CONTROL SYSTEM FOR UNCOILER WITH INDUCTION MOTOR DRIVE

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The paper presents results of an investigation into the control systems of uncoiler drives in the environment of a rolling mill at metallurgical plant. Variable diameter and variable inertia of coil and demand of stable stretch are important features of this machine. Control system of an uncoiler working without the need of a stretch sensor is presented. The current source inverter and AC motor are controlled by a digital system with field orientation. The variation of linear speed of sheet (if needed) and stable stretch are assured. Compensation of dynamical torque and static looses of the uncoiler is shown. The author does not know any uncoiler in exploitation with an AC motor drive. The presented system has not been implemented yet. Its verification was tested using a microcomputer simulation using Pascal language (Turbo Pascal v. 5.5). The simulation results (steady state values and transient plots) for start, steady state and brake of the AC drive system are presented.The simulation has proved that modern drive may replace the old DC system. The replacement will give better reliability and trouble free service thanks to the rugged AC motor and powerful electronics.

1. Introduction

Coilers and uncoilers of rolled metal strip and wire are examples of variable inertia machines in metallurgical industry. There are also many variable inertia machines applied e.g. in a paper and textile industry. The medium and small power DC motors are often used in the drive systems of such machines. Here, an induction motor with a current inverter was chosen as being much more rugged and reliable in industrial environments than a DC. The author does not know of any paper (or other information) describing an AC motor application in uncoiler drive.

The correct operation of the uncoiler should be assured not only during normal conditions of stable operation but also during the start or in the

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condition of the end of the sheet. The most important result is a stable and desired stretch force value without the need of very inconvenient stretch force sensors.

2. The Control Strategy

The stable and constant value of the stretch force and the desired value of linear velocity of the strip are the main conditions of the correct uncoiler operation. This condition yields (see Elisiejev, 1983) a constant value of the drive power $P_m = Tv/\eta$.

2.1. Field Orientation Control of Current Source Inverter (CSI)

A high performance CSI controller was described by Kaimoto and others (1982). The stator current is controlled as a vector quantity using components along two axes of a general reference frame d-q, rotating with synchronous velocity ω_e (Fig. 1).

The position of this axis is arbitrary, but induction motor equations are simpler when d-axis of the frame is locked on the rotor flux vector Ψ_r. Thus

$$\psi_{dr} = \Psi_r, \quad \psi_{qr} = 0 \tag{1}$$

The stator current is apportioned into two components i_{ds} and i_{qs}, where i_{ds} (magnetizing current) provides the rotor flux, and i_{qs} component (torque current, in quadrature with i_m) produces the torque. This relation is described by equations (2) and (3) and shown in Figure 1.

$$i_{ds} = i_s \cos\delta \tag{2}$$

$$i_{qs} = i_s \sin\delta. \tag{3}$$

In steady state δ remains constant, therefore i_{ds} and i_{qs} become DC quantities. By separation of the stator current in two components i_{ds} and i_{qs}, flux and torque can be controlled independently similar to the DC motor torque M_{el} which can be represented by

$$M_{el} = \frac{3}{2}\frac{M}{L_r} p_b \Psi_r i_{qs} \tag{4}$$

When the rotor flux Ψ_r is maintained constant, torque M_{el} is proportional to i_{qs}. Then this torque can be easily controlled by changing i_{qs}. The i_{qs} can be controlled by adjusting the magnitude of the stator current i_s and the angle δ between the stator current and rotor flux. The rotor flux Ψ_r can be held constant if i_{ds} is held constant. But to take full advantage of the field orientation method, some problems must be solved as precise observation of the flux vector or that related to the control of the current vector positioned on CSI. These problems are discussed by Kaimoto (1982), Leonhard (1985), Biswas (1988) and Mrozek (1988).

