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An Adaptive Control of Static Var Compensator on Power Systems

N.F.DJAGAROV Zh.G.GROZDEV M.B.BONEV G.D.GEORGIEV
Electrical Department
Technical University
1, Studentska str, Varna
BULGARIA

Abstract: The system means of compensating has been used for oscillation damping in power systems. In resent years the FACTS devices are extensively used. In the paper is suggested an adaptive SVC control using optimal singular observer. Like regulating the inductive part of L-C system device are improve the main indexes of transient processes at different oscillations in power systems.

Key words: FACT devices, SVC, adaptive control, optimal singular adaptive observer

1 Introduction

Power system oscillations can be damped using a wide variety of devices. Power system stabilizers nave been successfully applied to automatic voltage regulators and speed controllers [1,2,3,4]. Power system stabilizers design represents a formidable challenge since general techniques cannot be applied. Using of adaptive observers is optimal solution for this problem [5,6,7].

FACTs devices (static var compensators, thyristor controlled series capacitors, thyristor controlled phase angle regulator, etc.) have been suggested also [8,9,10]. FACT devices can be used to control the power flow and enhance system stability. The parameters in the transmission line, i.e. line impedance, terminal voltages, and voltage angle can be controlled by these devices. It is used for independent control of real and reactive power in transmission lines. Moreover, the FACTs can be used for voltage support and damping of electromechanical oscillations.

Advances in high power thyristor technology and electronics circuitry have prompted the development of controllable static var sources, often called var generators. Static Var Compensators or SVCs were to provide fast, continuous or step like voltage control for large, fluctuating industrial loads, such as electric arc furnace. They are primarily used to rapidly control voltage at a weak point in power transmission and large industrial networks. A controller regulating the ac system voltage with respect to a reference voltage with some droop characteristic varies the SVC current and reactive power. The droop value is selected according to the desired sharing of reactive power generation among various sources, as well as other needs of the system such as providing for an adequate margin for transient voltage stability.

The capacitor banks in a SVC are rated for full capacitive output, whereas the reactor banks are rated for full inductive output; the coupling transformer and electronic circuit could be dimensioned to withstand the sum of the maximum capacitive and inductive output. It should be emphasized that the SVC capacity for compensation is solely determined by the size of its reactive components implying significant physical size and maintenance.

A SVC can control only one of the three principal parameters, voltage, phase angle, or impedance, which determines the power flow in ac power systems [11]. Therefore, it does not posses the capability to independently control active and reactive power in the transmission line.

Fixed or mechanically switched capacitors and reactors together with synchronous compensator have long been employed to increase steady state power transmission by controlling the voltage profile along the transmission lines. It has been demonstrated that both the transient and steady state stability (i.e., first swing stability and damping) of a power system can be enhanced if the compensation device can react quickly by using solid-state, thyristor switches and electronic control.

The function of SVC is to minimize the magnitude and duration of system disturbances by regulating terminal voltage and damping power oscillations. To accomplish this, an control is employed that derives the necessary reference signals for the internal control of SVC to produce the desired reactive power output for the ac system to counteract the disturbances.

The main problem is choosing of series device for damping which should performed normal work during all different states and power disturbance. The best choice for the problem is an adaptive controller. During the past years an adaptive neuro-fuzzy controllers are used, but their main problem remains - the time for tuning-training is too long. In the paper is present a direct classical method for identification by using an optimal singular adaptive observer (OSA), which calculate direct the linear algebraic system equations [18].

One of the important advantages of OSA estimators is that their true poles may not coincide with the desired pole and that it doesn't interfere with their accuracy. Neither does the fact that the object being observed and identified may be instable. Another big advantage is avoiding synthesis of system with pole assignment, which is compulsory with Luenberger's observers. Except for that the OSA observer is robust to that coincidence.

By using the OSA observers has been created a family of adaptive OSA stabilizers, which effects on the automatic voltage regulator (AVR) and on the governor of the synchronous generator [13, 14, 15].

