The Turbogenerator Predictive Control

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Abstract: - An effective control design of the turbogenerator transient processes is proposed in this paper. The plant mathematical model is taken into consideration as a MIMO system with two inputs and two outputs. This system is decomposed into two subsystems, a voltage and an electromechanical one. The control objective is to ensure the requirements on the turbogenerator voltage control performances as well as a damping of the active power oscillations. The results verification is realized for the 259MVA turbogenerator models in Matlab simulation environment.

Key-Words: - MIMO system, nonlinear system, identification, predictive control, turbogenerator

1 Introduction

The turbogenerator complex control that aims to ensure the desired performances indices of the voltage control and the active power damping [4, 7] is not a new problem and new approaches improving this type of the turbogenerator control appear all the time. A broad development of this turbogenerator control structure is restricted by the implementation difficulties, because the approaches to the turbine control and the generator control used to be different. A spatial separation of the excitation control system and the turbine control system in many blocks also represents a problem.

In this paper, a decentralized turbogenerator control taking into account the spatial separation of the turbine and the excitation control systems is proposed using the predictive control methodology.

The predictive control has become popular over the past twenty years as a powerful tool in feedback control for solving many problems for which other control approaches were proved to be ineffective [3].

Two of these methods are described in section 2 and 3. The common feature of these methods is, that from data measured in past time $Y(k)=\{y(1),...,y(k)\}$ and $U(k)=\{u(1),...,u(k-1)\}$ one or several values of plant output is predicted. Values predicted in this way are also the functions of future manipulated variables $u(k)$, $u(k+1)$, ... The control strategy is then defined by minimization of functional with the loss function defined as a sum of differences between the values of reference signal and the values of predicted output (prediction of control error) and the penalization of manipulated variable.

There are many approaches to predictive control, which vary from each other by the number of predicted values, the functional and also by limiting conditions for control strategy. The generalized predictive control will be introduced in the next section.

The paper is organized as follows. First, design of the generalized predictive control is briefly introduced in section 2. The partial state reference model control continues in section 3. The synchronous generator and the turbine are then discussed in Section 4. Section 5 includes the experimental results. A summary and the conclusions are given in Section 6.

2 Generalized predictive control (GPC)

2.1 Plant model

Prediction itself can be realized only on the base of the known model of plant. This model should accurately enough describe dynamics of the real plant. Consider that the plant model is described by the ARMAX model

$$A(z^{-1})y(k)=B(z^{-1})u(k)+\frac{C(z^{-1})}{\Delta}\varepsilon(k) \qquad (1)$$

where $u(k)$ is the control input and $y(k)$ is the output value. This model allows to incorporate the internal model of state disturbances so that the control design can ensure the offset-free performance.

2.2 Basic principle of predictive control

The predictive control algorithm uses a moving horizon, as shown in Figure 1.

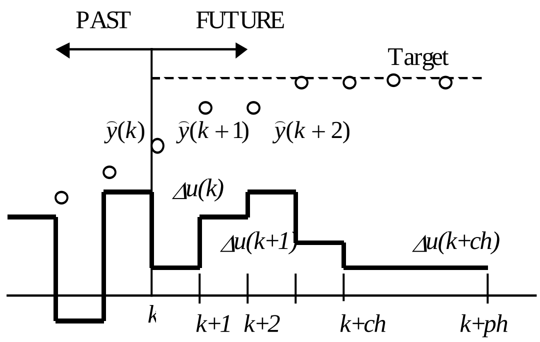

Fig.1 Basic principle of predictive algorithm

Based on the plant model, the size of the future output values depending on the changes of control input are to be predicted. The control input is generated so that the desired output characteristics are achieved. The plant behavior for ph steps ahead is predicted in the time k. The least-squares method is usually used to achieve the optimal output value behavior. In this method the constraints of the control input, the control input increment and also of the process output are usually considered.

