# Adaptive PF (PDF) Speed Control for Servo Drives

Laszlo Szamel*1

Department of Electric Power Engineering, Budapest University of Technology and Economics
Egry József u. 18, H-1111 Budapest, Hungary

*1szamel.laszlo@vet.bme.hu

***Abstract***

This paper proposes two model reference adaptive PF (PDF) speed control methods for servo drives. Following from the structure (PF-type) of model reference parameter adaptive control was developed to provide constant loop gain in speed control loop with changing gain (moment of inertia and/or torque factor) which makes it easier to reach nonovershooting step response as well as fast speed changing compensation caused by jump in load. The algorithm even keeps its stability at fast changing, jump-like load torque. Model reference signal adaptive control is used to provide constant loop gain in speed control loop with changing parameters exposed to a significant load. The block diagram of the adaptive control can be seen as an extended version of the PF controller, so one of the adaptation factors (which is the free parameter of the adaptive control) is given. Both model reference adaptive controls drawn up can be easily implemented because the adaptation algorithms do not need acceleration measuring (thanks to the first-order model). Simulation and experimental results demonstrate that the proposed methods are promising tools for speed control of electrical drives.

***Keywords***

*Adaptive Control; Adjustable Speed Drives; Motion Control, Pseudo-Derivative Feedback; Servo Drives; Switched Reluctance Drives; Variable Speed Drives*

## Introduction

Generally the controller of the speed loop in motion control systems is of PI-type. The integrator of the controller eliminates the error caused by the step change in load. The setting of speed controller is difficult as the closed-loop transfer functions are not identical to step changes in the load, as well as the reference signal. It seems to be preferable to use PF-type controller (proportional gain in a separate feedback) instead of the traditional PI one (Diep, N.V., and Szamel, L., 1990), (Ohm, D. Y., 1990), (Perdikaris, G. A. and VanPatten, K. W., 1982). Phelan named this structure "Pseudo-derivative feedback" (PDF) control (Phelan, R. M., 1977).

In motion control systems, there is robustness against parameter changes and disturbance rejection of main interest. The model reference adaptive control has the following features:

- It enables the compliance of the system with varying operational conditions possible and ensures the behavior of the controlled system according to the prescribed reference model.
- It means such a special type of adaptive systems, which results in nonlinear control systems. This is the reason why the analytical analysis is completed by the Lyapunov stability criterion or by hyper-stability principle.
- Its design and application are closely related to the use of computer methods.
- Simple implementation of the control algorithm.

## Speed Control of Servo Drives

A model reference adaptive control is used for the speed control. Such an adaptive control has been succesfully elaborated by using a suitable chosen Lyapunov function to compensate the gain of the speed control loop (Liu Hsu et al., 2007), (Szamel, Laszlo, 2002), (Szamel, Laszlo, 2004).

### *Model Reference Parameter Adaptive Control*

The adaptive control of servo-drives with a cascade arrangement is the most effective when it is applied to the inner loop containing the effect of variable parameters directly, i.e. the inertia ( $J_m$ ) and/or torque factor ( $k_m$ ). The speed control implemented by PI controller is of cascade arrangement in fact as it contains an inner, proportional feedback loop (PF controller, Fig.1.), (Perdikaris, G. A. and VanPatten, K. W., 1982). A one-storage proportional element can describe this inner loop neglecting the time constant of closed current control loop. In such a way our adaptation algorithm is the simplest.

$$Y_{\omega,(i-i_l)}(s) = \frac{A_i}{s} \tag{1}$$

where $A_i = \frac{k_m}{J_m}$.

Arrangement of control circuit can be seen in the following figure:

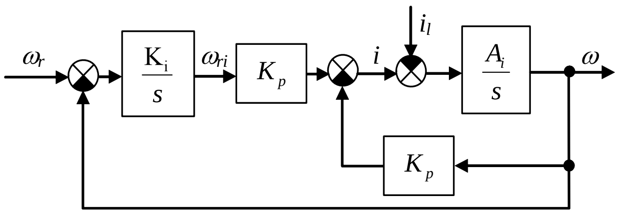


FIG. 1 BLOCK SCHEME OF PARAMETER ADAPTIVE PF SPEED CONTROL

where

| | |
|---|---|
| $\omega$ | is the speed, |
| $\omega_r$ | is the speed reference signal, |
| $i$ | is the current of the motor, |
| $i_l$ | is the current equivalent to the load-torque. |

Section determined by the transfer function $Y_{\omega,(i-i_l)}(s)$ is fed back by a proportional member of gain $K_P$. The task is to change the gain $K_P$ in such a way that the product $A_i K_P$ should remain constant despite the changing of parameter $A_i$.

