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PREDICTIVE SYNCHRONOUS GENERATOR EXCITATION CONTROL BASED ON LAGUERRE MODEL

Jozef Škultéty * — **Eva Miklovičová** * — **Ruth Bars** **

In this paper the synchronous generator excitation control is designed using the model reference control approach and its predictive extension. The control objective is to satisfy requirements on the synchronous generator performances imposed by the transmission system operator. The structure of both controllers is expressed in the form of modified Laguerre network. The efficiency of the proposed control design procedure is illustrated by simulation of the 259 MVA synchronous generator of the nuclear power plant Mochovce in Slovakia.

K e y w o r d s: model reference control, predictive control, Laguerre model, synchronous generator

1 INTRODUCTION

The electric power generation, transmission and distribution networks represent the largest and most complex man-made dynamic systems in the world. Due to the last blackouts in the United States and Europe, the issue of power system control and stabilization has recently gained more attention. Power systems can be stabilized either by regulating the power flow and the voltage level, or by controlling the excitation of synchronous generators which can stabilize and damp oscillations in the power system. For this reason the synchronous generator control system must be designed so that the satisfactory voltage regulation and damping performance is obtained [1]. In the Slovak power system a synchronous generator can be connected to the grid only if its performances satisfy conditions given by the European Network of Transmission System Operators and further specified in national standards. These conditions are formulated as the restrictions on: (a) – the terminal voltage maximum overshoot, (b) – the terminal voltage settling time, (c) – the active power oscillation damping.

The synchronous generator voltage regulators are mostly based on PI control structure and are designed so that the first two requirements are satisfied. However, this controller cannot ensure the desired damping of transient processes, so it is usually combined with a feedback controller that adds damping into the control loop. The typical structure of power system stabilizers in industrial power systems consists of wash-out filters and lead-lag compensators. The stabilizer input signal can be one of the locally available signals such as changes in rotor speed, rotor frequency, accelerating power or any other suitable signal. The conventional power system stabilizers are designed with the phase compensation technique in the frequency domain. For many years an intensive research activity has been devoted to new methods of PSS design aiming to improve the power system stability and performances. It can be said that almost all methods of control theory have subsequently been used in PSS design, such as adaptive [2, 3], robust [4, 5], optimal [6, 7], predictive [8, 9], fuzzy [10, 11] and their combinations [12, 13].

It would be advantageous to ensure the desired terminal voltage transient performance as well as the oscillation damping using one control algorithm. For this purpose the synchronous generator control design can be formulated as the control problem where the performance specifications are given in terms of a reference model. The objective is to design a controller such that the controlled system output resembles the output of the reference model. In this paper, the controller structure is expressed in the form of modified Laguerre network (called x expansion) [14]. The model reference control design results in open-loop controller. To ensure the disturbance rejection capabilities the control structure has been augmented by an internal model controller. This model reference control design has been further modified so that predicted values of the error signal are considered which provides a faster control system performance.

The paper is organized as follows. First the system modelling based on Laguerre networks is presented. Then the model reference control design using the Laguerre models and its predictive version are given. Finally the effectiveness of the proposed control design procedures for the synchronous generator excitation control is evaluated in simulation.

* Slovak University of Technology, Faculty of Electrical Engineering and Information Technology, Ilkovičova 3, 812 19 Bratislava, Slovakia, jozef.skultety@stuba.sk, eva.miklovicova@stuba.sk;

** Budapest University of Technology & Economics, Department of Automation and Applied Informatics, Hungary, bars@aut.bme.hu

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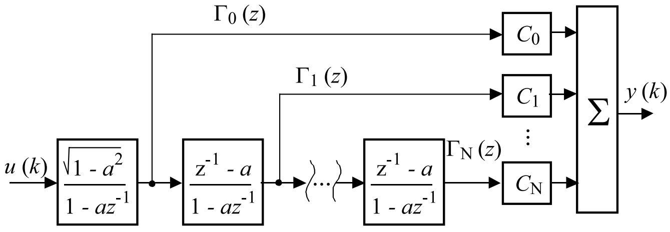

Fig. 1. Discrete-time Laguerre network

2 LAGUERRE MODELS

Model reference control design derived in the next section results in a controller in the form of modified Laguerre network (x-expansion). The Laguerre networks are suitable for modeling of stable processes with the impulse response decaying to zero [15, 16]. The quality of approximation depends on the choice of Laguerre network parameters, namely the number of Laguerre coefficients and the value of a scaling parameter. The model identification is simple due to the orthogonality of the Laguerre functions.

