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Self Tuning Wide Area Damping Control for Distributed Power Systems

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Abstract: Damping of low-frequency inter-area oscillations in a power system has been the main concern for ascertaining the small-signal stability. Much of these efforts had been paid on designing damping controller with controller parameters obtained by offline analysis using a linearized model of the power system around a most probable operating point. A modern power system is however subjected to frequent changes in operating points due to load, renewable penetration and topology variations. An adaptive controller has the advantage of flexibility in getting the controller parameters auto-tunned online thus can be used for different operating conditions. This paper presents a WADC controller using a self tunning control (STC) strategy. The evaluation of the designed controller under various conditions has been carried out with renewable integrated IEEE 11 bus and IEEE 39 bus test systems. From the results, it is found that the proposed WADC can provide improved damping on inter-area oscillations under variable operating conditions.

Keywords: Wide area damping control (WADC), Self Tuning Control (STC), Renewable Energy source.

1. INTRODUCTION

Low-frequency inter-area oscillations are intrinsic to a power system. These oscillations are in the range of 0.1-1 Hz and severely limits the power transfer capability in a power system. Traditionally used local power system stabilizers (PSS) are ineffective to damp out these oscillations due to their lack of global controllability ability. With recent advancement in WAMS system, the remote feedback signals are much readily available and using these feedback signals proper damping of the inter-area oscillations has been an area of recent studies Chakrabortty and Khargonekar (2013). There have been many efforts in the literature to design a WADC based on a linearized system around a most probable operating point. However, the modern power system is subjected to more variability in operations than ever in terms of changing load levels, generation patterns and network topology. These variabilities or uncertainties in a system are accounted by adaptive or robust controllers in the control system.

Many of the works on WADC are based on robust control techniques Kamwa et al. (2001); Li et al. (2017); Chakrabortty (2012). Generally in the formulation of a robust controller, the uncertainty is represented by a bound with a linearized model around its most probable operating point. With this model formulation, it is always difficult to find the uncertainty bound for a large system and may not account for all the possible operating points. Another approach to handle the uncertainty in a system is adaptive control techniques. Unlike the robust controller, the adaptive controller has the flexibility of online updating of its parameters. Thus, with the changing operating conditions, the controller parameters will get automatically updated. The advantage of adaptive controller operability in different operating conditions has attracted the attention of many researchers recently. In Chaturvedi and Malik (2005) an artificial neural network-based self-tuning adaptive PSS was discussed, in Zhang et al. (2014) an adaptive wide-area PSS has been discussed. In Liu et al. (2017) an ARMAX based transfer function model using wide-area measurements has been presented. In R. Pour Safaei et al. (2014), an adaptive switched controller has been proposed which for addressing inter-area oscillation, where explicit criteria for the switched controller has been expressed. In this paper, another approach is presented where the effect of renewable energy penetration has been taken into consideration while damping the low-frequency inter-area oscillations.

This paper presents an adaptive wide-area damping controller based on STC for addressing the different operating conditions in a renewable integrated power system. In the STC, firstly online system identification is carried out by recursive least square (RLS) algorithm using the feedback signals, then identified closed-loop system is compared with a reference model such that the controller gains can be obtained. The identification and controller tuning process is carried out simultaneously such that the inter-area oscillatory modes are damped in the desired time frame. The damping performance of the controller is verified in four different case studies such as changes in load, generating pattern and system topology.

The organization of the paper is as follows. Section 2 describes the problem statement where the formulation of the STC controller is carried out to achieve desired damping performance. In addition, the dynamics of the renewable energy resources (RES) has been described.

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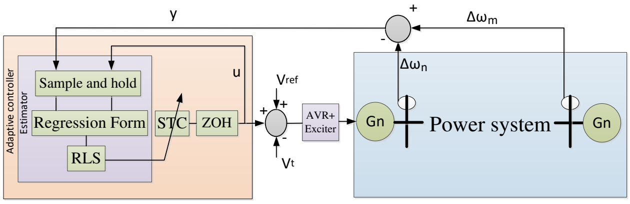

Figure 1. Schematic diagram of STC

In Section 3, the nonlinear model simulations are being carried out under four different case studies with detailed analysis of results. In Section 4, the conclusion of the paper is drawn.

