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COORDINATED DESIGNING BETWEEN PSS AND SVC POD CONTROLLER USING DE ALGORITHM

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Abstract- This paper presents a control method based on Differential Evolutionary (DE) algorithm to tune the parameters of the PSS and SVC power oscillation damping (POD) controller simultaneously in the SMIB system. The input signal of POD controller is selected based on the observability matrix for local signals. The controllers design is done in three states: first, for PSS, second, for SVC POD controller and third, coordinated design with PSS and SVC POD controller. The coordinated design is used to minimize the interaction between PSS and POD controller. The eigenvalue analysis and nonlinear simulation results show that the proposed method can significantly improve the small signal stability of the SMIB system.

Keywords: Differential Evolutionary Algorithm, Eigenvalue Analysis, Power Oscillating Damping, PSS, Small Signal Stability, SVC.

I. INTRODUCTION

Electromechanical oscillations have been observed in many power systems worldwide [1, 2]. Two modes of oscillation are generally experienced in power systems: Local mode, with a frequency between 0.8-3 Hz, which is related to oscillation in a single generator or a group of generators in the same area oscillate against each other; and inter-area mode, with a frequency between 0.2-0.8 Hz, in which the units in one area oscillate against those in other area [3].

Damping of power system oscillations plays an important role not only in increasing the transmission capability but also in stabilizing the power system, especially after critical faults [4]. In order to damp these power system oscillations and increase system oscillation stability, the installation of Power System Stabilizers (PSS) is both economical and effective [5, 6]. Several methods have been proposed in the literature to design the PSS. These include optimal control, adaptive control, variable structure control, robust control, intelligent control and heuristic methods.

The recent advances in power electronics have led to the development of reliable and high-speed flexible AC transmission system (FACTS) devices such as SVC, TCSC, STATCOM, SSSC, and UPFC [7-9]. The FACTS POD controllers are designed to enhance power system stability by increasing the system damping in addition to their primary function such as voltage and power flow control [10].

The first stage in the design of POD controllers are the selection of the best installing location and the input signal of controllers. Static interaction measures derived from decentralized control theory such as relative gain array (RGA) and controllability and observability have been applied in determining both the best location and the best input signals for multiple FACTS [11]. Stabilizing signal for SVC based on right-half plane (RHP) zeros, hankel singular value (HSV), RGA, and minimum singular value (MSV) are proposed in [12]. In [13] a reduced-order method of modal analysis, based on the extended Phillips-Heffron model, is proposed.

Various approaches are presented in the papers for designing the SVC POD controller. In [14-16] the concept of damping torque is used to design such controllers. The design of variable structure static VAR stabilizer using a sliding mode controls technique is proposed in [17]. The sliding mode control constrains the system motion to a state trajectory, and provides greater robustness to plant parameter variations than classical control schemes. The damping of electromechanical oscillations of synchronous generators using an output feedback SVC controller is investigated in [18].

An eigenstructure assignment technique is applied to design this controller. A novel scheme using H_∞ optimal control theory to design a H_∞ static VAR controller (SVC) for a static VAR system (SVS) connected at the generator bus is presented in [19]. An approach for designing a fuzzy logic-based adaptive SVC damping controller for damping low frequency power oscillations is presented in [20]. The proposed approach uses linear optimal controllers and, in addition, a fuzzy signal tuner is introduced to achieve adaptiveness. An artificial neural network (ANN)-based technique for tuning a damping controller for a SVC to improve the damping of power systems over a wide range of typical load models is presented in [21].

A Small Population based Particle Swarm Optimization algorithm (PSO) is applied to determine the optimal parameters of the damping controllers for small and large disturbances in [22]. Uncoordinated local control of FACTS POD controllers and PSS may cause destabilizing interactions [23]. To improve overall system performance, many researches were made on the coordination between PSS and FACTS controllers. A global tuning procedure for FACTS POD controllers and PSS in a multi-machine power system using a parameter-constrained nonlinear optimization algorithm implemented in a simulation program is presented in [24]. In [25] the coordinated design of SVC POD controller and PSS is treated as the design of single state feedback controller for the whole power system. The coordinated design between FACTS controllers and PSS is also considered in [26-28]. In [29] the problem of planning SVC in a power system is considered to maintain the nodal voltage magnitudes using DE.

