

A Fuzzy Logic based Adaptive Control of TCSC for Power Oscillations Damping

Vandai Le, Xinran Li, Caoquyen Le, Honghu Zhou

Abstract — This paper presents an approach to the designing of a fuzzy logic-based adaptive Thyristor Controlled Series Capacitor (FLBA-TCSC) controller via minimum total energy function method to improve the power oscillation damping of a wide area power system control and enhance system stability. Within the new control strategy, using a combination of a Fuzzy logic control (FLC) and SCADA signal to establish control rules, which monitor TCSC operations with respect to various working conditions of the power system. The effectiveness of proposed approach has been validated through various simulation cases of the three phase faults at different locations of the Vietnamese power network. In order to verify the performance of the proposed control, the proposed controller is compared with a traditional and none TCSC model. The simulation results show that the proposed control scheme improves the dynamic stability and provides the effective damping of generator angle oscillations and power ones.

Index Terms — TCSC, energy function, angle oscillation, power oscillation, dynamic stability.

I. INTRODUCTION

TCSC is an important FACTS device that is increasingly applied in modern power systems with long transmission lines. Basically, TCSC has more about the effects in control and operation of power system, for example adjusting power flow; decreasing unsymmetrical components and network loss; providing voltage support; limiting short-circuit currents; assuaging sub-synchronous resonance; damping the power oscillations; enhancing transient and dynamic stability [1]. However, the effectiveness of the TCSC controller depends on the strategic location and control input signals of TCSC. Recently, many researchers have proposed some methods to design the power damping controller for a TCSC based on different control schemes, such as, PI control scheme that is simple and easy to design, which has been suggested in the literature [1]-[3]. A hybrid controller of TCSC combines the advantages of a fuzzy logical controller and a conventional PI controller is proposed in [4]. A new method to reduce the rules of self-tuning fuzzy PI controller for TCSC is designed in [5]. PSO is used to search the optimal parameters of TCSC controller to damp oscillations [6].

A robust design algorithm for simultaneous coordinated tuning of the TCSC damping controller and PSS is proposed in [7]. A passivity-based controller is designed for TCSC rest on Hamiltonian formulation aimed at enhancing system stability [8]. Damping of generator oscillations is investigated using FACTS devices based on adaptive FLC schemes [9], [10]. A phase-plane fuzzy logic control scheme for TCSC to damp power oscillations is discussed in [11]. A new controller based on bacteria foraging algorithm for TCSC in a multi-machine power system to mitigate system oscillations is designed in [12]. However, their performance becomes complicated for large scale power systems when the system operating conditions promptly change and large disturbances occur.

Currently, a typical input signal of the TCSC controller unit based on the power or current variation along the transmission line that is equipped TCSC, while the output signal is a variable capacitive reactance depended on oscillations of power system. However, in several circumstances, the signal of the power of transmission line provided to TCSC after fault occurred higher than that of initial settings, and the role of TCSC is a fixed series capacitor during a grid fault. Therefore, the damping of power system oscillations will be very slow. Hence, the selection of the input signals of TCSC is very important for damping oscillations of the power system. Construction of intelligent control model for TCSC which would meet transient situations occurring in system with a view to put the system to the initial setting status as quick as possible that is the special concerns. In practice, it is not easy to change input signals of TCSC in various transient periods when instantaneous response of power system occurs at different times. This paper presents the adaptive control rules based on Fuzzy by monitoring TCSC operations to various working conditions of the system. The proposed controller uses a combination of a FLC and SCADA signal based on minimum total energy function to establish control rules. The rest of this paper is organized as follows: Section 2 briefly describes the typical TCSC model. Control scheme of adaptive model for TCSC is then described in Section 3, it is also the proposed strategy used in this paper. Section 4, the test system model based on the electrical system of Vietnamese is described; these results of applying the proposed TCSC controller for damping power system are also discussed in this section. Finally, Section 5 summarizes the main contribution of this study.

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II. SYSTEM MODEL

A. Typical TCSC model

TCSC is one of the most important and the best known devices in series of FACTS controllers, and it is used to increase line power transfer capacity as well as to improve dynamic performance of the system. A typical TCSC consists of three components: The capacitor banks C, bypass inductor L and bi-directional thyristors as shown in Fig. 1.

