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Improvement the work effectivenes of static var compensators by using of two-input adaptive controllers

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Abstract - **In the paper is suggested a two-input adaptive controller for control of static var compensator (SVC). The controlling system of adaptive controller is identifying in real time of the basis for estimated parameters and variables of identification model and after that controlling signal is created for the compensator. As result of this controlling is improving vastly damping of power system like all performances as in transient processes as in steady state mode are improved.**

I. INTRODUCTION

In modern power systems due increscent of sensitivities to power quality a high requirements is demanded. Power system oscillations, locals and inter-areas, voltages sags and swells, voltage spikes, and voltage harmonics are reflect negative over consumers. For efficient and reliable operation of power systems, the control of voltage and reactive power is very important. By adequate control of these parameters is increased reliability and effectiveness of power supplying at that the system could reach easy to maximal boarder loading.

The rapid development of power electronics allows growths of flexible alternate current transmission systems (FACTS). The main function of these systems like all is improvement of power flow of transmission lines [1].

Introduction of shunt compensation is using for improvement of naturally electrical characteristics of transmission line, for voltage control of transmission lines and for increase of power flow in steady state mode. These compensators are characterized with fast response, wide working range and high reliability. They mainly represents shunt connected static controlled generator or absorber which is adjusted to exchange capacitive or inductive current so as to maintain or regulate parameters of power systems in determined limits.

One of the best methods for control of SVC is adaptive methods. In the paper is suggested two-input adaptive controller, using optimal singular adaptive (OSA) observer for identification of controlling system [2], [3]. A two-node power system is investigated and its mathematical model is created like different transient processes are simulated.

II. INVESTIGATED SYSTEM

The investigated system "Fig. 1" is consisted from synchronous generator (SG) together with its automatic regulators for speed and voltage, static var compensator (SVC), transmission lines with resistances ZL1 and ZL2 and static active-inductive loads ZC1 and ZC2.

The control of thyristors is performing by two-input adaptive controller which creates proportional signal for inductor conductivity. This signal is transforms to controlling thyristors signal α.

The thyristors controlled reactor "Fig. 2" controlling continuously reactive energy by magnitude control of current through reactor which is performing by firing angle of thyristors (Th_1 and Th_2). In this way is regulating inductivity of the reactor L which is shunt connected to fixed capacitor C. The firing angle can alternate from 90º to 180º according to compensator's voltage as could be changed in one half-period from main frequency [4], [5]. In this manner is performing rapid and smooth regulation of supplied or absorbed energy to/from power system.

III. MATHEMATICAL MODEL OF INVESTEGATED SYSTEM

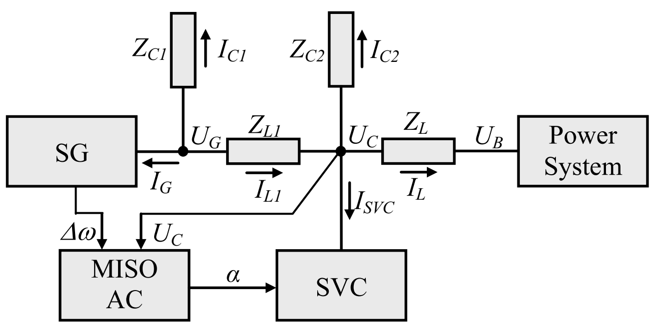

Fig. 1. Investigated system diagram

A. Synchronous generator

Equations of the generator are written of own coordinate system, which is fixed for its rotor. In this manner a variable coefficients are ignored [6] ÷ [8].

Equations of the other elements (static loads, lines, SVC) are written in synchronous rotating coordinate system. At creation of equations for connections the current equations of generator are transformed into d, q, 0 axes.