2 Power system model

Figure 1 show the investigated system which included synchronous generator connected to infinity bus through line produced by equivalent resistances $Z_l = r_l + jl_l$. On the generator terminal is connected alternate 3-

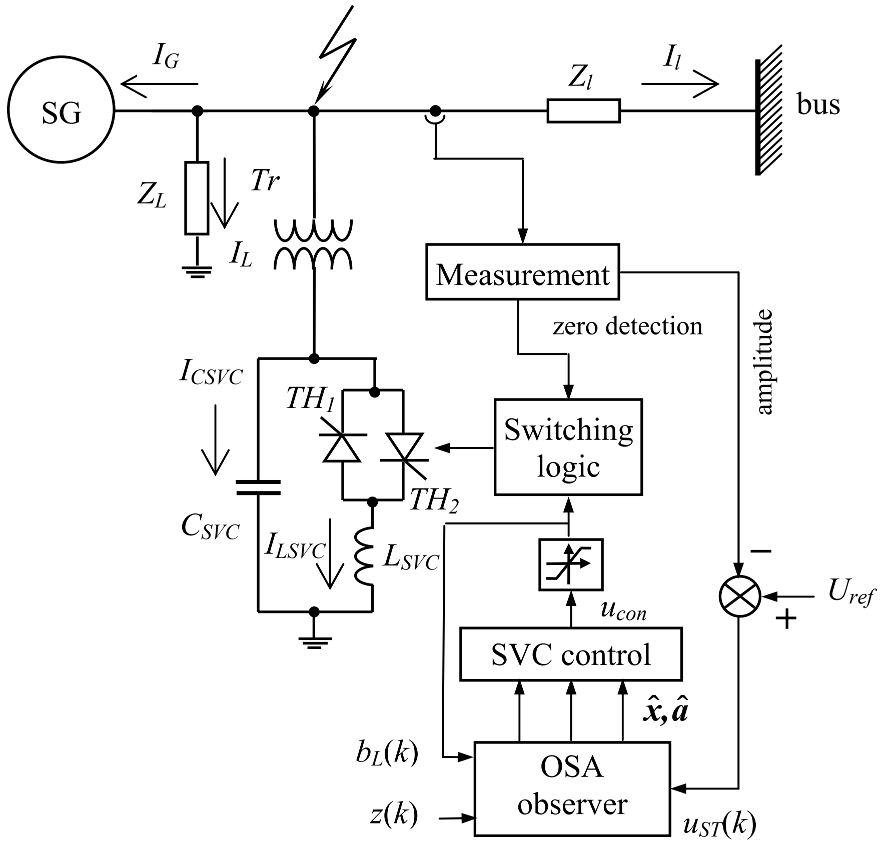

Fig.1. Investigation power system

phase symmetrical load $Z_L = r_L + jl_L$, by means is simulated the different oscillations - short cut, connecting/disconnecting of static load.

The assumed positive current directions for corresponding elements are shown by arrows.

SVC is present like damping shunt inductive *LC* device. The reactor conductivity is regulated by the adaptive controller, which control firing angle (α) for thyristors TH_1 and TH_2.

The adaptive controller is consisting of Optimal Singular Adaptive (OSA) observer, SVC control and control signal restrictor. On the input of observer is feed a stabilization signal (like terminal voltage, rotor speed, load angle, etc.). The estimations of variables and parameters on the model $\hat{\boldsymbol{x}},\hat{\boldsymbol{a}}$ are calculated by OSA observer. On this basis SVC control block create the control signal, which is transformed in firing angle for thyristors α by definite method.

2.1 Synchronous generator model

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

Equations of the other elements (static load, line, 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.