2. PROBLEM STATEMENT

As the objective is to improve the damping of the inter-area oscillations, the associated electro-mechanical (EM) oscillatory modes are required to be modulated to a desired location by the damping controller. However, with variations in the operating the EM modes may change, this will require updating of the damping controller parameters. Thus an adaptive controller has been proposed to online estimate the system and provides appropriate control signal such that the closed-loop response matches the desired damping performance under variation in parameters. The self-tuning control algorithm has been explained in this section where first the selection of input and out channels is obtained through geometric measures. A schematic diagram for the proposed WADC scheme from a n^{th} generator to a m^{th} generator is shown in Fig.1.

2.1 Geometric measure

The selection of input-output channels can be obtained through the geometric measure Heniche and Kamwa (2002). For a given system (1) the geometric measure can be calculated as (2).

$$\dot{x} = Ax + Bu; y = Cx + Du \tag{1}$$

the geometric measure is given by

$$Gb_j = \frac{\left| {b_j}^T w_i \right|}{\left\| {b_j}^T \right\| \|w_i\|}$$
$$Gc_j = \frac{\left| {c_j}^T v_i \right|}{\|{c_j}^T\| \|v_i\|} \tag{2}$$

where $Gc_j \in \Re^1 \equiv$ controllability measure, $Gb_j \equiv$ observability measure, $v_i \equiv$ right eigenvector, $w_i \equiv$ left eigen vector of modal interest (i), $b_j and c_j \equiv$ corresponding input and output vector respectively.

2.2 Self Tuning Control

In this subsection the procedure for formulation of STC by pole placement technique is presented **?**, then the procedure is extended for synthesis of STC as WADC.

STC Theory A general representation of a discrete system is given as (3).

$$A(z^{-1})y(k) = B(z^{-1})(u(k) + v(k)) \tag{3}$$

where z^{-1} is backward shift operator, $A(z^{-1})$ is a monic polynomial and $B(z^{-1})$ is polynomials of z^{-1} and $y(k), u(k)$ and $v(k)$ are output, input and noise respectively at k instants.

The parameters of the system (3) can be estimated by the RLS algorithm as

$$\begin{aligned} \hat{\theta}(k) &= \hat{\theta}(k-1) + K(k)\varepsilon(k); \\ \varepsilon(k) &= y(k) - \phi^T(k-1)\hat{\theta}(k-1); \\ K(k) &= \frac{P(k-1)\phi(k-1)}{(\lambda+\phi^T(k-1)P(k-1)\phi(k-1))^{-1}}; \\ P(k) &= (1 - K(k)\phi^T(k-1))P(k-1)/\lambda \end{aligned} \tag{4}$$

where $\hat{\theta}(k) = [a_{n-1}...a_0 b_{\delta(B)}...b_0] \equiv$ parameter vector of the system, $K(k) \equiv$ gain term, $\varepsilon(k) \equiv$ error term, $\lambda \equiv$ forgetting factor, $P(k) = [y(k-1)...y(k-n+1)u(k-1)...u(k-\delta(B)+1)]$.

The general representation of a controller structure is given as $Ru(k) = Tu_c(k) - Sy(k)$, where R, T and S are polynomials of z^{-1}, $Tu_c(k)$ and $Sy(k)$ represents feed-forward and feedback control terms respectively.

The closed loop system for (3) obtained after substitution of control input is given as

$$y_c(k) = \frac{BT}{AR + BS}u_c(k) + \frac{BR}{AR + BS}v(k) \tag{5}$$

Now, the desired performance of the system is described by a reference model given as $Y_m = \frac{B_m}{A_m}$. Thus, to obtain the desired performance the closed loop system (5) should be equated to the desired model Y_m. However, the closed loop polynomial may not be of same degree (δ) as the degree of the desired model polynomial. Thus, an observer polynomial (A_0) is multiplied to the desired model such that appropriate order of polynomial is maintained in both sides of the equation $y_c = Y_m$. The roots of observer polynomial are chosen such that their effect on desired model response dies out in quick succession of time. For a regulation problem the reference becomes zero ($u_c(k) = 0$) and the $y_c = Y_m$ may be written as (6)

$$\frac{BT}{AR + BS} = \frac{BT}{A_c} = \frac{A_0 B_m}{A_0 A_m} \tag{6}$$

where $A_0 \equiv$ observer polynomial.