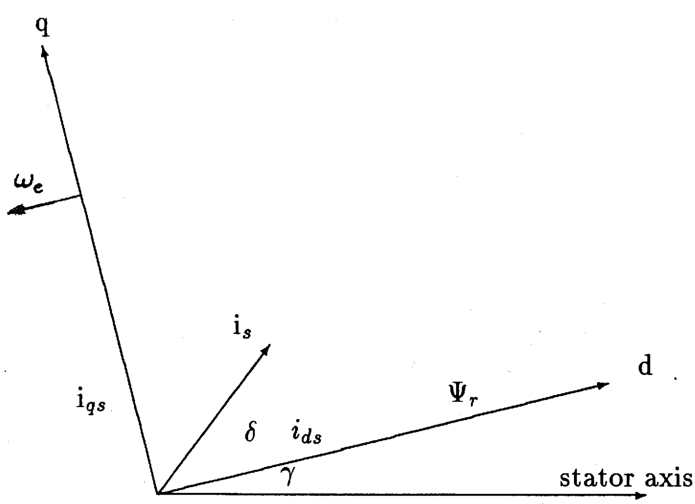

Fig. 1 Vector diagram for field orientation control

The steady state rotor equations of the induction motor have the following form

$$0 = -\frac{r_r}{L_r} M i_{ds} + \frac{r_r}{L_r}\psi_r, \tag{5}$$

$$0 = -\frac{r_r}{L_r} M i_{qs} + \omega\psi_r. \tag{6}$$

The slip frequency formula needed to maintain the field orientation of the reference frame, is derived from equation (6)

$$\omega = \frac{r_r M}{L_r}\frac{i_{qs}}{\Psi_r}, \tag{7}$$

then (5) yields

$$\Psi_r = M i_{ds} \tag{8}$$

The above equations show that electromagnetic torque M_{el} and slip ω depend linearly on stator current component i_{qs} only if rotor flux magnitude Ψ_r is constant.

2.2. Control Strategy of the Uncoiler AC Drive System

Constant value of mechanical power is desired for correct operation of an uncoiler (Elisiejev, 1983)

$$P_m = M_{el}\omega_r = Tv = \text{const.} \tag{9}$$

Linear velocity of metal strip is equal

$$v = \frac{D\omega_r}{2i_p} \tag{10}$$

Substituting (10) into equation (9), the electrical torque is described by

$$M_{el} = T\frac{D}{2i_p} \tag{11}$$

Comparing equations (11) and (4), the stretch force (its value should be constant) can be determined from

$$T = 3i_p p_b \Psi_r \frac{M}{L_r}\frac{i_{qs}}{D} \quad = \text{const} \tag{12}$$

which yields another condition

$$k_1\Psi_r = T = \text{const} \qquad \frac{i_{qs}}{D} = \text{const} \tag{13}$$

The uncoiler control strategy is based on the above formulas and may be expressed as:

- Absolute value of rotor flux should be stabilized and proportional to desired value of stretch force and equal $T = k_1\Psi_r = \text{const}$.
- The i_{qs} component of stator current should be inversely proportional with instantaneous radius of open lap coil to satisfy formula $i_{qs}/D = \text{const}$

The electrical torque should also be proportional with instantaneous radius of open lap coil and equal

$$M_{el} = \frac{3}{2} p_b r_r (\frac{M}{L_r} k_3)^2 D. \tag{14}$$

This guarantees constant value of the uncoiler shaft power. The uncoiler performance requirements can be satisfied when the electrical torque of the motor is controlled by variation of slip frequency ω. The constant value of rotor flux (Ψ_r = const) is assumed. This rule is derived from

$$M_{el}(t) = \frac{3}{2} p_b \Psi_r^2 \frac{\omega}{r_r}. \tag{15}$$

As the slip value ω should be proportional with instantaneous radius of open lap coil, the motor slip transient may extend its nominal values. This will decrease motor efficiency. The conclusion is that the range of open lap coil diameter variation $D_{\max}/D_{\min}$ is determined by compromise between the decrease of motor efficiency and the redimensioning of motor power. Stretch force may be controlled by the rotor flux value. Taking into account flux saturation phenomena, the maximal stretch force is related with nominal value of rotor flux $T_{\max} = k_1 \Psi_{rN}$, and minimal stretch with the lowest flux value.

