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Design of Weighted Wide Area Damping Controller (WWADC) Based PSS for Damping Inter-Area Low Frequency Oscillations

Wide Area Measurement System (WAMS) can extend and effectively improve the power system stabilizers (PSS) capability in damping the inter-area low frequency oscillations in interconnected bulk power systems. This paper proposes the implementation of Weighted Wide Area Damping Controller (WWADC) in which weighted factors are introduced for each remote feedback signals. Modal analysis approach is implemented for the purpose of identifying the optimal location as well as the input signals' optimal combination of WWADC. Based on the linearized model, Differential Evolution (DE) algorithm is applied to search for optimal controller parameters and optimal weighted factors. The successful application of the proposed approach is achieved in two power networks; the two-area 4-machine system and the IEEE-39 bus 10-machine system. The analysis of the eigenvalue and non-linear time domain simulations indicate that damping the inter-area oscillations and improving the system stability irrespective of the severity and the location of the disturbances can be effectively achieved by WADC. .

Keywords: Weighted Wide Area Damping Controller (WWADC), Low Frequency Oscillations (LFO) , Differential Evolution (DE)

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1. Introduction

The 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, inter-area oscillations' damping is attempted via the installation 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 wide area measurements in wide area damping controller (WADC) for the purpose of damping inter-area oscillations. It has been proven that application of remote signals will enhance the system dynamic performance and damp inter-area oscillations [6]. There are approaches in the literature for the design of WADC such as modal analysis based robust and optimal control techniques as well as adaptive methods. A structure that is decentralized/hierarchical structure with two loop PSSs: a local loop and a global loop that are based on a differential frequency between

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two remote areas was proposed by Kamwa et al., [4] . Simulation results show that WADC improved the dynamic performance of the system. Modal analysis is very useful in determining the best controller locations and the proper selection of control inputs..[7] uses residue phase compensation method for choosing the location of controller and input signals. Conducted simulations have proven that the inter-area modes damping has been improved with the proposed wide area PSSs. Modal analysis has also been used in [8] to select the wide-area controller location and the signals combination based on largest controllability and observability of the inter-area mode of concern. Validation of the proposed controller in two-area power system and simulation results have shown that the controller is effective and robust for damping all oscillation modes. Other techniques based on modern control theories such as phase shift compensation [9], Fruit Optimization [10], fuzzy control [11], neural networks [12], backtracking search algorithm (BSA) [13] and robust control [14] have also been utilized for WADC.

In this research paper, Weighted Wide Area Damping Controller (WWADC) is proposed and Differential Evolution (DE) algorithm is used to simultaneously tune the WWADC with CPSS for the purpose of damping inter-area low frequency oscillations. The WWADC is an enhanced model design of multi-bands controller structure since it requires significantly less components and therefore simplifies the design process. The WWADC optimal parameters' tuning, weighted factors and the design process are addressed in this paper. Modal analysis is utilised in determining the proper remote input signals and the optimal location and. The proposed controller performance is investigated for two different multi-machine networks, the two-area power system and the IEEE-39 bus ten-machine system. Time domain simulation as well as the eigenvalue analysis are conducted on the two-area system in order to obtain an evaluation of the performance of the controller.

The paper is organized as follows: Section (3) discusses the system modelling. The design approach and the optimization algorithm are given in Section (4). The simulation results are discussed in Section (5) discusses which is then followed by the conclusion in Section (6).

2. Notation

The notations used throughout the paper are stated below.

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
WWADC	: Weighted Wide Area Damping Controller
PMU	: Phasor Measurement Unit
δ	: Generator rotor angle
E_q'	: Internal voltage of the machine behind transient reactance x'_d.
ωb	: base angular velocity
ω	: angular velocity in per unit

M	: generator inertia constant
D	: damping coefficient
Tm	: Input torque of the generator
Te	: Output torque of the generator
E_{fd}	: Exciter output voltage
T'_{do}	: d-axis transient open-circuit time constant

3. Power System Modelling

3.1. Generator

A power system network with *n* number of generators is considered, where each generator can be modelled via the fourth-order model which comprises of swing equations as well as the equation for the internal voltage of the generator 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:

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

3.2. Excitation System and PSS

Excitation system of generators are assumed to be of IEEE Type-ST1 [15]. 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.

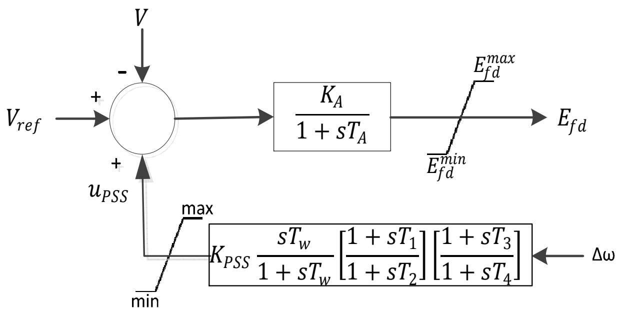


Figure 1: Excitation system IEEE-ST1 with CPSS

The ST1-IEEE model is represented by the following 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 KA and TA, respectively; and Vref is the reference voltage.