2.3 GPC design

The control objective is to minimize in a receding horizon sense the following cost function

$$J_{pc} = \sum_{j=sh}^{ph} \left[\tilde{y}(k+j) - r(k+j)\right]^2 + \sum_{j=sh}^{ph+sh-1} \rho\left[\Delta u(k+j-sh)\right]^2 \qquad (2)$$

where $sh \geq 1$ denotes a starting horizon, $ph \geq sh$ is a prediction horizon, ch is a control horizon and $\rho \geq 0$ it a penalization of control input. It is supposed, that future values of reference signal are known $r(k+j)$, for $j = 1,2,...$

The GPC control design then consists in performing the following three steps:

1. Prediction of output $\tilde{y}(k+j)$ for $j = 1,2,...$, which is a function of future controlled inputs $u(k+j)$ for $j = 1,2,...$, is calculated a few steps ahead.
2. Optimal sequence of future control inputs according to quadratic criteria (2) is calculated.
3. Only the first component - $u(k)$ out of this sequence of control inputs will be used for control, and the whole process will be repeated in the next sampling period.

Parameters of quadratic criteria (2) and additional constraint parameters can be chosen as follows:

sh: $sh = d + 1$ if plant delay time is known, otherwise $sh = 1$.

ph: is selected so as the essential part of time response of the controlled system is included in ph steps.

ch: $ch = 1$ is selected for stable and damped systems, otherwise ch will be equal to a number of unstable poles, or poles close to the stability boundary.

ρ: $\rho = 0$ is chosen in most cases. Less dynamic control is obtained by increasing ρ, but at the expense of regulation process of lower quality.

The right choice of these predictive control parameters is not simple, requires practice with the controlled plant and depends on control requirements.

The GPC control can be implemented using the general linear control law (Fig. 2)

$$S(z^{-1})D(z^{-1})u(k) + R(z^{-1})y(k) = T(z^{-1})r(k+1) \qquad (3)$$

i.e. the control input in the step k is obtained as follows

$$u(k) = \frac{T(z^{-1})}{S(z^{-1})D(z^{-1})} r(k+1) - \frac{R(z^{-1})}{S(z^{-1})D(z^{-1})} y(k) \qquad (4)$$

where

$$R(z^{-1}) = \sum_{j=sh}^{ph} g_j . F_j(z^{-1}) \qquad (5)$$

$$S(z^{-1}) = C(z^{-1}) + \sum_{j=sh}^{ph} g_j . z^{-1} . H_j(z^{-1}) \qquad (6)$$

$$T(z^{-1}) = C(z^{-1}) \sum_{j=sh}^{ph} g_j . z^{-ph+j} \qquad (7)$$

g_j : terms of the first line of matrix $\left[\overline{G}^T \overline{G} + \rho I_{ch}\right]^{-1} \overline{G}^T$

$\overline{G}$: matrix of dimension $\left[ph - sh + 1; ch\right]$.

Polynomials $F(z^{-1})$, $H(z^{-1})$ and $G(z^{-1})$ are solutions of the following polynomial equations

$$1 = E_j(z^{-1})A(z^{-1})\Delta + z^{-j} F_j(z^{-1}) \qquad (8)$$

$$E_j(z^{-1})\overline{B}(z^{-1}) = C(z^{-1})G_j(z^{-1}) + z^{-j} H_j(z^{-1}) \qquad (9)$$

This approach has been used in our implementation.

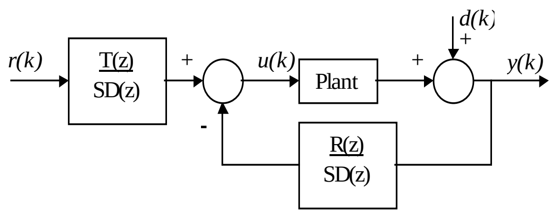

Fig.2 Simulation scheme of predictive control

3 Partial state reference model control

The partial state reference model control (PSRMC) design consists of a suitable combination of the pole placement control design with the linear quadratic or generalized predictive control design. The former is particularly motivated by the performance specification simplicity, while the later is used to ensure the numerical and stability robustness. To this end, the pole placement control objective is restated in terms of a regulation problem with respect to the suitable performance quantifiers, namely the input and output reference trajectories, respectively [2].