The synchronous generator is modeled by its complete model in the *d,q,0* frame is used, written in Cauchy form [16]:

$$\frac{d}{dt}\begin{bmatrix}\boldsymbol{I}_s\\ \boldsymbol{I}_r\end{bmatrix}=\begin{bmatrix}\boldsymbol{H}_s\\ \boldsymbol{H}_r\end{bmatrix}+\begin{bmatrix}\boldsymbol{B}_{ss} & \boldsymbol{B}_{sr}\\ \boldsymbol{B}_{rs} & \boldsymbol{B}_{rr}\end{bmatrix}.\begin{bmatrix}\boldsymbol{U}_s\\ u_f\end{bmatrix};$$
$$\frac{d}{dt}\omega_k=\frac{1}{T_m}\left(T_T-T_G\right); \qquad (1)$$

where subscript *s* refers to the stator parameters and variables, and subscript *r* - rotor; $\boldsymbol{I}_s=\left[i_d,i_q\right]^t$; $\boldsymbol{I}_r=\left[i_f,i_g,i_h\right]^t$; $\boldsymbol{U}_s=\left[u_d,u_q\right]^t$;the elements of matrices and vectors $\boldsymbol{H}$ and $\boldsymbol{B}$ are 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; $T_G = x_{ad}.\left(i_d+i_f+i_g\right).i_q - x_{aq}.\left(i_q+i_h\right).i_d$ - the generator electromagnetic torque; T_m - the turbine and generator mechanical time constant; u_f - field voltage; generator parameters in p.u.:

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:

$$\boldsymbol{B}^t_{ss}=\boldsymbol{T}_{tb}\boldsymbol{B}^b_{ss};\ \boldsymbol{H}^t_s=\boldsymbol{T}_{tb}\boldsymbol{H}^b_s;\ \boldsymbol{I}^t_s=\boldsymbol{T}_{tb}\boldsymbol{I}^b_s;$$
$$\boldsymbol{T}_{tb}=\begin{bmatrix}\cos\delta_{tb}; & \sin\delta_{tb}\\ -\sin\delta_{tb}; & \cos\delta_{ij}\end{bmatrix}; \qquad (2)$$
$$\delta_{tb}=\theta_{kt}-\theta_{kb}=\int_0^t\left(\omega_{kt}-\omega_{kb}\right)dt$$

2.2 Static RL load model

$$\frac{d}{dt}\boldsymbol{I}_L=\boldsymbol{H}_L+\boldsymbol{B}_L.\boldsymbol{U}_t \qquad (3)$$

Where: the elements of vector $\boldsymbol{H}_L$ and matrix $\boldsymbol{B}_L$ are functions of load parameters; $\boldsymbol{U}_t$ - generator terminal voltage vector.

2.3 Reactor model for SVC

$$\frac{d}{dt}\boldsymbol{I}_{LSVC}=\boldsymbol{H}_{LSVC}+\boldsymbol{B}_{LSVC}.\boldsymbol{U}_t \qquad (4)$$

Where: the elements of $\boldsymbol{H}_{LSVC}$ and matrix $\boldsymbol{B}_{LSVC}$ are function of load parameter.

2.4 Condenser model for SVC

$$\frac{d}{dt}\boldsymbol{U}_t=\boldsymbol{A}_{CSVC}\cdot\boldsymbol{I}_{CSVC}+\boldsymbol{U}_t \qquad (5)$$

Where: the elements of matrix $\boldsymbol{A}_{CSVC}$ are function of condenser parameter;
$\boldsymbol{I}_{CSVC}=-\left(\boldsymbol{I}_G+\boldsymbol{I}_L+\boldsymbol{I}_{LSVC}+\boldsymbol{I}_l\right)$.

3 SVC control

3.1. Control signal creating

The basic idea of stabilizer is, that the control object can be continuously estimate by linear model of low order and create additional control signal. The investigations present [13] that for the stabilizer the minimal models of 2[nd] order might be used, which provides a great

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speed and sufficient correctness. A single-input single-output (SISO) adaptive observer is being used in investigation system.

