



Computational Intelligence in Electrical Engineering
Vol. 14, No. 4, 2024
pp. 27-46
Research Paper

Adaptive Wide Area Controller for Damping Inter-Area Oscillations Using Global PSS and WAMS Data

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Abstract :

This paper presents an online scheme of a wide-area-damping-controller (WADC) for controlling the inter-area oscillatory modes in interconnected power systems using wide-area power system stabilizers and measuring signals. The proposed adaptive controller includes two individual approaches WSSS for evaluating the signal participation factor selection and GPSS as a global power system stabilizer for damping inter-area oscillations. For this purpose, considering the concept of center of inertia over inter-area signals, generators with the highest interactions are determined as oscillating areas while based on evaluating signal damping ratio, proper participation factors are estimated in which GPSS with positive damping performance is developed. In real-time working mode, based on oscillatory signals gathered from WAMS data, different combinations of PSSs are evaluated in which the combinations with the best controllability on damping the oscillations are selected. The effectiveness of the proposed wide-area damping controller scheme is evaluated on the IEEE test system and practical Iran national power grid with the potential of unstable inter-area oscillations. Results show the effectiveness of the proposed WADC approach for fast and secure damping of inter-area oscillation.

Keywords: Power System Stabilizer, Inter-Area Oscillations (IAO), Wide Area Measuring system (WAMS), Global PSS, Wide Area Damping Controller (WADC).

1. Introduction

Dynamic processes of interconnected electric systems are highly random, nonlinear to some extent, and intrinsically non-stationary even over short-time

durations especially for evaluating the case of severe dynamic oscillations in which the strategy of controlling actions or switching devices interact in different complex behaviors.

1.1. Paper Motivation

Based on the complex and diverse nature of the system oscillatory modes, severe oscillations contain broad scaling ranges of time-varying and highly nonlinear variables [1, 2]. Prediction of time-based dynamics,

Submission date: 25, 09, 2022

Acceptance date: 13, 12, 2022

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<https://doi.org/10.22108/ISEE.2023.135667.1596>

with application in real-time monitoring, protection, and control, remains a major research challenge for power engineers. Proper knowledge about the system dynamics is significant for reliable evaluations of the system base mechanisms in the observed fluctuations and required for presenting wide-area measuring and controlling systems resulting in operational reliability. Considering the time-varying and nonlinear parameters can present a suitable explanation with important information on the system oscillatory modes like moving patterns and modal shape properties.

1.2. Literature Review

Advances in processing online data with continuously growing computational resources and wide area monitoring systems make feasible solutions for analyzing transient processes through real-time information [1]. In this case, different approaches presented tested for controlling the inter-area oscillatory modes, while there were schemes of damping the oscillations using controlling devices like PSS and FACTS. In the case of designing global PSSs, presented approaches included approximate multi-modal decomposition method [2], H_∞ -based decentralized PSS [3], frequency response [4], inherent dead-band structure [5], modal decomposition method [6], eigen-structure-based performance index [7], and generic oscillation damping controller [8]. There are also other investigations concentrated on the concept of GPSS. The developed methods included mixed integer non-linear programming [9], cross-entropy approach [10], global error-driven power system stabilizer [11], collocated control [12], and GA-based dynamic search spaces [13]. In the case of selecting effective signals, recent research included normalized H_∞ loop-shaping technique [14], additional control signals [15], bus voltage [16], tie-line active power [17], signal coherency approach [18], geometric and residues approach [19], virtual generator [20],

trajectory-based approach [21], reinforcement learning algorithm [22], classification tree [23], relative gain array analysis [24] and classification and regression tree technique [25]. A brief review of the references is illustrated in Table 1. As can be seen, the offline and model-based algorithms were used by most references for designing GPSSs. Moreover, the use of local signals equipped with numerical techniques was the favorite of most research.

Table (1): A brief review of related references

Ref.	Category	Online	Offline	Model Based	Non Model Based	Local Signal	Global Signal
1	Selecting Control Signal	-	✓	✓	-	-	✓
2		-	✓	✓	-	✓	-
3		-	✓	✓	-	✓	-
4		✓	✓	✓	-	-	✓
5		✓	✓	✓	-	-	✓
6		✓	✓	✓	-	✓	-
7		-	✓	✓	-	-	✓
8		-	✓	✓	-	-	✓
9		✓	-	✓	-	-	✓
10		-	✓	✓	-	-	✓
11		✓	✓	✓	-	✓	-
12		-	✓	✓	-	-	✓
13		-	✓	✓	-	-	✓
14		-	✓	-	✓	-	✓
15		-	✓	-	✓	-	✓
16	PSS Design	-	✓	✓	-	✓	-
17		-	✓	✓	-	-	✓
18		-	✓	✓	-	✓	-
19		-	✓	✓	-	✓	✓
20		-	✓	✓	-	✓	-
21		-	✓	✓	-	✓	-
22		-	✓	✓	-	✓	-
23	GPSS Design	-	✓	✓	-	-	✓
24		-	✓	✓	-	-	✓
25		-	✓	✓	-	✓	-

1.3. Paper Contribution

In this study, an adaptive non-model-based numerical approach is developed to control the inter-area modes using wide-area signals and global PSSs. The developed scheme consists of two main online parts including (1) WSSS: Weighted Signal Selection and Synthesizing, and (2) GPSS:

Global Power System Stabilizer. In a real-time environment, using PMU phasor signals, generators' rotor speed oscillations are evaluated based on that, evaluating interactions between generator oscillations against each other, coherent groups, and corresponding oscillating areas are identified. In this case, based on the concept of center of inertia (COI), the signals of two oscillatory areas are merged in the COI frame in which an inter-area signal is provided. In the case of identifying inter-area oscillation, by using the signal peak points between three consecutive inter-area cycles, the damping ratio is evaluated. In the case of identifying unstable conditions, the proposed controller is activated which based on the concepts of observability and controllability, signals with the highest observabilities on damping the inter-area oscillations are identified. To find the most effective PSSs for damping the oscillations, the proposed WADC controller is performed on an IEEE test system consisting of 6 synchronous generators, which based on the system operating point, combinations with the highest damping ratio are provided.

The main merit and contribution of the proposed WADC scheme compared to previously published research can be developed as follows:

(1) Proposing an online three-step process to develop a wide area controlling signal and identifying the most effective generators with the potential of damping inter-area oscillations.

(2) An online approach to select the most effective wide-area signals based on inter-area observability criteria.

(3) Developing an online synthesizing technique for estimating the optimal gains of an individual WADC controller.

(4) Introducing the WADC controlling signal in four ND, ZD, LD, and HD dynamic responses.

2. The Proposed Algorithm

The main contributions of the proposed WADC scheme are developed as (1) Proposing an online three-step process to develop wide-area controlling signal, (2)

Developing an online approach to select the most effective wide-area signals based on inter-area observability criteria, (3) An online synthesizing technique for estimating the optimal gains of individual WADC controller and (4) Introducing the WADC controlling signal in four ND, ZD, LD, and HD dynamic responses. Fig. 1, shows the real-time structure of the proposed WADC scheme to damp the inter-area oscillations are categorized into five steps as follows:

Part 1: Detection of Inter-Area Oscillation (DIAO)

2.1. Wide Area Measurement System (WAMS)

In the case of using WAMS technology, it is assumed that all of the generator terminals are equipped with PMUs where data are transmitted to the control center through communication channels. It is worth noting that, although the use of the WAMS system is necessary for the proposed scheme, other structures like automation on substations and transmission lines are suitable enough to perform the proposed scheme. As a real example, the whole of the power plants of Iran national power grid is equipped with optic fibers which send information to the control center located in Tehran at each time sampling ratio. In this case, based on the infrastructure technology, signals are transmitted between different time scales. At the control center, based on analyzing the signals, proper decisions are performed. Based on the inter-area oscillation frequency between 0.1-1 Hz, it will take several seconds (i.e. more than 5 inter-area cycles) to form unstable oscillations. Therefore, since this paper is mainly focused on damping inter-area oscillation that occurred between different generator groups, it is required to evaluate generators' dynamic behaviors at each time window. In this case, by using at least the terminal phasor signals using SCADA systems and transmitting them over optical fibers, signals are evaluated at the control center in which the rotor angle and speed oscillations can be estimated.