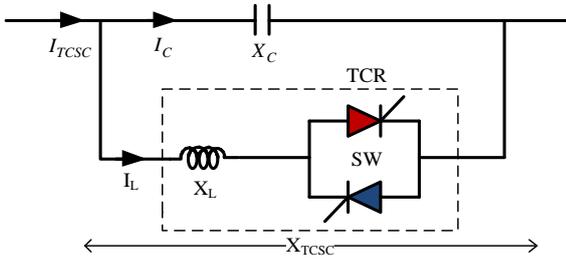


Fig. 1. Structure of the TCSC

The TCSC has four operating modes which are the blocking, bypass, capacitive boost, and inductive boost modes [13]. It can be seen from Fig. 2 that the modulation controller changing the reactance of the TCSC (X_{TCSC}) is achieved by controlling the firing angle (α) of Thyristor Controlled Reactor (TCR). The relationship between α and X_{TCSC} can be expressed as follows:

$$X_{TCSC}(\alpha) = \frac{X_C X_L(\alpha)}{X_L(\alpha) - X_C} \quad (1)$$

where $X_L(\alpha) = X_L \frac{\pi}{\pi - 2\alpha - \sin \alpha}$, $X_L \leq X_L(\alpha) \leq \infty$; in which X_C is nominal reactance of the fixed capacitor; X_L is the inductive reactance of inductor connected in parallel with the fixed capacitor; α is the firing angle of TCSC; X_{TCSC} is the reactance of TCSC.

Therefore, the TCSC has two operating ranges (inductive and capacitive regions) around its internal circuit resonance as illustrated in Fig. 2 [1].

B. Single machine infinite bus model with TCSC

The single machine infinite bus (SMIB) power system is considered in this paper. In this system, a synchronous generator is connected to an infinite bus through the transformer and double-transmission line. The TCSC is located between the transformer and infinite bus as shown in Fig. 3.

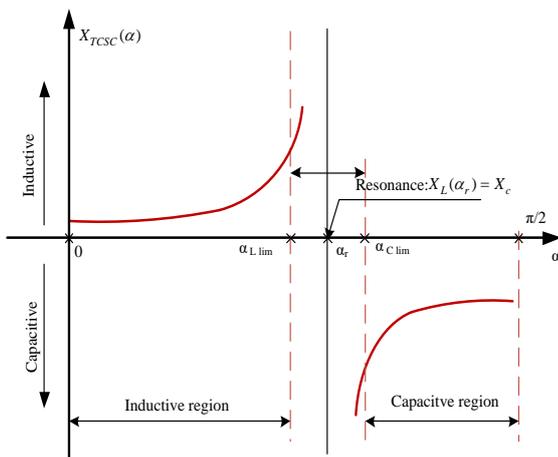


Fig. 2 The impedance and delay angle α characteristic of the TCSC

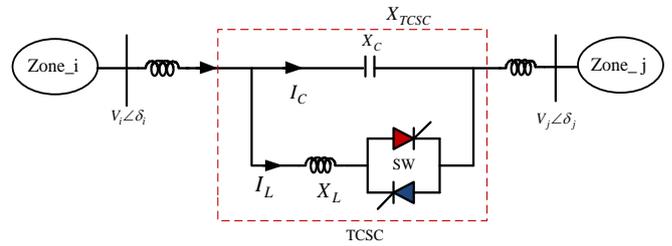


Fig. 3. Single line diagram for SMIB with TCSC

where E and V_∞ are the generator terminal and infinite bus voltages, respectively; X'_d , X_T , X_L and X_{TH} represent the d -axis transient reactance of the generator, the equivalent reactance of transformer, the resistance of transmission line and the Thevenin's impedance of the receiving end infinite bus, respectively. The derivative equations of dynamics for the machine are expressed by [14]-[16]

$$\frac{d\delta}{dt} = \omega \quad (2)$$

$$M \frac{d^2 \delta_{ij}}{dt^2} = P_m - P_e \sin \delta_{ij} \quad (3)$$

$$\frac{dE}{dt} = \frac{1}{T'_{do}} \left((E_{fd} - E) - (X_d - X'_d) i_d \right) \quad (4)$$

where δ and ω are the machine shaft angle in rad and the shaft angle velocity rad/s respectively; E and E_{fd} are the terminal voltage and excitation voltage, respectively; D and M are the damping coefficient and inertia constant, respectively, P_m and P_e denote the mechanical and electrical power, respectively; X_d is the d -axis synchronous reactance; T'_{do} is the d -axis time constant; i_d is the d -axis stator current. Thus, the equivalent reactance between the generator and the infinite bus is calculated as follows:

$$Z = X'_d + X_T + X_L + X_{TCSC} + X_{TH} \quad (5)$$

Thence the transmission line power flows are functions of X_{TCSC} and δ as expressed in equation (6). Suppose that the generator terminal voltage of E and the infinite bus voltage of V_∞ to be constants, the active and reactive powers generated from the generator to the infinite bus depend on the change of X_{TCSC} and δ . Usually the operating mode of TCSC is capacitive boosting, so the reactance of TCSC is negative. For convenience in description, the symbol X_{TCSC} in following context including equation (6) represents the absolute value of the reactance of TCSC.

