A Method for Magnetizing Curve Identification in Rotor Flux Oriented Induction Machines

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Abstract—Operation of an indirect rotor flux oriented induction machine in the field weakening region is usually realized by varying the rotor flux reference in inverse proportion to the speed of rotation. In order to provide the correct stator d-axis current reference at all speeds, it is necessary to incorporate the inverse magnetizing curve of the machine in the controller. The paper proposes an experimental method for identifying the inverse magnetizing curve, specifically developed for the type of vector controlled drives described. The method utilizes the same indirect vector controller and PWM inverter that are used in subsequent normal operation of the drive. It requires that the machine can run under no-load conditions and that the fundamental component of the stator voltage can be measured. The simplicity and accuracy of the method make it well suited for use during commissioning of the drive. The method is verified by extensive experimentation.

Index Terms—Induction machines, Identification, Magnetizing curve, Rotor flux oriented control.

I. INTRODUCTION

NUMEROUS applications of rotor flux oriented induction machines require operation in the field weakening region [1]. As the available voltage is limited in this region, it is necessary to reduce the rotor flux reference as speed increases. The issue of optimal rotor flux reference variation in the field weakening region has been a subject of great interest in recent times [1]–[4]. The simplest method is to vary the rotor flux reference above the base speed in an open-loop manner, in inverse proportion to the speed of rotation [5]. Such a rotor flux reference variation is not optimal [1], [3], [4] and a number of control schemes have been proposed for improving the operation of the drive at high speeds. A common feature of all such schemes is that some form of voltage controller is required [1]–[4]. Their good property is that, as the stator d-axis current reference is obtained from a voltage controller, information on the machine's magnetizing inductance is not required. Control is therefore insensitive to variation of the magnetizing inductance, caused by variation in the reference flux setting. Improved operation in the field weakening region is however achieved at the expense of substantially increased complexity of the control scheme.

Application of the additional voltage controller is inconvenient if the drive is a part of the system for multi-axis motion control. In such a case control algorithms for all the drives are usually realized in a single digital controller, whose outputs are appropriate current references for all the drives [6]. The preferred solution is then to change the rotor flux reference in inverse proportion to the speed. Such an approach, although not optimal, continues to treat the machine as current-fed even in the field weakening region. The simple structure of the control system is therefore retained in the whole speed control range. The drawback of this approach is that variation of the magnetizing inductance in the machine affects operation of the drive. It is therefore necessary to compensate for this variation, either by embedding the magnetizing curve in the control system [7], [8] or by providing on-line identification of the magnetizing inductance [9]. The simpler of the two approaches is to modify the vector control scheme by including the magnetizing curve in it. This method requires knowledge of the magnetizing curve, which has to be identified off-line, during commissioning of the drive.

Identification of the magnetizing curve, using a vector control system and PWM inverter, has been discussed extensively in recent past [10]–[15]. An ideal method for self-commissioning should enable identification at standstill with AC or DC supply, require measurement of currents only, and be simple to implement and accurate. Such a method is not available at present. If identification is performed on the basis of only current measurements at standstill, it is necessary to apply statistical methods in data processing, such as recursive least squares [10], [11]. The accuracy of the method deteriorates below a certain magnetizing current value [10], [11], so that this approach is neither simple nor accurate enough.

If measurement of stator voltages is allowed (use of reference voltages instead of measured voltages, [12], is unsatisfactory due to inverter nonlinearity which is very pronounced at low voltage levels), it is possible to avoid use of statistical methods and to perform identification purely from measurement data. Methods of this group [13], [14] are purely experimental in nature, and are applicable during drive commissioning if voltage sensors are available.