3.3. Wide Area Damping Controller (WADC)

As shown in Figure 2, in the proposed WADC system, the stabilizing signals selected are measured by Phasor Measurement Units (PMUs). Utilising the Global Positioning System (GPS), these measured signals are time synchronized and then transmitted to the controller. Then the WADC generates the required control signal to the generator excitation system for damping the interarea oscillations.

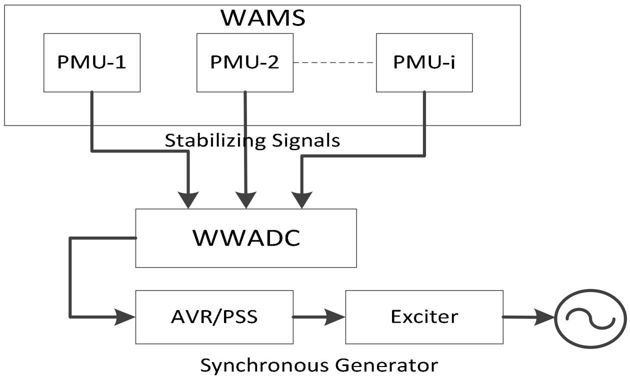


Figure 2: Structure of Wide Area Damping Control (WADC)

3.4. Linearized Multimachine System Model

In general, nonlinear differential set of equations [16] represent power system dynamics by:

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

where the variable of the state vector is represented by X is, $= [\delta, \omega, E'_q, E_{fd}]^T$, and U is variable for the PSS input vector, $U = [U_{PSS}]^T$, where UPSS are the PSS control signals. The linearized incremental model around a nominal operating point is utilized when designing electromechanical mode damping controllers. Linearization of equation (8) yields

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

where
The n state vector increment is represented by Δx
The m output vector increment is represented by Δy
The r input vector increment is represented by Δu
The (4n x 4n)matrixis represented by A
B is (4n x m) matrix
Δx is (4n x 1) state vector and
U is (m x 1) input vector

Here, n represents the number of machines and m represents the number of stabilizers. A and B are both evaluated at the nominal operating point.

4. The Weighted Wide Area Damping Controller (WWADC) Design

Weighted wide area damping controller (WWADC) utilizes remote measurements with weighted factors as feedback signals to enhance the damping of inter-area oscillations. Therefore, the appropriate location as well as the control inputs selection can be very critical in attaining the acceptable damping control performance and are the two key factors in the interarea damping controller design. In the design of WWADC, observability measurement defines the observation machines based on their output signals while controllability measurement defines the control machines based on their input signals that is related to the concerned mode. Thus, in a situation where the j^{th} machine output signal $\Delta\omega$'s maximum mode observability exists and the k^{th} machine's input signal u_{pss} possesses the maximum mode controllability relatng to the i^{th} interarea mode, it is recommended that the i^{th} mode is damped by feeding back the $\lambda\Delta\omega$ signal of the j^{th} machine as an input to the WWADC that located at k^{th} machine. So, for PSS and WWADC, controllability and observability measures can be introduced from

$$Cont._{ik} = \left|\boldsymbol{\Psi}_i \ \boldsymbol{B_k}\right| \qquad (10)$$

$$Obse._{ji} = \left|\boldsymbol{C}_j\boldsymbol{\Phi}_i\right| \qquad (11)$$

where the mode controllability of mode i from the kth input is measured by $Cont._{ik}$ and the mode observability of mode i from the jth output is measured by $Obse._{ji}$. The right and left eigenvectors are represented by $\boldsymbol{\Phi}$ and . To determine the best location of CPSS and WWADC, residue is considered as follows

$$R^i_{jk} = \boldsymbol{C}_k\boldsymbol{\Phi}_i\boldsymbol{\Psi}^T_i\boldsymbol{B_k} \qquad (12)$$

In cases where attaining theoutput signal $\Delta\omega_j$'s highest mode observability and the highest mode controllability concerning the i^{th} oscillation mode exists in the input signal U^k_{PSS} , dampening the i^{th} mode is suggested by feeding back the $\lambda_j\Delta\omega_j$ as an input to the WWADC located at k^{th} machine.

4.1. Tuning of Parameters

The eigenvalues of the system matrix A are determined with the help of the state equations relating to the linearized model eq. (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 JDE meant for increasing the system damping with respect to the electromechanical mode is defined as:

$J_{DE} = min\{\zeta_i\}$ in this case, where the the electromechanical mode's damping ratio of the i^{th} loading condition is represented by ζ_i. .

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

$K_{min} \le K_{PSS\text{-}i} \le K_{max}$

$T_{1\text{-}PSS}^{min} \le T_{1\text{-}PSS\text{-}i} \le T_{1\text{-}PSS}^{max}$;

$T_{3\text{-}PSS}^{min} \le T_{3\text{-}PSS\text{-}i} \le T_{3\text{-}PSS}^{max}$;

$K_{min} \le K_{WWADC} \le K_{max}$

$T_{1\text{-}WWADC}^{min} \le T_{1\text{-}WWADC} \le T_{1\text{-}WWADC}^{max}$;

$T_{3\text{-}WWADC}^{min} \le T_{3\text{-}WWADC} \le T_{3\text{-}WWADC}^{max}$;

$\lambda_{jmin} \le \lambda_j \le \lambda_{jmax}$;

The objective function involves different gains and time constants for both CPSS and WWADC in addition to the weighted factors λ_i for each remote signal. The detailed structure of the proposed WWADC 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 and weight factors settings of the proposed WWADC.

