Effectiveness of TCSC Controllers Using Remote Input Signals for Transient Stability Enhancement

Nguyen Tuan Anh

Anh.NguyenTuan@esat.kuleuven.be

Dirk Van Hertem

Dirk.VanHertem@esat.kuleuven.be

Johan Driesen

Johan.Driesen@esat.kuleuven.be

Department of Electrical Engineering, K.U. Leuven, Belgium

Abstract—This paper presents a method to improve the dynamic performance of a power system with Thyristor-Controlled Series Capacitor (TCSC) using remote measurement input signals. The remote signals are selected based on their effectiveness for damping the first swing oscillation. Phasor Measurement Units (PMUs) are used to measure real-time remote signals and transfer those to the TCSC stability control loop. The locations, the designs and the co-ordination of the TCSCs for damping power system oscillations are determined. Transient stability studies are performed for the Vietnamese system. The dynamic simulations demonstrate the suitable locations and good designs of the TCSCs. The case studies show the improvement of the transient stability comparing control using remote control signals instead of local signals.

Keywords—FACTS, Eigenvalue Sensitivities, Phasor Measurement Units, TCSC, Transient Stability, Vietnamese Power System.

I. INTRODUCTION

Flexible AC transmission system (FACTS) controllers are well known for their capability to improve power system stability. The use of these controllers gives grid planners and operators a greater flexibility regarding the type of control actions that can be taken at any given time [1]. Thyristor-controlled series capacitor (TCSC) is an important device in the FACTS family. It can have various roles in the operation and control of power systems [2]. To study the application of TCSC for damping electromechanical oscillations in the power system, three problems will be discussed: location, controller design and co-ordination of TCSCs. These problems will be addressed using the eigenvalue sensitivity approach that has been proposed in [3] and applied to the Vietnamese power system.

The use of TCSC for stability enhancement has been widely studied and reported in various papers, technical reports and several practical applications exist. The literature contains different control schemes and various input signals for TCSC controllers. The selection of the input control signals of the controller is important. Both local and remote input signals are considered. Due to measurement and communication difficulties, most applications select local variables as input signals for their TCSC control. However, only a limited number of signals are locally available, and this might limit the effectiveness of the controller. As power systems are continuously developing, using remote measurement signals

for compensation devices improves control capabilities and may be a better choice. The remote signals are selected based on their effectiveness for damping the first swing oscillation. Nowadays, the Phasor Measurement technology emerges in monitoring and managing dynamic system security of large power system. At present, Phasor Measurement Units (PMUs) are the most sophisticated time-synchronized tool available to measure inter-area oscillations in real-time. Advantages of the PMUs suggest using quasi real-time remote signals measured by PMUs as input for the TCSC controller for transient stability enhancement. Transient stability studies for Vietnamese power system (using actual system data) with TCSCs are implemented and the analyses of the simulation results are shown the improvement of transient stability.

This paper is structured as follows: Section II describes the stability control scheme for a TCSC module. Linearization analysis of power system with TCSC for selecting input signals, location and design of TCSCs are mentioned in section III. In Section IV, the transient stability simulations for the Vietnamese transmission system are implemented and the results are discussed. Section V concludes.

II. TCSC CONTROL SCHEME

A. TCSC Controller

A conventional stability control scheme for TCSC is shown in Fig. 1. It includes two main operational blocks as an external control and an internal control [1].

Fig. 1. TCSC model for stability studies

The function of the external control is to operate the controller to accomplish specified compensation objectives. Measured systems variables are used to define the reference for the internal control, which is usually the value of the controller reactance. The function of the internal control is to provide appropriate gate drive signals for the thyristor valves

to produce the desired compensating reactance. Thus, the external control is the one that defines the functional operation of the controller.

In [1], [2], [4], the external control includes different control loops depending on the control objectives. In the typical TCSC variable-reactance model for stability studies, a reference value of TCSC reactance, X_{pf} , is generated from a power-scheduling controller based on the power-flow specification in the transmission line. The reference X_{pf} value may also be set directly by manual control in response to an order from an energy-control centre, and it essentially represents the initial operating point of the TCSC [5]. In Fig. 1, X_m is the stability control modulation reactance value from the stability or dynamic control loop. The sum of these two values yields X_m , which is the final value of the reactance ordered by the external control block. The desired magnitude of the TCSC reactance, X_e , is obtained after a finite delay caused by the firing controls and the natural response of the TCSC. This delay is modelled by a lag circuit having a time constant, T , of typically 15-20 ms [6]. The output of the first-order lag is subject to variable limits based on the TCSC reactance-capability characteristic.

