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COORDINATED CONTROL OF PSS AND TCSC FOR IMPROVING TRANSIENT STABILITY IN POWER SYSTEM WITH COHERENT GENERATORS

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Abstract

In large electrical systems including FACTS devices, control approaches are complicated and time consuming. An integrated model for a part of power system which consists of an equivalent generator can fixed these problems. In this paper, the equivalent machine parameters are derived based on the weighted mean values of the parameters of the machines included in the group. TCSC control signals obtained from the integrated model is applied to the actual system. Linear optimal control method is used to stabilize a coherent three machines infinite bus using TCSC Controller .The purpose of the derived control laws for oscillation damping system seems to be simple and effective.

Key words: TCSC, PSS, LOC, transient stability

1. Introduction

Low frequency oscillations in large power systems are significant dynamic problems that occur due to the lack of sufficient damping in electromechanical modes. Considering the limitations of using only PSS in power systems, coordinated control of PSS and FACTS are very effective to improve stability.

In [1] an algorithm for the simultaneous coordinated tuning of the TCSC damping controller and PSS in multi-machine power system is presented. The nonlinear time-domain simulation results show the effectiveness of the proposed controllers and their ability to provide good damping of low frequency oscillations.

In [2] a PSO algorithm proposed to adjust the optimized PSS and TCSC and a new approach using eigenvalues and simulation of nonlinear functions are used simultaneously.

The modern power systems are so large and complicated. So the power system control approaches are very time consuming with the increasing of equation and complexity of structure. The use of dynamic equivalents for particular parts of these systems simplifies the designed control. Usually, the construction of a dynamic equivalent involves three steps. The first is the identification of coherent generators. The second is the aggregation of generators buses with elimination of load buses and the third the aggregation of coherent generators models including their control device [3].

The simulation tests of a large power system and the reduced system are performed to validate the proposed aggregation and results confirmed that the dynamic characteristics of the original network are preserved in the reduced network.

An aggregation method used in [4] to build a coherency-based dynamic equivalent of detailed generating units' models and their control systems. The proposed method has been applied to group coherent machines in a large power system. Each machine is represented by a detailed model (two-axis model) and equipped with IEEE-type DC1 excitation system and steam turbine governor system. However, this method is limited to group coherent machines equipped with the same type of control systems. In practice, this limitation can be overcome by using two or more equivalent machines to represent groups of machines having the same type of control system.

In [4] a new technique is described for the automatic formation of dynamic equivalents of generating units represented by detailed models. The proposed method is a practical approach to reduce the dynamic order of a power system representation. The program developed will form one of the key elements in a comprehensive package of programs for forming dynamic equivalents. Further tests in the time domain on the WSCC System will be performed to evaluate the accuracy of the reduced models. Satisfactory results were already.

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In this paper, first, a comprehensive assessment of PSS and TCSC effects on the system stability has been carried out based on coordinated linear optimal control approach. Simulation results are presented to demonstrate the effectiveness of the proposed controllers to improve the power system stability. In the next step the paper goal is to simplify the control of a power network. Because the power system is made up of coherent machines a simplified equivalent model for a part of the system is derived. Finally gained control signals are applied to the actual electrical power system. In this method control approach is simpler and faster. The simulation tests of a large power system and the reduced system are performed to validate the proposed aggregation and results confirmed that the dynamic characteristics of the original network compared to the reduced network.

2. Modeling the power system

The three-machine infinite-bus power system shown in Fig. 1 is considered in this study. The generators are connected to an infinite bus through the transformer and two transmission lines equipped with the TCSC in middle of them. System data are given in the paper Appendix.