In this paper, the most effective input signal is selected for SVC POD controller based on observability. The DE optimization algorithm is proposed too design SVC controller and PSS individually and simultaneously. This algorithm optimizes the system performance by minimizing the objective function in which the influence of both SVC POD controller and PSS are considered in the coordinated design.

II. SYSTEM MODELING

Figure 1 depicts a single machine infinite bus power system installed with a SVC. [2-4]. The synchronous generator is delivering power to the load and infinite bus through a double circuit transmission line.

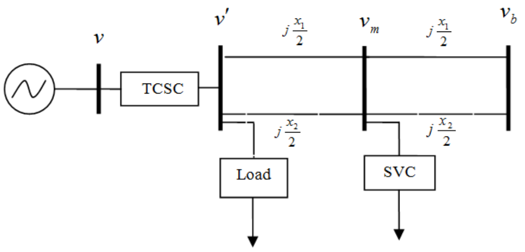

Figure 1. Single machine infinite bus system with SVC

A. Modeling of the Synchronous Generator

The synchronous generator is represented based on the third-order synchronous generator model. A first order model of a static type Automatic Voltage Regulator (AVR) is used. Figure 2 depicts the block diagram of AVR used in this paper.

The machine equations are [4]:

$$\dot{\delta} = \omega_b(\omega - 1) \tag{1}$$

$$\dot{\omega} = \frac{1}{M}(T_m - T_e - D\omega) \tag{2}$$

$$\dot{e}'_q = \frac{1}{T'_{do}}[E_{FD} - e'_q - (x_d - x'_q)i_d] \tag{3}$$

$$\dot{E}_{FD} = \frac{1}{T_A}[k_A(v_{ref} - v) - E_{FD}] \tag{4}$$

where T_m is assumed to be constant and T_e can be expressed as

$$T_e = P_e = v_d i_d + v_q i_q \tag{5}$$

where

$$v_d = x_q i_q \tag{6}$$

$$v_q = e'_q - x'_d i_d \tag{7}$$

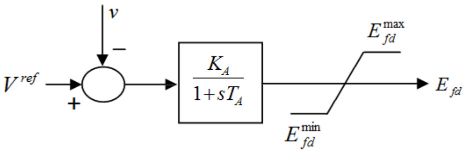

Figure 2. The Block diagram of AVR

B. Power System Stabilizer (PSS)

A PSS can be viewed as an additional block of a generator AVR, added to improve the overall power system dynamic performance, and specially control electromechanical oscillation. Figure 3 depicts the PSS controller model used here. In this paper, rotor speed deviation of generator is selected as PSS input signal [4].

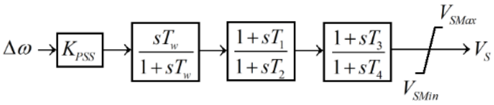

Figure 3. PSS controller

C. Modeling the Static VAR Compensator

A SVC is basically a shunt connected VAR generator/load whose output is adjusted to exchange capacitive or inductive currents so as to maintain or control specific power system variables. Typically, the controlled variable is the SVC bus voltage; however, an additional stabilizing signal, and supplementary control, superimposed on the voltage control loop of SVC can also provide oscillation damping [25]. The schematic diagram of Figure 4 shows the configuration of a SVC, in particular that of a fixed capacitor thyristor controlled reactor (FC-TCR) [7].

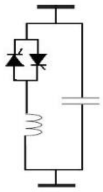

Figure 4. Basic structure of the SVC

The proposed POD controller is depicted in Figure 5. It consists of a general gain, a washout high pass filter, a dynamic compensator and an output limiter. The general gain determines the amount of damping produced by the stabilizer. The washout high pass filter is needed to avoid a controller response to the dc offset of the input signal. The dynamic compensator consists of two (or more) lead-lag blocks to provide the necessary phase lead characteristics [4, 5].

