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A Novel Combined Reactive Power-based Frequency and Power Oscillation Damping Control by PV-STATCOMs

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SUMMARY

In this paper, a new control is proposed for large scale PV plants to enhance both damping of power oscillations and frequency stability using their unutilized capacity. PV inverters are able to provide frequency support services if they keep power reserve by power curtailment. However, power curtailment brings revenue losses to generator owners. Furthermore, no real power is available during night.

Voltage-based frequency control is a technique in which load power is controlled through its voltage to help recover generation-demand balance during frequency deviations. Load voltage can be controlled via Automatic voltage Regulator (AVR) of synchronous generators or Flexible AC Transmission System (FACTS). It has been shown that PV inverters are able to perform reactive power/voltage control using the unutilized inverter capacity, similar to STATCOMs. PV inverters operating in this mode of operation are named PV-STATCOMs. In this paper, a Reactive power-based Frequency Control (RFC) is implemented in PV-STATCOM to augment frequency stability. Large disturbances that cause frequency deviations, *e.g.* generator trips, usually stimulate system oscillatory modes in poorly damped systems. PV-STATCOMs are also able to effectively stabilize low frequency power oscillations. Hence, in addition to RFC, a Power Oscillation Damping (POD) controller is added to reactive power/voltage control loop of PV-STATCOM to enhance system damping.

The proposed combined controller, POD+RFC, is designed and implemented on a PV plant connected to 12-bus study system. Dynamic models developed by Western Electricity Coordinating Council (WECC) are used for both PV plant and loads. The simulation results reveal that while enhancing system damping, the proposed RFC+POD control can improve the system frequency stability, on a 24/7 basis. Such grid support functionality from PV solar farms can significantly complement that from presently used devices in power systems at significantly lower cost and also without any need for power curtailment.

"**KEYWORDS**".
PV systems, smart inverters, PV-STATCOM, Frequency stability, Power oscillation damping, FACTS

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1.0 INTRODUCTION

Concerns about frequency stability of power systems have increased as conventional synchronous generators are being replaced by inverter-based power plants, like wind or solar generators. Frequency stability is the ability of a power system to maintain steady frequency after a large system disturbance which causes significant generation-demand imbalance. Frequency stability depends on the system's ability to retain the balance between generation and demand, with minimum unintentional load shedding [1]. Inverter-based generators typically operate in Maximum Power Point Tracking (MPPT) mode, and do not respond to frequency variations [2].

Some of recently developed grid codes, like IEEE 1547-2018 [3], mandate inverter-based plants to integrate a power-frequency droop function into their controls to support system frequency like conventional plants. This service, however, requires real power reserve, which is obtained by power curtailment or deployment of energy storage systems which may be cost-prohibitive. Power curtailment brings revenue losses to generator owners. Furthermore, energy storage systems need extra infrastructure and maintenance. Demand response is another alternative to help power system to maintain frequency stability after large disturbances. The participating loads are appropriately connected/disconnected to the grid to ensure the generation-demand balance. However, a well-designed demand response scheme needs elaborate communication and control infrastructures. [4].

Conservative Voltage Reduction (CRV), as a subcategory of demand response, has been deployed in distribution grids to reduce load consumption for energy conservation, load peak reduction, and reduction of system losses [5, 6]. However, dynamic voltage control of voltage-sensitive loads for lowering the generation-demand imbalance during system upsets is only addressed recently [7]. In other words, the system voltage is dynamically changed to reduce generation-demand gap. Field tests carried out in Guadeloupe, France have demonstrated the efficacy of this technique [8]. This control can be implemented on Automatic Voltage Regulator (AVR) of synchronous plants [9], or FACTS devices e.g., SVCs [10].

It has been demonstrated that PV inverters can operate like STATCOMs, named and patented as PV-STATCOMs [11]-[13]. PV-STATCOMs have been successfully deployed for stabilizing the power oscillations. POD controller is added to either real and/or reactive power control loop of PV-STATCOMs to increase system damping [12]. Furthermore, PV-STATCOM application for provision of reactive power-based frequency control during day and night is proposed in [13]. To achieve this goal, RFC controller is added to the voltage control loop of PV plant to properly modulate the voltage, within the permissible range, for reducing frequency deviations. RFC can provide a complementary frequency support service with the least costs.

