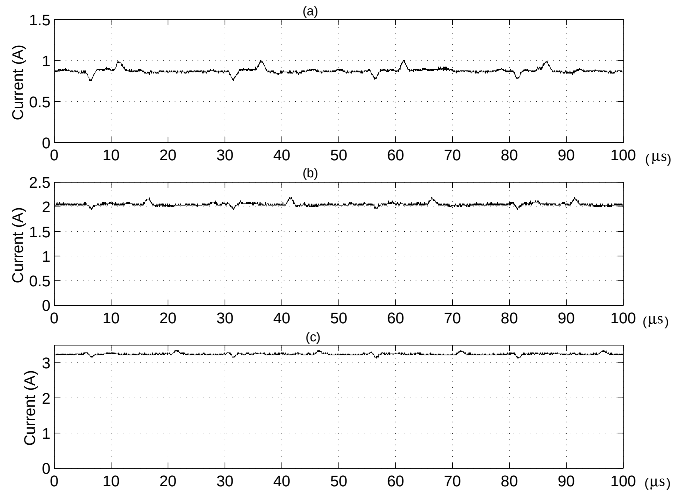

Figure 7: Current curves for r_s determination.

instants. The calculate resistance values, which have been obtained by applying DC currents into the machine windings, are shown in table 1. Additionally, the values of e_{sw} and e_{swd} (as a function of current) are shown.

$\tau(\mu s)$	$I\ (A)$	$e_{sw}(V)$	$e_{swd}(V)$	$r_s(\Omega)$
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 1: Phase resistance values

The rated value of the resistance used in the experimental setup is 2.2Ω.

IV. EXPERIMENTAL RESULTS

In Figure 8 is shown the test curve used to determine the value of l_c, which is subsequently utilized to compute the coefficients ml_m, ml_e. Note that there is a slight

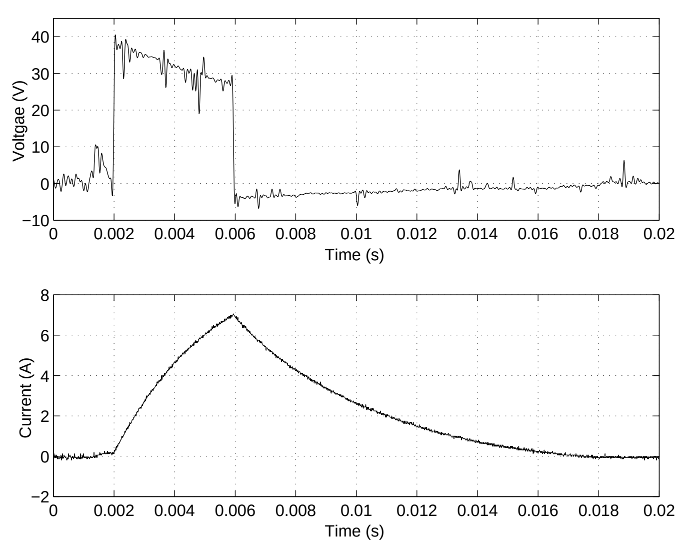

Figure 8: Voltage and current for l_c determination.

negative voltage when the current decreases, this value must be considered during the calculation of the time constant l_c/r_s. In Figure 9 is also shown the behavior of a RL circuit fed by a DC source. We can notice that the two curves of the unaligned phases are superposed, which is an indication that the two phases have the same time constant l_c/r_s, having a value of $5.64ms$.

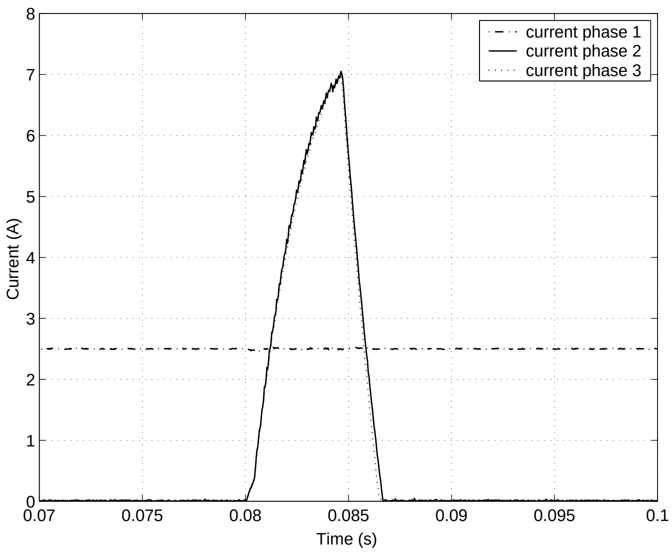

Figure 9: Current in aligned and unaligned phases.

