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Adaptive Controller for Thyristor Controlled Series Capacitors

Abstract

At the last time the shunt and series compensators are used for damping on subsynchronous oscillations in power systems. It is very important the choice of control for this devices. This paper develops an adaptive control for series compensator, which uses an Optimal Singular Adaptive (OSA) observer for controlled object identification. The control signal is calculated by estimation of parameters and variables for identification model. It is suggested the mathematical model for the adaptive controller study. Different disturbances causing transient processes have been simulated. The present results proof the effectiveness of the suggested adaptive control.

INTRODUCTION

Reconstruction of power production market is performed by market principle which brings to problems about power flow controls and insurances of stability work for power system. Continuously augmentation of power energy consumptions is limited by barrier capacity of transmission networks. Because of these conditions in the recent years are developed and improved the FACTS technology to ensure flexible control of power flows in free market conditions.

Using of series reactive compensation can be highly effective at: controlling power flow in the lines; augmentation of barrier capability of lines; augmentation of static stability limits; improving of dynamic behavior of the power system.

Expect for power flow controlling the FACTS compensators are using for damping of subsynchronous oscillations in power system [1,2]. This control modulate very fast impedance of the transmission line like in this manner improves characteristics of the system. In [1] is used the residue method to the linearized power system equations to create a form for controller design. In [2] is used lead-lag damping controller from different order.

In the paper is suggested an adaptive controller which is using a additional stabilized signal added with the main control signal created from PI-controller.

I. MODEL OF THE INVESTIGATED POWER SYSTEM

On fig.1 is shown the example system model including equivalent generator with power 650 MVA and parameters of the power system gives in the appendix.

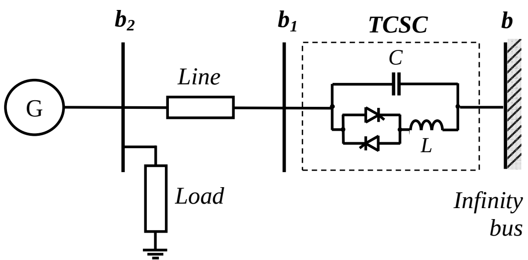

Figure 1. Investigated power system scheme

The model of the generator is written in Cauchy form in *d,q,0* frames, rotating synchronous with its rotor [3]:

$$\begin{aligned} &\frac{d}{dt}\boldsymbol{I_G} = \boldsymbol{A_G}.\boldsymbol{I_G} + \boldsymbol{B_G}.\boldsymbol{U_b} = \boldsymbol{H_G} + \boldsymbol{B_G}.\boldsymbol{U_{b2}} \\ &\frac{d}{dt}\omega_k = \frac{1}{\tau_m}\left(T_{PM} + T_G\right) \end{aligned} \tag{1}$$

where: the elements of matrices $\boldsymbol{A}$ and $\boldsymbol{B}$ are function of the stator and the rotor resistance and inductive impedance and a part of elements of matrices $\boldsymbol{A}$ are function of the rotor angular speed; τ_m – mechanical time constant; T_{PM} – primary motor torque; T_G – generator torque.

Equation of static RL load:

$$\frac{d}{dt}\boldsymbol{I_l} = \boldsymbol{A_l}.\boldsymbol{I_l} + \boldsymbol{B_l}.\boldsymbol{U_{b2}} = \boldsymbol{H_l} + \boldsymbol{B_l}.\boldsymbol{U_{b2}}\,. \tag{2}$$

where: the elements of matrices $\boldsymbol{A}$ and $\boldsymbol{B}$ are function of the load resistance and inductive impedance

The line voltage is calculated by:

$$\boldsymbol{U_L} = -\left(\boldsymbol{U_{b2}} + \boldsymbol{U_{TCSC}} + \boldsymbol{U_b}\right) \tag{3}$$

The equation of the line connected the compensator with infinity bus is written in synchronous system:

$$\frac{d}{dt}\boldsymbol{I_L} = \boldsymbol{H}_L + \boldsymbol{B_L}.\boldsymbol{U}_L\,. \tag{4}$$