To use the capacity of PV-STATCOMs more efficiently, both RFC and POD controllers are implemented on the PV-STATCOM control in this paper. The proposed control is especially useful in lightly damped power systems where large disturbances, *e.g.* generator trips, cause both power oscillations and frequency deviations. This service is provided on a 24/7 basis as it is not dependent on real power. Modern PV inverters are oversized to comply with requirements of recent grid codes [3], so substantial amount of reactive power capacity is always available even during nominal operating conditions. The simulation results show that POD+RFC controller brings significant benefits to the system with no need for new assets, PV power curtailment, or communication systems.

The simulation studies are conducted in Matlab/Simulink on the 12-bus test system. As voltage sensitivity of loads plays an important role in the effectiveness of RFC [13], the

Composite Load Models (CLM) developed and validated by WECC is used in the simulations [14]. The PV system is also represented by WECC generic dynamic models [15].

The rest of the paper is organized as follows: in Section 2 the study system and models are introduced. In Section 3, the proposed POD+RFC controller is elaborated. Simulation results are reported in Section 4.

2.0 Study System

Figure 1(a) shows the generic 12 bus system which is used in this paper for simulation studies [16]. A 111 MVA (100MWp) PV solar system is connected to bus 3 of the system. The PV plant is modelled using WECC generic dynamic models, which have been developed for study of power system stability. The PV plant model is developed in Matlab/Simulink as per WECC guidelines [15].

Load model also greatly affects the accuracy of the stability studies. The effectiveness of RFC is highly dependent on system load types, *e.g.* residential or industrial loads, as well as the reaction of dynamic loads like induction motors [13]. WECC Comprehensive Load Model (CLM) is an comprehensive and reliable representation of system loads for stability studies [14]. Figure 1(b) demonstrates the components of the CLM. The model consists of three induction motors A to C (MA-MC), motor D (MD), which represent single-phase air-conditioners, an electronic load (ME), a static load, and distribution network equivalent [14]. Table I shows the type and compositions of loads L1-L6 in 12-bus study system [17]. The load data corresponds to a normal summer day in Northwest Coast climate zone of WECC at 3:00 pm. L1 and L4, represent a steel mill and petrochemical plant, respectively.

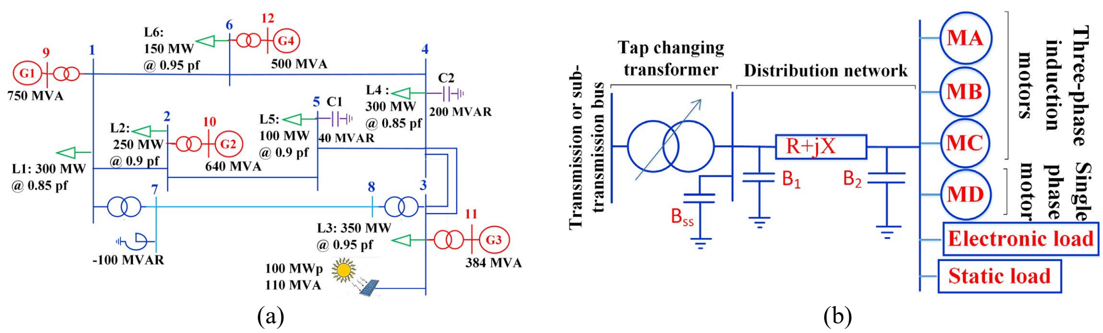

Figure 1: (a) 12-bus study system **(b)** WECC Comprehensive Load Model (CLM)

TABLE I: CLM COMPOSITIONS IN THE 12-BUS SYSTEM(ADOPTED FROM [17]

Load	P (MW)	Q (MVar)	Load type	MA%	MB%	MC%	MD%	ME%
L1	300	186	Industrial	20	25	30	0	20
L2	250	121	Residential	10	7	7	44	14
L3	350	115	Commercial	30	9	8	12	20
L4	300	186	Industrial	15	25	40	0	15
L5	100	48	Mixed	18	9	6	31	17
L6	150	49	Agricultural	10	7	17	23	17

3.0 Proposed combined RFC and POD controller

The proposed controller is composed of two controllers with different bandwidth, as shown in Figure 2. The output signal of the controller, ΔV_{PV}, is limited to ±10% of the PV plant nominal voltage and superimposed on the reference value of the PV plant POI voltage, V_{PV}.