2.3. Compensation of Dynamical Torque and Static Losses

In industry applications, uncoiler stretch force measurement problems still do not have a satisfactory solution to the cause of metal strip vibrations, so indirect methods of stretch control are used. This paper proposes stretch control using stabilization of the rotor flux. The presented method needs compensation of dynamical torque during metal strip acceleration or brake and compensation of static losses in driving gear. Formula (4) shows signals one can use for compensation. There are:

- flux controller input
- reference value of stator current component i_{qs}

Component i_{qs} of stator current signal was chosen for compensation. Changing flux value influence also drive velocity and drive torque.

2.3.1. Compensation of Dynamical Torque

Dynamical component of the shaft torque is equal

$$M_d = J\frac{d\omega_r}{dt} \tag{16}$$

The moment of inertia of the uncoiler is not constant, as the open lap coil diameter D decreases during operation

$$J = J_o + \rho l\frac{\pi}{32i_p^2}(D^4 - d_d^4) \tag{17}$$

Assuming that coil diameter variation during start and brake of uncoiler is relatively small ($\frac{dD}{dt} = 0$) and substituting (10) into (16) one sees

$$M_d = J\frac{2i_p}{D}\frac{dv}{dt} \tag{18}$$

Signal i_{qsd} used for dynamical compensation during acceleration and brake of drive is derived from electrodynamical torque formula

$$M_{eld} = \frac{3}{2}p_b(\frac{M}{L_r}\Psi_r)i_{qsd} \tag{19}$$

where, comparing the last three equations one sees

$$i_{qsd} = \frac{2}{3}\frac{L_r}{p_b M\Psi_r}[J_o + \frac{\pi}{32i_p^2}\rho l(D^4 - d_d^4)]\frac{2i_p dv}{D\, dt} \tag{20}$$

2.3.2. Compensation of Static Losses

Static losses are dependent on several parameters, the most important are those proportional to motor angular velocity. An extra electrical torque needed for compensation of static losses is equal $M_{st} = k_2\omega_r$ where k_2 is an empirical value. Substituting this equation into (4), an extra component of compensation current can be derived as

$$i_{qss} = \frac{2}{3}\frac{L_r}{p_b M}\frac{k_2\omega_r}{\Psi_r} \tag{21}$$

Signals i_{qsd} and i_{qss} are added respective signals of the decoiler control system (see Fig. 2) to obtain needed correction of static losses and dynamic torque. Absence of compensation signals is dangerous as it may kink or brake the metal strip.

3. Control System Structure

The structure of the proposed control of drive with current source inverter fed induction motor is presented on Fig. 2. It is assumed, that microprocessors are used in the proposed structure of the control system. The measured and feedback signals are inputs to current controller (**CC**), velocity controller (**VC**), rotor flux controller (**FC**) and to several function blocks.
The other function blocks are described below:

GFY division block is used for decoupling of flux and rotor velocity signals,

GFY_d block computes i_{qsd} - dynamic component of torque compensation signal (see eq. 20),

GFY_s block computes i_{qss} - static component of torque compensation signal (see eq. 21),

GF block computes reference magnitude of stator current and reference of slip of angular velocity

$$i_s^* = \sqrt{(i_M^2 + (i_T)^2} \tag{22}$$

$$\Omega = M\frac{r_r i_T}{L_r \Phi_r}. \tag{23}$$

The signal i_T is the reference for stator current component i_{qs} and i_M is the reference for component i_{ds}. Error of inverter input current i_D over stator current magnitude reference i_s^* is fed to the current controller block (CC) which is of PI type with saturation controller and produces a rectifier voltage command. The command is compared with the synchronization voltages coming from a three phase AC supply to define the rectifier firing angle.