The stability control loop is a pre-programmed open-loop control which is used to improve transient (or first swing) stability. When the system is subjected to a severe transient disturbance such as a fault on transmission facilities, loss of generation, or loss of a large load, the stability control loop acts initially, leading to the maximum compensation level during a certain time, so that the synchronizing torque is increased, improving the first-swing stability response of the system. The control then provides proper modulation to damp the subsequent power oscillations. There are many studies on the damping control of TCSC based on a transfer function-based linear control with a local input signal. However, this linear control is usually designed for a specific operating point and condition. They are effective at damping the oscillation under the design conditions [2]. The general structure of the stability controller is depicted in Fig. 2. It consists of a washout filter, a dynamic compensator, and a limiter. The washout filter is mainly provided to avoid the controller response to the dc offset of the input signal. The dynamic compensator consists of one or more lead-lag blocks to provide the necessary phase-lag characteristics. Finally, the limiter is used to improve controller response to large deviations in the input signal.

Fig. 2. Block diagram of conventional stability control of TCSC

B. Selection of input signals

The potential input signals that can be employed to modulate the TCSC reactance include both local and remote signals. The selection of the appropriate input is a fundamental issue in the design of an effective and robust controller. The

local signals constitute the following: line current, active-power flow, bus voltage, and local bus frequency. In the local signals, the line current and the active power flow are found to be almost equally effective. Local bus frequency is less responsive to system power swings compared to the synthesized-voltage frequency [5]. Based on the advantages of local input signals as easy installation, reliable operation, small delay, low cost, most controlled practical installations of TCSCs uses local measurements for controlling power flows and damping power oscillations. But TCSCs with only local input signals do not ensure optimal stability enhancement because not all oscillation modes can be correctly identified by local measurements. Especially changing grid topologies may have an adverse effect on controller performance. Alternatively, the possible remote signals constitute the following: rotor-angle/speed deviation of any remote generator, rotor-angle/speed (frequency) difference across the system, any bus voltage or phase and real-power flow on adjacent lines. Of course, every additional remote input signal used needs additional measurement devices and communication. Today, measurements by PMUs [7] have reached the point where it is possible to use them for wide scale applications in large power systems and they meet the measurement requirements. Of these possible input signals, based on small-signal stability analysis, the rotor-angle difference between the large generators of a power system is chosen as the remote signal. Since the rotor angles can not be measured directly by PMUs, the value of the rotor angle difference is approximated by the phase angles of the generator terminal voltages in the practical applications. Section III will present theoretically the effectiveness of damping rotor-angle oscillations using these remote signals and design method for TCSCs. The simulation results in the cases employing different control signals for TCSCs in section IV will be clear proofs for improving power system transient stability using the remote signals.

III. SMALL-SIGNAL STABILITY OF POWER SYSTEM WITH TCSC

A simplified power system (Fig. 3) is used to model an interconnected system consisting of two areas with a TCSC. Two interconnected systems are represented by their Thévenin equivalent generator and reactance, with the generators represented by the classical model: a constant emf behind the transient reactance and all resistances neglected. The system representation allows to gain physical insight into the effectiveness of enhancing stability through TCSC control. It is assumed that a TCSC is located on the intertie.

Fig. 3. System for inter-area power swing study

With stator resistance neglected, the air-gap power (P_e) is equal to the terminal power. In per unit quantities, the air-gap torque is equal to the air-gap power.

Hence,

$$T_{e1} = P_1 = \frac{E'_1 E'_2}{X_T + X_{TCSC}} \sin(\delta_1 - \delta_2) \quad (1)$$

$$T_{e2} = P_2 = -\frac{E'_1 E'_2}{X_T + X_{TCSC}} \sin(\delta_1 - \delta_2) \quad (2)$$

where $X_T = X'_{d1} + X_1 + X'_{d2} + X_2$

Linearizing Equations (1) and (2) about an initial operating condition represented by $\delta_1 = \delta_{01}$, $\delta_2 = \delta_{02}$, $X_{TCSC} = X_0$, yields:

$$\Delta T_{e1} = K_S(\Delta\delta_1 - \Delta\delta_2) - K_{TCSC}\Delta X_{TCSC} \quad (3)$$

$$\Delta T_{e2} = -K_S(\Delta\delta_1 - \Delta\delta_2) + K_{TCSC}\Delta X_{TCSC} \quad (4)$$

where

$K_S = \frac{E'_1 E'_2}{X_T + X_0} \cos(\delta_{01} - \delta_{02})$ - The synchronizing torque coefficient;

$K_{TCSC} = \frac{E'_1 E'_2}{(X_T + X_0)^2} \sin(\delta_{01} - \delta_{02})$ - The power damping coefficient of the TCSC.