2.2. Inter-Area Modes Identification (IAMI)

To order to damp inter-area oscillations, it is needed to identify the related modes specifications (including damping ratio and oscillation frequency). Some methods had been proposed to determine oscillation specifications such as prony analysis [25] and Hilbert Huang Transform (HHT) [26]. Although both methods can determine the above-mentioned specifications, prony analysis is used to determine them. It is done by calculating the eigenvalues of the network matrix and determining the mode specifications (damping ratio and oscillation frequency). As shown in Fig. 1, by using the obtained data through WAMS, the inter-area oscillation specifications are calculated, so that it is available at the mentioned time step.

Part 2: Signal Damping Ratio (SDR)

To design a controller, it is required to evaluate the signal damping ratio (SDR). The output of SDR is the oscillation behavior between three categories like positive (stable oscillations), zero (zero damping oscillations), and negative (unstable oscillations) during each time step.

The proposed SDR technique is implemented via the following steps:

Step 1) Oscillation amplitude is measured during each time step;

Step 2) SDR is calculated based on oscillation amplitude;

Step 3) The procedure will be initiated while not only oscillation amplitude exceeds a pre-determined threshold, but also negative damping oscillation occurs. In such cases, SDR will go to the third step on the WADC scheme to damp the oscillations.

Part 3: Wide Area Damping Controller (WADC)

It seems that to design an appropriate WADC, three main questions must be answered, as below:

1-Which signals must be selected to make WSSS?

2-What weighting factors should be

synthesized to make WSSS with the best observability?

3-Which PSSs on the network must be selected to make a GPSS with the best controllability to access to acceptable damping ratio for inter-area oscillations?

To achieve the best damping ratio using PSSs, the input signals must have the best observability on the related system modes. So signal selection is one of the most important steps for the realization of the suitable damping ratio. Since each control signal (e.g. speed variation, rotor angle, active power, voltage, current, etc.) has a particular observability value, its effect on the system modes should be investigated carefully to select the best observable ones.

As mentioned, each combination of signals can establish a global signal with specified observability, while access to the best observable WSSS on system modes is the goal. To generate WSSS, different mathematical operators (i.e. summation, subtraction, multiplication, etc.) can be used to synthesize global signals. Configuration of signal combination (including numbers and weighting factors of them) is denoted as signal synthesizer in this paper. A combination of improper signals and/or an incorrect combination of them may be terminated to a divergent oscillation. To achieve an optimized combination of the selected signals, various weighted combination of the selected signals is considered. Indeed, WSSS designing is done considering the Weighted Participation Factor (WPF) for signal combination, as detailed in Sec.4 part-b.

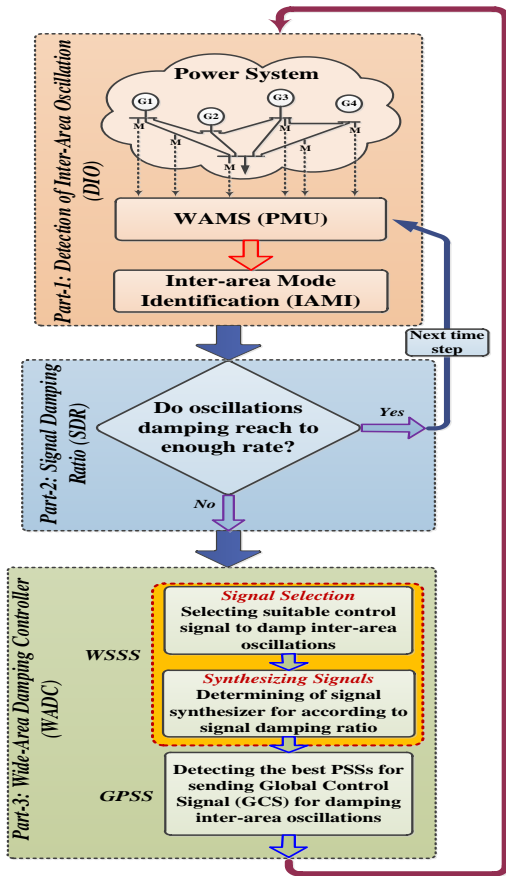


Fig. 1. Real-time procedure of WADC system

It should be noted that the possible uncertainties on transmitting signals through WAMS infrastructure can be developed within two main issues including Issue1- Phase delay and Issue2-Noise data.

In the case of phase delays, PMU signals are transmitted with individual time tags t_1, t_2, \dots, t_n to the main control center. To tackle this problem, at the control center, based on time stamps assigned upon each received signal, the total time delay $\Delta T = t_2 - t_1$ is computed. In this case, based on dominant inter-area oscillatory mode $\lambda_0 = \sigma_0 + j\omega_0$ with individual damping ratio and frequency ω_0 , evaluated ΔT is used as phase latency model $esp(-\lambda_0 \times \Delta T)$ which based on typical first-order controlling block, the signals phase delays are compensated.

Also, in the case of involving noisy data on WAMS transmitted signals, it should be noted that due to the widespread use of nonlinear loads, the PMU phasor signals transmitted to the control center are polluted with different noises and

harmonics may lead to a decrease in the WADC damping controller performances. In this paper, to decrease the noise effects, the PMU phasor signals pass through a moving average filter (MAF) which based on required adjustments, the output of MAF contains only signals in the range of inter-area oscillations frequency 0.1-1 Hz. MAF performs as a low-band filter in which through a simple equation, frequencies higher than specified components are attenuated.

By using the obtained WAMS data, controller devices on the power system can be used as a wide area damping controller. Constructed WSSS (by using signal selection and synthesizers) must be sent for candidate PSSs with the best controllability on the system modes.

For designing GPSS, each PSS capability to damp the oscillations must be analyzed; which is introduced as the PSS controllability index. Depending on the fault scenarios, each PSS has a different effect on the wide-area stability. In the face of oscillations, various combinations of PSSs can be terminated to high damping consequences or blackouts in the power system.

To find the best GPSS for damping inter-area oscillations, a wide area control scheme is proposed in this paper, in which PSS controllability is the main criterion for selecting it. To achieve this aim without any limitation, it is assumed that all of the generator units are equipped by the local PSS, while each PSS has two input channels for receiving local and global signals. Indeed, each PSS can be controlled by local and/or global signals.

3. Design of WSSS and GPSS

As shown in Fig. 2, the proposed scheme consists of three main parts, including 1- Signal Selection, 2-Signal Synthesizing, and 3-PSS (GPSS).

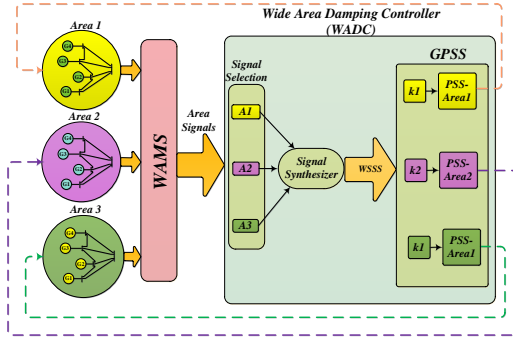


Fig. 2. Structure of the proposed WADC.