The POD controller is meant to enhance the stability of electromechanical oscillatory modes. The 12-bus study system has three electromechanical oscillatory modes with high participation of generators speed, as reported in Table II. It is noted that unlike FACTS whose location is determined based on their controllability over the oscillatory modes of interest, the location of PV plants is mainly chosen based on an economic analysis. Thus, PV-STATCOM location is not necessarily the best location for stabilizing the oscillatory modes. However, linear analysis shows that in the study system, PV plant located at bus 3 has acceptable controllability on modes 2 and 3 in Table II. As shown in Figure 2, the POD controller consists of two branches for modes 2 and 3. The observability analysis shows that the both modes 2 and 3 are highly observable in the power of line 8-7, $P_{8\text{-}7}$, so this signal is chosen as the input of the POD controller. Band-pass filters are used to only pass oscillations of interest. The central frequencies are 1.1678 Hz and 1 Hz, according to Table II. The phase compensators ($T1$, $T2$, α_1, α_2) and gains (K_{POD1} and K_{POD2}) are designed through eigenvalue analysis to achieve highest damping for all the oscillatory modes [18]. It is noteworthy that the oscillatory modes are located very closely to each other and the design procedure is challenging since for higher gains the modes start interacting. Accordingly, the gains and achievable damping is limited.

Similarly, RFC controller modulates the PV plant POI voltage to reduce the generation-demand imbalance by controlling the load power of voltage-sensitive loads. This objective is equivalent to enhancing the damping of the system "*frequency regulation mode*", which is a very low frequency common mode with high participation factor of all generator speeds and in phase modes shapes [19]. As demonstrated in Figure 2, RFC controller is very similar to POD controller. Frequency of bus 3 is chosen as feedback signal since frequency regulation mode has high observability in this signal. The central frequency of the band pass filter is set to 0.18 Hz, *i.e.* the frequency of frequency regulation mode shown in Table 2. The phase compensator parameters and the gains are calculated similar to POD controller tuning.

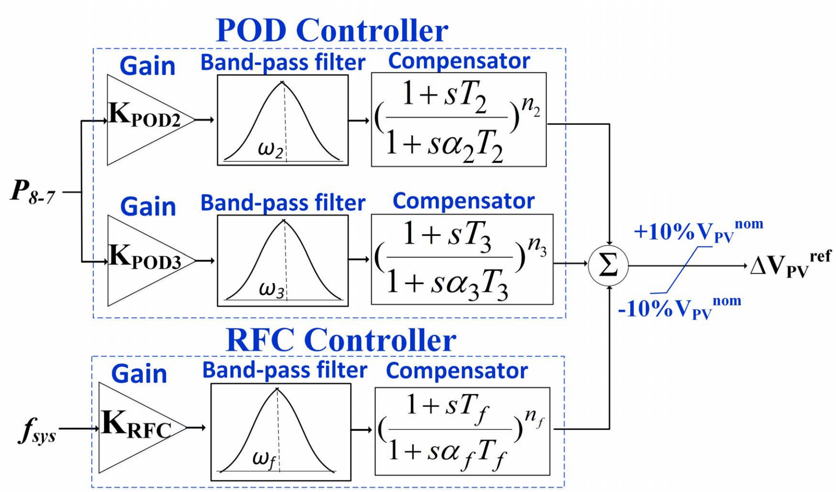

Figure 2: The proposed combined RFC and POD controller

Table 2: Modes of the 12-bus study system

Mode	Frequency (Hz)	Damping (%)	Mode nature	Participant generators
1	1.1962	5	Electro-mechanical	G1, G2, G3
2	1.1687	3.67	Electro-mechanical	G3,G4
3	1	5.32	Electro-mechanical	G2, G3,G4
4	0.1833	49.52	Frequency regulation	G1,G2,G3,G4

4.0 Simulation results

The performance of the proposed POD+RFC controller is studied during day and night. Figure 3 depicts real/reactive power capacity of the PV-STATCOM in the study system.