A reactor model from the compensator:

$$\frac{d}{dt}\boldsymbol{I_{TCR}} = \boldsymbol{H}_{TCR} + \boldsymbol{B_{TCR}}.\boldsymbol{U_{TCSC}}\,. \tag{5}$$

where: the elements of matrices $\boldsymbol{H}$ and $\boldsymbol{B}$ are function of the reactor resistance and inductive impedance

A condenser model from the compensator:

$$\frac{d}{dt}\boldsymbol{U_{TCSC}} = \boldsymbol{A_{TCSC}}\cdot\boldsymbol{U_{TCSC}} + \boldsymbol{B_{TCSC}}\cdot\boldsymbol{I_{TCSC}}\,; \tag{6}$$

where: $\boldsymbol{U_{TCSC}} = \boldsymbol{U_b} - \boldsymbol{U_{b1}}$.

From the Kirchhoff's first low for node b_1:

$$\boldsymbol{I_{TCSC}} = \boldsymbol{I_{TCR}} - \boldsymbol{I_C} \tag{7}$$

The Kirchhoff's first low in differential form for busses b:

$$m_G\frac{d}{dt}\boldsymbol{I_G} + m_l\frac{d}{dt}\boldsymbol{I_l} + \frac{d}{dt}\boldsymbol{I_L} = 0\,; \tag{8}$$

where: m_G, m_l - are scale coefficients respectively of generator and load which are calculating like relation of full power into power of the element.

Replacing the derivatives with their right part to the respectively equations (1), (2), (4):

$$\begin{aligned} &m_G.\boldsymbol{H_G} + m_G.\boldsymbol{B_G}.\boldsymbol{U_{b2}} + m_l.\boldsymbol{H_l} + \\ &+ m_l.\boldsymbol{B_l}.\boldsymbol{U_{b2}} + \boldsymbol{H_L} + \boldsymbol{B_L}.\boldsymbol{U_L} = 0 \end{aligned} \tag{9}$$

Whence is calculating a voltage vector in the node, where are connected the generator and the load:

$$\boldsymbol{U_{b2}} = -\frac{m_G.\boldsymbol{H_G} + m_l.\boldsymbol{H_l} + \boldsymbol{H_L}}{m_G.\boldsymbol{B_G} + m_l.\boldsymbol{B_l} + \boldsymbol{B_L}}\,. \tag{10}$$

II. THYRISTOR-CONTROLLED SERIES CAPACITOR PERFORMANCE

Thyristor-controlled series capacitor mainly represents a capacitive reactanse compensator which consists of a series capacitor bank shunted by a Thyristor-controlled reactor in order to provide smoothly variable series capacitive reactance.

The equivalent impedance may be defined by using the following equation [7]

$$X_{TCSC} = -X_C\left[1-\frac{\lambda^2}{\lambda^2-1}\frac{\sigma+\sin\sigma}{\pi}+ \right.$$
$$\left.+\frac{4\lambda^2\cos^2(\sigma/2)}{\pi(\lambda^2-1)}\left(\lambda\tan\frac{\lambda.\sigma}{2}-\tan\frac{\sigma}{2}\right)\right] \tag{11}$$

where: $\sigma = 2(\pi-\alpha)$, $\lambda=\sqrt{-X_C/X_L}$

The operating modes are blocking mode, bypass mode, capacitive boost mode and inductive boost mode. They are characterized by so-called boost factor.

$$K_B = \frac{X_{TCSC}}{X_C} \tag{12}$$

At *blocking mode* the thyristor valve is not triggered and the thyristors are kept in nonconducting state. The line current passes only through the capacitor (X_{TCSC}=X_C). Thus, the boost factor is equal to one. In this mode the TCSC working likes a fixed series capacitor. At *bypass mode* the thyristor valve is triggered continuously and therefore the valve stays conducting all the time. Thyristor controlled reactor bypassed the capacitor and thus the impedance has inductive character and the boost factor is negative. When λ is considerably larger than unity the amplitude of U_C is much lower in bypass than in blocking mode. Therefore, the bypass mode is utilized to reduce the capacitor stress during faults. At capacitive boost mode if the trigger pulse is supplied to the thyristor having forward voltage just before the capacitor voltage crosses the zero line a capacitor discharge current pulse will circulate through the shunt inductive branch. The discharge current pulse adds to the line current through the capacitor bank. It causes a capacitor voltage that adds to the voltage caused by the line current. The capacitor peak voltage thus will be increased in proportional to the charge that passes trough the thyristor branch. The charge depends on the conduction angle α