At fig.3 is seen that for OSA observer inputs discrete parts of input $\boldsymbol{u_{ST}}(\boldsymbol{k})$ and output $\boldsymbol{B_L}(\boldsymbol{k})$ for resulting inductivity are fed, also a signal $z(k)$, which represent a limited input sequence for identification is fed too.

The observed system might be present by a following type of a linear model in the state space:

$$\boldsymbol{x}(k+1) = \boldsymbol{A}.\boldsymbol{x}(k) + \boldsymbol{b}.[\boldsymbol{u_{ST}}(k) + z(k)] = \\ = \boldsymbol{A}.\boldsymbol{x}(k) + \boldsymbol{b}.\boldsymbol{v}(k),$$

$$\boldsymbol{x}(0)=\boldsymbol{x}_0, \tag{6}$$

$$\boldsymbol{y}(k) = \boldsymbol{c}^t.\boldsymbol{x}(k), \qquad k=0,1,2,\ldots; \tag{7}$$

Where: $\boldsymbol{x}(k)$ is an unknown current state vector; $\boldsymbol{x}(0)$ is an unknown initial state vector; $u_{ST}(k)$ is an input signal; $z(k)$ is a limited input sequence for identification;

A, b and ***c*** are unknown matrix and vectors of the following type:

$$\boldsymbol{A} = \begin{bmatrix} \boldsymbol{0} & \boldsymbol{1} \\ \hline & \boldsymbol{a}^t & \end{bmatrix} = \begin{bmatrix} 0 & 1 \\ a_1 & a_2 \end{bmatrix}; \quad \boldsymbol{b} = \begin{bmatrix} b_1 \\ b_2 \end{bmatrix};$$

$$\boldsymbol{c} = \begin{bmatrix} 1 \\ 0 \end{bmatrix}. \tag{8}$$

The input/output data are shaped on the Hankel and Toeplitz matrices [12]:

$$\boldsymbol{Y_1} = \begin{bmatrix} y(0) \\ y(1) \end{bmatrix}; \quad \boldsymbol{Y_2} = \begin{bmatrix} y(2) \\ y(3) \end{bmatrix}; \quad \boldsymbol{Y_3} = \begin{bmatrix} y(4) \\ y(5) \end{bmatrix};$$

$$\hat{\boldsymbol{\eta}}(\boldsymbol{0}) = \begin{bmatrix} \eta_1(0) \\ \eta_2(0) \end{bmatrix}; \tag{9}$$

$$\boldsymbol{U_{11}} = \begin{bmatrix} 0 & 0 \\ u(0) & 0 \end{bmatrix}; \ \boldsymbol{U_{21}} = \begin{bmatrix} u(1) & u(0) \\ u(2) & u(1) \end{bmatrix};$$

$$\boldsymbol{U_{31}} = \begin{bmatrix} u(3) & u(2) \\ u(4) & u(3) \end{bmatrix}$$

The vector estimation $\hat{\boldsymbol{h}}$ is calculated through the following vector-matrix expression:

$$\hat{\boldsymbol{h}} = -\boldsymbol{N_2^{-1}} \cdot \boldsymbol{Y_{32}} \cdot \boldsymbol{Y_{22}^{-1}} \cdot \boldsymbol{Y_2} + \boldsymbol{N_2^{-1}} \cdot \boldsymbol{Y_3} \tag{10}$$

където: $\boldsymbol{N_2} = \boldsymbol{U_{31}} - \boldsymbol{Y_{32}} \cdot \boldsymbol{Y_{22}^{-1}} \cdot \boldsymbol{U_{21}}$.