Rotor velocity Ω_R and DC current link are measured with the A/D converter. Error of rotating speed Ω_R over velocity reference

$$\omega_r^* = \frac{k_v i_p}{\pi}\frac{V}{D} \tag{24}$$

is fed to the speed controller block (VC) which is PI (proportional integrating) controller with saturation. It must be emphasized that reference velocity value ω_r^* may change its value as it is inverse proportional with coil diameter.

The flux controller is also of PI type - with saturation. The rotor flux signal Φ_r is generated in observer block **BO** using motor phase currents and line voltages as input. Reference of rotor flux is determined to receive the needed value of metal strip stretch.

The value of rotor flux reference is constant, but proportional to the desired stretch force T. The flux and speed regulators are the reference value of the d- and q-axis components of stator current respectively.

It is assumed, that current controller (CC), velocity controller (VC) and flux controller (FC) are digital controllers. Their parameters are computed using the method of the discrete frequency characteristics using block structures as described by (Mrozek, 1985). The signal proportional to coil diameter is determined using the average method formula $0.5D = Vi_p/\omega_r$. The formula is computed using microprocessor software.

4. Simulation

In order to verify the control theory described in this paper a digital system simulation program in Pascal language (Turbo Pascal v. 5.5) has been developed. The program covers the whole system as a decoiler drive with CSI fed induction motor.

Parameters used in the simulation were derived on the basis of technical data of the decoiler and DC motor drive working in one metallurgical plant. This motor and decoiler data is listed in Appendix A. The actual CSI and AC motor parameters used in the simulation program are listed in Appendix B. The simulation program takes into account changes of moment of inertia of the open lap coil, as its diameter and weight do change their value during uncoiler operation. A motor load torque is the function of stretch reference and actual coil diameter.

A mathematical model of induction motor is described by a set of ordinary differential equations in a general reference frame d-q, rotating with synchronous velocity ω_e is used. The influence of the stator and rotor slots, hysteresis and eddy currents are neglected but the dependence of the stator and rotor resistances on temperature is taken into account. It is assumed, that the leakage inductances of the stator and rotor are constant. The main inductance of the induction motor strongly depends on the nonlinearities of magnetization curve. In the simulation model of induction motor the approximation of magnetizing curve by spline function was used. The influence of the magnetic saturation on the current and voltage harmonics, space fields harmonics, and the torque ripple is not considered.

The current source inverter output is approximated by a sinusoid (first harmonic). It is assumed, that losses of converter and inverter are small. A total input DC power is converted to the fundamental frequency power on output. In the model the supply system and the supplying rectifier are replaced by an ideal voltage source. The voltage drops on the DC side are taken into account by the appropriate increase of DC link resistance. A DC link choke inductance is constant and large enough, so there is no current pulsation in this DC circuit. The current control and the frequency control of the current source inverter are quite independent. The simulation model of the current source inverter - induction motor drive system was described by Mrozek (1985), and (1988).

As the described microcomputer system is still under development, the simulation program considers only its most important behaviours. The following simulation method of control system of decoiler with AC drive is used. The simulation model is divided into two segments: continuous and discrete.

The continuous part consists of differential equations which describe the mechanical part of coiler with coil, AC motor, inverter model and sensors of current and velocity. The equations used in this model are easy to find in literature (Leohard, 1985) and in chapter 2. The Runge-Kutta method of 4-th order is used for integration of that continuous model.