The purpose of this paper is to describe an alternative experimental method of magnetizing curve identification. Its main advantages, when compared to the existing methods, are the simplicity of the procedure and good accuracy. The method is developed for indirect feed-forward control scheme and is applicable when the inverse magnetizing curve is embedded in the controller as a suitably chosen analytical function with unknown coefficients. Identification is performed on the basis of measurement of the stator voltage fundamental component in steady-state (this is the only measurement required) under no-load conditions at various operating speeds in the field weakening region. As the machine rotates and as voltage

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measurement is required, the method is suitable for factory and on-site commissioning, provided that the machine is not coupled to the load and that voltage measuring equipment is available.

The identification method requires knowledge of the rated magnetizing current and the stator leakage inductance. The rated magnetizing current of the machine can be estimated relatively accurately for low to medium power machines from nameplate data (rated stator current and power factor), while the stator leakage inductance can be obtained from numerous already available procedures for induction motor parameter identification during the commissioning stage.

II. INDIRECT FEED-FORWARD ROTOR FLUX ORIENTED CONTROL IN THE FIELD WEAKENING REGION

The rotor flux reference ψ_r^* is equal to the rated rotor flux below base speed. In the drive dealt with in this paper [6], the rotor flux reference is varied in the field-weakening region using the pre-programmed law,

$$\psi_r^* = \psi_{rn}\omega_B/\omega, \tag{1}$$

where subscripts n and B denote the rated value and base speed at which field weakening starts, respectively.

Operation with reduced rotor flux leads to an increase in the magnetizing inductance in the machine. If the stator d-axis current command is to be correctly set, it is necessary to compensate for the variation of main flux saturation in the machine, by including the inverse magnetizing curve in the control system [7]. As shown in [7], an indirect feed-forward rotor flux oriented controller with partial compensation of main flux saturation is described with the following equations:

$$\psi_m = \psi_r^* + \tau_{\sigma r}d\psi_r^*/dt \tag{2}$$

$$i_{ds}^* = i_m(\psi_m) + (1/L_{\sigma r})\tau_{\sigma r}d\psi_r^*/dt \tag{3}$$

$$\omega_{sl}^* = K_1 i_{qs}^*/\psi_r^* \tag{4}$$

$$i_{qs}^* = (1/K_2)T_e^*/\psi_r^*, \tag{5}$$

where $K_1 = L_{mn}^*/\tau_{rn}^*$ and $K_2 = (3/2)P L_{mn}^*/L_{rn}^*$ are constants. The subscript m identifies magnetizing flux, current and inductance. The subscripts σ and r denote leakage and rotor, respectively. An asterisk denotes reference values, symbol τ stands for time constants, and the rotor leakage time constant is $\tau_{\sigma r} = L_{\sigma r}/R_r$. The symbols T_e, ω_{sl} and i stand for torque, angular slip frequency and current, respectively. An indirect vector controller, described by (2)–(5), ignores the cross-saturation effect and neglects the change in the ratio of magnetizing inductance to rotor inductance in (4)–(5) [7].

If the rotor speed is assumed to vary much more slowly than the electromagnetic transients, then the rate of change of the rotor flux reference in (2)–(3) is slow. It is therefore possible to further simplify (2)–(3), by neglecting the rate of change of rotor flux reference. Hence:

$$\psi_m = \psi_r^* \qquad i_{ds}^* - i_m(\psi_m). \tag{6}$$

It should be pointed out that this approximation has no impact on the method of inverse magnetizing curve identification, since
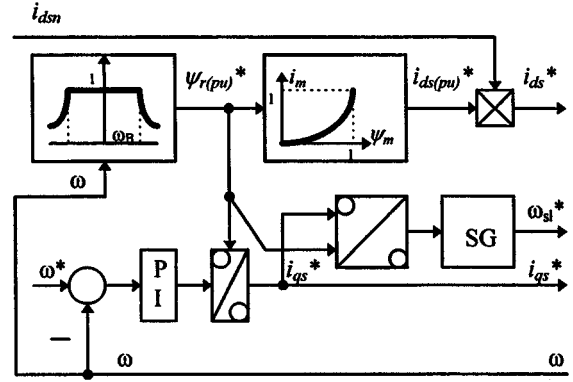

Fig. 1. Indirect feed-forward vector controller with compensation of main flux saturation variation.

all the measurements are performed in steady-state operation. It merely reflects the actual situation in a commercially available drive [6], on which this work is based.