$$P_e = \frac{EV_\infty}{Z} \sin(\delta) \quad (6)$$

$$Q_e = \frac{E^2 - EV_\infty \cos(\delta)}{Z}$$

Establishment of objective function is of critical importance to comment goals of transient control. Generally, that is defined as: (a) to ensure steady-state transient, (b) to ensure damping of transient period and quickly to steady-state. According to the SMIB, the total energy function can be as follows [13], [15].

$$V(\delta, \omega) = \frac{1}{2} M \omega^2 - P_m (\delta - \delta^s) - P_e (\cos \delta - \cos \delta^s) \quad (7)$$

Assuming that P_m and E are constants, the total equivalent electrical impedance of the system depends on control strategy of TCSC according to following conditions:

$$Y = \begin{cases} Y_{\max} & \text{if } X_{TCSC} = X_{TCSC \max} \\ Y_{\min} & \text{if } X_{TCSC} = X_{TCSC \min} \end{cases} \quad (8)$$

where $Y = Y_{\max}$ when capacitor reactance has the highest value; $Y = Y_{\min}$ when capacitor reactance has the lowest value; $X_{TCSC \max}$ and $X_{TCSC \min}$ are the maximum and minimum values of X_{TCSC} , which represent the absolute value of the reactance of TCSC.

In this study, the main aim of the controller is to minimize the total energy function at time of T that is the end time of control process. Accordingly, the total energy function must be shown as following.

$$V(\delta, \omega)|_{t=T} \rightarrow \min(V(\delta, \omega)) \quad (9)$$

In order to show the advantages of modeling the TCSC controller dynamically, decreasing total equivalent electrical impedance of the system to make sure that the total energy function shall be minimized at all times. The law of controller is used as following:

$$Y = Y_{\min} + \frac{Y_{\max} - Y_{\min}}{2} [1 - \text{sign}(\omega \sin(\delta))] \quad (10)$$

Equation (10) indicates the possibility of creating optimized input signal of TCSC based on measuring information. According to the operating conditions, the membership functions are adapted by the adaptive rules based on the following proposed algorithm.

$$Y = \begin{cases} Y_{\max} & \omega \sin(\delta) < 0 \\ Y_{\min} & \omega \sin(\delta) > 0 \end{cases} \quad \sin(\delta) \in P; \omega \in \frac{\partial \delta}{\partial t} \quad (11)$$

C. Multi-machine system with TCSC

In multi-machine system, the total energy function is described as equation (12) [17].

$$V = \frac{1}{2} \sum_{i=1}^n M_i \omega_i^2 - \sum_{i=1}^n P_{Mi} (\theta_i - \theta_i^s) - \sum_{i=1}^{n-1} \sum_{j=i+1}^n [C_{ij} (\cos \theta_{ij} - \cos \theta_{ij}^s) - \int_{\theta_j + \theta_j^s}^{\theta_i + \theta_i^s} D_{ij} \cos \theta_{ij} d(\theta_i + \theta_j)] \quad (12)$$

where

$$P_{mi} = \text{Re}(\dot{E}_i \dot{I}_i^*) = \text{Re} \dot{E}_i \left(\sum_{j=1}^n Y_{ij}^* \cdot \dot{E}_j \right) = E^2 G_{ii} + \sum_{\substack{j=1 \\ j \neq i}}^n E_i \cdot E_j [B_{ij} \sin(\delta_i - \delta_j) + G_{ij} \cos(\delta_i - \delta_j)]$$

$$\theta_i = \delta_i - \delta_0; \delta_0 = \left(\sum_{i=1}^n M_i \delta_i \right) / \sum_{i=1}^n M_i; \theta_{ij} = \theta_i - \theta_j; C_{ij} = E_i E_j B_{ij}$$

; $D_{ij} = E_i E_j G_{ij}$, G_{ij} , and B_{ij} are the real and imaginary parts of the admittance between generator i and generator j ; i and j are the numbers of generators; ω_i are the angle speed of generator i ; M_i is the inertia constant of generator i .

If the angle speeds $\omega_i > 0$, the TCSC control

signal $\sin(\delta)$ will follow adaptive control rules shown in equation (13).

$$Y = \begin{cases} Y_{\max} & \Delta \delta < 0 \\ Y_{\min} & \Delta \delta > 0 \end{cases} \quad (13)$$

where $\Delta \delta = \delta_{t=T} - \delta_{t=0}$; $\delta_{t=T}$, and $\delta_{t=0}$ denote the voltage angle of two buses install TCSC for transient and steady states period, respectively.