2.1 Discrete-time Laguerre network

The z-transforms of the discrete-time Laguerre functions are written as [17]

$$\begin{aligned} \Gamma_0(z) &= \frac{\sqrt{1-\alpha^2}}{1-\alpha z^{-1}}\,, \\ \Gamma_1(z) &= \frac{\sqrt{1-\alpha^2}}{1-\alpha z^{-1}}\frac{z^{-1}-\alpha}{1-\alpha z^{-1}}\,, \\ &\vdots \\ \Gamma_N(z) &= \frac{\sqrt{1-\alpha^2}}{1-\alpha z^{-1}}\left(\frac{z^{-1}-\alpha}{1-\alpha z^{-1}}\right)^N \end{aligned} \tag{1}$$

where $M = N+1$ is the number of the discrete-time Laguerre functions and α is the time scaling parameter. For stability reasons α has to be chosen from the interval $< 0, 1)$. The discrete-time Laguerre network is shown in Fig. 1.

Note that

$$\begin{aligned} \Gamma_k(z) &= \Gamma_{k-1}(z)\frac{z^{-1}-\alpha}{1-\alpha z^{-1}}, \\ \text{with} \quad \Gamma_0(z) &= \frac{\sqrt{1-\alpha^2}}{1-\alpha z^{-1}}\,. \end{aligned} \tag{2}$$

Let $l_0(k)$ denote the inverse z-transform of $\Gamma_0(z,\alpha)$, $l_1(k)$ the inverse z-transform of $\Gamma_1(z,\alpha)$ and so on to $l_N(k)$ the inverse z-transform of $\Gamma_N(z,\alpha)$. This set of discrete-time Laguerre functions is expressed in a vector form as [17]

$$L(k) = [\, l_0(k) \quad l_1(k) \quad \dots \quad l_N(k)\,]^\top . \tag{3}$$

Taking advantage of the network realization (2), the set of discrete-time Laguerre functions satisfies the following difference equation [17]

$$\hat{L}(k+1) = A_l L(k) + L(0)u(k+1) \tag{4}$$

where matrix A_l is of dimension $(M\times M)$, $M = N+1$, and it is a function of parameter α, and $\beta = 1-\alpha^2$, and the initial condition is given by

$$L(0) = \sqrt{\beta}\,[\,1 \quad -\alpha \quad \alpha^2 \quad -\alpha^3 \quad \dots \quad (-1)^N\alpha^N\,]^\top . \tag{5}$$

For example, in the case where $M = 5$,

$$A_l = \begin{bmatrix} \alpha & 0 & 0 & 0 & 0 \\ \beta & \alpha & 0 & 0 & 0 \\ -\alpha\beta & \beta & \alpha & 0 & 0 \\ \alpha^2\beta & -\alpha\beta & \beta & \alpha & 0 \\ -\alpha^3\beta & \alpha^2\beta & -\alpha\beta & \beta & \alpha \end{bmatrix}; \; L(0) = \sqrt{\beta}\begin{bmatrix} 1 \\ -\alpha \\ \alpha^2 \\ -\alpha^3 \\ \alpha^4 \end{bmatrix}. \tag{6}$$

For control design purposes the Laguerre model of the system to be controlled is needed. In the system identification procedure it is necessary to choose the value of the time scaling factor α and the number of the weighting coefficients M. Then the values of the weighting coefficients $c_0, c_1, \dots, c_N$ can be determined from the system impulse function $H(k)$ [17]

$$H(k) = c_0 l_0(k) + c_1 l_1(k) + \dots + c_N l_N(k)\,. \tag{7}$$

Taking into account the orthogonality of the discrete-time Laguerre functions, the weighting coefficients can be calculated as follows

$$\sum_{k=0}^{\infty} l_i(k) l_j(k) = \begin{cases} 0\,, & \text{if } i \neq j\,, \\ 1\,, & \text{if } i = j\,, \end{cases} \tag{8}$$

$$c_i = \sum_{k=0}^{\infty} H(k) l_i(k) \quad \text{for } i = 0, 1, \dots, N\,. \tag{9}$$