The equations of motion of the generators in per unit are

$$\Delta\dot{\omega}_1 = \frac{1}{2H_1}(T_{m1} - T_{e1} - K_{D1}\Delta\omega_1) \quad (5)$$

$$\Delta\dot{\omega}_2 = \frac{1}{2H_2}(T_{m2} - T_{e2} - K_{D2}\Delta\omega_2) \quad (6)$$

where

δ_1, δ_2 - rotor angles corresponding to machine 1 and 2;

ω_1, ω_2 - rotor electrical speeds;

$\Delta\delta_1, \Delta\delta_2$ - rotor angle deviations;

$\Delta\omega_1, \Delta\omega_2$ - rotor speed deviations;

H_1, H_2 - inertia constants;

K_{D1}, K_{D2} - damping factors;

E'_1, E'_2 - transient q-axes voltages;

X'_{d1}, X'_{d2} - d-axis transient reactances;

X_{TCSC} - effective reactance of the TCSC.

Linearizing Equations (5), (6), and substituting for ΔT_{e1} , ΔT_{e2} by Equations (3) and (4), we obtain

$$\Delta\dot{\omega}_1 = \frac{1}{2H_1} \{ \Delta T_{m1} - K_S(\Delta\delta_1 - \Delta\delta_2) + K_{TCSC}\Delta X_{TCSC} - K_{D1}\Delta\omega_1 \} \quad (7)$$

$$\Delta\dot{\omega}_2 = \frac{1}{2H_2} \{ \Delta T_{m2} + K_S(\Delta\delta_1 - \Delta\delta_2) - K_{TCSC}\Delta X_{TCSC} - K_{D2}\Delta\omega_2 \} \quad (8)$$

The linearized forms of equations 7 and 8 are in a more generalized form:

$$\begin{aligned} \Delta\dot{X} &= A\Delta X + b\Delta u \\ \Delta y &= c\Delta X + d\Delta u \end{aligned} \quad (9)$$

Fig. 4. Hybrid form of the system model [3].

The *hybrid* form [3] in Fig. 4 assumes that the system model is divided into two parts: one part is expressed in state-space form, and other part is described by a transfer function $F(s, q)$ describing the TCSC controller. The sensitivity of a closed loop eigenvalue λ_i with respect to a parameter q of the transfer function $F(s, q)$ is given by [3]:

$$\frac{\partial \lambda_i}{\partial q} = R_i \cdot \left. \frac{\partial F(s, q)}{\partial q} \right|_{s=\lambda_i} \quad (10)$$

where R_i is the residue of the closed loop transfer function $\Delta y / \Delta r$:

$$\begin{aligned} R_i &= w_i^T b \cdot \frac{1}{(1 - F(\lambda_i, q) \cdot d)^2} \cdot c v_i \\ &= w_{i, \Delta u} \cdot \frac{1}{(1 - F(\lambda_i, q) \cdot d)^2} \cdot v_{i, \Delta y} \end{aligned} \quad (11)$$

and v_i, w_i are respectively the right and left eigenvectors associated to the eigenvalue λ_i . It should be noted that

$w_{i, \Delta u}, v_{i, \Delta y}$ are respectively the modal controllability and observability factors. b, c are respectively the input and output matrix in the state equation (9).

When the controller is a TCSC, the input variable to the transfer function is the series reactance deviation and the output is the TCSC control signals. The controllability of *ith* mode indicates the effect of the input on the mode. The modal observability shows the impact of the output signals. This case arises when appropriate locations of damping controllers are sought in a power system. The magnitude of eigenvalue sensitivity informs about the best location. The phase of the eigenvalue sensitivity also provides valuable information: the phase compensation required at the eigenvalue frequency to maximize the controller effect [3].