Because of the presence of tangent in equation (11) this formula has asymptote at

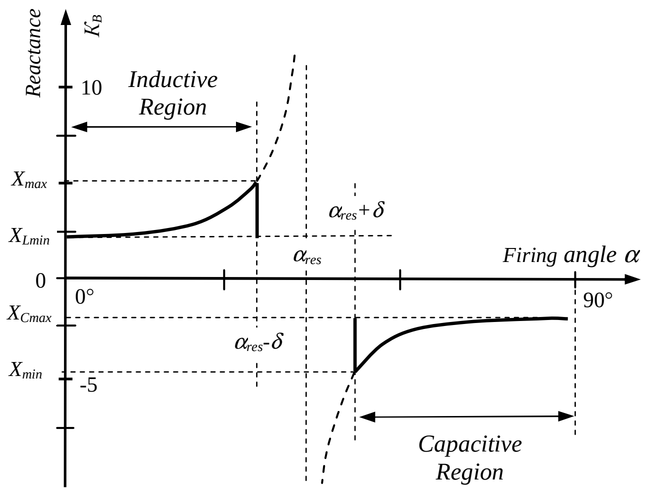

Figure 2. TCSC operating range and boost factor versus firing angle

$$\alpha_{res} = \frac{\pi}{2}\left(1-\omega\sqrt{L.C}\right) \tag{13}$$

TCSC operates in capacitive boost mode when $\alpha_{res} > \alpha > 90^\circ$. The characteristic is shown on fig.2.

The susceptance $B_{TCSC}(\alpha)$ is calculated by next expression:

$$B_{TCSC}(\alpha) = B_L\frac{\pi-2\alpha-\sin 2\alpha}{\pi}+B_C \tag{14}$$

where: B_L is susceptance of the inductor L and B_C is susceptance of the capacitor C (fig.1)

The firing angle α can be controlled between $0^\circ \div 90^\circ$. Thus the limit values of conductivity for inductor and capacitor will be

$$X_{L\,min} = \frac{1}{1/X_L+1/X_C} = \frac{1}{B_L+B_C}; \tag{15}$$

$$X_{C\,max} = X_C = \frac{1}{B_C}. \tag{16}$$

where: $B_L = 1/\omega.L$; $B_C = -\omega.C$

The compensator has a resonance angle α_{res} where the resulting inductive reactance is in resonance with the capacitive reactance. Because of this a security margin δ must be kept around the resonance angle α_{res}.

$$\alpha < \alpha_{res}-\delta \text{ and } \alpha > \alpha_{res}+\delta \tag{17}$$

In fig.2 the resonant angle is indicated as a vertical separate line between inductive and capacitive region. The outer limits X_{min} and X_{max} have to be calculated using the reasonable firing angle α_{res} and security margin α_{res}.

The value of the reference thyristor angle is varied in interval between 0 and $\pi/2$ and for each angle the value of the TCSC voltage is observed. Since al other parameters are constant, the TCSC voltage is

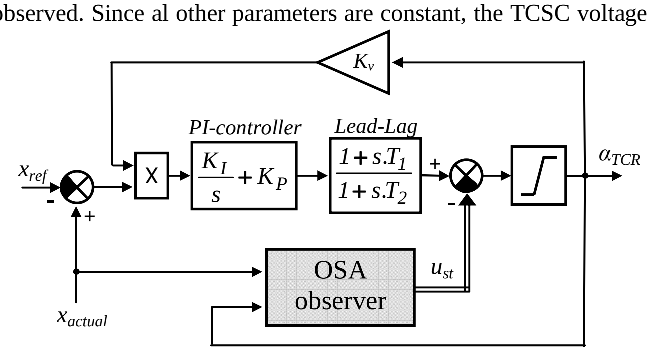

Figure 3. TCSC control block diagram

directly proportional to the TCSC impedance and this is an effective way to obtain accurate information on the fundamental TCSC impedance [8].

TCSC operates in the constant impedance mode and uses voltage and current feedback for calculating the compensator impedance. The reference impedance indirectly determines the power level, although although an automatic power control mode could also be introduced.

