

Dynamic Stability Enhancing Control Strategy for Power Oscillation Damping in Power Systems with High-Level PV Penetration

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Abstract— The deregulated power system has paved the way for a significant number of distributed energy resources (DER). This results in a large installation of renewable sources in the grid. Thus large installations of PV systems are becoming more common. These Centralized PV systems can cause major issues in the existing grid if these are not adequately addressed. The significant contribution of these systems can cause problems with the dynamic stability of the power system. The intermittent and inertia-less nature of PV systems can produce significant power oscillations. At the present condition, the penetration level of PV into the grid is limited by the utilities, to prevent problems of power oscillation. Thus the PV plant capacity cannot be increased beyond the penetration limit. The penetration limit depends on several factors such as the types of loads, stability enhancement devices on the grid. The penetration limit regulated cyclically. This paper proposes a control strategy for power oscillation damping in power systems implemented in Grid-connected converters (GCC) so that the power system stability is enhanced without any additional cost of equipment. This, in turn, helps to provide a penetration margin and thereby to increase the PV capacity of the grid.

Keywords— Distributed generation (DG), Grid connected converter (GCC), PV penetration, Power oscillation damping (POD)

I. INTRODUCTION

The global energy demand is increasing every year, to meet the future demand more energy resources are required. The International Energy Agency (IEA) says the world's energy needs could be 50% higher in 2030 than they are today [1]. The security of global energy supplies continues to be problematic. Today, oil and gas reserves are in the hands of a small group of nations, several of which are considered political unstable or have testy relationships with large consuming countries [2]. As an effort to reduce carbon emissions, many of the nations are turning towards renewable sources of energy. With the development of fast-acting controllers & power electronics, it is possible to integrate renewable energy sources into the grid either at the transmission or distribution levels. In 2010, the total renewable energy capacity was only 5% of the total capacity, but as of now, we have about 18% of renewable capacity [1]. Among the renewable source of energy, the most prominent are the PV systems; the declining prices of solar panels coupled with government incentives have made solar PV systems much favorable among other sources of renewable energy. In 2010, among world's total installed power capacity, the contribution of PV systems was less than 5%. In the new policy scenario, power generated from PV systems is expected to be 600 GW as of 2035. The National Solar

Mission under the brand name "Sun powered India" set a driven focus of including 20 GW of Grid connected and 2 GW of Off-grid capacity by 2022. Moreover, now we have centralized PV plants of large capacities such as the 648 MW plant in Tamil Nadu & 12 MW in Kerala, resulting in a significant amount of PV penetration into the grid.

The existing grids were designed for systems with powerhouses at one end & the load at the other. The integration of several renewables has caused several detrimental effects on the grid. Besides the power quality & protection issues, one of biggest concern is the system stability. The PV-DG systems are inertia-less systems, integration of such systems into the grid can result in reduced system inertia and thereby affecting the transient system stability. Several studies [3-6] has concluded that the system stability is compromised during high PV penetration. During high PV penetration, a large number of loads is met by the PV system; extreme weather variations can cause power oscillations due to intermittent and inertia- less nature of the PV system. To overcome this issue of transient stability most of the utilities have come up with regulations limiting the amount of PV penetration to their respective grids. As a result, the PV capacities cannot be expanded without violating the penetration limits. However, the penetration limit is dependent on the strength of the grid.

Low-frequency power oscillations have been a major concern for power systems since it was first reported in 1920's [7]. Conventional power system stabilizers associated with generating stations continue to maintain the dynamic stability of power systems. FACTS based technologies such as SSSC and STATCOM can also be used to provide power oscillation damping (POD) and hence improve the dynamic stability [8]. In the case of high PV penetration, one primary concern is to maintain stability and prevent the system from falling out of step to separate islands. The inertia-less nature of the PV system can cause prolonged power oscillations, and this could cause a complete blackout, which is undesirable [3]. Several studies [4-5] show that the increasing the penetration limit could induce negative damping. Some authors have concluded that a 20% PV penetration limit causes relatively large peak overshoot and sustained oscillation in load angle after a fault [5]. Some studies indicate problems with voltage

regulation, reverse power flow and protection issues [6], and stability enhancement using LVRT scheme is investigated in [9-10].

