

# Coordinated Control Strategy of TCSC and SVC for Damping Power System Oscillation Enhancement

**Abstract.** This paper proposes a combination of the Thyristor Controlled Series Capacitor (TCSC) and Static Var Compensator (SVC) installation for enhancing the damping performance of a power system. The developed scheme employs a damping controller which coordinates measurement signals with control signals to control the TCSC and SVC. Controller performance over a range of operating conditions is investigated through simulation studies on a single-machine infinite-bus (SMIB) power system. In this paper, a current injection model of TCSC is developed and incorporated in the transmission system model. By using equivalent injected currents at terminal buses no modification of the bus admittance matrix is required at each iteration. Furthermore, an ADaptive LInear NEural (ADALINE) network as a model of coordinated control to control the flow injection model, TCSC and SVC is used. The results of this model in the simulation compared with a coordinated FACTS controller (LQR model). As you will see, ADALINE network power system damping is improved.

**Streszczenie.** W artykule przedstawiono propozycję zastosowania układu pojemności szeregowych z łącznikami tyrystorowymi (TCSC) oraz statycznego kompensatora mocy biernej (SVC) do polepszenia wydajności tłumienia oscylacji w sieci elektroenergetycznej. Działanie zastosowanego sterownika poddano badaniom symulacyjnym w zakresie operacyjnym w systemie jednomaszynowym, linii nieskończenie długiej. Opisano model kontroli prądu przez TCSC, który włączono w model systemu przesyłowego. Dodatkowo, w celu zamodelowania kontroli współrzędnych w modelu przepływu TCSC i SVC, zastosowano sieć neuronową typu ADALINE (ang. ADaptive LInear NEural). Wyniki badań symulacyjnych zostały porównane z działaniem sterownika FACTS (model LQR). (Strategia kontroli współrzędnych w układzie TCSC i SVC w zwiększeniu wydajności tłumienia oscylacji w systemie elektroenergetycznym).

**Keywords:** ADALINE network, damping enhancement, SVC, TCSC.  
**Słowa kluczowe:** ADALINE sieć, polepszenie tłumienia, SVC, TCSC.

## Introduction

A problem of mind for years electrical engineers have worked to reduce its oscillations and increase stability in power systems. Today, with the power industry development and applying of new equipment, including the Flexible AC Transmission System (FACTS) devices have been able to reach this goal [1,2]. The Thyristor Controlled Series Capacitor (TCSC) and Static Var Compensator (SVC) are both members of the Flexible AC Transmission System (FACTS) family [3,4]. The TCSC is a series compensation device. With the firing control of the thyristors, it can change its apparent reactance smoothly and rapidly. This characteristic meets the demands of the modern power system that must operate flexibly and react quickly. The SVC is a shunt compensation device. It is originally designed for voltage support in power systems. Much as the TCSC, the SVC is also capable of rapid and flexible adjustment. Individually, the TCSC and the SVC can improve the damping performance of the power system[5].

In this paper, a ADaptive LInear NEural (ADALINE) network control scheme for the simultaneous coordination of TCSC and SVC to enhance the damping performance of a power system. The method presented here demonstrates the control action of the TCSC in conjunction with the control action of the SVC to increase system damping and power transfer capabilities beyond those achievable with a single device. It also illustrates how the measurement and control signals are coordinated to form an effective controller. Controller performance over a range of operating conditions is investigated using nonlinear time domain simulations. The simulation results in a single-machine infinite-bus (SMIB) power system show that the proposed controller with coordinated control of TCSC and SVC can significantly improve system damping performance. A SMIB power system is used for simulation studies because it qualitatively represents the behavior of a multi machine system and is extremely useful in describing the general concepts of power system stability.

## The single machine infinite bus test system (SMIB)

In this paper, we examine the small signal stability of the single machine infinite bus system. To test the effectiveness

of the proposed coordinated FACTS controller and ADALINE network, a simplified model of a power system is considered. The system consists of a single generator connected to a large system through two transmission lines as shown in Fig. 1. The generator is described by a sub transient 6th model equipped with the IEEE type ST3 exciter. The locations of TCSC and SVC are indicated in the figure. The effects of the transmission line series resistance and shunt capacitance are ignored. It is assumed that generator deliver 0.9 p.u. active power to the large system.

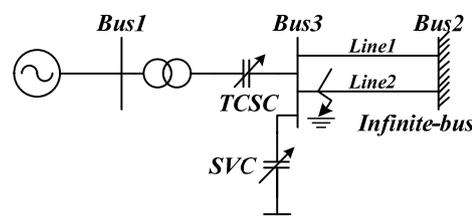


Fig. 1. A single-machine infinite-bus system with TCSC and SVC.