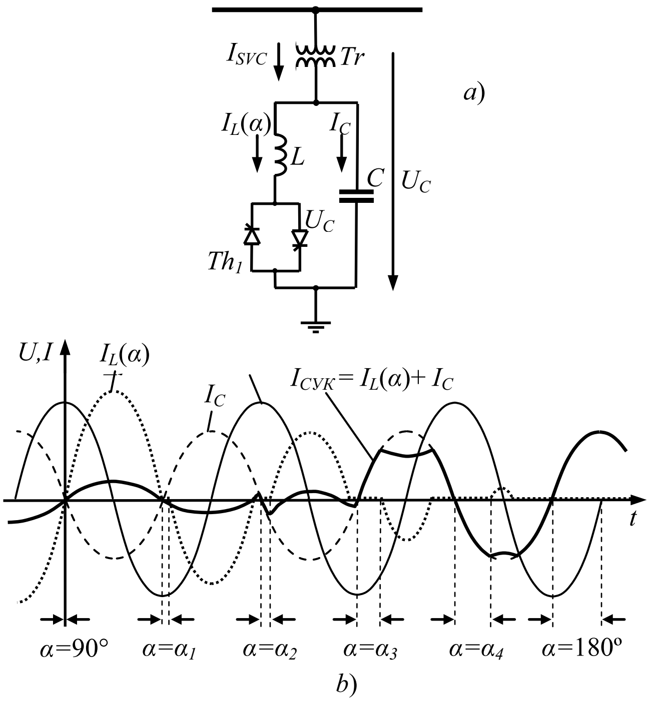

Fig. 2. Basic diagram of SVC (*a*) and specific forms of currents and voltages according to controlling angle *α* (*b*)

The synchronous generator is modeled by its complete model in the d, q, 0 frame is used, written in Cauchy form:

$$\frac{d}{dt}\begin{bmatrix} I_s \\ I_r \end{bmatrix} = \begin{bmatrix} H_s \\ H_r \end{bmatrix} + \begin{bmatrix} B_{ss} & B_{sr} \\ B_{rs} & B_{rr} \end{bmatrix} . \begin{bmatrix} U_s \\ u_f \end{bmatrix};$$
$$\frac{d}{dt}\omega_k = \frac{1}{T_m}\left(T_T - T_{SG}\right); \qquad (1)$$

where subscript s refers to the stator parameters and variables, and subscript r - rotor; the elements of matrices and vectors H and B are in function of the stator and rotor resistance and inductive impedance and the rotor angular speed (axes d, q, 0) - ω_k; T_T - turbine torque; T_G - the generator electromagnetic torque; T_m - the turbine and generator mechanical time constant; u_f - field voltage; generator parameters in p.u.:

$$I_G = I_s = \left[i_d, i_q\right]^t; \quad I_r = \left[i_f, i_g, i_h\right]^t; \quad U_G = U_s = \left[u_d, u_q\right]^t$$

Since the equations of power system are written in axes d, q, 0, which are rotating synchronous, the stator matrix and vectors are transformed in same coordinate system with the help of next expressions:

$$B_{ss}^t = T_{tb} B_{ss}^b \;; H_s^t = T_{tb} H_s^b \;; I_s^t = T_{tb} I_s^b$$

$$T_{tb} = \begin{bmatrix} \cos\delta_{tb}; & \sin\delta_{tb} \\ -\sin\delta_{tb}; & \cos\delta_{ij} \end{bmatrix}$$

$$\delta_{tb} = \theta_{kt} - \theta_{kb} = \int_0^t \left(\omega_{kt} - \omega_{kb}\right) dt \qquad (2)$$

B. Static active-inductive load

$$\frac{d}{dt}\boldsymbol{I}_{Ci} = \boldsymbol{H}_{Ci} + \boldsymbol{B}_{Ci} . \boldsymbol{U}_{Ci}, \quad i = \overline{1,2} \qquad (3)$$

where: the elements of vector H_{Ci} and matrix B_{Ci} are functions of load parameters;

C. Transmission line

$$\frac{d}{dt} I_{L2} = H_{L2} + B_{L2} . \left(U_C - U_B\right) \qquad (4)$$

where: the elements of vector H_{L2} and matrix B_{L2} are functions of transmission line parameters; U_B – voltage vector of infinity buses.

D. Reactor from SVC

$$\frac{d}{dt} I_L = H_L + B_L . U \qquad (5)$$

where: the elements of vector H_L and matrix B_L are functions of transmission line parameters.