2.2 Discrete-time x-expansion

Let us express the discrete-time x function in the following form

$$x = \frac{z^{-1}-\alpha}{1-\alpha z^{-1}}\,. \tag{10}$$

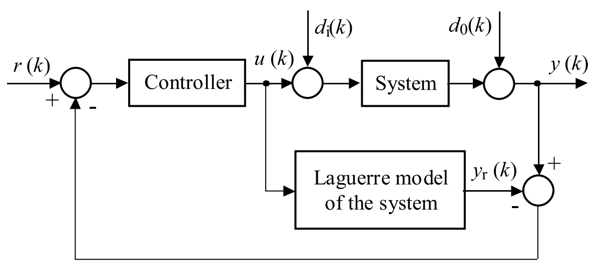

Fig. 2. Internal model control

Since the following relationship holds

$$x^j \Gamma_i(z) = \Gamma_{i+j}(z)\,, \tag{11}$$

it can be shown, that the sequence $\{x^k;\ k = 0, 1, 2, \dots\}$ forms a complete orthonormal system in H^2. Any function in H^2 can be expanded into a convergent series according to x. A discrete pulse transfer function can be expressed as the ratio of the z-transforms of the output and the input signal, respectively. Supposing that the input is the first Laguerre function and the output is expressed in a Laguerre series form, the discrete pulse transfer function is obtained in x-expansion form as

$$H(z) = \frac{\sum_{i=0}^{\infty} d_i \Gamma_i(z)}{\Gamma_0(z)} = \sum_{i=0}^{\infty} d_i x^i\,. \tag{12}$$

So x-expansion of controllers with discrete transfer functions, where the degrees of the numerator and the denominator are the same, can be given.

3 MODEL REFERENCE CONTROL DESIGN

Model reference control design based on the continuous Laguerre network has been proposed in [14]. However, the model-reference control based on the Laguerre expansion can also be used in the discrete-time domain.

The aim of model reference control design is to find such a controller $H_2(z)$ that satisfies (at least approximately) the following equation

$$H_1(z) H_2(z) = H_m(z) \tag{13}$$

where $H_1(z)$ is the system model and $H_m(z)$ is the reference model, both in the form of Laguerre network. In the proposed approach the controller is expressed in the form of the modified Laguerre model, *ie* x-expansion

$$H_2(z) = \sum_{j=0}^{N} d_j \Big(\frac{z^{-1} - \alpha}{1 - \alpha z^{-1}}\Big)^j \tag{14}$$

$$\begin{aligned} d_0 &= m_0 / c_0\,, \\ d_1 &= (m_1 - d_0 c_1)/c_0 \\ &\vdots \\ d_N &= \frac{1}{c_0}\Big(m_N - \sum_{i=0}^{N-1} d_i c_{N-i}\Big) \end{aligned} \tag{15}$$

m_i and c_i, $i = 0, \dots, N$, are the reference model weighting coefficients and the system model weighting coefficients, respectively.

The model reference control design results in an open-loop controller. Therefore, in order to ensure the disturbance rejection the control structure is augmented by the internal model control (IMC) according to Fig. 2, where $r(k)$ is the reference value, $u(k)$ is the control action, $y(k)$ is the measured output of the system, $d_i(k)$ and $d_o(k)$ are input and output disturbances respectively, $y_r(k)$ is the output of the Laguerre model of the system.

