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Wide Area Oscillation Damping using Utility-Scale PV Power Plants Capabilities

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ABSTRACT

With increasing implementation of Wide Area Measurement Systems (WAMS) in power grids, application of wide area damping controllers (WADCs) to damp power system oscillations is of interest. On the other hand, it is well known that rapidly increasing integration of renewable energy sources into the grid can dangerously reduce the inertia of the system and degrade the stability of power systems. This paper aimed to design a novel WADC for a utility-scale PV solar farm to damp out inter area oscillations while the main focus of the work is to eliminate the impact of communication delays of wide-area signals from the WAMS. Moreover, the PV farm impact on inter area oscillation mitigation is investigated in various case studies, namely, with WADC on the active power control loop and with WADC on the reactive power control loop. The Quantum Particle Swarm Optimization (QPSO) technique is applied to normalize and optimize the parameters of WADC for inter-area oscillations damping and continuous compensation of time-varying latencies. The proposed method is prosperously applied in a 16-bus six-machine test system and various case studies are conducted to demonstrate the potential of the proposed structure.

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1. INTRODUCTION

Inter area oscillations may result when large generation and load complexes are separated by long transmission lines. In a large power system, these oscillations are typically between 0.2 and 1.0 Hz and may persist for extended periods due to low damping. There is a large economic motivation for mitigating these oscillations. First, low frequency oscillations can lead to a system breakup if the damping becomes too low. Second, the power flow through some transmission lines is limited to preserve small signal stability. Improving the small signal stability allows higher power flows, which has a considerable economic benefit [1]. In the literature, it has been shown that various devices such as: Power System Stabilizers (PSSs) [2], Flexible AC Transmission Systems (FACTS) [3] and High Voltage Direct Current (HVDC) links [4] can provide an effective solution to mitigate the Inter-area oscillations. Recently, the increasingly widespread use of renewable power plants on power networks, has led researchers to focus on the use of these renewable power plants to enhance power system stability. For example, wind energy is one of the fastest growing industry worldwide and the positive role of doubly-fed induction generator (DFIG) based wind farms in damping power system oscillations have been revealed by the latest research in the relevant literature [5-6].

Besides widespread installation of large scale wind farms, worldwide capacity of grid-connected PV power plants is growing rapidly in recent years [7]. Although the current PV penetration is nearly 1% of the peak load demand, for the present growth rate, it is anticipated that this amount will increase to 10 – 15% over the next decade [8-10]. Furthermore, among these installed capacities, 33% are centralized grid-connected PV systems [11]. A significant number of large-scale PV plants such as Ontario (100 MW) in Canada, Perovo (100 MW) in Ukraine, and Briest (91 MW) in Germany are already in operation. Moreover, PV plants over hundred MW size such as Charanka (214 MW) in India and New South Wales (154 MW) in Australia will be in operation or build soon [8] and [12]. When the penetration of PV plant is significant, the damping of oscillations by controlling the PV plant becomes a feasible and important option.

Owing to the fact that FACTS devices and HVDC links are commonly located in the central areas of power systems, say as bulk generation centers or transmission corridor terminals, local signals show adequate content to be used in damping controller of this equipment. This assumption is however, not true regarding PV farms which are commonly installed far away from the power system central areas thus the necessity of using WAMS technology in designing damping controllers for PV farms is clear.

Wide-area measurement system (WAMS) enabled by dispersed deployment of phasor measurement units (PMUs), is capable of capturing the dynamic information of power system including voltage, current, angle, and frequency with a high resolution and in a near real-time manner. WAMS accordingly offers an unprecedented opportunity in controlling power system dynamics and oscillations. The achievements are mostly due to time-stamped synchronous measurements applicable to various points of a geographically spread electric network [13]. However, the issue of communication delay in these systems should be addressed. The time which is demanded to communicate PMU data in the system or regional control center plus that of transferring commands to control devices is totally considered as the communication delay or latency. This time delay depends on the communication system loading and, in the feedback control loop, diminishes the effectiveness of the control system and may even result in the system instability [14]. Accordingly, considering the latency during the controller design process is an essential requirement. In the literature, a few papers have been proposed to govern the latency impacts on PV based wide area damping controllers [15-16]. In [15] a mini max linear quadratic Gaussian-based power oscillation damper (POD) for a large-scale PV plant is proposed for inter area oscillation damping. Only one controller is designed, and reactive control loop is used for applying auxiliary damping controller. Furthermore, constant time delays are considered in WADC design. In [16] a norm bounded linear quadratic Gaussian controller synthesis method is utilized to design a WAMS-based power oscillation damping controller at PV plants. In this paper like previous one, only one controller is designed, and reactive control loop is used for applying auxiliary damping controller.

