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Emergency Controlling Scheme for Damping the Inter-Area Oscillation Based on Estimating Critical Inter-area Angle

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Abstract

This paper presents a new scheme of controlling inter-area oscillation consisting of WAC and *CIA* index as controlled islanding criteria. For this purpose, based on the WAMS, the correlation factor between all SGs pairs is calculated which the coherent SGs are determined. In this case, by identifying two oscillating areas, the inter-area oscillation is evaluated in *COI* frame which uses as the GIS through the proposed WAC scheme. Also, for estimating the IDR, a RD technique is proposed which by evaluating GIS signals through consecutive time windows, the signals IDRs are evaluated. In the case of identifying an unstable IDR, by evaluating the GIS signal and identifying the GIS zero crossing points ZCPs as the *CIA* tripping index, the corresponding emergency action (islanding/damping) is determined. The proposed approach is an online and non-model-based scheme which by evaluating GIS signals through consecutive time windows, the system dynamic securities and emergency actions are provided. The effectiveness of the proposed scheme is evaluated on the IEEE 39-bus system with indicating positive effects through damping the inter-area oscillation.

Keywords: Inter-Area oscillations, WAMS, WAC, COI, Power system islanding.
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1. Introduction

Operating modern power systems near to their stability margins lead to systems involve with different challenges which the IAOs are one of most important types of instabilities through todays large blackout.

1.1 Paper motivation

As a definition, IAO is a type of low frequency oscillation which there are two or more oscillating areas are oscillating against each other within the frequency ranges $f_{inter\text{-}area}$=0.1~1 Hz.[1] In this case, there are different SGs are incorporating through each IAO which the local controllers tuned with local controlling signals are unable to control the oscillations damping ratios. An unstable IAO is known as a serious threat for large blackouts and power system separation through different uncontrolled islands. Therefore, real-time evaluations of the IAOs and developing proper controlling actions are two important issues remain still through the power system dynamic security criteria.

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1.2 Literature review

In the case of providing inter-area controlling actions, there are many approaches have been proposed by power engineers which are classified within two main categories including *Category*1- Topological/Operational based methods as SGs operation changing pattern, load shedding and network restructure and *Category*2- Controlling based methods as the effectiveness of FACTS/PSS controllers through damping the oscillation. Also, in *Category*2, researcher have been concentrated through four separated fields including *Field*1- Determining controlling signals, *Field*2- Designing PSS structure, *Field*3-Designing WAPSS, and *Field*4- Compensating time delays caused form communication links. Based on the developed categorizes, the performance of local speed deviation combined with tie-line active powers are investigated in Ref. [1] for controlling both local and inter-area oscillations. However, in two Refs. [2] and [3] the performance of SGs bus voltage magnitudes have been represented as the additional damping signals. In Ref. [4], based on the coherency concept between the SGs oscillatory signals, a set of global controlling signals are represented. In Ref. [5], considering the signals oscillatory patterns, an online trajectory-based technique is proposed to determine controlling signal. However, Ref. [6] represents an offline and model-based approach based on $H\infty$ loop-shaping scheme to determine the additional damping signal. Similarly, two residue and geometric methods are investigated in Ref. [7] to identify proper signals where in Ref. [8], by developing the variance minimization parameter through the residue concept, wide are signals are determined. Also, two model-based observability and controllability concepts are proposed in Refs. [9] and [10] which by developing the residue technique through RGA evaluations, the wide area signals are provided. In Ref. [11], based on the concept of VGs, power system is simplified through two oscillating areas which the area signals are produced. In Ref. [12-14], the performance of decision tree scheme through estimating the wide area signals are evaluated. In these four references, by using the observability evaluation through input signals and developing the linear correlation criteria between the estimated and trained values, effective signals are identified. The second and third fields of the presented controller schemes are assigned to the WAPSS designing structure. In Ref. [15], by developing a dead-band designing structure, an adaptive WAPSS is presented. However, in two Refs. [16] and [17] by developing the model-based H∞ concept evaluated through conic programming logic, WAPSS structures are designed. In Ref. [18], a modal decomposition-based approach is presented to design WAPSS. However, in Ref. [19], by developing the decomposition concept,[20] a multi-modal decomposition technique is proposed to design WAPSS. In Refs. [21] and [22], by using the model-based eigenvalue analysis for the system oscillating modes, the corresponding frequency responses are used to design WAPSS structure. Also, the performance of WAMS technology[23] and integrated controlling scheme[24] are used to design the WAPSS and corresponding wide-area signals. The Field4 of the developed Category2 is devoted to present compensation schemes through providing proper wide are signals. In Ref. [25], by developing the pade approximation technique, the system time delays caused form communication links are estimated which the corresponding compensation blocks are provided. Also, in Ref. [26], by using WAMS data equipped with geographic positioning system (GPS) technology, the signals sending the receiving moments are

Table 1. Brief review on the related references.

Technique(s)	Adaptive	WAMS	Complexity	Real-time	Large Cases	Renewable	Cost
GA[1]	●	-	●	-	-	-	Medium
CART[2]	●	●	-	●	●	●	Low
Residue[3]	-	-	●	-	-	-	High
Gradient[4]	-	-	●	-	-	-	High
WADC[5]	-	●	-	●	-	-	Low
Delay[6]	-	-	●	-	-	-	Medium
MIMO[7]	●	●	●	-	-	-	High
Rescheduling[8]	-	●	●	●		-	High
Load-Generation[9]	-	●	●	●	●	-	Low
Switching[10]	●	●	-	●	●	-	High
Gain Scheduling[11]	●	-	●	-	●	-	High
Multiple Mode[12]	-	-	●	-	●	-	Medium
GrHDP[13]	-	-	●	-	-	-	High
Bi-layer[14]	-	-	-	-	-	-	Medium
Delay[15]	-	●	●	-	-	-	High
C5.0[16]	-	●	-	●	-	-	Medium
Aggregated Load[17]	●	-	●	-	-	-	High
Data-Driven[18]	-	-	●	-	-	-	Medium
WAC[19]	-	●	●	-	-	-	Medium
Feedback[20]	-	●	●	-	-	-	High
Neural Network[21]	●	-	-	●	-	-	High
H∞[22]	-	●	●	-	-	-	Medium
Residue[23]	-	-	●	-	-	-	High
Multi-Zone[24]	●	●	-	●	●	-	Low
Cross-Gramian[25]	-	-	●	-	-	●	High
Robust Control[26]	-	●	●	-	-	●	Low

evaluated which the corresponding phase shifts are compensated. A brief review of the presented techniques is summarized in Table 1.

From Table 1, it is deducted that most of techniques are associated through the offline and model-based categorizes which the use of local signals is also attended to determine the controlling signal and designing WAPSS structure.

1.3 Paper contribution

Based on the gaps of previous studies identified on Table 1, this paper presents and adaptive cost-effective WAC for damping the inter-area oscillation through large power systems. To do this, based on developing the concept of EAC and WAMS technology, the proposed WAC islanding scheme is formulated in which based on estimating *CIA* index as an online criterion, the system dynamic criterion is evaluated. In this case, through online evaluations, by using inter-area rotor angle $\Delta\delta_{COI\text{-}AB}$ and speed deviations $\Delta\omega_{COI\text{-}AB}$ evaluated in *COI* frame, a set of GIS signals are provided which the corresponding emergency controlling actions (islanding/damping) for damping the IAOs are estimated. In the case of providing GIS signals, by using the correlation theory between all SGs pairs signals, the coherent groups and corresponding oscillating areas are identified. Also, a RD technique is proposed to determine the GIS signal damping ratios which by using the signal average values through a set of consecutive time windows, the signal damping ratios are evaluated. In the case evaluating an IAO, the proposed GIS signal $\Delta\delta_{COIAB}$ is evaluated with the online *CIA* criteria is adopted. In the case of evaluating $\Delta\delta_{COIAB} \geq CIA$, the proposed emergency controller is activated which a controlled islanding scheme is provided. However, in the case of $\Delta\delta_{COIAB} < CIA$, by using the WAPSS designed through the test system, a damping controlling scheme is provided.