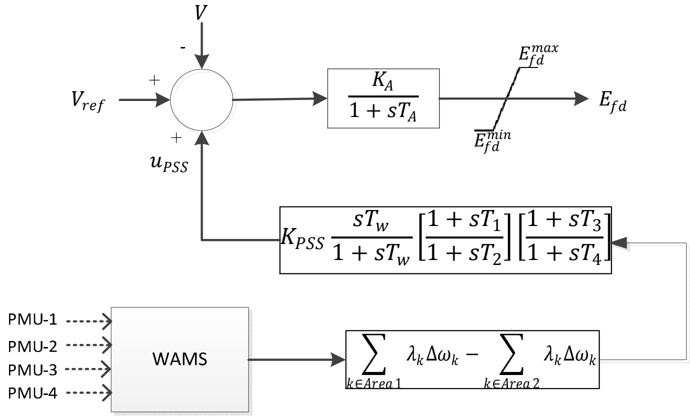


Figure 3: WADC with Lead-Lag Structure

DE is viewed as an Evolutionary Algorithm [17] due to its capacity to work in multi-modal, non-differentiable and nonlinear objective functions. New off-springs are created of DE 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*.

5. Case Studies and Simulation Results

To evaluate the the proposed controller effectiveness in multi-machine power system network, MATLAB based simulation is carried out in the linearized model of a two-area, four-machine system and IEEE-39 bus ten-machine system. The simulation results for WWADC based PSS have been compared with WADC and CPSS. For both WWADC-based PSS and CPSS, DE technique have been employed and the dimension of the problem for each generator, population size and total generation are set to 5, 100 and 500 respectively. The time constant for the 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]. In case of WWADC, the weighted factors (λi) range is [0.01 to 2.00]. Table 1 gives the values of the parameters of differential evolutionary (DE).

Table 1: DE parameters

DE control parameters	
Population size (NP)	50
Max. no. of gen. (GMAX)	100
Mutation (fm)	0.2
Crossover (CR)	0.6

5.1. Two-Area 4-Machine System

The two-area 4-machine power system [16] consists primarily of two areas that are identical, each area having two generators of 900 MVA each. This is based on the assumption that a power transfer of 400MW from Area 1 to Area 2 exists over the tie line.

Table 2 shows the system's open loop eigenvalues along with their characteristics. From this Table, it can be observed that three electromechanical modes occursin this system. These are (i) an inter-area mode, with negative damping ratio and frequency of a value of 0.6129 Hz, where those two generators that operate in the first area will oscillate against the second area generators, (ii) In the first area, a local mode, having a frequency value of 1.106 Hz where the machines in the first area oscillate against one another and (iii) In the second area, a local mode, having a frequency of 1.0741 Hz where the machines in the second area oscillate against each other.

Table 2: Open Loop System Eigenvalues

	Eigenvalues	Frequency (Hz)	Damping Ratio	Mode of oscillations
Mode 1	-1.2753 ±6.949i	1.1060	0.1805	Local
Mode 2	-1.1983 ±6.748i	1.0741	0.1748	Local
Mode 3	0.0281 ± 3.810i	0.6129	-0.0073	Inter-Area

The participation factor (PF) for each machine to these three modes is given in Table 3. Since generators in each area are electrically near to each other and they are all identical, it can be seen that they have close values of PF for a mode of oscillation. For the inter-area mode, the table highlights the fact that in the second area, the generators that are located at the receiving end produced larger PF figures in comparison to the generators in the first area at the sending end.

Table 3: Machines Participation Factor to Oscillation Modes

Eigenvalues	Machines Participation Factor			
	Area 1		Area 2	
	G1	G2	G3	G4
-1.2753 ±6.9492i	0.2867	0.3146	0.0052	0.0127
-1.1983 ±6.7486i	0.0110	0.0062	0.2890	0.3103
0.0281 ± 3.81i	0.1200	0.0808	0.1631	0.1435

Once the dominant machine participation factors are identified for each mode, determining the mode shape can be achieved from the elements in the right-eigenvector related to the state variables involved in the mode. The rotor angle right-eigenvector elements for the three modes are illustrated in Table 4. Determining the mode shape can be obtained from the magnitude and the sign of the real part of the eigenvector entries. For mode-1, the eigenvalue of G_1 has a positive real part while that of G_2 eigenvalue is negative. This indicates that G_1 rotate against G_2 locally in area 1. Similarly, the second local oscillation of area 2 is between G_3 and G_4 as these have real parts of the eigenvalues with different signs. Since both G_1 and G_2 have the real parts of eigenvalues with same signs but opposite to that of G_3 and G_4, it can be inferred that Mode-3 is the interarea mode.

Table 4: Right-eigenvector elements (Corresponding to Δδ)

Generator	Right Eigenvector Entry
Mode 1	
1	0.0148 - 0.0472i
2	-0.01895 + 0.0458i
Mode 2	
3	0.0089 - 0.0488i
4	-0.0144 + 0.0480i
Mode 3	
1	-0.0240 + 0.0790i
2	-0.0286 + 0.0486i
3	0.0584 - 0.0948i
4	0.0491 - 0.0883i

5.1.1. Optimal Placement of PSSs and WWADC

From Table 3, it can be seen that G_2 has the largest PF in mode-7. Thus, this machine has more effect and can influence the oscillation in this mode more than the other machines in the same area. Similarly, in mode-8, G_4 has the largest PF. Thus, the local PSSs are located at G_2 and G_4 respectively in order to make damping of local modes oscillations in the respective areas more effective. Furthermore, as G_3 has a higher participation inter-area oscillation when compared with G_1, WWADC is located at G_3. The schematic diagram of the proposed damping control is shown in Figure 4.

