Identification of the magnetising curve during commissioning of a rotor flux oriented induction machine

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Abstract: Numerous operating regimes of a rotor flux oriented induction machine require variation of the rotor flux reference. Correct setting of the stator d-axis current reference for each value of the rotor flux reference is only possible if an approximation of the magnetising curve of the machine is incorporated in the control system. Consequently, the magnetising curve has to be identified during commissioning of the drive. An experimental method for identification of the magnetising curve is proposed, developed specifically for vector controlled drives. The method utilises the same vector controller and the same PWM inverter used in normal operation of the drive. The identification relies on the signals that are already present within the drive controller (stator currents only, or stator currents and the DC link voltage), so that additional measurements are not required. The identification function proposed ensures precise acquisition of the magnetising curve, robust against the stator resistance variation and the inverter lock-out time. The algorithm does not require any test signals. It is sufficient to perform the measurements during running of the unloaded motor at around 100 rpm. The developed procedure is verified by extensive experimentation and is believed to be well-suited for application during commissioning of the drive, provided that rotation is permitted.

List of principal symbols

v, i, ψ = voltage, current and flux linkage, respectively
ψ_r = magnitude of rotor flux space vector
ϕ_r = instantaneous angular position of the rotor flux space vector
ω, ω_{sl} = rotor speed of rotation (electrical) and angular slip frequency (electrical)
ω_e = angular speed of the rotor flux space vector (i.e. stator current and voltage angular frequency in the steady-state)
ψ_m, i_m = magnetising flux and magnetising current
ψ_{dm}, ψ_{qm} = magnetising flux d-q axis components
i_{dm}, i_{qm} = magnetising current d-q axis components
i_{ds}, i_{qs} = stator current d-q axis components
T_e = electromagnetic torque
P = number of pole pairs
T_r = rotor time constant
L_s, L_r, L_m = stator self-inductance, rotor self-inductance and magnetising inductance
$L_{\sigma s}, L_{\sigma r}$ = stator and rotor leakage inductance
R_s, R_{Fe} = stator resistance, equivalent iron loss resistance
V_{DC} = DC link voltage
$\underline{v}_s, \underline{i}_s$ = stator voltage and stator current space vectors

Subscripts:
n = rated value
B = base value
pu = per-unit value
dr, qr = d-q axis components of rotor quantities
a, b, c = stator phase quantities
α, β = variables in the stationary two-axis reference frame

Superscripts:
$*$ = reference values and values of machine parameters in the controller

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1 Introduction

If a rotor flux oriented induction machine is operated in the base speed region only, with constant rated rotor flux reference, knowledge of the machine's magnetising curve is not required [1]. However, in many applications rotor flux reference is variable rather than constant. Variation of the rotor flux reference is used when a rotor flux oriented induction machine is operated with maximum efficiency [2, 3], when development of an increased short-term transient torque with limited current capability of the converter is required [4, 5], or when accelerated build-up of the rotor flux is to be achieved [6]. The most frequently met case of rotor flux reference variation is operation in the field weakening region, where the rotor flux reference has to be reduced below the rated value [7, 8]. A decrease in the rotor flux reference is usually in inverse proportion to the rotor speed [9], although this is not optimal from the point of view of the torque capability [7, 8]. Variation of the rotor flux reference implies a variable level of the main flux saturation in the machine. The magnetising inductance of the machine is therefore a variable parameter, determined with the instantaneous level of saturation. Although it is possible to perform on-line identification of the magnetising inductance [10], such an approach is usually not satisfactory as the variation in the saturation level is rapid. An alternative approach, which enables correct setting of the stator d-axis current reference for each value of the rotor flux reference, consists of embedding the magnetising curve of the machine in the control system [11–13]. This approach requires identification of the magnetising curve during commissioning of the drive.

Identification of the magnetising curve, using a vector control system and a PWM inverter, has recently been discussed extensively [14–22]. A method, ideal for self-commissioning, should enable identification at standstill with either single-phase AC or DC supply, it should require measurement of stator currents and DC voltage only, and it should be accurate. Additionally, an important consideration is the complexity of the algorithm. As it is aimed at on-site commissioning, it should be possible to add the algorithm within the existing digital controllers, so its implementation needs to be simple. Unfortunately, a method that satisfies all these requirements is not available at present. If identification is performed with DC excitation at standstill, statistical methods such as recursive least squares [14, 15] have to be used in data processing. As voltages are reconstructed rather than measured, it is necessary to pre-determine inverter nonlinear characteristic by appropriate tests, prior to the magnetising curve identification [14–16]. The accuracy of the method significantly deteriorates below a certain magnetising current value [14–16], due to the pronounced impact of the inverter lock-out time on identification results. This technique is therefore regarded as inappropriate for magnetising curve identificafion [19]. Another similar method, which performs identification at standstill using a single-phase AC supply, is described in [20]. Problems regarding the inverter nonlinearity and the lock-out time are very much the same as when a DC voltage is used.

If the measurement of the stator voltages is allowed, it is possible to avoid the use of statistical methods and to perform identification purely from the measurement data using either a single-phase AC [17] or DC [18] supply. These methods are applicable during the drive commissioning if the voltage sensors are available, although this is rarely the case.

Approaches to the magnetising curve identification, described in [21–23], are more involved and therefore less suitable for on-site commissioning of the drive. Identification of the magnetising curve, described in [21], is performed at standstill and only current measurements are needed. However, all the three phases of the machine are energised and the standstill condition is achieved by means of closed loop speed control. The method requires that the vector controlled induction motor is coupled mechanically to a controllable load. It is therefore not suitable for on-site commissioning of the drive. A similar conclusion applies to the broad-band excitation method [19, 22], which requires injection of a multiple frequency supply into the machine's stator terminals. The method of [23], although apparently very accurate, is rarely applicable as it requires that the neutral point of the stator star-connected winding is accessible.