Equations (7) and (8) represent an additional damping torque by the TCSC in the two-machine system, i.e. $K_{TCSC}\Delta X_{TCSC}$. The initial line power is transferred from machine one to machine two and the initial relative angle $\Delta\delta_0 (= \Delta\delta_{01} - \Delta\delta_{02})$ is positive. During a power swing, the machines oscillate at a relative speed $\Delta\omega (= \Delta\omega_1 - \Delta\omega_2)$. If the receiving end-machine speed is lower than the sending end-machine speed, i.e. $\Delta\omega$ is positive, the rotor angle difference $\Delta\delta (= \Delta\delta_1 - \Delta\delta_2)$ is positive and machine one decelerates if the TCSC damping torque is negative. Since K_{TCSC} is positive, this means that ΔX_{TCSC} is negative. It also shows that machine two accelerates in this condition. In other words, while the sending

end-machine accelerates, the TCSC control should attempt to draw more power from this machine, to create a reduction of the kinetic energy responsible for its acceleration. When $\Delta\omega$ is negative, the TCSC must decrease the power flow in the line, i.e. ΔX_{TCSC} becomes positive. Analysis of the TCSC damping torque during a power swing brings out an effective control strategy in damping system oscillations using the TCSC. The control signal is selected as the difference between the rotor angle deviations of the two machines ($\Delta\delta_2 - \Delta\delta_1$). For previous reasons, this signal can contribute directly to oscillation damping and enhance stability in power systems. As local signals are also available, this can resolve in an improved control using only local signals. Hence, the locations and controller designs of the TCSCs using the local input signal will be addressed using the formulation of eigenvalue sensitivities, the controllability and observability factors that has been represented in [3]. These study results will be used for designing the TCSCs using the remote measurement signals.

IV. TRANSIENT STABILITY STUDIES

A. Vietnamese power transmission system

The Vietnamese 220-500 kV transmission system is used to analyze the small-signal stability for location and design of the controllers and study the transient stability enhancement with the TCSCs. The test system was indicated in [8]. Fig. 5 depicts a North-South 500 kV section of the system. Table I gives information about generation, loads and losses of the 220-500 kV transmission system. The loads in the system are modelled with 50% constant current and 50% constant susceptance for real and reactive power loads in dynamic simulations. The largest hydro-power plant is Hoabinh (G1) with a total capacity of 1,920 MW. The biggest thermal power plant, Phumy (G2), has a capacity of 4,166 MW.

Fig. 5. 500-KV transmission system: (a) one-line diagram with possible TCSC locations; (b) geographical depiction.

The North-South 500 kV transmission system can count as an intertie which consists of four 500 kV sections: Nhoquan-Hatinh, Hatinh-Danang, Danang-Pleiku, and Pleiku-Daknong

(Dilinh). Each section has two parallel circuits equipped with fixed series capacitors compensating approximately from 51% to 86% of the corresponding line reactance. Table II gives information on the intertie lines and the present series compensator ohmic sizes and current ratings.

TABLE I
CAPACITIES AND LOSSES OF TRANSMISSION SYSTEM

	Unit	Quantity
Total installed generation capacity	MW	19228
Total generation	MW	13528
Total loads	MW	13293
Total losses	MW	235
Total loss ratio	%	1.74

TABLE II
TRANSMISSION LINES AND SERIES COMPENSATION

	Nhoquan-Hatinh	Hatinh-Danang	Danang-Pleiku	Pleiku-Daknong	Pleiku-Dilinh
Transmission Lines					
Length	307 km	393 km	294 km	300 km	312.5 km
Reactance	86.6 Ω	110.8 Ω	82.9 Ω	84.6 Ω	88.1 Ω
Power transfer	-365 MW	-639 MW	-1208 MW	-323 MW	-151 MW
Series Compensation					
Rated Current	2200 A	2200 A	2200 A	2200 A	2200 A
Reactance	2x23 Ω	2x30.5 Ω	2x21.5 Ω	(41.5+18.8) Ω	(46+30) Ω
Percentage	51.4%	55.1%	51.7%	71.3%	86.3%

To absorb the reactive power generated by the long 500 kV transmission lines, the intertie circuits are equipped with fixed shunt reactors. With these fixed series and shunt compensations, the North-South transmission system is currently rated for 2,000 MW power transfer. The steady-state power flow result without TCSCs shows that maximum active power of 1,208 MW is delivered from Pleiku to Danang, 639 MW from Danang to Hatinh and 323 MW from Daknong to Pleiku.