The plant model is described in following partial state representation

$$\begin{aligned} A(z^{-1})D(z^{-1})x(t) &= D(z^{-1})u(t-d-1) \\ y(t) &= B(z^{-1})x(t) \end{aligned} \qquad (10)$$

where $x(t)$ denotes the partial state. We consider the ideal control objective

$$x(t) - x^*(t) = 0 \qquad (11)$$

where $x^*(t)$ represents the desired partial state reference sequence. The latter may be specified as the output of an asymptotically stable system as follows

$$x^*(t) = \beta . y^*(t) \qquad (12)$$

with

$$A_m(z^{-1})y^*(t+d+1) = B_m(z^{-1})u^*(t) \qquad (13)$$

$$\beta = \frac{1}{B(1)} \qquad (14)$$

where $\frac{B_m(z^{-1})}{A_m(z^{-1})}$ denotes the transfer function of reference model, $u^*(t)$ is a bounded set-point sequence of and β is a scalar introduced to get a unitary closed-loop static gain. Substituting the control objective (11-14) into the plant model (10) we obtained

$$\begin{aligned} A(z^{-1})D(z^{-1})\beta y^*(t) &= D(z^{-1})u(t-d-1) \\ y(t) &= B(z^{-1})\beta y^*(t) \end{aligned} \qquad (15)$$

This allows to restate the ideal deadbeat PSRMC objective (11-14) as follows

$$e_y(t) = D(z^{-1})e_u(t) = 0 \qquad (16)$$

with

$$e_y(t) = y(t) - B(z^{-1})\beta y^*(t) \qquad (17)$$

$$e_u(t) = u(t) - A(z^{-1})\beta y^*(t+d+1) \qquad (18)$$

The control objective consists of minimizing the following linear quadratic cost function

$$J(t, ph, ch, sh, \rho) = E\left\{ \sum_{j=sh}^{ph} \left(e_y(t+j)\right)^2 + \rho\left(e_u(t+j-sh)\right)^2 \right\} \qquad (19)$$

subject to

$$e_u(t+i) = 0 \text{ for } ch \le 1 < ph \qquad (20)$$

4 The turbogenerator predictive control

The turbogenerator is considered to be a MIMO system with two inputs (v_f and u_t) and two outputs (v_t and P_e). The decentralized control is based on the system decomposition into subsystems and its structure is implemented so that the control of the isolated subsystems is realized utilizing only its own variables. For the control design purposes the subsystems linearized models will be identified in the operating point.

4.1 Synchronous generator model

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

The machine motion equation:

$$\begin{aligned} \frac{d\Delta\omega}{dt} &= \frac{1}{M}\left(p_m - p_e - D\Delta\omega\right) \\ \Delta\omega &= \omega - \omega_s = \frac{d\delta}{dt} \end{aligned} \qquad (10)$$

Equation describing the electromagnetic processes:

$$\begin{aligned} T''_{d0}\dot{e}''_q &= e'_q - e''_q + i_d\left(x'_d - x''_d\right) \\ T''_{q0}\dot{e}''_d &= e'_d - e''_d + i_q\left(x'_q - x''_q\right) \\ T'_{d0}\dot{e}'_q &= e_b - e'_q + i_d\left(x_d - x'_d\right) \end{aligned} \qquad (11)$$

Meaning of symbols is presented in Appendix no. 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.