The purpose of this paper is to describe an alternative experimental method of magnetising curve identification in rotor flux oriented induction machines. Its development is motivated by the wish to overcome most of the problems encountered in the existing identification procedures, such as the high complexity of the algorithm, the requirements for sophisticated mathematical procedures in post-processing of the measurement data, the impossibility of accurate identification in the region of low magnetising current values, the inverter lock-out time problem, and the requirement for additional voltage sensors. The method requires that the stator d-axis current reference can be varied. Measurement of only those quantities that are normally measured anyway in a vector controlled drive (stator currents only, or stator currents and the DC link voltage) is needed. Stator voltages can be reconstructed from the known switching functions of the inverter and the measured DC link voltage, or stator voltage references (when available in the digital part of the controller) can be used. Measured stator currents and reconstructed stator voltages (or voltage references) are further used to calculate a conveniently defined identification function. This function is defined in such a way that its value is independent of the stator resistance and the inverter lock-out time, and it was proposed originally for on-line rotor time constant identification [24]. The special form of the identification function enables, as shown in the paper, direct calculation of the magnetising curve. The only required parameters of the machine are the total leakage inductance and the rated value of the rotor time constant. These parameters have to be determined prior to the magnetising curve identification using one of the many available procedures [19]. The identification algorithm is sufficiently simple to enable incorporation within the existing digital controllers, and it does not require complicated mathematical processing of the data. Identification is performed at a certain speed of rotation, under steady-state no-load operating conditions, by performing a series of simple calculations for different values of the stator d-axis current reference. The method is believed to be well-suited for the commissioning of a drive, provided that rotation is permitted and the load is not connected to the shaft.

2 Description of the drive

Commercially available vector controllers typically rely on the indirect feed-forward method of rotor flux oriented control [1]. The rotor flux reference is varied in the field-weakening region using the pre-programmed law

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

A reduction in the rotor flux leads to an increase in the magnetising inductance in the machine. If the stator d-axis current reference is to be correctly set, it is necessary to compensate for the variation of the main flux saturation by including the inverse magnetising curve in the control system [11]. As shown in [11], an indirect feed-forward rotor flux oriented controller with partial compensation of main flux saturation is described with the following equations:

$$\psi_m = \psi_r^* \tag{2}$$

$$i_{ds}^* = i_m(\psi_m) \tag{3}$$

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

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

where $K_1 = L_{mn}^*/T_{rn}^*$ and $K_2 = (3/2)P\, L_{mn}^*/L_{rn}^*$ are constants. It is assumed that the rotor speed varies much more slowly than the electromagnetic transients, so that the rate of change of the rotor flux reference is neglected in eqns. 2

and 3 (it should be pointed out that this approximation has no impact on the method of the magnetising curve identification described in this work; it merely reflects the actual structure of the controller in a commercially available drive [25], used in the experiments). An indirect vector controller, described by eqns. 2–5, ignores the cross-saturation effect and neglects the change in the ratio of the magnetising inductance to rotor inductance in eqns. 4 and 5 [11].

If rated magnetising current is taken as an independent input to the system, it is possible to introduce the normalised rotor flux value and the normalised inverse magnetising curve. The indirect feed-forward rotor flux oriented controller then takes the form shown in Fig. 1 [25]. The constant K_2 and the variable rotor flux reference value, required for generation of the stator q-axis current reference in eqn. 5, are taken care of by the PI speed controller. The stator d-axis current reference 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 magnetising curve as a function of the per unit rotor flux reference (which is a function of speed). All the per unit values in Fig. 1 are identified with the index *pu*. The slip gain of the drive (denoted in Fig. 1 as SGD) is a constant parameter, given by eqn. 4 with SGD = $L_{mn}^* /(T_{rn}^* \psi_{rn})$.

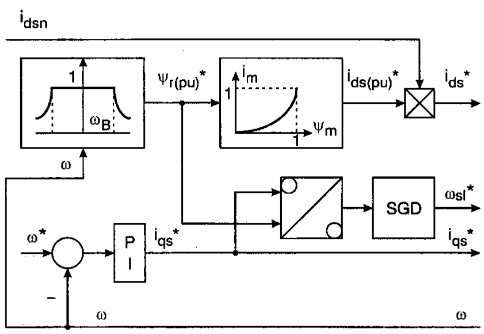

Fig. 1 *Indirect feed-forward vector controller of an industrial drive [25] with compensation of main flux saturation*

The rated magnetising current can be relatively accurately estimated from the rated stator current and rated power factor for low to medium power machines. Alternatively, it can be experimentally determined by running the machine in the 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 magnetising current will correspond to the value of the stator d-axis current reference that yields the rated voltage at the machine terminals. The rated magnetising current was determined here using the former approach.

3 Selection of identification function and identification procedure

3.1 Identification function used in identification process

Magnetising curve identification will be performed in steady-state operation of a rotor flux oriented induction machine that runs at a certain speed. Rotor flux oriented induction motor drives are normally equipped with stator current sensors and with a DC link voltage sensor. Any identification method that is to be applied during the drive commissioning should make use of the existing sensors only. Let the measured values of stator currents and DC link voltage be i_a, i_b, i_c and V_{DC}. Stator voltages are not measured and therefore have to be either reconstructed using a measured value of the DC link voltage and known binary control signals fed to the inverter power switches (i.e. switching functions), or the voltage references (if available) have to be used. Let the reconstructed stator phase voltages be v_a, v_b and v_c.

As the stator voltages are not measured, we face the problem of the lock-out time of power switches. The lock-out time causes a difference between the reconstructed (or reference) voltage values and the actual voltages across the motor. Next, as it is intended to use the voltages in the formulation of the function for the magnetising curve identification, stator resistance will inevitably appear in this function. Any function that is to be selected for identification purposes should therefore be of such a form that the discrepancy between the reconstructed and the actual voltages due to the lock-out time effect does not affect its value. Furthermore, the function should be formulated in such a way that knowledge of the stator resistance is not required, as this is a varying parameter. One such function has been proposed in [24] as a convenient choice for the process of on-line rotor resistance estimation in vector controlled induction machines. The function is defined as

$$\begin{aligned}F(v_a, v_b, v_c, i_a, i_b, i_c) &= F(\underline{v}_s, \underline{i}_s)\\ &= i_a \int v_a dt + i_b \int v_b dt + i_c \int v_c dt\\ F(\underline{v}_s, \underline{i}_s) &= i_{\alpha s} \int v_{\alpha s} dt + i_{\beta s} \int v_{\beta s} dt \qquad (6)\end{aligned}$$

As shown in the following two Sections, this function satisfies the two requirements stated above.