III. ADAPTIVE ALGORITHM OF TCSC

Based on the conditions given in equation (13), the Fuzzy TCSC control mode has been well established with continuous function expressed as equation (14)

$$\begin{cases} \text{if } 0 < t < t_{start} & \text{then } X = X_{start} \\ \text{if } t_{start} \leq t \leq t_{clear} & \text{then} \\ \quad \text{if } \Delta \delta > 0 & \text{then } X = X_{\min} \\ \quad \text{if } \Delta \delta < 0 & \text{then } X = X_{\max} \\ \text{if } t > 8 \text{sec} & \text{then } X = X_0 \end{cases} \quad (14)$$

where t_{start} , t_{clear} , X_{max} , X_{min} , X_0 , and X_{start} denote fault time, fault clearance time, the highest and lowest equivalent reactance of the transmission line, the equivalent reactance of the transmission line after fault clearance, and equivalent reactance of the transmission line at initial steady-state, respectively.

The rules of fuzzy logic system are defined in easy human language and based on specialist knowledge, such as "if...then..." [18]. There are many other types of fuzzy logic controllers, but typically all of them are based on the model shown in Fig. 4.

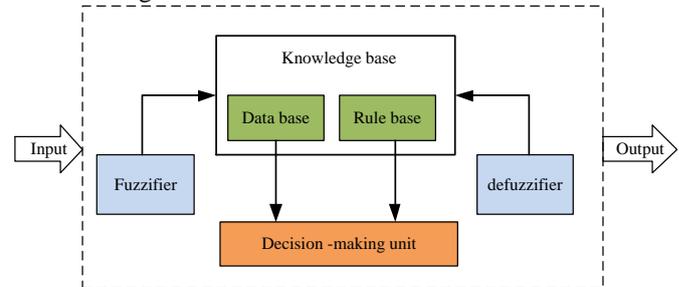


Fig. 4. Fuzzy construction system

In this study, the application of fuzzy logic to TCSC control model is based on these rules by overseeing the operations of conventional TCSC during power system fault period. Assuming that the short-circuit fault occurs on arbitrary location of the transmission line as shown in the Fig. 5, the transmission line differential protection relay 7SD60 and F85 will send commands to signal receiving center controller located in substation where TCSC is installed. The input signal containing the address of faulty transmission line will be sent to the fuzzy logic controller to analyze and select a set of preset control sample (this set of control sample is recorded during the transient for cut-out of three phases short-circuits) which will be used for activating TCSC. Dependent functions of fuzzy TCSC control model in this study were established as shown in Table 1.

Table 1. Membership functions of fuzzy TCSC control model

IF “Three-phase fault occurred in transmission line no.1”
 THEN “TCSC is controlled as per rule no. 1”
 IF “Three-phase fault occurred in transmission line no.2”
 THEN “TCSC is controlled as per rule no. 2”
 IF “Three-phase fault occurred in transmission line no.3”
 THEN “TCSC is controlled as per rule no. 3”

where control rules no.1, 2, 3 are constructed as follows:

