STUDY OF MAIN FLUX SATURATION EFFECTS IN FIELD-ORIENTED INDUCTION MOTOR DRIVES

Emil Levi, St.Member IEEE V.Vučković S.Vukosavić

Dept. of El. Engineering
University of Novi Sad
Novi Sad, Yugoslavia

El.Engineering Institute "Nikola Tesla"
Viktora Igoa 3
Belgrade, Yugoslavia

ABSTRACT

The paper deals with effects caused by variable degree of main flux saturation in induction machines with field-oriented control. Indirect vector controller with fixed value of magnetizing inductance is assumed and influence of variable saturation in steady-state and during transients is investigated. It is shown that saturation effect is likely to be pronounced during operation in the field - weakening region, while its influence is small in the constant flux region if the value of magnetizing inductance in the controller is correctly set. Experimental identification of rotor time constant in the field-weakening region is performed and the results are included. A modified flux calculator is derived, which can provide satisfactory operation in the field-weakening region. Its structure involves magnetizing curve of the machine. The proposed flux calculator is verified by the aid of digital simulation.

I. INTRODUCTION

The indirect field-oriented control scheme for induction machines has gained substantial popularity during last few years due to its relative simplicity, compared to other methods which require either main flux and stator currents or stator voltages and currents sensing for rotor flux calculation [1]. The problem which arises in the application of this method is the variation of induction machine parameters. Rotor resistance changes due to temperature variation and magnetizing inductance is a function of main flux saturation. The influence of rotor resistance variation is thoroughly investigated and numerous means for compensation are proposed in Refs. [2-10]. The influence of saturation effect is discussed to some extent in [6,8,9,10], where it is treated as being a consequence of rotor resistance deviation and the analysis is mainly restricted to steady-state behaviour of the drive. Some important features of a saturated field-oriented induction machine are elaborated in [11], while the proper selection of flux level in field-oriented induction machine controllers under saturated conditions is treated in [12]. A method for on-line estimation of mutual inductance on the basis of stator currents, voltages and rotor speed measurement is proposed in [13].

The saturated dynamic models of induction machines with field-oriented control are discussed in recent Refs. [14-17]. As shown in [15-17], if the main flux saturation effect is taken into account, the equations which describe current-fed induction machine with field-oriented control are not decoupled any more. The scheme discussed in [16,17] comprises rotor flux and slip frequency calculation on the basis of stator currents and rotor speed measurement. The representation of saturated induction machine for simulation purposes is based on saturated current state space model given in [18,19]. A number of transients is simulated and it is shown that the effect of main flux saturation significantly influences drive behaviour in field-weakening range and during rapid accelerations with high value of maximum allowed torque. Finally, a new rotor flux and slip frequency estimation scheme based on stator currents and rotor speed as measured variables, which fully accounts for saturation effects and which can be realised without difficulties, is discussed in [20].

The study carried out in this paper analyses effects caused by missmatch between actual value of magnetizing inductance and the value used in the controller. Steady-state behaviour of the drive in the torque mode and in the speed mode is discussed. Dynamics are elaborated as well. It is assumed throughout the paper that rotor resistance and leakage inductance are constant parameters. Experimental investigation of saturation influence is carried out and theoretical analysis is verified. As a result of this study, a new structure of the rotor flux calculator is proposed, which accounts for saturation effects caused by change in stator d-axis current and neglects influence of q-axis magnetizing current on total magnetizing current. Due to the simplifying assumption that q-axis magnetizing current can be neglected, the structure of the calculator is simpler than the one discussed in [20]. The accuracy is satisfactory as long as the drive is operated with low maximum allowed torque value. Simulation results which verify the applicability of the modified flux calculator are included.

II. SATURATION EFFECTS IN STEADY-STATE

The indirect vector controller is shown in Fig.1. and described with the following equations

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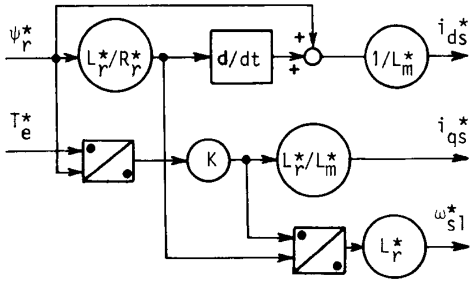