3.2 Impact of stator resistance on identification function value

Let us assume for the time being that the reconstructed (or reference) and the actual stator voltages are the same. The stator voltages can then be written as

$$\begin{aligned}v_a &= R_s i_a + d\psi_a/dt\\ v_b &= R_s i_b + d\psi_b/dt\\ v_c &= R_s i_c + d\psi_c/dt \qquad (7)\end{aligned}$$

Substitution of eqn. 7 into eqn. 6 yields

$$\begin{aligned}F(\underline{v}_s, \underline{i}_s) &= i_a\psi_a + i_b\psi_b + i_c\psi_c\\ &\quad + R_s \int (i_a + i_b + i_c) dt\\ &= i_a\psi_a + i_b\psi_b + i_c\psi_c \qquad (8)\end{aligned}$$

as the sum of the three stator currents equals zero at any instant of time. The value of the function F defined in eqn. 6 is therefore independent of the stator resistance.

3.3 Impact of inverter lock-out time on value of identification function

Suppose that the stator voltages used in eqn. 6 are reconstructed from the PWM pattern having the lock-out time of power switches τ and period equal to T. The reconstructed voltages are then correlated with actual voltages (primed symbols) through

$$\begin{aligned}v_a &= v_a' - V_{DC}\frac{\tau}{T}\mathrm{sgn}(i_a)\\ v_b &= v_b' - V_{DC}\frac{\tau}{T}\mathrm{sgn}(i_b)\\ v_c &= v_c' - V_{DC}\frac{\tau}{T}\mathrm{sgn}(i_c) \qquad (9)\end{aligned}$$

Substitution of eqn. 9 into eqn. 6, assuming a sinusoidal stator current of amplitude I and angular frequency ω, and taking into account eqn. 8, yields

$$F(\underline{v}_s, \underline{i}_s) = i_a\psi_a + i_b\psi_b + i_c\psi_c + \varepsilon(\tau) \quad (10)$$

As shown in [24], $\varepsilon(\tau)$ has zero mean value within the period of the fundamental component. It therefore follows that the lock-out time of the inverter switches does not affect the value of the function F in the steady state as long as the average value of the function is considered. The following considerations are therefore based on the value of the function F given on the right-hand side of eqn. 8. It is convenient to transform this equation into the rotor flux oriented reference frame of the controller in order to show how the magnetising curve of the machine can be identified. After performing the coordinate transformation, eqn. 8 becomes

$$F(\underline{v}_s, \underline{i}_s) = i^*_{ds}\psi_{ds} + i^*_{qs}\psi_{qs} \quad (11)$$

3.4 Magnetising curve identification principle

The identification function F of eqn. 11 can be expressed in terms of the magnetising flux d-q axis components as

$$F(\underline{v}_s, \underline{i}_s) = L_{\sigma s}i_s^2 + \psi_{dm}i^*_{ds} + \psi_{qm}i^*_{qs} \quad (12)$$

where $i_s = \sqrt{(i_{ds}^2 + i_{qs}^2)} = \sqrt{(i_{ds}^{*2} + i_{qs}^{*2})}$, $\psi_{dm} = L_m i_{dm}$, and $\psi_{qm} = L_m i_{qm}$. Under the no-load conditions, if mechanical and iron losses in the machine are neglected, the stator q-axis current reference is zero so that the magnetising flux along the q-axis is zero as well. The stator current then equals the stator d-axis current reference, and eqn. 12 reduces to

$$F(\underline{v}_s, \underline{i}_s) = (L_{\sigma s} + L_m)i_s^2 \approx (L_{\sigma s} + L_m)i_{ds}^{*2} \quad (13)$$

However, this approximation turns out to be insufficiently accurate for low values of stator d-axis current reference. Experiments show that under this condition, the stator q-axis current reference can become comparable to the value of the stator d-axis current reference. An alternative expression for the function F, in terms of rotor flux components, is therefore utilised:

$$F(\underline{v}_s, \underline{i}_s) = \sigma L_s i_s^2 + \frac{L_m}{L_r}(\psi_{dr}i^*_{ds} + \psi_{qr}i^*_{qs}) \quad (14)$$

where $\sigma = 1 - L_m^2/(L_sL_r)$ is the total leakage coefficient of the machine. For any induction machine $\sigma L_s \approx L_{\sigma s} + L_{\sigma r}$ holds true. Eqn. 14 yields eqn. 13 for the ideal no-load operation (i.e. $i^*_{qs} = 0$).

If the correct field orientation is maintained in all the operating conditions, then $\psi_{qr} = 0$ and $\psi_{dr} = \psi_r$. Furthermore, in any steady state $\psi_r = L_m i^*_{ds}$. Hence eqn. 14 becomes

$$F(\underline{v}_s, \underline{i}_s) = (L_{\sigma s} + L_{\sigma r})i_s^2 + \frac{L_m^2}{L_r}i_{ds}^{*2} \quad (15)$$

The stator current can be easily calculated from the known stator d-q axis current references as

$$i_s = i_s^* = \sqrt{i_{ds}^{*2} + i_{qs}^{*2}}$$

3.5 Identification procedure

Eqn. 15 suggests the following procedure for the magnetising curve identification. The machine is allowed to run at a certain constant speed in the closed-loop speed mode under no-load conditions. A series of steady-state measurements are performed for different values of the stator d-axis current reference. The value of the function F is evaluated for each setting of the stator d-axis current reference using eqn. 6. The first term on the right-hand side of eqn. 15 is at first calculated on the basis of the known stator d-q axis current references and total leakage inductance, and is further deducted from the appropriate function F value. The magnetising inductance is then obtained by equating the second term on the right-hand side of eqn. 15 to this difference. The magnetising characteristic, obtained from eqn. 15, is of the form $L_m = f(i_m)$, where $i_m = i^*_{ds}$ is assumed. The magnetising curve is finally calculated as $\psi_m = L_m i_{ds}^*$.