During night, the entire capacity of the PV plant, *i.e.* 111 MVA, is unutilized and used by the controller. During day, however, the available reactive power capacity depends on real power generation. The minimum reactive power capacity, *i.e.* 48 MVar, corresponds to nominal operating point when 100 MW solar power is generated during noon.

A frequency drop event is initiated by connecting a 100 MW load to bus 2 at t=2 s. This disturbance also excites the system oscillatory modes. Four different control cases are simulated: 1) No control; 2) Only RFC; 3) Only POD; 4) Combination of RFC and POD (POD+RFC). The controller parameters are the same for both day and night studies.

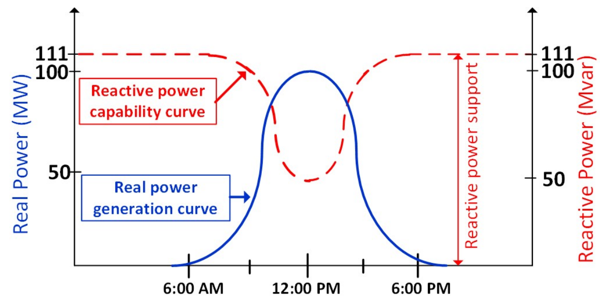

Figure 3: Real/reactive power capacity of the PV plant over the course of a day

4.1 Night time operation

Figure 4 shows the simulation results for night time operation. Figure 4 (a)-(d) show the average frequency of the system (*Hz*), power flow in line 8-7 (MW), PV plant POI voltage (pu), and PV inverters reactive power (MVar), respectively. PV plant real power is zero and hence not shown here.

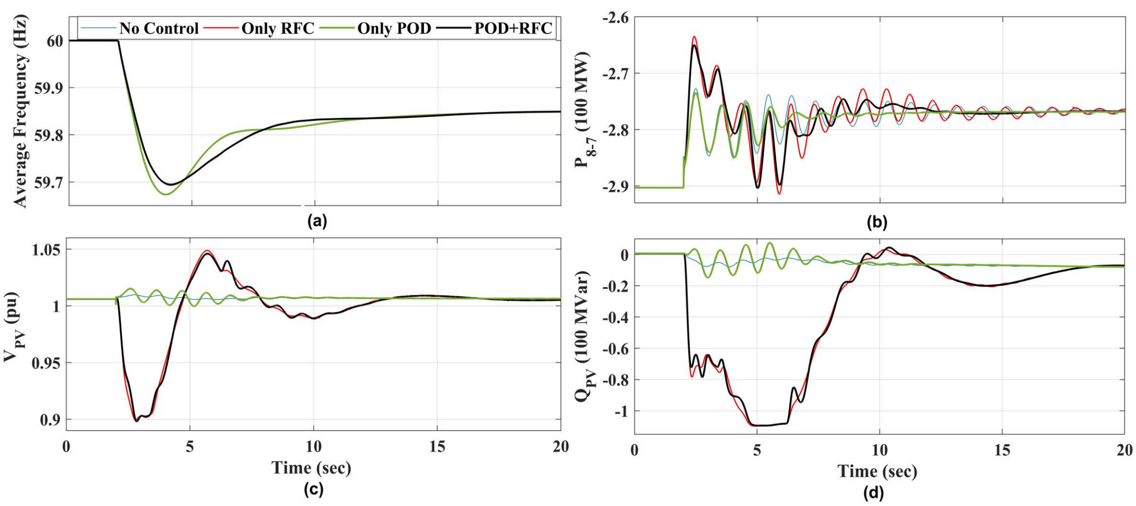

Figure 4: Night time operation **(a)** system average frequency **(b)** power flow of line 8-7 **(c)** PV plant POI voltage **(d)** PV plant reactive power