A serious bottleneck in effective design of wide-area damping controller (WADCs) while accommodating the impact of feedback signal latency is the uncertainty associated with the single delays. The availability of time information associated with the received data, and controller location renders the precise calculation of time delays a feasible opportunity. However continuous compensation of time-varying latency might be hard to achieve since 1) a large number of pre-designed controllers should be in use for switching from one to another depending on the actual latency, or 2) the designed controller should be inherently robust against the variable time latencies.

The main contribution of this paper is demonstrating the applicability of PV farms in improving the oscillatory behavior of a power system, particularly when wide-area information is available. In all papers that published in the literature about the application of PV plant on inter area oscillation damping [15-16], just reactive power modulation of PV plant is used. But in this paper, both active and reactive power control loops of PV plant is considered to applying auxiliary damping controller and also a comprehensive comparison between active and reactive power modulation is presented. Regarding wide-area applications, the adverse effect of signal latency is a bottleneck and should be truly accommodated in the analysis. Otherwise, the outcomes might be theoretically outstanding but lacking practical merits. The proposed WADC is a conventional damping controller tuned by the Quantum Particle Swarm Optimization (QPSO) approach for inter-area oscillations damping and continuous compensation of feedback signal latencies. In all papers that published in the literature about design of WADCs, a constant time delay is considered in wide area signals. But in practical applications, time varying time delay on WAMS signals causes instability on damping controllers. So in this paper a time varying latency is considered in the WADC design process.The PV farm impact on inter area oscillation mitigation is interrogated in various case studies, namely with the WADC on the active power control loop and with WADC on the reactive power control loop. In the following sections, coordinated tuning of the WAMS based active and reactive damping controllers to enhance the damping of the oscillatory modes using QPSO technique is presented.

2. PV MODEL

Numerous PV generator models have been developed and used in literatures. However, a PV model based on a manufacturer-provided field or factory tests as a benchmark for stability analysis is required. Thus in this paper, a generic (standardized) model of a PV plant is considered as it has been validated and widely used for power system stability analysis [17].

For power system dynamic studies the solar farm is modeled as a single-generator equivalent. A complete model of solar farm with a large-number of PVs increases the computational burden. Moreover, this assumption is reasonable when the power system under consideration is large, and the main purpose is to observe the effect of penetration on the external network rather than within the large-scale PV plant. But in this study for accurate controller tuning, the model of the PV plant includes the PV array, converter dynamics, and associated control systems dynamics [15]. As seen from Figure 1(a), there are two main components contributing into the dynamic behavior of the PV: converter and converter controller. Figure 1(b) depicted the block diagram of the grid-side converter and controller of a PV power plant. According to NERC's special report on standard models for variable generation [18], a PV model can be based on the grid-side model of the type-4 wind turbine generator (WTG) as shown in Figure 1(a). From the figure, it can be seen that the power generated is processed through the power converter which serves as a buffer between the generator and the grid and controls reactive power or voltage at the point of common coupling (PCC).

There are different possibilities for converter transfer functions; however, the following two models are probably the most appropriate ones [19]: 1) the first-order function with unity steady-state gain; and 2) the closed-loop controller transfer function. Moreover, both provide very similar results and hence the first one is adopted in this paper. Figure 1(a) dictates that the active power to be delivered to the system is based on the solar power profileP_{PV}, whereas reactive power generation depends on the comparative signal generated from the reactive power controller. Figure 1(b) shows the reactive power controller of PV. This controller can be switched to power factor control or voltage control mode. Depending on the required control task, each of these control units can be activated by a proper flag. In this paper, the voltage control mode operation of a PV plant has been considered and the reference voltage V_{ref} generated by the voltage control becomes a reactive power control input to the converter control in Figure 1(b). The details of the model presented here can be found in [20].