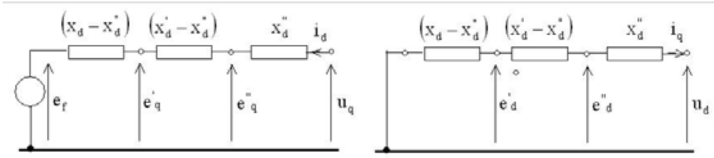

Fig. 3: Generator equivalent circuits

$$\begin{bmatrix} u_d \\ u_q \end{bmatrix} = \begin{bmatrix} e''_d \\ e''_q \end{bmatrix} - \begin{bmatrix} R & x''_q \\ -x''_q & R \end{bmatrix}\begin{bmatrix} i_d \\ i_q \end{bmatrix} \qquad (12)$$

The synchronous generator active power can be described as follows:

$$p_e = \left(u_d i_d + u_q i_q\right) + \left(i_d^2 + i_q^2\right)R \qquad (13)$$

and after the substitution of (12) we obtain:

$$p_e = \left(e''_d i_d + e''_q i_q\right) + \left(x''_d - x''_q\right) i_d i_q \qquad (14)$$

During the operation of large power systems it is necessary to ensure an effective oscillation damping process. The damping index γ must be less then or equal to 0,5 (norm PNE-34-01-2002) and is defined as follows:

$$\gamma = \frac{|\Delta P_2| + |\Delta P_3|}{|\Delta P_1| + |\Delta P_2|} \qquad (15)$$

where $\Delta P_1, \Delta P_2, \Delta P_3$ are first three consecutive peak magnitudes of the active power transient response after the terminal voltage set point step change.

4.2 Turbine model

The turbine and governor are defined by a six order model [1] with appropriate limits on valve position and velocity

$$p\,Y_{HP} = \left(G_M\ P_O - Y_{HP}\right)/\,\tau_{HP} \qquad (16)$$

$$p\,Y_{RH} = \left(Y_{HP} - Y_{RH}\right)/\,\tau_{RH} \qquad (17)$$

$$p\,Y_{IP} = \left(G_I\ Y_{RH} - Y_{IP}\right)/\,\tau_{IP} \qquad (18)$$

$$p\,Y_{LP} = \left(Y_{IP} - Y_{LP}\right)/\,\tau_{LP} \qquad (19)$$

$$T_m = F_{HP}\ Y_{HP} + F_{IP}\ Y_{IP} + F_{LP}\ Y_{LP} \qquad (20)$$

where P_O is the boiler steam pressure, Y_{XX} is the output of the stage XX in p.u. and τ_{XX} is the associated time constant. G is the valve position, T_m is the mechanical torque and FY is the contribution of the turbine stage to the total mechanical torque. Each of the main (M) and interceptor (I) values has been simulated by a single-lag transfer function $(1/(1+\tau s))$ which leads to equations of the form

$$p\,G_M = \left(U_{GM} - G_M\right)/\,\tau_{GM} \qquad (21)$$

$$p\,G_I = \left(U_{GI} - G_I\right)/\,\tau_{GI} \qquad (22)$$

where U_G is the valve actuating signal, and τ is the valve time constant.

Meaning of abbreviations is presented in Appendix no. 1.

5 Experimental results

The proposed turbogenerator control algorithm has been verified using an example of the 259MVA synchronous generator with turbine of the nuclear power plant Mochovce (EMO) in Slovakia [6]. The turbogenerator has been described by the non-linear model of 7th order (10), (11) and (16) - (22). This model can be decomposed into two subsystems:

- „voltage“ subsystem of the 5th order, where the input is the field voltage v_f and the output is the terminal voltage v_t
- „electromechanical“ subsystem of the 4th order, where the input is the valve actuating signal u_t and the output is the generator active power P_e.