B. Location, design and co-ordination of TCSCs

The eigenvalue sensitivity approach [3] is applied for location, controller design and co-ordination of TCSCs for the system. To study on the suitable locations of the TCSCs, an assumption is 14 fixed series capacitors are replaced by TCSCs of the same current rating 2200 A and of the same series compensator ohmic sizes as shown in Fig.5. The linearized model of the system contains two critical electromechanical modes. Table III contains the eigenvalues, the mode shapes and the participation of the generators corresponding to two critical electromechanical modes.

TABLE III
ELECTROMECHANICAL MODES

Mode	Eigenvalues	Mode Shape	Participation
1	$-0.7388 \pm j7.5156$	G1: 0.8736 $\angle 0^\circ$ G2: 0.0118 $\angle 3^\circ$ G3: 0.0263 $\angle -3.9^\circ$	G1: 0.5199 G2: 0.0002 G3: 0.0004
2	$-0.8101 \pm j7.9422$	G1: 0.0228 $\angle 6.5^\circ$ G2: 0.9245 $\angle 180^\circ$ G3: 0.1186 $\angle 146^\circ$	G1: 0.0002 G2: 0.52 G3: 0.0013

TCSC damping control schemes are designed to improve the damping of mode 1 and 2 without deteriorating the damping

of other modes. The mode shapes show that mode number 1 corresponds to an oscillation of Hoabinh (G1) against Phumy (G2) and Yaly (G3) whereas mode number 2 describes an oscillation of Phumy (G2) against Hoabinh (G1) and Yaly (G3). The participations indicate that mode number 1 is dominated by Hoabinh (G1) generator and mode number 2 is dominated by Phumy (G2) generator.

The magnitude of the eigenvalue sensitivities will be used to discuss the most appropriate location of a TCSC to stabilize the electromechanical modes. Fig. 6 and 7 present respectively the magnitude of sensitivities of the two dominant eigenvalues $-0.7388 \pm j7.5156$ and $-0.8101 \pm j7.9422$ with respect to the reactance modulation using active power as input signal. It is noted that the most effective TCSCs to stabilize mode 1 are SC5 and SC6, whereas SC11 and SC12 are best locations of the TCSCs to improve the damping of mode 2. The best co-ordinated controls of the TCSC devices can be achieved by using the TCSCs in the locations SC5 and SC6 to damp mode 1 and SC11 and SC12 to damp mode 2.

Fig. 6. Sensitivities of the eigenvalues $-0.7388 \pm j7.5156$ with respect to the TCSC modulation using active power as input.

Fig. 7. Sensitivities of the eigenvalues $-0.8101 \pm j7.9422$ with respect to the TCSC modulation using active power as input.

The controller design process can be split into two parts: (i) the design of the controller phase compensation network so that the phase of eigenvalue sensitivity after the controller installation becomes 180° and (ii) the computation of the controller gain to achieve the desired damping. The dynamic model of the stability controller is shown in Fig. 2. The response of the TCSC to a reactance modulation command is

represented by a first order system of 0.05 seconds time constant. The time constant of the washout has been assumed to be equal to 1.5 seconds. The phase compensation network of the controller should be designed such that the phase of the sensitivity of the eigenvalues with respect to a variation of K_C becomes 180° :

$$\frac{\partial \lambda}{\partial K_C} = w_{\Delta x} \cdot \left(\frac{1 + \lambda T_2}{1 + \lambda T_3} \cdot \frac{\lambda \cdot 1.5}{1 + \lambda \cdot 1.5} \cdot \frac{1}{1 + \lambda \cdot 0.05} \right) \cdot v_{\Delta P} \quad (12)$$

where $w_{\Delta x}$ and $v_{\Delta P}$ are respectively the modal controllability factor of the TCSC and the modal observability of active power through the TCSC. The gain of the controller can also be determined using the eigenvalue sensitivity so that the eigenvalue of our interest moves from the original location λ^0 to the desired location λ^d as:

$$\Delta K_C = \left| \frac{\lambda^d - \lambda^0}{\partial \lambda / \partial K_C} \right| \quad (13)$$

Following the procedure that is presented above, the design results for SC5, SC6, SC11 and SC12 controllers are shown in Table IV.