Fig. 1 - Indirect vector controller

$$i_{qs}^* = K \frac{T_e^*}{\psi_r^*} \frac{L_r^*}{L_m^*}$$

$$i_{ds}^* = \frac{1}{L_m^*} \left[1 + T_r^* p\right] \psi_r^* \tag{1}$$

$$\omega_{sl}^* = \frac{L_m^*}{T_r^*} \frac{i_{qs}^*}{\psi_r^*}$$

where K=4/(3P), P is the number of poles and T_r^* is the rotor time constant. Asterisk denotes wanted quantities. Due to difference between assumed and actual value of magnetizing inductance (L_m^* and L_m), actual values of rotor flux and torque will be different from commanded values. If the notation

$$L_m/L_m^* = \beta \;, \qquad L_r/L_r^* = \alpha \tag{2}$$

is applied, in the torque mode (i.e. with open speed loop) the following relations hold true

$$\frac{\psi_r}{\psi_r^*} = \beta \sqrt{\frac{1 + (\omega_{sl}^* T_r^*)^2}{1 + \alpha^2(\omega_{sl}^* T_r^*)^2}}$$

$$\frac{T_e}{T_e^*} = \beta^2 \frac{1 + (\omega_{sl}^* T_r^*)^2}{1 + \alpha^2(\omega_{sl}^* T_r^*)^2} = \left[\frac{\psi_r}{\psi_r^*}\right]^2 \tag{3}$$

where the conditions $\omega_{sl} = \omega_{sl}^*$ and $i_s = i_s^*$ are taken into account. Defining the error quantities as

$$\Delta\psi_{dr} = \psi_{dr} - \psi_{dr}^* = \psi_{dr} - \psi_r^*$$

$$\Delta\psi_{qr} = \psi_{qr} - \psi_{qr}^* = \psi_{qr} \tag{4}$$

the steady-state deviations of rotor flux components become

$$\lim_{t\to\infty} \Delta\psi_{dr} = \frac{(\beta-1) + \left[\omega_{sl}^* T_r^*\right]^2 (\beta-\alpha)\alpha}{1 + \alpha^2\left[\omega_{sl}^* T_r^*\right]^2} \psi_r^* \tag{5a}$$

$$\lim_{t\to\infty} \Delta\psi_{qr} = - \frac{\omega_{sl}^* T_r^* (\alpha-1)\beta}{1 + \alpha^2\left[\omega_{sl}^* T_r^*\right]^2} \psi_r^* \tag{5b}$$

and the error in orientation angle in steady-state is

$$\lim_{t\to\infty} \Delta\varphi_r = \text{arc tan} \left\{ - \frac{\omega_{sl}^* T_r^* (\alpha-1)}{1 + \omega_{sl}^{*2} T_r T_r^*} \right\} \tag{6}$$

Actual to commanded stator axis current components are

$$i_{ds}/i_{ds}^* = \frac{1}{\beta} \psi_r/\psi_r^*$$

$$i_{qs}/i_{qs}^* = \frac{\alpha}{\beta} \psi_r/\psi_r^* \tag{7}$$

In order to obtain more general solution which is independent of the actual machine, the ratio of rotor inductances α is given as

$$\alpha = \frac{\beta + \varepsilon}{1 + \varepsilon} \;, \quad \varepsilon = \frac{L_{\gamma r}}{L_m^*} \approx \begin{cases} 0{,}1 & \text{for small machines} \\ 0{,}01 & \text{for machines of high rating} \end{cases} \tag{8}$$

Due to small value of ε for machines of high rating, assumption that $\beta \approx \alpha$ is valid. Fig. 2 depicts relations (3) as functions of saturation degree β for the small machine with ε=0.1, whose data are given in Appendix together with the magnetizing curve.

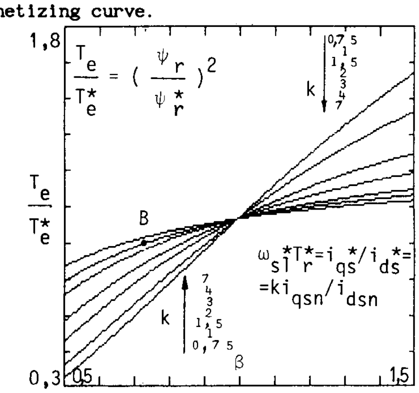

Fig. 2 - Steady-state characteristics $\psi_r/\psi_r^* = f(\beta)$, $T_e/T_e^* = f(\beta)$ with $\omega_{sl}^* T_r^* = i_{qs}^*/i_{ds}^*$ as parameter