As the GPC and PSRMC synthesis are based on the plant model transfer function, it is necessary to identify the ARX model of these nonlinear systems around an operating point using the least-squares method. The operating point of the “voltage” subsystem corresponds to v_t=1p.u. and the operating point of the “electromechanical” subsystem corresponds to P_e=0,7p.u. The periodic square signal with amplitude 0,05p.u. and frequency 0,01Hz has been used as the input signal for the “voltage” subsystem and the same signal with amplitude 0,02p.u. has been used for the “electromechanical” subsystem. In both cases the sampling period 0,05s has been used. The comparison of the plant and the identified model outputs around the operating point is shown in Fig. 4 and Fig. 5.
The identified model transfer functions are as follows:

$$T_{vt}(z^{-1}) = \frac{0{,}00124z^{-2} - 0{,}00116z^{-3}}{1 - 2{,}362z^{-1} + 1{,}7859z^{-2} - 0{,}4236z^{-3}} \qquad (23)$$

$$T_{Pe}(z^{-1}) = \frac{0{,}000938z^{-3} + 0{,}006766z^{-4}}{1 - 3{,}305z^{-1} + 4{,}197z^{-2} - 2{,}404z^{-3} + 0{,}5204z^{-4}} \qquad (24)$$

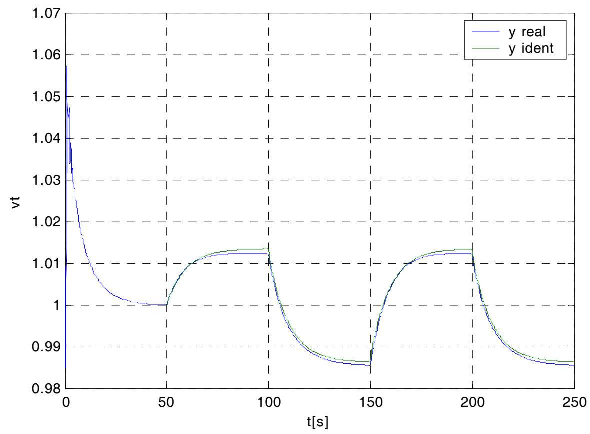

Fig.4 “Voltage” subsystem identification

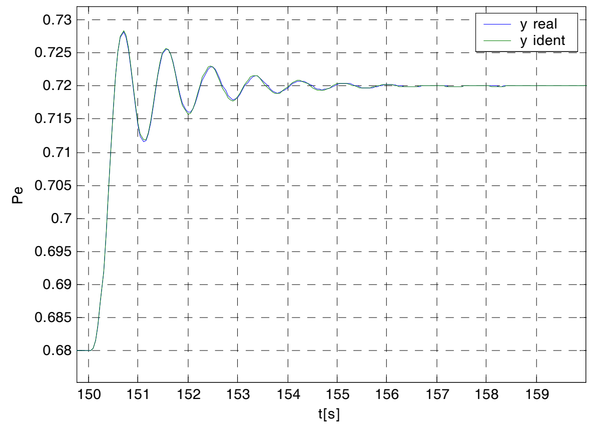

Fig.5 “Electromechanical” subsystem identification

Based on the transfer functions (23) and (24) the GPC and the PSRM control design has been carried out for each subsystem separately. In both cases the following control design parameters have been chosen:

$$sh = 1,\ ph = 20,\ ch = 1,\ \rho = 0{,}2 \qquad (25)$$

The resulting RST polynomials have been used for the control of terminal voltage v_t and the active power P_e to its desired values w_{vt} and w_{pe}, respectively, using the control scheme in Fig. 2. The following simulation experiments have been performed:

- decentralized GPC control of both subsystems
- decentralized PSRM control of both subsystems.