TABLE IV
DESIGN OF THE TCSCS

	Design of SC5 & SC6	Design of SC11 & SC12
Original eigenvalues (λ^0)	$-0.7388 \pm j7.5156$	$-0.8101 \pm j7.9422$
Desired eigenvalues (λ^d)	$-0.7391 \pm j7.5163$	$-0.8758 \pm j7.8216$
γ^*	72°	62.24°
Compensated phases	124.25°	135.46°
T2 (second)	0.1002	0.1362
T3 (second)	10.0	10.0
ΔK_C	0.2054	0.0313

γ^* – The phase of product of the modal controllability and observability factors.

C. Parameter Settings

Based on the results of the location and co-ordination of the TCSCs, it is assumed that four existing fixed series capacitors, two in the Hatinh–Danang lines near to Hatinh bus and two others in the Danang–Pleiku and Docsoi–Pleiku lines near the Pleiku bus, are replaced by four TCSCs with the maximum series compensated level of 70% of the line reactances. The locations of TCSCs are shown in Fig. 8. The normal compensation requirement is entirely met by the TCSC operating with thyristors blocked. The TCSC capacitor current ratings are adequate for the normal steady-state conditions at the base 2000 MW loading. The steady-state TCSC reactance (set-point) for the normal steady-state conditions at the base loading is $X_{net} = X_{pf}$. In transients, the TCSC net reactance is limited by its ratings $X_{emin} \leq X_{net} \leq X_{emax}$. The capability characteristics of the TCSCs are represented in Table V.

Fig. 8. TCSC locations and three-phase fault on 500-KV transmission system.

TABLE V
CAPABILITY CHARACTERISTICS OF TCSCs

	TCSC 1	TCSC 2	TCSC 3	TCSC 4
Steady-state reactance (set point)				
X_{pf}	-30.5 Ω (-0.0122 p.u.)	-30.5 Ω (-0.0122 p.u.)	-21.5 Ω (-0.0086 p.u.)	-30.5 Ω (-0.0122 p.u.)
Limits of TCSC net reactance				
Maximum (X_{max})	-64.25 Ω (-0.0257 p.u.)	-64.25 Ω (-0.0257 p.u.)	-43.0 Ω (-0.0172 p.u.)	-43.0 Ω (-0.0172 p.u.)
Minimum (X_{min})	-15.25 Ω (-0.0061 p.u.)	-15.25 Ω (-0.0061 p.u.)	-15.25 Ω (-0.0061 p.u.)	-15.25 Ω (-0.0061 p.u.)

The parameters of the stability controllers are given in Table VI. The parameters T_w , T_2 , T_3 of each controller are the same for local and remote input signals and depend on the locations. Only the controller gain K_C and time constant T_1 differ: K_C , which depends on amplitude of TCSC's input signals, to ensure good first swing damping and to provide positive overall damping. T_1 to take the measurement delay (local and remote) into account.

TABLE VI
PARAMETERS OF THE TCSC CONTROLLERS

	Input signals	K_C	T_w	T_1	T_2	T_3
TCSC 1	Local active power (P)	0.2054	1.5	0.05	0.1002	10
TCSC 2	Remote rotor angle deviation ($\Delta\delta$)	288	1.5	0.1	0.1002	10
TCSC 3	Local active power (P)	0.0313	1.5	0.05	0.1362	10
TCSC 4	Remote rotor angle deviation ($\Delta\delta$)	44	1.5	0.1	0.1362	10

D. Measurements, Input Signals and Time-Delay

Remote measurements and information are used for the transient stability control. Phasor Measurement Units (PMUs) are placed at Hoabinh and Phumy to obtain synchronized phasors representing the receiving and sending end-machine respectively. The steady-state power flow results show that active powers transferring through the TCSCs are from Phumy to Hoabinh. With remote input signals for the TCSC controllers, the angle difference between Hoabinh and Phumy stations represents the inter-area swing angle

$\Delta\delta (= \Delta\delta_{Hoabinh} - \Delta\delta_{Phumy})$. This angle deviation is used as an input signal for all four TCSCs. To compare the effectiveness of local and remote input signals, transient simulations are done, using the active power flows as local signal input, and compared with the effect of the remote signals.

There is a need to address the delay introduced by transmitting and processing the signals from the remote site to the location of the TCSC controller. Depending on the distance of the measurement site, the mode of signal transmission and the processing time, a typical time-delay is in the range of 0.01 s to 1.0 s can be expected [9]. The delay using optical fiber communication in a PMU/WAMS system, is typically 40-60 ms according to [10] and in the Bonneville Power Administration (BPA), the delay is approximated as 38 ms [11]. In this paper, the remote communication delay is assumed to be 100 ms (which is an additional delay of 50 ms compared to the local measurement delay).