## Nomenclature

$\delta$ : Rotor angle of a synchronous generator in radians -  $\omega_B$ : Rotor speed deviation in rad/sec -  $S_m$ : Generator slip in p.u. -  $S_{mo}$ : Initial operating slip in p.u. -  $H$ : Inertia constant -  $D$ : Damping coefficient -  $T_m$ : Mechanical power input in p.u. -  $T_e$ : Electrical power output in p.u. -  $E_{fd}$ : Excitation system voltage in p.u. -  $T'_{do}$ : Transient OC d-axis time constant in sec -  $T''_{do}$ : Sub transient OC d-axis time constant in sec -  $I_d$ : d-axis component of armature current -  $I_q$ : q-axis component of armature current -  $R_s$ : stator resistance -  $X_d$ : d-axis synchronous reactance in p.u. -  $X'_d$ : d-axis transient reactance in p.u. -  $X''_d$ : d-axis Sub transient Reactance in p.u. -  $X_q$ : q-axis synchronous reactance in p.u. -  $X'_q$ : q-axis transient reactance in p.u. -  $X''_q$ : q-axis Sub transient Reactance in p.u.

## Synchronous Generator

The synchronous generator is represented by 6th order model. The 6th order model extends on the classical model by including the effects of the field winding and damper windings which one on the d-axis and two on the q-axis. The second damper winding on the q-axis improves the accuracy in modeling multiple paths for circulating eddy currents.

The differential equations corresponding to the rotor winding dynamics are in p.u.:

$$\begin{aligned}
 (1) \quad & \frac{d\delta}{dt} = \omega_B (S_m - S_{mo}) \\
 (2) \quad & \frac{dS_m}{dt} = \frac{1}{2H} (-D(S_m - S_{mo}) + T_m + T_e) \\
 (3) \quad & \frac{dE'_q}{dt} = \frac{E_f + (X_d - X'_d) \cdot I_d - E'_q}{T'_{d0}} \\
 (4) \quad & \frac{dE'_d}{dt} = \frac{-(X_q - X'_q) \cdot I_q - E'_d}{T'_{d0}} \\
 (5) \quad & \frac{dE''_q}{dt} = \frac{E'_q + (X'_d - X''_d) \cdot I_d - E''_q}{T''_{d0}} \\
 (6) \quad & \frac{dE''_d}{dt} = \frac{E'_d - (X'_q - X''_q) \cdot I_q - E''_d}{T''_{d0}}
 \end{aligned}$$

The electromagnetic torque equation is in p.u.:

$$(7) \quad T_e = E''_d \cdot I_d + E''_q \cdot I_q - (X'_d - X'_q) I_d \cdot I_q$$

The stator equations are in p.u.:

$$\begin{aligned}
 (8) \quad & V_d = E''_d - R_s \cdot I_d + X''_q \cdot I_q \\
 (9) \quad & V_q = E''_q - R_s \cdot I_q + X''_d \cdot I_d
 \end{aligned}$$

### TCSC current injection model and control

Flow injection model presented in this paper using Norton law has been shown in the Fig. 2 through Fig. 5. When TCSC is installed in power system admittance matrix  $Y_{bus}$  will be changed into an unsymmetrical matrix. When the TCSC is used for time domain simulations, the modification of  $Y_{bus}$  is required at each iteration. In accordance to change of TCSC reactance in the process of transient stability calculation, this method has the disadvantage that a constant factorized  $Y_{bus}$  cannot be repeatedly used. To avoid modification of  $Y_{bus}$  at each iteration, a current injection model of TCSC is developed. The current injection model, which can be used for small signal stability and transient stability studies, is obtained by replacing the voltage across the TCSC with the current source. By using equivalent injected currents at terminal buses to simulate a TCSC no modification of  $Y_{bus}$  is required at each iteration. This model can easily be incorporated in a dynamic simulation program, Power System Toolbox. This model is also helpful for understanding the effect of the TCSC on system damping enhancement. This method has the advantages of fast computational speed and low computer storage compared with that of modifying  $Y_{bus}$  method. It is assumed that a TCSC is connected between nodes  $i, k$ . These nodes are two ends of a line with impedance  $jX_l$  (Fig. 2.) and its equivalent circuit is shown in Fig. 3. From these Figures can be shown that[6]:

$$(10) \quad \bar{I}_k = \frac{\bar{V}_k - \bar{V}_i}{j(X_l - X_c)}$$

$$(11) \quad \bar{V}_c = -j\bar{I}_k \cdot X_c$$

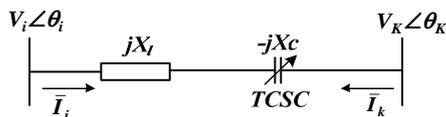


Fig. 2. Schematic diagram of TCSC.