The vector $\hat{\boldsymbol{a}}$ is calculated through the following expression:

$$\hat{\boldsymbol{a}} = \left(\boldsymbol{Y_{22}^{-1}} + \boldsymbol{Y_{22}^{-1}} \cdot \boldsymbol{U_{21}} \cdot \boldsymbol{N_2^{-1}} \cdot \boldsymbol{Y_{32}} \cdot \boldsymbol{Y_{22}^{-1}}\right)\boldsymbol{Y_2} - \\ - \boldsymbol{Y_{22}^{-1}} \cdot \boldsymbol{U_{21}} \cdot \boldsymbol{N_2^{-1}} \cdot \boldsymbol{Y_3} \ . \tag{11}$$

The vector estimate is calculated $\hat{\boldsymbol{\eta}}^t(\boldsymbol{0})$:

$$\hat{\boldsymbol{\eta}}^t(\boldsymbol{0}) = \boldsymbol{Y_1} + \boldsymbol{U_{11}} \cdot \boldsymbol{N_2^{-1}} \cdot \boldsymbol{Y_{32}} \cdot \boldsymbol{Y_{22}^{-1}} \cdot \boldsymbol{Y_2} - \boldsymbol{U_{11}} \cdot \boldsymbol{N_2^{-1}} \cdot \boldsymbol{Y_3} \cdot) \tag{12}$$

The vector estimate $\hat{\boldsymbol{b}}$ is calculated by the linear system equations of following type:

$$\boldsymbol{T}.\hat{\boldsymbol{b}} = \hat{\boldsymbol{h}}, \tag{13}$$

Where: $\boldsymbol{T} = \begin{bmatrix} 1 & 0 \\ -\hat{a}_2 & 1 \end{bmatrix}$ is Toeplitz matrix.

The initial vector estimate is calculated by the optimal estimator of following type:

$$\hat{\boldsymbol{x}}(\boldsymbol{0}) = \hat{\boldsymbol{\eta}}(\boldsymbol{0}) + \boldsymbol{U_{11}} \cdot \left(\hat{\boldsymbol{h}} - \hat{\boldsymbol{b}}\right) \tag{14}$$

The current vector is estimated by the degenerate OSA observer:

$$\hat{\boldsymbol{x}}(\boldsymbol{k+1}) = \hat{\boldsymbol{A}}.\hat{\boldsymbol{x}}(\boldsymbol{k}) + \hat{\boldsymbol{b}}.\boldsymbol{u}(\boldsymbol{k}), \quad \hat{\boldsymbol{x}}(\boldsymbol{0}) = \boldsymbol{x_0},$$

$$k=0,\ 1,\ 2,\ \ldots, \tag{15}$$

The control signal will calculated by estimate state vector and model parameters [12]:

$$b_L(p) = -\hat{\boldsymbol{a}}^t(p).\hat{\boldsymbol{x}}(p) = -\hat{a}_1.\hat{x}_1 - -\hat{a}_2.\hat{x}_2 \tag{16}$$

Where: $p=k,k+1,\ldots,k+n$.

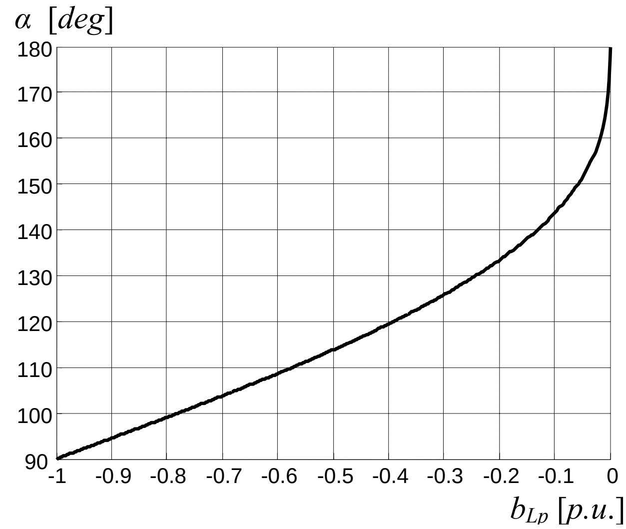

Fig.2. Used function for thyristor control

After the control signal b_L has been determined ought to transformation of specific values for b_L into real values for thyristor firing angle α in degrees.

$$b_{Lp} = [2 - 2\alpha/\pi + sin(2\alpha)/\pi]b_{L.nom} \tag{17}$$

Where: b_{Lp} are values of b_L set to real system in p.u.; $b_{L.nom}$ – nominal value of b_L.