Transfer factor of the inner closed loop is given by the reciprocal ($1/K_P$) of feedback member that is not constant because of the change in inertia and/or torque factor. Consequently loop gain of the outer speed control loop would change as well. In order to get a one-storage element with unity transfer factor, we have to insert a member with gain $K_P$ between the integrator of the PF controller and the reference signal of the inner loop. First-order reference model with time constant $T_m$ gets sum of the input signals of above member ($\omega_{ri}$) and the signal $\omega_{lm}$ compensating the load effect for the model. So dynamics of reference model can be described by the following differential equation:

$$\dot{\omega}_m T_m + \omega_m = \omega_{ri} + \omega_{lm}. \tag{2}$$

Dividing (2) with $T_m$ and applying designation $q_m = 1/T_m$, the following equation can be obtained.

$$\dot{\omega}_m + q_m \omega_m = q_m(\omega_{ri} + \omega_{lm}) \tag{3}$$

The differential equation of the first-order controlled section is as follows:

$$\dot{\omega} + (K_p A_i)\,\omega = (K_p A_i)\,\omega_{ri} - A_i i_l. \tag{4}$$

Factor $K_p$ can be described as the sum of $K_{p0}$ determined by mean $A_i$ and $\Delta K_p$ accomplished by the adaptation algorithm. So:

$$K_p A_i = (K_{p0} + \Delta K_p)\,A_i = q + \Delta q, \tag{5}$$

where $K_{P0}$, and $q$ are constant.

It is assumed that the change of $A_i$ is slow from the viewpoint of adaptation and therefore the effect of this change can be neglected.

Substituting (5) into (4) we get:

$$\dot{\omega} + (q + \Delta q)\,\omega = (q + \Delta q)\,\omega_{ri} - A_i i_l. \tag{6}$$

By using (3) and (6) and substituting expression of model error $\varepsilon = \omega_m - \omega$ the dynamic equation will be:

$$\dot{\varepsilon} = -q_m \varepsilon + x\,\omega - x\,\omega_{ri} + q_m \omega_{lm} + A_i i_l, \tag{7}$$

where $x = (q + \Delta q) - q_m$.

Dynamic of model error should be asymptotically stable to follow the system with proposed model. For determination of $\Delta q$ the following Lyapunov function should be composed:

$$V = \frac{1}{2}\left(\varepsilon^2 + \beta\,x^2\right), \tag{8}$$

where $\beta$ is a positive number.

When choosing the Lyapunov function both purposes, i.e. the termination of the model error ($\varepsilon = \omega_m - \omega$) and loop gain deviation have been taken account.

The time derivative of the Lyapunov function is:

$$\dot{V} = \varepsilon\;\dot{\varepsilon} + \beta\,x\,\dot{x}. \tag{9}$$

Substituting (7) into (9) the following equation is valid:

$$\dot{V}=-q_m\varepsilon^2+\varepsilon\, x\,\omega-\varepsilon\, x\,\omega_{ri}+ \varepsilon\,(q_m\omega_{lm}+A_i i_l)+\beta\, x\,\dot{x}. \tag{10}$$

If

$$\varepsilon\, x\,\omega-\varepsilon\, x\,\omega_{ri}+\beta\, x\,\dot{x}=0, \tag{11}$$

that is

$$\dot{x}=\varepsilon\,(\omega_{ri}-\omega)/\beta \tag{12}$$

and

$$\varepsilon\,(q_m\omega_{lm}+A_i i_l)<0, \tag{13}$$

then

$$\dot{V}<-q_m\varepsilon^2. \tag{14}$$

The above equation is a negative definite function that shows the asymptotic stability of the error dynamic (7). By using (5), (7) and (12) the following adaptation algorithm is true:

$$\Delta\dot{K}_p=\gamma\,\varepsilon\,(\omega_{ri}-\omega), \tag{15}$$

where $\gamma$ may be an arbitrary positive number. The inequality (13) shows how we have to change the signal $\omega_{lm}$ representing the load of model.