A. Signal Selection

Due to a swing occurrence in one area of the system, different interactions between generator groups can appear, while the generators with anti-phase in comparison with the others (while $\Delta\delta$ is around 180°) can be considered as the candidates to provide the effective signals. As shown in Fig. 2, there are three areas including A1, A2, and A3. To select effective and suitable signals, the obtained signals by WAMS should be analyzed carefully. In this paper, the Central Of Inertia signal for speed variation between two generator groups i and j is considered as a PSS input signal, as:

$$GS = \Delta\omega_{COI}^{i-j} \quad i, j = 0, 1, 2, 3 \quad (1)$$

that means the proposed signal is a function of speed deviation. It is assumed in this paper that all PMUs on the related network are available and the speed deviation signal can be estimated by using a voltage phasor signal at generator terminals.

For calculating $\Delta\omega_{COI}$ by using PMU data, the speed deviation ($\Delta\omega$) of all generators at each time step is estimated and $\Delta\omega_{COI}$ for the i th generation group is calculated as follows:

$$\Delta\omega_{COI}^i = \left[\sum_{j=1}^n H_j \Delta\omega_j \right] / \left[\sum_{j=1}^n H_j \right] \quad (2)$$

where H_j and $\Delta\omega_j$ are the inertia and speed deviation of the j th generator unit among the i th generation area, respectively.

The inter-area $\Delta\omega_{COI}^{i-j}$ could be

defined as:

$$\Delta\omega_{COI}^{i-j} = \Delta\omega_{COI}^i - \Delta\omega_{COI}^j \quad i, j = 1, 2, 3 \quad (3)$$

By considering the three areas in Fig. 2, three

inter-area signals can be designed as $\Delta\omega_{COI}^{1-2}$, $\Delta\omega_{COI}^{1-3}$, and $\Delta\omega_{COI}^{2-3}$. Also, these inter-area signals should be convolved together to construct modified inter-area signals, as shown in Table 2. As shown, category I includes one COI, category II contains the convolution of two COIs, and finally, three COIs are convolved together in category III.

By using WAMS data, at each time window, inter-area signals are evaluated and based on identifying oscillating areas, a global inter-area signal is generated.

Table (2): The proposed convolved signals to construct various inter-area COIs

Number	Category	Used Signals
1	I	$\Delta\omega_{COI}^{1-2}$
2		$\Delta\omega_{COI}^{1-3}$
3		$\Delta\omega_{COI}^{2-3}$
4	II	$\Delta\omega_{COI}^{1-2} + \Delta\omega_{COI}^{1-3}$
5		$\Delta\omega_{COI}^{1-2} + \Delta\omega_{COI}^{2-3}$
6		$\Delta\omega_{COI}^{1-3} + \Delta\omega_{COI}^{2-3}$
7	III	$\Delta\omega_{COI}^{1-2} + \Delta\omega_{COI}^{1-3} + \Delta\omega_{COI}^{2-3}$

Inter-area signals with higher amplitudes and opposite polarities (anti-phase) between areas will be considered effective signals to damp the oscillations. This priority can be used to sort the suitable signals and to make signal synthesizers at the next part.

B. Signal Synthesizing

The combination of the weighted effective signals is denoted as signal synthesizing. In this case, Signal Damping Ratio (SDR) plays an important role in decision-making.

To evaluate SDR, it is assumed that the system experiences an oscillation similar to Fig. 3; where X1 and X2 are two positive (or negative) sequential swing peaks as shown in Fig. 3.

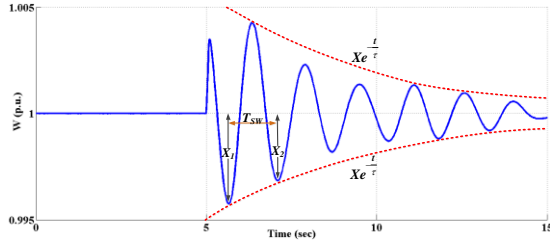


Fig. 3. Damping index for sample signal.

By using X_1 and X_2 , τ can be calculated as below to predict the swing push curve:

$$X_2 = X_1 \cdot e^{-\frac{T_{SW}}{\tau}} \rightarrow \tau = [T_{SW}] / [\ln(X_1 / X_2)] \quad (4)$$

By assuming a quintuple cycles SDR criterion, the signal ability to damp the oscillations can be considered as:

$$SDR = \frac{X_{5cycles}}{X_1} = \exp\left(\frac{-5T_{SW}}{T_{SW}} \ln \frac{X_1}{X_2}\right) = \left(\frac{X_2}{X_1}\right)^5 \quad (5)$$

The oscillation can be categorized as follows:

-High Damping (HD): Oscillation reduced by more than 50% during 5 cycles (i.e. $SDR < 0.5$).

-Low Damping (LD): Oscillation is reduced by less than 50% during 5 cycles (i.e. $SDR > 0.5$).

-Zero Damping (ZD): The oscillation cannot be damped during 5 cycles (i.e. $SDR \sim 1$).

-Negative Damping (ND): The oscillation amplitude is increased during 5 cycles (i.e. $SDR > 1$).

To design the related WSSS, suitable signals should be synthesized. So, various weighted combinations of all $\Delta\omega$ COI (Table 2) should be compared together based on the related SDRs. The weighting participation factor (WPF) for each $\Delta\omega$ COI can be specified based on the related SDR and is chosen as 0, 1, 2, or 4 for negative, zero, low, and high damping ratios, respectively, as shown in Fig. 4.

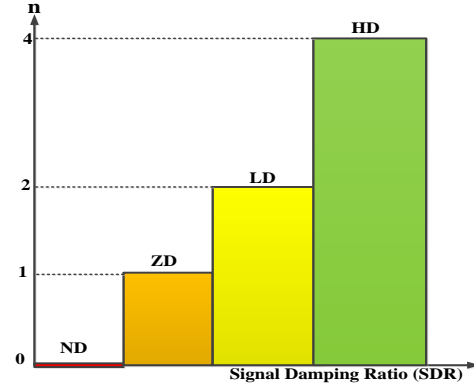


Fig. 4. The specified WPF to design WSSS

By considering WPF for the related SDR, the designed synthesizer can be specified for the measured SDR.

For each inter-area oscillation on the power system, the synthesizer will be implemented via Fig. 5.

By calculating SDR at each time step, it is possible to determine WPF and design WSSS. Finally, WSSS could be designed by using signal selection and synthesizer as follows:

$$WSSS = (\text{The selected signal}) \times (\text{WPF}) \quad (6)$$

Based on (6), by using selected signals and specified WPF, the WSSS is constructed as an input to Global PSS.

C.GPSS (Global Power System Stabilizer)

An actuator with good modal controllability is the trait of an effective controller. In this section, a method is proposed to design global PSS. For designing GPSS, the basic question is: How and which PSSs must be combined together so that the best controllability on system mode can be obtained?