The discrete part of the model is used for computation of control signals as described on system block diagram (Fig. 2) in chapter 3. Current controller (CC), flux controller (FC), velocity controller (VC) are digital PI control blocks with saturation. The mathematical model of PI control block with saturation and with aperiodic element is described by the following equation

$$U_{wi} = T_i \frac{dU_{1i}}{dt} + U_{1i} \tag{25}$$

$$U_{2i} = \frac{F_{1i}}{T_{1i}} \int_0^t U_{1i} dt + \frac{T_{2i}}{T_{1i}} U_{1i} \tag{26}$$

$$U_i = F_{2i} U_{2i} + F_{0i} U_{0i} + F'_{0i} U'_{0i} \tag{27}$$

where

$F_{1i} = a_{1i} a_{4i} + a_{5i} a_{2i}$; $F_{2i} = a_{4i} a_{6i}$; $F_{0i} = a_{3i}$; $F'_{0i} = a_{5i}$;

$a_{1i}, a_{2i}, a_{3i}, a_{4i}, a_{5i}, a_{6i}, F_{1i}, F_{2i}, F_{0i}, F'_{0i}$ - logic function, value 0 or 1

$a_{1i} = 1 \ \ for \ \ U_{1i} >= 0; \qquad a_{2i} = 1 \ \ for \ \ U_{1i} < 0;$
$a_{3i} = 1 \ \ for \ \ U_{2i} > U_{0i}; \qquad a_{4i} = 1 \ \ for \ \ U_{2i} <= U_{0i};$
$a_{5i} = 1 \ \ for \ \ U_{2i} < U'_{0i}; \qquad a_{6i} = 1 \ \ for \ \ U_{2i} >= U'_{0i};$

U_{wi} - input voltage, U_i - PI block with saturation output voltage, U_{0i}, U'_{0i} - saturation voltage, T_i - time constant of aperiodic element, T_{1i} - integral constant; T_{2i}/T_{1i} -integral control factor.

The Euler method is used for digital integration of U_{1i} voltage signal. It is assumed, that quantization time is equal T_{pr}=3.3 ms. This value is the equal maximal value of time lag of the rectifier response. All algorithms control system structures (as described in chapter 3) are prepared as a single subroutine. The program computes control voltage values for rectifier input and desired frequency of inverter.

Equations 25 to 27 permit amplitude quantization during single sample period T_{pr}. On the other hand simulation for a longer time is done as follows. For the continuous part of the simulation model, the integration procedure step is 10 times less than sample period T_{pr}. After each tenth step, the discrete control system subroutine is called, passing actual values of control, reference and feedback signals. New values received from the subroutine (quantization period T_{pr} =3.3 ms) are used as input for the next 10 steps of integration procedure. This method gives proper a simulation of the coiler drive system.

Simulation covers all typical modes of decoiler operation as: steady state, start and brake. Simulation results are presented for open lap coil diameter equal D=1.3 m and for D=1.0 m. The start operation parameters were: initial strip linear velocity v=1.25 m/s, acceleration dv_r=0.2 m/s^2 (for brake dv_h=0.2 m/s^2). The constant value of the stretch force was F=4032 N, as in decoiler technical data.

The simulation results are presented in diagrams Fig. 3 (open lap coil diameter D=1.0 m) and on Fig. 4 (for D=1.3 m). Maximal rotor flux deviation *(the most important drive parameter which determines uncoiler stretch force)* was only 5 %. These results show the correct response of control system on disturbances such as variation of moment of inertia, load torque variation and motor velocity changes. This means the proposed control system (field orientation **CSI** fed induction motor) performs all needed assumptions as constant stretch value and constant linear velocity of metal strip. Its performance is as high as that of the DC motor.

5. Conclusions

An analysis of a possible substitution of an old DC motor with the new AC drive system for the decoiler in metallurgical works is presented. A control system synthesis was performed, taking into account that the rolling mill imposes special demands on a decoiler operation as:

- large range and stabilization accuracy of stretch force control
- large ratio of maximal and minimal diameter of open lap coil

For the DC motor drive the typical parameters are as follows : stretch force range is $1 \div 7$; stabilization accuracy of the stretch force control is about 10-20% (botch values for indirect method of control) and the ratio of maximal and minimal diameter of the open lap coil $D_{\max}/d_{\min} = 4$ if complex two zone velocity control method is used.