If

$$\varepsilon>0,\ \text{ then }\ \omega_{lm}<-\left|i_l\right|_{\max}A_i T_m, \tag{16}$$

respectively if

$$\varepsilon<0,\ \text{ then }\ \omega_{lm}>-\left|i_l\right|_{\max}A_i T_m.$$

***Model Reference Signal Adaptive Control***

The controlled loop has been approximated by an integral element. Time constant of the closed current control loop has been neglected. The control consists of a P-element with the gain $K_p$. Input of P-element contains not only the control error signal but an adaptation signal ($g$) as well. Applying the signal adaptation control, a P type controller with $K_p$ gain can ensure zero speed error as the adaptation signal can produce a current reference signal to compensate the loading current at zero speed error.

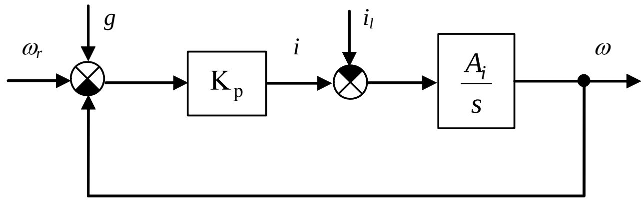


FIG. 2 INITIAL BLOCK SCHEME OF SIGNAL ADAPTIVE SPEED CONTROL

Regarding the block diagram of control loop, following differential equation is valid for the closed loop:

$$\dot{\omega}+A_iK_p\omega=A_iK_p\left(\omega_r+g\right)-A_i i_l. \tag{17}$$

The feature of the closed speed control loop has been taken into consideration by a parallel control model to be expressed by a first order proportional element. The differential equation of the first order system is:

$$\dot{\omega}_m+q_m\omega_m=q_m\omega_r, \tag{18}$$

where index $m$ refers to the model and $q_m$ is the reciprocal of model time constant.

Using (17) and (18) and introducing the expression $\varepsilon=\omega_m-\omega$ for model error, the dynamic equation for the model error is as follows:

$$\dot{\varepsilon}+q_m\varepsilon=\left(q_m-A_iK_p\right)\left(\omega_r-\omega\right)+A_i\left(i_l-K_pg\right). \tag{19}$$

The adaptation signal $g(t)$ can be written in the following form:

$$g(t)=g_1(t)\left(\omega_r-\omega\right)+g_2(t). \tag{20}$$

Substituting (20) for (19):

$$\dot{\varepsilon}=-q_m\varepsilon+b_1\left(\omega_r-\omega\right)+b_2, \tag{21}$$

where

$$b_1=q_m-A_iK_p\left(1+g_1(t)\right),$$

$$b_2=A_i\left(i_l-K_pg_2(t)\right).$$

Let us compose the following Lyapunov function to produce the signal $g_1(t)$ and $g_2(t)$:

$$V=\frac{1}{2}\varepsilon^2+\frac{1}{2}\left(\beta_1b_1^2+\beta_2b_2^2\right), \tag{22}$$

where $\beta_1$ and $\beta_2$ are positive constants.

Time-derivation of the Lyapunov function is:

$$\dot{V}=\varepsilon\dot{\varepsilon}+\beta_1b_1\dot{b}_1+\beta_2b_2\dot{b}_2. \tag{23}$$

Substituting (21) for (23):

$$\dot{V} = -q_m\varepsilon^2 + (\omega_r - \omega)b_1\varepsilon + b_2\varepsilon + \beta_1 b_1\dot{b}_1 + \beta_2 b_2\dot{b}_2 \,. \tag{24}$$

If

$$\dot{b}_1 = -(\omega_r - \omega)\varepsilon / \beta_1 \tag{25}$$

and

$$\dot{b}_2 = -\varepsilon / \beta_2 , \tag{26}$$

then

$$\dot{V} = -q_m\varepsilon^2 , \tag{27}$$

and it ensures asymptotical stability of the model error. On the basis of (21), (25), (26) and by assuming that variation of $A_i$ can be neglected compared to the speed of adaptation, the following adaptation algorithm is valid:

$$\dot{g}_1(t) = \gamma_1\varepsilon(\omega_r - \omega) , \tag{28}$$

$$\dot{g}_2(t) = \gamma_2\varepsilon , \tag{29}$$

where $\gamma_1$ and $\gamma_2$ are positive constants, the free parameters of adaptation. Taking relations (20), (28), (29) into consideration, the following equation comes true:

$$g(t) = \gamma_1(\omega_r - \omega)\int \varepsilon(\omega_r - \omega)\,dt + \gamma_2\int \varepsilon\, dt \,. \tag{30}$$