To achieve this goal, different combinations of PSSs must be analyzed and PSSs with the best controllability in oscillation mode must be founded. As a roll, GPSS could be introduced as the following equation:

$$GPSS = \sum K_i PSS_i \quad (7)$$

Based on Fig. 5, to validate the global

inter-area signals, three different weighted participation factors $WPF=1$, $WPF=2$ and $WPF=4$ are considered. In fact, in the case of presenting small $WPF<1$, the final controlling signal will not have positive effects on damping the oscillation. On the other hand, in the case of presenting large $WPF>4$, the controllers will have a sensitivity that decreases their damping performances. Therefore, based on experimental analysis, the WPF between 1 and 4 would be suitable enough to present positive effects on damping the inter-area oscillation. In Fig. 5, in the case of identifying inter-area oscillation, at each time moving window, the oscillation damping ratio (SDR) is evaluated in which based on measured SDR, the corresponding WPF is determined. In this case, if the evaluated SDR is between $0.95<SDR<0.5$, it means that the oscillation damping ratio is very weak where the highest $WPF=4$ is determined as the controlling signals weighted participation factor. Simulation results showed that $WPFs$ higher than 4 present lower damping performances. Therefore, any time $SDR<0.95$, the highest nominated WPF is selected where by multiplying the WPF with the inter-area signals and sending them to nominated PSSs, proper results with positive damping ratios are achieved.

For designing GPSS by using local PSSs, there are many combination techniques such as combining two different PSSs, three different PSSs, and so on.

Since the related test system has six generating units so six different PSS combinations can be considered. A view of various PSS combinations for designing GPSS is presented in Table 3.

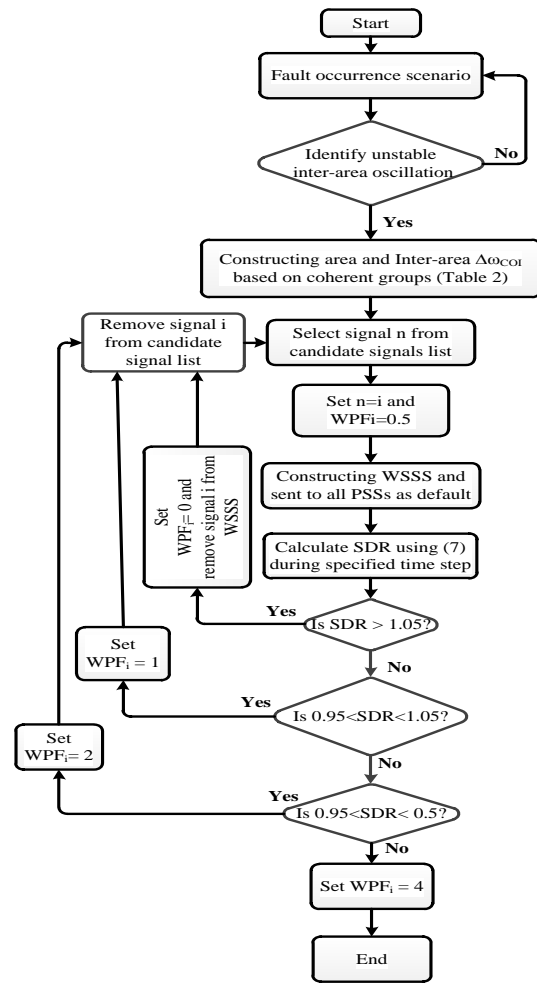


Fig. 5. Real-Time Procedure to determine WSSS

Table (3): The combinations of PSSs to produce GPSS

Group Number	Combinations	GPSS Type
1	Single PSS on GPSS	GPSS1
2	Two different PSSs on GPSS	GPSS2
3	Three different PSSs on GPSS	GPSS3
4	Four different PSSs on GPSS	GPSS4
5	Five different PSSs on GPSS	GPSS5
6	Six different PSSs on GPSS	GPSS6

As seen in Table 3, there are six types of GPSS including GPSS1, GPSS2, GPSS3, GPSS4, GPSS5, and GPSS6. The number in GPSS type shows the number of PSSs that are used on GPSS. To design GPSS, the controllability of each combination (from Table 4) on system modes is

analyzed carefully and the best combination is introduced.

4. Simulation Studies

In this section, the proposed WADC scheme is simulated over a modified IEEE test system. The simulations are carried out for a comprehensive list of scenarios. Since the input scenarios should cover all the credible contingencies in the modified network, some generators and lines have been added to the system. The view of the test system is shown in Fig. 6. The network details including line impedance, load, and generation data are given in [2]. As can be seen, the test system contains six generators equipped with local PSSs.

The scenarios are generated for two main objects (1) The ability of local PSS to

damp the oscillation and (2) The ability of the proposed WADC to damp inter-area oscillations. Based on the oscillation frequency simulation period $T \approx 50$ s is suitable for identifying and analyzing the proposed WADC control strategy.

Also, for analyzing PSS ability, two different types of scenarios are introduced. The first scenario is specified to analyze PSS's ability for damping local oscillations and the second scenario is specified to analyze PSS's ability for damping inter-area oscillations. The main aim of the second scenario is focused on the ability of the proposed WADC scheme for damping oscillations. Based on the mentioned discussion, the simulation results for two introduced scenarios are presented.

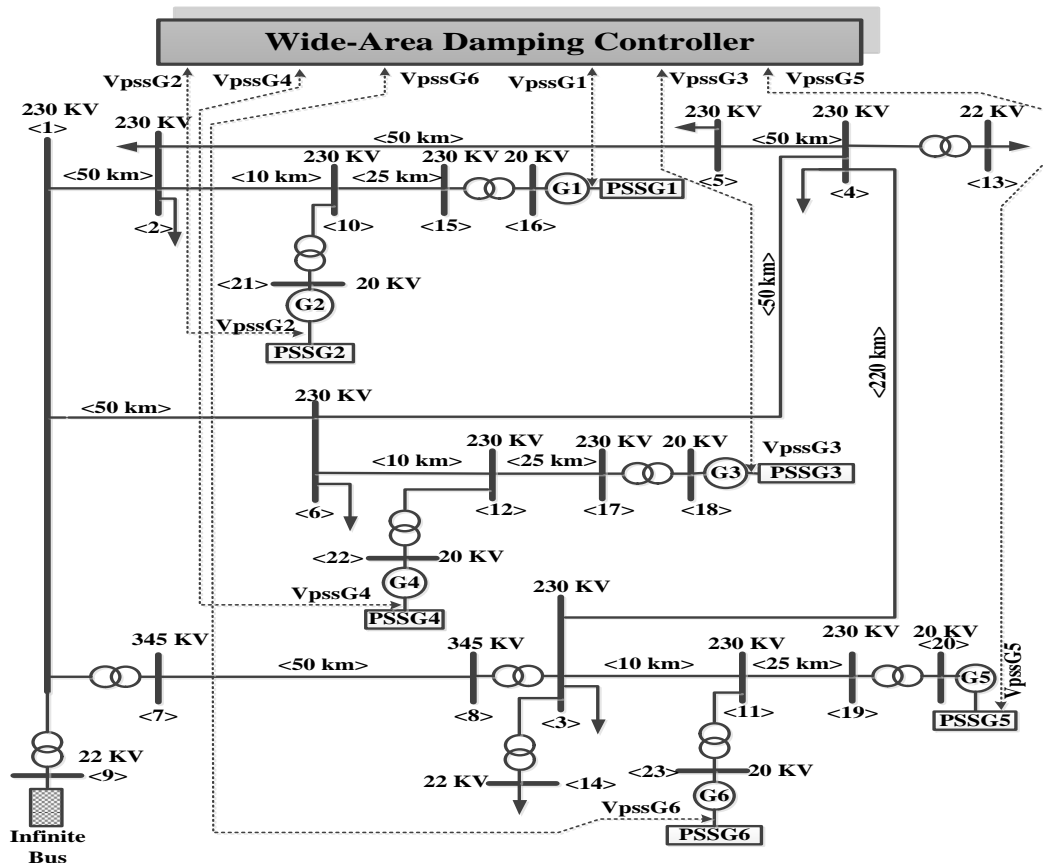


Fig. 6. The modified IEEE 14 bus power system

4.1. Analyzing local PSSs to damp the local oscillation

The first simulation scenario is focused on PSS's ability to damp local mode. From Fig. 5, it is assumed that a three-phase short

circuit fault occurred at bus 19 and then cleared after 5 cycles. For analyzing PSS's ability to damp oscillation, the introduced fault is analyzed for two conditions including 1- without acting PSS and 2- with

acting PSSs. The view of rotor angles` oscillations without acting local PSSs is

shown in Fig. 7.