Existing literature suggest the use of FACTS devices such as STATCOM, SSSC or SVC for power oscillation damping to improve the dynamic stability of systems with high PV penetration. Most of the existing works are based on STATCOM. Superimposing a supplementary power oscillation damping controller on the automatic voltage control loop [11] of a STATCOM is a useful method of providing damping alongside the voltage controller; however, this approach assumes that the remote parameters for the controller are readily available. Fuzzy based controller for STATCOM [12] can also be used for power oscillation damping; however, this is not reliable, since network upgradation may require retuning the fuzzy parameters. Most of other literature use WAMS based technology [13-14] to provide power oscillation damping using STATCOM, this method uses PMU's & PDC's to obtain unknown parameters, such as the tie-line power, for the controller action. Issues such as time delay, data loss, disordering, and communication failure can affect the power oscillation damping & performance of the system when using WAMS technology because the transient period is in order of several seconds. State estimation is also used for determining the unknown state variables [15]. Others recommend the use of a separate STATCOM [12] or SSSC for power oscillation damping, the use of such dedicated power oscillation damping systems is highly reliable, but not economic, as the power oscillations on the system do not occur that often and the period of operation is minuscule. Schemes using remote parameters for power oscillation damping are not recommended due to their low reliability and vulnerability to noise [16].

This paper proposes a modified controller to provide power oscillation damping as an ancillary service by the PV-DG inverter. This method only uses the locally available parameter, i.e. the PV station voltage (PCC voltage). Thus the use of state estimation & WAMS technology can be avoided. A Grid connected converter (GCC), having two stage converters; i.e. a DC-DC Boost converter for MPPT operation and a two-level PWM VSI is used for converting the DC from PV to AC. The GCC is tied to the grid through an LC filter and a transformer. The PV penetration limit can be increased with the negligible cost of additional equipment for stability enhancement.

II. FACTS TECHNOLOGY & DYNAMIC STABILITY

FACTS technology has facilitated a drastic increase in power flow capability, transient stability, power oscillation damping and sub-synchronous resonance damping [8]. FACTS devices can be broadly classified as Shunt and Series compensators. Shunt Compensators such as SVC and STATCOM are connected in shunt with the system, and Series compensators such as SSSC are connected in series. These compensators are mostly used for voltage compensation. Most of the Power oscillation damping in a power system are done by STATCOM's and SSSC's due to their superior performance compared to SVC, TSC, etc.

SVC's are only switching devices where reactors or capacitors are switched according to the requirement of the system. However, the significant disadvantage of the SVC is that the amount of compensation depends on the system voltage. Only an exact amount of compensation can be applied, and variable compensation cannot be achieved using a SVC.

STATCOM's are VSI which is similar to the operation of a synchronous compensator, and hence the name. The STATCOM injects a voltage into the power system thereby providing voltage regulation. Power oscillation damping is provided by varying the voltage according to the power of the alternators during the transient period [16]. The voltage of the system is increased during the retardation of the alternator and voltage is decreased during the acceleration of the alternator's rotor, and hence power oscillation damping is provided. SSSC is a VSI connected in series with the system. The operation of a SSSC is similar to the STATCOM and provides power oscillation damping in the same method. STATCOM stands out as a superior device for power oscillation damping compared to SSSC, because the cost is high for a SSSC. STATCOM's require tie-line power flow as an observable signal for feedback. The operation of STATCOM with remote state variables is not recommended due to their low reliability and vulnerability to noise [16]. STATCOM's with locally available signal for feedback is also proposed [17]; however such dedicated equipment for power oscillation damping is relatively expensive for power oscillations which don't occur very often.

This paper proposes a modified controller for providing power oscillation damping using the GCC, rather than the utilization of a STATCOM. The PV-DG system provides power oscillation damping as an ancillary service, using locally available signal and requires no additional changes in the power circuit of the existing PV-DG system, and the active power control is not affected. Thus the cost of providing power oscillation damping is little, and the PV-DG utilization factor is improved.