A block diagram of the control circuit introducing adaptation signal $g(t)$ and assuming that $g_1(t)$ is constant can be seen in Fig. 3. The structure of control contains two parts. In the first part the reference signal is led through a first order system and a PI controller with variable gain and integration time. The second one is a differentiating filter which takes effect only on changing of reference signal. The gain and differentiation time are also changing. The adaptation gain factor $\gamma_2$ gives the reciprocal of integrating time constant of controller type PI, assuming $g_1(t)$ = 0. To fulfill the constant integrating time constant, it is preferable to substitute $\gamma_2$ by $\gamma_2(1+g_1(t))$. In such a way the neglect of time constant of current control loop can be compensated.

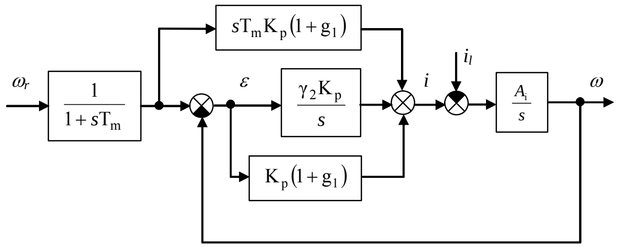


FIG. 3 BLOCK SCHEME OF THE SIGNAL ADAPTIVE SPEED CONTROL WITH ADAPTATION SIGNAL

The approaching block diagram of the adaptive control can be seen as extended version of the PI controller, so $\gamma_2$, one of the adaptation factors (which is the free parameter of the adaptive control) is given. Contraction of model-filtered reference signal and the PI controller can be transformed into a so-called PF controller when integration time of PI controller equals to the time constant of the model (Fig.4.).

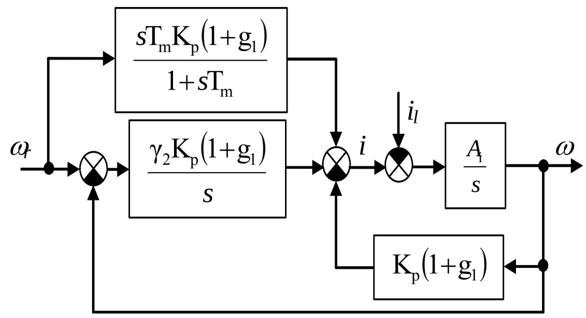


FIG. 4. BLOCK SCHEME OF THE SIGNAL ADAPTIVE PF SPEED CONTROL (EXTENDED VERSION)

The basic structure of the signal adaptive speed controller is also PF type which on the one hand provides nonovershooting step response with its structure. Moreover, it ensures fast compensation of speed variation caused by a jump in motor load.

The transfer-function between $\omega$ and $\omega_r$ is as follows:

$$\frac{\omega}{\omega_r} = \frac{1}{1+sT_m}\,\frac{1 + sT_m + s^2\dfrac{T_m}{\gamma_2}}{1 + s\dfrac{1}{\gamma_2} + s^2\dfrac{1}{A_i\gamma_2 K_p(1+g_1)}} \,. \tag{31}$$

Assuming that the adaptation signal $g_1(t)$ is constant (at the end of the adaptation), the following equation is valid:

$$(1+g_1) = \frac{\gamma_2}{A_i K_P} \,. \tag{32}$$

Substituting (32) into (31):

$$\frac{\omega}{\omega_r} = \frac{1}{1+sT_m} \frac{1+sT_m+s^2\frac{T_m}{\gamma_2}}{1+s\frac{1}{\gamma_2}+s^2\frac{1}{\gamma_2^2}} . \quad (33)$$

Choosing $T_m = \frac{1}{\gamma_2}$, the transfer function is as follows:

$$\frac{\omega}{\omega_r} = \frac{1}{1+sT_m} . \quad (34)$$

So the system follows the model without time delay.

This control has been tested by a simulation program developed in our Department. Firstly the adaptation has been examined without current limitation and load in order to take into consideration only the non-linearity of the motor and the adaptation. In the interest of the adaptation stability, the speed of change of the adaptation signal $g_1$ has to be limited. The signal $g_1$ can results in the significant oscillations without limitations as the change of the signal is possible in discrete times.