2. Developing the Inter-area oscillation model

Into the real power systems, based on the SGs controlling actions, there are two main local and inter-area oscillations which can provide the rotor angle instability conditions. In this case, the local oscillations type is related to interactions of one single SG against the rest of power system which generally occurs in the dynamic frequency ranges 1-3 Hz. However, in the case of IAOs, the operated SGs are divided through different coherent groups which based on the inertia constants, they oscillate into the frequency ranges 0.1-1 Hz against each other. An unstable local oscillation is caused from the OOS of one single generator, whereas, in the case of an unstable IAO, a wide area OOS condition is occurred which resulted in power system separation through several uncontrolled islands. Therefore, identifying and modeling the IAOs are two main requirements to develop proper controlling actions and avoid large blackouts.[1] To do this, considering a IEEE test system consisting of multiple coherent areas presented in Fig. 1, the concept of modeling IAOs are provided.

From Fig. 1, system has a potential of forming an IAO between two oscillating areas *Area1* and *Area2*. Also, it can be deducted that for developing each unstable IAO, there are three main specifications are required as (a) Forming the SGs oscillatory signals into different coherent groups, (b) Oscillating at least two coherent groups with the inter-area

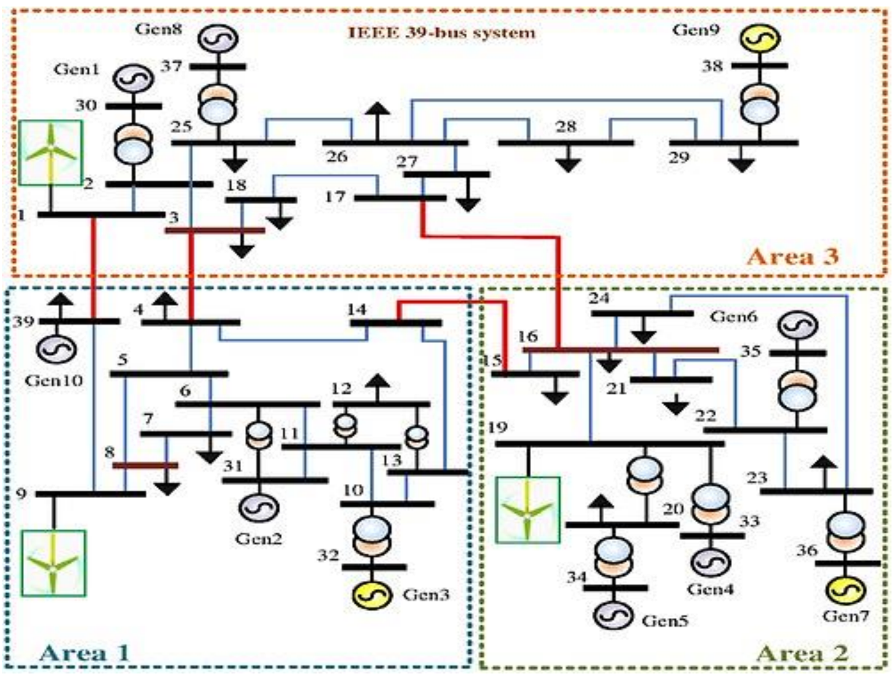

Fig. 1 IEEE test system with the potential of two oscillating areas.

rotor angle difference higher than 90 degrees against each other and (c) Providing IAOs with the negative or weak damping ratios. In this case, based on the *COI* concept, each coherent group can be modeled as one equivalent VG with the area rotor angle (δCOI), the area speed deviation (ωCOI) and the area inertia constant (*HCOI*) equaled in *COI* frame as three dynamic parameters as follows:[1]

$$H_{COI} = \sum H_i \tag{1}$$

$$\delta_{COI} = [\sum_{i=1}^{n} H_i \times \delta_i] \ / \ [\sum H_i] \tag{2}$$

$$\omega_{COI} = [\sum_{i=1}^{n} H_i \times \omega_i] \ / \ [\sum H_i] \tag{3}$$

From Eqs. (1)-(3), δi, ωi and *Hi* are the SGs rotor angle, the SGs speed deviation and the SGs individual inertia constant, respectively. By this way, two identified oscillating areas *Area-A* and *Area-B* can be modeled with two VGs as *VGAreaA* and *VGAreaB* connected by tie-lines as represented in Fig. 2.

Based on Fig. 2, by evaluating the inter-area rotor angles and speed deviations between two oscillating areas, the proposed GIS signals are developed as follows:[1]

$$\Delta\delta_{COI-AB} = \delta_{COIA} - \delta_{COIB} \tag{4}$$

$$\Delta\omega_{COI-AB} = \omega_{COIA} - \omega_{COIB} \tag{5}$$

$$H_{AB} = [H_A \times H_B] / [H_A + H_B] \tag{6}$$

From Eqs. (4)-(6), $\delta_{COI\text{-}AB}$ and $\omega_{COI\text{-}AB}$ are the inter-area rotor angle and speed deviations between two oscillating areas *Area-A* and *Area-B* evaluated in *COI* frame. Also, *HAB* is the inter-area inertia constant valuated between two oscillating areas.

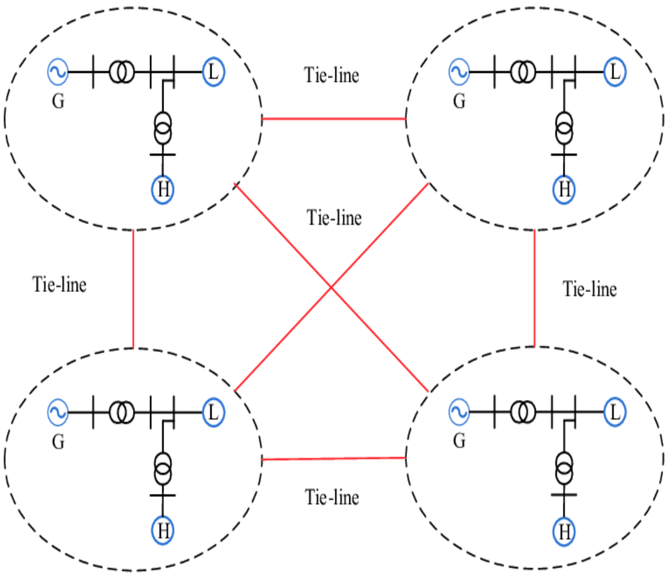

Fig. 2 The system oscillating areas defined into the VGs models.

Based on the developed model in Fig. 2 and corresponding GIS signals, it can be deducted that the general concept of well-known SMIB system can be extended for the IAOs. In this case, the oscillating areas VG_{AreaA} and VG_{AreaB} can be merged together in the form of new equivalent generator known as IVG which is connected to a virtual infinite generator G_∞ as shown in Fig. 3. The presented model developed in Fig. 3 is defined as the GSMIB system which can be used for modeling the inter-area oscillations.

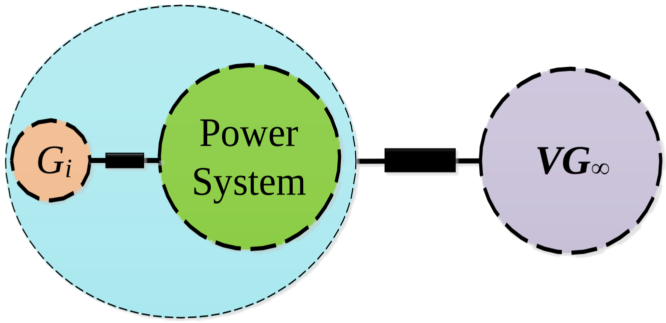

Fig. 3 GSMIB system for modeling IAOs.

From Fig. 3, it can be deducted that the conventional SMIB system is a specific state of developed GSMIB system which there is a single SG oscillates against the rest of power system with individual local oscillations. The proposed GSMIB system developed through inter-area model is presented in Fig. 4.

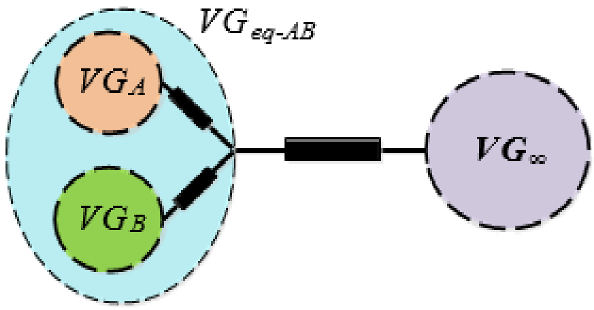

Fig. 4 GSMIB system for inter-area model.

From Fig. 4, it should be noted that through developed GSMIB system for modeling local oscillation, a real finite case (SYS) is considered for the whole of power system. However, considering the developed model, in the case of considering infinite system ($Hsys=\infty$, $\omega SYS=\omega 0$, $\delta SYS=0$), the equivalent inertia constant of the rest of power system (*Hg-sys*) is equaled with the local inertia (*Hg*) which the generalized GSMIB system is simplified to the traditional SMIB model with one single SG connected to an infinite bus.