E. Equations of connection

The compensator voltage U_C represents a condenser voltage (condenser C from SVC) and is calculating by next expression:

$$\frac{d}{dt} U_C = A_C \cdot I_C + U_C \qquad (6)$$

$$I_C = -\left(I_L + I_{L2} + I_{L1} - I\right) \qquad (7)$$

where: elements from matrix A_C are functions from condenser parameters.

The generator voltage U_G is calculating from first Kirhoff's law in differential form for generator connection node.

$$\frac{d}{dt} I_G + \frac{d}{dt} I_{C1} + \frac{d}{dt} I_{L1} = 0 \qquad (8)$$

The expression for generator voltage is obtained after replacement current derivatives with their right parts:

$$U_G = -\frac{H_{C1} + H_{L1} + H_G - B_{L1} . U_C}{B_{C1} + B_{L1} + B_G} \qquad (9)$$

F. Control of reactor from SVC

The basic function of controller is, that in real time the controls object can be continuously estimate by linear model of low order and create additional control signal. In investigated system is used two-input optimal singular adaptive (OSA) observer (MISO - multy-input, single output). On the observer inputs is feed discrete parts from compensator voltage U_{meas}, generator rotor angle deviation $\Delta\omega$ and output of resulting inductivity B_L.

On "Fig. 3" is presented block-diagram of controller for SVC. The diagram is consisting from classical PI - regulator, group for determination of desired characteristic's slope, two-input OSA observer, limiter for output signal. On the OSA observer inputs is feeding signals – voltage of SVC - U_C and generator rotor angle deviation - $\Delta\omega$. The OSA observer calculates estimation of parameters and variables of model and creating additional controlling signal B_L, which is adds to main signal from PI - regulator. In this way is improving the control in whole controlling range.

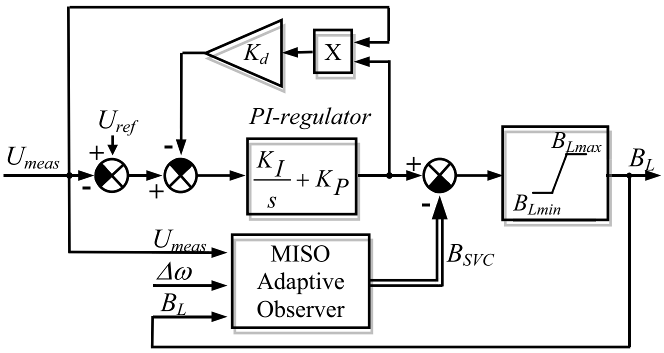

Fig. 3. Block-diagram of SVC controller

G. Adaptive control for the compensator

The observed system might be present by a following type of a linear model in the state space describing from following differential equations [9]:

$$x(k+1) = A.\,x(k) + B.\left[u(k) + z(k)\right] = A.\,x(k) + B.\,v(k),$$

$$x(0)=x_0, \qquad (10)$$

$$y(k) = c.x(k)\,,\; k = 0,\, 1,\, 2, \ldots \qquad (11)$$

where: x(k), x(k+1) are an unknown current state vector in two neighbour moments of discretization; x(0) is an unknown initial state vector; u(k) is an input signal; z(k) is a limited input sequence for identification; A, b and c are unknown matrices and vectors of the following type:

$$A = \begin{bmatrix} 0 & \vdots & 1_{n-1} \\ \cdots & \cdots & \cdots \\ & a^t & \end{bmatrix};\; a = \begin{bmatrix} a_1 \\ a_2 \\ \vdots \\ a_n \end{bmatrix};\; B = \left[b_1 \mid b_2 \mid \cdots \mid b_r\right];$$

$$c^t = \left[1, 0, 0, \ldots., 0\right];$$

$$b_i^t = \left[b_{i1}, b_{i2}, \ldots., b_{in}\right];\; 1 \le i \le r \qquad (12)$$

For the "(10)" and "(11)" describing the investigated system corresponds to following "input/output" difference equations:

$$H(z) = c^t.(z.I - A)^{-1}.B\,, \qquad (13)$$

As and following difference equation "input/output":

$$Y(z) = H(z).\,U(z)\,, \qquad (14)$$

Also if is read the next expression:

$$H(z) = L^{-1}.(z).Q(z)\,, \qquad (15)$$

Can be presented in following way:

$$L(z).Y(z) = Q(z).U(z)\,. \qquad (16)$$

The input/output data are shaped in following matrices and vectors.