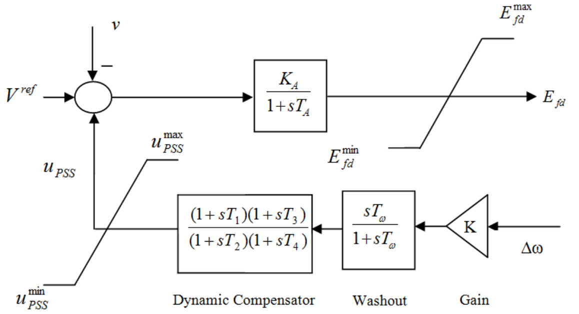

Figure 5. SVC with conventional lead-lag stabilizers

The transfer function of the POD controller can be expressed as

$$G_c(s) = K\frac{sT\omega}{1+sT\omega}\frac{1+sT_1}{1+sT_2}\frac{1+sT_3}{1+sT_4} \tag{8}$$

From the Figure 5 the SVC dynamics can be expressed as

$$\dot{B}_{SVC} = \frac{1}{T_s}[k_s(B_{SVC}^{ref} - u_{SVC}) - B_{SVC}] \tag{9}$$

D. Linearized Power System Model

In the design of a damping controller the linearized model around a nominal operating point is usually used [2]. Linearizing the expression of i_d and i_q as well as substituting into the linear form of Equations (1)-(9), yield the following linearized power system model

$$\begin{bmatrix} \Delta\dot{\delta} \\ \Delta\dot{\omega} \\ \Delta\dot{e}'_q \\ \Delta E_{FD} \end{bmatrix} = \begin{bmatrix} 0 & \omega_b & 0 & 0 \\ -\frac{k_1}{M} & -\frac{D}{M} & -\frac{k_2}{M} & 0 \\ -\frac{k_4}{T'_{do}} & 0 & -\frac{1}{k_3T'_{do}} & \frac{1}{T'_{do}} \\ -\frac{k_Ak_5}{T_A} & 0 & -\frac{k_Ak_6}{T_A} & -\frac{1}{T_A} \end{bmatrix} \times \begin{bmatrix} \Delta\delta \\ \Delta\omega \\ \Delta e'_q \\ \Delta E_{FD} \end{bmatrix} + \begin{bmatrix} 0 & 0 \\ 0 & -\frac{k_p}{M} \\ 0 & -\frac{k_q}{M} \\ \frac{k_A}{T_A} & -\frac{k_Ak_v}{T_A} \end{bmatrix} \times \Delta B_{SVC} \tag{10}$$

In short, the linearized system model can be written as

$$\Delta\dot{X} = A\Delta X + B\Delta U$$
$$\Delta Y = C\Delta X + D\Delta U \tag{11}$$

The block diagram of the linearized power system model is depicted as shown in Figure 6.

III. DESIGN STEPS

As a first step toward the design, we mathematically set up the design problem. It is easy to verify that the linearizability condition is guaranteed. Let:

A. Selection of the POD Controller Input Signal

Before the parameters of FACTS-based stabilizer installed in a power system are set, one of the first stages in the design of the stabilizers is the selecting of their input signal. The following are some of the main characteristics of a proper input signal [30]:

- The input signal should preferably be locally measurable. This is desirable to avoid additional costs associated with communication and to improve reliability.
- The oscillation modes to be damped should be "observable" in the input signal.
- The selected input signal must yield correct control actions when a severe fault occurs in the system.

Line active power, line reactive power, line current magnitude and bus voltage magnitudes are all candidates to be considered in the selection of input signals for the SVC stability control loop. Mode observability analysis can be used to select the most effective signal to damp out the critical [31].

Considering equation (11), the modal observability matrix is define, as [4]

$$C' = C\Phi \tag{12}$$

An appropriated feedback signal should have significant observability of the critical modes that need to be damped out.

B. Optimization Problem Formulation

To optimize the stabilizer parameters, an eigenvalue based objective function is considered. From Equation (11), the eigenvalues $\lambda_i = \sigma_i \pm j\omega_i$ of the total system can be evaluated. The proposed method is to search the best parameter sets of the controllers, so that a comprehensive damping index (CDI) can be minimized [32]:

$$CDI = \sum_{i=1}^{n}(1-\zeta_i) \tag{13}$$

where ζ is the damping ratio, and n is the total number of the dominant eigenvalues which include the local modes, exciter mode and controllers mode Among the dominant eigenvalues, only those, which have a damping ratio less than 0.1 are considered in the optimization. The objective of the optimization is to move the total considered eigenvalues to the negative region, and thus to maximize the damping ratio as much as possible.

