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TCSC-Based Wide Area Damping Controller (WADC) for Inter-area oscillations in Saudi Power Network

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Abstract

Wide Area Measurement System (WAMS) can extend and effectively improve the FACTS-Based stabilizers capability in damping the inter-area low frequency oscillations in interconnected bulk power systems. This paper discusses the design and implementation aspects of a Wide Area Damping Controller (WADC) to Thyristor Controlled Series Capacitor (TCSC) based supplementary stabilizers. Modal analysis is performed to identify the modes of oscillations and the optimal combination of input signals of FACTS-based WADC through controllability analysis. The paper presents the impact of upgrading the existing fixed series capacitor (FSC) installed between a weak interconnection of Saudi Arabia power network to TCSC. Differential Evolution (DE) algorithm is applied to search for optimal controller parameters. The eigenvalue analysis and non-linear time domain simulations indicate that TCSC-based WADC can effectively damp the inter-area oscillations and improve the system stability irrespective of the severity and the location of the disturbances.

Keywords: Wide Area Measurement System (WAMS), Oscillation Damping; Differential Evolution (DE), Low Frequency Oscillations, Flexible AC Transmission System (FACTS), Wide Area Damping Controller (WADC), Phasor Measurement Unit (PMU)

Nomenclature

DE	: Differential Evolution
LFO	: Low Frequency Oscillations
PSS	: Power System Stabilizer
CPSS	:Conventional Power System Stabilizer
WAMS	: Wide Area Measurement System
WADC	: Wide Area Damping Controller
PMU	: Phasor Measurement Unit
δ	: Generator rotor angle
E'_q	: Internal voltage of the machine behind transient reactance x'_d.
ω_b	: base angular velocity
ω	: angular velocity in per unit
M	: generator inertia constant
D	: damping coefficient
T_m	: Input torque of the generator
T_e	: Output torque of the generator
E_{fd}	: Exciter output voltage
T'_{do}	: d-axis transient open-circuit time constant

INTRODUCTION

Power system control is becoming more and more complex with the increase in the interconnected operation of various areas in the system, particularly during periods of system loadings closer to the operational limits of the respective areas. At the same time, the low frequency oscillations resulting from heavy load conditions constraint the utilization of tie-lines up to their full capacities. Over the past decades, damping of inter-area oscillations is attempted by installing conventional power system stabilizers (CPSSs) [1] [2]. Each installed CPSS receives a local signal such as generator speed or power as an input and provides a supplementary signal to the generator excitation control. These local measurements based PSSs can provide sufficient damping for local mode oscillations, on the other hand there seems to be a limitation to their effectiveness in damping inter-area mode oscillations [3] [4] and sometimes cannot be even stabilized [5].

Many researchers have explored the effectiveness of PSS-based wide area measurements in wide area damping controller (WADC) to damp inter-area oscillations. It has been proven that application of remote signals will enhance the system dynamic performance and damp inter-area oscillations [6] [7] [8]. Alternatively, WADC could be used with Flexible AC Transmission System (FACTS) which are installed at critical locations in power networks and thus can provide much better performance when compared with PSS. Normally, the input control signal of TCSC and SVC can be obtained locally from signals such as voltage, current, active power flow, frequency, etc [9]. Installation of Phase Measurement Units (PMUs) are at various buses in a system contributes to better performance in the detection of the inter-area oscillation. If FACTS and WAMS technologies are utilized together, it can enhance the system dynamic performance [10].

In this paper, TCSC-Based Wide Area Damping Controller (WADC) is proposed and Differential Evolution (DE) algorithm is used to tune the proposed controller for damping inter-area low frequency oscillations. Modal analysis is used to determine the optimal remote feedback input signals. The performance of the proposed controller is investigated for Saudi Arabia power network. Eigenvalue analysis and time domain simulation are performed to the two area system in order to evaluate the performance of the controller.

POWER SYSTEM MODELING

Generator

A power system network with n number of generators is considered, where each generator can be modeled by the fourth-order model consisting of swing equations and the equation for the generator internal voltage E_q' behind transient reactance x_d'. Each generator is assumed to be provided with an excitation system consisting of PSS [2]. The equations of i^{th} generator corresponding to this dynamic model are:

$$\dot{\delta} = \omega_b(\omega - 1) \quad (01)$$
$$\dot{\omega} = (T_m - T_e - D(\omega - 1))/M \quad (02)$$
$$\dot{E'_q} = (E_{fd} - (-x'_d + x_d) * i_d - E'_q)/(T'_{d0}) \quad (03)$$
$$\dot{E_{fd}} = (K_a * (-V_t + V_{ref}) - E_{f\,d})/(T_a) \quad (05)$$

Excitation System and PSS

Excitation system of generators are assumed to be of IEEE Type-ST1 [11]. The transfer function model of the excitation system is shown in *Figure 1*. There is a PSS attached with the excitation system where the deviation of generator angular velocity is used as an input to the PSS. A phase lag exists between the machine electrical torque and the input of the exciter which would be compensated by the two lead-lag blocks as shown in Fig.1.