The input/output data are shaped in following matrices and vectors.

$$\overline{Y} = \begin{bmatrix} y(0) \\ y(1) \\ \vdots \\ y(n-1) \end{bmatrix};\; \overline{\overline{Y}}_m = \begin{bmatrix} y(n) \\ y(n+1) \\ \vdots \\ y\left[n(2+r)-1\right] \end{bmatrix};$$

$$Y = \begin{bmatrix} y(0) & \cdots & y(n-2) & y(n-1) \\ y(1) & \cdots & y(n-1) & y(n) \\ y(2) & \cdots & y(n) & y(n+1) \\ \vdots & \vdots & \ddots & \vdots \\ y\left[n(1+r)-1\right] & \cdots & y\left[n(2+r)-3\right] & y\left[n(2+r)-2\right] \end{bmatrix}$$

$$U_{0i} = \begin{bmatrix} 0 & 0 & \cdots & 0 \\ u_i(0) & 0 & \cdots & 0 \\ u_i(1) & u_i(0) & \cdots & 0 \\ \vdots & \vdots & \ddots & \vdots \\ u_i(n-2) & u_i(n-3) & \cdots & u_i(0) \end{bmatrix};\; 1 \le i \le r\,;$$

$$U_i = \begin{bmatrix} u_i(n-1) & u_i(n-2) & \cdots & u_i(0) \\ u_i(n) & u_i(n-1) & \cdots & u_i(1) \\ u_i(n+1) & u_i(n) & \cdots & u_i(2) \\ \vdots & \vdots & \ddots & \vdots \\ u_i[n(2+r)-2] & u_i[n(2+r)-3] & \cdots & u_i[n(1+r)-1] \end{bmatrix}$$

where: Y - Hankel matrix; U_{0i}, U_i - Toeplitz matrices.

By linear system of algebraic equations:

$$\Omega_2 . \hat{\Theta} = \overline{\overline{Y}} \tag{17}$$

is calculating the estimations of n-dimension vectors $\hat{h}_1, \hat{h}_2, ..., \hat{h}_r$ and $\hat{a}$, where:

$$h_i^t = [h_{i1}, h_{i2}, ..., h_{in}], \ 1 \le i \le r,$$

$$\Omega_2 = [U_1 \mid U_2 \mid \cdots \mid U_r \mid Y];$$

$$\hat{\Theta}^t = \left[\hat{h}_1^t \mid \hat{h}_2^t \mid \cdots \mid \hat{h}_r^t \mid \hat{\alpha}^t\right].$$

The lower-triangle Toeplitz matrix with dimension nx(n-1) is shaped:

$$\overset{\Delta}{A} = \begin{bmatrix} 0 & 0 & \cdots & 0 & 0 \\ \hat{a}_n & 0 & \cdots & 0 & 0 \\ \hat{a}_{n-1} & \hat{a}_n & \cdots & 0 & 0 \\ \vdots & \vdots & \ddots & \vdots & \vdots \\ \hat{a}_2 & \hat{a}_3 & \cdots & \hat{a}_{n-1} & \hat{a}_n \end{bmatrix}.$$

The vector estimate b_i, $1 \le i \le r$ is calculated by linear system equations of following type:

$$\hat{b}_i = \hat{h}_i + \overset{\Delta}{A} . \hat{\bar{b}}_i; \tag{18}$$

where: $\hat{\bar{b}}_i = \left[\hat{b}_{i1}, \hat{b}_{i2}, ..., \hat{b}_{i,n-1}\right].$