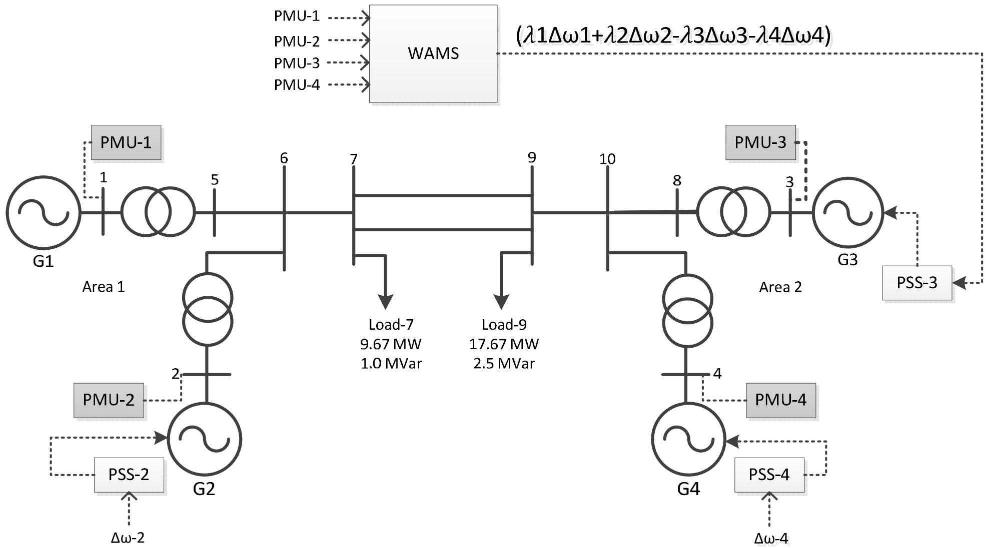
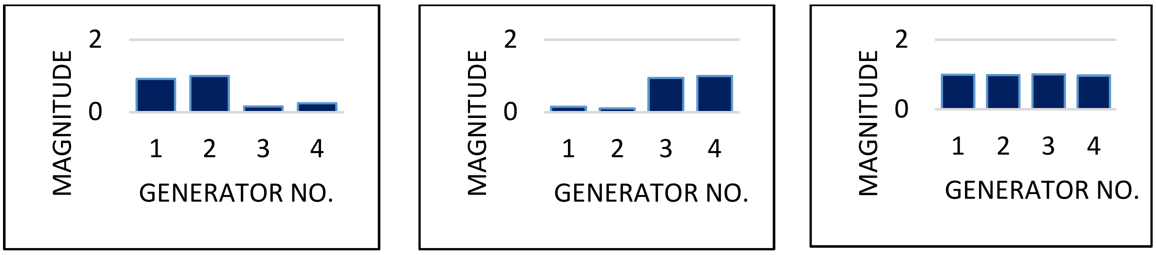


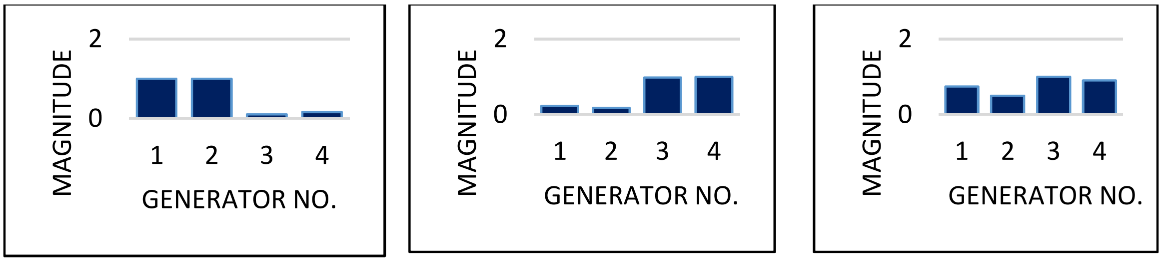
Figure 4: Schematic diagram of the proposed damping control of the Two-Area Network

Controllability, observability and residue measurements for all the modes have also been conducted as per equations (10)-(12) so as to confirm the placement of the proposed controllers. The overall damping stabilizer design will enhance damping for all oscillation modes. The residues of the system generators related to the local modes, namely Mode-1 and Mode-2 indicates that G_2 has the largest magnitude in Mode-1 and G_4 in Mode-2. Hence, CPSS will be placed at G_2 and G_4 as optimal locations for damping local area oscillations. The inter-area mode controllability measurement has also confirmed the placement of WWADC at G_3 since it has the largest controllability value. The combined combination signal is $\left(\sum_{k=1,2} \lambda_k \Delta\omega_k - \sum_{k=3,4} \lambda_k \Delta\omega_k\right)$.