Although these characteristics show general trends, the value of rotor flux and torque ratio which is going to be met in the operation of the drive depends on the actual shape of the magnetizing curve, adjusted value of L_m^* in the controller and commanded torque value. Fig. 3 displays the ratios ψ_r/ψ_r^*, T_e/T_e^* and actual saturation degree β as functions of commanded torque obtained through iterative procedure on the basis of the magnetizing curve of the machine given in Fig. A1 for three different values of L_m^*: $L_m^* = L_{mn}$ (point at the magnetizing curve which corresponds to operation with rated rotor flux and torque), $L_m^* = 1{,}45\ L_{mn}$

(initial slope of the magnetizing curve) and $L_m^* = L_{mn}/1{,}45$ (value which corresponds to operation in the highly saturated region). Commanded value of rotor flux is held constant and equal to rated. Dotted lines denote regions which are usually of no practical interest.

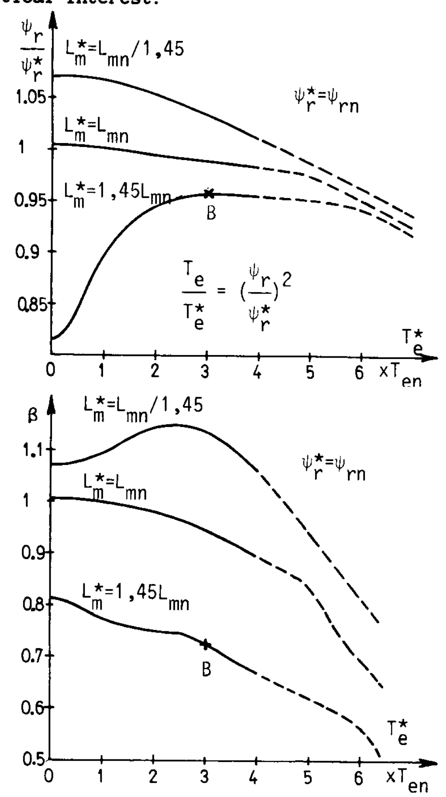

Fig. 3 - Steady-state characteristics $\psi_r/\psi_r^* = f(T_e^*)$, $T_e/T_e^* = f(T_e^*)$ and $\beta = f(T_e^*)$ for three values of L_m^* and operation in the constant rotor flux region $\psi_r^* = \psi_{rn}$ (index "n" denotes rated values).

Fig. 3 indicates that for proper adjustment of L_m^* (that is, $L_m^* = L_{mn}$) deviation of flux and torque caused by different saturation degree is likely to be very small in the whole region of interest ($T_e^* =$ 0 ... 2 - 3 T_{en}) for operation with constant commanded flux (i.e., beyond base speed). However, deviations become significant for improper setting of L_m^* in the controller.

In the speed mode, due to closed speed loop, apart from $\omega_{sl} = \omega_{sl}^*$ and $i_s = i_s^*$, the condition $T_e = T_L$ has to be satisfied and the third order algebraic equation provides solution for commanded torque value

$$T_e^{*3} + T_e^{*2}\left[-\frac{\alpha^2}{\beta^2} T_L\right] + T_e^* \frac{1}{h^2} + \left[-T_L \frac{1}{\beta^2 h^2}\right] = 0 \quad (9)$$

where $h = KL_r^*/\psi_r^{*2}$. Fig. 4 shows ratios ψ_r/ψ_r^* and T_e/T_e^* as functions of load torque T_L for different saturation degrees β, with $L_r^* = L_{\gamma r} + L_{mn}$. Dotted lines are valid for $\varepsilon = 0{,}1$ while continuous lines correspond to $\alpha = \beta$.

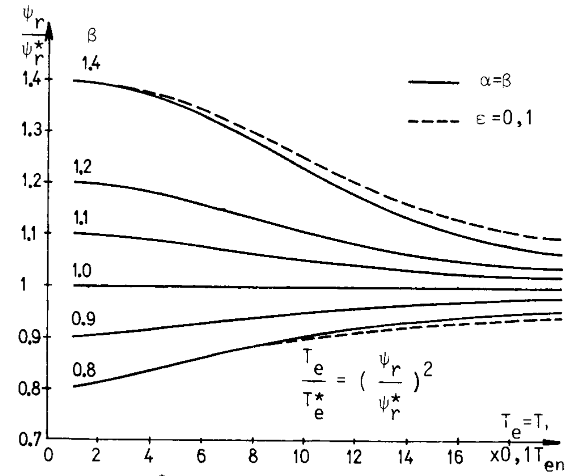

Fig. 4 - $\psi_r/\psi_r^* = f(T_L)$ and $T_e/T_e^* = f(T_L)$ with β as parameter in the speed mode.