Figure 4(a) shows that the frequency nadir is alleviated by 30 mHz, from 59.670 Hz to 59.70 Hz, in only RFC and POD+RFC cases (the curves are overlaid). Only POD controller has no improving impact on the system average frequency and frequency deviation is similar to the No control case. However, in Figure 4(b) it is shown that line power oscillations are effectively stabilized in less than 5 s when only POD controller is implemented. Before the disturbance, 290 MW power is injected at bus 8 as shown in Figure 4(b) (notice the negative sign of power). With RFC controller, immediately after disturbance the injected power drops to 263 MW (27 MW power drop) whereas in no control case it only reaches 273 MW. In fact, with RFC controller, load consumption at bus 3 is partially reduced since RFC reduces the voltage of bus 3. In Figure 4(b) it is shown that RFC performance results in occurrence of a very low frequency oscillation in the line power flow. In fact, RFC controller modulates the system voltage with frequency of the frequency regulation mode, *i.e.* around 0.18 Hz. When RFC and POD controllers work together, power oscillations are damped in a longer time, around 8 s, compared to the only POD case mainly because majority of the reactive power capacity is deployed for RFC.

Figure 4(c) shows the PV plant POI voltage in different study cases. In no control case, PV plant voltage controller regulates the PV plant voltage. When RFC controller is activated, the PV plant voltage is modulated properly to enhance the damping of the frequency regulation mode. The voltage deviation remains within ±10% range (voltage reaches 0.9 pu), which is permissible transient voltage range in some systems like Ontario [20]. When only POD controller is implemented, the POI voltage is modulated with frequency of electromechanical modes. With both POD and RFC controllers implemented, the modulating signals are superimposed on the POI voltage. Figure 4(d) illustrates the utilized reactive power capacity of the PV-inverters. In no control case, reactive power changes slightly, for voltage regulation. In contrast, with RFC controller the entire capacity of the PV plant, *i.e.* 110 MVar, is used in the time interval 4.8-6.2 s. With only POD controller, reactive power is modulated in the range of ±10 MVar. The reactive power responses of controllers are added in POD+RFC case. When reactive power limit is reached because of RFC controller operation, there is no room for POD controller to modulate the reactive power/voltage so POD+RFC performs like Only RFC case. The unwanted deactivation of POD controller is avoided by lowering the RFC controller gain, but the effectiveness of RFC is reduced. In summary, this study shows that the unused capacity of PV-STATCOMs during night can be effectively deployed to enhance frequency stability and power oscillations damping, simultaneously.

4.1 Noon time operation (Maximum real power generation)

During day the priority is given to real power generation and reactive power capacity is limited as shown in Figure 3. In this section, the PV plant is generating nominal power of 100 MW so 48 Mvar of capacity is remaining for reactive power control by RFC and POD controllers. The system demand is the same as nighttime operation and extra 100 MW PV generation is compensated by reducing the power generation of G3. Thus, the injected real power to bus 3 is kept at 270 MW like night operation [16]. Figure 5 demonstrates the simulation results. The variables shown are correspondingly similar to those of Figure 4. PV real power is 100 MW and does not change during simulations and hence not shown here. Figure 5(a) shows that RFC improves frequency nadir by 20 mHz, compared to 30 mHz in night time operation. The lower effectiveness of RFC is attributed to availability of smaller reactive power capacity compared to night. The POD controller has no improving impact on system frequency whereas it is shown in Figure 5(b) that POD controller effectively stabilizes the power oscillations in line 7-8. In only RFC case, the injected power to bus 8 drops from 290 MW to 270 MW immediately after power imbalance occurrence while in no control case the injected power reaches 275 MW. The difference of 5 MW is explained by the performance of RFC, which reduces the load at bus 3. This demand reduction is lower than nighttime operation, *i.e.* 10 MW, mainly due to limited reactive power capacity which restricts the effectiveness of RFC.