The current limitation can result in further problems. This limitation hinders the tracking of the model, so the effect of the above signal $g_1$ will be too large or it can change in the reverse direction. To eliminate the above problem, signal $g_1$ is not to be changed in the period of the current limitation.

## Drive System

Block scheme of the examined drive system with switched reluctance motor (SRM) (Borka, Jozsef et al, 1993), (Bose B. K. and Miller, T.G.E., 1985) is shown in Fig. 5. This work is a part of the investigation of an HTS (high temperature superconductor) energy storage flywheel system (Vajda, Istvan et al., 2003). The main advantages of this motor type are the following:

- no need for an extra generator;
- relatively big torque can be achieved, it is easier to pass critical speeds;
- no iron losses at stand-by.

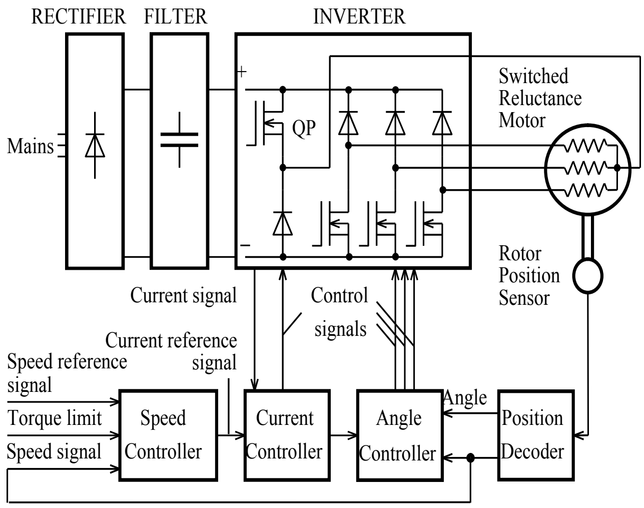

FIG. 5 BLOCK SCHEME OF DRIVE SYSTEM

It is followed from the operational principle of SRM that its phase windings are to be excited at a well determined angle of the rotor position in an appropriate order. This is why a Rotor Position Sensor is to be mounted on the shaft of the motor. In our case the position sensor is a resolver. It can be calculated from the teeth numbers (6/8) that the phase switchings have to follow each other by 15 degree. The resolver is supplied by an oscillator circuit, whose signals are evaluated by a Position Decoder.

The Position Decoder has two outputs: the Angle and Speed signals. Based on the two signals, the Angle Controller composes the Control signals for the phase switching transistors.

The supply unit consists of three main blocks, namely the RECTIFIER, the FILTER and the INVERTER. The inverter is a pulsed width modulated (PWM) one, marked by QP in the figure and it contains a one-one switching transistor per phase as well as a brake chopper, which excludes from showing in the figure. The common point of phase windings is supplied by the PWM inverter. It is of autonomous operation and has an inner current control loop. The other ends of phase windings are connected to the phase switching transistors.

Fundamentally, SRM drives have two control loops, that is, the outer one is the speed loop, Speed Controller and the inner one is the current loop, Current Controller.

Neglecting the saturation, the motor torque is proportional to the square of current, which means that the current reference signal can be composed from the torque reference signal, produced by the speed controller by the help of a square-root function after composing its absolute value. The saturation of motor, depending greatly on the motor construction, complicates the transient analysis of the system further. In consequence of the saturation, the square relation between the current and the torque will be valid approximately only. Furthermore, the inner voltage of motor at high speed causes an additional problem, since the current control of PWM cannot produce constant current, given by the command signal. One solution to solve the task is the compensation in the function of speed and torque, using calculated values from a look-up table, stored in the memory.The other solution is the application of an adaptive control.

The output signal of the Speed Controller serves for a Current reference signal of the Current Controller. The hardware and software tools together fulfil the two-loop control. The Current Controller produces the control signal for the PWM inverter, and receives the Current signal from the PWM inverter at the same time. Based on the current reference signal, the Current Controller controls the PWM inverter of fix frequency by installing an analog controller.

For the control of the sum of phase currents (Fig. 5.) it is suitable a simpler four-transistor inverter and is not necessary a six-transistor one as in the case of control of phase currents independently from each other. But the detriment of the previous solution is that the torque pulsation can be decreased in a smaller degree by changing the turn-on and turn-off angles.