III. SYSTEM DESCRIPTION

The PV-DG systems are available from ranges of 50kW and above. Usually, PV-DG systems consist of several strings of inverters combined to form a large PV system. These installations are integrated into the grid at distribution or transmission levels. Without any loss of generality these can be considered as a single large capacity PV-DG system or only a Centralized PV-DG system (CPV), and hence this is used to study the impact of PV penetration on system stability.

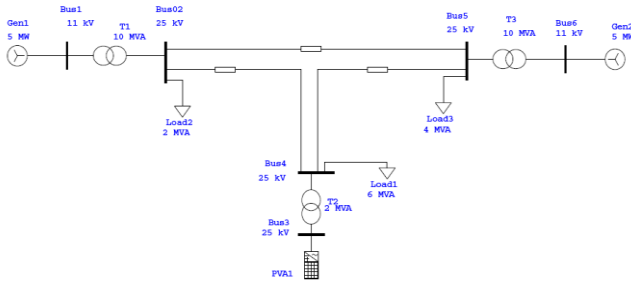


Fig.1 Two machine system with double transmission line, with large PV penetration, used for study.

The proposed system is a simple two machine system, each having a 5MW capacity; one is selected to be the swing bus and the other as the PV bus. The system also has a PQ bus, the PV-DG system is connected to the third bus, at the center of the second transmission line. The two machines are connected by a double transmission line as in figure (1). Similar systems are used for the study of system stability and protection coordination etc. [18]. The alternators are supported by their Load frequency control (LFC) and Automatic voltage regulator (AVR) with Power system stabilizers (PSS). The PV-DG system of 1MW capacity is used (20% penetration) and connected to the center of the transmission line. The inverter of PV-DG system is designed for 30% additional capacity. The excess capacity is meant for reactive power component [16].

In this paper, the alternator one is selected as the PV bus, providing constant voltage and real power; the alternator two is chosen as the swing bus, providing constant voltage and floating power control, so as to achieve power balance under steady state. The PV-DG system is typically designed to operate at unity power factor [16], but here reactive power is injected during the transient period. Also, it is assumed no other stability enhancement equipment is used.

IV. CONTROL DESIGN

A. POD control

Power system issues such as disturbances, protection coordination, relay settings, and power system stabilizer design, etc., can be investigated using energy function analysis [19]. Energy function analysis is an easy method to comment on the stability of the system, without the need for determining the solution of the system equations. Structure Preserving Energy Functions (SPEF) is a form of Energy function which has several advantages compared to standard energy functions [20]. The major advantage is the ability to modify the Energy function after the addition of a system element [20]. A considerable amount of work is available with SPEF for FACTS technology [21]. This paper proposes SPEF method to determine the control law for PV-DG system, to provide stability enhancement. The SPEF model of a system is given by,

$$V(\tilde{\omega}, \tilde{\phi}, \tilde{V}) = \frac{1}{2} \sum_{i=1}^m M_i \tilde{\omega}_i^2 - \sum_{i=1}^m P_{mi} (\tilde{\phi}_i - \tilde{\phi}_{i(s)}) + \sum_{i=1}^n P_i (\tilde{\phi}_i - \tilde{\phi}_{i(s)}) + \sum_{i=1}^n \int_{V_{i(s)}}^{V_i} \frac{Q_i(V_i)}{V_i} dV_i + \frac{1}{2} \sum_{1}^{line} Q_{series} \quad (1)$$

The SPEF is provided as a function of angular velocity ' ω ', phase angle ' ϕ ' and the voltage ' V ', and ' m ' is the number of PV buses and ' n ' is the number of PQ buses. ' Q_{series} ' is the reactive power in all the lines of the system. The subscript ' s ' is used to indicate the synchronous reference [19]. $Q_i(V_i)$ denotes the reactive power functions associated with various buses and reactive power controlling devices such as DVR, STATCOM, SSSC, etc. The SPEF equation is formulated in the Center of Angle (COA), and Center of Inertia (COI) references [20].