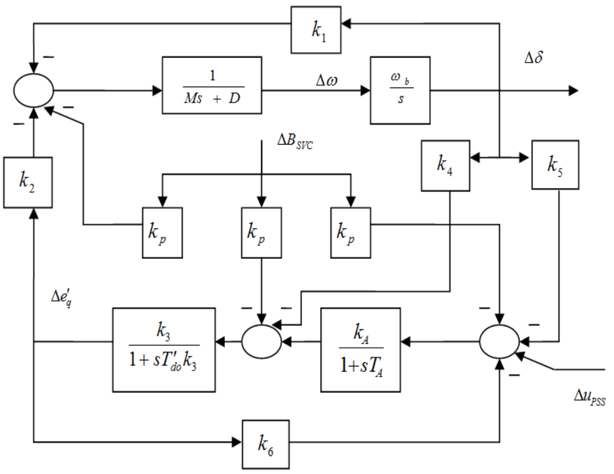

Figure 6. Block diagram of the linearized power system model

In this study, the CDI is objective function and the problem constraints are the stabilizer optimized parameter bounds. Therefore, the design problem can be formulated as the following optimization problem:

$$\begin{aligned}
&\min. \quad f(x) = CDI = \sum_{i=1}^{i=n}(1-\zeta_i) \\
&k_{PSS}^{\min} \le k_{PSS} \le k_{PSS}^{\max} \\
&T_{l,PSS}^{\min} \le T_{l,PSS} \le T_{l,PSS}^{\max} \qquad l = 1,\ldots,4 \\
&k_{SVC}^{\min} \le k_{SVC} \le k_{SVC}^{\max} \\
&T_{l,SVC}^{\min} \le T_{l,SVC} \le T_{l,SVC}^{\max}
\end{aligned} \tag{14}$$

The proposed approach employs DE algorithm to solve this optimization problem and search for optimal set of the stabilizer parameters.

C. Differential Evolution (DE) Algorithm

Differential Evolution algorithm is a population based algorithm like genetic algorithm using similar operation; crossover, mutation and selection. The main difference between Genetic and Differential Evolution algorithms is that the Genetic Algorithm uses crossover operation as a probabilistic mechanism to exchange information among solutions to improve solutions, while evolutionary strategies use mutation as the primary search mechanism. In this method a population of solution vectors is successively updated by addition, subtraction, and component swapping.

Differential Evolution (DE) utilizes N_P parameter vectors as a population for each generation (G) that has shown in Equation (15). The N_P does not change during the optimization process.

$$\begin{aligned}
&X_{i,j} = [x_{1,i,G}, x_{2,i,G}, \ldots x_{D,i,G}] \\
&i = 1,2,\ldots,N_P,\ j = 1,2,\ldots G
\end{aligned} \tag{15}$$

In equation (15) G is the generation number and D is the problem's dimension. In each generation, for individual $X_{i,j}$, we use mutation operation and get the V_i^G vector

$$V_i = X_{r1,G} + F \times (X_{r2,G} - X_{r3,G}) \tag{16}$$

In Equation (16) the weighting factor F is a user-supplied constant in the range $(0 < F < 1.2)$, which the upper limit value, 1.2 , is determined empirically. The optimal value of F in most functions lies in the range 0.4 to 1.0. By mutating vectors (V_i), DE ensures that the solution space will be efficiently searched in each dimension. Three vectors $X_{r1,G}$, $X_{r2,G}$ and $X_{r3,G}$ are selected randomly such that the indices i, r_1, r_2 and r_3 are distinct from interval $[0, N_P - 1]$. Then crossing operation is used and the trial vector $u_{j,G+1}$ is gotten as

$$u_{j,G+1} = \begin{cases} v_{j,i,G+1} \text{ if } \mathrm{rand}_{j,i} \le CR \text{ or } j = I_{rand} \\ x_{j,i,G+1} \text{ if } \mathrm{rand}_{j,i} > CR \text{ or } j \ne I_{rand} \end{cases} \tag{17}$$
$$i = 1,2,\ldots,N_P;\ j = 1,2,\ldots,D$$

where $\mathrm{rand}_{j,i}$ is a random number between 0 and 1, I_{rand} is a random integer from $[1,2,\ldots,D]$, CR is a user defined number between 0 and 1, which called crossing factor.