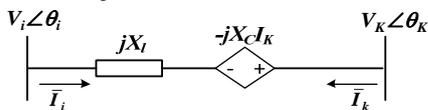


Fig. 3. TCSC equivalent circuit.

The injection model will be obtained by using Norton equivalent circuit. The source current is named  $I_{ks}$  (Fig. 4) which can be calculate from equation (10), (11):

$$(12) \quad \bar{I}_{ks} = \frac{\bar{V}_c}{jX_l} = -\frac{\bar{V}_k - \bar{V}_i}{j(X_l - X_c)} \frac{X_c}{X_l} = j \frac{K_c}{X_l(1-K_c)} (\bar{V}_k - \bar{V}_i)$$

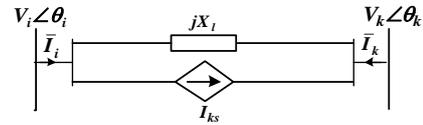


Fig. 4. Replacement of a voltage across the TCSC by a current source.

By source transformation, one can obtain the following model (Fig. 5):

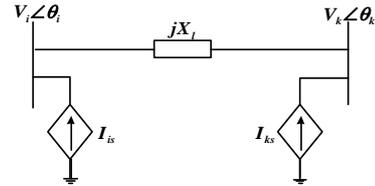


Fig. 5. Current injection model for a series compensated TCSC.

Where

$$(13) \quad \bar{I}_{is} = -\bar{I}_{ks} = -j \frac{K_c}{X_l(1-K_c)} (\bar{V}_k - \bar{V}_i)$$

$K_c = X_c/X_l$  is the degree of compensation of TCSC which depends on the line where TCSC is installed, there. Equation (12) and (13) for current injection model of TCSC simulation is used in time domain analysis. For small signal stability studies, the equations could be studied in d-q frame.

$$(14) \quad \bar{I}_{is} = I_{id} + jI_{iQ}$$

$$(15) \quad \bar{I}_{ks} = I_{kd} + jI_{kQ}$$

$$(16) \quad \bar{V}_{is} = V_{id} + jV_{iQ}$$

$$(17) \quad \bar{V}_{ks} = V_{kd} + jV_{kQ}$$

Replacing equations (14) to (17) in (12) and (13), equations (18) to (21) for current injection model of TCSC will be obtained.

$$(18) \quad I_{id} = \frac{K_c}{X_l(1-K_c)} (-V_{iQ} + V_{kQ})$$

$$(19) \quad I_{iQ} = \frac{K_c}{X_l(1-K_c)} (V_{id} - V_{kd})$$

$$(20) \quad I_{kd} = \frac{K_c}{X_l(1-K_c)} (V_{iQ} - V_{kQ})$$

$$(21) \quad I_{kQ} = \frac{K_c}{X_l(1-K_c)} (-V_{iQ} + V_{kQ})$$

$K_c$  characterized the TCSC compensated system is the same interface between the controller model and the optimal current injection model of TCSC is impaired when the power system with rapid reaction damping power system could well increase.

### SVC current injection model and control

A SVC connected at node  $k$  is shown in Fig. 6 and its current injection model is represented in Fig. 7. In this study, the SVC is treated as a variable capacitance. In Figs. 6 and 7,  $I_{ksvc}$  is the complex SVC injected current at node  $k$ ,  $V_i \angle \theta_i$  and  $V_k \angle \theta_k$  are the complex voltages at nodes  $i$  and  $k$ .

From Figs. 6 and 7, it can be shown that:

$$(22) \quad \bar{I}_{k_{svc}} = -j\bar{V}_k \cdot B_{svc}$$

This relation is suitable for calculation of time domain analysis.

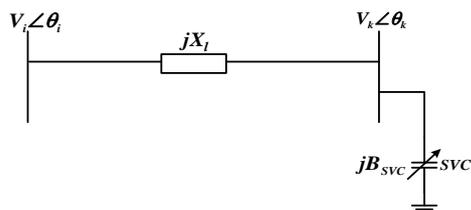


Fig. 6. Representation of a SVC.