According to the Lyapunov's stability criteria, for the system to be stable, the SPEF function should be positive definite and the derivative with respect to time of the SPEF function should be negative. The stability criteria do not provide the necessary condition for stability; however, the sufficient condition for stability can be achieved. The derivative of equation (1) with respect to time yields the following

$$V'(\tilde{\omega}, \tilde{\phi}, \tilde{V}) = \sum_{i=1}^m M_i \tilde{\omega}_i' \tilde{\omega}_i - \sum_{i=1}^m P_{mi} \tilde{\phi}_i' + \sum_{i=1}^n P_{gi} \tilde{\phi}_i' + \sum_{i=1}^n P_i \tilde{\phi}_i' + \sum_{i=1}^n \frac{Q_i(V_i)}{V_i} + \frac{d}{dt} \int_{V_{i(s)}}^{V_i} \frac{-I_{Qg} V_g}{V_g} dV_g + \frac{d}{dt} \frac{1}{2} \sum_{1}^{line} Q_{series} \quad (2)$$

The above equation (2) can be modified for the system under study, where I_{Qg} is the PV station reactive power component [16]. The various terms in the equation (2) on the RHS, can be equated to zero, owing to the real and reactive power balances in the buses. The last term on the RHS of the equation can also be related to zero if the network is assumed to be lossless [19]. The only term remaining is the sixth term on the RHS. Using Lyapunov's stability criteria, i.e. $V(\tilde{\omega}, \tilde{\phi}, \tilde{V}) > 0$ and $V'(\tilde{\omega}, \tilde{\phi}, \tilde{V}) \leq 0$. The sufficient condition for effectively damping the electromechanical oscillations is that the time derivative of the total energy function must be negative. The energy released during a disturbance must decrease with time to ensure damping of power oscillations [16]. Hence the following can be derived from equation (2).

$$\frac{d}{dt} \int_{V_{i(s)}}^{V_i} \frac{-I_{Qg} V_g}{V_g} dV_g \leq 0 \quad (3)$$

The active damping of electromechanical oscillations can be achieved if equation (3) is incorporated into the control law as below,

$$I_{Qg} = K_g \frac{dV_g}{dt} \quad (4)$$

The term V_g is the PV station voltage in the Synchronously Rotating Reference Frame (SRRF). From the above equation (4), the electromechanical oscillations during a disturbance can be curbed by controlling the reactive current from the PV-DG system, as in a STATCOM. Since the locally available signal, V_g is used the process of state estimation and WAMS technology can be eliminated. The gain K_g can be tuned to obtain optimum performance.

B. GCC Control

A Grid connected converter (GCC) is used to interface between DC and AC in a PV-DG system. Here a two stage converter is used, i.e. DC-DC Boost converter for MPPT and 2 level PWM VSI for DC-AC conversion. The MPPT

algorithm is implemented in the boost converter to extract the maximum power available and ensure maximum available power flows into the DC link [22-23].

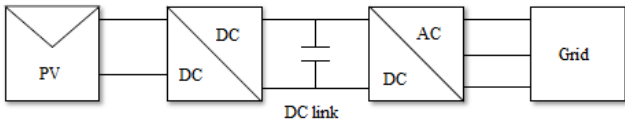


Fig.2 Two stage converter topology of a PV-DG system.

The GCC uses the vector control; this consists of a nested loop structure composed of a faster inner current loop and a slower outer loop. Because a conventional vector control has some limitations [24], we used the Direct current vector control (DCC) [25]. The DCC also has a similar structure of a typical vector control, shown in figure (4). The outer loop is used for dc-link voltage control. The dc-link voltage is regulated based on instantaneous power balance method of active power; the fundamental concept behind this theory is that the capacitor voltage depends on the energy balance of the power received by the VSI and the power delivered by it. If these two are equal, then the dc-link voltage will remain constant. If the power received by the VSI is greater than the power delivered by it, the extra energy will be put into the capacitance which in turn will elevate its voltage. On the other hand, if the power provided by the VSI is greater than the power received, then the additional power is supplied by the capacitor, results in the reduction of its voltage [25-26].

The inner loop is used for controlling the real and reactive powers [25]. The d-axis controller is used for real power control, and the q-axis controller is used for reactive power control or the grid voltage control. The decoupling term $\omega_s L$ prevents any adverse impact on oscillation damping control on the active power control [25]. Here ω_s is the angular frequency of PCC voltage.