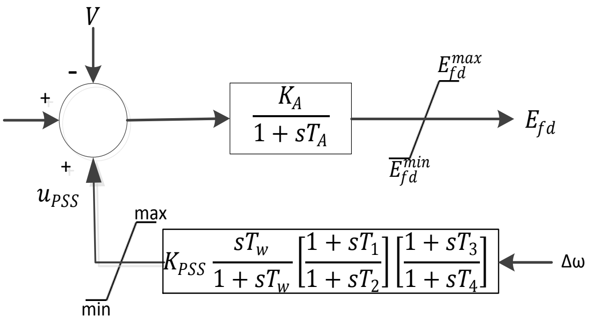

Figure 1: Excitation system IEEE-ST1 with CPSS

The ST1-IEEE model is represented by the equation

$$\dot{E}_{fd} = \left(K_A * \left(-v + V_{ref} + U_{pss}\right) - E_{fd}\right)/(T_A) \quad (06)$$

The gain and time constant are represented by K_A and T_A, respectively; and V_{ref} is the reference voltage.

TCSC Controller Model

The block diagram in Figure 2 represents the TCSC device in addition to being given the equation (9).

$$\dot{X}_{TCSC} = \frac{1}{T_S}\left[K_S\left(X_{ref} + U_{CSC}\right) - X_{TCSC}\right] \quad (9)$$

With respect to the device, K_s represents the gain while T_s is the time constant. Figure 2 indicates installation of the lead-lag blocks in the feed-back loop for generation of stabilizer output U_{TCSC} for compensation. WAMS remote signals are utilized in this study as controller input.

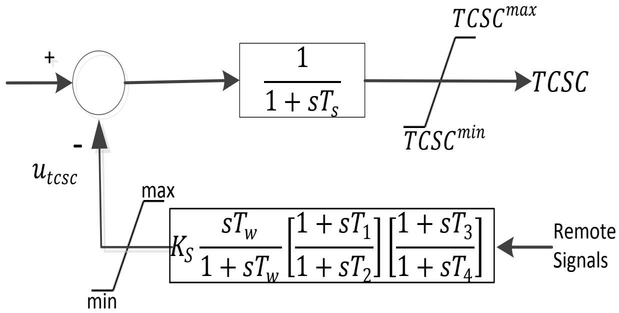

Figure 2: TCSC dynamic model with Lead/Lag Blocks

Linearized Multi-Machine System Model

In general, power system dynamics is represented by a set of nonlinear differential equations [12] given by:

$$\dot{\boldsymbol{x}} = f(\boldsymbol{x}, \boldsymbol{U}) \quad (07)$$

where X is the state vector, $\boldsymbol{x} = [\delta, \omega, E_q', E_{fd}, X_{tcsc}]^T$, and U is the input vector, $\boldsymbol{U} = [U_{PSS}, U_{TCSC}]^T$, where U_{PSS} is the PSS control signals and U_{TCSC} is the TCSC control signal. In the design of electromechanical mode damping controllers, linearized incremental model around a nominal operating point is utilized. Linearization of equation (7) yields

$$\Delta\dot{\boldsymbol{x}} = \boldsymbol{A}\,\Delta\boldsymbol{x} + \boldsymbol{B}\,\boldsymbol{U} \quad (08)$$
$$\Delta\boldsymbol{y} = \boldsymbol{C}\,\Delta\boldsymbol{x} + \boldsymbol{D}\,\Delta\boldsymbol{u} \quad (09)$$

where
$\Delta\boldsymbol{x}$ represents the state vector increment for n machines
Δy represents the output vector increment for m stabilizers
$\Delta\boldsymbol{u}$ represents the r input vector increment
$\boldsymbol{A}$ is a (4n x 4n) matrix
B is a (4n x m) matrix
Δx is a (4n x 1) state vector and
U is a (m x 1) input vector.