For the actual machine the same curves as in Fig. 3 result, the only change being in torque value used as x-axis (T_e^* in torque mode, T_L in speed mode).

Operation in the field-weakening range in the speed mode is shown in Fig. 5 where actual to commanded rotor time constant ratio and flux ratio ψ_r/ψ_r^* are given. It is assumed that for $\psi_r^* = k\psi_{rn}$, $T_L = T_e = kT_{en}$, where k=0...1. For $T_L = T_e > T_{en}$, $\psi_r^* = \psi_{rn}$. Adjusted value of L_m^* in the controller is equal to L_{mn} and it is a constant in the figure. This figure indicates that influence of saturation effect becomes important in the field-weakening range and influences the drive behaviour, although the value of L_m^* is correctly set for the rated operating point.

Experimental measurement of actual rotor time constant was carried out on the drive with field-oriented control, which comprises induction machine used in digital simulation. Rotor time constant was determined for different levels of rotor flux. The identification method is based on linear relationship between torque and stator q-axis current, which has to be satisfied for each commanded stator d-axis current (rotor flux), if the value of the rotor time constant in the controller corresponds to the actual rotor time constant. It has already been emphasized that the influence of operation with variable torque in the

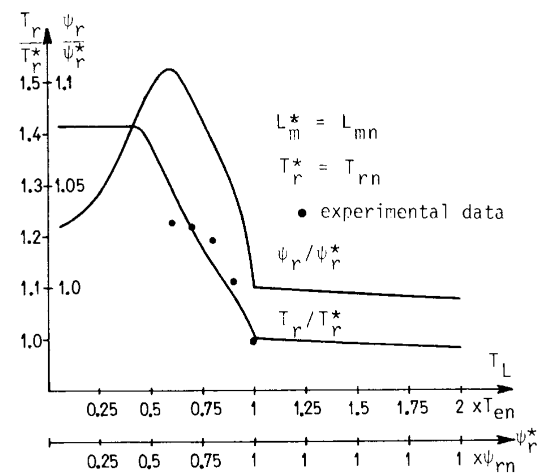

Fig. 5 - Actual to commanded rotor time constant ratio T_r/T_r^* (simulation results and experimental data) and ratio ψ_r/ψ_r^* in the field-weakening range.

constant (rated) flux region is insignificant if the value of magnetizing inductance is correctly set. These small deviations from the ideal behaviour are not detectable with the employed identification method. Therefore, only the behaviour of the drive in the field-weakening range was investigated experimentally. Obtained results are given in Fig. 5, together with simulation results. Direct comparison shows that they are in good agreement.

III. SATURATION EFFECTS DURING TRANSIENTS

The following model can be utilized for the digital simulation of transients in the torque mode

$$\frac{d\psi_{dr}}{dt} = -\frac{1}{T_r}\psi_{dr} + \frac{1}{T_r}L_m i_{ds}^* + \omega_{sl}^*\psi_{qr}$$

$$\frac{d\psi_{qr}}{dt} = -\frac{1}{T_r}\psi_{qr} + \frac{1}{T_r}L_m i_{qs}^* - \omega_{sl}^*\psi_{dr} \qquad (10)$$

$$T_e = \frac{1}{K}\frac{L_m}{L_r}\left[\psi_{dr} i_{qs}^* - \psi_{qr} i_{ds}^*\right]$$

where i_{qs}^*, i_{ds}^* and ω_{sl}^* are given with Eqns. (1). Actual value of L_m is calculated by the aid of

$$L_m = \psi_m/i_m \qquad i_m = \sqrt{i_{dm}^2 + i_{qm}^2}$$

$$i_{dm} = i_{ds}^* + i_{dr} \qquad i_{qm} = i_{qs}^* + i_{qr} \qquad (11)$$

$$i_{dr} = \left[\psi_{dr} - L_m i_{ds}^*\right]/L_r \qquad i_{qr} = \left[\psi_{qr} - L_m i_{qs}^*\right]/L_r$$

$$L_r = L_{\gamma r} + L_m \qquad T_r = L_r/R_r$$

Fig. 6 shows time variation of actual rotor flux, torque, magnetizing inductance and error quantities defined with Eqns. (4). The value of L_m^* corresponds to 1,45 L_{mn}. The machine is initially excited and brought into steady-state. The torque command equal to three times rated torque is then applied, as shown in Figure. The final steady-state corresponds to points marked with B in Figs. 2 and 3. Rotor flux is less than the commanded value due to much higher value of magnetizing inductance used in the controller. Consequently, the machine torque is smaller than the commanded torque.