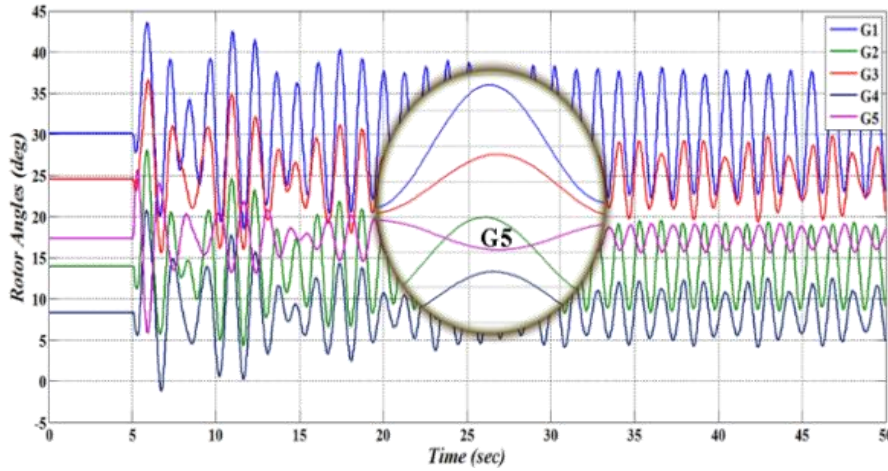


Fig. 7. Rotor angles` oscillations without acting PSSs.

From Fig. 7, it is concluded that the rotor angle of G5 is antiphase against other generators. This means that a local mode (e.g. local mode G5) has been stimulated. As it can be seen, in the case of without any acting PSSs, the oscillations are not damped at a short time duration. Then, it is assumed that all generators are equipped with local PSSs. Also for each PSS, the signal of generator speed deviation ($\Delta\omega$) of the local generator is considered as input. The results of the oscillations damping ratio with acting local PSSs are shown in Fig. 8.

From Fig. 8, for acting local PSS, the oscillations are damped successfully at a short time duration.

The results in this section show that local PSSs have tuned optimally for damping local modes.

4.2. Local PSS for damping inter-area oscillation

As previously mentioned in section II, inter-area modes are generated on the networks consisting of long-length lines and severe load levels and an inter-area

oscillation occurs on the power system when a group of generators swings against another group. In this condition, the system experiences a severity event so that local PSSs may not be able to damp oscillations. In this section, the ability of local PSSs for damping inter-area oscillations is analyzed.

For analyzing local PSSs to damp inter-area mode, following a three-phase short circuit fault at the middle point of lines 3-4 and tripped after 15 cycles, the system dynamic behavior is investigated. For analyzing mentioned fault scenario, a set of signals are calculated based on the following equations.

$$COI_{\delta}^1 = [H_1 \times \delta_1 + H_2 \times \delta_2] / [H_1 + H_2] \quad (8)$$

$$COI_{\delta}^2 = [H_3 \times \delta_3 + H_4 \times \delta_4] / [H_3 + H_4] \quad (9)$$

$$COI_{\delta}^3 = [H_5 \times \delta_5 + H_6 \times \delta_6] / [H_5 + H_6] \quad (10)$$

$$COI_{\delta}^{1-2} = COI_{\delta}^1 - COI_{\delta}^2 \quad (11)$$

$$COI_{\delta}^{2-3} = COI_{\delta}^2 - COI_{\delta}^3 \quad (12)$$

$$COI_{\delta}^{1-3} = COI_{\delta}^1 - COI_{\delta}^3 \quad (13)$$

The angles` oscillations (11)-(13) are shown in Fig. 9.

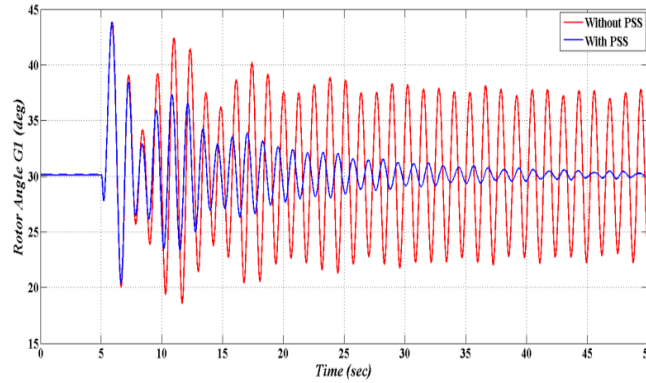


Fig. 8. Rotor angles' oscillations with acting PSSs.

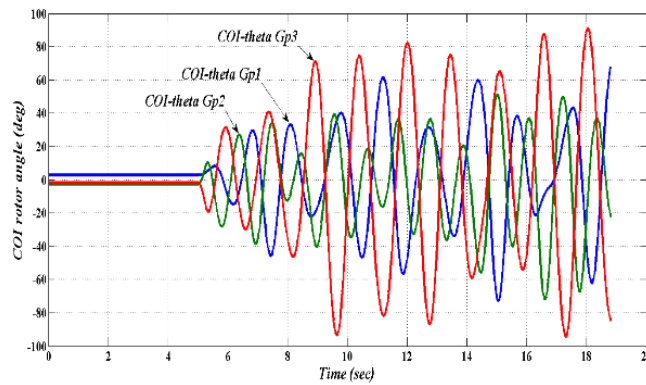


Fig. 9. COI_{δ} of generator groups for introduced fault scenario without acting local PSSs

As it can be seen, for mentioned fault scenario, COI_{δ} area1 swings against COI_{δ} area3 with equal frequency (which means anti-phase with each other). In this case, an inter-area mode has been stimulated. Also, the COI_{δ} area 2 swings between COI_{δ} 1 and COI_{δ} 3 with different frequencies. In this condition, the network experiences severe oscillations so that the amplitude of the oscillations is increased during the period. From Fig. 8, it is shown that without acting local PSSs, 14 sec after fault occurrence rotor angle instability occurred. From another view, the COI_{δ} between two areas 1 and 3 using equation (21) is shown in Fig. 10.

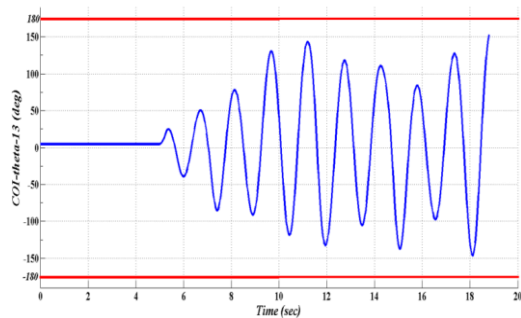


Fig. 10. $\Delta\delta_{COI-1-3}$ without acting local PSSs.

From Fig. 10, it is illustrated that interaction between two areas 1 and 3 is increased with an increasing period so that 14 sec after the fault occurrence, the phase difference reached 180 degrees which means angular instability has occurred. From the results, it is concluded that the instability network is due to interactions between two areas 1 and 3. Then, it is assumed that all generators are equipped with local PSSs and the signal of local speed deviation is used as input to PSS. The simulation results for COI_{δ} of generator Areas with the acting local PSS are shown in Fig. 11.