E. Dynamic Simulations and Results

Transient stability studies are conducted using the PSS/E-32 program. The data files include power flow and dynamic simulation data files. The generator model for the dynamic simulations includes exciters, voltage regulators, power systems stabilizers, and governors are chosen from the PSS/E model library [12] in accordance with the actual generators of the Vietnamese power system. For the TCSC model, code is written and compiled to run dynamic simulations by the PSS/E software. The input signals for the TCSC controller are put in this code. A three-phase fault occurs in one of two parallel circuits of the 500 kV North-South transmission system depicted in Fig. 8. The fault at Hatinh – Danang (N1) is a major disturbance. The fault is applied at $t = 1.0$ s, and cleared after 100 ms (5 cycles). The rotor angle oscillation of the two main power plants (Hoabinh and Phumy) located at two ends of the 500 kV transmission system is used to study the transient stability of the transmission system. To analyze and compare the controlling effects of the TCSCs for the transient stability enhancement along with the different input signals, the simulations of the rotor angle oscillations involve three cases: transient stability of the system without the TCSCs, with the TCSCs together with the remote signals (rotor angle derivations) and the local signals (active power flows). Fig. 9 represents the simulation results of rotor angle oscillations of Hoabinh and Phumy power plants with respect to the system average angle when the system suffers the fault N1. The simulations are conducted with and without the TCSCs. Pre-fault, power is transferred from Phumy to Hoabinh through the TCSCs. Applying the effective control strategy in damping system oscillations using TCSC, the rotor angle difference $\Delta\delta$ between the two machines ($\Delta\delta_{Hoabinh} - \Delta\delta_{Phumy}$) is selected as the control signal of the TCSCs. This angle difference is approximated by using the bus voltage angles of these two generator.

Fig. 9. Excursions of machine angles with and without TCSCs. Fault N1 at 500kV Hatinh-Danang line. Remote input signal is rotor angle deviation ($\Delta\delta$).

Fig. 10. TCSC equivalent reactance variations. Fault N1 at 500kV Hatinh-Danang line. Remote input signal is rotor angle deviation ($\Delta\delta$).

The lines 3 and 4 in Fig. 9 show the excursions of machine angles when the TCSCs are not installed. The system without the TCSCs is transiently unstable, losing synchronism after about 2-3 seconds as shown in Fig. 9. In this case, appropriate control is needed to damp first swings. Making an examination of the lines 3 and 4, the rotor angles of two-end generators of the system (Hoabinh and Phumy) swing in opposite ways during the first 2 seconds of the swings. Control law for the TCSCs is applied and compensation using the full transient capabilities of the TCSCs during the first swing conditions is needed. This maximizes the device effectiveness for the first swing stability and provides positive damping. The lines 1 and 2 in the figure represent the angle swings of Hoabinh and Phumy generators respectively when all four TCSCs using the remote input signal are installed. Fig. 10 illustrates the TCSC net reactances varying with the remote input signals (angle differences). The TCSC's stability

controllers are activated immediately following the disturbance (fault N1) and they stabilize the system and damp the remaining oscillations in only 12 seconds. The performance of the TCSC controllers when the angle deviation between generators Hoabinh and Phumy is used as the input signal is higher transient stability improvement. This confirms the results obtained from the analysis presented in Section III.

Fig. 11. Excursions of machine angles with TCSCs. Fault N1 at 500kV Hatinh-Danang line. Remote and local input signals are rotor angle deviations ($\Delta\delta$) and active power P respectively.

Fig. 12. TCSC equivalent reactance variations. Fault N1 at 500kV Hatinh-Danang line. Local input signals are active power P .

Fig. 11 and 12 describe the machine angle excursions and the TCSC reactance variations for the fault N1 when the active power flows P through the lines are used as the TCSC control input signals (local). Fig. 11 compares the effectiveness of the local and the remote signals. When using remote signals, a time delay occurs due to communication delays. This delay is taken into account and a value of 100 ms is used. Fig. 11

shows, when using local signals, the TCSCs maintain the stability of the system after 21 seconds. This is an evidence for selecting the suitable locations of the TCSCs and good controller using eigenvalue sensitivity. It should be realized that the stabilizing effect of the controllers when P is used as the input signal is much weaker than that when the remote signal $\Delta\delta$ is utilized even when a transmission delay of 100 ms is taken into account. However, the use of the local signals results in smaller initial excursions of the rotor angles.