It is important to emphasise that identification of the magnetising curve, using eqn. 15 and the described procedure, assumes that the correct field orientation is maintained during measurements. This is only possible if the calculation of the reference slip in Fig. 1 accounts for the nonlinearity of the magnetising curve. At the identification stage, the magnetising curve is not known and therefore calculation of the reference slip will always be inaccurate to a certain extent. One could say that calculation of the slip reference is irrelevant as the testing is performed under no-load conditions (so that stator q-axis current reference and slip reference are sufficiently close to zero). This is, however, not the case at low settings of the reference stator d-axis current (unless the speed at which testing is performed is sufficiently small, Section 3.6). The experiments show that in this region no-load losses can produce such a stator q-axis current reference, which, combined with an incorrect setting of the slip gain, leads to detuned operation. The setting of the slip reference during experiments is discussed in more detail in Section 4.1.

3.6 Selection of no-load speed for identification purposes

The magnetising curve identification method is developed under the assumption that the existence of the iron losses and the mechanical losses in the machine can be ignored. As the indirect vector controller neglects both types of losses, the stator q-axis current reference inevitably has a non-zero value, even under no-load conditions. Iron losses depend on the frequency of the supply, while mechanical losses are a function of the speed of rotation. It is therefore desirable to qualitatively investigate the impact of the speed at which testing is performed on the accuracy of the identification, and provide guidelines for selecting the most appropriate speed.

An attempt is first made to evaluate the extent to which the accuracy of the identification, based on the experimental determination of the identification function F of eqn. 6 and calculations related to eqn. 15, is affected by the iron losses. Let the iron losses be modelled with an equivalent frequency-dependent resistance R_{Fe}, placed in parallel to the magnetising branch, as proposed in [26]. The function F, expressed in terms of the magnetising flux d-q axis components in the form of eqn. 12, remains valid. However, the magnetising current components are now determined with the following expressions in the reference frame of the controller:

$$i_{dm} = \frac{1}{1 + (\omega_e^* T_{Fe})^2(L_{\sigma r}/L_r)^2} \times \left\{\frac{L_{\sigma r}}{L_r}i^*_{ds} + \frac{\psi_{dr}}{L_r} + \omega_e^* T_{Fe}\left(\frac{L_{\sigma r}}{L_r}\right)^2\left(i^*_{qs} + \frac{\psi_{qr}}{L_{\sigma r}}\right)\right\}$$

$$i_{qm} = \frac{1}{1 + (\omega_e^* T_{Fe})^2(L_{\sigma r}/L_r)^2} \times \left\{\frac{L_{\sigma r}}{L_r}i^*_{qs} + \frac{\psi_{qr}}{L_r} - \omega_e^* T_{Fe}\left(\frac{L_{\sigma r}}{L_r}\right)^2\left(i^*_{ds} + \frac{\psi_{dr}}{L_{\sigma r}}\right)\right\} \quad (16)$$

A variable time constant T_{Fe} is defined as $T_{Fe} = L_m/R_{Fe}$. Substitution of eqn. 16 into eqn. 12 yields a function F of the following form:

$$F(\underline{v}_s, \underline{i}_s) = L_{\sigma s} i_s^2 + \frac{1}{1 + (\omega_e^* T_{Fe})^2 (L_{\sigma r}/L_r)^2} \times \left\{ \frac{L_m L_{\sigma r}}{L_r} i_s^2 + \frac{L_m}{L_r} \left(\psi_{dr} i_{ds}^* + \psi_{qr} i_{qs}^*\right) + \omega_e^* T_{Fe} \frac{L_{\sigma r}}{L_r^2} \left(\psi_{qr} i_{ds}^* - \psi_{dr} i_{qs}^*\right) \right\} \quad (17)$$

Eqn. 17 is substantially more complicated than the corresponding eqn. 14, obtained when the iron losses are neglected. It should be noted that the q-axis component of the rotor flux is now always different from zero, as ideal field orientation cannot be achieved without compensation of the iron losses in the control system [26]. Eqn. 17 reduces to eqn. 14 if the iron losses are neglected by letting $R_{Fe} \to \infty$, i.e. $T_{Fe} \to 0$.

Inspection of eqn. 17 shows that the lower the supply frequency, the smaller the impact of iron losses on the function F. In the limit when $\omega_e^* = 0$ (i.e. supply is DC), the iron loss in the machine becomes zero and eqn. 17 becomes identically equal to eqns. 14 and 15. It therefore follows that, ideally, magnetising curve identification should be performed with the DC supply in order to avoid any impact of the iron losses on the function F values. As this is not possible, owing to the integration that is involved in eqn. 6, testing should be performed at the lowest practically possible speed of rotation.

Similar considerations apply to the mechanical losses as well. Mechanical losses vary, approximately, with the square of the speed. The higher the speed, the higher the value of the stator q-axis current reference in no-load operation. It is therefore desirable to perform the identification of the magnetising curve at as low a speed as possible.

If the testing is performed at a given speed of rotation, mechanical losses are constant for all the measurement points. However, iron losses depend on the stator d-axis current reference, and are significantly higher at a high stator d-axis current reference (e.g. $i_{ds}^* = i_{dsn}$) than at a very low value of the stator d-axis current reference (e.g. $i_{ds}^* = 0.2 i_{dsn}$). At high settings of the stator d-axis current reference, the dominant part of the no-load losses are therefore the iron losses, while mechanical losses are dominant at low settings.

The importance of selecting an identification function that is robust with respect to the stator resistance variation and the inverter lock-out time, such as eqn. 6, is obvious from these considerations. The accuracy of identification tends to be affected to a great extent at standstill and at low speeds of rotation by these two phenomena. As the tests are to be performed at low speeds of rotation, it is of paramount interest that the stator resistance variation and the inverter lock-out time do not influence the value of the identification function.