The initial vector estimate $\hat{x}(0)$ is calculated by the optimal estimator of following type:

$$\hat{x}(0) = \overline{Y} - \Omega_3 . \hat{b}*; \tag{19}$$

where: $\Omega_3 = [U_{01} \mid U_{02} \mid \cdots \mid U_{0r}],$

$$\hat{b}^t * = \left[\hat{\bar{b}}_1^{\ t} \mid \hat{\bar{b}}_2^{\ t} \mid \cdots \mid \hat{\bar{b}}_r^{\ t}\right]$$

The current vector is estimated by the degenerate OSA observer of the form:

$$\hat{x}(k+1) = \hat{A}.\hat{x}(k+1) + \hat{B}.u(k);$$

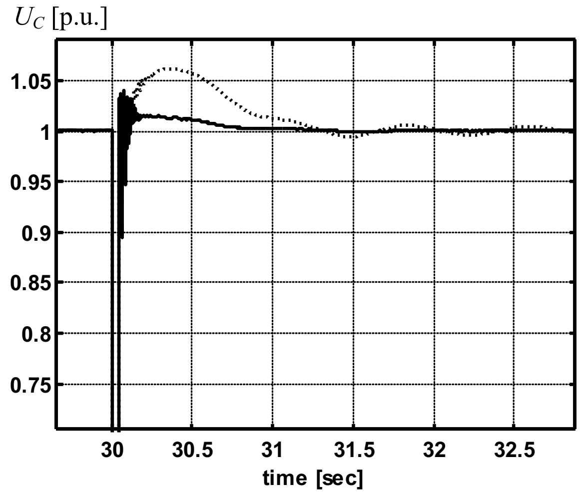

Fig. 4. Compensator voltage at three-phase earth fault

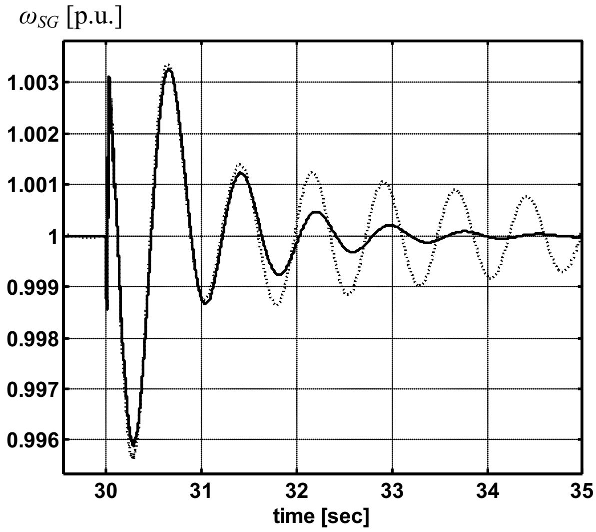

Fig. 5. Generator rotor speed at thee-phase earth fault

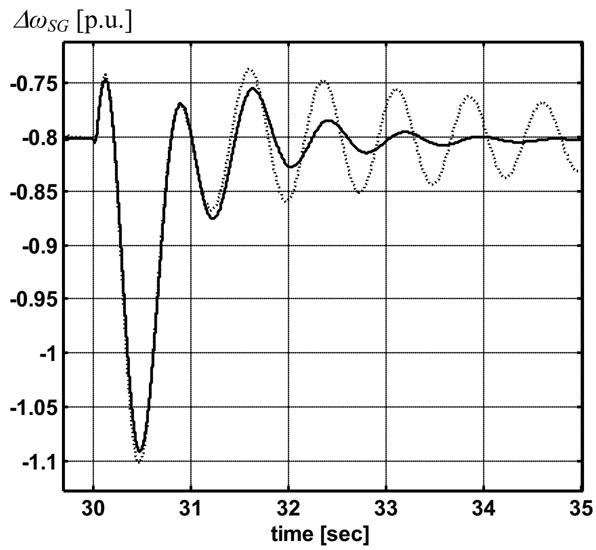

Fig. 6. Generator rotor angle deviation at three-phase fault

$$\hat{x}(0) = \hat{x}_0 \text{; } k=0, 1, 2, \ldots \qquad (20)$$

The investigations have shown that controlling system can be identified with the help of model from second order i.e. n = 2