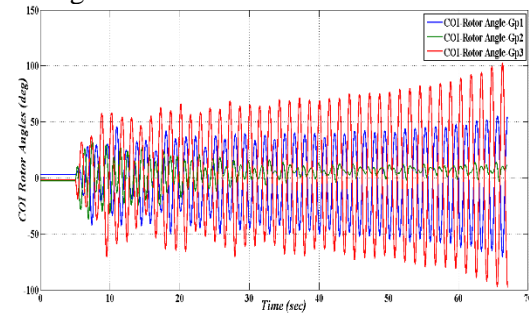


Fig. 11. COI_{δ} generator areas with acting local PSSs

As can be seen in Fig. 11, the oscillation amplitudes are increasing during the period and angular inter-area instability occurred at $t=67$ s. Similar to Fig.9, the COI of the rotor angle of areas 1 and 3 (COI_{δ}^{1-3}), is shown in Fig. 12.

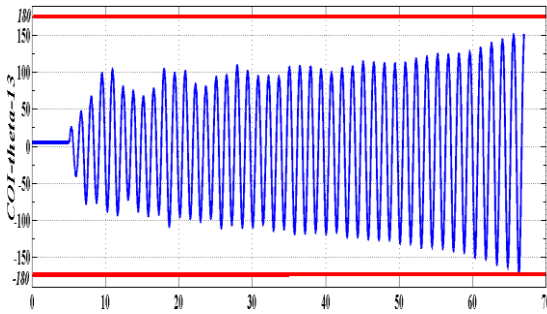


Fig. 12. Deviation of rotor angle of COI of groups 1 and 3 ($\delta^1_{COI} - \delta^3_{COI}$) with acting of local PSSs

From Fig. 12, it can result that the interaction between two generator groups GP1 and GP3 is caused network instability. The simulation results in this section illustrated that local PSSs are not able to damp inter-area oscillation. In this case, a strategy based on global signals and global PSS could be considered an effective solution for damping oscillations. The rest of this paper is focused on damping inter-area oscillations using the proposed WADC scheme.

4.3. Simulation Results from the WADC scheme

As previously mentioned, the main aim of this part is to analyze the ability of the proposed WADC scheme to damp inter-area oscillations. In this part, a set of scenarios is carried out based on different parts of WADC. Based on Table 4 and Table 5 there are selected signals \times WPF=44 different combinations for generating WSSS. Also based on Table 5, there are GPSS=24 different combinations for designing GPSS.

Based on simulation scenarios, by combining various signals, WPF and GPSS, in addition, there are a total number of $24 \times 44 = 1056$ different combinations as

$$WADC = \text{Signal} \times \text{WPF} \times \text{GPSS} = 1056$$

At this point, it should be noted that during WADC scheme simulation studies, the local PSSs have the same settings and any change has not been done to PSS parameters for producing GPSS. Each scenario has been simulated by the MATLAB@ software. In this case, the system response has been monitored during 100 sec simulation time.

Simulation results for different combinations of global signals and GPSS contain different damping ratios as the following table.

Table (4): Different damping oscillations from simulation scenarios

Number	Damping type	Description
1	HD	Oscillation amplitude decreased to half, during 5 cycles after fault clearance.
2	LD	Oscillation amplitude decreased by less than half, during 5 cycles after fault clearance.
3	ZD	On oscillation amplitude, any damping has been obtained.
4	ND	Oscillation damping has been increased during the period.

From Table 4, four different damping ratios have been resulted as following definitions:

1-Hi Damping ratio (HD): This damping type is specified for schemes that the oscillation amplitudes have been decreased to half, during 5 cycles after fault clearance.

2-Low Damping ratio (LD): The second type of damping index is specified for schemes with Low Damping (LD). In this case, the oscillation amplitudes have been decreased by less than half during 5 cycles after fault clearance. For applying this scheme, more time is required to damp oscillations.

3-Zero Damping ratio (ZD): The third type of damping ratio is specified for WADC schemes that are resulted in a zero-damping ratio. In this case, the oscillations damping ratio are about zero and the oscillations are not damped during 100 sec after fault clearance.

4-Negative Damping ratio (ND):

Finally, the fourth type is specified for oscillation with negative damping. In this type of oscillation, the system experiences a pole slipping point (i.e., $\delta=180$).

Simulation results for damping inter-area oscillations based on WADC schemes are shown in Table 5.

Table (5): Summary of simulation results for damping inter-area oscillations based on the WADC scheme

Damping Index				
HD	LD	ZD	ND	Sum
Scce.Nu m.	Scce.Nu m.	Scce.Nu m.	Scce.Nu m.	Scce.Nu m.
26 (2.46%)	98 (9.28%)	467 (44.22 %)	465 (44.03 %)	1056 (100%)

As can be illustrated in Table 5, between 1056 simulated scenarios, there are 26 scenarios (2.46%) with an HD damping ratio, 98 scenarios (9.28%) with an LD damping ratio, 467 scenarios (44.22%) with a ZD damping ratio and 465 scenarios (44.03%) with an ND damping ratio. From Table 5, it is concluded for 26 scenarios, an unstable inter-area oscillation is converted to scenarios with the HD damping ratio by applying the WADC scheme based on WSSS and GPSS. Also for 98 scenarios, an unstable inter-area scenario has been converted with the LD damping ratio due to WADC schemes.

The rest of the scenarios in this table could not damp oscillations so for 467 scenarios, the ZD damping ratio is obtained and for 465 remaining scenarios, the damping ratios are ND, and the network experiences angular instability. In these two damping cases (ZD and ND), other control devices such as FACTS devices must be considered.

5. Discussion

In a power system, different selections or combinations of global signals and global PSSs have different effects on damping oscillations. With a suitable combination, the oscillations on the power system are

well-damped while an incorrect selection can lead to instability network quickly. In this section, the influence of various signals, WPF, and GPSS are analyzed on damping oscillation. According to WADC parts, there are three variables as following:

1-The influence of different signal categories (Table 1),

2-The influence of different WPF,

3-The influence of different GPSS types (Table 2).

5.1. The influence of different signal categories

According to Table 1, the related signal has been classified into 3 types including Category 1, Category 2, and Category 3. The number of inter-area signals in WSSS is used for the signal categories. The influence of different signal categories on damping oscillations is given in Table 6.

As can be illustrated, Category 2 (including two different inter-area signals) has the highest damping ratio. In this section, it is adopted for damping inter-area oscillations, the best signal is Category 2 that is included two inter-area signals. The important question asked in this section is:

Which two inter-area signals must be combined?

To answer this question, from the sample network, there are three different combinations including:

1-Areas 1-2 and Areas 1-3,

2-Areas 1-2 and Areas 2-3,

3-Areas 1-3 and Areas 2-3.

By measuring inter-area signals and analyzing them with each other based on signal amplitudes, it is possible to find, the best inter-area signal. From simulation results in section V part B, it concluded that areas 1 and 3 are antiphase against each other. As a role for Category 2, it is proposed that two inter-area signals consisting of two areas 1 and 3 could be selected as global signals to reach the best observability signals on inter-area modes.