The controller parameter can be obtained by solving the Diophantine equation (7)

$$\begin{aligned} AR + BS &= A_0 A_m \\ BT &= A_0 B_m \end{aligned} \tag{7}$$

STC Application as WADC Now, the controller design procedure is extended for synthesis of WADC. The EM oscillation among oscillating generators is modelled as a second order system response which in discrete form is represented as

$$T_{sys} = \frac{b_1 z + b_0}{z^2 + a_1 z + a_0} = \frac{B}{A} \tag{8}$$

The represented second order system parameters (8) are identified online with RLS algorithm (4) with $P(k) = [y(k-1), y(k-2), u(k-1), u(k-2)]$ and as $\hat{\theta}(k) = [a_1, a_0, b_1, b_0]$ shown in (9)

$$
\begin{aligned}
&y(z^2+a_1z+a_0)=u(b_1z+b_0)\\
&y(k+2)+a_1y(k+1)+a_0y(k)=b_1u(k+1)+b_0u(k)\\
&y(k+2)=-a_1y(k+1)-a_0y(k)+b_1u(k+1)+b_0u(k)\\
&y(k)=-a_1y(k-1)-a_0y(k-2)+b_1u(k-1)+b_0u(k-2)
\end{aligned} \tag{9}
$$

The parameters of the desired model is set in accordance with the desired system performance specifications. The objective of the damping controller is to improve the settling time of inter-area oscillation. For a standard second order model in continuous domain, the representation of transfer function is given as (10)

$$G(s)=\frac{1}{s^2+2\zeta\omega_n s+{\omega_n}^2} \tag{10}$$

where $\omega_n \equiv$ natural frequency and $\zeta \equiv$ damping ratio and required to be specified from the desired system performance specifications. As the objective is to improve the damping of the inter-area oscillation. The settling time (T_s) of the inter-area oscillation is set to 6 seconds. The expression for settling time of a second order system is given as $T_s = \frac{4}{\zeta\omega_n}$ $(2\%criteria)$. Now, the ζ value can be set to 0.7 judiciously such that the maximum overshoot is not very high. Thus, the resulting reference model may be given as 11

$$
\begin{aligned}
G_{des} &= \tfrac{1}{s^2+1.3332s+19.36}\\
G_{z\_des} &= \tfrac{4.977\times10^{-5}z+4.955\times10^{-5}}{z^2-1.985z+0.9868}
\end{aligned} \tag{11}
$$

The discrete form of the desired continuous model is obtained with sampling time as 0.01 seconds. To satisfy the order of polynomial in the both side of (7) and to have low order controller structure, the observer polynomial is modelled as $A_o = z + 0.5$.

Now, to obtain the order of the controller, order matching of both side of (7) is carried out. Let $\delta(X)$ represents degree of X, then $\delta(A) = 2, \delta(B) = 1, \delta(A_m) = 2, \delta(B_m) = 1, \delta(A_0) = 1 \Rightarrow \delta(R) = 1, \delta(S) = 1$. Thus, the controller structure is given as (12)

$$u=\frac{S(z)}{R(z)}=\frac{s_1z+s_0}{r_1z+r_0}y \tag{12}$$

Now, the solution of the Diophantine equation (7) upon substitution of appropriate polynomials from the (12), 11 leads to the following tuning laws.

$$
\begin{aligned}
r_1 &= 1\\
r_0 &= \frac{-0.0057-0.4934\frac{b_1}{b_0}-\frac{2.485-a_1r_1}{b_1}b_0}{a_1-\frac{a_0b_1}{b_0}-\frac{b_0}{b_1}}\\
s_1 &= \tfrac{-1.485-a_1r_1-r_0}{b_1}\\
s_0 &= \tfrac{0.4934-a_0r_0}{b_0}
\end{aligned} \tag{13}
$$

It can be noticed from (13) that the controller parameters are represented in terms of system parameters. Thus, there is simultaneous updation of controller parameters along with online identification of system parameters (9).

3. CASE STUDIES

Here four case studies have been carried to study the performance of the proposed adaptive controllers. The objective of the controllers is to improve the damping of the low-frequency inter-area oscillation under various conditions. In this aspect, the efficacy of the adaptive controller under variation in system loading, generating and structure is tested. In the first case study, adaptive damping controller performance is tested under base loading condition in IEEE 4 machine, 11 buses power system Canizares et al. (2017). In the second case study, the adaptive controller is verified for a different loading condition under the circumstance where the system structure has been changed. In the third case study, the effectiveness of the adaptive controller is studied for variability in a generation where the renewable generators are penetrating power into the system. In the last case study, the efficacy of the controller under in different power system is tested by changing the test system to IEEE 10 machine, 39 bus system Canizares et al. (2017). The simulation study of the above nonlinear system models has been carried out in MATLAB-SIMULINK environment.