On fig. 3 is displayed a suggested block diagram for a design controller for TCSC. The scheme is consist from a classical PI-regulator, lead-lag units [8], OSA observer and variable gain which compensates for the gain changes in the system, caused by the variations in the impedance. On the input of the observer is feed a discrete part of controller input signal (measuring line impedance - x_{actual}) and output signal from controller (α_{TCR}). The OSA observer calculates an additional stabilizing signal (u_{st}) on the basis of the estimated variables and parameter of the model. This signal is add to the signal from PI-regulator, like in this manner is improving controller performance over all operating range.

The characteristic of the variable gain is achieved from of equation (11). On fig.4 is plotted a values of variable gain K_V in corresponds to α_{TCR}.

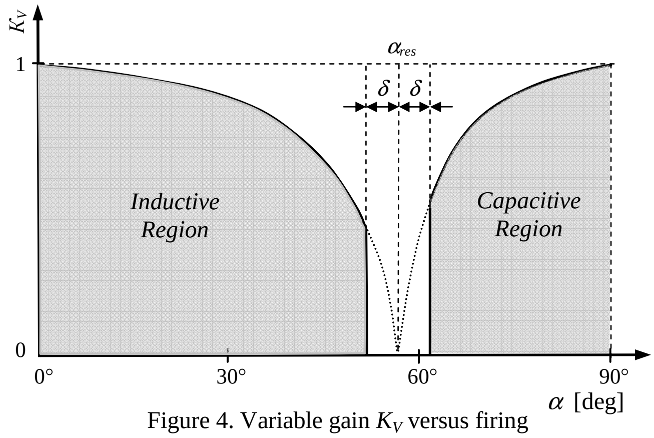

Figure 4. Variable gain K_V versus firing thyristor angle α

The resonance point of the series compensators must be avoided to prevent a harmonic problems and large internal currents that may damage the controller, as well as avoid line current interruption. Operation of this controller "*close*" to the resonant point is not practical in steady-state either, as this may induce essential harmonics in line currents [7]. Steady-state operation in the inductive region is atypical, as this would be equivalent to reducing the transmission system capability, while producing voltages with high harmonics content.

The converter is modelled with the help of the thyristor model given in [5] (fig.5) in which resistor R_{ON} and inductor L_{ON} simulate the transient regime of *pn*-junction and DC voltage source representing the forward voltage U_f which is connected in series whit a switch. The thyristor switching performance is simulated with switch K witch is controlled from switching logic. The switching element is controlled from logical signal in dependence from the voltage anode-cathode U_{AK}, current I_{AK} and controlling signal G.

The thyristor firing circuit uses Phase-Locked Loop (PLL) unit for synchronization with the line current. Line current is preferred for synchronization, rather than line voltage, since the TCSC voltage can vary widely during the operation.

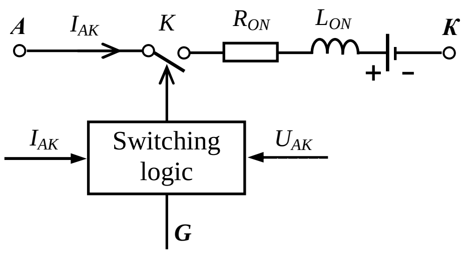

Figure 5. Thyristor model

III. AN ADAPTIVE CONTROL FOR THE COMPENSATOR

TCSC control is performed by different methods of automatic control. Also for creation of the appropriative controllers are used different methods for design. It is used both classical controllers for control and neuron networks and fuzzy logic controllers. The adaptive control has undeniable advantages but the goal of its using is a necessary computing resource for realization.

In the paper is suggested a combine control for the compensator including standard PI-regulator and additional adaptive stabilizing control witch uses an optimal singular adaptive (OSA) observer [6]. With the help of the estimated parameters and variables of the model for identification is calculate the additional stabilizing signal.