Also, in the case transient stability analysis, considering SMIB model, it is developed through EAC which by presenting the SGs active power and corresponding rotor angle through x-y axis as shown in Fig. 5, the system transient stability criteria is evaluated.

From Fig. 5, $\delta_{COI\text{-}AB}$ is the inter-area rotor angle and $P_{tieline\text{-}AB}$ is the inter-area active power transferred between two oscillating areas *Area-A* and *Area-B*. As it can be seen, similar to proposed GSMIB model, the concept of EAC theory can be

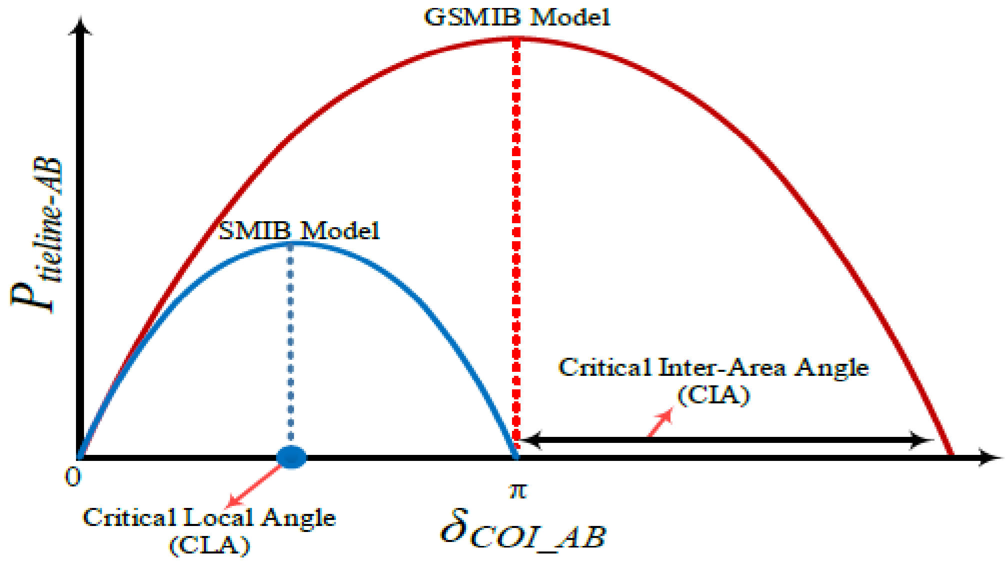

Fig. 5 Equal Area Criterion (EAC) for two SMIB and GSMIB models.

extended for the inter-area oscillation with critical inter-area angle (*CIA*) parameter as the main inter-area transient stability index. In this case, contrary to SMIB model specified for local oscillation which the angle δ_{SG}=90 degree is determined as the critical local angle (*CLA*), in the case of inter-area oscillations, the EAC curve is generalized correspondingly which the inter-area CIA parameter is evaluated close to or lower than δ_{SG}=180 degree. Accurate value of *CIA* is highly depends on the inter-area inertia constant *HAB* which based on the forming the oscillating areas and corresponding operated SGs at each area, the proposed *CIA* is adapted. It is worth noting that considering ant types of IAOs, the *CIA*= 180deg is the highest critical angle which in the case of reaching to this angle, an inter-area transient instability will be occurred between two oscillating areas. Therefore, by defining the *CIA* index as the critical parameter, at each time moving time window through real-time evaluations, the system oscillatory inter-area modes are identified which by evaluating $\delta_{COI\text{-}AB}$ between two oscillating areas, the *CIA* index and corresponding dynamic security are evaluated.

3. Real-Time structure of STATCOM-based WADC

The real-time overall view of the proposed *CIA* identification scheme based on WAMS technology is presented in Fig. 6. Based on developed scheme in Fig. 6, at each time moving window, based on the WAMS measuring data, the SGs oscillatory signals ω and δ are evaluated. In this case, by evaluating the system dynamic behaviors through consecutive time windows, the signals correlation coefficients are evaluated which based on developing clustering technique[33] through evaluated signal coefficients, the SGs coherent groups are identified. In the case of identifying the oscillating areas, by processing the GIS inter-area signals through RD evaluations, the signals damping ratios are provided. In the case of identifying GIS signals ($\Delta\omega COI\text{-}AB$, $\Delta\delta COI\text{-}AB$), it is extended through generalized EAC scheme which the *CIA*

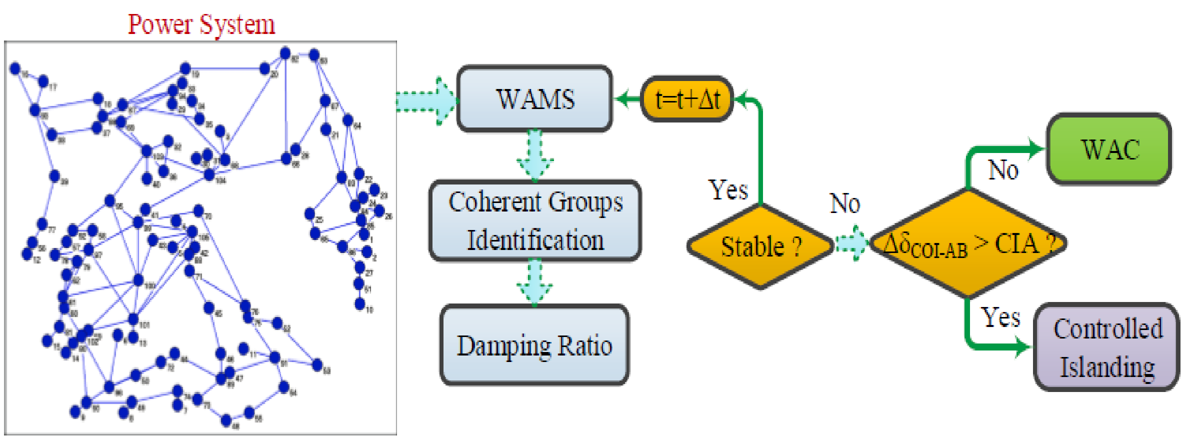

Fig. 6 Real-time evaluations of the proposed *CIA* scheme.

critical angle is estimated online.

If δCOI-AB evaluates lower than CIA value (δCOI-AB<CIA), by using WACs controllers equipped with GIS as input signals, a set of GCSs are provided through SGs excitation systems which present proper damping powers in-phase with the IAOs with positive damping effects. However, in the case of evaluating $\delta_{COI\text{-}AB} \geq CIA$, it means the developed WACs are unable to damp IAOs which a controlled islanding scheme must be implemented to establish stable subsystems permanently. Detailed structure of the proposed WAC scheme consists of GIS and GCS data as two input-output pairs signals is presented in Fig. 7.

Based on Fig. 7, in the proposed WAC scheme, through real-time evaluations of the identified IAOs, an effective GCS is provided at the control center which sent through the SGs excitation systems between two oscillating areas. It is worth noting that, based on the inter-area angle differences, the *GCSs* are in-phase with each area signals (*i.e.* *theta*(*GCSA*)=*theta*($\delta_{COI\text{-}AB}$) and *theta*(*GCSB*)=*theta*($\delta_{COI\text{-}BA}$)) and anti-phase with each other (*i.e.* *theta*(GCS_A)=-*theta*(*GCSB*)). Also, it should be noted that communication delays in wide area signals is an important challenge through WAC applications which reduce the system damping performances. However, there are several techniques[30,31] have been proposed to compensate the delays. In this paper, by developing pade approximation technique,[31] the GIS and GCS signals delays are compensated. Based on developed *GCSs* as input signals though generator AVRs, a set of damping powers in-phase with the inter-area oscillations are provided which present positive effects through damping the inter-area oscillations. However, in the case of estimating controlled islanding scenario, by identifying the inter-area tie-lines between two oscillating areas, two/more stable subsystems are provided. The mathematical formulations of the proposed *CIA* scheme are detailed through following steps. It is worth noting that, in the proposed scheme, each synchronous generator equipped with one PSS and AVR which the output of PSS or proposed WADC signal goes through AVR controller to damp inter-area oscillation. In this case, AVR receives two different types of signal including local signal from local PSS and global signal from proposed WADC controller. The developed local signal is used to damp individual local mode where global once is used to control inter-area oscillation identified into the system dynamic behaviors. Therefore, there is not any strategy for selecting PSSs or AVRs which the main novelty of this paper is to prepare global damping signal achieved from proposed WADC as input signal to generator AVRs with the potential of damping the inter-area oscillation. However, in the case of wide area signal unable to damp the oscillation, by using the proposed islanding strategy, candidate inter-area buses are identified which a controlled islanding strategy is performed.