Figure 5(c) depicts that POI voltage is regulated at pre-disturbance value in no control case. With only POD controller, the voltage is modulated to damp electromechanical modes. With RFC, the magnitude of voltage reaches 0.94 pu to reduce the load consumption in the system. With both controllers added, the voltage is reduced for frequency control and also modulated for power oscillation damping. Figure 5(d) clearly shows that PV plant reactive

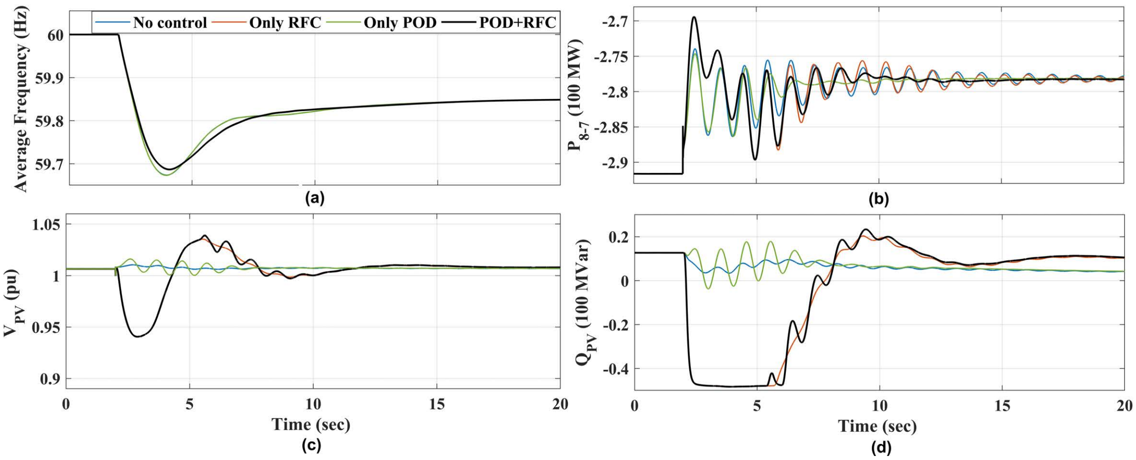

Figure 5: Noon time operation **(a)** system average frequency **(b)** power flow of line 7-8 **(c)** PV plant POI voltage (d) PV plant reactive power

power capacity is almost half of that at night, 48 MVar vs 110MVar, which reduces the effectiveness of RFC. Overall, this study shows that despite the lower available reactive power capacity during daytime operation, the proposed POD+RFC controller can augment both frequency stability and system damping.

5.0 Conclusion

This paper proposes an innovative control for simultaneous enhancement of frequency stability and system damping using unutilised capacity of PV-STATCOMs. The proposed control consists of two controllers: i) Reactive power-based Frequency Controller (RFC), which enhances the stability of the system frequency regulation mode; and ii) Power Oscillation Damping (POD) controller which acts on the system electromechanical oscillatory modes. Both controls deploy PV inverters for reactive power/voltage modulation during day and night. Simulation results demonstrate the efficacy of the proposed combined controller and the following conclusions are made:

1) While RFC is less effective than real-power based frequency control, it reduces system frequency deviations with no real power reserve or new generators. RFC performance is however restricted by system voltage limits and PV-STATCOM reactive power capacity.

2) The location of PV plants may not be necessarily optimal for POD controller. Nonetheless, a PV-STATCOM is able to enhance the damping of some of the system oscillatory modes like STATCOMs.

3) When POD and RFC controllers operate together, the reactive power responses of both controllers are superimposed. RFC controller utilizes a larger share of reactive power. If the inverter capacity limit is reached, voltage modulation by POD controller cannot be performed and POD is deactivated temporarily. However, the overall performance of the POD+RFC significantly enhances system stability.

The proposed POD+RFC controller is a new opportunity for PV system owners to receive revenues from grid operators for provision of this frequency stabilization and power oscillation damping service on a 24/7 basis. No new infrastructure or power curtailment is required for the service.

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