(a): Mode-1 (b): Mode-2 (c): Mode-3

Figure 5: Controllability Measures for all modes



(a): Mode-1 (b): Mode-2 (c): Mode-3

Figure 6: Observability Measures for all modes

5.1.2. PSSs and WWADC Parameters Tuning Simultaneous Tuning Using DE

For the chosen system base case, the optimal values of the controller parameters are obtained by the application of DE algorithm are given in Table 5.

Table 6 gives a comparison of the system eigenvalues and damping ratios for the four cases; (i) no control, (ii) with three CPSS (iii) with WADC and (iv) with WWADC. From this Table, it can be seen that the system damping ratios especially for the inter-area mode is improved with WADC at G_3 which is further enhanced with WWADC. The variation of the objective functions for CPSS, WADC and WWADC designs with respect to number of generations of the differential evolution is shown in Figure 7. From this figure, it can be seen that in comparison with other controllers, WWADC provides the minimum damping ratio for all the electromechanical modes of oscillations in an improved manner.

Table 5: Controller Optimal Settings

	Conventional Local PSS design			Coordinated Design In case of WADC			Coordinated Design In case of WWADC		
	PSS-2	PSS-3	PSS-4	WADC @3	PSS-2	PSS-4	WWADC @3	PSS-2	PSS-4
K	88.176	16.757	14.3065	8.5161	8.6685	29.887	5.4890	12.018	49.102
T1(s)	0.0702	0.0012	0.3246	0.0021	0.0014	0.0349	0.2230	0.0014	0.0874
T3(s)	0.0616	0.0010	0.0021	0.0831	0.2617	0.1111	0.0747	0.1704	0.0336
T2/T4	0.0500	0.0500	0.0500	0.0500	0.0500	0.0500	0.0500	0.0500	0.0500
$\lambda1$	0.000	0.000	0.000	1.000	0.000	0.000	0.4850	0.000	0.000
$\lambda2$	1.000	0.000	0.000	1.000	0.000	0.000	0.6647	0.000	0.000
$\lambda3$	0.000	1.000	0.000	1.000	1.000	0.000	1.58	1.000	0.000
$\lambda4$	0.000	0.000	1.000	1.000	0.000	1.000	0.9469	0.000	1.000

Table 6: System eigenvalues with and without controllers

	No Control	Three Local PSS G2/G3/G4	Two Local PSS @ G2/G4 One WADC @G3	Two Local PSS @ G2/G4 One WWADC @G3
Local Mode-1	-1.2753 ±6.9492i 1.106**, 0.1805*	-3.8112±5.7968i 0.5494*	-4.6675±7.1449i 0.5469*	-5.5667±7.2756i 0.6077*
Local Mode-2	-1.1983 ±6.7486i 1.0741**, 0.1748*	-2.7173 ± 4.6833i 0.5019*	-3.8480±6.0857i 0.5344*	-5.2252±6.7795i 0.6105*
Interarea Mode	0.0281 ± 3.81i 0.613**, -0.0073*	-1.8669 ± 3.2191i 0.5017*	-2.4199±3.6550i 0.5521*	-2.4433±3.1979i 0.6071*

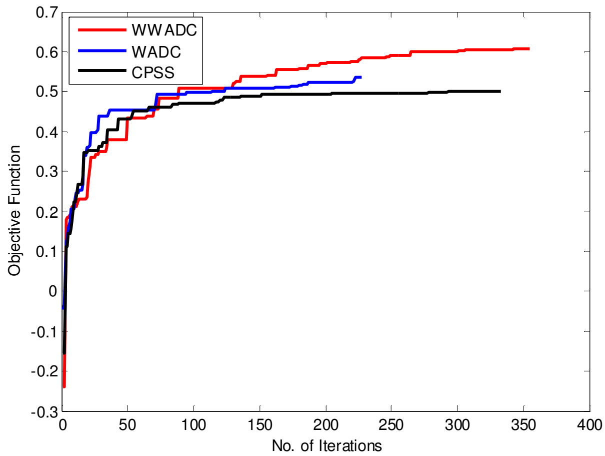


Figure 7: Variation of objective functions for DE based optimization technique

5.1.3. Non-Linear Time Domain Simulation

Figure 8 to Figure 11 show the simulation results of the two-area power system for a three phase short-circuit fault that is initiated at Bus 9 at the time instant t= 0.5 seconds which is removed after 6-cycles of 60 Hz. The system without any of the controllers, will experiences significant oscillations in the relative rotor angles of various machines in the systems. It can be seen from these figures that these oscillations get damped with PSSs, at G_2, G_3 and G_4. The damping performance is seen to be significantly improved with the local PSS at G_3 replaced with the proposed WWADC.

The WWADC, in addition to the local PSSs, better damping characteristics are provided to the power oscillations and thus, the dynamic stability of the power system is enhanced. The results of the nonlinear time domain simulation confirm the conclusion drawn from the eigenvalues analysis.