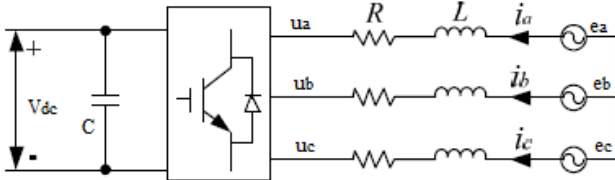


Fig.3 Structure of a Grid connected converter with L filter.

The real power injection does not interfere with the reactive power control; this is achieved by the decoupling terms between active and reactive power components of the currents in the VSI control [25]. Thus the performance of a vector control is improved. The mathematical model of a GCC is given by the equations (5, 6) as per figure (3).

$$e_d = u_d - L \frac{di_d}{dt} - Ri_d + \omega_s Li_q \quad (5)$$

$$e_q = u_q - L \frac{di_q}{dt} - Ri_q - \omega_s Li_d \quad (6)$$

The d-axis & q-axis reference are given by,

$$u_d^* = e_d - \omega_s Li_q + \dot{u}_d \quad (7)$$

$$u_q^* = e_q + \omega_s Li_d + \dot{u}_q \quad (8)$$

The term \dot{u}_d & \dot{u}_q in the equation (7, 8) are the controller outputs. The output energy and power factor can be controlled via changing d-axis current and q-axis current. Hence, using the DCC vector control, it is possible to regulate the real and reactive powers independently. The reactive power component of current injected by the PV-DG system into the grid is modulated by the control law, equation (4).

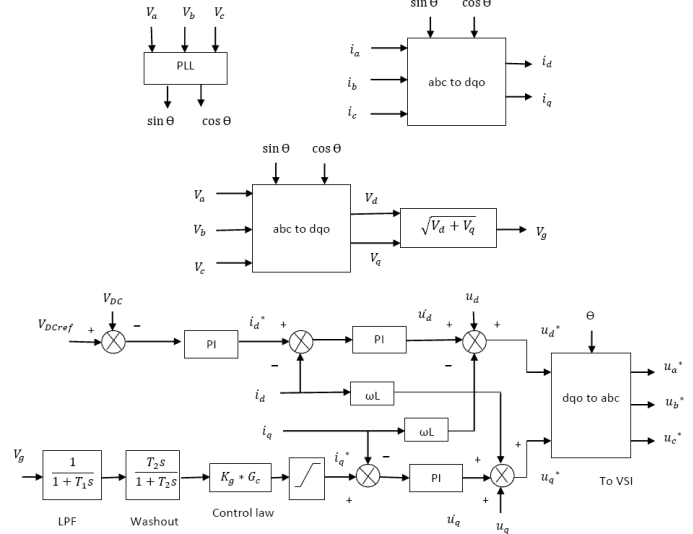


Fig.4 Proposed control strategy for enhancing the dynamic stability (POD) of a power system during high level penetration from a CPV system.

The modified DCC vector control of GCC is shown in figure (4), here a washout filter (High pass) prevents the controller from responding to the DC offset and steady state DC components of the voltage, whereas the Low pass filter (LPF) is used to eliminate noise in the PV station voltage signal. The control law is implemented, and a limiter is used to limit the amount of reactive power being injected into the grid. The various elements used for the GCC were designed according to [26-27]. The Perturb and Observe (P&O) algorithm is used for MPPT [22] using a Boost converter [23].

V. SIMULATIONS & RESULTS

The detailed model was developed and validated in the MATLAB-Simulink software. Two types of transients were simulated, i.e. the load switching's and faults, to trigger disturbances. The response of the system with and without the proposed controller for power oscillation damping is studied. Based on the type of transients, the study is classified into two cases.

A. Load switching at the PV bus

A load of several MW was switched on during the steady state of the system, i.e. t=6s, to trigger the disturbance and the corresponding change in load angle of the machine, voltage and reactive power on the grid, was studied with and without the proposed controller.

1) Without proposed controller

The load is switched at t=6s, and disturbance is introduced into the system. The typical PV-DG system is operating at unity power factor without reactive power injection. The

transient period lasts for few seconds until the system reaches a steady state.