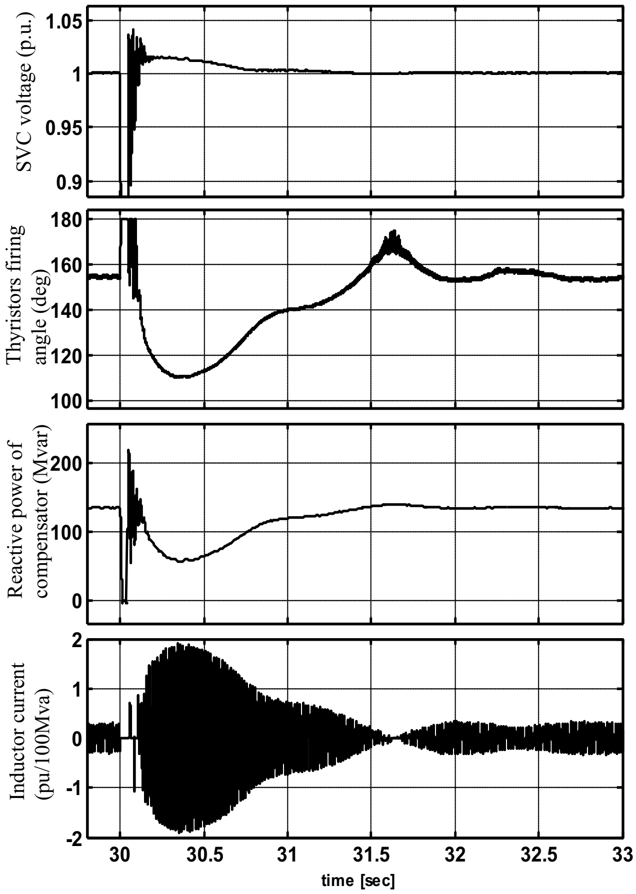

Fig. 7. Basic parameters of SVC

$$B_{SVC}(p) = -\hat{a}_1 \cdot \hat{x}_1(p) - \hat{a}_2 \cdot \hat{x}_2(p) \qquad (21)$$

where: p=k, k+1,…, k + n.

After determination of regulating signal B_{SVC} follow transformation of specific values of B_{SVC} into values of firing angle α for thyristors in degrees. This transformation is performed by next expression:

$$B_{Lpu} = \left(2 - 2\alpha/\pi + \sin(2\alpha)/\pi\right) B_{Lnom} \qquad (22)$$

where: B_{Lpu} - values of B_{SVC} converted into real system in per units (p.u.); B_{Lnom} – nominal value of B_{SVC}.

H. Control of thyristors

The thyristors model is simulated as series connecting resistor R_{ON} and inductor L_{ON}, together with direct current voltage source U_f. The thyristors is switching by switch K. The switching element is controlling by logical signal according to voltage anode-kathode, current through thyristors and gate signal [10].

IV. SIMULATION STUDY

To prove of rightness and effectiveness of investigation system work a computer model of suggested system was created in MATLAB space. Different disturbances causing transient processes have been simulated. The simulated transient processes are: three-phase earth short circuit and it's disconnection from circuit breaker, connection/disconnection of powerful static active-inductive load. The obtained simulations are compared with system of identical parameters in which including compensator from fixed capacitor and reactor. The parameters of that fixed compensator are same as investigated compensator in steady state mode. The following figures show some typical parameters of investigated power system. On the figures: SVC with adaptive controller-solid line, fixed capacitor and reactor with same parameters - doted line. First transient process which has been simulated is three-phase earth fault at time 30sec and it's disconnection from circuit breakers for time 30.03sec.