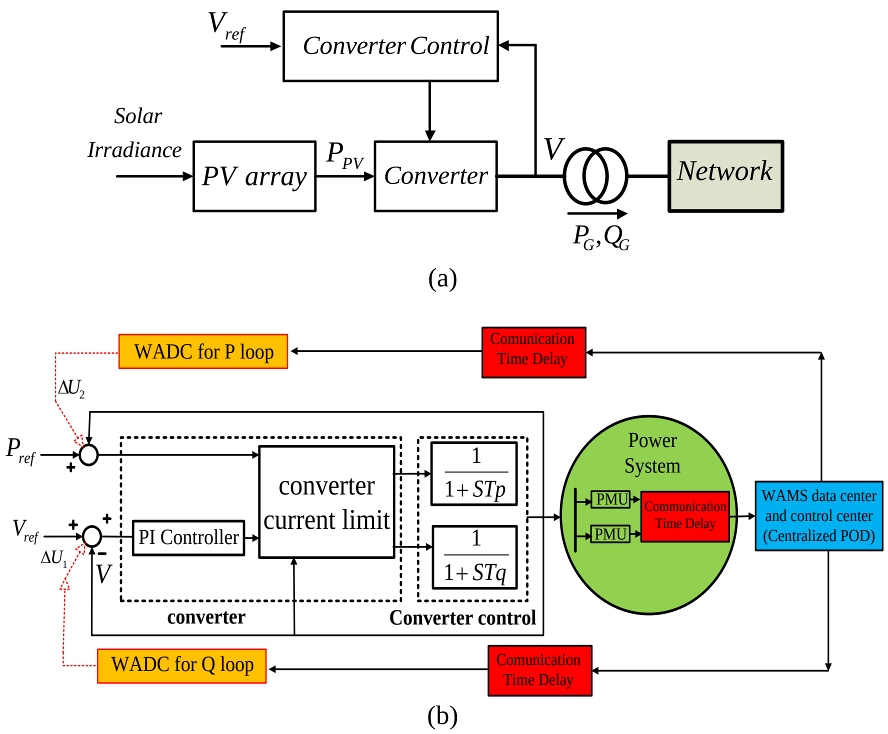

Figure 1. (a) Block diagram of PV with a type-4 WTG grid-side converter; (b) Block diagram of a grid-side converter and controller of the PV power plant

3. WAMS-BASED DAMPING CONTROLLER DESIGN

The use of Phasor Measurement Units (PMUs) is growing around the world due to its large extent applications. The most significant feature of PMUs is the matter of time synchronization availing of the global positioning system. This ability makes measurements accurate enough to achieve phase angles which are essential information in the system transient studies. A Wide Area Monitoring System (WAMS) is required to gather PMUs' data which is sent from selected locations in the power system and stored in a data concentrator every 100 milliseconds. One of the most practical applications of WAMS is oscillation damping, which is highly depended on the number and location of PMUs placed in the grid. The PMU placement problem is a well investigated subject area and many aspects of this issue have been so far assessed in depth [21-23]. For oscillation damping it seems that a definite number of PMUs will meet the objective if the places of PMUS are chosen properly. The numerical studies presented in the following sections support this conclusion. The authors intend to work on this issue in the future while some pioneering research is available presently [24].

A local damping controller is not able to access any global inter-area oscillation signals with wide-area modal observability. In contrast, WAMS implementation makes it possible to achieve global inter-area oscillation information to apply to the damping controller. The most important contributing factor in the effective performance of WADC is feeding the feedback signal delays to the controller while, there is no such a concern in the local damping controller design. Obviously, WADC and local controller structure design are basically different due to the difference in their input signals. WADC is capable of damping out multi-mode fluctuations. This feature is indicated by multi-band controllers which each of them exerts its own global input signal for damping one of the oscillation modes. But the local damping controller has merely one band to damp one oscillation mode. So for a multi area power system with several different oscillatory modes, a multi band WADC should be designed according to Figure 2(a). The WADC output that is indicated by Equation (1) is thus utilized to modulate PV plant active or reactive power and consequently adjusts to yield a proper damping of inter-area oscillations. Each WADC1 to WADCn is a conventional damping controller that is shown in Figure 2(b). Each of the band controllers is denoted by WADC1 to WADCn and the whole unit is recognized by WADC.

$$output = W_1 Out_1 + W_2 Out_2 + \ldots . + W_n Out_n \quad (1)$$

where, W_1, W_2 and W_n considered as weighting factors which should be obtained from the Prony analysis inversely proportional to normalize damping ratio of their dominant mode.

If the parameters of damping controllers are properly optimized, the damping of oscillation will be achieved effectively. For this reason, damping controller parameters will be optimized by an optimization algorithm that will be introduced in the next sections.

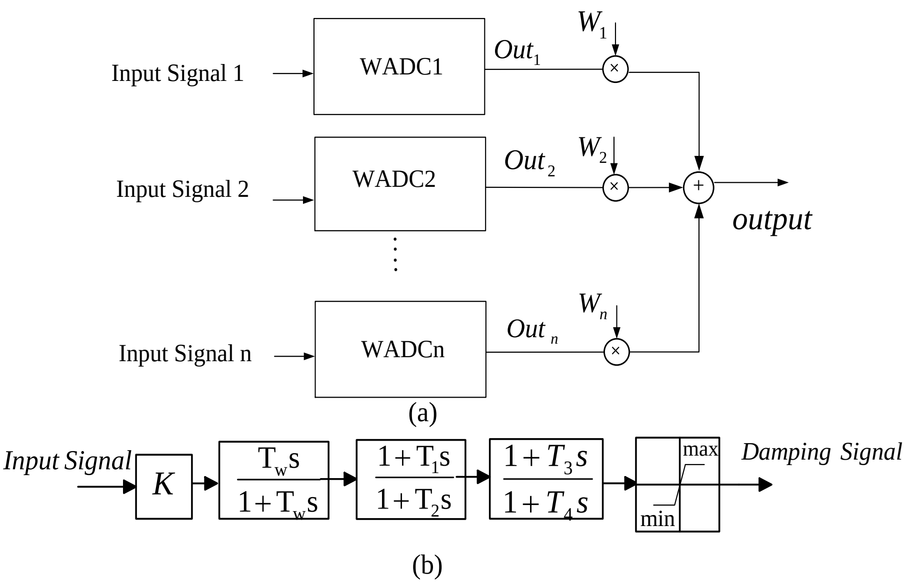

Figure 2. Structure and the block diagram of the classical wide area damping controller (a) Structure of a multi-band WADC and (b) The block diagram of the classical damping controller