TUNING OF PARAMETERS

The eigenvalues of the system matrix **A** are determined with the help of the state equations related to the linearized model given by equations. (09) and (10) . Some of these eigenvalues correspond to the mode of oscillations associated with the inertia of the machine. These are to be identified in order to ensure the effectiveness of the stabilizers. An objective function J_{DE} meant for increasing the system damping with respect to the electromechanical mode is defined as:

$$J_{DE} = min\{\zeta_i\}$$

In this case, ζ_i represents the electromechanical mode damping ratio representing the i^{th} loading condition.

The role of the objective function is to maximize the minimum value of damping ratio computed in the design process corresponding to the electromechanical modes of the current loading condition. Thus the problem is to

Maximize J_{DE}

Subject to

$$K_{min} \leq K_{PSS\text{-}i} \leq K_{max}$$
$$T_{1\text{-}PSS}^{min} \leq T_{1\text{-}PSS\text{-}i} \leq T_{1\text{-}PSS}^{max}$$
$$T_{3\text{-}PSS}^{min} \leq T_{3\text{-}PSS\text{-}i} \leq T_{3\text{-}PSS}^{max}$$
$$K_{min} \leq K_{TCSC} \leq K_{max}$$
$$T_{1\text{-}TCSC}^{min} \leq T_{1\text{-}TCSC} \leq T_{1\text{-}TCSC}^{max}$$
$$T_{3\text{-}TCSC}^{min} \leq T_{3\text{-}TCSC} \leq T_{3\text{-}TCSC}^{max}$$

The objective function involves different gains and time constants for both CPSS and TCSC-based WADC. The detailed structure of the proposed TCSC-Based WADC is shown in *Figure 3*. With respect to the linearized power system model in equation (09), Differential Evolution is applied to determine the optimum parameters settings of the proposed WADC.

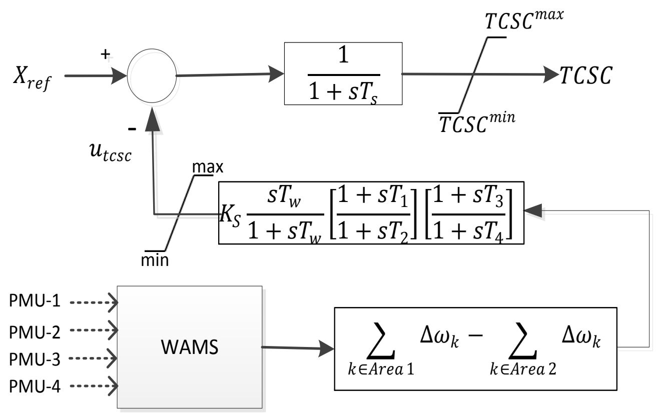

Figure 3: TCSC-Based WADC with Lead-Lag Structure

DE is [13] and has the capacity to work in multi-modal, non-differentiable and nonlinear objective functions. In DE, new off-springs are created through the formation of a trial vector of each parent individual of a population. Selection, mutation and crossover operations are performed so as to improve the effectiveness of the population in the successive generations. The control parameters in the algorithm are the size of the population NP, crossover constant CR and mutation constant F. Table 1 gives the values of the parameters of differential evolutionary (DE). The time constant for reset block, T_w is set to be 10s. The range of variation of K_i is [0.0 to 50.0] and that of T_{1i}, T_{2i}, T_{3i} and T_{4i} is [0.01 to 5.00].

Table 1: DE parameters

DE control parameters	
Population size (*NP*)	50
Max. no. of gen. (G_{MAX})	100
Mutation (f_m)	0.2
Crossover (*CR*)	0.6

TCSC-BASED WADC FOR SAUDI NETWORK

The Saudi power consists of four interconnected regional grids. The electrical map is shown in Figure 4 and the 380 kV interconnections system single line diagram is shown in Figure 5. There are four main operating areas; Eastern Operating Area (EOA), Central (COA), Western (WOA) and Southern (SOA). A reduced version of Saudi 380 kV network has been developed in ref. [14]. This system is considered which consisting of 29 generators, 127 bus and 222 circuits. The system reduction methodology has been presented given in [14]. It has been concluded that the reduced model is sufficiently accurate in representing the dynamic characteristics of the complete system. This system consisting of 29 generators, 127 bus and 222 circuits is utilized in this paper for the investigation of the impact of WADC on the minimization of the inter-area oscillations.