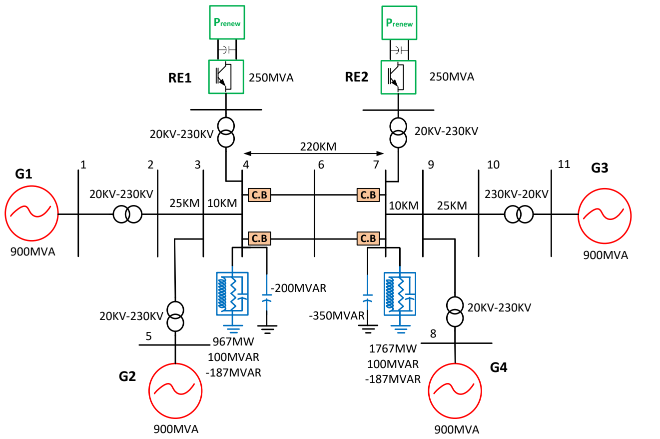

Figure 2. Two Area System

3.1 Case 1:With IEEE 11 bus/ 4 machines test system

A modified IEEE 4 machines, 11 buses test system is shown in Fig.2, where the renewable generators are not penetrating any power into the system in this case study and the system is operated at the Kundur (1994) operating condition. From the geometric measure, it is observed that the highest controllability is at G2 and the highest observability at G3 for the inter-area oscillation. Thus, the feedback signal is taken as speed deviation between the generator 2 and three i.e $\Delta\omega_{23} = \Delta\omega_2 - \Delta\omega_3$ and the control input signal is added to the automatic voltage regulation (AVR) signal of the excitation system of G2 as shown in Fig.1.

To emulate the small-signal disturbance in the power system, a step disturbance of magnitude 1% for 0.1 seconds is added to the voltage reference of G2 after 5 seconds at the base operating condition. Fig.3 (a-c) shows disturbance response and it is observed that the damping of inter-area oscillation is well achieved within 5 seconds. It is also observed that the controller is not having any adverse effects on the local oscillation damping. The Fig.3(d) shows online updation of STC controller (12) parameters.

3.2 Case 2: With change of load and one tie line outage

In this case study, the adaptive property of the STC WADC controller is tested for a different operating point from that of case 1. The system configuration is now