Table (6): The influence of signal categories on damping oscillations

Damping Type Signal Category	HD	LD	ZD	ND	Sum
	Num of Sce.	Num of Sce.	Num of Sce.	Num of Sce.	Num of Sce.
Cat.1	10(0.94%)	28(2.64%)	165(15.62%)	193(18.2%)	396(37.5%)
Cat.2	13(1.23%)	51(4.82%)	218(20.64%)	213(20.17%)	495(46.87%)
Cat.3	3(0.28%)	19(1.8%)	84(7.95%)	59(5.58%)	165(15.62%)
Sum	26(2.46%)	98(9.28%)	467(44.22%)	465(44.03%)	1056(100%)

5.2. The influence of different WPF

In this section, the influence of different WPF on damping inter-area oscillations is analyzed. The results of different WPF are shown in Table 7. As it can be seen, it is concluded that with an increase of WPF, the numbers of HD scenarios have increased so that for WPF4, the highest HD

number has been obtained. Also, it is shown that by increasing WPF (e.g. over 2), the damping ratio is reduced. In this section, it is proposed that a weighted-based logic is effective in damping oscillation, and based on SDRs, an optimal WPF is specified for each signal and finally, a global signal is designed.

Table (7): The influence of different WPF on damping inter-area oscillations

Damping Type WPF Type	HD	LD	ZD	ND	Sum
	Num of Sce.	Num of Sce.	Num of Sce.	Num of Sce.	Num of Sce.
WPF1=0	---	---	---	---	---
WPF=0.5	2(0.19%)	13 (1.23%)	57(5.39%)	291(27.55%)	363(34.37%)
WPF=1	7(0.66%)	25(2.36%)	117(11.07%)	82(7.76%)	231(21.87%)
WPF=2	10(0.94%)	31(2.93%)	141(13.35%)	49(4.64%)	231(21.87%)
WPF=4	7(0.66%)	29(2.74%)	152(14.4%)	43(4.07%)	231(21.87%)
Sum	26(2.46%)	98(9.2%)	467(44.22%)	465(44.03%)	1056(100%)

Similar to the signal selection, the important question asked in this section is:

-Which signal synthesizer must be selected based on related signals?

In this section, it is proposed that based on the proposed signals, a weighted-based logic could be considered to combine signals and generate WSSS. According to the proposed scheme, the participation factor of each inter-area signal can be designed based on its observability in inter-area modes.

6. The influence of different GPSS types

In this section, the influence of PSSs combinations is analyzed. The number of PSS participations on GPSS is denoted as GPSS type. The results of different GPSS

types are illustrated in Table 8.

From Table 7, it is concluded with the acting all PSSs on the network (GPSS6), any HD damping ratio is obtained. In this section, it is concluded that acting all PSSs have a negative influence on damping oscillations. From Table 9, it is concluded that the best damping ratio (e.g. HD and LD damping ratios) is adopted for GPSS2 (acting two local PSSs on GPSS) with a total number of 15(%58 of total HD scenarios) for HD damping ratio and a total number of 38 (%38 of total LD scenarios) for LD damping ratio.

Similar to the signal selection and WPF sections, the important question asked in this section is:

Which two PSSs combinations have the best damping ratio on GPSS?

To answer this question, the best one and two PSSs combinations (with HD

damping ratio) on GPSS have been exported and given in Table 9.

Table (8): The influence of different GPSS types on damping oscillations

Damping Type GPSS Type	HD	LD	ZD	ND	Sum
	Num of Scenarios	Num of Scenarios	Num of Scenarios	Num of Scenarios	Num of Scenarios
GPSS1	1 (0.094%)	10 (0.94%)	45 (4.26%)	136 (12.87%)	192 (18.18%)
GPSS2	15 (1.42%)	38 (3.59%)	214 (20.26%)	213 (20.17%)	480 (45.45%)
GPSS3	3 (0.28%)	34 (3.21%)	137 (12.97%)	82 (7.76%)	256 (24.24%)
GPSS4	7 (0.66%)	13 (1.23%)	51 (4.82%)	25 (2.36%)	96 (9.09%)
GPSS5	0 (0.0%)	10 (0.94%)	35 (3.31%)	14 (1.32%)	51 (4.82%)
GPSS6	0 (0.0%)	3 (0.28%)	20 (1.89%)	9 (0.85%)	32 (3.03%)
Sum	26 (2.46%)	98 (9.28%)	467 (44.22%)	465 (44.03%)	1056 (100%)

Table (9): The best combinations of one and two PSSs with HD damping ratio

Signal Combinations with different WPF			PSS Combinations					
Areas 1-2	Areas 1-3	Areas 2-3	PSS G1	PSS G2	PSS G3	PSS G4	PSS G5	PSS G6
			900 MW	500 MW	900 MW	500 MW	900 MW	500 MW
0	1	1	1	0	1	0	0	0
0	2	0	1	0	0	1	0	0
0	2	2	0	1	1	0	0	0
0	2	2	1	0	1	0	0	0
2	2	0	1	1	0	0	0	0
0	0	4	0	1	1	0	0	0
0	0	4	1	0	1	0	0	0
0	4	4	0	1	1	0	0	0
4	4	0	1	1	0	0	0	0
4	4	4	1	1	0	0	0	0
4	4	4	1	0	0	0	0	0
0	0	6	0	1	1	0	0	0
0	0	6	1	0	1	0	0	0
0	6	6	0	1	1	0	0	0
6	6	0	1	1	0	0	0	0
6	6	6	1	1	0	0	0	0

As can be seen, it is concluded that the generators of area 1 (Including G1 and G2), have the most participants on GPSS and the generators of area 3 have not participated in any HD damping ratio. Based on the mentioned discussion, it results that when an inter-area oscillation occurs, GPSS must be designed based on PSSs of larger areas for damping oscillations. In this section, it is proposed that based on areas` ability on damping oscillations, the GPSS scheme should be designed based on area 1 (including PSS1 and PSS2) for the central controller. Also, the results show beside area 1, PSS3 from area 2 has the highest participation on GPSS for HD damping ratio. From the simulation results in this

section, it is proposed that the central controller system (GPSS) could be designed based on PSS1, PSS2 from area 1, and PSS3 from area 2.

7. Comparison Study of the Proposed Scheme with New Studies

In this section, to evaluate the effectiveness of the proposed scheme, a comprehensive comparison study is investigated between the proposed WADC approach and a few recent studies as summarized in Table 10. In the case of evaluating suitable results, considering the same inter-area scenario developed in Section 5, the system dynamic behavior and controllers damping performances are investigated.

Table (10): Comparison of the proposed WADC scheme with a few recent techniques.

Ref	Damp Index (pu)	Cycles	Model-based	Complexity	Large Grids?
[1]	0.51	4	No	Medium	Yes
[2]	1.31	6	High	Medium	No
[3]	0.96	5	Medium	High	No
[4]	0.53	6	No	Medium	Yes
[6]	0.85	>10	High	Medium	Yes
[8]	0.71	8	Medium	High	No
[10]	0.55	9	High	High	No
[11]	0.76	8	Medium	High	No
[14]	0.58	>10	Medium	High	No
[19]	0.61	>10	Medium	Medium	Yes
[22]	0.89	6	No	Medium	No
--	0.267	2	No	Medium	Yes

From Table 10, the proposed WADC scheme presents better results with specified parameters. The main major advantage is its no-model-based strategy to the system settings and medium complexity which resulted in its performance under a wide variety of applications. Also, in comparison, most other techniques require several inter-area cycles with a high dependency on the system to control the oscillation. In this case, their performances highly depend on the system's operational and topological conditions which in the case of changing operating points, updated adjustments are needed. Also, since an online approach based on wide area signal measurement is

proposed, it can be easily used on different power systems with lower costs and complexities.