The rated rotor flux value is in general not known. On the other hand, the rated magnetizing current can be estimated from the rated stator current and rated power factor for low to medium power machines. Alternatively, it can be determined experimentally by running the machine in vector control mode under no-load conditions at the rated frequency. If the fundamental voltage component is measured for different settings of the stator d-axis current reference, the rated magnetizing current will correspond to the value of the stator d-axis current reference that yields the rated voltage at the machine terminals. In this study rated magnetizing current was determined using the former approach.

If rated magnetizing current is taken as an independent input into the system, it is possible to introduce the normalized rotor flux value and normalized inverse magnetizing curve (base values are peak rated rotor flux and peak rated magnetizing current). The indirect feed-forward rotor flux oriented controller then takes the form shown in Fig. 1, [6]. Note that all the quantities in Fig. 1, except for the normalized inverse magnetizing curve, are in absolute values. The constant K_2 and the rated rotor flux value, required for generation of the stator q-axis current command in (5), are taken care of by the PI speed controller. The stator d-axis current command is generated as the product of the rated value and a per unit value. The per unit value is obtained at the output of the inverse magnetizing curve as a function of the per unit rotor flux command (which is a function of speed). All the per unit values in Fig. 1 are identified with the subscript pu. Slip gain (SG) is a constant parameter, given with $\text{SG} = L_{mn}^*/(\tau_{rn}^*\psi_{rn})$.

The correct operation of the controller of Fig. 1 in the field weakening region depends on accuracy of the inverse magnetizing curve representation within the control system. The same control system is therefore at first used to identify the magnetizing curve, by means of a procedure described in the next Section. The results of the identification are the inverse magnetizing curve, rated value of the magnetizing inductance and rated value of the rotor flux. The remaining parameters, required for correct setting of the slip gain (rotor resistance and rotor leakage inductance), have to be identified independently, using any of

the available procedures. The same applies to the stator leakage inductance, whose value is not needed for control but is required for the magnetizing curve identification.

The controller of Fig. 1 is used to drive a 50 Hz, four-pole, 2.3 kW induction machine. Rated magnetizing current is estimated as described previously (4.15 A) and stator leakage inductance is obtained from standard locked rotor test with sinusoidal supply ($L_{\sigma s} = 3.86$ mH).

III. EXPERIMENTAL PROCEDURE FOR IDENTIFICATION OF THE MAGNETIZING CURVE

A. Approximation of the Inverse Magnetizing Curve in the Controller

Implementation of the scheme of Fig. 1 requires analytical representation of the inverse magnetizing curve. Many functions, of different complexity, can be selected for this purpose [15]. The experimental method, to be described further on, does not depend on the selected type of the analytical function. However, from the practical point of view, it is desirable to use the simplest possible representation. As the curve is given in terms of per unit values, a convenient choice is the following simple two-parameter function:

$$i_{m(pu)} = a\psi_{m(pu)} + (1 - a)\psi_{m(pu)}^b. \tag{7}$$

Coefficients a and b are unknown and they have to be determined by the process of the experimental magnetizing curve identification. Figs. 2a and 2b illustrate the approximation given by (7), when parameter b is a variable, while parameter a is fixed. Fig. 2c shows the inverse magnetizing curve for various values of a, with $b = 7$. As can be seen from Fig. 2, the influence of the parameter b on the inverse magnetizing curve approximation is very small for flux values of interest, from zero up to 1 p.u.. The influence of parameter a is dominant in this region.