Figure 4: Saudi Arabia 380 kV Map

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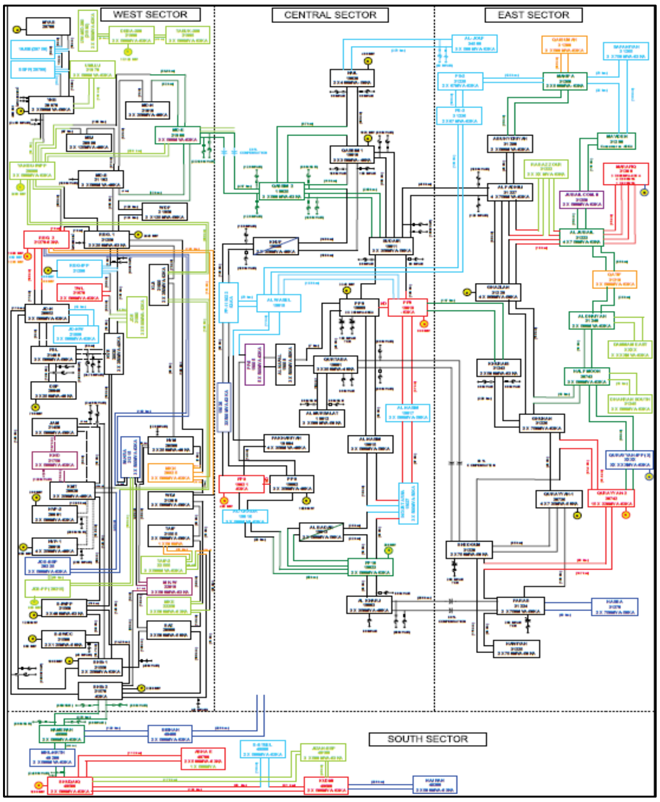

Figure 5: Saudi Arabia 380 kV Map

TCSC Site Location

Fixed Series Compensation (FSC) is installed in the tie-lines between COA-WOA as shown in SEC 380 kV tie-lines interconnection diagram in *Figure 6*. The primary objective of this installation is to increase the power transfer among areas and enhance the overall grid stability. This paper proposes upgrade of FSC to Thyristor Controlled Series Compensation (TCSC) so as to introduce new functionalities that allow better utilization of assets. The COA-WOA is a strategic interconnection, since it connects two large systems. It has been observed that COA-WOA interconnection is weak and hence it is vulnerable to small signal oscillations between these two systems.

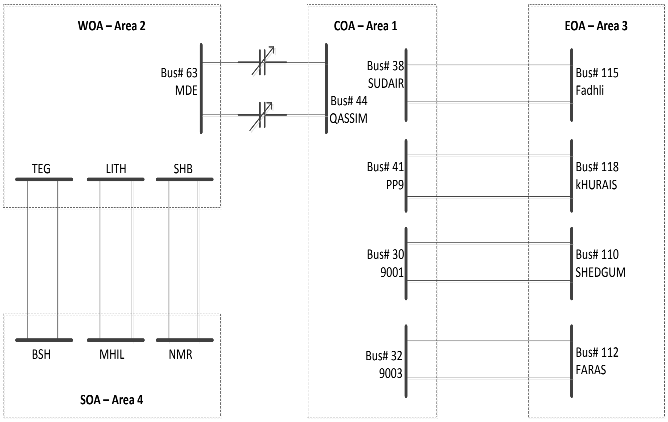

Figure 6: Saudi 380 kV Interconnection Tie-lines with TCSC between COA and WOA

Modal Analysis for the existing power system

The open loop system eigenvalues given in *Table 2* indicates that the system exhibits 28 modes of electromechanical oscillation. All modes are classified as local modes except Mode-28 is classified as inter-area mode of oscillation with eigenvalue -0.1040±2.449i, frequency (0.389 Hz), and very low damping ratio of (0.042). The participation factor analysis has shown that Machine#28 in Area#2 has the largest contribution to the inter-area mode.

Once the dominant machine participation factors are identified for the interarea mode, the mode shape is determined from the elements in the right-eigenvector related to the state variables involved in the mode. From the magnitude and the sign of the real part of the eigenvector entries, the mode shape corresponding to the rotor angle states for mode#28 is shown in Figure 7. It indicates an interarea oscillation between area 2 generators and area 1 & 3 generators.