3.1 Identifying inter-area oscillation

For creating each IAO into power system, there are different issues through developing the IAOs oscillatory patterns. In this case, (a) the system operational condition, (b) the network topological structure and (c) the location of fault event are three main reasons which known as the main parameters of forming inter-area oscillations. Therefore, it can be deducted that online evaluation of the SGs oscillatory signals is an

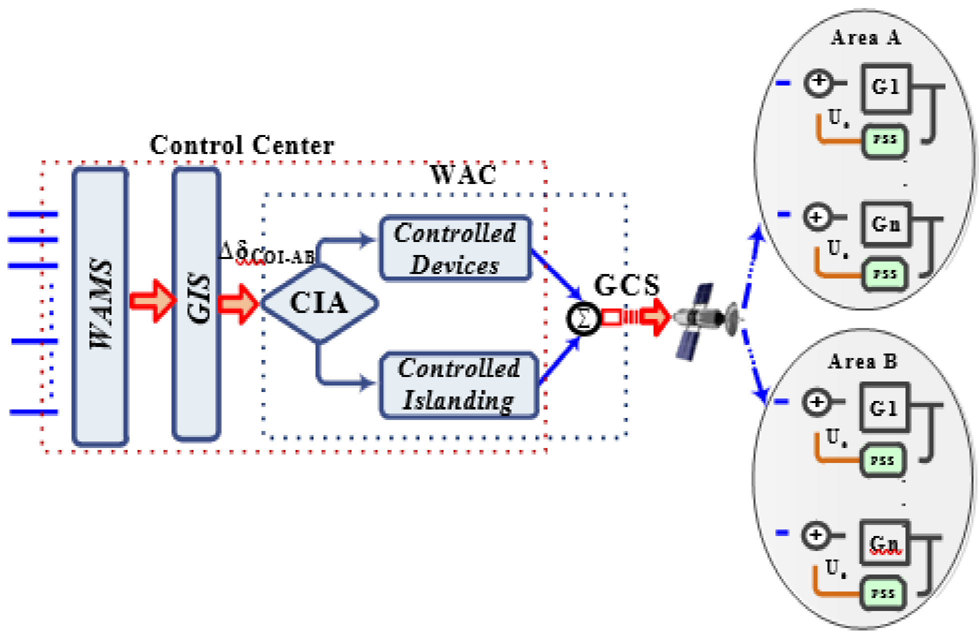

Fig. 7 Detailed structure of the proposed WAC scheme.

emergency action for identifying the SGs coherent groups and corresponding oscillating areas which based on evaluated signal processes, proper controlling scheme can be developed. In this paper, at each time moving window Δt, the CC_{ij} between each two pairs of SGs oscillatory signals (δ_i-δ_j and ω_i-ω_j) are evaluated which the system coherent generators are provided as follows:[19]

$$CC_{ij} = n\sum \delta_i\delta_j - (\sum \delta_i)(\sum \delta_j)/\sqrt{[n\sum \delta_i^2 - (\sum \delta_i)^2][n\sum \delta_j^2 - (\sum \delta_j)^2]} \quad (7)$$

From Eq. (7), n represents the length of time moving window consists of SGs oscillatory signals. Based on the evaluated measuring data and the length of time window, CC_{ij} varies between $+1>CC_{ij}>-1$ values. In the case of $CC_{ij}=+1$ and $CC_{ij}=-1$ two evaluated generators SGi and SGj are completely in-phase and anti-phase with each other, respectively. Finally, in the case of evaluating $CC_{ij}\approx 0$, there is not any relation between two generators SGi and SGj signals. After evaluating all pairs of SGs signals, the corresponding correlations CC_{ij} are sorted from top to down which the $CC_{ij}>0.8$ and $CC_{ij}<-0.8$ are known as the coherent and anti-phase generators, respectively. Correspondingly, the other values $0.8>CCij>-0.8$ are ignored and not considered through identification algorithm. By identifying different coherent groups, the inter-area rotor angle value $\delta_{COI\text{-}AB}$ between all pairs of coherent groups are evaluated which areas with the inter-area rotor angle differences larger than $\delta_{COI\text{-}AB}>90$ degree are known as two oscillating areas where the corresponding GIS signals $\Delta\delta_{COI\text{-}AB}$ and $\Delta\omega_{COI\text{-}AB}$ are provided.

3.2 Damping Ratio (DR) of the inter-area oscillation

In the case of evaluating two/more oscillating areas and developing the GIS signals, it is required to estimate the GIS damping ratios as a decisioning index to perform the proposed WAC scheme. For this purpose, by applying the RD technique through each evaluated time moving window, the signals damping ratios are estimated. The proposed RD methods, is an online and non-model-based scheme which by averaging the GIS signals within consecutive short-length time windows (Δtsh-length) and developing one averaged value through each consecutive Δtsh-length, the signal damping ratio is provided. Actually, by averaging the GIS signal through different consecutive Δtsh-length, the zero response values and corresponding noisy data are disappeared which only the signal initial values are remained. In this case, considering the rotor angle GIS signal $\Delta\delta_{COI\text{-}AB}(t)$, the RD parameter within a specified N numbers measuring data is evaluated as follows:

$$\text{RD}(t) = \frac{1}{N}\sum_{i=1}^{N} \delta_{COI-AB}\,(t+\Delta t_{sh-lenghti}) \quad (8)$$

From Eq. (8), during each short time window $\Delta t_{sh\text{-}length}$, the average value is evaluated which considering N number of measuring data, the signal damping ratio is evaluated. Real-time procedure of the proposed RD method can be described through following steps:

Step 1 - Determing length of time window $\Delta t_{sh\text{-}length}$ and N number of measuring data.

Step 2 - Calculating the *RD* value (8) at each $\Delta t_{sh\text{-}length}$.

Step 3 - Developing curve fitting between evaluated *RDs* and estimating the signal damping ratio.

As it can be seen, by using *RD* averaging method, the effects of noisy data is reduced through final decision. The feature is one of the most important advantages of RD scheme since in real-time evaluations, the SGs oscillatory signals are included different noise components. Finally, by developing curve fitting through evaluated *RDs*, the signal damping ratio is estimated.

3.3 Online Evaluation of the Proposed *CIA* Index

In the case of identifying an inter-area oscillation, the proposed WAC scheme is activated which considering GIS signals, proper GCSs are used as input signals through SGs excitations systems. Consequently, by generalizing the power system through two equivalent virtual models VG_{AreaA} and VG_{AreaB}, the inter-area angle $\delta_{COI\text{-}AB}$ between two oscillating areas are evaluated and compared with the *CIA* critical index as follows:

$$\left\{\begin{matrix} \delta_{COI-AB} = \delta_{COIa} - \delta_{COIB}\ \forall\ if\ \delta_{COI-AB} > CIA\ then\ block \\ \delta_{COI-AB} = \delta_{COIa} - \delta_{COIB}\ \forall\ if\ \delta_{COI-AB} \le CIA\ then\ Trip \\ CIA = 180 - \delta_{COI-AB}\,(ZCP_o) \end{matrix}\right\} \quad (9)$$

From Eq. (9), in the case of evaluating *CIA* index, by developing the inter-area angle $\delta_{COI\text{-}AB}$, its trajectory pattern is evaluated which the first zero crossing point (ZCP_0) is identified. From this time onward, the inter-area angle $\delta_{COI\text{-}AB}$ is compared with the estimated $CIA(ZCP_0)$ which in the case of $\delta_{COI\text{-}AB} < CIA(ZCP_0)$ means the proposed WACs are worked properly and the oscillations will be damped. However, by intersecting $\delta_{COI\text{-}AB}$ with the $CIA(ZCP_0)$, means an unstable condition is occurred and the controlled islanding scheme will be activated. This point is illustrated in Fig. 8, through generalized EAC curve (*i.e.* $P_{tie\text{-}line}$-$\delta_{COI\text{-}AB}$ axes) for modeling the GSMIB theory through inter-area oscillation cases.