Apparently, it is essential to have n (The number of oscillating modes) suitable supplementary signals containing all modes of oscillations to damp out multi-mode oscillations. One of the fundamental issues in designing a suitable WADC is the selection of wide area input signal for the WADCs. Any kind of input signal that has a good modal observability of inter-area oscillation can be used such as the power of tie line interconnecting areas, the frequency difference between areas, the angle difference of two buses in two areas and etc.

Another fundamental issue in designing a damping controller for PV plant is the choice of proper point for applying damping controller output signal for oscillation damping. As shown in Figure 1(b), the control system of PV plant consists of two control loops; namely active power control and reactive power control loop. Because of existing two separate controllers in the PV control system additional functions can be carried out by supplementing the auxiliary controllers. The active and reactive power modulations will be achieved if the auxiliary controller is added to the active power or reactive power control loops respectively.

Active power modulation for oscillation stability enhancement has been applied in HVDC and DFIG [4] while reactive power modulation for oscillation stability has been applied in Static Var Compensator (SVC) and again DFIG [3] and [5]. In this paper, both active and reactive power modulation is investigated. The active power modulation will modulate the active power reference value while the reactive power modulation will modulate the reactive power reference value.

Time synchronized data gathering and sending by PMUs equipped with the time stamp makes the communication latency computable if the local time of controller location is available through a dedicated GPS device. The total latency of transferred data is calculated by subtracting the local time at the controller location and the instant of origin at the PMU locations [25]. It is necessary to note that if the equipment under control is far away from the controller location, the transmitting time of the commands should be considered as well. Due to the uncertainty of the communication system, the latency does not get fixed completely.

Here we tend to design a delay-compensated WADC in order to compensate the destructive effects caused by the time delays. To meet this end an additional input signal indicating the latency of feedback signal is required to feed the PV farm location to the damping controller. The parameter of the time delay is considered in the simulation setup during the design process and then the controller parameters are optimized by the QPSO algorithm. In this method the parameters of lead-lag compensators are adjusted so that the phase shift between speed deviation and resulting electrical damping torque is compensated for, and the adverse effect of latency is minimized also.

The main drawback of the PSO algorithm has convinced the researchers to improve this optimization method. This drawback can be mentioned as: it cannot be considered for global convergent. In traditional PSO technique, the trajectory of the particle is determined through its position vector X_i and velocity vector V_i. The main problem is that the exact values of the X_i and V_i cannot be determined because the dynamic characteristics of the particle is different from that is considered in traditional PSO.

According to uncertainty principle, the X_i and V_i of each particle cannot be specified simultaneously. So the term trajectory doesn't have any definitions in quantum world. As a result, if a particle in a PSO system has quantum behavior, the PSO algorithm will be bound to work in a different manner. In a quantum based PSO, terms position and velocity are eliminated and the state of a particle is defined by wave function $\psi(x,t)$. By using the Monte Carlo method, the particles will move according to these Equations [26]:

$$
\begin{aligned}
X_{id}(t+1) &= p+\beta.\left|Mbest_t - X_i(t)\right|.\ln\left(\frac{1}{u}\right) \text{ if } K\le 0.5 \\
X_{id}(t+1) &= p-\beta.\left|Mbest_t - X_i(t)\right|.\ln\left(\frac{1}{u}\right) \text{ if } K>0.5
\end{aligned} \tag{2}
$$

where u and K are values which are generated according to a uniform probability distribution in range, the parameter β is contraction or expansion coefficient which if be tuned will be able to control the convergence speed of the particle. In order to guarantee the convergence of the particle, the β should be selected in range of $\beta<1.782$ [26]. So the Equation 2 is the basic Equation of the particle's position in QPSO method. Furthermore the QPSO needs no velocity vector and also has fewer parameters than traditional PSO algorithm because only β should be controlled. So this fewer parameters make the implementation of this algorithm easier. It is revealed by the manuscripts that the QPSO acts more efficient than the classic PSO algorithm [26]. In Equation above, Mbest is the mean best position which is the mean of the Pbest of all particles:

$$Mbest = \frac{1}{N}\sum_{d=1}^{N} P_{id}(t) \tag{3}$$

If each particle converges to its local attractor, the convergence of the QPSO algorithm will be achieved:

$$P = (c_1 P_{id} + c_2 P_{gd}) / (c_1 + c_2) \tag{4}$$

In the following a brief explanation of the procedure for implementation of the QPSO algorithm is expressed:

1. A random distribution of positions will be initialized in n-dimensional space for each particle.
2. The fitness value of each particle is evaluated.
3. The fitness value which is obtained in the last section will be compared to Pbest. If the fitness value is better than the Pbest, the Pbest is set to current fitness value and the location of Pbest is set to the current location.
4. The fitness will be compared with the overall previous best of population. If the current value is better than gbest, then the gbest is set to current particle's array index and value.
5. Calculate the Mbest through Equation 3
6. The position of each particle will be changed through Equation 2 and the algorithm will be proceed through the second step

It should be noted that, c_1 and c_2 are two random numbers between 0 and 1. If the convincible criterion is not achieved, the evolutionary cycle will be repeated. The termination criterion is usually a sufficient fitness, or a maximum number of iteration of process.

In order to ameliorate the overall system dynamic stability and achieve the best damping of oscillations, the parameters of the proposed WADCs shown on figure 2 should be tuned. The parameter T_w and limiter parameter are set manually but the other parameters will be optimized by QPSO algorithm in order to yield optimal performance in oscillations suppression. In this study an objective function which is come from speed deviation of the rotor shafts (which means the inter-area signal come from speed deviation of generators) is utilized in order to yield the fittest output parameters for WADC. The mentioned objective function is an integral of time multiplied absolute value of the speed deviation, and can be expressed by:

$$J = \sum_{1}^{iteration}\int_{0}^{t_{sim}} t.\left|\Delta\omega_{ij} + \Delta\omega_{kl}\right|.dt \tag{5}$$

where, t_{sim} is the simulation time, and Iteration is the number of iterations. The main aim of optimization is to minimize the objective function with the following constrains:

$$\begin{aligned} &K^{\min} \le K \le K^{\max} \\ &T_1^{\min} \le T_1 \le T_1^{\max} \\ &T_2^{\min} \le T_2 \le T_2^{\max} \\ &T_3^{\min} \le T_3 \le T_3^{\max} \\ &T_4^{\min} \le T_4 \le T_4^{\max} \end{aligned} \tag{6}$$

The QPSO algorithm search for the optimal value of parameters above in range of: [0.001-200] for K and [0.001-3] for T_1, T_2, T_3 and T_4. These parameters are defined in Figure 2. With implementing the time domain simulation model of the power system on simulation period, the objective function is computed and after reaching to specified criterion, the optimal parameters of the controller will be obtained.

4. THE POWER SYSTEM UNDER STUDY AND SIMULATION RESULTS

The power system adopted for this study is illustrated in Figure 3 [1], [5], [14]. It has originally 15 buses and six machines in three areas. Bus 16 is added here to host a utility scale PV farm. The PV farm is connected to one of the system central buses, bus 7, through a 100 km transmission line located in area 1. Aggregation of collector system can be done by the National Renewable Energy Laboratory equivalency method [17]. Entire capacity of the PV plant is 202.5 MW and it means that the PV plant penetration is adopted to provide 20% of the system installed capacity. In this study the time frame of analysis (oscillation) is restricted to a few seconds. It is accordingly reasonable to assume that the sunlight remains constant during this period and the PV plant output power is also constant.

The power system under study has five distinct oscillatory modes: three local modes and two inter-area modes which have been obtained by the Eigen value analysis. The inter-area mode 1 is characterized by having a slightly higher frequency (0.78 Hz) than mode 2 (0.46 Hz). Mode 1 consists of generators of area 1 swinging against those of area 3. While, mode 2 consists of generators of area 2 oscillating against those of areas 1 and 3 [5]. As a result in order to mitigate the unstable oscillation modes, two QPSO-based WADC is designed and added to the main control loop of the PV farm.