Table 2: Open Loop System Analysis for Saudi Network

	Eigenvalues	Freq. (Hz.)	Damping Ratio
1	-0.4608 + 12.1695i	1.9368	0.037
3	-0.8865 + 11.0973i	1.7662	0.079
5	-0.2952+ 10.518i	1.6740	0.028
7	-0.4867 + 10.586i	1.6848	0.045
9	-0.4422 + 9.9178i	1.5784	0.044
11	-0.1872 + 9.4819i	1.509	0.019
13	-0.4349 + 9.3251i	1.4841	0.046
15	-0.3611 + 9.3704i	1.4913	0.038
17	-0.3552 + 8.8637i	1.4107	0.040
19	-0.3112 + 8.7874i	1.3985	0.035
21	-0.4485 + 8.2598i	1.3145	0.054
23	-0.2939 + 8.3084i	1.3223	0.035
25	-0.2897 + 8.2699i	1.3161	0.035
27	-0.2391+ 8.0673i	1.2839	0.029
29	-0.2200 + 7.6753i	1.2215	0.028
31	-0.2794 + 7.6203i	1.2128	0.036
33	-0.2734 + 5.4143i	0.86171	0.050
35	-0.4605 + 6.1002i	0.9708	0.075
37	-0.3709 + 7.5064i	1.19469	0.049
39	-0.2666 + 6.4366i	1.02442	0.041
41	-0.3372 + 7.0021i	1.11441	0.048
43	-0.3425 + 7.1568i	1.1390	0.047
45	-0.4280 + 7.2257i	1.1500	0.059
47	-0.4585 + 7.1232i	1.1336	0.064
49	-0.3088 + 6.5138i	1.0367	0.047
51	-0.2269 + 4.6636i	0.7422	0.048
53	-0.2444 + 4.8919i	0.7785	0.049
55	-0.1040 + 2.4490i	0.3897	0.042

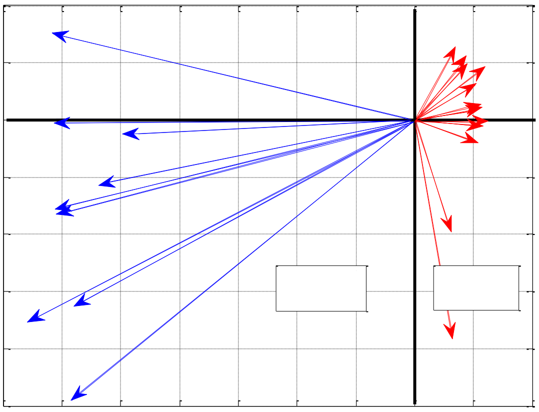

Figure 7: Mode Shape for rotor angle (interarea mode)

WADC Controller Design

In this paper, the impact of the upgradation of the existing Fixed Series Capacitor (FSC) installed on the tie-lines between COA-WOA to Thyristor Controlled Series Compensation (TCSC) with supplementary damping controller is investigated. The modal analysis has identified the dominant machine participation factors for each mode and the controllability analysis has provided the best remote combination signals to be used as feedback signal to TCSC as $\left(\sum_{k=28} \omega_k - \sum_{k=11,16} \omega_k\right)$. The schematic diagram of the proposed damping control is shown in Figure 8.

The optimal values of the controller parameters are given in Table 3. Comparing the damping ratio analysis with and without the TCSC, it can be observed that without the TCSC, the highest damping ratio of the rotor speed deviations is 0.079. Whereas, after deploying the optimized TCSC, the highest damping ratio is 0.224. On the other hand, the smallest damping ratio for the existing power system without TCSC is 0.019, while after incorporating the new optimized TCSC, the lowest damping ratio is 0.064.

In general, by comparing the performance of the power system without and with the TCSC, it can be seen that by deploying the optimized TCSC most of the rotor speed deviations' damping factors are shifted to more stable regions. Also, their damping ratios are greatly improved. Thus, it is evident that the overall dynamic performance is significantly enhanced after the deployment of the TCSC.

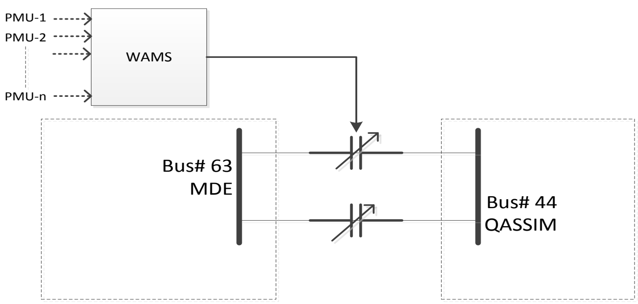

Figure 8: TCSC-Based WADC Structure

Table 3: The Optimized Parameters of TCSC Controller

Parameter	Values
K_{TCSC}	32.00
T_1	0.400
T_2	0.500
T_3	0.025
T_4	0.500
T_w	0.210

Non-Linear Time Domain Simulation

In order to validate the proposed controller design, 3-phase fault has been applied at heavily loaded line connecting EOA and COA. The fault is at bus 110 cleared by tripping the duple circuits to COA. Figure 9 shows the output power response for machine#28 located in area-2. This figure compares the dynamic stability of the power system before and after deploying the proposed TCSC-based WADC. From this ~~the~~ figure, it can be seen that the dynamic behavior of the power system with the optimized TCSC is considerably enhanced. The overshot and settling time are also significantly reduced.