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

$$\mathbf{x}(k+1)=\mathbf{A}.\mathbf{x}(k)+\mathbf{b}.u(k),\quad \mathbf{x}(0)=\mathbf{x}_0, \tag{18}$$

$$y(k)=\mathbf{c}^t.\mathbf{x}(k),\qquad k=0,1,2,\ldots; \tag{19}$$

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

$$\mathbf{A}=\begin{bmatrix} \mathbf{0} & \vdots & \mathbf{I}_{n-1} \\ \cdots & \cdots & \cdots \\ & \mathbf{a}^t & \end{bmatrix};\quad \mathbf{b}=\begin{bmatrix} b_1 \\ \vdots \\ b_n \end{bmatrix};\quad \mathbf{c}=\begin{bmatrix} 1 \\ 0 \\ \vdots \\ 0 \end{bmatrix}. \tag{20}$$

where: $\mathbf{a}^t=[a_1,a_2,\ldots,a_n]$; $\mathbf{I}_{n-1}$ - identity matrix with dimensions $(n-1)x(n-1)$; $\mathbf{0}$ – zero vector with dimensions $(n-1)x1$.

For the equations (18) and (19) describing the investigated system corresponds to following "input/output" difference equations:

$$y(k+n)-a_n y(k+n-1)-a_{n-1}y(k+n-2)-\ldots-a_2 y(k+1)-a_1 y(k)=$$
$$=h_1 u(k+n-1)+h_2 u(k+n-2)+\ldots+h_{n-1}u(k+1)+h_n u(k)$$
$$k=0,1,2,\ldots \tag{21}$$

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

$$\mathbf{Y}_1^t=[y(0),y(1),\ldots,y(n-1)];$$
$$\mathbf{Y}_2^t=[y(n),y(n+1),\ldots,y(2n-1)];$$
$$\mathbf{Y}_3^t=[y(2n),y(2n+1),\ldots,y(3n-1)];$$

$$\mathbf{U}_{11}=\begin{bmatrix} 0 & 0 & \cdots & 0 & 0 \\ u(0) & 0 & \cdots & 0 & 0 \\ u(1) & u(0) & \cdots & 0 & 0 \\ \vdots & \vdots & \ddots & \vdots & \vdots \\ u(n\text{-}2) & u(n\text{-}3) & \cdots & u(0) & 0 \end{bmatrix};$$

$$\mathbf{U}_{21}=\begin{bmatrix} u(n-1) & u(n-2) & \cdots & u(0) \\ u(n) & u(n-1) & \cdots & u(1) \\ u(n+1) & u(n) & \cdots & u(2) \\ \vdots & \vdots & \ddots & \vdots \\ u(2n-2) & u(2n-3) & \cdots & u(n-1) \end{bmatrix};$$

$$\mathbf{U}_{31}=\begin{bmatrix} u(2n-1) & u(2n-2) & \cdots & u(n) \\ u(2n) & u(2n-1) & \cdots & u(n+1) \\ u(2n+1) & u(2n) & \cdots & u(n+2) \\ \vdots & \vdots & \ddots & \vdots \\ u(3n-2) & u(3n-3) & \cdots & u(2n-1) \end{bmatrix};$$

where $\mathbf{U}_{11}$, $\mathbf{U}_{21}$, $\mathbf{U}_{31}$ are Toeplitz matrices with dimensions nxn;

$$\mathbf{Y}_{12}=\begin{bmatrix} y(0) & y(1) & \cdots & y(n\text{-}1) \\ y(1) & y(2) & \cdots & y(n) \\ y(2) & y(3) & \cdots & y(n+1) \\ \vdots & \vdots & \ddots & \vdots \\ y(n\text{-}1) & y(n) & \cdots & y(2n\text{-}2) \end{bmatrix};$$

$$\boldsymbol{Y}_{22}=\begin{bmatrix} y(n) & y(n+1) & \cdots & y(2n\text{-}1) \\ y(n+1) & y(n+2) & \cdots & y(2n) \\ y(n+2) & y(n+3) & \cdots & y(2n+1) \\ \vdots & \vdots & \ddots & \vdots \\ y(2n\text{-}1) & y(2n) & \cdots & y(3n\text{-}2) \end{bmatrix};$$

where $\boldsymbol{Y}_{12}$ и $\boldsymbol{Y}_{22}$ are Hankel matrices with dimensions nxn;