Based on Fig. 8, considering an inter-area fault occurrence at $t=t0$ and $\delta_{COI\text{-}AB}=\delta 0$, the oscillating areas *Area-A* and *Area-B* oscillate against each other which increases the inter-area angle $\delta_{COI\text{-}AB}$. By reaching the $\delta_{COI\text{-}AB}$ to the first ZCP point, this point is identified and determined as the *CIA* index through proposed WAC scheme. From this time onward, the inter-area signal $\delta_{COI\text{-}AB}$ is compared with the identified *CIA*

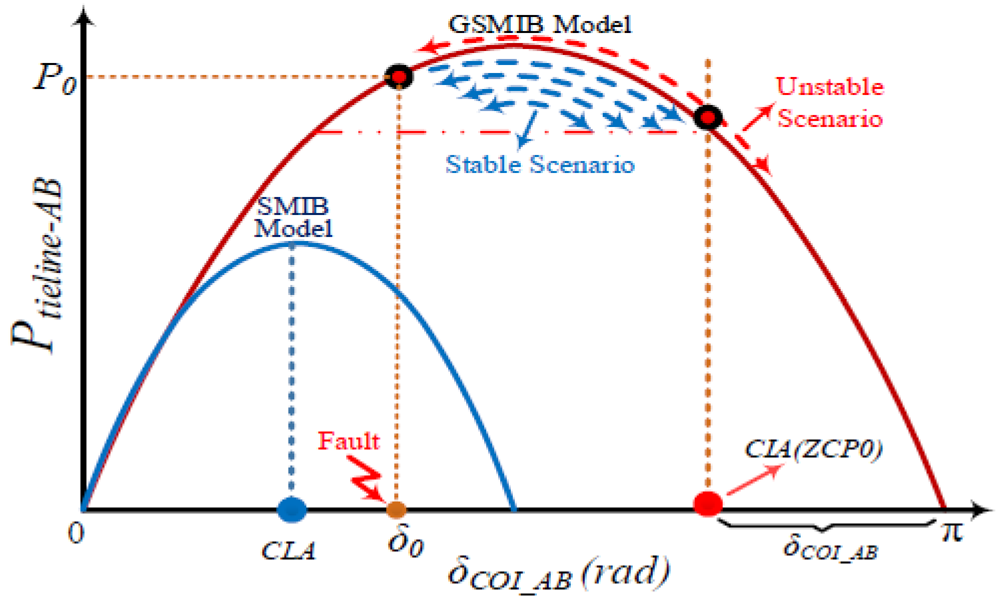

Fig. 8 Illustrating the proposed *CIA* scheme through generalized EAC model.

index, which in the case of intersecting the *CIA* point and $\delta_{COI\text{-}AB}$ signal with together, an unstable condition is estimated and the corresponding controlled islanding scheme is performed. In this case, be evaluating the system tie-lines connected between two identified oscillating areas, the splitting locations are determined which in the case of evaluating the 2th intersection of $\delta_{COI\text{-}AB}$ signal with estimated *CIA* index, the corresponding tie-lines are tripped as the controlled islanding scheme. Based on developed description, it is revealed that the proposed *CIA* index is an adaptive parameter which based on the identified oscillating areas and the inter-area oscillation, the inter-area ZCP point and corresponding *CIA* index are adopted. Through real-time evaluations, in the case of intersecting the inter-area angle $\delta_{COI\text{-}AB}$ with *CIA* index, it means that two identified areas are oscillating against each other through unstable inter-area oscillation with negative damping ratio. In this case, by identifying inter-area tie-lines, the system islanding locations are determined which in the case of splitting estimation, power system is divided through two separated islands.

4. Simulation Studies

In this section the effectiveness of the proposed WAC and *CIA* schemes for controlling the unstable IAOs are evaluated. To do this, considering a modified IEEE-39 bus test system including 10 SGs, the proposed schemes damping performances are evaluated. SLD of the developed test system is illustrated in Fig. 9.

As it can be seen, by modifying the SGs operating points and the tie-line impedances, system has a potential of forming inter-area oscillation between two oscillating areas *Area-A* and *Area-B*. Also, all of operated SGs are equipped with AVRs which receive to different signals. The first signal is from local PSSs for damping the local oscillations and the second signal is received from the proposed WAC scheme which is concentrated to damp the IAOs through power system.

It is worth noting that, there is not any strategy for selecting PSSs or AVRs which the main novelty of this paper is to prepare global damping signal achieved from proposed WADC as input signal to generator AVRs with the potential of damping the inter-area oscillation. However, in the case of wide area signal unable to damp the oscillation, by using the proposed islanding strategy, candidate inter-area buses are identified which a controlled islanding strategy is performed. Also, in order to identify IAOs, considering PMU devices installed at SGs terminals, the SGs oscillatory signals are sent to the WAC control center which the system dynamic security is evaluated. All inter-area fault scenarios required for evaluating the proposed WAC and *CIA* schemes are simulated through DigSILENT@ which is powerful software for evaluating power system dynamic stability analysis. In simulation studies, considering two different inter-area cases as *Case Study 1* and *Case Study 2*, the system damping performances are evaluated.

4.1 Case Study 1-WAC damping performance

In the first case study, at the system operating point 5855 MW, a 3-phase short circuit fault is occurred at t=1 *second* in the middle of the line 16-17 which based on the relay actions t=1.1 *second*, the line is tripped. The SGs dynamic oscillations

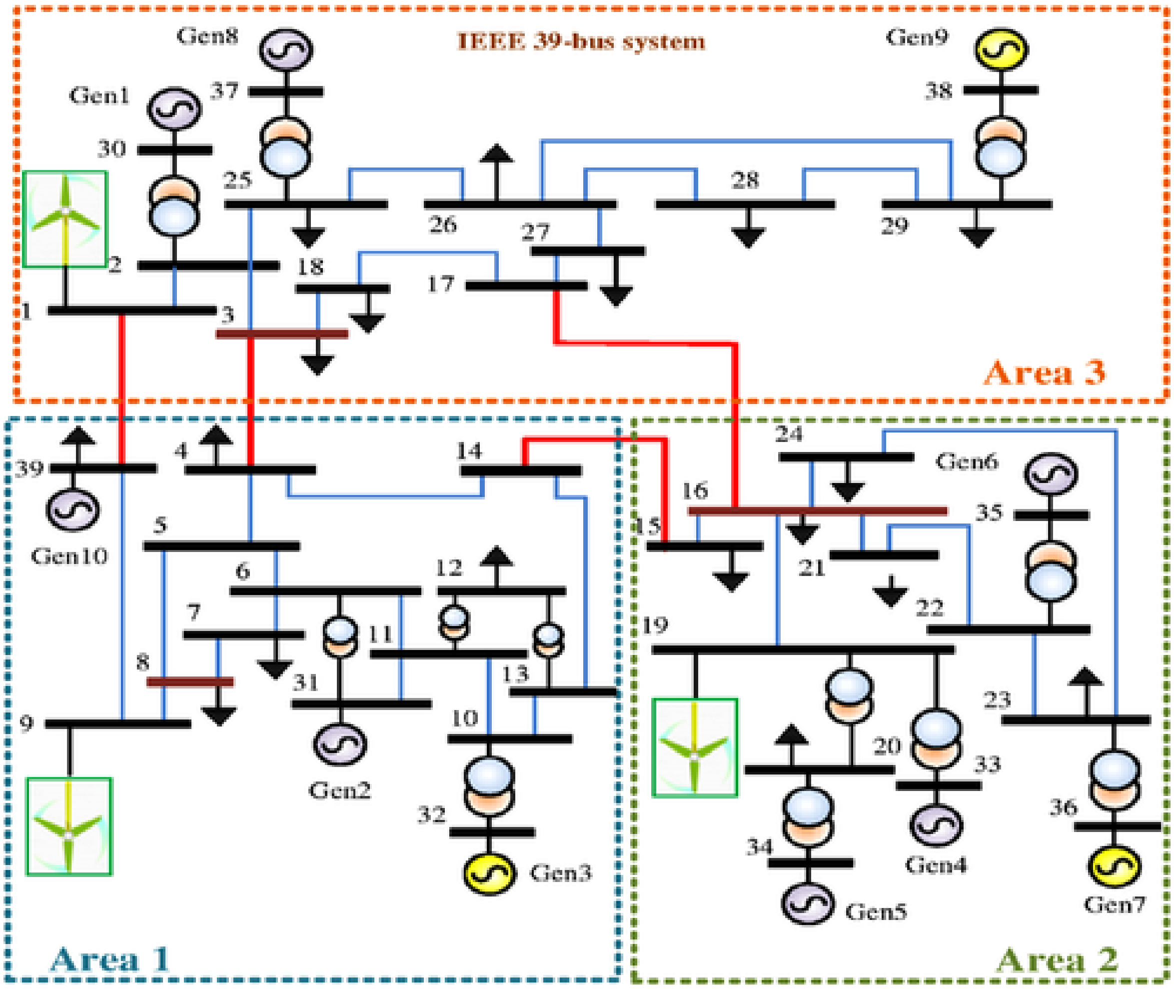

Fig. 9 The IEEE-39 bus SLD structure.

without implementing the proposed WAC scheme are shown in Fig. 10.