In the presented system, control of stretch is achieved by stabilization of absolute value of rotor flux. Using current source inverter fed induction motor the ratio $D_{\max}/d_{\min} > 4$ can be gained without special arrangement. If only the first zone of the AC motor is used, the ratio of maximal and minimal fed frequency is equal to about $\frac{50Hz}{10Hz} = 5$ .The ratio $D_{\max}/d_{\min}$ can be even higher than 5, if PWM modulation is used in a two zone control system or if larger AC motor looses are permissible.

Digital simulation of the system shows that static and dynamic performance of AC drive with **CSI** is as high as that of a DC motor drive. The author believes this drive system should apply in the high accuracy systems formerly composed for DC motors.

Symbols

open lap coil diameter	D
stator current	i_s
d-q components of stator current	i_{ds}, i_{qs}
angle between i_s *and* Ψ_r	δ
rotor velocity $\frac{rad}{s}$	ω_r
rotor flux	Ψ_r
linear velocity of metal sheet	v
moment of inertia	J,J_o
weigh density of steel	ρ

width of coil	l
slip frequency	ω
stretch force	T
gear ratio	i_p
mutual inductance	M
rotor inductance and resistance	L_r, r_r
number of poles	p_b
uncoiler drum diameter	d_d

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Appendix A

In the following there are given the parameters of DC drive and decoiler used for simulation purposes.

Decoiler parameters *(Variation, 1975)*

metal strip velocity	75 m/min
acceleration during start	0.2 m/s^2
deceleration during brake	0.25 m/s^2
stretch force	4032 N

Open lap coil parameters

maximal open lap coil diameter	2 m
minimal diameter	0.61 m
wide of strip	0.63÷ 0.43 m
gear ratio	$i_p = 40$

DC motor parameters

power	5.5 kW
rotor current and voltage	U_N=240V, I_N=29A
stator current and voltage	U_N=115V, I_N=3.7A
nominal rotations	n_N=470 RPM
maximal rotations	n_{max}=1570 RPM

Using respective formulas (9) and (10), one can obtain the desired range of velocity equals $477 \div 1565$ RPM and torque equals $30.7 \div 100.8\ Nm$.

Appendix B

In the following there are given the parameters of AC drive used for simulation purposes.

Inverter parameters

input three phase voltage	U_N=220/380 V
DC link choke inductance	L_d=86 mH
DC link resistance	R_d=0.1 Ω
commutation capacitance	$C_k = 6\ \mu$F
current gain factor	$K_p = 56.4$

The desired frequency range is $f = 16Hz \div 52.1Hz$, slip may vary from $\omega = 0.7 \div 2.3\ \omega_N$.

AC motor parameters

It is assumed, that the AC motor shall substitute the above DC motor. The new drive parameters should be equal to or better than before. The chosen AC motor is overdimensioned cause to higher harmonics looses. Its overload capacity was verified in several working points. Its parameters are (*AC Motors*, 1982).

three phase voltage	U_N=220/380 V
power	7.5 kW
number of poles	p_b=2
synchronous rotations	n_O=1500 RPM
cos φ	cos φ_N=0.86
current	I_N=26.1/15.1 A
slip	s_N=2.9%
resistance	r_s=0.699Ω, r_r=0.481Ω
mutual inductance	M=139.12 mH
inductance	L_s=143.06 mH, L_r=145.15 mH