4 PREDICTIVE MODEL REFERENCE CONTROL DESIGN

In the model reference control derived in the previous section the current control action is calculated using the value of the current error signal. If the future reference

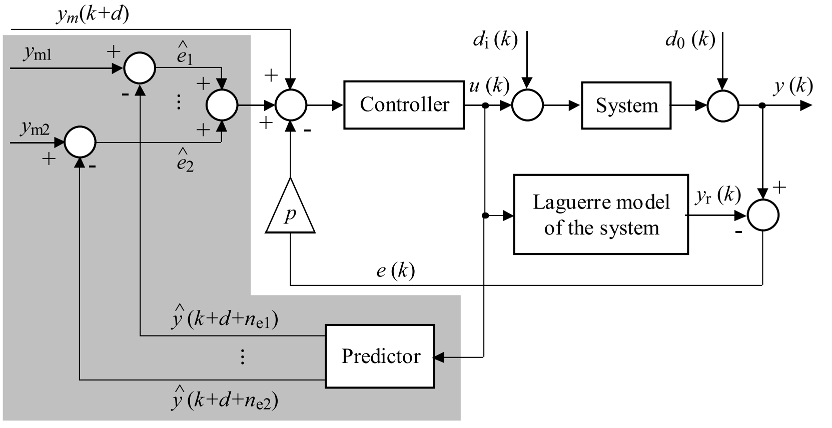

Fig. 3. Predictive model reference control

trajectory is known, a series of predicted error values over a given prediction horizon can be used to improve the control system performances, similarly to predictive PID control [18]. A block diagram of the predictive model reference control is shown in Fig. 3.

The structure of the controller is given by x-expansion (12). The error signal is composed as a sum of the differences between the predicted reference signal and the predicted output signal over a given prediction horizon.

$$\begin{aligned} \hat{e}_1 &= \hat{e}(k+d+n_{e1}|k) = y_{m1} - \hat{y}_1 \\ &= y_m(k+d+n_{e1}) - \hat{y}(k+d+n_{e1}) \\ &\vdots \\ \hat{e}_2 &= \hat{e}(k+d+n_{e2}|k) = y_{m2} - \hat{y}_2 \\ &= y_m(k+d+n_{e2}) - \hat{y}(k+d+n_{e2}) \end{aligned} \tag{16}$$

where $n_{e1} \le n_e \le n_{e2}$, $n_{e1} \ge 1$, d is the discrete dead time, $y_{m1}, \dots, y_{m2}$ are the outputs of a chosen reference model and $\hat{y}_1, \dots, \hat{y}_2$ are the predicted output signals from the k current time instant $(d+n_e)$ step ahead. In this case the number of all paths is $p = (n_{e2} - n_{e1}) + 2$. The input disturbance is denoted by $d_i(k)$, the output disturbance is denoted by $d_o(k)$, $u(k)$ is the control action, $y(k)$ is the output of the system and $y_r(k)$ is the output of the discrete Laguerre model of the system and $e(k)$ is the error signal. The future disturbances are not known at the current time. Therefore it is supposed that these values are constant for all paths and $e(k)$ is multiplied by p.

If the grey parts of Fig. 3 will be removed, $y_m(k+d)$ will be set to $r(k)$ and $p = 1$, then the scheme of internal model control shown in Fig. 2 will be obtained.

4.1 Prediction

Prediction of the future system outputs based on Laguerre network is realized by

$$\begin{aligned} \hat{y}(k+d+n_{e1}|k) &= \eta \hat{L}(k+d+n_{e1}|k) \\ &\vdots \\ \hat{y}(k+d+n_{e2}|k) &= \eta \hat{L}(k+d+n_{e2}|k) \end{aligned} \tag{17}$$

where $\eta = [c_0 \quad c_1 \quad \dots \quad c_N]$ is the vector containing M Laguerre coefficients. $\hat{L}(k+d+n_e|k)$ are predicted Laguerre function outputs which can be calculated based on (3) as follows

$$\begin{aligned} \hat{L}(k+1|k) &= A_l L(k) + L(0)u(k+1|k), \\ \hat{L}(k+2|k) &= A_l \hat{L}(k+1|k) + L(0)u(k+2|k), \\ &\vdots \\ \hat{L}(k+d+n_{e2}|k) &= A_l \hat{L}(k+d+n_{e2}-1) \\ &\quad + L(0)u(k+d+n_{e2}|k). \end{aligned} \tag{18}$$

If the future control actions are not known then $u(k+1|k) = u(k|k), \dots, u(k+d+n_{e2}|k) = u(k|k)$ can be considered. The predictor can be realized based on (17) and (18).