From Fig. 10(a), through real-time evaluations, it can be deducted that based on the SGs dynamic oscillations and their coherencies, there are two different coherent groups are oscillating against each other which can be developed as *Area1*{G1,G2,G3,G4,G5,G6,G7} and *Area2*{G8,G9,G10}. In this case, by evaluating the SGs oscillatory signals in *COI* frame, and developing the GIS signals (4) and (5), the inter-area oscillations are provided which is illustrated in Fig. 10(b). It can be seen that without activating the proposed WAC scheme, an unstable oscillation with the inter-area frequency $f_{inter\text{-}area}$=0.125 Hz is occurred. In this case, at t=5.46 *second*, the first *ZCP*(0)=87.3deg is occurred which increases through real-time evaluations *ZCP*(2)> *ZCP*(1)>*ZCP*(0). In the case of activating WAC scheme, considering four inter-area cycles, it can be reached that PSSs with local signals are unable to damp the inter-area oscillations. Therefore, by using GISs as input signal through generators AVRs, the effectiveness of the proposed WAC scheme is evaluated. In this case, based on oscillatory behavior, the proposed GCS signal is included as follows:

$$GCS_{Area1} = (k_1 \times \Delta\delta_{COI-12}) + (k_2 \times \Delta\omega_{COI-12}) \quad (10)$$

$$GCS_{Area2} = -GCS_{Area1} = (k_1 \times \Delta\delta_{COI-12}) + (k_2 \times \Delta\omega_{COI-12}) \quad (11)$$

It is worth noting that contrary to local oscillation in which only a single generator is responsible for oscillation and developing damping power, in inter-area oscillation, all coherent generators participating in oscillation in both oscillating areas are responsible for developing inter-area damping power. In other words, the nature of inter-area damping power is a global damping power which all oscillating coherent generators should participate for its development. It means that each individual generator should contribute to produce a part of the global damping power as a supplementary power. Also, it could be concluded that the most effective control signal for damping inter-area oscillation is global inter-area signals developed in Eqs. (10) and (11) into the main manuscript. In this case, the gain factors K1 and K2 are two controlling gains multiplied with two individual inter-area signals which GCS in phase with the oscillations with the potential of damping performance is developed. Considering different values of gain values K1 and K2, the phase and

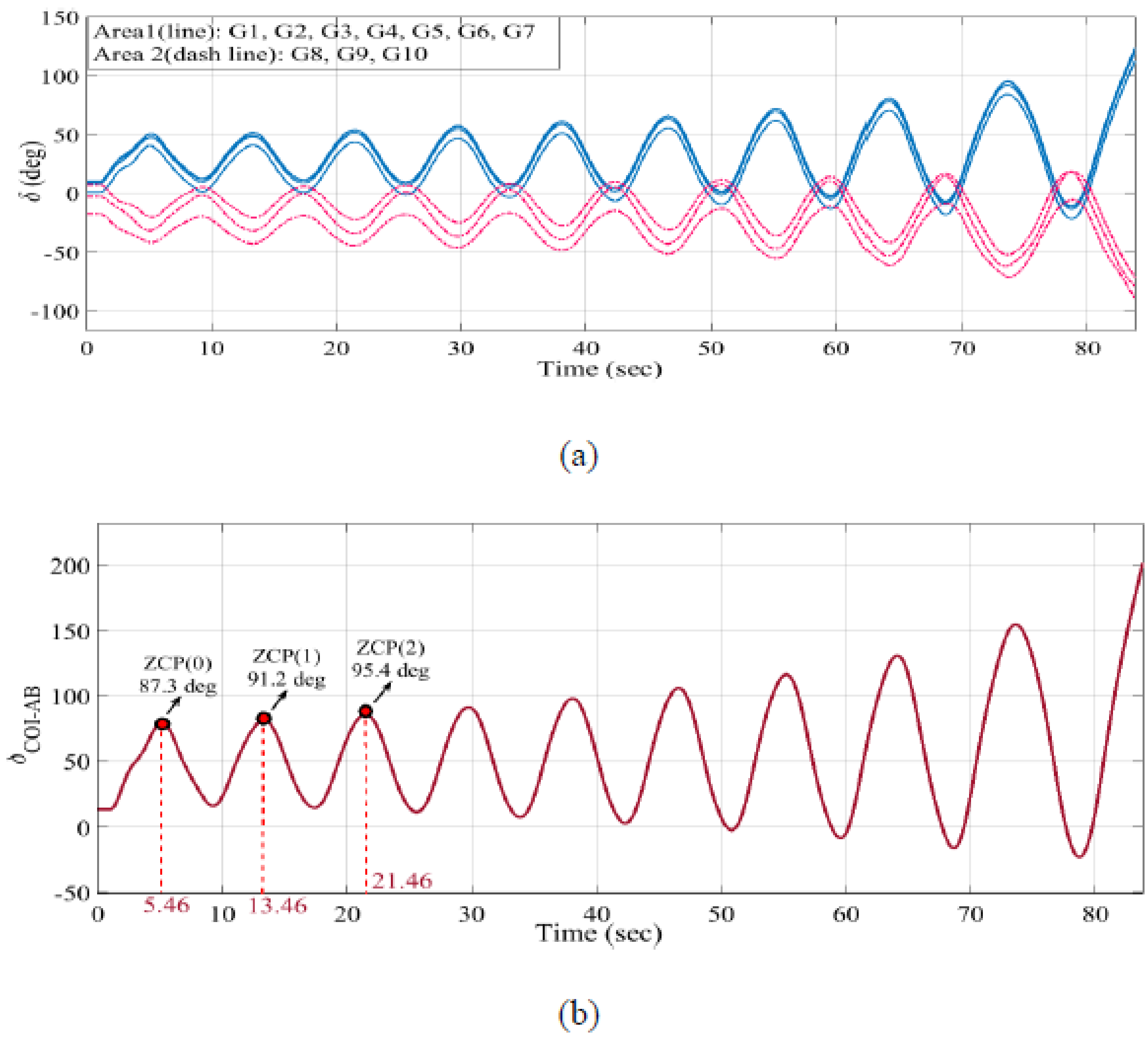

Fig. 10 The SGs dynamic behaviors without applying WAC scheme. (a) Rotor angle oscillations; (b) Inter-area oscillation in *COI* frame.

frequency of the proposed GCS (10) will be changed which presents different damping performance into the system.

In the case of evaluating the GCS controlling gains *k1* and *k2*, based on evaluating the oscillation damping ratio through 4 inter-area cycles, they are determined.

It is worth noted that, in order to provide positive performance of proposed WADC controller for damping inter-area oscillation, the output controlling signal must be in-phase with the oscillation frequency. Based on developed controlling signal GCS (10) and (11), the output of GCS includes inter-area rotor angle deviations between two oscillating areas as depicted in Fig. 11. As it is shown, in the case of presenting

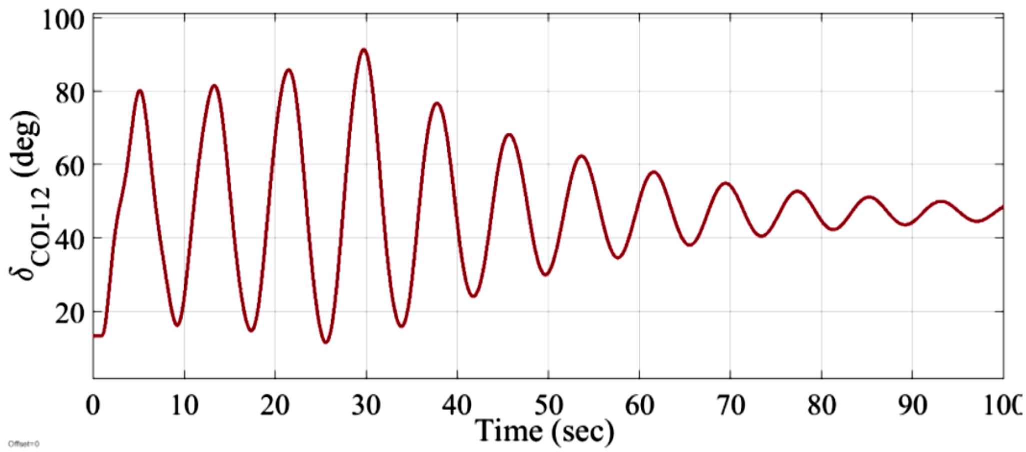

Fig. 11 Inter-area oscillation in *COI* frame after activating WAC scheme.

inter-area deviations as input to proposed damping controller, the output controlling signal is in-phase with the oscillation frequency resulted in damping power through power system. The system damping performances considering GCS as the proposed WADC output signal is illustrated in Fig. 11.