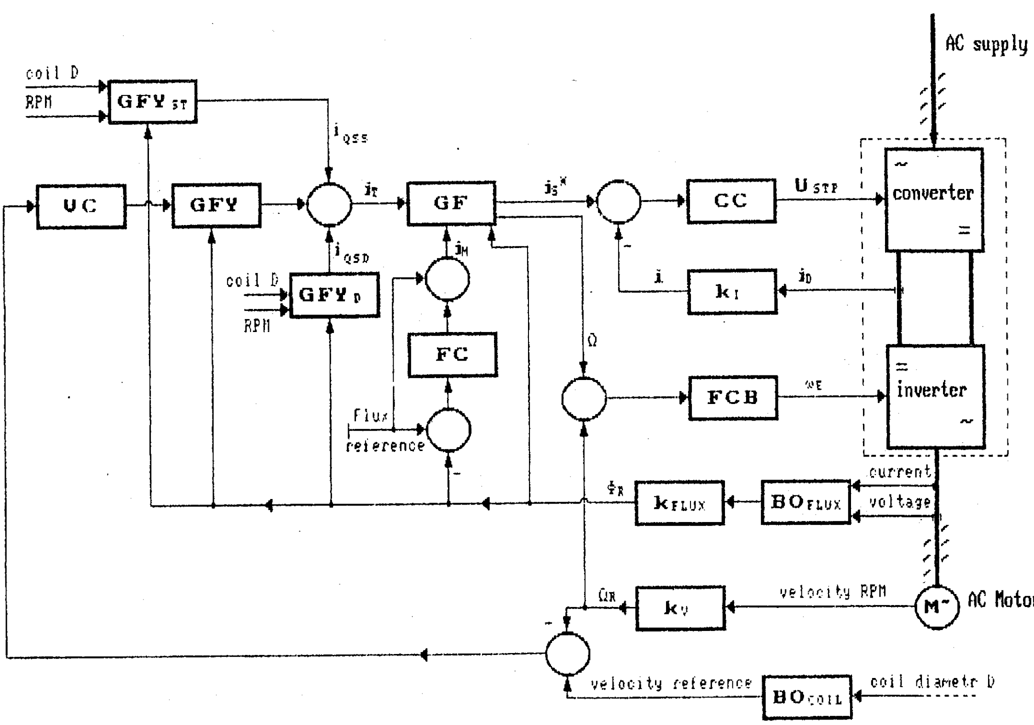

Fig. 2. Structure of the control system

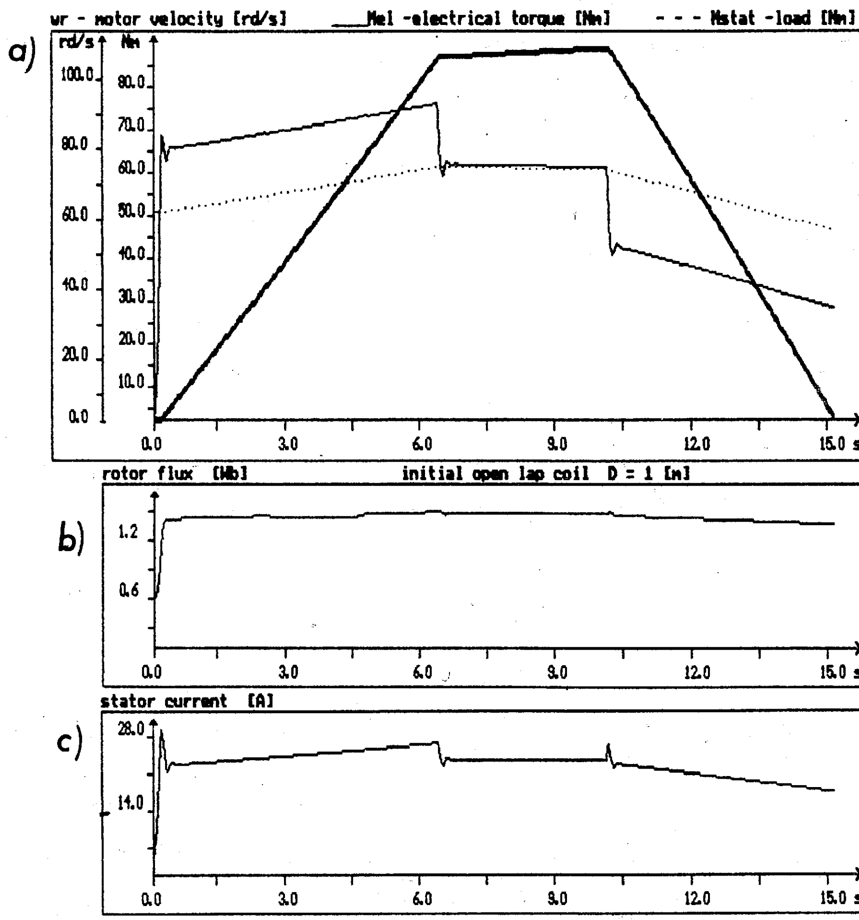

Fig. 3. Simulation results for start, steady state and brake operation for drive of metal strip decoiler with AC motor and current source inverter. Initial open lap coil diameter D = 1 [m] (diagram noncontinuities are due dot matrix printer).

a) motor velocity [rd/s] (thick line), electric torque [Nm] (solid line), load torque [Nm] (dashed line),

b) rotor flux [Wb],