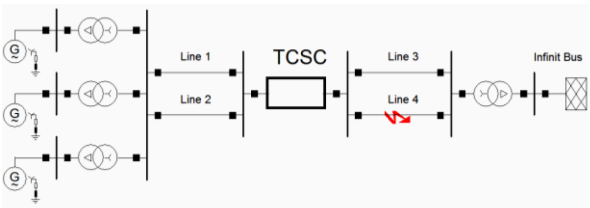


Fig. 1: Three machine infinite bus power system equipped with a TCSC

Generators are represented by the eighth-order model. In computer simulations the eighth order model is a fairly complete and detailed model of the synchronous generator which has been generalized to analyze its behavior. It includes six electrical nonlinear dynamic equations and two mechanical nonlinear dynamic equations. A machine equations are written in terms of the flux per second, to derive the equations appear in only one operator. Because the differential equations are solved numerically. The synchronous machine dynamic equations can be summarized as follow [6, 7]:

$$\begin{cases} M\dot{\omega} = T_m - T_e - D\omega \\ \dot{\delta} = \omega_b\,(\omega - \omega_s) \end{cases} \tag{1}$$

$$\begin{cases} \dot{\psi}_{qs} = \omega_b[\upsilon_{qs} - \dfrac{\omega_r}{\omega_b}\psi_{ds} + \dfrac{r_s}{x_{ls}}(\psi_{mq} - \psi_{qs})] \\ \dot{\psi}_{ds} = \omega_b[\upsilon_{ds} - \dfrac{\omega_r}{\omega_b}\psi_{qs} + \dfrac{r_s}{x_{ls}}(\psi_{mq} - \psi_{ds})] \\ \dot{\psi}_{kq1} = \omega_b[\upsilon_{kq1} + \dfrac{r_{kq1}}{x_{kq1}}(\psi_{mq} - \psi_{kq1})] \\ \dot{\psi}_{kq2} = \omega_b[\upsilon_{kq2} + \dfrac{r_{kq2}}{x_{kq2}}(\psi_{mq} - \psi_{kq2})] \\ \dot{\psi}_{fd} = \omega_b[\dfrac{r_{fd}}{x_{md}}e_{xfd} + \dfrac{r_{fd}}{x_{lfd}}(\psi_{mq} - \psi_{fd})] \\ \dot{\psi}_{kd} = \omega_b[\upsilon_{kd} + \dfrac{r_{kd}}{x_{kd}}(\psi_{md} - \psi_{kd})] \end{cases} \tag{2}$$

The total power injection at the equivalent bus is equal to the sum of the injections at the terminal buses of generators.

$$S_e = \sum_{k=0}^{3} S_k \tag{3}$$

The equivalent mechanical equation of generators can be written as:

$$\left(\sum_{k=1}^{3} M_k\right).\dot{\omega} = \sum_{k=1}^{3} P_{mk} - \sum_{k=1}^{3} P_{ek} - \left(\sum_{k=1}^{3} D_k\right).\omega \tag{4}$$

The equivalent mechanical parameters are obtained by [8]:

$$D_{eq} = \sum_{i=1}^{N} D_i \tag{5}$$

$$M = \sum_{i=1}^{3} M_i \tag{6}$$

Control signal will be derived by linearizing equivalent model in the next chapter.

A TCSC has been placed in series with the transmission line to change the line flow. Therefore, a TCSC can extend the power transfer capability and provide additional damping for low frequency oscillations. The configuration of a TCSC is shown in Fig. 2. It comprises a fixed capacitor in parallel with a thyristor-controlled reactor. Controlling the firing angles of the thyristors can regulate the TCSC reactance and its degree of compensation.

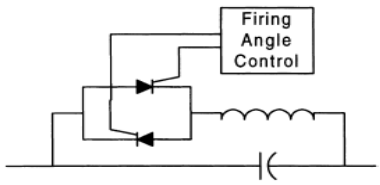


Fig. 2. The configuration of TCSC.

3. Linearized power system model

A synchronous generator can be represented by its third-order model comprising the electromechanical swing equation and the generator internal voltage equation. The dynamic equation can be stated by the following equations:

$$M\dot{\omega} = T_m - T_e - D\omega \quad (7)$$

$$\dot{\delta} = \omega_b\,(\omega - \omega_s) \quad (8)$$

$$T_{do}'\dot{E}_q' = E_{fd} - E_q' - (X_d - X_d')I_d \quad (9)$$

In the design of damping controller, the linearized incremental model around a nominal operating point is usually employed. Fig.5 illustrates the block diagram of the linearized power system model. The expressions of constants K_1 to K_6, K_P, K_Q, and K_V are given in the paper Appendix.