The output of the Laguerre model of the system for IMC control can be calculated by the following relationship

$$y_r(k) = \eta L(k). \tag{19}$$

5 SYNCHRONOUS GENERATOR EXCITATION CONTROL

5.1 Synchronous generator model

The synchronous generator model has been derived and described in many papers. In our paper the synchronous generator model of 5th order will be considered in the following form [19]

- the machine motion equations

$$\begin{aligned} \Delta\dot{\omega} &= \frac{1}{M}(p_m - p_e - D\Delta\omega), \\ \dot{\delta} &= \omega - \omega_s = \Delta\omega. \end{aligned} \tag{20}$$

- the equations of the electromagnetic processes

$$\begin{aligned} T''_{d0}\dot{e}''_q &= e'_q - e''_q + i_d(x'_d - x''_d), \\ T''_{q0}\dot{e}''_d &= e'_d - e''_d + i_q(x'_q - x''_q), \\ T'_{d0}\dot{e}'_q &= e_b - e'_q + i_d(x_d - x'_d). \end{aligned} \tag{21}$$

The meaning of symbols is stated in Appendix 1.

In this model the screening effect of the rotor body eddy-currents in the q-axis is neglected, so that $x'_q = x_q$ and $e'_d = 0$. This model reverts to the classical five winding model with armature transformer emfs neglected.

The synchronous generator active power can be expressed as follows

$$p_e = (v_d i_d + v_q i_q) + (i_d^2 + i_q^2)R. \tag{22}$$

After the substitution of

$$\begin{bmatrix} v_d \\ v_q \end{bmatrix} = \begin{bmatrix} e''_d \\ e''_q \end{bmatrix} - \begin{bmatrix} R & x''_q \\ -x''_q & R \end{bmatrix} \begin{bmatrix} i_d \\ i_q \end{bmatrix} \tag{23}$$

we get

$$p_e = (e''_d i_d + e''_q i_q) + (x''_d - x''_q) i_d i_q. \tag{24}$$

For control design and simulation purposes the parameters of 259 MVA synchronous generator of the nuclear power plant Mochovce (EMO) in Slovakia [20] have been used, see Appendix 2.