Namely, in the case of the constant current reference signal, the current increase is limited by the switched-off, but conducting phase current as the regulator controls the sum of two phase currents. The increase of the phase current at starting of the conducting state can be forced by the modification of the current reference signal (Szamel, Laszlo, 2001):

$$i_r = u\sum_{j=1}^{3} C_j + \sum_{j=1}^{3}(1-C_j)\cdot i_j . \quad (35)$$

where:

$i_r$ is the current reference signal,

$i_j$ is the current signal of phase $j$ ,

$u$ is the output of the speed controller,

$C_j$ is the control signal of phase $j$ (0 or 1).

The supplement of the first member of Eq. 35 makes the overlap of the phase conduction possible, while the effect of second member is to increase the reference signal with the current of the switched-off, but not current-free phase.

The ripple free operation can be realize only with a current waveform depending on the angle, speed and torque (Szamel, Laszlo, 2001), (Vujicić, V.P., 2012). The proposed ripple reduced method changes only the turn-on and the turn-off angle in function of the speed and current reference. The optimum turn-on and turn-off angles of the SRM drive has been determined by computer simulation based on the measured results of the analysed drive. The optimum solution has been fulfilled by four cycles embedded into each other. Two outer cycles give the current and speed reference signals, while two inner ones provide the turn-on and turn-off angles. By this one-one optimum angle pair can be determined to all operating points.

It can be considered an interesting result that the criteria of the minimum torque pulsation does not provide an optimum solution in all cases. The torque pulsation will be minimum in the speed-current plane only in that case if the torque of the motor is relatively small. For this reason a good result can be achieved in such a way if the relative, i.e. compared to the torque of motor, torque pulsation is minimised.

The angle control of the drive determines the actual turn-on and turn-off angles with a two-variable interpolation from the results stored in a look-up table and calculated by the above method.

## Simulation Results

In Fig. 6 and Fig. 7 two of many executed simulations are shown. Fig. 6 shows the run-up with model reference parameter adaptive control (15), (16), while Fig. 7 with model reference signal adaptive control (30) and in both cases with turn-on and turn-off angles depending on the speed and current reference as well as with current reference compensation (35).