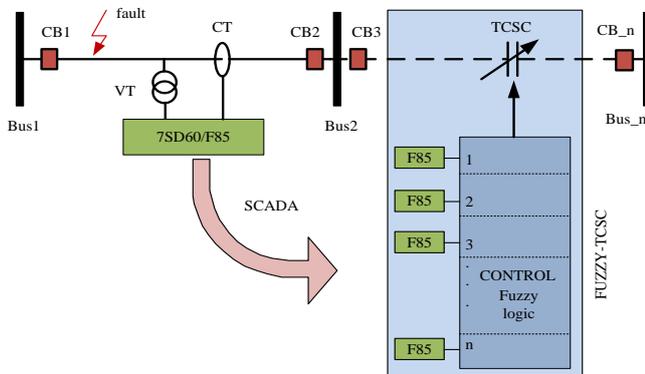


Fig. 5. Adaptive control structure for TCSC

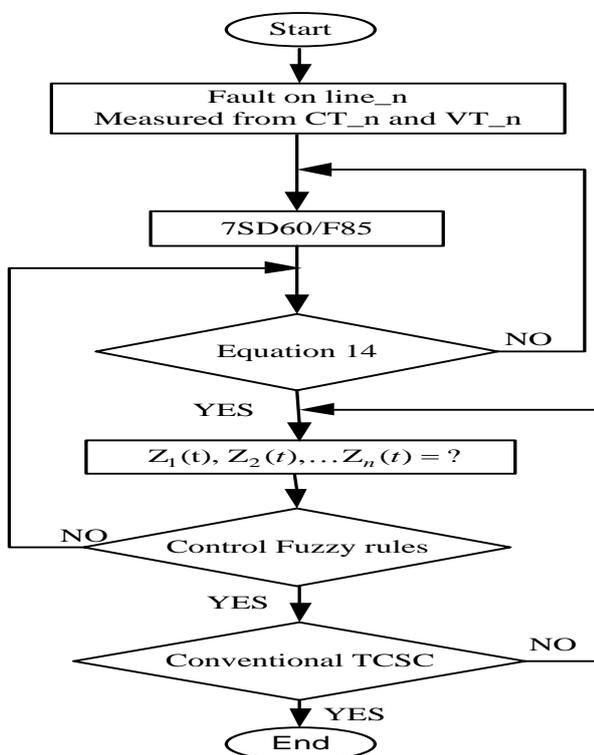


Fig. 6. Diagram of construction of adaptive mode for TCSC

The control set $Z_1(t)$, $Z_2(t)$, $Z_3(t)$ is established via continuous function from equation (9) according to the oscillation of voltage angle difference between two buses installed conventional TCSC. The input signal of conventional TCSC is the active power of transmission line based on damping oscillation power system in the shortest time.

IV. SIMULATION AND RESULTS

A. Simulation cases

In order to show the advantages of the proposed TCSC control strategy, the controller is applied to the power system of Vietnamese as shown in Fig. 7. This 500kV system consists of 179 generators, 36 transmission lines and 29 transformer stations at 500/220kV; the 220kV system consists of 271 transmission lines and 162 transformer sub-stations at 220/110kV; the total generator output power is 31.504MW; the total system load is 30.539MW. The TCSC is installed at 500kV PLEIKU-CAUBONG transmission line with total length of 437km, the TCSC parameters and control function are given in Appendix and Fig. 8. To evaluate the usefulness of the proposed method for TCSC, assuming the scenarios are given shown in Table 2.

Table 2. Scenarios for studying

Case	Three-phase fault at	Tripping of the transmission line after 150ms
1	Phulam	Phulam-Duchoa
2	Danang	Danang-Docsoi
3	Hatinh	Nhoquan-Hatinh

The calculations are based on the cases assumed in previous shown that there appeared two transmission lines with input signals of line active power for TCSC controller which given the best possibility for damping the power system oscillations. Two different cases are considered as follows:

- (a) When three-phase fault occurs on overhead transmission lines at Southern Viet Nam power system, the selected input signal is the active power of Pleiku–Thanhmy overhead transmission line.
- (b) When three-phase fault occurs on overhead transmission lines at Northern Viet Nam power system, the selected input signal is the active power of Caubong-Duchoa overhead transmission line. As illustrated in Fig. 7.

Table 3. Membership functions of fuzzy TCSC control model corresponding to rules

IF “Three-phase fault occurred in Phulam–Duchoa transmission line”
 THEN “TCSC is controlled as per rule no. 1”
 IF “Three-phase fault occurred in Danang–Docsoi transmission line”
 THEN “TCSC is controlled as per rule no. 2”
 IF “Three-phase fault occurred in Nhoquan–Hatinh transmission line”
 THEN “TCSC is controlled as per rule no. 3”

The adaptive controller of TCSC has been well established by studying various conditions and the proposed control rules. The membership function shown in the Table 3.

Control rules are as follows:

Rule no.1: The control sample $Z_1(t)$ was recorded according to reactance oscillations of the conventional TCSC and the input signal of TCSC is an active power of Pleiku-Thanhmy transmission line.

Rule no.2: The control sample $Z_2(t)$ was recorded according to reactance oscillations of the conventional TCSC and the input signal of TCSC is an active power of Caubong-Duchoa transmission line.

Rule no.3: The control sample $Z_3(t)$ was recorded according to reactance oscillations of the conventional TCSC and the input signal of TCSC is an active power of Caubong-Duchoa transmission line.

B. Simulation results

Some of contingency cases are taken in Table. 2 with three different conditions; namely, without TCSC, with the traditional TCSC and the proposed TCSC controller, Fig. 9 and Fig. 10 show the response time of the generator rotor angle oscillation of Pleiku, Duyenhai, Vinhtan, in case 1, respectively, respectively.

Fig. 11 depicts the response time of the power oscillation of overhead Danang-Vungan transmission line in case 1.

The response of the reactance is shown in Fig. 12.

Fig. 13 and Fig. 14 also show the response time of the generator rotor angle oscillation of Vinhtan and Duyenha in case 2 and case 3, respectively

C. Analysis and discussion

In order to investigate the impacts of the proposed controller, the simulation of transient stability in time domain is applied to both the traditional TCSC controller and the proposed FLBA-TCSC controller. The criterion for selection of optimized control model is based on the lowest time of damping the power system oscillations. In addition, the assessment of transient stability improvement of the power system with the TCSC controlled by Fuzzy is based on damping the oscillation of typical rotor angle oscillation, power oscillation, and the reactance oscillation of transmission line installed TCSC.