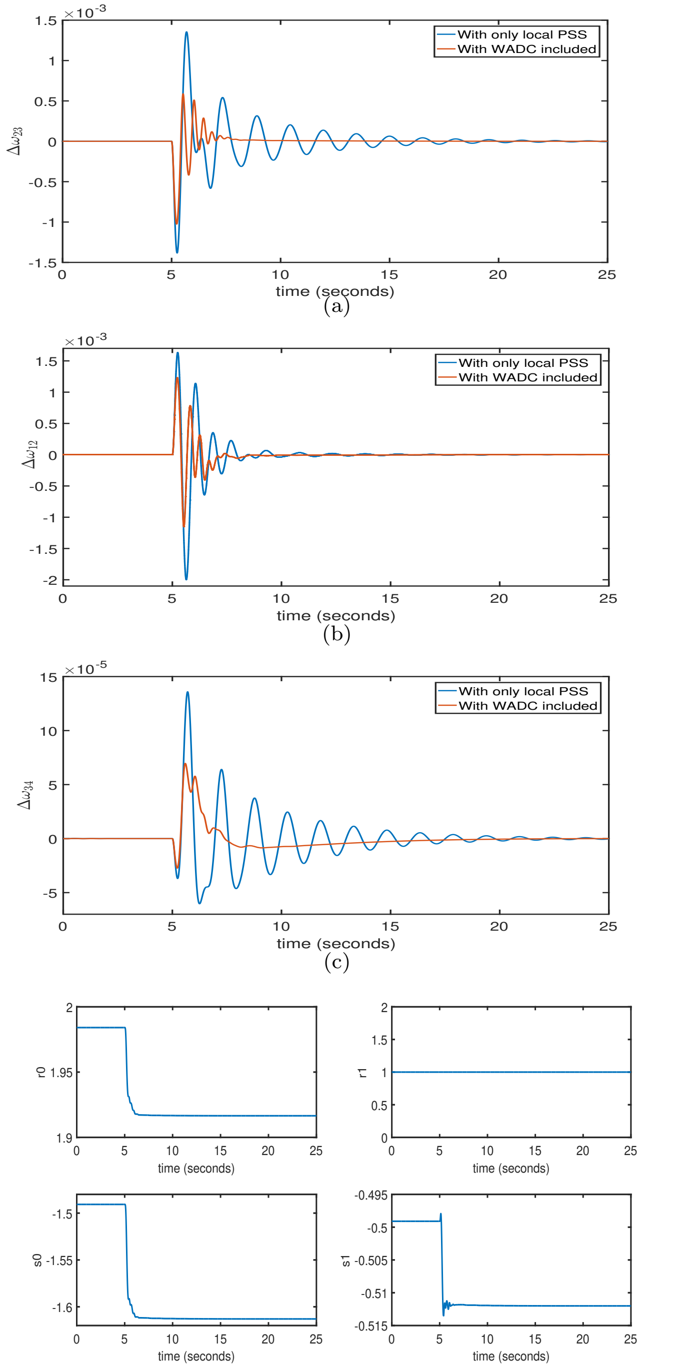

Figure 3. Response with STC WADC a)$\Delta\omega_{32}$, b)$\Delta\omega_{12}$, c)$\Delta\omega_{34}$ d) Online updation of STC controller parameters

changed with one of the tie line open-circuited by circuit breaker. The real power loading at area 1 of the system is also increased by 20%.

From the responses in Fig.4(a) it can be inferred that in this case study the damping of EM oscillation is deteriorated than the previous case under only local PSS. This because the area 1 which was supplying power to area 2 is now in more stressed condition as the area 1 loading is increased. In addition, the tie-lie impedance is increased with the outage one circuit breaker. Thus any

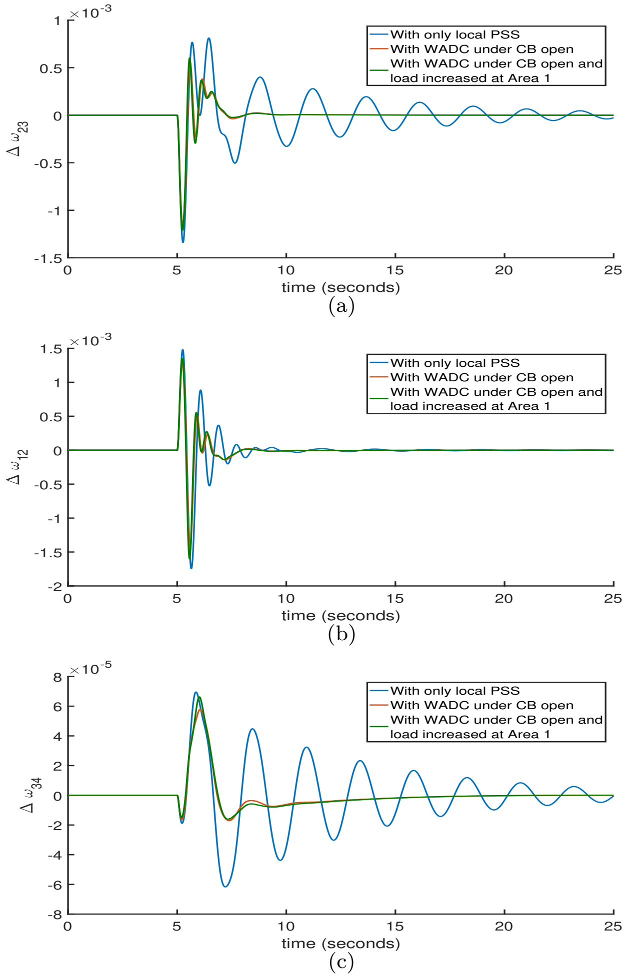

Figure 4. Response when one of tie-line is open circuited and the load in area 1 is increased a)$\Delta\omega_{23}$, b)$\Delta\omega_{12}$ c)$\Delta\omega_{34}$

disturbance, in this case, results in large settling time of inter-area oscillation. With the inclusion of STC WADC, it is observed that the EM oscillation is very well damped. This case study verify the adaptive property of controller for a load change and structural change in the system.