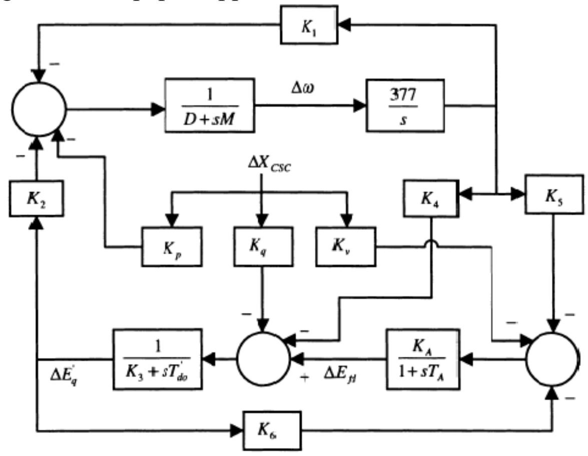


Fig. 3. Block diagram of the linearized power system model.

In short, the linearized system model can be rewritten as:

$$\dot{x} = Ax + Bu \quad (10)$$

Where:

$$X = [\Delta\omega \quad \Delta\delta \quad \Delta E_q' \quad \Delta E_{fd}]^T \quad (11)$$

$$u = X_{TCSC} \quad (12)$$

$$A = \begin{bmatrix} 0 & \omega_b & 0 & 0 \\ \frac{-K_1}{M} & \frac{-K_2}{M} & 0 & 0 \\ 0 & \frac{-K_4}{T'_{do}} & \frac{-1}{K_3 T'_{do}} & \frac{1}{T'_{do}} \\ 0 & \frac{K_A K_5}{T_A} & \frac{-K_A K_6}{T_A} & \frac{-1}{T'_A} \end{bmatrix} \quad (13)$$

$$B = \begin{bmatrix} 0 & -\frac{K_P}{M} & -\frac{K_q}{T_{do}'} & -\frac{K_V K_A}{T_A} \end{bmatrix}^T \quad (14)$$

4. Linear optimal control

Optimal control is a particular branch of modern control that sets out to provide analytical designs of an especially appealing type. The plant that is controlled is assumed linear, and the controller, the device which generates the optimal control, is constrained to be linear. That is, its output, the optimal control, is supposed to depend linearly on its input, which will consist of quantities derived from measurements on the plant. Central to the optimal stabilizer design problem is the formulation of the cost function and the choice of the state and control weighting matrices. Consider a linear, time-invariant system as shown in (10). Where x is an n-dimensional state vector, u is an r-dimensional control vector A, B and C are constant real matrices. One can define a linear quadratic performance measure for (10) as:

$$J = \int_0^\infty \left[x^T Q x + u^T R u \right] dt \quad (15)$$

For this measure, optimal stabilizing control is:

$$u = -R^{-1}B^T p \quad (16)$$

Where p is the symmetric positive semi-definite solution of the Algebraic Riccati Equation [8]:

$$pA + A'p + Q - pBR^{-1}B'p = 0 \quad (17)$$

5. Simulation

Linear optimal control signal is obtained by writing the generators third-order model linearized equations. The eighth-order synchronous machine model used to simulate the actual power system. A 0.1second 3-phase fault happened on the line 4 shown in Fig.1 and breakers tripe the line at both sides. After one second, the fault is cleared and the line is reclosed. Eigenvalues of the system with no control are:

-0.0174 ± j 39.01401
-8.7750
-1.2992
-0.0080 ± j 61.9001
-5.1840 ± j 9.2045
-0.2673 ± j 55.0987
-5.1474 ± j 5.1130

By applying optimal control, eigenvalues are transferred to the left side of the imaginary axis which improves the system stability. Eigenvalues of the system with optimal control are:

-2.4179 ± j 61.8740
-2.7852 ± j 39.0492
-4.6395 ± j 54.9992
-25.8674 ± j 25.0725
-44.2847 ± j 44.6366
-40.3024 ± j 41.0262