Lastly, in selection operation vector $x_{i,G+1}$ is compared with the trial vector $u_{i,G+1}$ and the one with the lowest function value is admitted to the next generation

$$x_{i,G+1} = \begin{cases} u_{i,G+1} & \text{if } f(u_{i,G+1}) \le f(x_{i,G}) \\ x_{i,G} & \text{otherwise} \end{cases} \tag{18}$$

Mutation, crossing and selection will be continuing until the population converges hopefully to optimum [29].

IV. SIMULATION RESULTS

A. Input Signal Selection

The system eigenvalues without any controller are given in Table 1. It is shown that the system has an oscillating mode with damping ratio less than 10%. This mode is known as critical mode.

Table 1. Eigenvalue of SMIB System

Eigenvalue	Frequency [Hz]	Damping Ratio
-0.0859±j8.4117	1.3387	0.0102
-16.9502	0	1
-3.2901	0	1

The active power, line current magnitude and bus voltage magnitude are considered as possible input signals of the POD controller. To select an appropriate input signal of SVC POD controller, the modal observability analyses are carried out for candidate signals considering three different operating conditions. These three operating conditions are: case 1, changing of the nominal operating point to the new operating point with P=1.2 pu and Q=0.6 pu; case 2, line X_1 outage and, case 3, line X_2 outage.

Table 2. The Obsevability of Oscillating Mode to the Input Signal

	Nominal Condition	Case 1	Case 2	Case 3
P	0.8506	0.3519	0.0227	0.2735
$\|I\|$	0.7412	0.3080	0.0305	0.2650
$\|V\|$	0.0261	0.0217	0.0088	0.0268

Table 2 shows the results of the open loop mode observability analysis for system critical mode. In the case 2, the observability indices for $|I|$ signal is more than P signal, but in other cases the observability indices for P is greater, so the P is selected as the input signal of the SVC POD controller.

B. Application of DE to the Design Process

Based on the linearized power system model, the DE algorithm has been applied to search for the optimal parameters of the PSS and SVC POD controller. The optimization problem is carried out for both individual and coordinated designs. The final settings of the optimized parameters for the proposed controllers are given in Table 3. Change of the system critical eigenvalues along with damping ratios with and without the proposed PSS and SVC controller are given in Table 4. It is obvious that the system stability is greatly enhanced with the proposed controllers. It can also be seen that the coordinated design enhances stability of system more than individual design. Comparison between PSS and SVC POD controller shows that PSS has greater effect than SVC controller.

Table 3. Optimal Parameter Setting of the Proposed Controllers

	Individual Design		Coordinated Design	
	PSS	SVC	PSS	SVC
K	18.5401	74.9086	38.9811	61.2094
T_1	0.1494	0.1031	0.1021	0.7265
T_2	0.1201	0.4318	0.1404	0.3517
T_3	0.2039	0.8438	0.3476	0.2735
T_4	0.1518	0.281	0.3471	0.2769

Table 4. System Eigenvalues with and without Control

	No Control	PSS Only	SVC Only	Coordinated Design
Oscillating Mode	-0.08±j8.41	-3.41±j6.62	-1.47±j11.47	-4.19±j5.86
Damping Ratio	0.0102	0.458	0.127	0.582

C. Nonlinear Simulation

The single machine infinite bus system shown in Figure 1 is considered for nonlinear simulation studies. 6-cycle 3 phase fault, on the infinite bus was created to study the performance of the proposed controllers. The rotor angle and speed deviation response of generator are shown in Figure 7 and Figure 8 for individual and coordinated design. It can be readily seen that the system response has been improved greatly by PSS and SVC POD controllers. Also, it can be seen that the coordinated design of PSS and SVC provides the best damping characteristics. This is consistent with the eigenvalues analysis.

Figure 9 and Figure 10 show the control effort provided by the stabilizing signal of PSS, U_{PSS} and the susceptance of SVC (B_{SVC}), respectively.

V. CONCLUSIONS

In this paper, modal observability analysis has been used to select the best input signal of the SVC POD controller from the local signals. For selecting the best input signal, several fault condition has been considered in the modal analysis and line active power is selected as input signal.