Fig. 9, Fig. 10, and Fig. 11 clearly show that the oscillation damping time of the power system equipped the proposed TCSC controller is about 7 to 8 seconds, while it is about 15 seconds for the system equipped with traditional TCSC controller. As observed in Fig. 12, due to applying the conventional TCSC controller, of which the input signal

is much smaller than the FLBA one, the variations of reactance of Pleiku-Caubong transmission line during the transient period are very small, while it varies from lowest to highest about 6 seconds for the proposed TCSC controller. Hence, the observations indicate that the proposed TCSC controller is better.

Fig. 13 and Fig. 14 clearly show that the oscillation damping time of the power system that is equipped with proposed TCSC controller is about 6 to 7 seconds, while it is about 13 seconds for the system that is equipped with traditional TCSC controller.

V. CONCLUSION

The optimized control standard of TCSC based on fuzzy logic via the minimum total energy function method is proposed in this paper. An application of this method for “reduced practical system of Vietnamese power network” shows the effective damping performance. Operating the proposed TCSC controller receives the measured signals that are the variation of voltage angle between two buses installed the TCSC during transient state period in comparison with steady-state after removing the fault to control the reactance of transmission line via dependent function that relates to the various reactance values of transmission line, which are constructed by selecting the best cases that have been chosen by comparing the dynamic performance of conventional TCSC with different input line active power signals.

The simulation results show that the response speed of the generator rotor angle oscillation, power oscillation on the line, and reactance oscillation of overhead transmission are significantly improved, when using the proposed method.

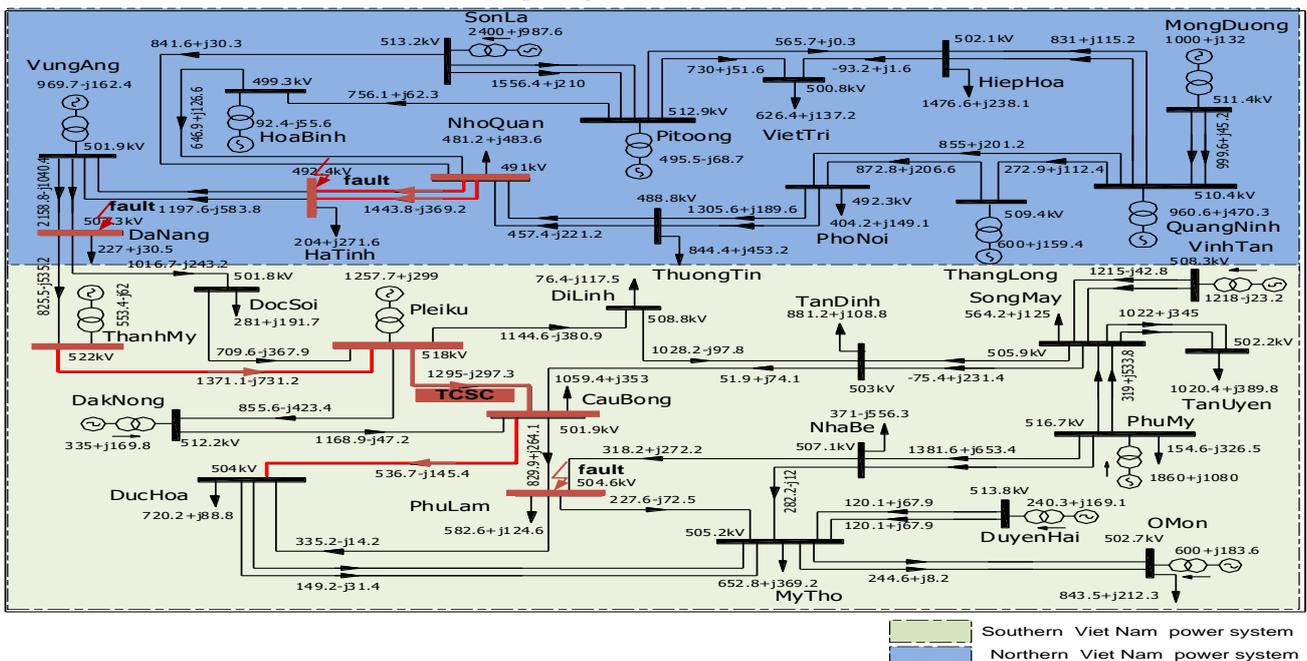


Fig. 7. Practical system of Vietnamese power network.