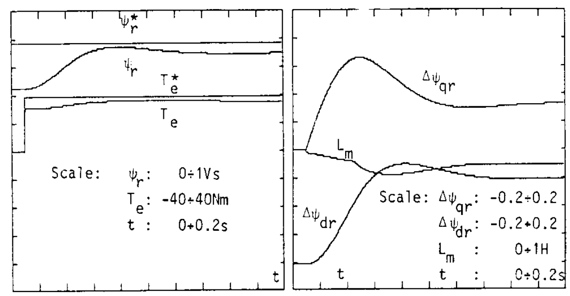

Fig. 6 - Time variation of torque, rotor flux, error quantities and L_m in torque mode

The analysis and simulation results, together with experimental investigation presented in the second and the third section indicate that influence of saturation effect is likely to be important in field-weakening region while it is rather insignificant in the region of constant rotor flux operation, if the controller setting is adequate (that is, $L_m^* = L_{mn}$). However, if the value of magnetizing inductance used in the controller differs significantly from the correct value, saturation effect causes performance distorsion in the constant flux region as well.

IV. COMPENSATION FOR SATURATION EFFECT

In order to take into account the saturation effect, the basic equations which describe field-oriented control

$$T_r d\psi_r/dt + \psi_r = L_m i_{ds}$$

$$\omega_{sl}\psi_r T_r = L_m i_{qs} \qquad (12)$$

$$T_e = \frac{1}{K}\frac{L_m}{L_r}\psi_r i_{qs}$$

are rearranged to the following form

$$T_\lambda d\psi_r/dt + \psi_r = \psi_{dm}$$

$$\omega_{sl}\psi_r T_\lambda = \psi_{qm} \qquad (13)$$

$$T_e = \frac{1}{K}\psi_r\psi_{qm}/L_{\gamma r}$$

where $T_\lambda = L_{\gamma r}/R_r$ and

$$\psi_{dm} = \psi_r + L_{\gamma r}\left\{i_{ds} - i_{dm}(\psi_m)\right\}$$

$$\psi_{qm} = L_{\gamma r}\left\{i_{qs} - i_{qm}\,(\psi_m)\right\} \qquad (14)$$

Magnetizing flux ψ_m is a function of the magnetizing current i_m which in turn depends on d and q axis magnetizing current components

$$i_m = \sqrt{i_{dm}^2 + i_{qm}^2} \qquad (15)$$

where $i_{dm} = i_{ds} + i_{dr}$, $i_{qm} = i_{qs} + i_{qr}$ and $\psi_m = \sqrt{\psi_{dm}^2 + \psi_{qm}^2}$. Taking into account that, if the field-orientation is maintained, $i_{qm} = i_{qs}(1-L_m/L_r)$, the model described with Eqns. (13)-(14) can be simplified assuming that $i_m \approx i_{dm}$ (The full model (13)-(15) is discussed in detail in Ref. [20]). Detailed investigation carried out in Refs. [16-17] shows that this assumption closely approximates the actual situation in the machine as long as the maximum value of allowable torque (that is, i_{qs}) is restricted to about three times rated torque or less.

The indirect vector controller based on Eqns. (13), (14), (15) with approximation $i_m \approx i_{dm}$ can be easily constructed. However, the indirect vector controller is not convenient if the drive requires operation in the field-weakening region. In this case usually applied field-oriented control scheme comprises rotor flux and slip frequency calculator in conjunction with rotor flux controller. For this reason saturated rotor flux calculator is discussed further on.

If the rotor speed is available and stator currents are measured and converted into rotor flux oriented reference frame, rotor flux calculator based on the same equations can be constructed, Fig. 7.