The vectors estimations $\hat{\boldsymbol{h}}$ и $\hat{\boldsymbol{a}}$ of difference equations (21) are calculated through the following vector-matrix expression:

$$\begin{bmatrix} \hat{\boldsymbol{h}} \\ \hat{\boldsymbol{a}} \end{bmatrix}=\left[\begin{array}{c|c} -\boldsymbol{N}_1^{-1}.\boldsymbol{Y}_{22}.\boldsymbol{Y}_{12}^{-1} & \boldsymbol{N}_1^{-1} \\ \hline \boldsymbol{Y}_{12}^{-1}+\boldsymbol{Y}_{12}^{-1}.\boldsymbol{U}_{21}.\boldsymbol{N}_1^{-1}.\boldsymbol{Y}_{22}.\boldsymbol{Y}_{12}^{-1} & -\boldsymbol{Y}_{12}^{-1}.\boldsymbol{U}_{21}.\boldsymbol{N}_1^{-1} \end{array}\right].\begin{bmatrix} \boldsymbol{Y}_2 \\ \boldsymbol{Y}_3 \end{bmatrix}$$

where: $\boldsymbol{N}_1=\boldsymbol{U}_{31}-\boldsymbol{Y}_{22}.\boldsymbol{Y}_{12}^{-1}.\boldsymbol{U}_{21}$.

The Toeplitz matrix $\boldsymbol{T}$ with dimension nxn is shaped.

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

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

$$\boldsymbol{T}.\hat{\boldsymbol{b}}=\hat{\boldsymbol{h}}.$$

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

$$\hat{\boldsymbol{x}}(0)=\boldsymbol{Y}_1-\boldsymbol{U}_{11}.\hat{\boldsymbol{b}};$$

where: $\hat{x}_1(0)=y(0)$.

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

$$\hat{\boldsymbol{x}}(k+1)=\hat{\boldsymbol{A}}.\hat{\boldsymbol{x}}(k)+\hat{\boldsymbol{b}}.u(k), \qquad \hat{\boldsymbol{x}}(0)=\hat{\boldsymbol{x}}_0,$$

k=0, 1, 2, … ,

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

$$\hat{u}_{st}(p)=-\hat{a}_1.\hat{x}_1(p)-\hat{a}_2.\hat{x}_2(p) \tag{22}$$

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

IV. COMPENSATOR WORK STYDIES

For proofs of the rightness and effectiveness of the adaptive control for TCSC a computer model in MATLAB space have been created. The control effectiveness is interred from the fast and adequate creation of control signal for the thyristors according to system condition. Taken numerous investigations proofs rightness of the adaptive control. Investigated control is compared with conventional PI-controller [8]. In part of the studies is shown the modification of the regime parameters for the system at absence of control for TCR. The taken studies are performed at different compensation levels (40%, 60%, 75% etc.) as are shown only at one level of compensation. The results of the rest compensation levels are identical to present results. The performed experiments are in capacitive mode for TCSC at 3-phase short circuit in buses $\boldsymbol{b}_1$ at time 5sec and following protection trip after 35ms.