B. Theoretical Considerations

Let the machine operate in the field weakening region, with the rotor flux reference value determined by (1). The stator d-axis current reference is then determined by

$$i_{ds}^* = (\psi_{rn}/L_m^*)(\omega_B/\omega), \tag{8}$$

where L_m^* is a variable parameter, whose value for each speed setting depends on the actual values of parameters a and b of the inverse magnetizing curve approximation (7) implemented in the controller of Fig. 1. If the machine operates under no-load conditions,the value of the slip gain parameter (SG) is irrelevant, as the stator q-axis current command is zero. Mechanical and fundamental harmonic iron losses are neglected, and the rotor electrical speed of rotation ω is regarded as equal to the stator fundamental angular frequency ω_e. Regardless of the value of the magnetizing inductance used in the controller, the orientation angle error is zero under such an idealized no-load operation. The steady-state stator voltage equations for fundamental harmonic

$$v_{ds} = R_s i_{ds} - \omega_e \psi_{qs}$$
$$v_{qs} = R_s i_{qs} + \omega_e \psi_{ds} \tag{9}$$

therefore reduce to

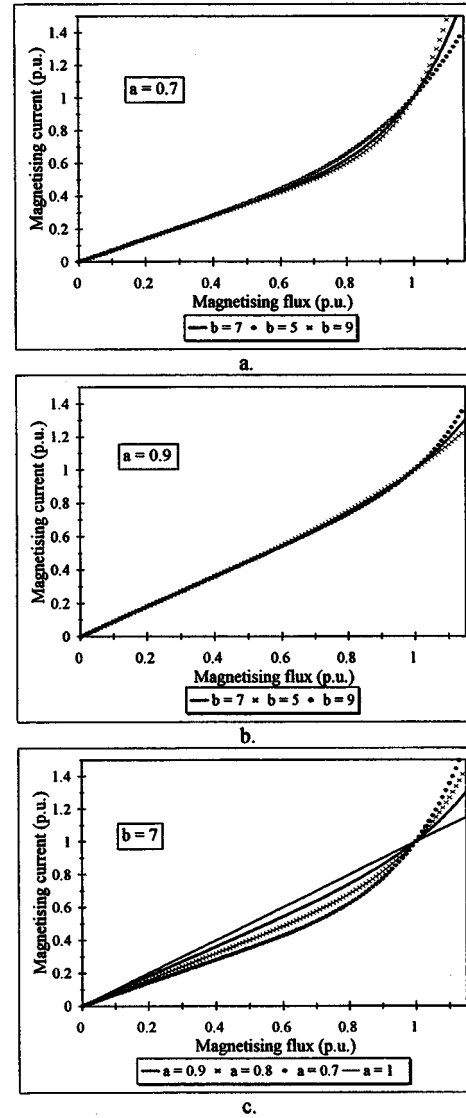$$v_{ds} = R_s i_{ds}^* \qquad v_{qs} = \omega L_s i_{ds}^*, \tag{10}$$

Fig. 2. Impact of parameters a and b on the inverse magnetizing curve approximation.

where $\omega = \omega_e$ is accounted for and reference and actual stator d-axis currents are equal due to absence of an orientation angle error. The magnitude of the fundamental component of stator voltage follows from (10),

$$v = \sqrt{v_{ds}^2 + v_{qs}^2} = i_{ds}^* \sqrt{R_s^2 + (\omega L_s)^2}, \tag{11}$$

where L_s is stator self-inductance. Provided that the speed at which field weakening is initiated, ω_B, sufficiently high, the stator resistance in (11) can be neglected. The peak value of the fundamental stator voltage is then from (8) and (11)

$$v = \psi_{rn}\omega_B \frac{L_{\sigma s} + L_m}{L_m^*}. \tag{12}$$

Taking the product of the rated rotor flux and base speed as 1 p.u., equation (12) can be re-written as per unit voltage in the field weakening region,