4 Experimental set-up and measurement procedure

4.1 Description of testing procedure

The identification procedure developed in Section 3 was experimentally tested using the commercially available indirect feed-forward rotor flux oriented controller [25]. The original structure of the control system is that in Fig. 1. As the magnetising curve of the machine is not known, it had to be bypassed in the controller of Fig. 1 during measurements. The stator d-axis current reference is therefore taken as an independent input to the system. It is varied in all the experiments (unless otherwise stated) from 0.2 to 1.7 of the rated value, with 0.1 step (the rated value of the stator d-axis current is 0.52p.u. on the rated stator current base; the range of the stator d-axis current variation is therefore $i_{ds}^* \in [0.104, 0.884]$ p.u.). The relevant data for the four-pole 50 Hz induction motor used in the experiments are given in the Appendix.

The correct calculation of the reference slip in Fig. 1 requires knowledge of the magnetising curve that is at present unknown. Consequently, the calculation of the slip reference is bound to be inaccurate to some extent. The experiments are performed with two different methods of calculating the reference slip:

$$\omega_{sl}^* = (SG) i_{qs}^* \qquad SG = 1/(T_{rn} i_{dsn})$$
$$\omega_{sl}^* = (SG_n) i_{qs}^* / i_{ds}^* \qquad SG_n = 1/T_{rn} \quad (18)$$

The reasoning behind this selection is as follows. For small stator d-axis current references, calculation of the slip reference according to the first method of eqn. 18 gives too low a value of the slip reference (with respect to the correct one), while calculation according to the second method of eqn. 18 gives too high a value of the slip reference. The opposite holds true for $i_{ds}^* > i_{dsn}$. The errors in the identified magnetising curve (if any) are therefore expected to be of the opposite signs for these two methods of the slip reference calculation. Fig. 2 illustrates the controller structure used in the experimental magnetising curve identification.

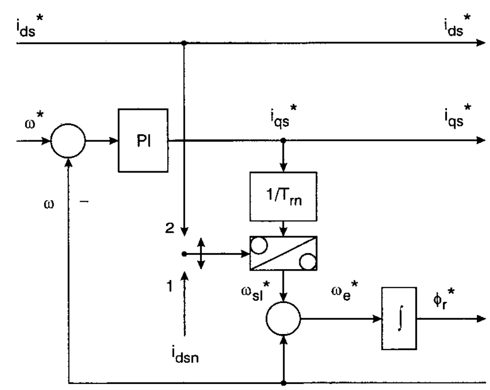

Fig. 2 *Structure of control system used in experiments*
Method 1: $\omega_{sl}^* = (SG) i_{qs}^*$
Method 2: $\omega_{sl}^* = (SG_n) i_{qs}^* / i_{ds}^*$

On the basis of the discussion in Section 3.6, one can anticipate inaccuracies in the identification procedure at very low settings of the stator d-axis current reference, caused by the mechanical losses, unless the speed of rotation is sufficiently low. Mechanical losses are machine specific and it could happen for a certain machine that, due to the integration related restrictions on the minimum speed of rotation at which the testing can be performed, an accurate identification in the region of low stator d-axis current reference is not possible. It was therefore decided to artificially increase the mechanical losses of the induction motor in experiments by connecting it to a DC machine. A kind of worst case scenario is therefore used in the experimental work. If there is a certain speed at which accurate identification is achieved under these conditions, then it can be concluded that the identification will be applicable to all the induction motors in true no-load operation. Furthermore, a general guideline for the selection of the speed for the testing can be provided as well.

4.2 Implementation of function F calculation

The implementation procedure for function F calculation, as well as the remaining part of the control system of the drive, are shown in Fig. 3. The complete vector control algorithm and the function F calculation are implemented in a DSP. The drive is equipped with current control in the rotating reference frame so that the stator voltage reconstruction is not needed, and stator voltage references in the stationary reference frame are used instead. As shown in Fig. 3, the d-q axis voltage references in the synchronous reference frame, generated at the output of the current controllers, are transformed into the stationary reference frame and are then used for function F calculation on the basis of eqn. 6. Stator current feedback is acquired by scaling and filtering the signals from the current sensors. Stator current components in the stationary α-β reference frame are thus produced and these signals are applied in the evaluation of eqn. 6. Digital filtering and conditioning of the current feedback (not shown in Fig. 3) aims to filter out the ripple and the commutation noise, and does not affect in any way the average value of the identification function F.

The problem encountered most frequently in the process of deriving the flux from the motor terminal quantities is the offset of the voltage integrators. The proposed calculations involve digital integration of the internal voltage commands. Although the identification function F is robust with respect to the integration offset, as proved in [24], practical implementation of the digital integrator and the necessity to avoid the numerical overflow require that a nonideal, relaxed integrator be used instead of the ideal one. The constant ξ in the expression $\xi\omega_{en}/(z - 1 + \xi)$ of Fig. 3 is set in such a way that the initial offset in the integrated voltage decays exponentially with the time constant of 750ms. The integrator's phase error therefore has negligible effects on the function F values for all the fundamental frequencies above 0.5Hz. Although the inverter lock-out time and the offset do not influence the average value of the function F, the instantaneous value (block A in Fig. 3) might still carry some pulsation, as discussed in [24]. By averaging the instantaneous values within each period of the fundamental frequency (block B in Fig. 3), pulsation in the function F is fully suppressed [24]. For improved accuracy, average values thus obtained are additionally averaged within a 1 s interval for each measurement point (i.e., for $i_{ds}^* \in [0.104, 0.884]$ p.u.).