3.3 Case 3: With penitration of renewable energy in the test system

Now the efficacy of the adaptive WADC under penetration from the renewable energy is verified. The dynamics of the RES can be obtained from Yazdani and Iravani. (2010) where the schematic control flow diagram is shown in Fig.5.

With the large penetration of energy from renewable generator which is a non-inertial system, it has been studied that the overall system damping is decreased Eftekharnejad et al. (2013). In this operating condition, the renewable generator is penetrating 250MW of real power into the power system at bus 4 and bus 7 as shown in Fig.2.

From the response in Fig.6(a-c) it can be observed that the damping of the oscillatory modes has severely decreased. With the inclusion of the adaptive WADC, the controller

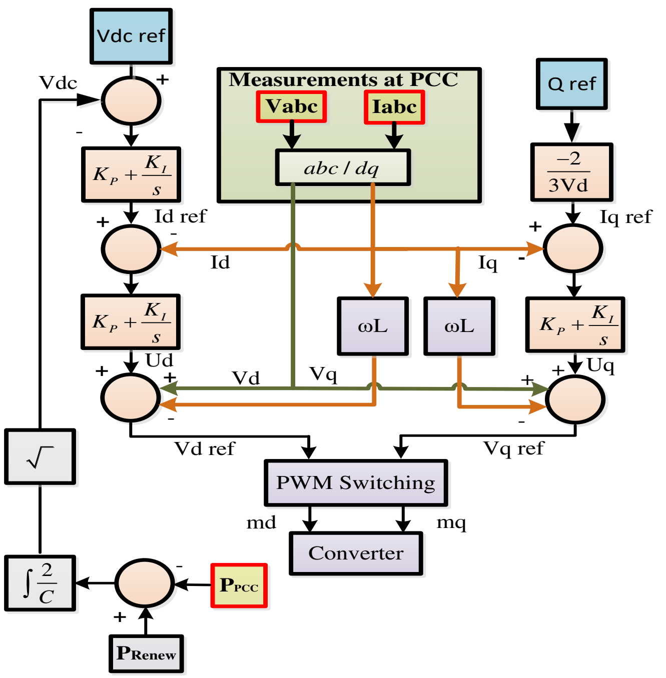

Figure 5. Schematic control flow diagram of Renewable generator

was effectively able to achieve improved damping. This case study shows the controller adaptive property under variable type of generation.

3.4 Case 4: Comparative study in New England System

In this case study, the IEEE benchmark New England (NE) system Canizares et al. (2017) is considered for the study. NE system is a complex system with 10 generators (G1-G10) and 39 buses with system data obtained from Canizares et al. (2017).

In this test system, it is observed that two modes (mode 1 and mode 2) are having large settling time. For mode 1 and mode 2 the control signal is given to G3 and G4 with feedback taken as $\Delta\omega_{13}$ and $\Delta\omega_{57}$ respectively. For the analysis of the EM oscillation behavior, disturbance in the power system is emulated by adding a pulse disturbance of magnitude 10% to G5 AVR reference for duration of 0.1 seconds.

The oscillatory response for the NE system is shown in Fig.8(a-c). The Fig.8(a) and Fig.8(b) corresponds to the mode 1, mode 2 where $\Delta\omega_{13}$ and $\Delta\omega_{13}$ are the speed deviations between the generator 1 and 3, and generator 8 and 3 respectively. It can be observed that the EM oscillations are much better damped with the inclusion of WADC than with only local PSS. This case study shows that the adaptive controller is able to adapt to a structural/ topology variations.

4. CONCLUSION

This paper presents the synthesis of STC for implementation as adaptive WADC. A modern power system is subjected to various operating conditions with variability in loading conditions as well as inclusion of renewable generating system which brings variability in their operating conditions. Thus an adaptive controller as WADC has been used to address the variable operating conditions. To verify the controller efficacy under variable operating conditions four case studies have been considered in this paper. It is observed the adaptive WADC was able to effectively damp the inter-area oscillations in all the operating conditions.