$$v_{pu} = \frac{L_{\sigma s}}{L_m^*} + \frac{L_m}{L_m^*}. \tag{13}$$

If the inverse magnetizing curve approximation in the controller exactly matches the actual magnetizing curve, then at all speeds
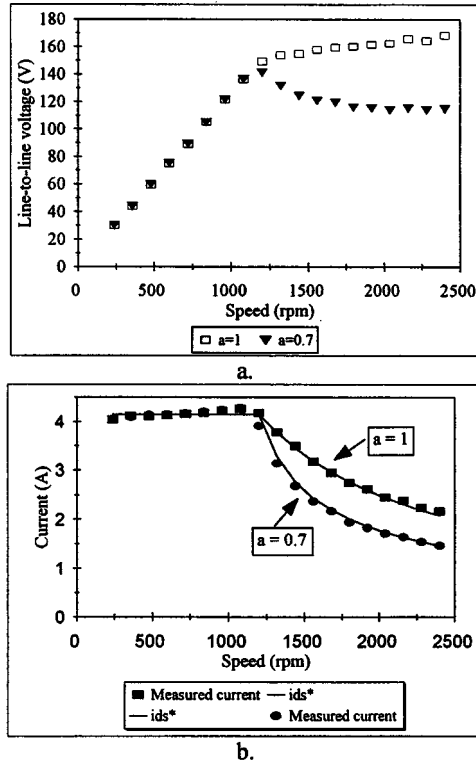
Fig. 3. Measured fundamental components of stator voltage (a) and stator no-load current (b), for $b = 7$ and two values of parameter a (stator d-axis current reference rms values included in (b)).

Fig. 4. Measured fundamental stator voltage for different settings of parameter a and $b = 7$ (a), and calculated inverse magnetizing curve (b)(all values are rms).

$L_m \equiv L_m^*$. Variation of voltage in (13) with increase in speed is then negligibly small and is only due to variation in the term $L_{\sigma s}/L_m^*$, as magnetizing inductance in the controller changes from the rated value toward the unsaturated value. However, if the inverse magnetizing curve approximation is incorrect, the variation in voltage of (13) can be substantial. This is confirmed by performing the following experiment (experimental set-up is described in Appendix). Parameters a and b of (7) are arbitrarily selected and the machine is operated as vector controlled (using the controller of Fig. 1) in the field-weakening region under no-load conditions. Fundamental components of the stator line-to-line voltage and stator current are measured for different operating speeds. Fig. 3 illustrates measurement results (fundamental components of the stator line-to-line voltage and stator current in terms of rms values) for two values of coefficient a of (7), with $b = 7$. Cases with $a = 1$ (saturation ignored in the controller) and $a = 0.7$ (magnetizing curve too saturated) are shown. The base speed is selected as 1150 rpm, while the rated synchronous speed of the machine is 1500 rpm. (As the fundamental iron loss is of the highest value at rated frequency [16], and as mechanical losses increase with speed, the base speed is taken below 1500 rpm in an attempt to reduce the effects of the neglected losses on accuracy of the identification.) If the main flux saturation is neglected in the controller ($a = 1$), the stator voltage increases in the field weakening region, so that the voltage margin available for current control reduces (Fig. 3a). If saturation is over-compensated ($a = 0.7$), the voltage in the field weakening decreases (Fig. 3a). The stator d-axis current is reduced too much (Fig. 3b), leading to a de-
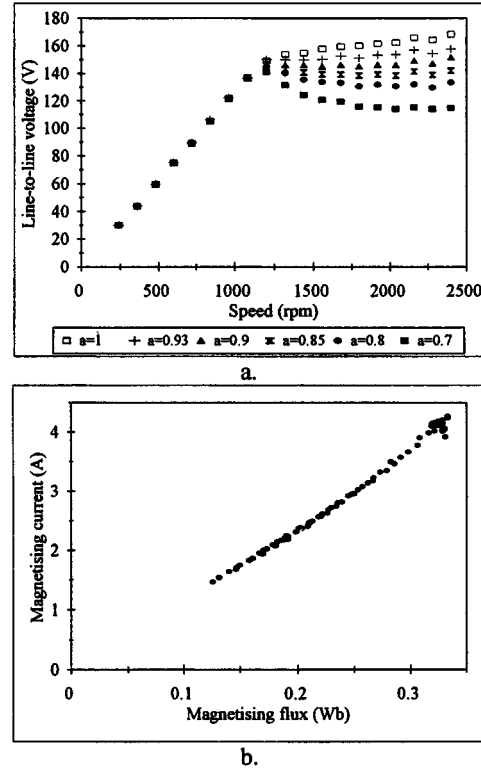
crease in the motor's torque capability. Thus only correct setting of parameters of the inverse magnetizing curve (here a and b) enables operation with the correct voltage margin necessary for current control, with torque capability of the motor preserved.