4.3 No-load test with sinusoidal supply

The magnetising curve of the induction motor was at first determined using the standard no-load test with variable voltage 50Hz sinusoidal supply. Figs. 4 and 5 display the magnetising curve and the corresponding magnetising inductance obtained in this way. The abscissa is given in Figs. 4 and 5, and in all the subsequent Figures, in terms of the relative value of the stator d-axis current reference with respect to the rated stator d-axis current references, i_{ds}^*/i_{dsn}. All the relevant results of the developed identification procedure, presented in the next Section, are plotted to the same scales as Figs. 4 and 5. Direct overlapping of cor-

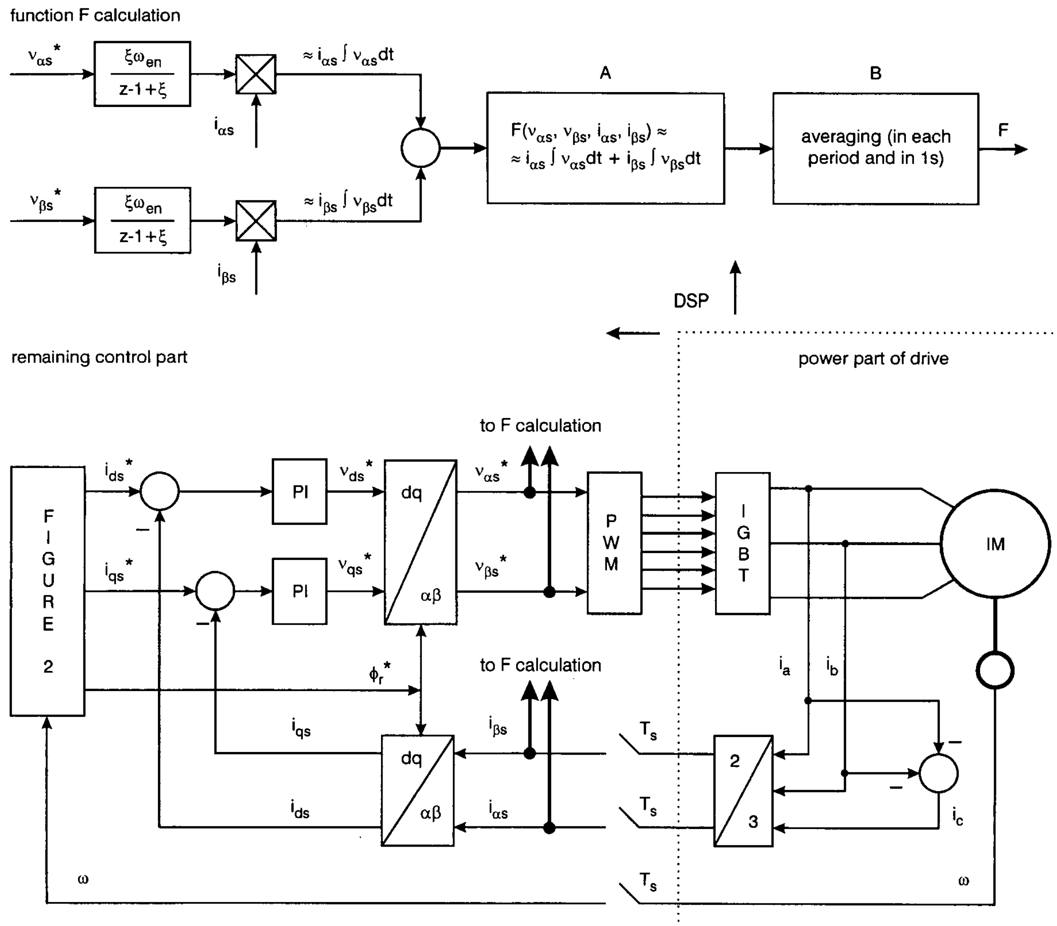

Fig. 3 *Implementation procedure for calculation of identification function F*

responding Figures thus enables direct comparison of the accuracy of the proposed procedure. Actual measurement and/or identification points are denoted in all the figures with a circle or a square.

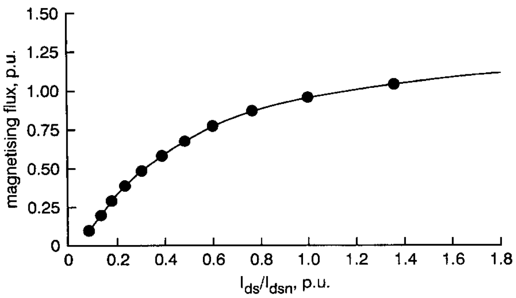

Fig. 4 *Magnetising curve obtained from standard no-load test with sinusoidal supply (variable voltage, 50Hz supply)*

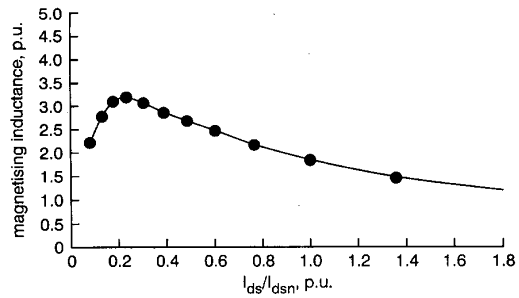

Fig. 5 *Magnetising inductance obtained from the standard no-load test with sinusoidal supply (variable voltage, 50Hz supply)*

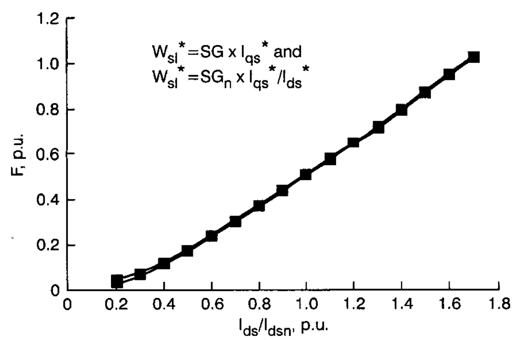

Fig. 6 *Function F values for 375rpm and 1050rpm tests for both methods of slip reference calculation*

5 Experimental results

Tests were performed initially at two speeds of rotation, selected quite arbitrarily as 375rpm and 1050rpm. Fig. 6 depicts values of the identification function F, obtained using eqn. 6, and the implementation procedure of Section 4.2, for the both speeds of rotation and for the both methods of calculating the slip reference. The four curves completely overlap, indicating that the function F is independent of both the speed of rotation and the method of slip reference calculation.