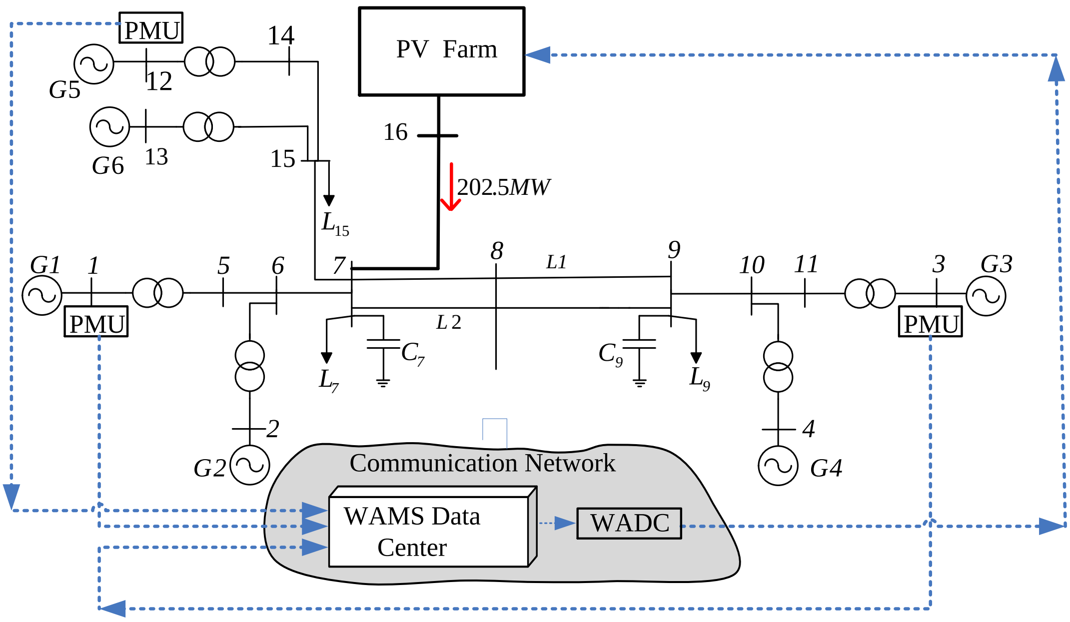

Figure 3. Three-area six-machine power system aggregated with a PV farm

To evaluate the effects of time delay, an ideally designed WADC is examined in this study where the feedback signal has various levels of time delay. As shown in Figure 4, the total latency is the summation of a constant value plus a random number, say 300 ±rand(100)ms where the time delay variable is applied randomly.

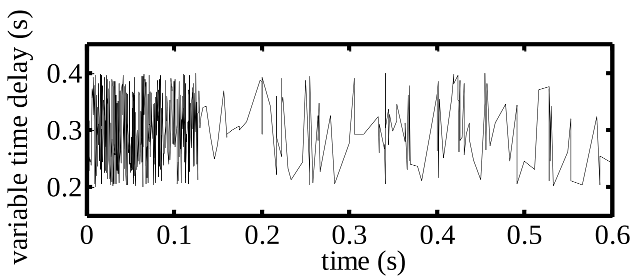

Figure 4. Random time delay of the remote feedback signal

300 ± rand (100) ms latencies in remote feedback signals are considered here in order to design the delay-compensated WADC. It should be noted that for WADC parameter optimization, the number of particles are set to 30, the particle size is set as 5, number of iteration is 40 and β is set to 1.4. The final values of the WADC parameters obtained through the proposed optimization process are presented in Table 1 and 2. Figure 5 shows dynamic response of power system following a fault at bus 8

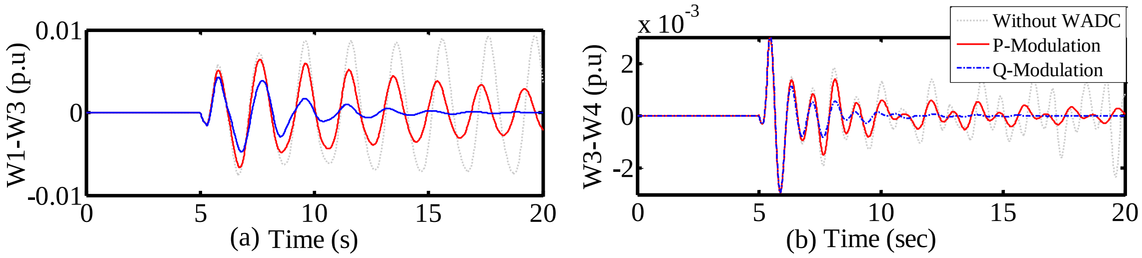

Figure 5. Dynamic response of power system following a fault at bus 8: (a) rotor speed difference of G1 and G3, (b) rotor speed difference of G3 and G4.

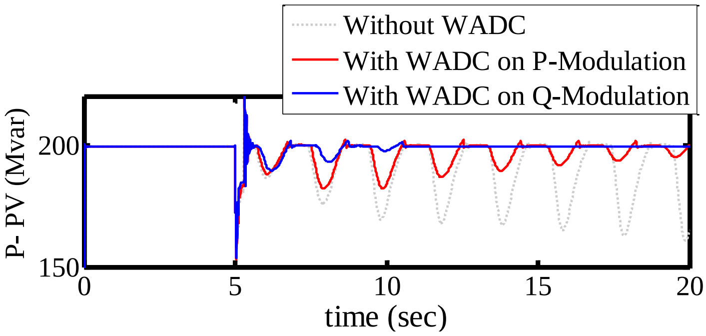

Figure 6. Dynamic response of PV plant active power following the fault at bus 8

Table 1. Parameters of Latency-Compensated QPSO-Based WADCs for P loop

Type	*K*	T_W	T_1	T_2	T_3	T_4	min & max
WADC1	40	2	1.887	2	0.034	1.087	±0.15
WADC2	40	2	2	0.589	0.008	1.468	±0.15