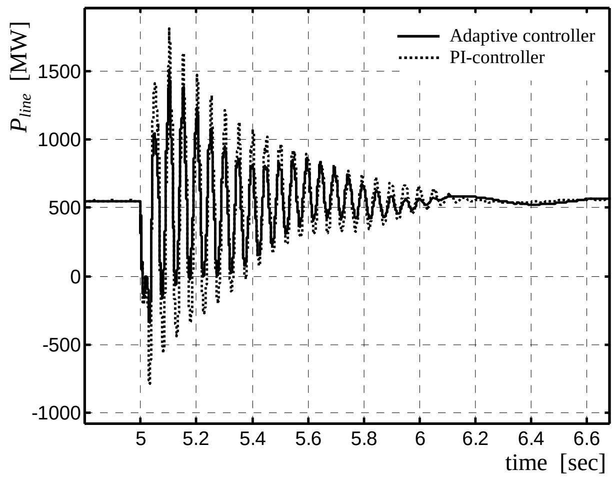

Figure 6. Active power through the line

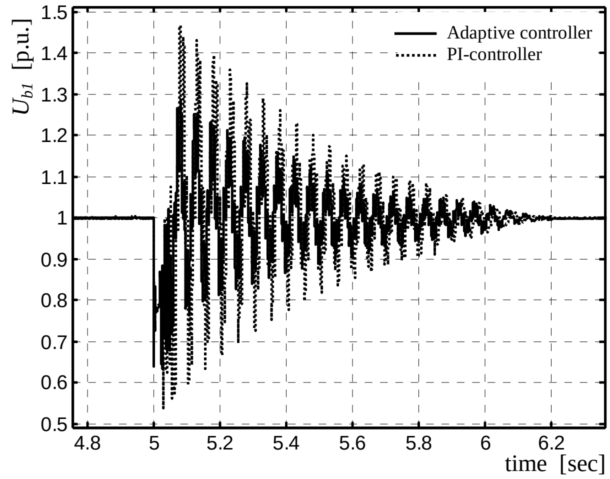

Figure 7. Voltage at buses $\boldsymbol{b}_1$

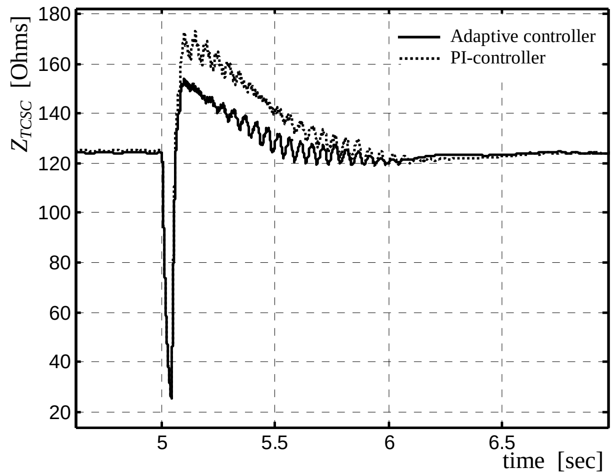

Figure 8. Transmission impedance

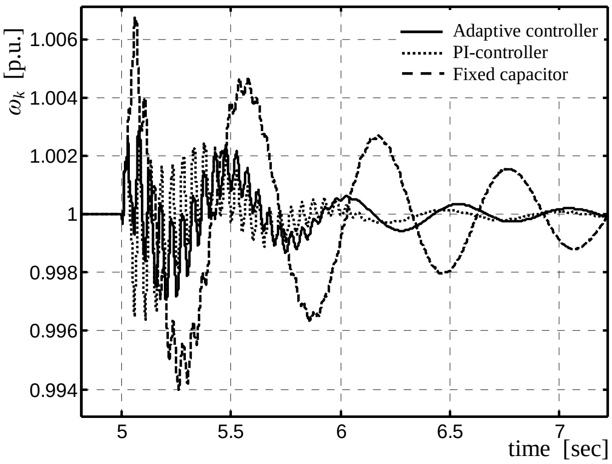

Figure 9 Generator angular speed

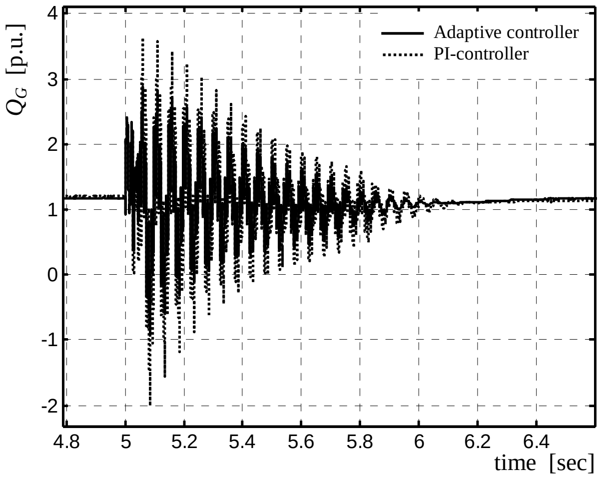

Figure 10. Generator reactive power

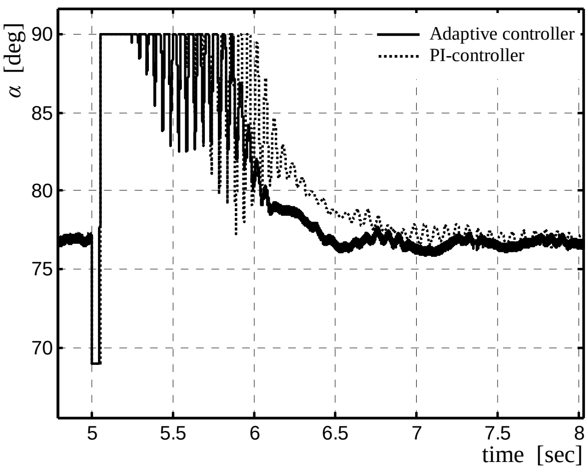

Figure 11. Firing angle for the thyristors of TCR.