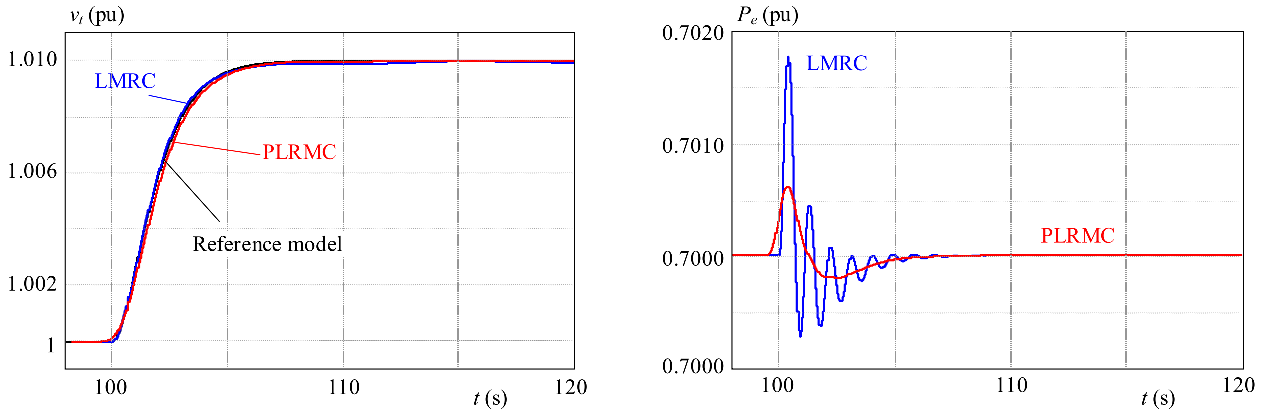

Fig. 4. Terminal voltage and electric power time responses

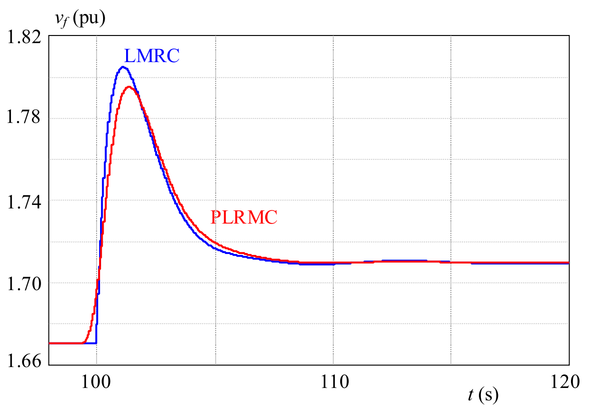

Fig. 5. Field voltage time responses

5.2 Control design

The synchronous generator control objective is to satisfy conditions prescribed for the synchronous generator transient behavior by the national standard PNE-34-01-2002

- the terminal voltage maximum overshoot less then 5 %,
- the terminal voltage settling time less then 15 s,
- the active power oscillation damping

$$\gamma = \frac{|\Delta P_2| + |\Delta P_3|}{|\Delta P_1| + |\Delta P_2|} \leq 0.5 \tag{25}$$

where γ is a damping index and ΔP_1, ΔP_2, ΔP_3 are the first three consecutive peak magnitudes of the active power transient response after the terminal voltage set point step change.

Let us denote the model reference control based on Laguerre model as LMRC and predictive model reference control as PLMRC. In this section the performances of these two controllers will be compared.

The synchronous generator discrete-time Laguerre model has been estimated around an operating point corresponding to $v_t = 1\,\text{pu}$ with sampling period $T_s = 0.05$ s using the time scaling parameter $\alpha = 0.981$ and $M = 10$. The estimated values of weighting coefficients are

$$sys = \{0.0115;\ 0.0068;\ 0.0033;\ 0.0023;\ 0.0008;\ 0.0009;\ 0.0001;\ 0.0004;\ -0.0001;\ 0.0003\}\,. \tag{26}$$

For both controllers, the desired control system performances have been prescribed by the reference model with $\alpha = 0.981$, $M = 10$ and the following vector of weighting coefficients has been obtained

$$rm = \{0.1004;\ 0.0148;\ -0.0330;\ 0.0264;\ -0.0169;\ 0.0097;\ -0.0053;\ 0.0027;\ -0.0013;\ 0.0006\}\,. \tag{27}$$

Using the control design procedure described in Section 3 the x-expansion weighting coefficients for the controller have been obtained

$$cont = \{8.7164;\ -3.8740;\ -3.1002;\ 3.5299;\ -2.5293;\ 1.5528;\ -0.8814;\ 0.4771;\ -0.2502;\ 0.1282\}\,. \tag{28}$$

For PLMRC the reference signal has been given as the output of the reference model (27) and the predicted error values have been calculated using $n_{e1} = 1$ and $n_{e2} = 15$.

The simulation results are shown in Figs. 4 and 5. The terminal voltage time response is almost identical for both controllers; it tracks the output of the reference model which has been chosen so as its transient behavior is in accordance with the standard requirements. The resulting terminal voltage settling time is 6.5 s. Its maximum overshoot is 0 %. The contribution of the predictive extension becomes evident in the active power time response. For LMRC the damping coefficient calculated from the peaks $\Delta P_1 = 0.0018$, $\Delta P_2 = 0.0007$, $\Delta P_3 = 0.0004$ is $\gamma = 0.466 < 0.5$ and for PLMRC $\Delta P_1 = 0.0006$, $\Delta P_2 = 0.0002$, $\Delta P_3 = 0.0000$ which yields $\gamma = 0.251 < 0.5$. The active power oscillation damping condition is satisfied for both controllers, but the damping coefficient for PLMRC is considerably decreased. Figure 5 shows the control actions of both controllers. It can be seen, that in PLMRC the controller reacts before the real reference change, which results in a gentler rise of control signal and consequently less oscillating active power.