Table 2. Parameters of Latency-Compensated QPSO-Based WADCs for Q loop

Type	*K*	T_W	T_1	T_2	T_3	T_4	min & max
WADC1	40	2	0.154	0.001	2	0.001	±0.15
WADC2	40	2	1.548	0.048	1.65	0.008	±0.15

To simulate a disturbance on the system, a self-cleared three phase fault with duration of 0.3 second is applied at t = 5 s near bus 8 to confirm the control operation of PV farm based WADC.To show the superior performance of the proposed WADC, simulations are repeated in four scenarios. In the first scenario there is no damping controller on the PV plant control loop, in the second case the WADC is added to active control loop of PV plant. In the third case, the WADC is applied to reactive power control loop of PV plant and finally both active and reactive power control loops are enhanced with WADCs. Figure 5 displays the dynamic reaction of the system with the disturbance. It is obvious that in the case without WADC there are unstable inter-area and local oscillations between power system areas, which is obviously displayed by the rotor speed difference of G1 and G3 and G3 and G4 (shown in Figure 5a-b). In contrast when the designed WADCs is added to the main control loop of PV farm, all sorts of oscillations are well damped and the PV farm equipped with WADC can easily mitigate the inter-area oscillations with stochastic latency on remote feedback signals (shown in Figure 5a-b). In addition, from these figures it can be noted that reactive power modulation can effectively enhance the damping of the oscillations but the operation of WADC on active power control loop prepares very little damping in comparison with implementation of WADC on reactive power control loop. These figures approves that designed WADCs display a good robustness against the time delay unpredictability and this feature of proposed WADC could be of interest for real-world applications.

In Figure 6, the active poweroutput of the PV plant is shown. It can be seen on Figure 6 that the proposed PV plant equipped with WADC can stabilize the system even with 300 ± rand (100) ms latency on remote feedback signals and the designed WADC can easilydamp system oscillations. Alsowith considering 300 ± rand (100) ms latency on feedback signals, the designed WADC displays a good robustness against the time delayunpredictability and this feature of proposed WADC could be of interest for real-world applications.

5. ROBUSTNESSVALIDATION

In section 4 it was shown that the designed QPSO based WADC displays a good robustness against the time delay unpredictability. But other important subject in designing wide area damping controllers is robustness of proposed controller against changes on power system operation point. In this section this feature of proposed WADC would be investigated. Robustness of the proposed WADC is validated for a range of operating conditions i. e. PV farm generated power changing and power system reconfiguration. However due to space restriction, only a few representative case studies are reported here. The robustness analysis is carried out to find out the capability of the proposed controller in tolerating the unfavorable conditions as well as the accuracy of its performance. It would be beneficial for the damping controller to keep its performance balanced even in harsh conditions.

Two different cases are examined to evaluate designed controller performance in oscillation mitigation. The cases considered here are as follows:

a. robustness against increasing the fault clearing time and system reconfiguration
b. robustness against changing PV farm output power

In the subsequent sections, simulation results are obtained for each situation individually and a complete discussion is presented.

5.1. Robustness against Increasing Fault Clearing Time and Power System Reconfiguration

The effect of the system configuration on the success of the proposed supplemental control in mitigating oscillations is investigated at a different system topology. In this section in order to change the system configuration, the fault duration is increased to 0.4 sec near bus 8. It is also assumed that this fault will be cleared by the operation of distance relays. As a result after the occurrence of the fault, distance relays of the line between buses 7 and bus 8 respond to the fault with tripping this line. As a result of this action, the line between bus 7 and 8 is switched off from the system and the system topology will be changed. Simulation results of the rotor speed difference of G1 and G3, and the power flow in the tie-line 7–9, during and after clearing the fault, with and without supplemental control are shown in Figure 7(a-b) respectively. It can be seen from the simulation results that in such situation the system will be faced with very severe fluctuations but the supplemental control is also capable of damping all sorts of oscillations resulting from such a disturbance with the new system configuration.