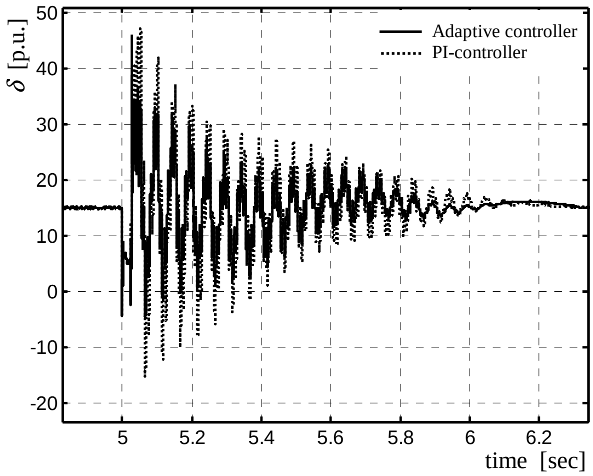

Figure 12. Generator load angle

CONCLUSION

The developments of the power electronics have been allowed to control of compensate devices in power grids. As result of this a static and dynamic characteristics are improved.

In the paper is suggested adaptive control of series compensator using an optimal singular adaptive observer. The taken simulations and present experimental data shows the effectiveness and advantages of the suggested control at low-frequency oscillation damping and stability of the power systems.

APPENDIX

AC system data:

Generator: P_n=650MVA; U_n=539kV; f_n=60Hz; Reactanses in p.u.- x_d=1.305; x_d'=0.296, x_d''=0.252; x_q=0.476; x_q''=0.243; x_l=0.18; Stator resistanse -2,8544e^{-3}[p.u.]; Coeff.of inertia - 3.7 [p.u.]; Friction factor – 0; Pole pairs – 32;

Line: R=0.015 Ω/km; L=1.08 mH/km; 400km;

Load: $P_н$=50 MW;

TSCS: At 75% compensation - C=21.98 μF; L=0.052 mH; R_L=0.0392 Ω;

Controller data: K_I=10; K_P=0.2; T_1=0.08s; T_2=0.009s

REFERENCES

[1] *N. Yang, Q. Liu, J. D. McCalley,* "TCSC Controller design for damping interarea oscillations", *IEEE Transactions on Power Systems*, vol. 13, No. 4, November, 1998, pp.1304-1310.

[2] *N. Martins, H. J. C. P. Pinto and J. Paserba,* "Using a TCSC for line power scheduling and system oscillation damping-small signal and transient stability studies", *Proceedings of Power Engineering Society IEEE Winter Meeting*. Seattle, USA 2000. vol. 2, pp. 1455-1461.

[3] *N. F. Djagarov,* "Transient electromechanical processes calculation of power systems with complex topology", *Electricity*, Moscow, No. 1, 1990, pp.9-16.

[4] *C. Schauffner, G. Andersson,* "Performance of a TCSC for congestion relief", *Inter. Conference IEEE PowerTech*, 2005, St. Petersburg, Russia, June, 2005.

[5] *V. Rajagopalan, Computer-Aided Analysis of Power Electronic Systems,* Marcel Dekker, Inc., New York, 1987.

[6] *L. N. Sotirov*, Selected chapters from the modern control theory, Technical University-Varna, 1998, 282p.

[7] *Canizares C. A., Faur Z. T.,* Analysis of SVC and TCSC controllers in voltage collapse, *IEEE Trans. on Power Syste.*, Vol. 14, pp. 158-165, Feb. 1999.

[8] *D. Jovcic, G. N. Pillai*, “Analytical Modeling of TCSC Dynamics”, IEEE Transaction on Power Delivery, vol.20, Issue 2, April 2005, pp.1097-1104.

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