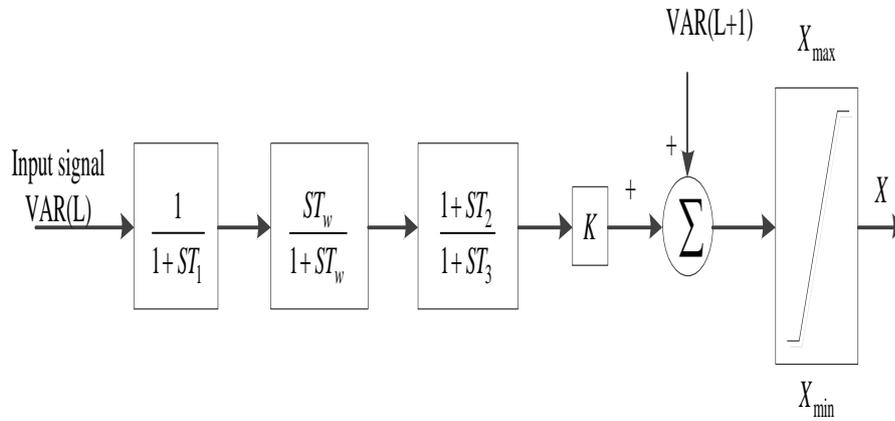


Fig. 8. Diagram of the control function of TCSC-CRANI

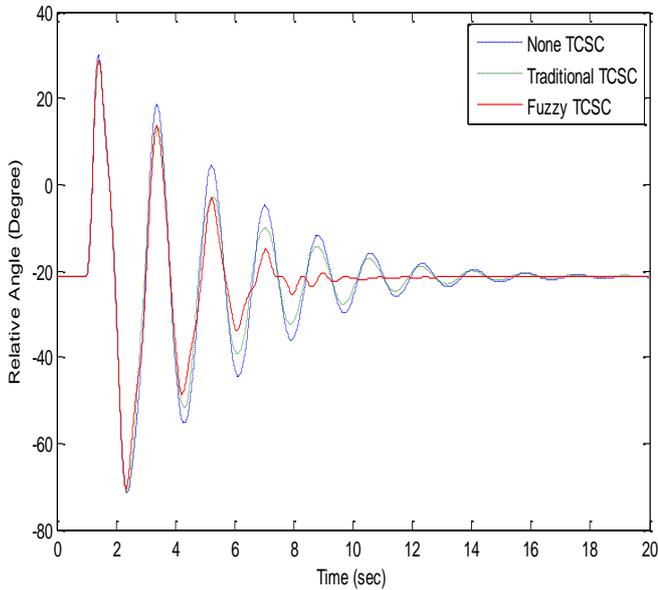


Fig. 9. Generator rotor angle oscillation of Pleiku, case 1

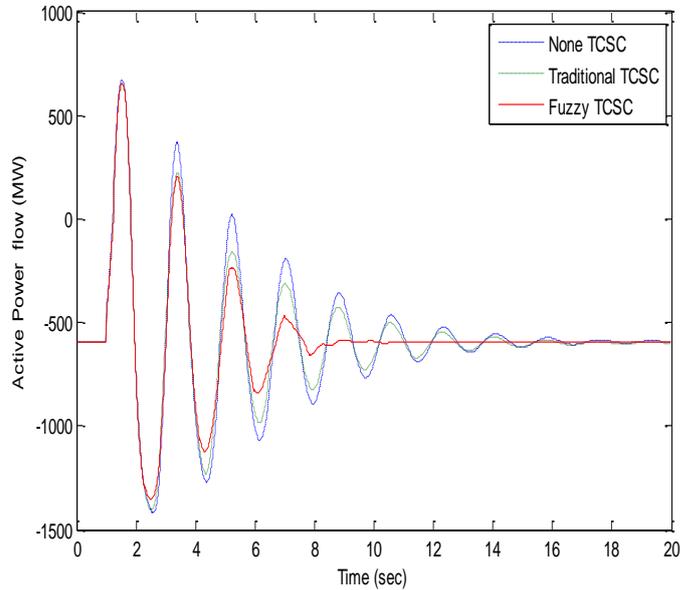


Fig. 11. Power oscillation of overhead Danang-Vungan transmission line, case 1

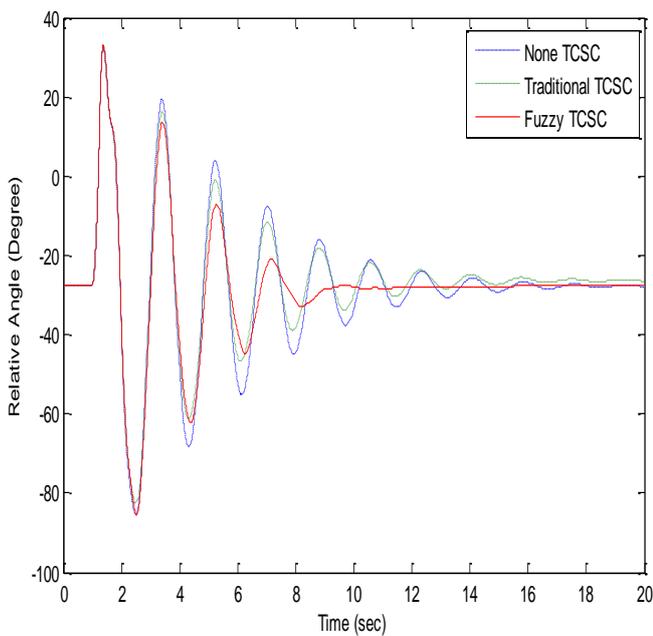


Fig. 10. Generator rotor angle oscillation of Duyenhai, case 1

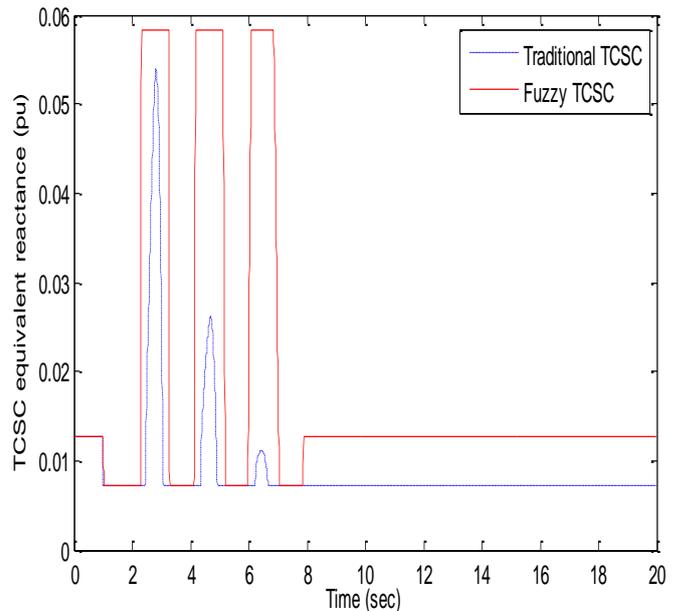