It should be noted that, the developed 4 inter-area cycle is a suggested time which the proposed WAC scheme could be activated before that through either ZCP(0), ZCP(1),… points. It can be revealed that the proposed WAC scheme works properly which after a few cycles, the inter-area oscillation well damped through proper damping ratio.

It can be seen that without activating the proposed WAC scheme, an unstable oscillation with the inter-area frequency *finter-area*=0.452 Hz is occurred. Also, two *ZCPs* including *ZCP*(0)=60.12.3deg at *t*=3.13 *second* and *ZCP*(1)=63.16deg at *t*=5.34 *second* are identified which after a few second, the inter-area rotor angle instability is occurred. In this case, the proposed WAC scheme is activated which based on developing the GCSs signals (10) and (11) through generators AVRs, the system damping performances are evaluated as shown in Fig. 13.

4.2 Case Study 2-*CIA* Online evaluation

In this case study, considering different fault event with the potential of unstable inter-area oscillation, the performance of proposed *CIA* index is evaluated. For this purpose, at the system operating point 7610 MW, a 3-phase short circuit fault is occurred in the middle of the line 4-14 at *t*=2 *second* which is tripped after 250 *ms* at *t*=2.25 *second*. The system dynamic behavior without implementing proposed WAC scheme is shown in Fig. 12.

From Fig. 13, it is revealed however WAC improves the system dynamic behavior but the produced damping power is not sufficient which after a few seconds, rotor angle inter-area instability is occurred. In this case, based on WAC damping performances, different ZCPs values are identified which each two pairs of consecutive *ZCP*s with increase ratio (*i.e.* *ZCP*(2)>*ZCP*(1) or (*ZCP*(3)>*ZCP*(2)) can be determined as *CIA* through controlled islanding scheme. In this case by intersecting the $\delta_{COI\text{-}AB}$ with specified *CIA*(*ZCP*(*i*)), a controlled islanding scheme is performed. For this purpose, based on evaluated inter-area oscillation, the tile lines 16-17, 3-18 and 1-2 is nominated as the inter-area tie-lines which are tipped based on *CIA* evaluations.

The SGs individual speed deviations after splitting two oscillating areas are shown in Fig. 14.

As it can be seen, by using the *CIA* index as a splitting index and separating two oscillating areas against each other, ωthe inter-area oscillation well-damped which each area is operated properly through stable islands. However, it should be noted that at each time moving window by identifying the GIS signals, the proposed WAC and *CIA* index parameters must be updated to provide proper damping performances.

5. Comparison of the Proposed Scheme with Recent Investigations

In the case of evaluating the proposed scheme, considering a set of recent techniques developed in Table 2, the damping performance of the proposed controller is compared. In this case, different indexes of technique's effectiveness consisting of Required damping Cycles, Real-time Applications, Expansion on large cases and Cost effective are considered and presented within continuous columns on Table 2. Also, in the case of proper validations, the same scenarios presented in Section 4.1 and 4.2 are performed which techniques damping performances are investigated.

It is resulted, the proposed controlling approach provides proper damping performance with cost effective criterion compared with all investigated techniques evaluated on Table 2. In this case, it can be implemented on large networks with the potential of developing the proposed WADC on real-time applications. This advantage is known as the most important features of the proposed controller against other techniques

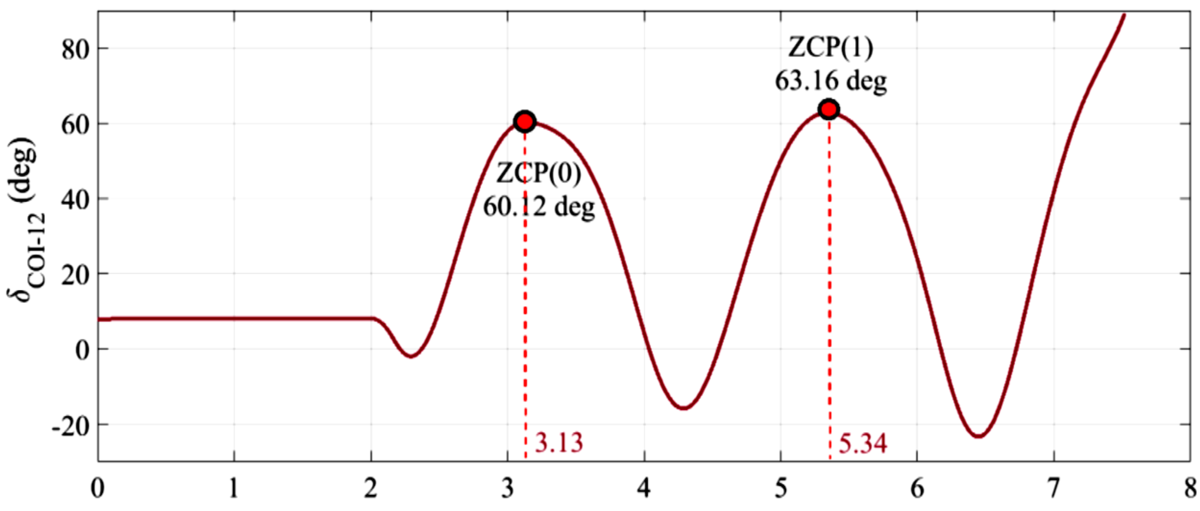

Fig. 12 Rotor angle oscillation of all generators without emergency control.

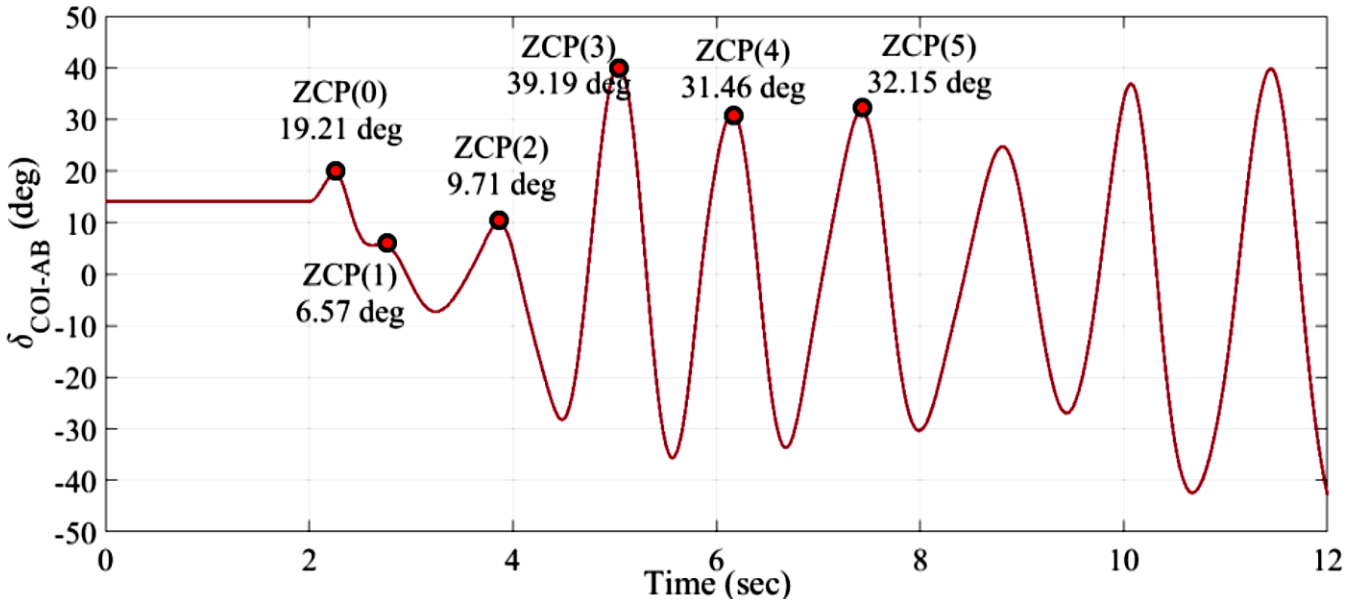

Fig. 13 Inter-area oscillation after activating WAC scheme.