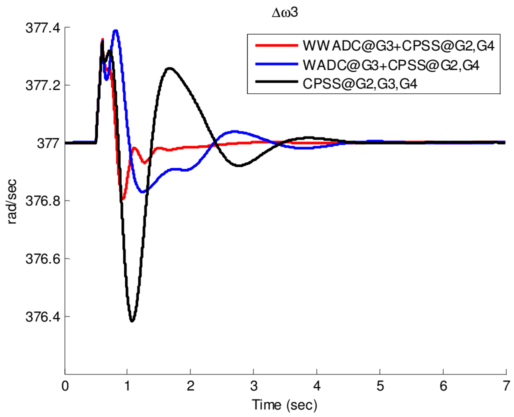


Figure 8: G3 Rotor speed responses for 3-ph short circuit

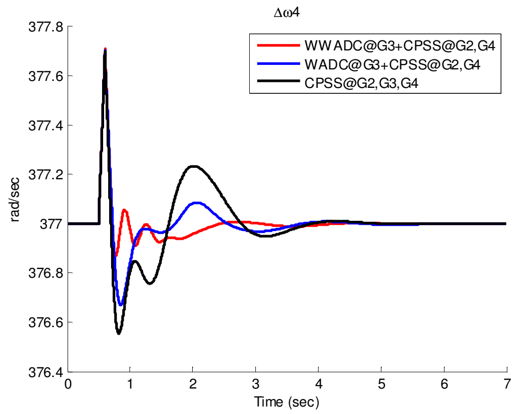


Figure 9: G4 Rotor speed responses for 3-ph short circuit

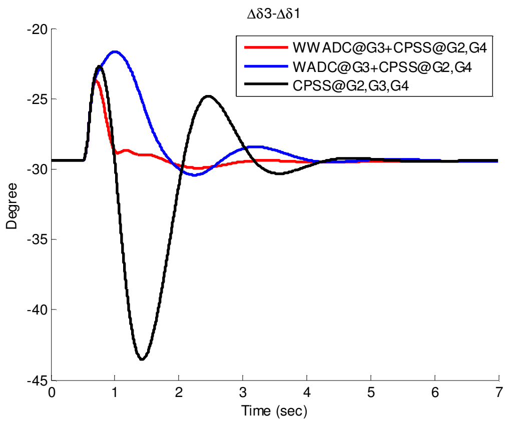


Figure 10: G3 Relative angle responses for 3-ph short circuit

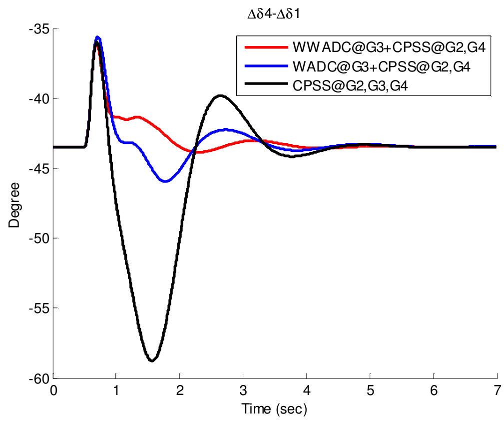


Figure 11: G4 Relative angle responses for 3-ph short circuit

5.2. IEEE-39 BUS 10-machine System

This section considers the New England 39-bus 10-generator system [1] for the weighted wide-area damping controller WWADC design. Generator-1 is an equivalent unit and is taken as the reference generator. All synchronous machines, except unit-1, are assumed to be with static excitation system, and CPSS.

Table 7: Open Loop System Analysis for IEEE 39-bus

No.	Eigenvalues	Freq.	Mode	Damping Ratio	Mode Shape	Max. Controllability
1	-1.363 ± 12.398i	1.973	Local	0.1093	G4,G6 vs. G5,G7	G7
2	-0.3241 ± 11.782i	1.875	Local	0.0275	G7 vs. G6	G4
3	-0.2112 ± 10.118i	1.610	Local	0.0208	G8 vs. G10	G8
4	-0.2098 ± 9.448i	1.503	Local	0.0222	G2 vs. G3	G2
5	-0.0954 ± 8.328i	1.325	Local	0.0114	G8,G10 vs. G9	G10
6	-0.2307 ± 8.104i	1.289	Local	0.0284	G6,G7 vs. G2,G3	G6
7	-0.104 ± 6.984i	1.111	Local	0.0149	G2,G3 vs. G5,G4	G5
8	0.1212 ± 5.976i	0.951	Local	-0.0202	G5,G4 vs. G9	G9
9	0.1341 ± 4.164i	0.662	Inter-area	-0.0322	G1 vs. all others	G7

The modal analysis results are provided in Table 7. From the open loop system eigenvalue, the system exhibits nine (9) electromechanical oscillation's modes. Eight (8) modes are classified as local modes while Mode-9 is classified as inter-area mode of oscillation with eigenvalue 0.1342±4.1647i, frequency (0.662 Hz), and negative damping ratio of (-0.0322).

The participation factor (PF) analysis for each oscillation modes is presented in Table 8. It is clear that generators contribute to the local modes are located in one area, while the contribution by the inter-area mode comes from different generators and from different area.