The stator d-axis current reference and the measured fundamental component of the stator no-load current coincide, Fig. 3b. Stator current measurement is thus not necessary, as the stator d-axis current reference can be used instead.

C. Determination of the Magnetizing Curve

On the basis of the theoretical considerations, the following procedure is suggested. Parameters a and b are arbitrarily selected and a variable frequency no-load test is performed in the field weakening region. Fig. 4a illustrates a set of experimental results, obtained using a procedure identical to the one described in conjunction with Fig. 3. Field weakening is initiated at 1150 rpm and fundamental stator voltage is measured for various values of the coefficient a in the control system, with $b = 7$. As discussed in conjunction with (13), accurate representation of the inverse magnetizing curve will lead to a practically constant value of the fundamental stator voltage in the field weakening region. Thus, by performing measurements for various values of coefficients a and b, it is possible to determine the most appropriate pair a, b purely by visual inspection of the measured voltage curves. From Fig. 4a the flattest voltage curve results for $a = 0.9$ with $b = 7$.

A more exact approach involving calculations based on (11), can be used for determination of the magnetizing inductance as a function of the magnetizing current (i.e., stator d-axis current

reference). If the stator resistance is not known, it is neglected. The magnetizing inductance is obtained from (11) as:

$$L_m = \frac{v}{\omega}\frac{1}{i_{ds}^*} - L_{\sigma s}. \tag{14}$$

It is necessary to measure only the fundamental component of the stator voltage, v. The speed of rotation equals the set speed and the stator d-axis current reference is used instead of the measured stator no-load current. For each set of points of Fig. 4a, that correspond to one pair of values of a and b, the magnetizing inductance is calculated using (14) at all speeds. The inverse magnetizing curve of the machine, calculated in this way, is shown in Fig. 4b. Fig. 4b includes data obtained with all of the parameter a values used in Fig. 4a ($b = 7$).

Fig. 4b shows that, regardless of the setting of the parameters a and b in the indirect vector controller, the identified points will always belong to the same curve. It is therefore sufficient to carry out the no-load test in the field weakening region with a single set of values of parameters a and b and then to calculate the inverse magnetizing curve using (14). Fitting of the curve of Fig. 4b yields the required values as $a = 0.9$ and $b = 7$. These values are the same as those that follow from Fig. 4a without any calculations (the flattest behavior of the measured voltage in the field-weakening region, with all the values close to 1 p.u.).

D. Accuracy of the Procedure

The identification procedure requires that the machine can run under no-load conditions, that the fundamental component of the stator voltage can be measured, and that the stator leakage inductance is known. Implementation of the inverse magnetizing curve in the controller by means of (7) is not a pre-requisite. As already pointed out, any other suitable function can be used instead.

Selection of the speed at which field weakening is started is rather arbitrary. This is confirmed by another experiment, that fully corresponds to those described in the previous sub-section. Field weakening is now initiated at 650 rpm and the tests are conducted up to a speed of around four times base speed. The inverse magnetizing curve, calculated under these conditions by means of (14), is shown in Fig. 5. Overlapping of Figs. 5 and 4b shows that the two curves coincide.