Now, the eigenvalue analysis and TCSC control signal obtain from an integrated model of coherent generators is applied to the system. TCSC based stabilizer outperforms the power system stabilizers in terms of the first swing stability and the voltage profile. The results show that the proposed control by simplified model has the similar effectiveness compared to conventional linear optimal control method. Eigenvalues for conventional method are:

-0.0115 ± j 52.6419
-68227
-3.2582

and for the proposed method they are:

-11.5215 ± j 52.1463
-5.1903 ± j 1.0020

Eigenvalues of the system is shifted to the left side of the imaginary axis and show by using the optimal control, stability of the system has been improved. To show the proposed method effectiveness, first, the test system is evaluated without TCSC and PSS controllers. The generators and TCSC variables for all cases (without control and with coordinated control) are shown in Figs. 4-7.

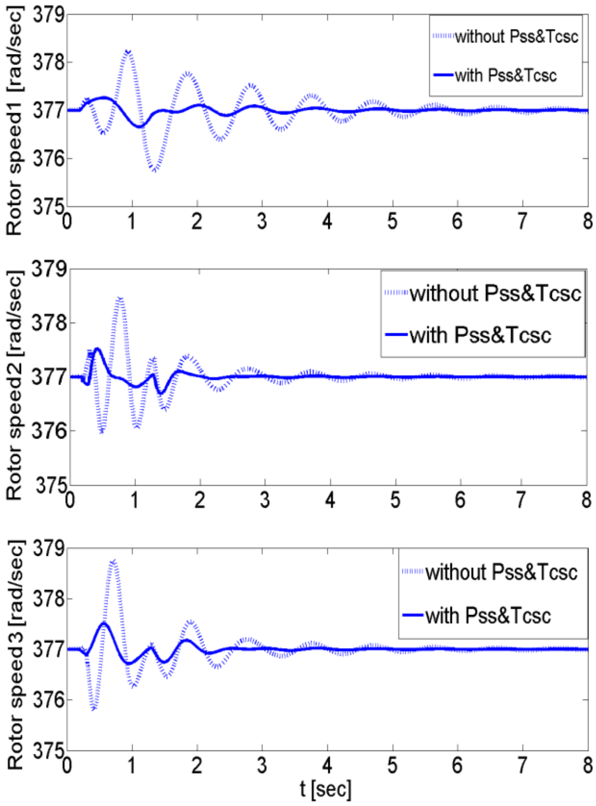
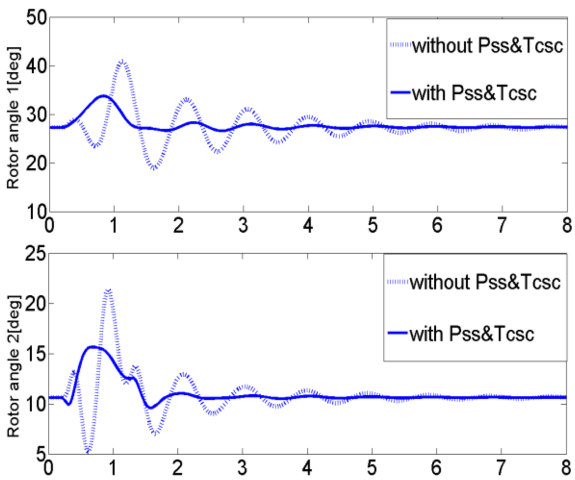


Fig. 4. Speed deviations of generators without coordinated control and with coordinated control



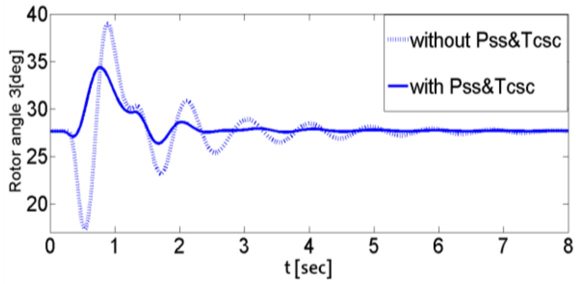


Fig. 5. Rotor angles deviations of generators without coordinated control and with coordinated control