Figure 2 shows the modification of firing angle α in dependence of b_{Lp}.

3.2 Thyristor control

The thyristor model (fig.3) [17] is simulated as a resistor Ron, an inductor Lon, and a DC voltage source representing the forward voltage Vf, connected in series with a switch. The switch is controlled by a logical signal depending on the voltage Vak, the current Iak,

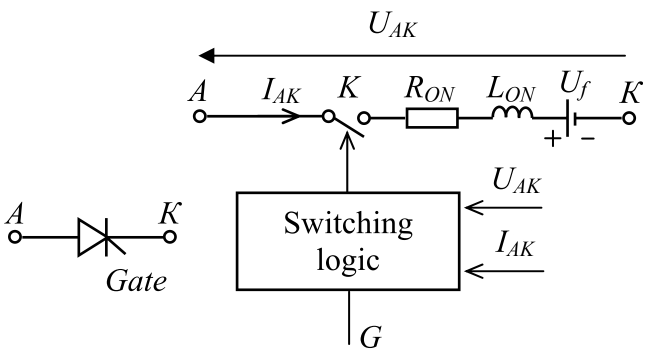

Fig.3. Thyristor model.

and the gate signal g. The Thyristor block also contains a series Rs-Cs snubber circuit that can be connected in parallel with the thyristor device.

4 Simulation study

Different disturbances causing transient processes have been simulated. The represent simulations are taken by three-phase ground

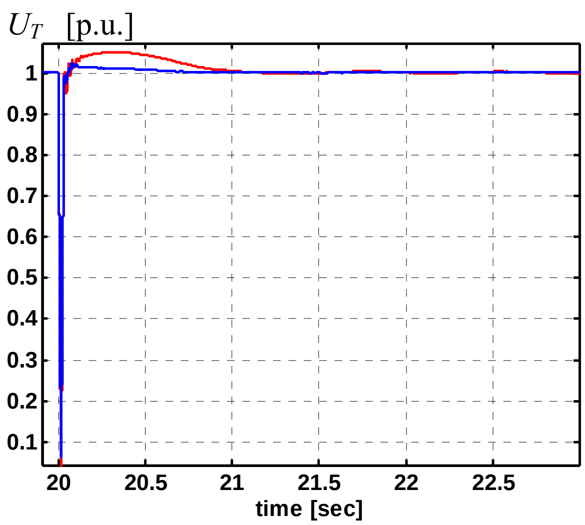

Fig.4. Generator terminal voltage.

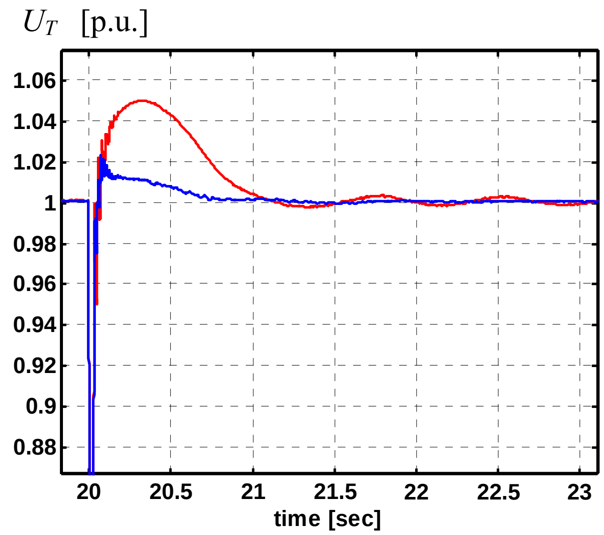

Fig.5. Generator terminal voltage.