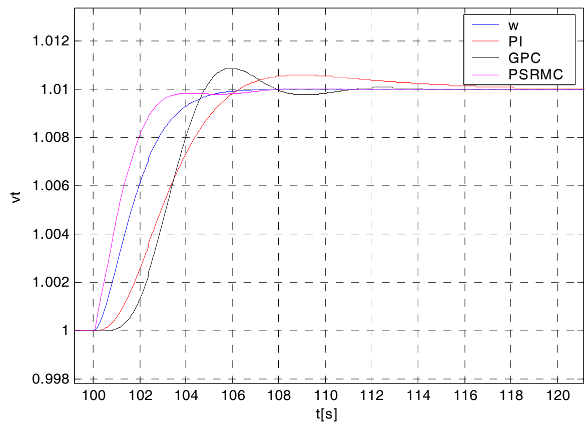

Fig.6 Time responses of the terminal voltage v_t and its desired value w_{vt}

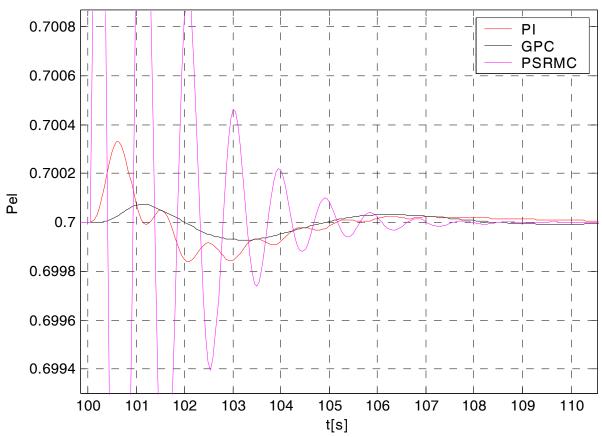

Fig.7 Time responses of the active power P_e

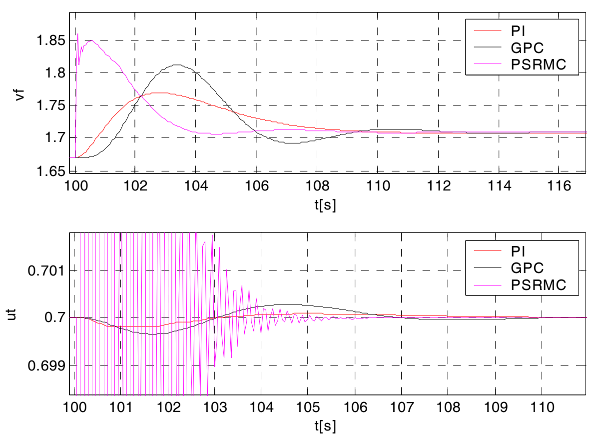

Fig.8 Time responses of the field voltage v_f and valve actuating signal u_t

Figure 6 shows the terminal voltage time responses to a step change of its desired value, the corresponding time responses of the active power are in Figure 7 and the field voltage and the valve actuating signal are in Figure 8.

Figure 9 shows the active power time responses to a step change of its desired value, the corresponding time responses of the terminal voltage are in Figure 10 and the valve actuating signal and the field voltage are in Figure 11.