Table 2. Comparison results of proposed controlling schemes with recent studies.

Ref.	Required Damping Cycles	Real-time Applications	Expansion on Large Cases	Cost Effective
GA[1]	> 10 Cycles	No	No	Expensive
CART[2]	5 Cycles	Yes	Yes	Inexpensive
Residue[3]	> 10 Cycles	No	No	Expensive
Gradient[4]	6 Cycles	No	No	Medium
WADC[5]	8 Cycles	Yes	Yes	Medium
Delay[6]	7 Cycles	Yes	No	Expensive
MIMO[7]	6 Cycles	No	Yes	Expensive
Rescheduling[8]	> 10 Cycles	No	Yes	Expensive
Load-Generation[9]	> 10 Cycles	No	Yes	Medium
Switching[10]	> 10 Cycles	Yes	Yes	Medium
Gain Scheduling[11]	7 Cycles	No	No	Medium
Multiple Mode[12]	9 Cycles	Yes	Yes	Expensive
GrHDP[13]	> 10 Cycles	No	No	Expensive
Bi-layer[14]	8 Cycles	No	Yes	Medium
Delay[15]	7 Cycles	Yes	No	Expensive
C5.0[16]	8 Cycles	Yes	Yes	Medium
Aggregated Load[17]	> 10 Cycles	No	No	Expensive
Data-Driven[18]	6 Cycles	No	No	Medium
WAC[19]	> 10 Cycles	Yes	Yes	Expensive
Feedback[20]	7 Cycles	Yes	No	Medium
Neural Network[21]	5 Cycles	No	Yes	Medium
H∞[22]	> 10 Cycles	No	No	Expensive
Residue[23]	> 10 Cycles	No	No	Expensive
Multi-Zone[24]	4 Cycles	Yes	Yes	Inexpensive
Cross-Gramian[25]	> 10 Cycles	No	No	Medium
Robust Control[26]	7 Cycles	No	No	Expensive
Proposed Scheme	2 Cycles	Yes	Yes	Low

within different operating conditions. Comparing with other researches, the proposed controller requires only two oscillating cycles to identify and damp the oscillations which with respect to inter-area frequency in the range of 0.1-1 Hz, it will take around 1 to 10 seconds based on the system oscillating modes. In this case, most of recent techniques require more than 5 inter-area cycles to damp the oscillations with high dependency on network impedance matrixes. Also,

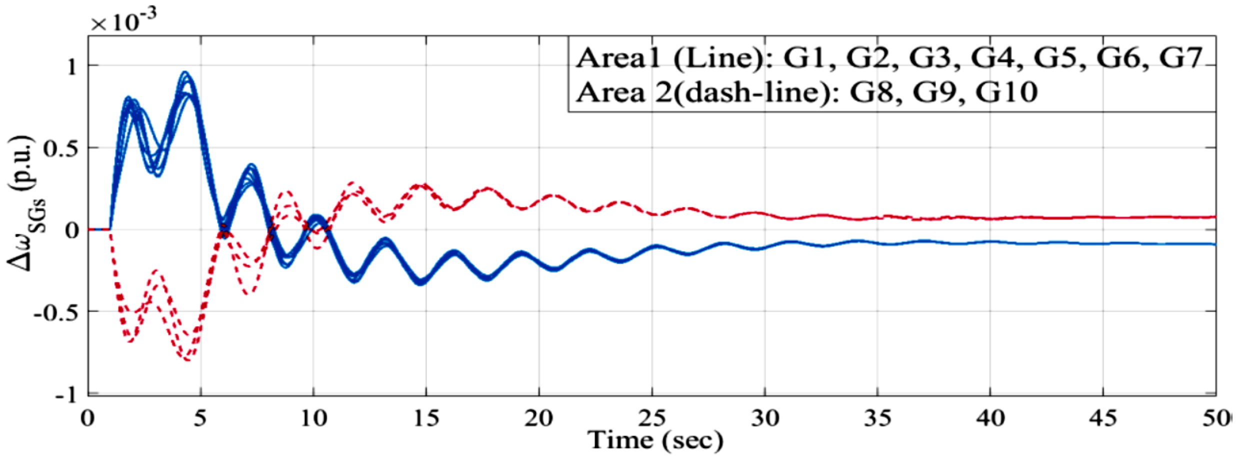

Fig. 14 Rotor angle oscillations after activating WAC.

because of cost effective criterion, the proposed approach can be applied effectively on different test/real power systems.

6. Further discussion

Through simulation results developed in *Sections 5*, damping performance of the proposed WADC approach for damping the inter-area oscillation and presenting controlled islanding scheme in the case of controller inabilities have been cleared. Based on the evaluated results, the main worthiness and shortcomings are listed through following descriptions. Developing controlled islanding scheme might considerably vary due to failing performance of controller blocks, while in the proposed approach, sustainable performance through different operating conditions are warranted. In this case, according to required decision-making time, frequent actions with the potential of leading the system security decrement are prevented in which the system dynamic responses through both long and short terms are improved.

However, in order to present positive effects, some offline arrangements need to be redefined on WADC settings and then use it on real-time applications. For example, through different topological structure, the network impedance matrix is changed which require WADC input and output signals be updated to present positive damping effect. Another issue will be occurred in the case of transmitting global signals within communication delays which highly effects on WADC damping performance. If the signals will not be sent to the controller or incorporated with delays and noises, the proposed scheme cannot affect properly and may even failed on damping inter-area oscillation. In this case, WADC should be deactivated.

7. Conclusion

In this paper a comprehensive scheme of controlling inter-area oscillation consisting of two WAC scheme and adaptive *CIA* was proposed. For this purpose, through online evaluations, by evaluating the SGs oscillatory signals gathered from WAMS data, the correlation factors are calculated which the correspondingcoherent SGs are determined. In this case, by identifying two oscillating areas *A* and *B*, the inter-area $\Delta\delta_{COI-AB}$ and $\Delta\omega_{COI-AB}$ are provided which use as the GIS signals through WAC scheme for direct presentation to SGs excitation systems. By identifying an unstable IAO, the proposed WAC scheme is activated which use to damp the oscillation. In the case of WAC inability through damping the inter-area oscillation, the GIS zero crossing points are evaluated which the first once $ZCP(0)$ is determined as the *CIA* critical angle. In the case of evaluating $\delta_{COI-AB} > CIA$, an unstable IAO is estimated which a controlled islanding scheme is performed. The proposed comprehensive approach is an online and non-model-based scheme which by evaluating GIS signals through consecutive time windows, the system dynamic securities and emergency actions is provided. The effectiveness of the proposed scheme is evaluated on the IEEE 39-bus system with indicating proper damping performance through controlling the inter-area oscillation.

Also, in the case of future discussions, one of significant suggestion can be found on evaluating WADC through real data on experimental cases. In this case, using detailed structures of the proposed WADC modeled on power system laboratories, the system damping response through real-time evaluations are validated. Also, presenting the proposed scheme on large power system consisting of multi inter-area modes is an interesting topic can be applied on future researches.

Conflict of Interest

There is no conflict of interest.

Supporting Information

Not applicable.

Nomenclature

Abbreviations	
CIA	Critical inter-area rotor angle
COI	Center-of-Inertia
CLA	Critical Local Angle
CC	Correlation Coefficient
EAC	Equal Area Criterion
GIS	Global Inter-area Signal
GPS	Geographic Positioning System
GSMIB	Generalized SMIB
GCS	Global Controlling Signal
IDR	Inter-area Damping Ratio
IAO	Inter-Area Oscillation
OOS	Out-Of-Step
RD	Random Decrement
RGA	Relative Gain Array
SGs	Synchronous Generators
SLD	Single line diagram
SMIB	Single Machine Infinite Bus
VG	Virtual Generator
VIG	Inter-Area VG
WAC	Wide Area Controller
WAMS	Wide Area Measuring System
WAPSS	Wide Area PSS
ZCP	Zero Crossing Points

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