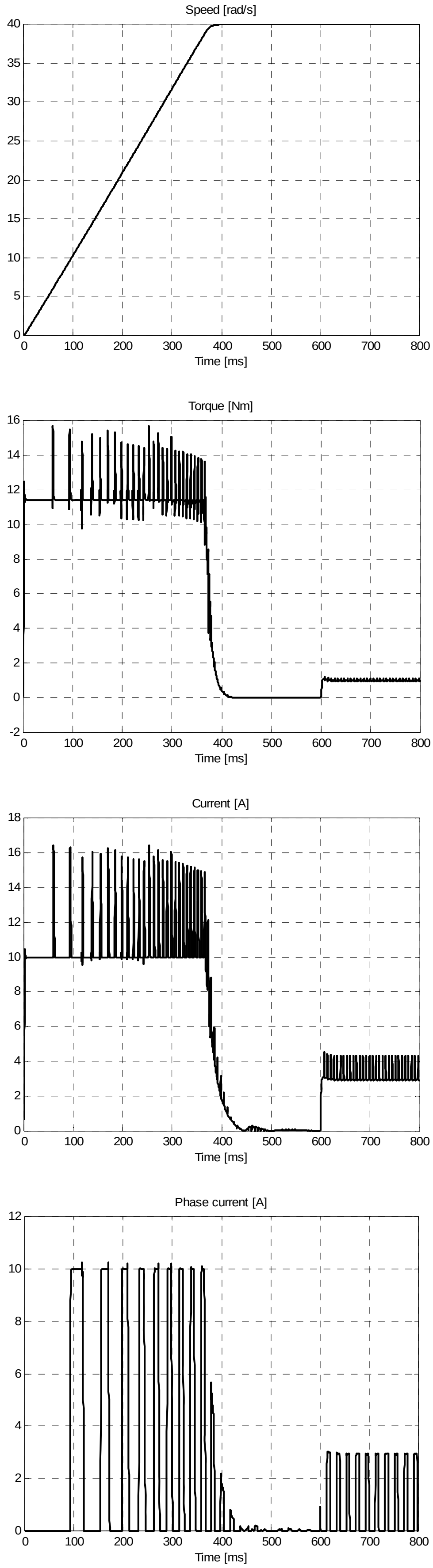


FIG. 6 SIMULATION RESULTS WITH MODEL REFERENCE PARAMETER ADAPTIVE SPEED CONTROL

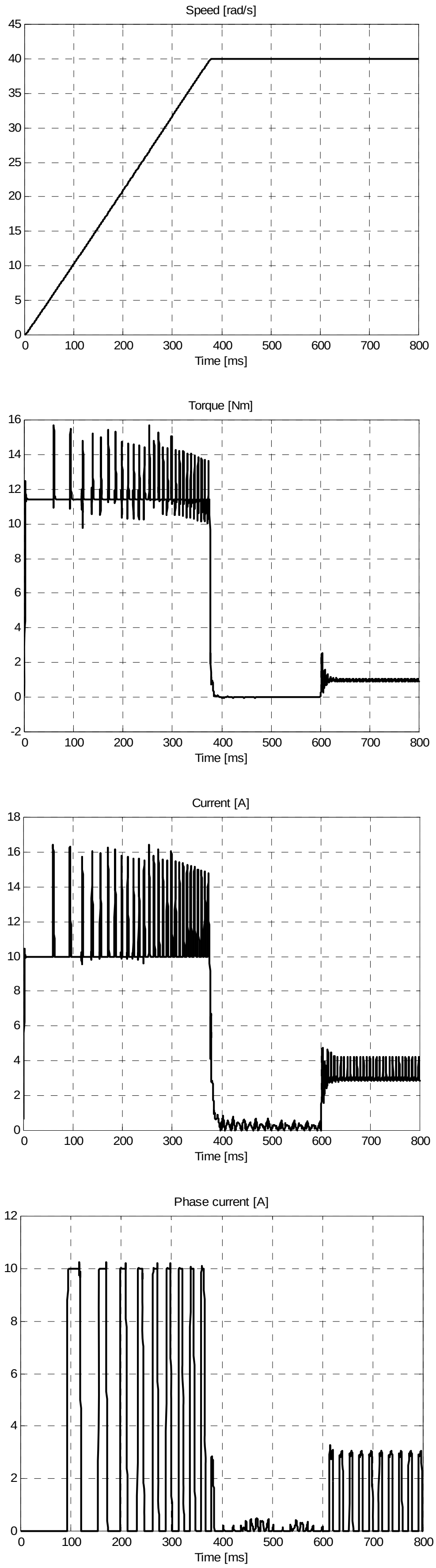


FIG. 7 SIMULATION RESULTS WITH MODEL REFERENCE SIGNAL ADAPTIVE SPEED CONTROL

According to the simulation investigations convergence of the model reference adaptive controls at switched reluctance drives with significant torque ripples can be ensured with the next conditions:

- Input of the first-order reference model only determines its output when the filtered current reference signal is lower with a given ΔI value (in the simulation it has been set to 1 A) than its limit otherwise output is identical to the speed feedback signal. So the model works like a first-order proportional lag element only in operation without current limitations.
- Adaptation is executed when two conditions are true at the same time:
- Filtered current reference signal is lower with a given ΔI value (in the simulation it has been set to 1 A) than current limit.
- Absolute value of the speed error signal is higher than a given Δn value (in the simulation it has been set to 20 revolution/min).
- The appropriate selection of the adaptation factor also has important effect on the sufficient convergence.

Because of the restrictions described in point 2. adaptation practically works only in a relatively narrow speed error track (adaptation range) which is approximately 20-100 revolution/min absolute value of speed error. The drawback of this limitation is the relatively short time for the algorithm to operate. At the same time the convergence of the algorithm is extremely fast, which significantly reduces the effect of this drawback. Two more important advantages emerge when adaptation works only with small speed errors. First of all the controller at changing drive parameters adapts to parameters around the value specified by speed reference signal which also assists to speed the adaptation. The other significant positive effect is the disappearance of the problem coming from nonlinear systems that the response of the system can even differ in its character when the value, amplitude of the reference signal is changed.

## Results

The tests were completed by the described drive system. The test results have supported our theoretical investigations. The oscillograms in the following figures illustrate some typical starting curves and wave forms. The loading machine was a DC motor. Its inertia is about a triple of that of SRM.