V. CONCLUSIONS

Based on the analysis on effectiveness of using remote control signals, information available from PMUs is used providing the machine angle difference between two main power plants to the TCSC stability controllers. The analysis of eigenvalue sensitivities is an effective approach for location, configuration, parameters and co-ordination of the TCSC controllers using the remote input signal. Transient stability studies are performed using the PSS/E program. The simulation results indicate potential loss of transient stability during severe disturbances. Proper parameters, input signals and locations of the controllers provide better damping of transient swings, and TCSC automatically adjusts the compensation to enhance transient stability of power system. The TCSC controllers using the rotor angle deviations as remote measurement signals supplied from the PMUs improve transient stability much better if as compared with the local control signals.

VI. ACKNOWLEDGMENT

Nguyen Tuan Anh would like to thank the Belgian Technical Cooperation for granting him a scholarship to carry out his Ph.D. studies at the Katholieke Universiteit Leuven, Belgium.

VII. REFERENCES

- [1] Alberto D. Del Rosso, Claudio A. Canizares, and Victor M. Dona, "A Study of TCSC Controller Design for Power System Stability Improvement," *IEEE transactions on power systems*, Vol. 18, No. 4, November 2003, pp. 1487-1496.
- [2] X. Zhou and J. Liang, "Overview of Control Schemes for TCSC to Enhance the Stability of Power Systems," *IEE Proc. Gener. Transm. Distrib.*, Vol. 146, No. 2, March 1999, pp. 125-130.
- [3] L. Rouco, P. L. Pagola, "An eigenvalue sensitivity approach to location and controller design of controllable series capacitors for damping power system oscillations," *IEEE Transactions on Power System*, Vol. 12, No.4, Nov. 1997.
- [4] John J. Paserba, Nicholas W. Miller, Einar V. Larsen, and Richard J. Piewko, "A Thyristor Controlled Series Compensation Model for Power System Stability Analysis," *IEEE transactions on power delivery*, Vol. 10, No. 3, July 1995, pp. 1471-1478.
- [5] R. Mohan Mathur and Rajiv K. Varma "Thyristor-Based FACTS Controllers for Electrical Transmission systems," *IEEE Series on Power Engineering*, Mohamed E. El-Hawary, Series Editor.
- [6] S. Nyati, C. A. Wegner, R. W. Delmerico, D. H. Barker, R. J. Piewko, and A. Edris, "Effectiveness of Thyristor-Controlled Series Capacitor in Enhancing Power System Dynamics: An Analog Simulator Study," *IEEE Transactions on Power Delivery*, Vol. 9, No. 2, April 1994, pp. 1018-1027.
- [7] The Electric Power Research Institute (EPRI) WO 3789-05, "Assessment of Application and Benefits of Phasor Measurement technology in Power Systems," Final Report by General Electric (GE) Company, EPRI Report TR-107903, April 1997.

- [8] Nguyen Tuan A., Van Hertem D., Driesen J., "Transient Stability Enhancement by TCSC Controllers using Remote Input Signals," *The 9th International Conference on AC and DC Power Transmission (IET ACDC 2010)*, London, UK, October 2010.
- [9] B. Chaudhuri, R. Majumder, and B. C. Pal, "Wide-Area Measurement-Based Stabilizing Control of Power System Considering Signal Transmission Delay," *IEEE Transactions on Power Systems*, Vol. 19, No. 4, pp. 1971-1979, Nov. 2004.
- [10] R. K. Varma, R. P. Gupta and S. Auddy, "Damping of Inter-Area Oscillation in Power Systems by Static Var Compensator (SVC) Using PMU-Acquired Remote Bus Voltage Angles," *International Journal of Emerging Electric Power Systems*, Vol. 8, Issue 4, 2007.
- [11] C. W. Taylor, M. V. Venkatasubramanian, and Y. H. Chen, "Wide-Area Stability and Voltage Control," *Proceedings of the VII Symposium of Specialists in Electric Operational and Expansion Planning*, 2000, pp. 1-9.
- [12] PSSTME-32 Program, "Program Operation Guide," "Program Application Guide", PTI-Software Solutions, Siemens, December 2007.