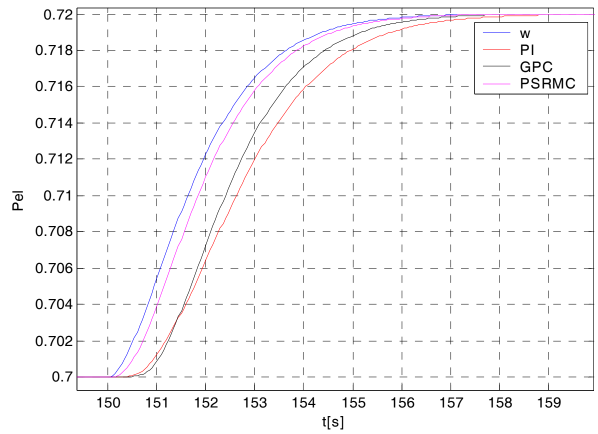

Fig.9 Time responses of the active power P_e and its desired value w_{Pe}

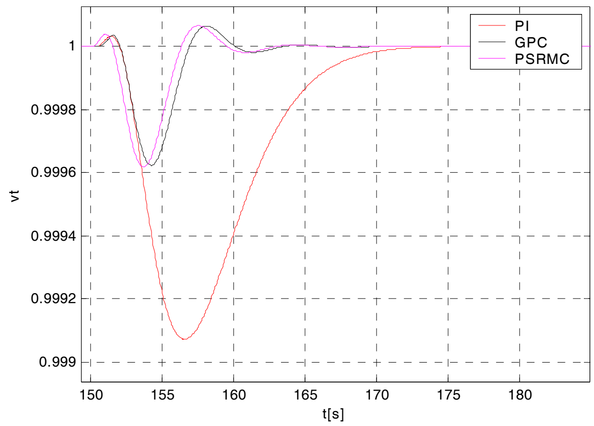

Fig.10 Time responses of the terminal voltage v_t

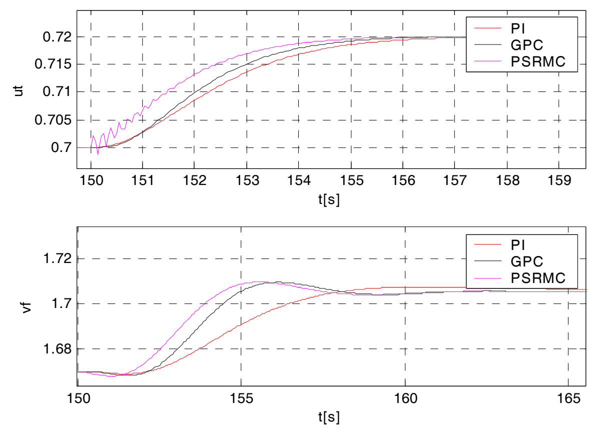

Fig.11 Time responses of the valve actuating signal u_t and the field voltage v_f

6 Conclusion

The decentralized predictive control and the partial state reference model control of the synchronous generator excitation and turbine have been proposed in this paper.

The terminal voltage time response after the step change of its desired value (Fig.6) using GPC is more oscillatory comparing to the PI control, but it faster settles on the desired value and the corresponding active power time response (Fig.7) is more damped. The PSRM control results in better tracking of the terminal voltage desired value, but the corresponding active power time response is much more oscillatory as those obtained using the PI or GPC controller.

In the active power control the PSRM ensures the best tracking (Fig. 9) and the terminal voltage control is also satisfactory (Fig. 10).

It can be concluded that for the "voltage" subsystem the GPC control and for the "electromechanical" subsystem the PSRM control are suited. The proposed decentralized GPC and PSRMC controls are able to ensure the desired terminal voltage control performances as well as the effective damping of the active power transient processes without the power system stabilizer.

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Appendix no. 1 – Symbols and abbreviations

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

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

i_d, i_q - currents flowing in the fictitious d- and q-axis armature coils

e_q - steady-state emf induced in the fictitious q-axis armature coil proportional to the field winding self-flux linkages

e'_d - transient emf induced in the fictitious 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 fictitious q-axis armature coil proportional to the field winding flux linkages

e''_d - subtransient emf induced in the fictitious d-axis armature coil proportional to the total q-axis rotor flux linkages

e''_q - subtransient emf induced in the fictitious q-axis armature coil proportional to the total d-axis rotor flux linkages

x_d, x'_d, x''_d - total d-axis synchronous, transient and subtransient reactance between (and including) the generator and the infinite busbar subtransient reactance between (and including) the

x_q, x'_q, x''_q - total q-axis synchronous, transient and generator and the infinite busbar

H.P. - turbine high pressure stage

I.P. - turbine intermediate pressure stage

L.P. - turbine low pressure stage

RH - reheater

Appendix no. 2 - Parameters of the synchronous generator

$T_{d0} = 7{,}7$	$x_d = 1{,}99$	$x_q = 1{,}82$
$T_{d2} = 0{,}04$	$x^{\mathsf{I}}_d = 0{,}267$	$x^{\mathsf{II}}_q = 0{,}204$
$T_{q2} = 0{,}23$	$x^{\mathsf{II}}_d = 0{,}13$	$x_t = 0{,}14$
$T_j = 0{,}0315$		$x_l = 0{,}14$