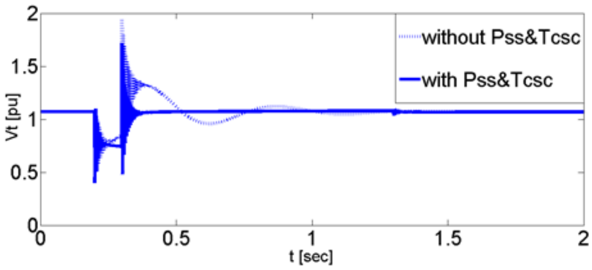


Fig. 6. Terminal voltage deviations of generators without coordinated control and with coordinated control

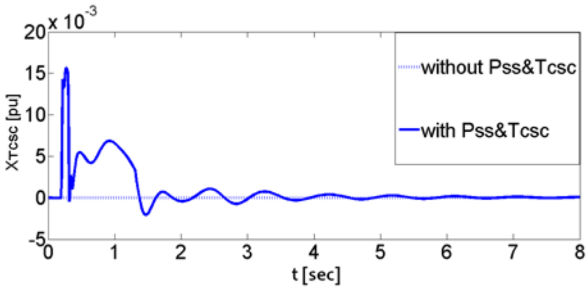


Fig. 7. X_{TCSC} deviations without coordinated control and with coordinated control

These time domain simulations are also in well agreement with the results of eigenvalue analysis. It is clear from these figures that, the simultaneous design of the PSS and TCSC damping controller by the proposed approach significantly improves the stability performance of the example power system and low frequency oscillations are well damped out. The proposed controllers have been tested on a weakly connected power system. The eigenvalue analysis and simulation results show the effectiveness and robustness of the proposed controllers to enhance the system stability.

In the next step the integrated model is used, as generators are replaced by one equivalent generator. The equivalent machine parameters are based on the weighted mean values of the parameters of the machines included in the group. TCSC Control signals are obtained from the integrated model and are applied to the actual system. The results of such a study are presented in Figs. 8-10. These results show that the proposed control is simpler but has the similar effectiveness compared to conventional linear optimal control method.

7. Conclusion

This paper aim is based on linear optimal control method to stabilize a coherent three machines infinite bus using the TCSC Controller. The purpose of the derived control laws for oscillation damping system seems to be the effective. To ease the implementation of the proposed algorithm, third model of synchronous machine is used to drive the control law. For simulations, eighth-order model is used to show the actual response of the network. The system state equations are linearized around the operating point and then linear optimal control method is applied. By applying a symmetrical three-phase fault in one of the transmission lines, and coordinated control, system stability is analyzed.

The eigenvalue analysis and simulation results show the effectiveness and robustness of the proposed controllers to enhance the system stability. Simulations are done in MATLAB. Since control system of large electrical system is complex and time consuming, an integrated model of coherent generators prepared and TCSC control signal is applied to the previous system. The results are shown that the proposed control by simplified model has the similar effectiveness compared to conventional linear optimal control method.

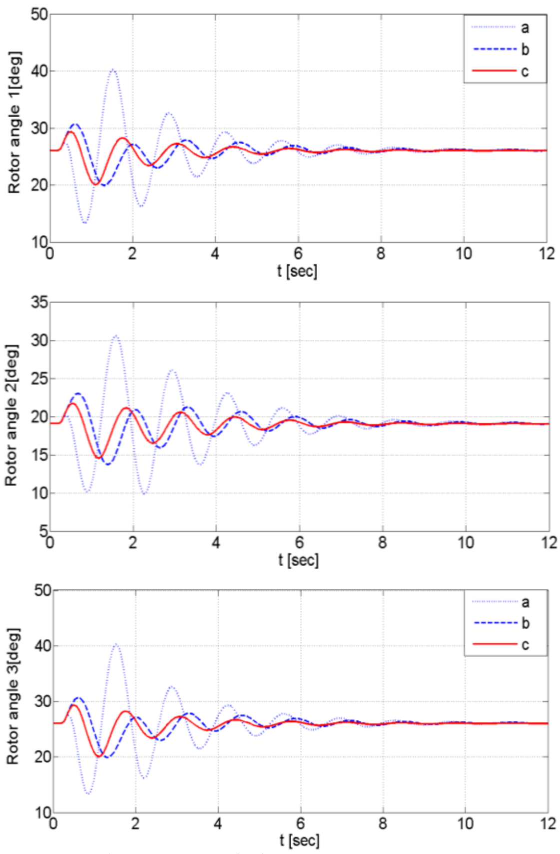


Fig.8.rotor speed of generator 1,2,3
(a) without control,
(b) with control obtained from integrated model,
(c) with control obtained from actual model