c) stator current magnitude [A]

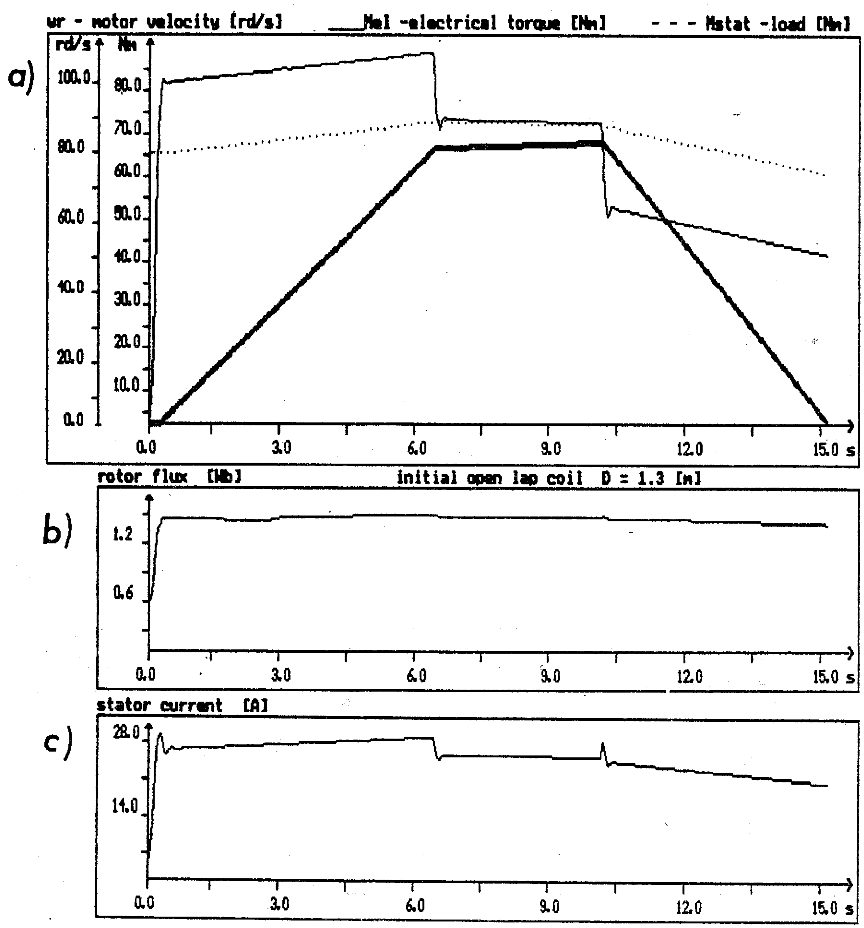

Fig. 4. Simulation results for start, steady state and brake operation for drive of metal strip decoiler with AC motor and current source inverter. Initial open lap coil diameter D = 1.3 [m] (diagram noncontinuities are due dot matrix printer).

a) motor velocity [rd/s] (thick line), electric torque [Nm] (solid line), load torque [Nm] (dashed line),
b) rotor flux [Wb],
c) stator current magnitude [A]