The calculated values of l_c, ml_e and ml_m are $l_c = 12.41mH$, $ml_e = 0.3279 \times 10^{-3}$ and $ml_m = 2.6233 \times 10^{-3}$, respectively. Defining a commutation angle having a value of 11.0^o (mechanical), and a current of $1.4A$, the flux reference can be calculated by using the equations (9) and (5), which defines the commutation instant. Therefore, the computed flux reference value is $\lambda = 0.0581Wb$.

The saturation effect over the $L(\theta) \times \theta$ curves can be seen in Figure 10. The curves in this figure represent the lines, whose sloping coefficients are shown in Table 2. In

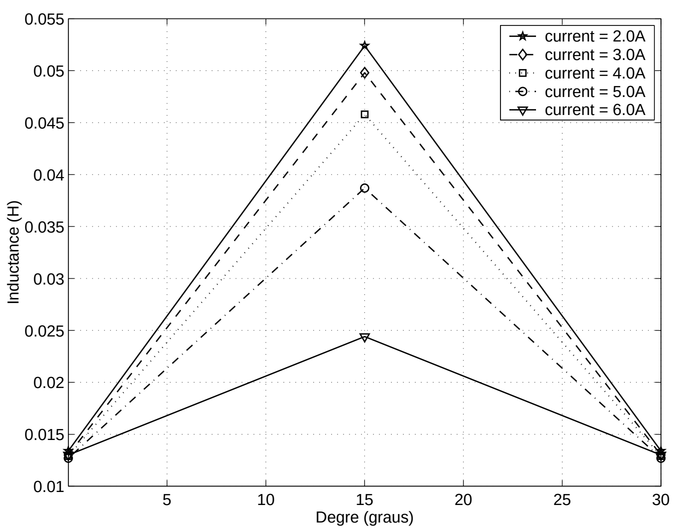

Figure 10: Saturation effect over $L(\theta) \times \theta$ curves.

$I\ (A)$	$l_c\ (H)$	$l_{\max}\ (H)$	$ml_e \times 10^{-3}$	$ml_m \times 10^{-3}$
2.0	0.0134	0.0524	0.325	2.600
3.0	0.0130	0.0498	0.307	2.453
4.0	0.0129	0.0458	0.274	2.193
5.0	0.0127	0.0387	0.217	1.733
6.0	0.0130	0.0244	0.095	0.760

Table 2: Inductance curve coefficients

Figure 11 the measured and reference currents are depicted for operation of the machine in steady state, using the flux $\times$ current strategy. The results here presented show a scheme in which the phases of the variable reluctance machine are fed by current pulses, which are generated from a PWM voltage source and regulated by a predictive current controller. The reference flux is only used to indicate the commutation instant for the current between phases.

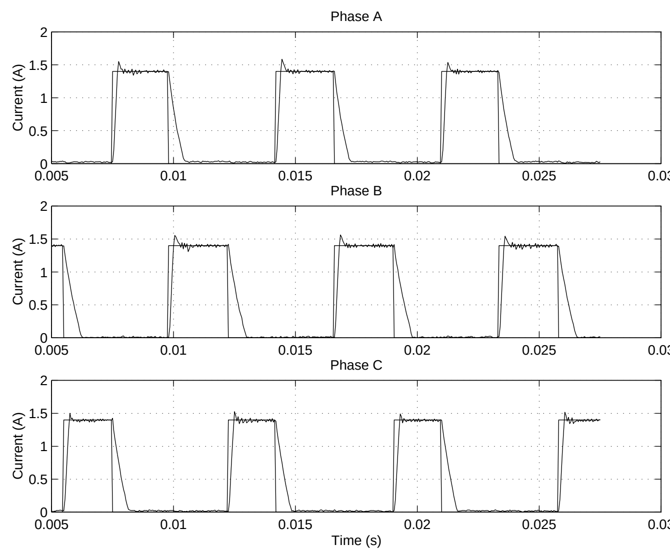

Figure 11: Reference and measured current , phases 1, 2 and 3 respective.

V. CONCLUSION

This paper presented a simplified method to obtain the $L(\theta) \times \theta$ characteristics. The $L(\theta) \times \theta$ curves are approximated by straight-lines, and their sloping coefficients are obtained from $l_{\max}$ and l_c. The $l_{\max}$ and l_c values are calculated on using the flux $\times$ current machine characteristics and/or the time constant l_c/r_s. Both procedures do require the r_s knowledge, whose value is found by applying a DC current into the machine windings. The saturation effect changes the slope of the $L(\theta) \times \theta$ curve. To determine this change, the $l_{\max}$ values are calculated on for the possible operational machine currents, which are then used to find the slope coefficients. The computed curves $L(\theta) \times \theta$ can be utilized to determine the reference flux, which define the instant for current commutation between phases, in sensorless position strategies like the flux $\times$ current. The method makes use of the same machine driving structure, in this way, it is not necessary adding switches or sensors in the structure. The knowledge of the inverter is important because the average voltage values can be found using the DC bus value and the PWM pulse widths.

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