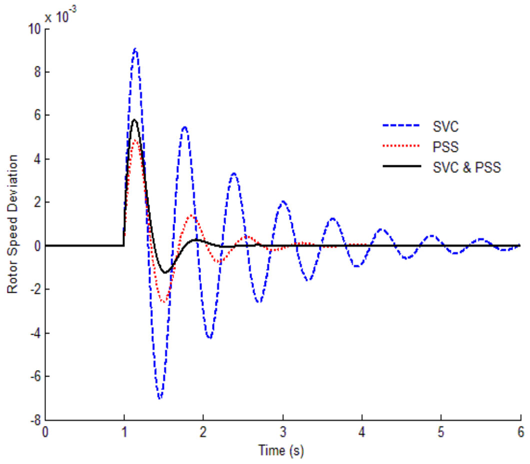

Figure 7. Rotor speed deviation response for 6-cycle three-phase fault

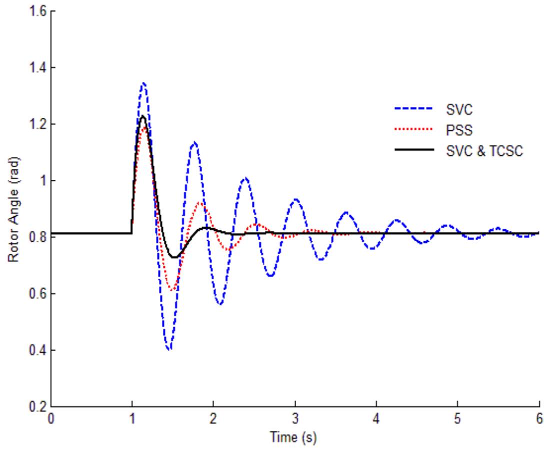

Figure 8. Rotor angle response for 6-cycle three-phase fault

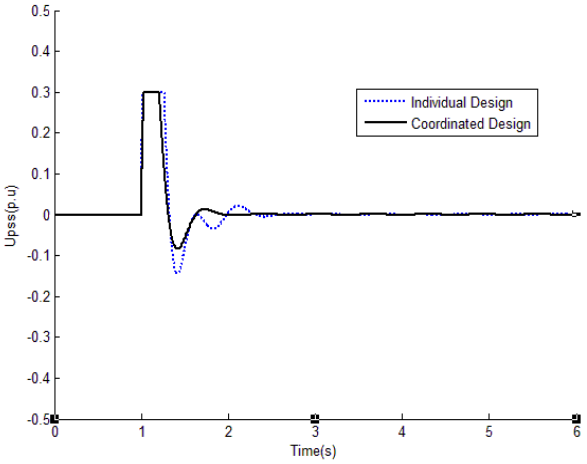

Figure 9. PSS stabilizing signal response for 6-cycle fault

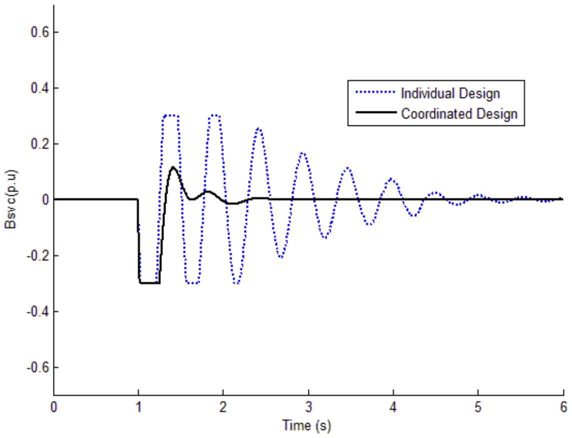

Figure 10. B_{SVC} stabilizing signal response for 6-cycle fault

An optimization technique has been proposed to design the PSS and SVC POD controller individually and simultaneously. DE algorithm has been used to search for the optimal controller parameter settings that minimize the CDI objective function.

The eigenvalue analysis and nonlinear simulation results show the effectiveness of the proposed controllers to enhance the system stability.

APPENDIX

The system data are shown in Table 3.

Table 3. Value of the Parameters

Parameter	Value	Parameter	Value
M	13	g	0.249
x_d	1.8	x'_d	0.3
T'_{do}	8	x_q	1.7
D	0	b	0.262
X_1	0.5	K_A	50
X_2	0.93	T_A	0.05
Ks	1	T_s	0.05
V	1.05 pu	P_t	1 pu
Q_t	0.3 pu	$\lvert X_{TCSC}\rvert \leq 0.5\ X$	

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