6 CONCLUSION

In the paper, the synchronous generator excitation control design based on the model reference control approach has been presented. The control objective has been to satisfy the conditions imposed on the synchronous generator performances by the transmission system operator. The controller has been designed using the model reference approach and has been expressed in the form of modified Laguerre network called x-expansion. As the model reference control design results in open-loop controller, the control structure has been augmented by the internal model control in order to ensure the disturbance rejection. Predictive version of the model reference control design has also been proposed, where the series of predicted error values over a given prediction horizon has been used to improve the control system performances. In this case the control performances can be influenced not only by the reference model dynamics but also by the controller tuning parameters. The proposed control design procedure effectiveness has been illustrated by simulation of the 259 MVA synchronous generator of the nuclear power plant Mochovce in Slovakia. The simulation results have shown that for both controllers the conditions imposed on the control system performances by the national standard have been satisfied. The terminal voltage time response is almost identical for both controllers, but using the predictive version the oscillation damping coefficient has been considerably decreased which contributes to the power system stability.

Appendix 1 — Symbols used in synchronous generator model

- ω – angular velocity of the generator (in electrical radians)
- ω_s – synchronous angular velocity in electrical radians
- $\Delta\omega$ – rotor speed deviation
- M – inertia coefficient
- p_m – mechanical power supplied by a prime mover to a generator
- p_e – electromagnetic air-gap power
- D – damping coefficient
- i_d, i_q – currents flowing in the d- and q-axis armature coils
- e_q – steady-state emf induced in the q-axis armature coil proportional to the field winding self-flux linkages
- e'_d – transient emf induced in the d-axis armature coil proportional to the flux linkages of the q-axis coil representing the solid steel rotor body
- e'_q – transient emf induced in the q- axis armature coil proportional to the field winding flux linkages
- e''_d – subtransient emf induced in the d-axis armature coil proportional to the total q-axis rotor flux linkages
- e''_q – subtransient emf induced in the q-axis armature coil proportional to the total d-axis rotor flux linkages
- T'_{d0}, T''_{d0} – open-circuit d-axis transient and subtransient time constants
- T'_{q0}, T''_{q0} – open-circuit q-axis transient and subtransient time constants
- x_d, x'_d, x''_d – total d-axis synchronous, transient and subtransient reactance between (and including) the generator and the infinite busbar
- x_q, x'_q, x''_q – total q-axis synchronous, transient and subtransient reactance between (and including) the generator and the infinite busbar

Appendix 2 — Synchronous generator parameters

$T_{d0} = 7.7$	$x_d = 1.99$	$x_q = 1.82$
$T_{d2} = 0.04$	$x'_d = 0.267$	$x'_q = 0.204$
$T_{q2} = 0.23$	$x'_d = 0.13$	$x_t = 0.14$
$T_j = 0.0315$		$x_l = 0.14$

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Jozef Škultéty was born in Žarnovica, Slovakia, in June 1986. He received the MSc degree in Applied Informatics in 2010 from the Slovak University of Technology in Bratislava, Faculty of Electrical Engineering and Information Technology (STU). He spent 3 months of year 2011 at the Budapest University of Technology and Economics, Department of Automation and Applied Informatics, Hungary as visiting researcher. He is a PhD student at STU in 3rd year of study. He has published papers in the area of predictive control and model reference control based on Laguerre network.

Eva Miklovičová was born in Piešťany, Slovakia, in May 1967. She received the MSc degree in Automatic Control Systems in 1990 and the PhD degree in Automation in 1997, both from the Slovak University of Technology in Bratislava, Faculty of Electrical Engineering and Information Technology (STU). She is currently Associate Professor at the Institute of Control and Industrial Informatics at the Faculty of Electrical Engineering and Information Technology, STU in Bratislava. Since 2011 she has been a vice-director of the Institute of Control and Industrial Informatics. Her research interests cover predictive control, adaptive control, system modeling and identification and networked control systems.

Ruth Bars received the MSc degree in Electrical Engineering in 1964 and the doctor of the university degree in 1976, both from the Technical University of Budapest. In 1992 she has gained the PhD from the Budapest University of Technology and Economics (BME). She received the honorary professor status in 2012 from BME. From 1996 2002 she was the head of the IFAC TC on Optimal Control and from 2002 2008 she served IFAC as the head of the Coordinating Committee on Design Methods. Her research interests cover control engineering, digital control algorithms, predictive control, new ways of control education.