Table 8: Oscillation Modes PF for IEEE-39 bus system

Gen.	Mode (1)	Mode (2)	Mode (3)	Mode (4)	Mode (5)	Mode (6)	Mode (7)	Mode (8)	Mode (9)
1	0	0	0	0.00015	0.00216	0.00021	0.01035	0.00051	0.18565
2	0.00028	0.00165	0.00058	0.36731	0.00364	0.04719	0.05163	0.00107	0.00919
3	0.00035	0.0016	0	0.12747	0.0270	0.1798	0.12189	0.00252	0.01866
4	0.03915	0.44417	0.00012	0	0.00044	0.00246	0.0001	0.01076	0.02293
5	0.00117	0.02556	0	0	0.00477	0.02223	0.17048	0.16781	0.07987
6	0.08062	0.0391	0.00114	0.0008	0.0755	0.2041	0.03651	0.00929	0.04238
7	0.41361	0.01754	0	0	0.01443	0.04079	0.00994	0.00401	0.02576
8	0.00044	0.00248	0.37571	0.00018	0.08245	0.00432	0.01162	0.0028	0.011252
9	0	0.00037	0.0017	0	0.010	0.00388	0.06278	0.28861	0.07022
10	0	0.00123	0.1227	0.00256	0.2979	0.0113	0.034068	0.002655	0.01452

5.2.1 PSSs and WWADC Placement

From the participation factor results in Table 8, it can be seen that each oscillation mode has a generator with the largest PF among the others. This means that this machine has more effectiveness and can influence the oscillation on this mode more than the other machine in the same area. Therefore, the local PSSs should be located at these generators in order to get the best improvement in damping local area oscillations. Controllability, observability, and residue measurements have also been conducted for all modes to confirm placing of the proposed controllers. The overall damping stabilizer design will enhance damping for all oscillation modes. The controllability analysis concludes that CPSS will be placed at each Generator except G_7 as optimal locations for damping local area oscillations. The inter-area mode controllability measurement has also confirmed placing WWADC at G_7 since it has the largest controllability value as shown in Figure 12.

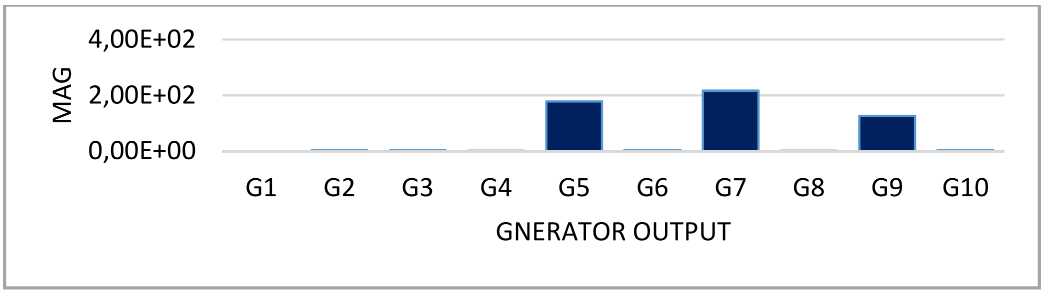


Figure 12: Controllability analysis for Mode-9 - (inter-area mode)

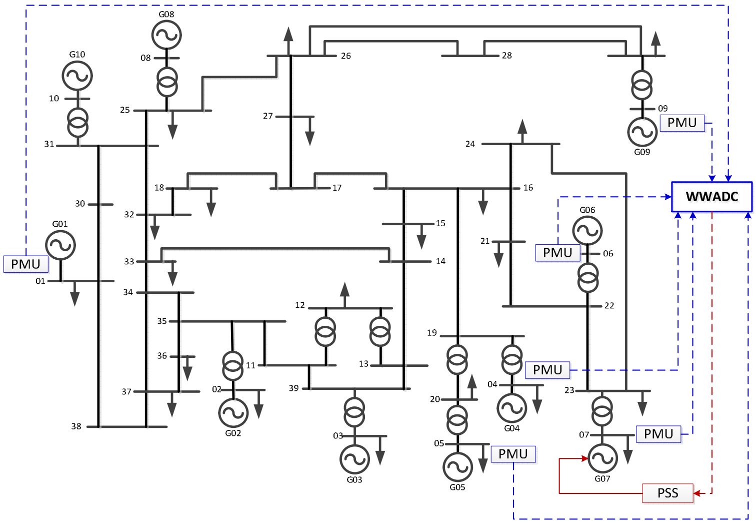


Figure 13: WWADC Proposed Connection for IEEE 39-bus system

5.2.2. PSSs and WWADC Parameters Simultaneous Tuning Using DE

In the previous section, the controllers have been placed based on the participation factor and controllability measurement. The controllers' parameters tuning is carried out using DE for the chosen system base case. For the purpose of comparison, the tuning was performed for three cases, (i) A case where it considers only CPSS at all generators where local feedback signal is used except for G1 since it represents and equivalent system, (ii) WADC-G_7 and CPSS at all remaining units, and (iii) WWADC-G7 and CPSS at all remaining units.

Table 9 represents the system's minimum damping ratio measured for no control, local CPSS only, WADC with CPSS, and the proposed WWADC with CPSS. At no control case, the 39-bus system exhibits negative damping ratio of (-0.0332) which related to inter-area mode of oscillation. The inter-area mode has been greatly improved to (0.0408) after adding CPSS at each generator utilizing local speed feedback signal and to (0.0493) after introducing WADC for G_7. A further improvement to the minimum damping ratio has been achieved to (0.0569) by applying the proposed WWADC for G_7 and assigning suitable combination of wide area measurements.