8. Iran Nation Power Grid

In this section, the effectiveness of the proposed scheme over a practical large system is evaluated. To do this, considering the IRAN national power grid consisting of 1219 high voltage transmission lines and 1721 buses indicated in Fig. 13, WADC damping performance is investigated. Detailed parameters of the developed practical system are given in [1].

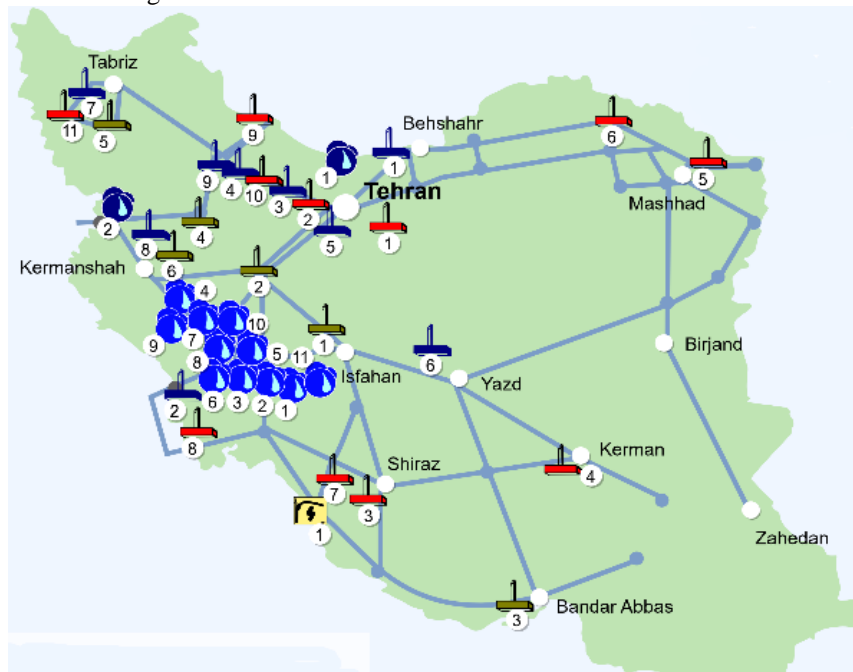


Fig.13. Iran national power grid.

The power grid consists of 2626 generators and loads buses connected within 419 transmission lines. Evaluating modal analysis showed that the system has a potential for inter-area oscillation between three areas Area A (East North), Area B (West North), and Area C

(South). To evaluate the proposed WADC, at operating point 62119 MW, following a fault event at line DP119 between two main buses 6ASMKS01, and 9ASGS03 and tripping the line, system dynamic behavior is simulated as shown in Fig.14.

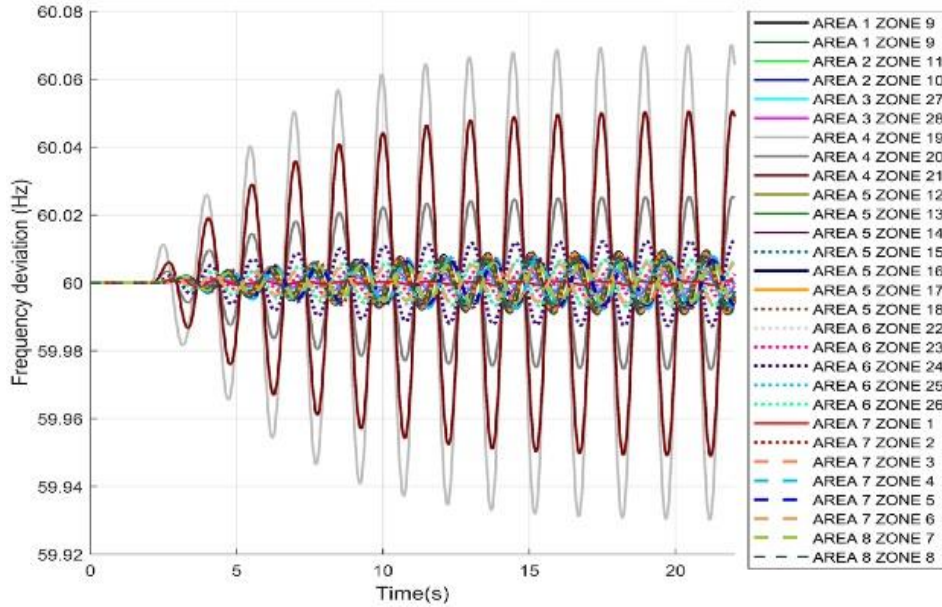


Fig.14. Dynamic oscillations without WADC.

Following the fault scenario, SGs experience severe unstable inter-area oscillation. In this case, WADCs are activated and based on measuring inter-area signals as $IAS_{AB} = \Delta\delta_{COI-AB} + \Delta\omega_{COI-AB}$, $IAS_{AC} = \Delta\delta_{COI-AC} + \Delta\omega_{COI-AC}$, $IAS_{BC} = \Delta\delta_{COI-BC} + \Delta\omega_{COI-BC}$ between oscillatory groups, corresponding controlling gains are achieved. The system damping performance based on developed IAOs is shown in Fig.15.

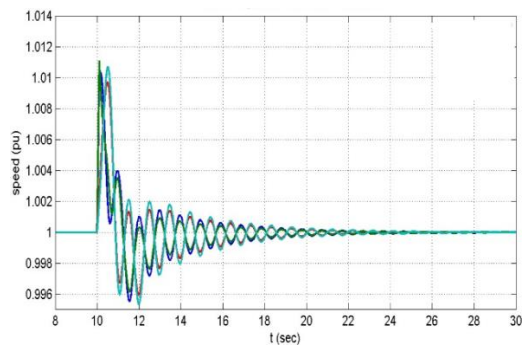


Fig. 15. Dynamic oscillations with WADC.

As can be seen, the proposed WADC scheme can damp inter-area oscillations with a suitable damping ratio. In this case, considering global controlling signals, WADC produces damping powers in-phase with inter-area oscillations resulting in positive damping

performance.

9. Conclusions

In this paper, an effective Wide-Area Damping Controller scheme has been proposed to damp inter-area oscillations based on Global Signals and Global PSS. The simulation results have shown that the proposed control scheme can damp oscillation with hi damping ratio. From the simulation results some notes have been concerned as follows;

1-WSSS: Global signal has shown its ability to damp inter-area oscillations.

2-Signal Selection: The type of global signals has an important influence on damping oscillations. So in this case, signals with the best observability on oscillation modes should be selected. In this paper, the inter-area signal of $COI\Delta\omega$ (central inertia of speed deviation) has been introduced as the best control signal for damping inter-area oscillations.

3-Signal Synthesizer: The simulation results have shown that different combinations of global signals have different influences on damping oscillation. In this case, it was proposed that the combination of inter-area signals contains interaction with two areas based on weighted-based logic, resulting in the best combination for designing WSSS. Also,

from simulation results, it can be adopted an increase in signal Participation Factors is caused to different influences on the damping ratio so that an inappropriate WPF is caused to unsuitable performance on the damping ratio. In this part, it was proposed that WPF must be designed based on the related signal.

4-Global PSS (GPSS): The simulation results have shown that some PSS combinations resulted in angular instability on the sample network (ND damping ratio). In this condition, an effective combination of PSSs must be selected. Also, the simulation results have shown that PSSs of larger generators have more ability on damping oscillation. As a role, it was proposed that GPSS be designed based on controller devices of larger generators.

Based on the simulation results, the proposed WADC scheme showed its ability on damping inter-area oscillation with Hi Damping (HD) ratio. From the mentioned results, the proposed WADC scheme could be successfully applied for various implementations of wide-area stability.

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