Fig. 12. reactance oscillation of overhead transmission line is installed the TCSC, case 1

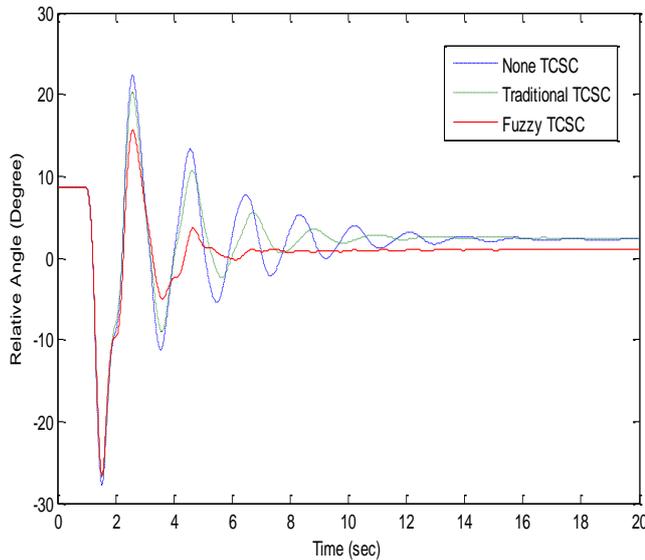


Fig. 13. Generator rotor angle oscillation of Vinhtan, case 2

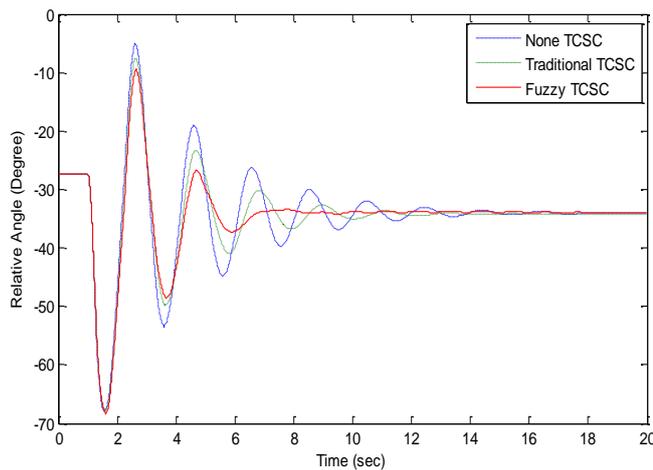


Fig. 14. Generator rotor angle oscillation of Duyenhai, case 3

VI. APPENDIX

Parameters of TCSC model “CRANI”

Model	T_1	T_2	T_3	T_w	K	X_{max}	X_{min}
CRANI	0.1	0.1	0.4	100	7.5	$1.2 * X$	$0.25 * X$

where X is the reactance of transmission line.

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