Table 9: System minimum damping ratio measured for different types

	No Control	Local CPSS	WADC@G7 and CPSS's	WWADC@G7 and CPSS's
Minimum Damping Ratio	0.1341 ± 4.164i 0.662 Hz, -0.0332*	-0.2035 ± 4.9840i 0.793 Hz, 0.0408*	-0.2381 ± 4.8264i 0.7681 Hz, 0.0493*	-0.2736 ± 4.8029i 0.7644 Hz, 0.0569*

5.2.3. Non-Linear Time Domain Simulation

Simulation of the time domain is performed so as to validate the proposed damping controller effectiveness. A three-phase fault, 6-cycles, at Bus#17 is applied. Figure 14 to Figure 17 show machines responses of the IEEE-39 bus system for the severe disturbance. Each figure shows the system response for three cases; (i) CPSS as proposed [13], (ii) WADC, and (iii) the proposed WWADC in this paper. The system without control experiences serious power oscillations, however, with implement of CPSSs, at all generator except G_1, such power oscillations are damped out better than without applying any control. Taking the last case and replacing the local PSS at G7 with the proposed WADC, this greatly improves the system responses comparing to the other cases. The WADC in addition to the local PSSs provide better damping characteristics to the power oscillations and thus enhance the dynamic stability of the power system. The nonlinear time domain simulation results confirm the conclusion drawn from eigenvalues analysis.

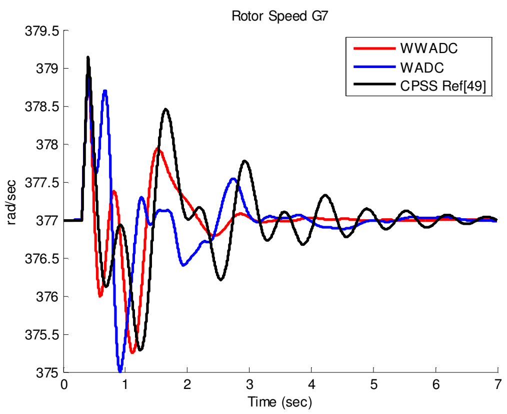


Figure 14: G7 Rotor speed responses for 3-ph short circuit

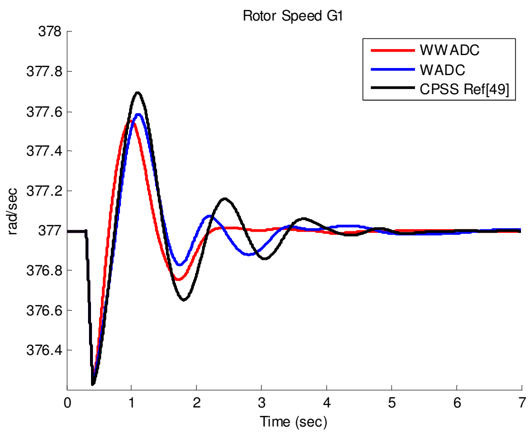


Figure 15: G1 Rotor speed responses for 3-ph short circuit

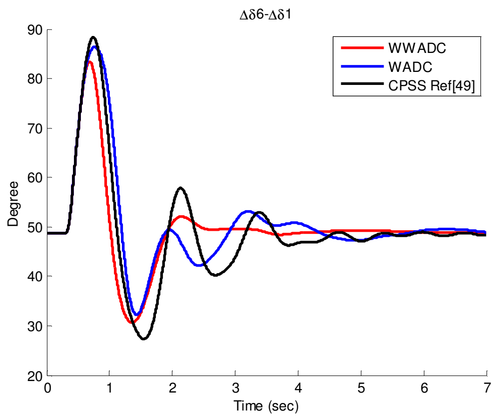


Figure 16: G6 relative angle responses for 3-ph short circuit

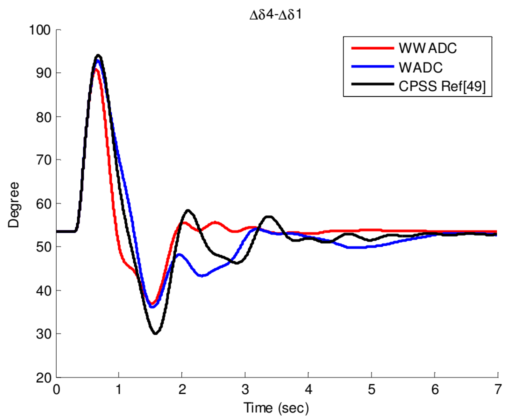


Figure 17: G4 relative angle responses for 3-ph short circuit

6. Conclusion

In this paper, the effectiveness of Weighted Wide Area Damping Control (WWADC) system to enhance the power system stability has been investigated. The WWADC structure consists of weighting factors for each feedback signal and a lead-lag compensation blocks. These feedback signals are measured by PMUs installed at different locations in the system. The WWADC has been designed such that it focuses on stabilizing the interarea oscillations in the system while leaving local modes of oscillations to be controlled by local PSSs.

The performance of the designed WWADC was investigated by applying severe disturbances and results show great improvements in damping the inter-area mode. This is evident from the calculated eigenvalues of the system which show that the eigenvalue corresponding to the interarea is shifted to the left side of the imaginary plane. The enhancement in the system stability can also be observed from the non-linear time domain simulation responses. Clearly, the simulation results confirmed that applying the proposed WWADC improves the damping characteristics and accordingly overall system stability enhanced.

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