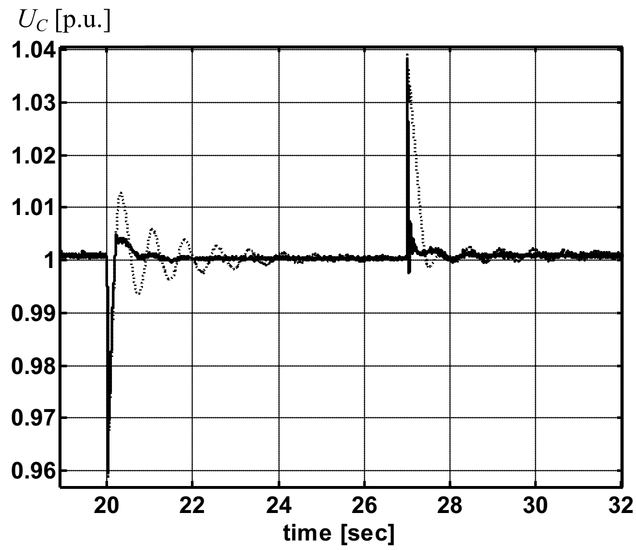

Fig. 8. Compensator voltage at connect/disconnect of static RL-load

On "Figures 8÷10" is shown characteristics of studied system at connect (25sec) and disconnect (27sec) of powerful static active-inductive (RL) load.

V. CONCLUSION

With the help of suggested mathematical model is investigated the work of two-node power system including static var compensator (SVC). The control of shunt compensator is performs from PI-regulator with additional feedback, realizing of optimal singular adaptive observer. The performed simulations and comparison of received results shows work effectiveness of adaptive control improving all parameters of transient processes: - decrease of transient processes time, limitation of maximal deviation of operating parameters and decrease of process oscillation.

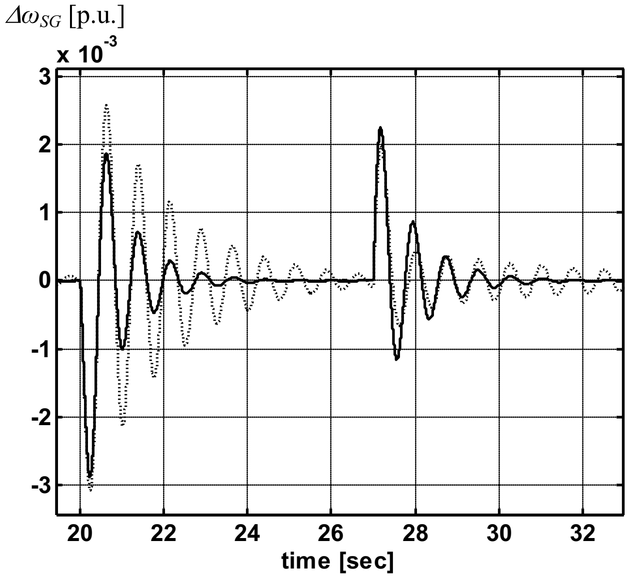

Fig. 9. Generator rotor speed deviation at connect/disconnect of static RL load

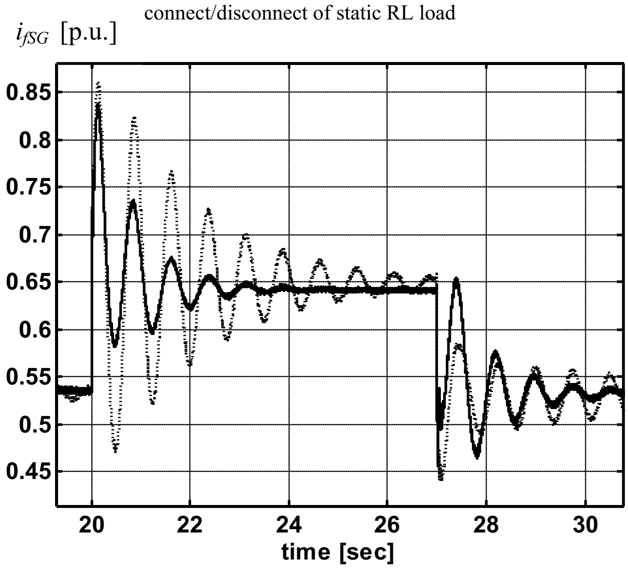

Fig. 10. Exiting current for generator at connect/disconnect of static RL load

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