Figure 10 and Figure 11 show the voltage responses for the boundary buses connecting COA with WOA. By analyzing these figures, it is quite evident that even the voltage profiles of the considered power system is improved after deploying the TCSC-based WADC.

The impact of upgrading the existing FSC to TCSC on improving the overall dynamic stability of the considered power system has been demonstrated by the simulation results. It has been confirmed that by installing the TCSC in series with the intertie tie-line connecting COA and WOA with optimizing its parameters, the existing power oscillations are greatly damped. Moreover, it has been shown that the maximum power transfer between the two areas is significantly increased from 420 MW to 800 MW with the proposed TCSC

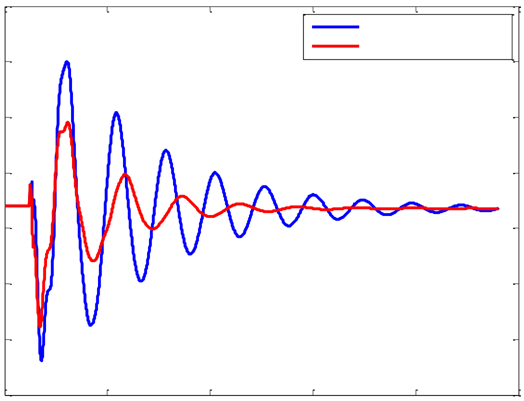

Figure 9: Machine-28 Output power response due to 3-phase short circuit and its removal after 6 cycles of 60 Hz

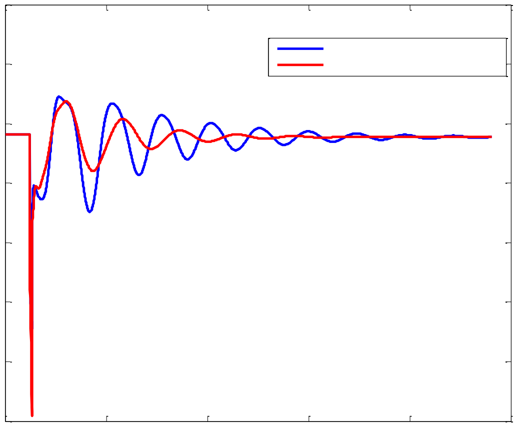

Figure 10: Voltage of Bus-63 at WOA due to 3-phase short circuit and its removal after 6 cycles of 60 Hz

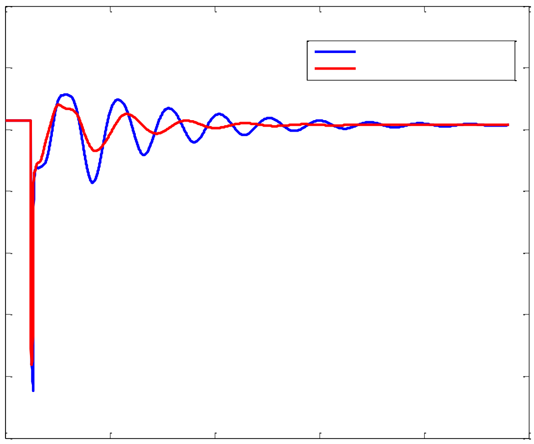

Figure 11: Voltage of Bus-44 at COA due to 3-phase short circuit and its removal after 6 cycles of 60 Hz

CONCLUSION

This paper reports the details of investigations on the impact of a TCSC-based WADC in damping the inter-area oscillation of practical interconnected power system. The necessary stabilizing signals were derived out of the data acquired through the PMUs installed at various locations in the system. The TCSC-based WADC was designed so as to stabilize the inter-area oscillations in the system, while leaving the local modes of oscillation to be controlled by local PSSs. The preliminary investigations indicate that the performance of the TCSC-based WADC shows significantly better performance than the conventional damping controller even under severe disturbance conditions.

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