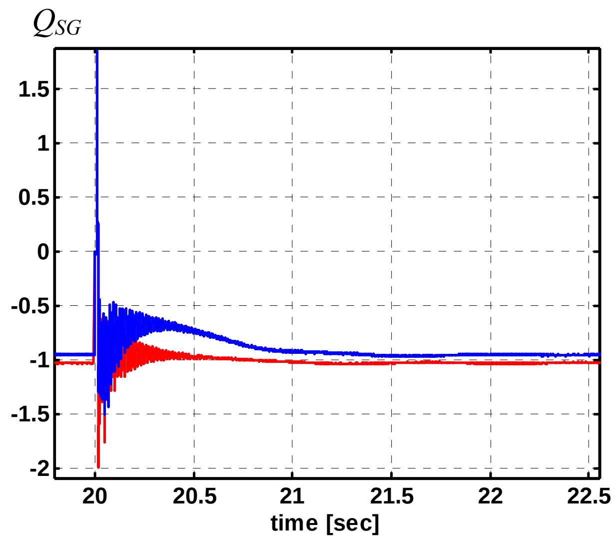

Fig.6. Generator reactive power.

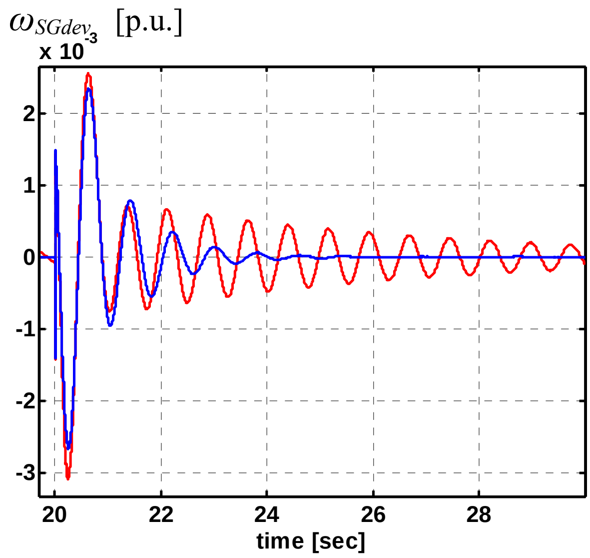

Fig.7. Generator rotor speed deviation.

short cut for time at 10*ms*, after that the protection is activate. The follow simulations are compared with same system, which include compensator from fixed condenser and reactor.