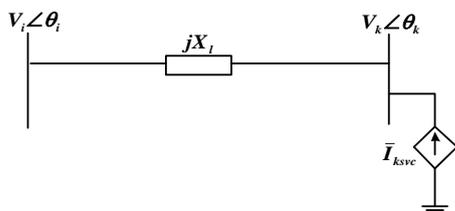


Fig. 7. Current injection model for a shunt compensated SVC.

For small signal stability studies, the SVC injection current  $I_{k_{svc}}$  and the nodal voltage  $V_k$  corresponding to the SVC injection model are expressed in the network d-q reference frame to couple with other components through the network as[7,8]:

$$(23) \quad I_{k_{svc}} = I_{k_{svcD}} + jI_{k_{svcQ}}$$

$$(24) \quad V_k = V_{kD} + jV_{kQ}$$

Substituting (23) and (24) into (22), the algebraic equations (25) and (26) of the SVC current injection model are obtained as:

$$(25) \quad I_{k_{svcD}} = B_{svc} \cdot V_{kQ}$$

$$(26) \quad I_{k_{svcQ}} = -B_{svc} \cdot V_{kD}$$

Equivalent circuit of a power system with Current injection model for a TCSC and a SVC is shown in Figure.8.

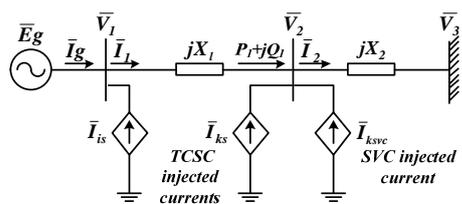


Fig. 8. The equivalent circuit of the system with TCSC and SVC.

### ADaptive Linear NEural (ADALINE) network

Neural networks are dynamical systems, which process information on the experimental data is connected to the power system. Learning ability, parallel processing of information also Proper response to errors, including neural networks are features. Linear adaptive neural network learning algorithm of the type of learning is the observers. In this type of learning that the network learning error between the desired value and actual value is access, and it makes the optimum. This type of network is usually a layer of neurons. These neurons, weighted by total inputs with a bias and results gathered from a linear function will pass. The ADALINE network is shown in Fig.9.

This type of education networks in each step the amount of weights ( $w$ ) and bias ( $b$ ) using Widrow-Hoff law is changed in such a way that mean square error is minimal.  $e_{(k)}$  out of the error value between the desired value and

output network. For mean square error should be minimal weights matrix and bias at each stage to be corrected error is zero[9-10]:

$$(27) \quad w_{(k+1)} = w_{(k)} + 2\alpha e_{(k)} P_{(k)}$$

$$(28) \quad b_{(k+1)} = b_{(k)} + 2\alpha e_{(k)}$$

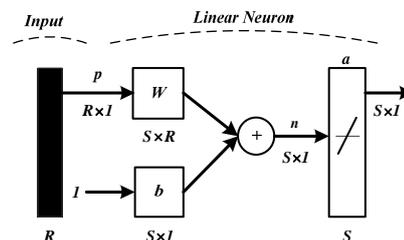


Fig. 9. The ADALINE network structure

Primary values of weights obtained from the coordinated FACTS controller, and have been used. Network inputs simultaneously and parallel to with other parts of the power system is connected. According to equation (27) and (28), when the error in the power system, neural network will begin to generate new weights. As long as the equation (29) is not equal to zero, the cycle continues Entered. ADAPtive Linear NEural (ADALINE) network control in this model included a layer consisting of two neurons, seven inputs and two outputs. Neural network inputs are:

$$P_e, I_d, I_q, E_d, E_q, \Delta P_{1-3}, \Delta V_3$$

ADAPtive Linear NEural (ADALINE) network outputs variables are  $B_{svc}$  and  $XC$ .  $XC$  in the KC equation also TCSC injected model and  $B_{svc}$  in the SVC injection model makes controlling and improving power system damping error is at this point. It must be said here that the observer (e) is calculated according to the following equation:

$$(29) \quad e = t - y$$

where the objective function of  $t$  and  $y$  is also power transition of power systems. Fig.10. shows how ADALINE network is used.

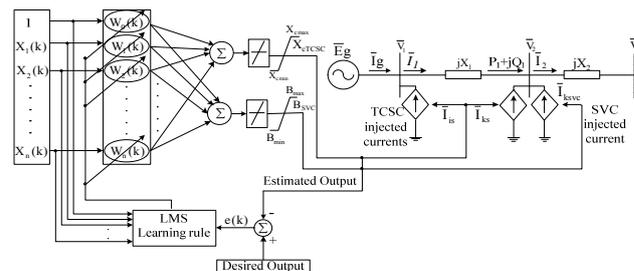


Fig.10. Schematic diagram of Power network and controller.