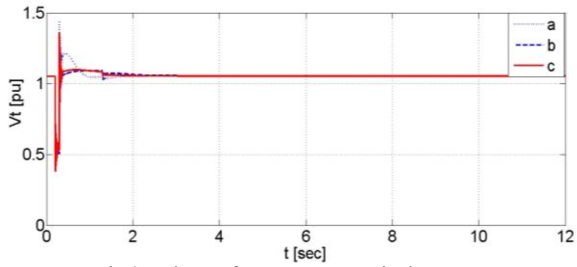


Fig.9. voltage of generator s terminal
a) without control
b) with control obtained from integrated model
c) with control obtained from actual model

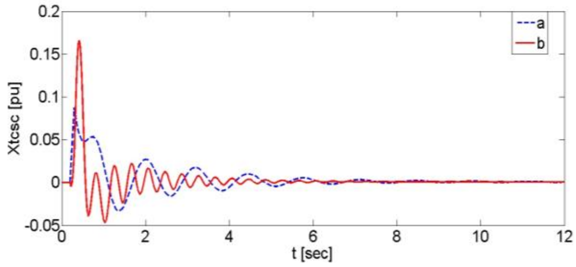


Fig.10. Variations of TCSC reactance:
a) with control obtained from integrated model
b) with control obtained from actual model

Appendix

	G1	G2	G3
H	4	4	4
X_d	1.81	0.85	1.8
X_{lfd}	1.82	0.2049	0.1414
X_{lkq1}	2.3352	0.110	0.8125
R_{fd}	0.0006	0.00041	0.000929
R_{kq1}	1.81	0.10	0.00178
X_q	1.76	0.480	1.8
X_{ls}	0.15	0.120	0.19
X_{lkd}	1.8313	0.160	0.08125
X_{lkq2}	1.735	0.1029	0.0939
R_{kd}	0.028	0.0141	0.01334
R_{kq2}	0.02368	0.0136	0.00841
K_A	100	100	100
T_A	1	1	1

K_P, K_Q, K_V are obtained from [9, 10]

$$B=\begin{bmatrix} 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & -K_P/M_1 \\ 0 & 0 & 0 & -K_q/\tau'do \\ K_A/T_A & 0 & 0 & -K_AK_V/T_A \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & -K_{P2}/M_2 \\ 0 & 0 & 0 & -K_{q2}/\tau'do2 \\ 0 & K_A/T_A & 0 & K_AK_{V2}/T_A \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & -K_{P3}/M_3 \\ 0 & 0 & 0 & -K_{q3}/\tau'do3 \\ 0 & 0 & K_A/T_A & K_AK_{V3}/T_A \end{bmatrix}$$

Symbols Definition and Abbreviations

Pm	Mechanical input power of the generator
Pe	Electrical output power of the generator
Z	Transmission line impedance
D	Damping constant of the generator
δ	Rotor angle of the generator
ω	Speed of the generator
Efd	Field voltage
T_{do}	Open circuit field time constant
$X_{d,}$	d-axis reactance of the generator
X_d	d-axis transient reactance of the generator
X_q	q-axis reactance of the generator
K_A	Gain of the excitation system
T_A	Time constant of the excitation system
V_{ref}	Reference voltage
V	Terminal voltage of the generator
V_d	d-axis component of the terminal voltage
V_q	q-axis component of the terminal voltage
i_d	d-axis component of the armature current
i_q	q-axis component of the armature current
Eq	Transient EMF in q-axis of the generator
U_{PSS}	Output signal of the PSS
U_{CSC}	Output signal of the TCSC-based stabilizer
X_{CSC}	TCSC reactance

FACTS	Flexible Ac Transmission Systems
PSS	Power System Stabilizer
TCSC	Thyristor Controlled Switched Capacitor

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