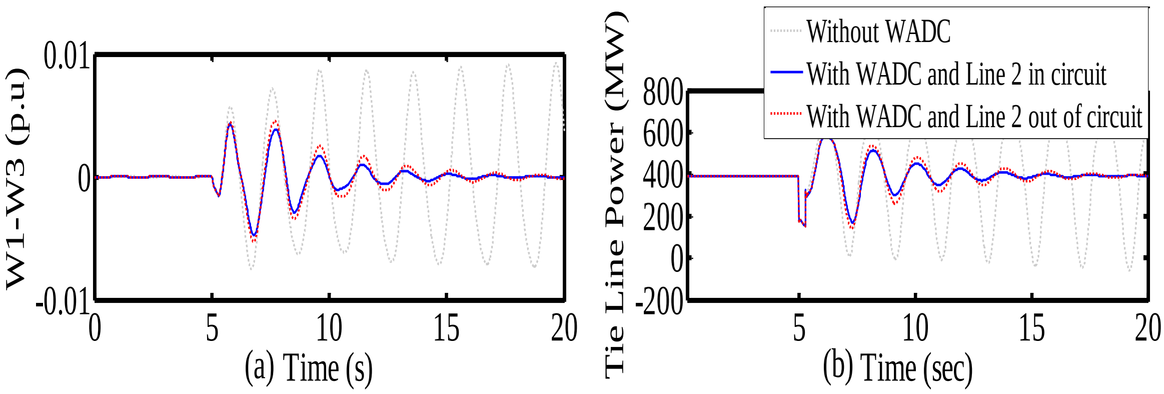

Figure 7. Dynamic response of power system following a fault at the line between bus 7 and 8 when the power system configuration is changed: (a) rotor speed difference of G1 and G3, (b) the power flow in the tie-line 7–9.

5.2. Robustness against Decreasing of PV Farm Generated Power

To evaluate the robustness of the proposed WADC when the PV plant active power delivered to the system varies to a lower value, simulation results are carried out in lower values for PV plant output active power. For this case the PV plant active power is set to 120 MW and again the contingency occurs at t = 15sec near bus 8. Figure 8(a) and (b) shows the generator rotor speed deviations between G1 and G3 and the power flow in the tie-line 7–9, during and after clearing fault, with and without supplemental control. As observed in these figures, the proposed structure successfully damps out the oscillations when the PV farm active power varies to lower values.

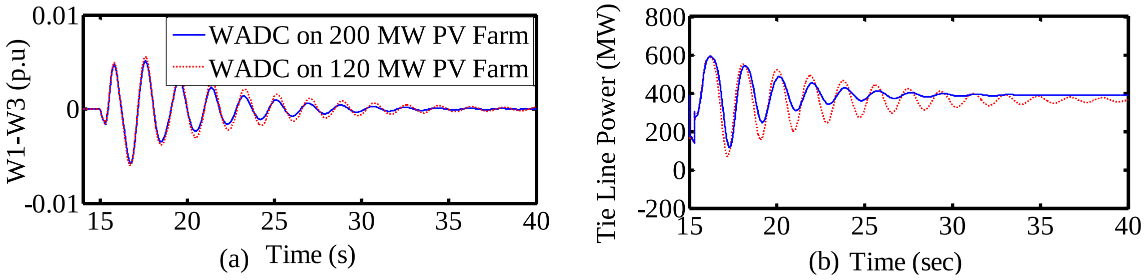

Figure 8. Results of proposed WADC in oscillations attenuation when the PV farm active power is changed: (a) rotor speed difference of G1 and G3, (b) the power flow in the tie-line 7–9

6. CONCLUSION

In this paper, oscillation damping is realized not by additional FACTS controller but by adjusting the active and reactive power of a PV plant own converter with two conventional double channel WADC. The PV plant auxiliary damping controllers used the different areas' generator rotor speed variations as a feedback signal to produce the auxiliary damping signal and the active and reactive power regulation of the PVs was utilized for inter-area fluctuation damping. The rotor speed deviations for damping controller were obtained through wide-area information thanks to the utilization of PMUs dispersed over the network. The QPSO method was used for best tuning of the controller parameters and possible signal delay of feedback signals on WAMS was considered in the controller design process. It was properly shown that the designed WADC operates suitably and displays excellent robustness against the transmission time delay uncertainties. Simulation results demonstrated that the PV plant with WADC on reactive power control loop offers better damping of the oscillations than the one associated with the active power control loop. This feature arises due to the stronger effect of PV's reactive power on the power system buses voltage by injecting or absorbing reactive power into the buses. Hence, it would be so fruitful to make use of PV's reactive power control loop as the controller of the fast response oscillations.

This study demonstrated that the idea of having a PV plant with supplementary controller on reactive power control loop would be more beneficial in attenuating inter area oscillations as well as enhancing power system stability. Also simulation results with robustness analysis revealed that the performance of the proposed latency-compensated WADC is very robust against changing the PV plant active power or the power system working point. With the rapidly increasing application of utility-scale PV plants and PMUs, designing WAMS based supplementary control for PV plants for power systems dynamic enhancement is necessary and needs many research activities. In this subject area, the most important issue is the coordinated design of PVs and other renewable power generation systems like wind farms with the use of WAMS technology and considering the time-varying communication system delays. These subjects are open future research themes in the scope of renewable energy systems and smart transmission grids.

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