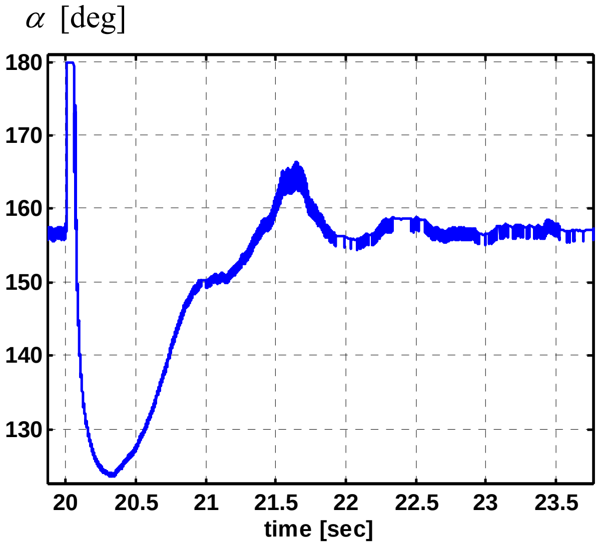

Fig.8 Firing angle for thyristor

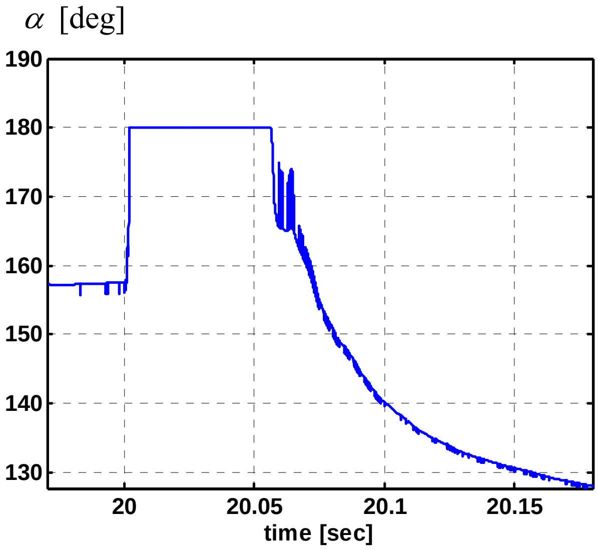

Fig.9 Firing angle for thyristor

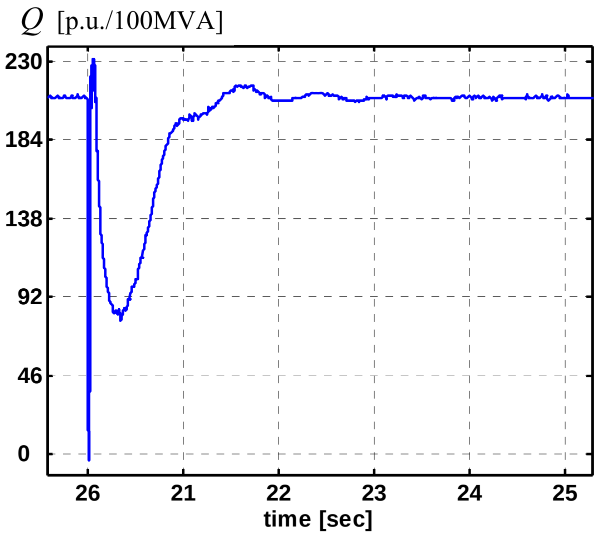

Fig.10 Reactive power of SVC

With blue lines on following figures are shown results when the OSA observer is active, with red lines – system with fixed capacitor and inductor.

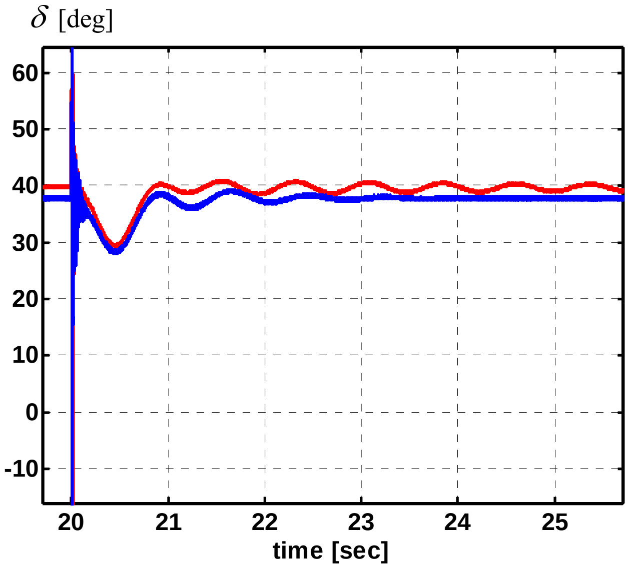

Fig.11 Generator load angle

5 Conclusion

Using the adaptive control of FACTS is optimal solution power flow control in power systems. Otherwise these devices can damping the oscillations and improve the quality of transient processes. The suggested adaptive control for SVC is simple therefore minimal computing devices are needed, which define very good damping properties. The obtained simulation studies prove its quality and perspectives for control and regulating of transient processes and improve power system stability.

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