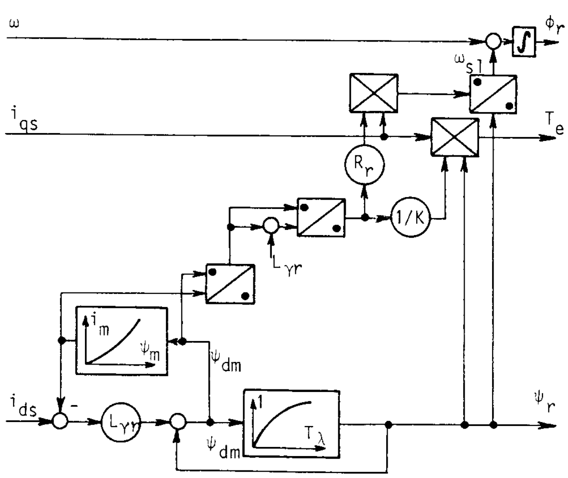

Fig. 7 - Saturated rotor flux calculator

Digital simulation was performed with the configuration of the drive which includes speed, torque and flux controller, rotor flux calculator and speed dependent rotor flux reference creation for operation in the field-weakening range. Induction machine is represented with current state-space saturated model in the stationary reference frame, given in [20], which is based on the model presented in [18,19]. Current feeding is assumed and inverter is substituted with small first order delay. Estimation of rotor flux, torque and slip frequency is carried out with saturated rotor flux calculator (Fig.7) and with unsaturated commonly used calculator [1] which utilizes the same input variables (i.e., measured stator currents and rotor speed in rotational reference frame). Fig.8 presents a sample of simulation results which give rotor flux in the machine and estimated value, machine actual torque and its estimated value, as well as commanded and actual speed of the drive. Previous steady-state corresponds to operation with rated load torque (which remains constant during process), rated rotor flux and speed equal to 5/6 of the rated value. New reference speed, equal to 7/6 of the rated speed, is commanded and the drive enters field-weakening region. After some time speed command is brought back to the initial value.

Torque attains approximately four times rated value during acceleration and this causes reduction of rotor flux in the machine in both cases. As the saturated flux computer neglects influence of i_{qm} on magnetizing current, this reduction cannot be compensated. However, in the field-weakening range, saturated flux computer provides correct value of rotor flux, while unsaturated computer causes operation with higher value of rotor flux than the wanted one, due to constant parameter $L_m^* = L_{mn}$ used in the computer.

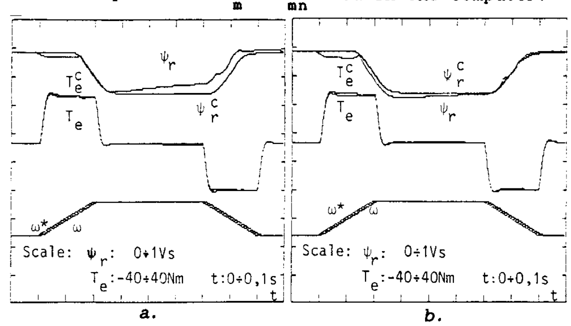

Fig. 8 - Simulation results for operation in the field-weakening range, with application of unsaturated (a.) and saturated (b.) rotor flux computer (Superscript "c" denotes outputs of the flux calculator)

V. CONCLUSION

The paper discusses influence of main flux saturation on performance of a current-fed field-oriented controlled induction machine. It is shown that operation of the drive is insignificantly affected in the constant flux region, provided that the value of the magnetizing inductance used in the controller corresponds to the rated operating point. However, if the magnetizing inductance value in the controller is not properly set, significant performance distorsion can result even in constant flux region. Saturation effect becomes important in the field-weakening region as proved by theoretical analysis, simulation and experimental investigation. A saturated rotor flux calculator which can provide accurate estimation of rotor flux in base speed and field-weakening range, for low adjusted torque limits, is derived and verified by the aid of digital simulation.

VI. APPENDIX

Motor data:

0,75kW	P=4	220/380V	3,6/2,1A
R_s=10Ω	R_r=6,3Ω	$L_{\gamma s}$=43,067mH	
$L_{\gamma r}$=40,107mH	L_{mn}=0,42119H	T_{en}=5.15Nm	
J=0,00442kgm^2	i_{qsn}/i_{dsn}=1,007		

Magnetizing curve of the machine is given in Fig. A1 and Table I in terms of rms values.

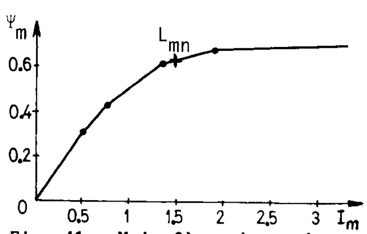

Fig. A1 - Main flux piece-wise linear approximation

I_m [A]	Ψ_m [VS]
0	0
0,5	0,306
0,75	0,425
1,35	0,615
1,875	0,667
14,14	0,848

Table I

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