### Nonlinear time domain simulations

To verify the results of linear analysis and to evaluate the performance of the designed controller, nonlinear time domain simulations of the system with the coordinated FACTS controller and ADALINE network were performed for two types of disturbance:

- (a) Small disturbance - switching off a transmission line was applied at 0.1s on line #2 of the system (Fig. 1).
- (b) Large disturbance - a three-phase fault was applied at 0.1s on line #2 near bus 3 for 0.1s followed by the permanent tripping of the line (Fig. 1).

### Small disturbance analysis

Fig. 11 through Fig. 14 show the simulation results for the case with the coordinated FACTS controller compared with the case the ADALINE network when a small disturbance as mentioned above was applied to the system. Fig. 11 through Fig. 14 show the dynamic responses of the machine rotor angle, machine speed, machine active power output and bus voltage to the small disturbance, respectively. The simulation results indicate that ADALINE network in power system damping improvement compared with coordinated FACTS controller.

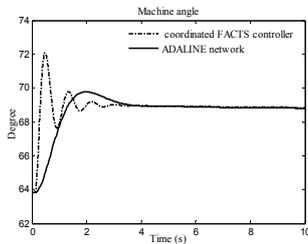


Fig. 11. Machine angle.

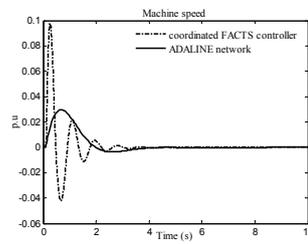


Fig. 12. Machine speed.

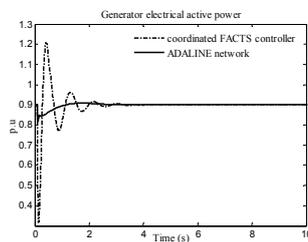


Fig. 13. Machine active power output.

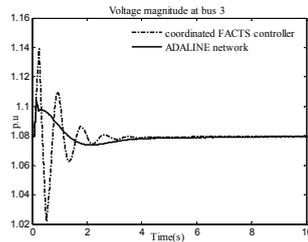


Fig. 14. Voltage magnitude at bus 3.

### Large disturbance analysis

Fig. 15 through Fig. 18 summarize the simulation results for the case with the coordinated FACTS controller compared with the case the ADALINE network when a large disturbance as mentioned above was applied to the system. Fig. 15 through Fig. 18 show the responses of the machine rotor angle, machine speed, machine active power output and bus voltage to the large disturbance, respectively. The simulation results indicate that ADALINE network in power system damping improvement compared with coordinated FACTS controller. However, compared with ADALINE networks are seeing a better damping.

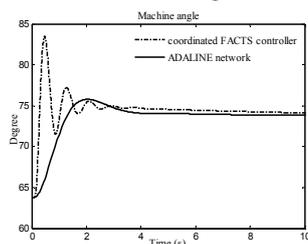


Fig. 15. Machine angle.

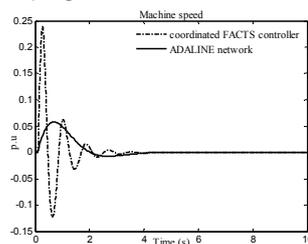


Fig. 16. Machine speed.

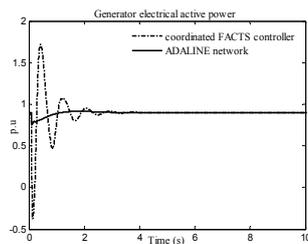


Fig. 17. Machine active power output.

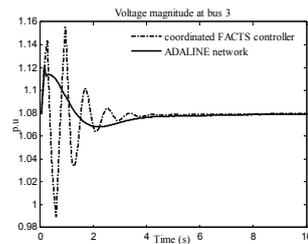


Fig. 18. Voltage magnitude at bus 3.

### Conclusions

Simulation results reveal the fact that ADALINE controller in comparison with coordinated FACTS controller can more effectively improve fluctuations of power system caused by small or large disturbances for coordinated control of TCSC and SVC. This controller can also yield further flexibility of system versus change of working point leading to enhancement of transmission power thanks to its intrinsic characteristics such as responsiveness speed, adaptation to system and simplicity.

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**Authors:** Reza Sedaghati, Young Researchers and Elite Club, Beyza Branch, Islamic Azad University, Beyza, Iran.  
Email: reza\_sedaghati@yahoo.com