Fig. 5 includes results of the standard no-load test, performed with variable voltage, 50 Hz sinusoidal supply. Agreement between the data obtained by two different experimental procedures is very good.

The sensitivity of the procedure to incorrect values of the stator leakage inductance is examined by reconstructing the magnetizing curve, by means of (14), from data obtained for $a = 0.9$, $b = 7$ and the base speed of 1150 rpm. Three traces are shown in Fig. 6. The first one corresponds to the correct value of the stator leakage inductance ($L_{\sigma s n}$). This trace at the same time verifies that a single set of voltage measurements in the field weakening region, for any pair of values of parameters a and b, is sufficient for calculation of the magnetizing curve. The other two traces are obtained with an underestimate ($0.5 \times L_{\sigma s n}$) and an overestimate ($2 \times L_{\sigma s n}$) of the stator leakage inductance, respectively. Errors in magnetizing curve reconstruction appear to be rather small if error in the stator
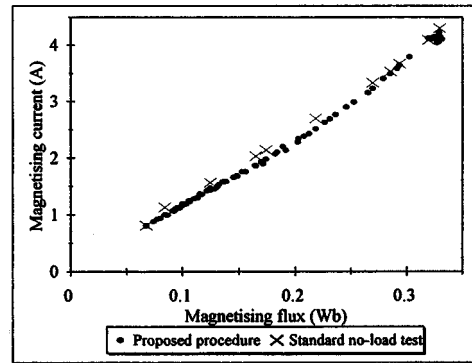

Fig. 5. Inverse magnetizing curve reconstructed from voltage measurements, using 650 rpm as the base speed, and curve obtained from standard no-load test with sinusoidal 50 Hz supply.
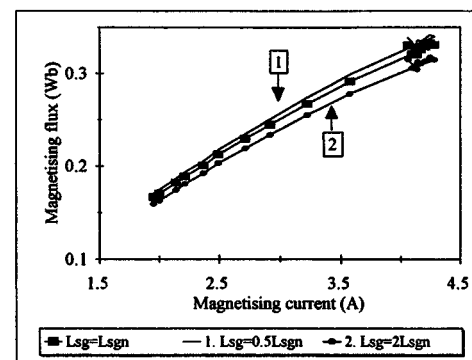

Fig. 6. Illustration of sensitivity of the identification procedure to incorrect value of the stator leakage inductance ($Lsg \equiv L_{\sigma s}$).

leakage inductance is up to 50%. Fig. 6 confirms that reasonable accuracy is obtained with a moderately correct estimate of the stator leakage inductance.

It should be pointed out that the use of (7) implies limited accuracy in the very low flux region, if the magnetizing curve has a point of inflexion [10], [11]. This is an inevitable consequence of the inverse magnetizing curve approximation adopted, that treats the initial part of the curve as a straight line through the origin.

The rated magnetizing inductance is obtained from any of the Figs. 4b, 5 or 6 as equal to 78 mH. The rated rotor flux is therefore 0.33 Wb (or 0.458 Wb peak).

IV. CONCLUSION

The paper describes a simple and reliable method of magnetizing curve identification in vector controlled induction machines. A suitably chosen analytical function (in general any function that accurately represents the inverse magnetizing curve) is implemented in the indirect rotor flux oriented controller. The values of the unknown parameters of the analytical function are identified by performing no-load test in the field weakening region, with arbitrarily selected initial parameter values and base speed. The identification method requires measurement of the fundamental component of the stator voltage only, as rotor speed and stator d-axis current reference are known. The procedure is verified by experimental investigation

and is believed to be well suited for both factory-based and on-site commissioning of the drive.

APPENDIX

LIST OF EQUIPMENT USED IN EXPERIMENTS

- Tektronix AM6203 Hall-effect probe and Tektronix AM503 amplifier (current measurement);
- Hewlett-Packard HP35665A dynamic signal analyzer (voltage measurement);
- PC controlled DBS 04 indirect vector controller of [6].

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