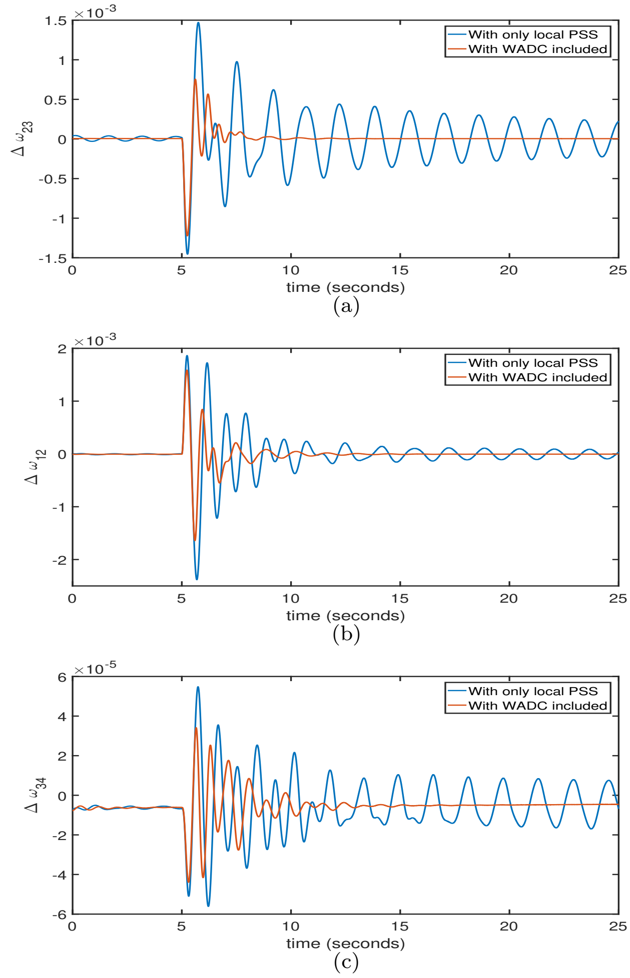

Figure 6. Response with 250MW of renewable power penetration a)$\Delta\omega_{23}$, b)$\Delta\omega_{12}$, c)$\Delta\omega_{34}$

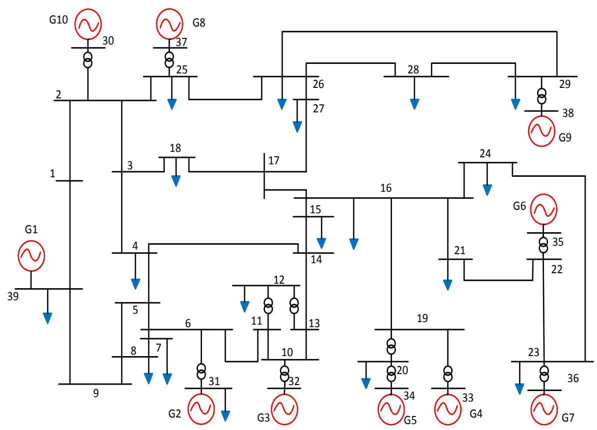

Figure 7. 10 Machine, 39 Bus system

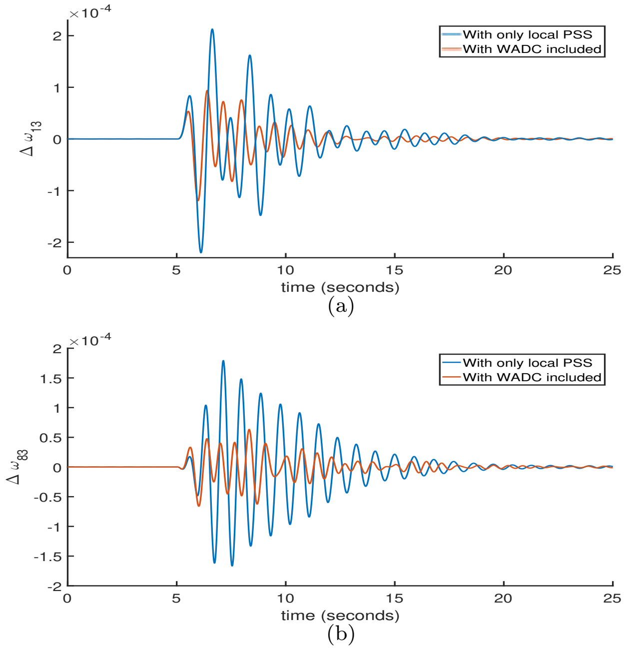

Figure 8. Response in 10 machine power system a)$\Delta\omega_{13}$ b)$\Delta\omega_{38}$

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