On the basis of the discussion of Section 3.6, one expects that the results of the identification will be better at the lower of the two speeds. Indeed, experimental results have confirmed this expectation. It is for this reason that only results for 375rpm are shown. Fig. 7 shows the variation of the stator q-axis current reference (as a relative value with respect to the rated stator current) for the two methods of the reference slip calculation. The two methods of slip reference calculation give the same slip reference (for the given stator q-axis current reference) when the stator d-axis current reference equals the rated value. Hence, the stator q-axis current reference curves intersect at the point where $i_{ds}^* = i_{dsn}$. Corresponding results for 1050rpm speed have shown that a substantially higher stator q-axis current reference is required for any setting of the stator d-axis current reference, and regardless of the method of the reference slip calculation. This is a consequence of an increase in the mechanical and iron losses at 1050rpm, when compared to the losses at 375rpm. Values of the stator q-axis current reference become rather high at 1050rpm (up to 0.1p.u.) for very low settings of the stator d-axis current reference, where the mechanical losses are dominant.

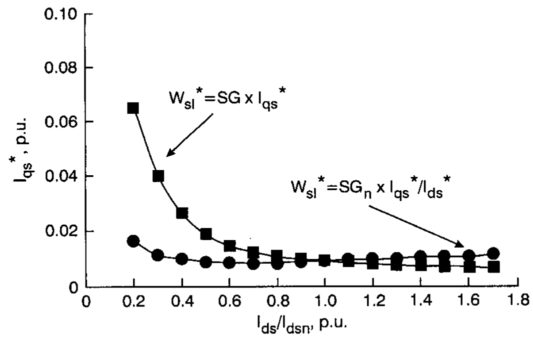

Fig. 7 *Variation of stator q-axis current reference at 375rpm for both methods of slip reference calculation*

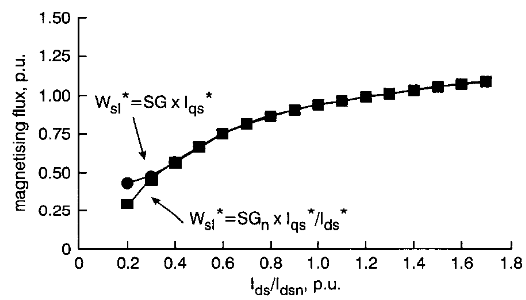

Fig. 8 *Identified magnetising curve on basis of measurements at 375rpm*

The values of function F of Fig. 6 and stator q-axis current reference of Fig. 7 are further used to reconstruct the magnetising curve of the machine by means of eqn. 15. The identified magnetising curve is shown in Fig. 8 for the 375rpm speed. Both methods of slip reference calculation are considered. At sufficiently high values of stator d-axis current reference, above $0.3i_{dsn}$ (and above $0.5i_{dsn}$ at 1050rpm), detuning caused by incorrect setting of the slip reference is negligibly small. Consequently, both methods of the slip reference calculation lead to the same reconstructed magnetising curve. Overlapping with Figs. 4 and 5 shows excellent matching. However, for small values of the stator d-axis current reference, detuning becomes pronounced so that eqn. 15 is essentially not valid any more. As a consequence, the two methods of the reference slip calculation give two different predictions of the magnetising curve that are positioned at opposite sides of the correct curve. Deviations of the reconstructed curve from the correct one at very low stator d-axis current reference setting are considerably higher at 1050rpm than at 375rpm. These findings underpin the theoretical considerations of Section 3.6, and confirm that the identification should be performed at as low as possible speed of rotation.

Fig. 9 shows the magnetising inductance variation calculated from Fig. 8. It is even more evident from Fig. 9 that considerable divergence of the two curves, obtained by two different slip reference setting methods, takes place in the region of the low stator d-axis current values. The attempt to predict the existence of the point of inflexion that occurs at approximately $i_{ds}^* = 0.2 i_{dsn}$ (Figs. 4 and 5) has failed. The lower limit of the stator d-axis current reference setting at which accurate identification is still possible at 375rpm appears, therefore, to be of the order of $i_{ds}^* = (0.2$ to $0.3) i_{dsn}$. It is worth noting that from the practical point of view, the region of the magnetising curve below this current value is highly unlikely to be of any interest.