Fig. 8 and Fig. 9 show the speed and current curves in the course of starting. The upper curve is the speed, and the lower one is the current flowing in the common point of stator windings. It is related to the no-load operation mode.

The experiences show that the model reference parameter adaptive and signal adaptive control suggested in this paper work without overshooting.

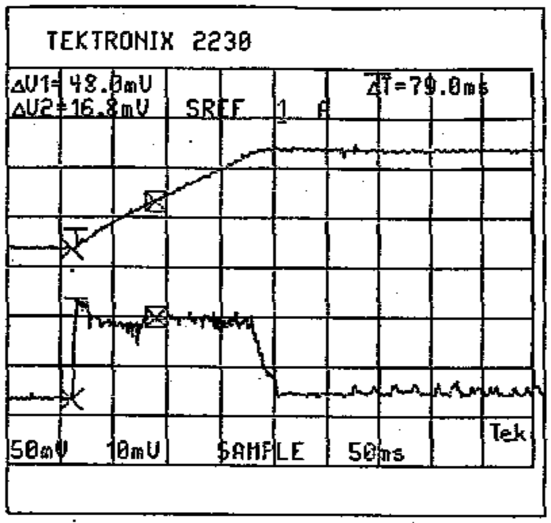


FIG. 8 OSCILLOGRAM OF SPEED AND CURRENT WITH MODEL REFERENCE PARAMETER ADAPTIVE SPEED CONTROL

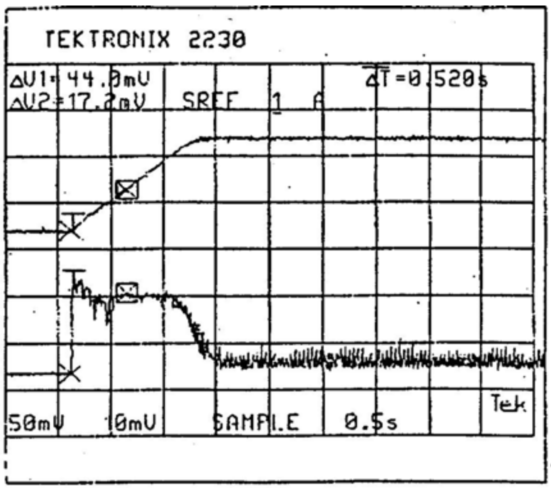


FIG. 9 OSCILLOGRAM OF SPEED AND CURRENT WITH MODEL REFERENCE SIGNAL ADAPTIVE SPEED CONTROL

## Conclusion

To provide constant loop gain in speed control loop with changing parameters (moment of inertia and/or torque factor), parameter and signal adaptive model reference adaptive control were developed.

Following from the structure (PF-type) of model reference parameter adaptive control was developed to provide constant loop gain in speed control loop with changing gain (moment of inertia and/or torque factor) which makes it easier to reach nonovershooting step response as well as fast speed changing compensation caused by jump in load. The algorithm even keeps its stability at fast changing, jump-like load torque.

Model reference signal adaptive control is used to provide constant loop gain in speed control loop with changing parameters (moment of inertia and/or torque factor) exposed to a significant load. The approaching block diagram of the adaptive control can be seen as an extended version of the PF controller, so one of the adaptation factors (which is the free parameter of the adaptive control) is given.

The adaptive controls suggested in this paper work without overshooting. Though these methods require a longer calculation period, it is less sensitive to the variations of parameters. Both model reference adaptive controls drawn up can be easily implemented, because the adaptation algorithms do not need acceleration measuring (thanks to the first-order model). Simulation and experimental results demonstrate that the proposed methods are promising tools to speed control of electrical drives.

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**Laszlo Szamel** was born in Budapest, in 1964. He received the M.Sc., dr. univ. and Ph.D. degrees in electrical engineering from Technical University of Budapest in 1988, 1995 and 2005, respectively.

Until 1997 he worked for Computer and Automation Research Institute of Hungarian Academy of Science, since then he is with Budapest University of Technology and Economics. His educational and research fields are electrical drive control, servo and robot drives, digital systems, switched reluctance motor drives, high-accuracy position and speed measurements of electrical drives.

Dr. Laszlo Szamel is associate professor, a member of the Hungarian Electrotechnical Association and several Committees of Hungarian Academy of Science.