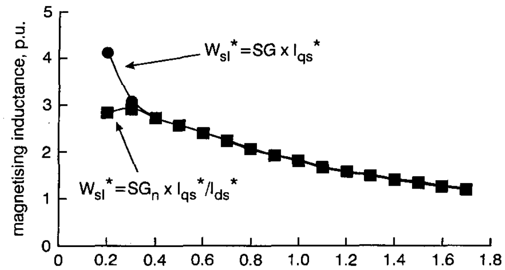

Fig. 9 *Identified magnetising inductance on basis of measurements at 375rpm*

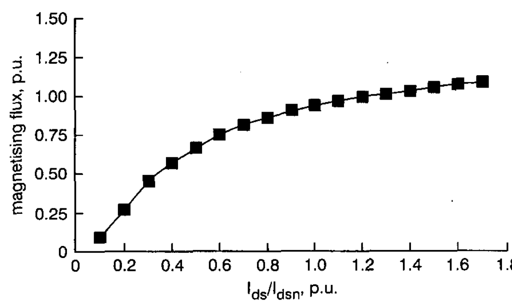

Fig. 10 *Identified magnetising curve at 100rpm*

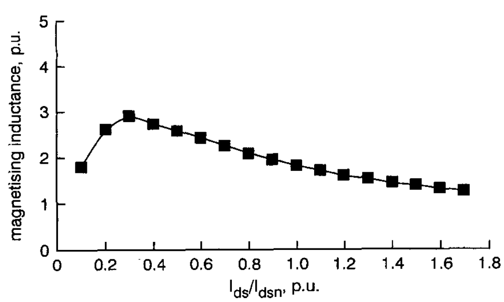

Fig. 11 *Identified magnetising inductance at 100rpm*

In order to further improve the accuracy of the magnetising curve identification, the third no-load test is performed. The speed of rotation is reduced to just 100rpm. Mechanical losses are now made negligibly small. Consequently, the stator q-axis current reference is so small, even in the region of the low stator d-axis current reference, that it becomes irrelevant which method of the slip reference calculation is used. Detuning is practically completely eliminated and both methods of the slip reference calculation lead to the same identified magnetising curve. Hence, in practice, one can choose any of the two methods of the reference slip setting of eqn. 18 and perform the testing with that method only. Testing is now performed for the stator d-axis current reference from 0.1 to 1.7 of the rated value. Fig. 10 displays the magnetising curve, while Fig. 11 shows the corresponding magnetising inductance. Overlapping of Figs. 4 and 10 shows extremely small differences in the region of the very small stator d-axis current references. Fig. 11 shows that a sufficient reduction of the speed at which testing is performed enables even identification of the point of inflexion. This is known to be a problem with most of the existing methods [14, 15].

Eqn. 15, used for the magnetising curve identification, is universally valid regardless of the machine's loading, as long as detuning effects due to the incorrect slip reference setting are negligibly small. An attempt was therefore made to investigate whether there is at least a region of the magnetising curve that could be identified with sufficient accuracy in the loaded operation. On the basis of the results obtained for no-load operation, one cannot expect that any reasonable accuracy can be achieved for low stator d-axis current reference. However, the situation might be different in the region of high stator d-axis current references. The speed at which testing is performed now becomes irrelevant as no-load losses are much smaller than the load at the shaft. The same testing procedure is repeated at the speed of 1050rpm for two values of the load torque, 12Nm and 22Nm (0.27p.u. and 0.49p.u., respectively). Both methods of the slip reference calculation are applied. Fig. 12 summarises the results. The magnetising inductance, calculated from eqn. 15, is shown for both load torques and both methods of the slip reference setting. Additionally, results for no-load operation (not shown previously for this speed) are included for comparative purposes.

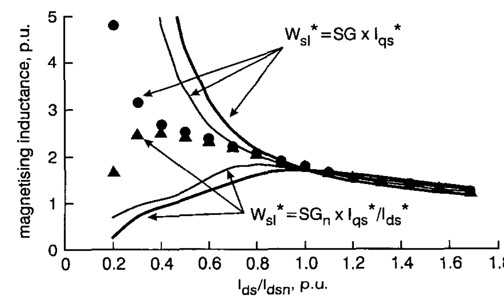

Fig. 12 *Magnetising inductance variation obtained from tests with loaded machine (load = 0, 12, 22Nm at 1050rpm)*
▲, ● 0Nm
—— 12Nm
—— 22Nm

Fig. 12 clearly indicates that higher the load, the larger the error in the identification of the magnetising curve will be for stator d-axis current references below the rated value. This is valid regardless of the method of the slip reference calculation. The interesting and somewhat unexpected conclusion that follows from Fig. 12 applies to the highly saturated region of the magnetising curve where $i_{ds}^* \geq i_{dsn}$. Discrepancies between values obtained with the different load torques and different methods of the slip reference calculation are very small. Thus it appears that the developed method of the magnetising curve identification can be used even when the load is connected to the shaft, and it is not possible to perform the no-load test. The region of the magnetising curve that can be identified in the loaded operation is restricted to the stator d-axis current higher than rated. While this region is of no interest with regard to operation in the field weakening region, it is exactly the region which is required for flux forcing and development of an increased short-term transient torque [4–6].

6 Conclusion

This paper presents a novel method of the magnetising curve identification that offers numerous advantages over the existing methods. First, only stator currents (or stator currents and the DC link voltage) have to be measured so that voltage sensors are not required. The measured values are used for evaluation of a conveniently defined identification function that overcomes the second frequently encountered problem: the inverter lock-out time. Evaluation of the identification function requires very modest hardware and software, so that the third problem, complexity of the algorithm, is eliminated. The magnetising curve is reconstructed from the identification function values using simple calculations. Hence, the fourth shortcoming of many of the existing methods, use of the complicated mathematical procedures, does not take place. Finally, the method enables very accurate identification, even in the region of the very low magnetising current values, including the point of inflexion, where most of the existing procedures fail.

Extensive experimental investigation shows that the magnetising curve can be accurately identified for all magnetising current values above a certain threshold value. The value of the magnetising current, below which identification becomes inaccurate, depends on the speed at which the no-load testing is performed. In general, the lower the speed, the lower the threshold value will be. Excellent accuracy is achieved for all the magnetising current values above 0.1p.u. at 100rpm. As a deliberate increase in the mechanical loss was introduced by connecting the DC machine to the shaft, it can be concluded that the proposed method of identification will yield the same accuracy for other induction motors tested in true no-load operation. The test should be performed at a speed of around 100rpm, using any of the available two methods for the slip reference setting during the experiment. The identification procedure is believed to be well suited to the requirements of on-site commissioning of vector controlled induction machines, provided that the running of the machine is permitted and that the machine is not loaded.

The identification procedure requires knowledge of the total leakage inductance and the rated rotor time constant. These parameters therefore have to be determined prior to the magnetising curve identification. The procedure is equally applicable to both sensored and sensorless drives.

Applicability of the identification method is experimentally investigated for loaded operation as well. It is shown that in such a case only the highly saturated region of the magnetising curve can be identified with sufficient accuracy. However, this is exactly the region that is required in some applications of the variable rotor flux reference other than field-weakening.

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8 Appendix: Motor and inverter data

90V 58A 50Hz $P = 2$ star

$R_s = 0.039$p.u. $R_r = 0.043$pu. $\sigma L_s \approx L_{\sigma s} + L_{\sigma r} = 0.16$p.u.

$L_{mn} = 1.84$p.u. $T_{en} = 45$Nm $I_{dsn} = 30.2$A $= 0.52$p.u.

Rated stator d-axis current is the RMS value.

Inverter switching frequency: 4kHz

Inverter lock-out time: 4 to 7μs, 5μs on average (not compensated)