2) With proposed controller

The control strategy is activated and dynamic stability enhanced. During the instance of switching at $t=6s$, the reactive power is injected into the grid. A voltage is injected into the grid to retard the motion of machine during acceleration and vice versa. The proposed controller has improved damping capability, the load angle of the machine is damped, and the peak overshoot of the load angle was reduced figure (5). The settling time is cut by a small fraction compared to the conventional controller. The active power is not affected during the transient period as per figure (6). The PV station voltage figure (7) shows oscillations corresponding to the disturbance; this verifies the use of PV station voltage (PCC) as the feedback signal.

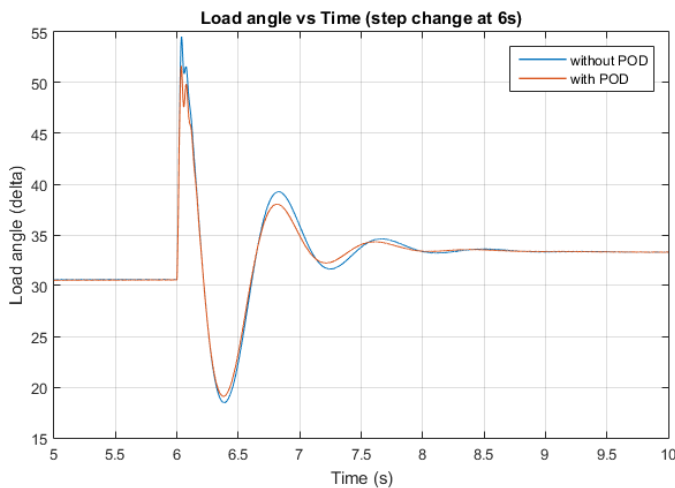


Fig.5 Load angle of the PV bus with and without the proposed POD

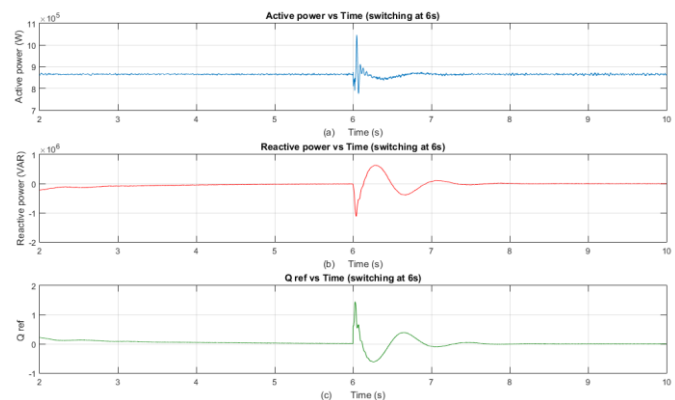


Fig 6. Simulation results of the system corresponding to a switching transient at $t=6s$, (a) active power (b) reactive power (c) reference to VSI (iq)

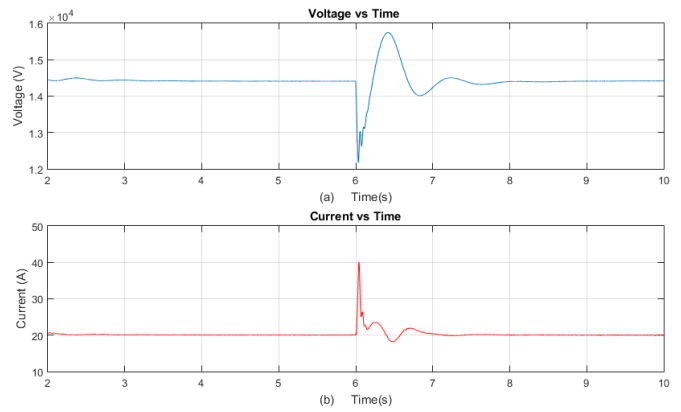


Fig 7. Simulation results of the system corresponding to a switching transient at $t=6s$, (a) voltage at PCC, (b) current at PCC

B. Symmetrical fault on the bus 4

In this case, a 3 phase fault is simulated from $t=4s$ to $t=4.1s$. The breaker action prevents the system from falling out of step, thus ensuring synchronism. This system is studied with and without the proposed controller.

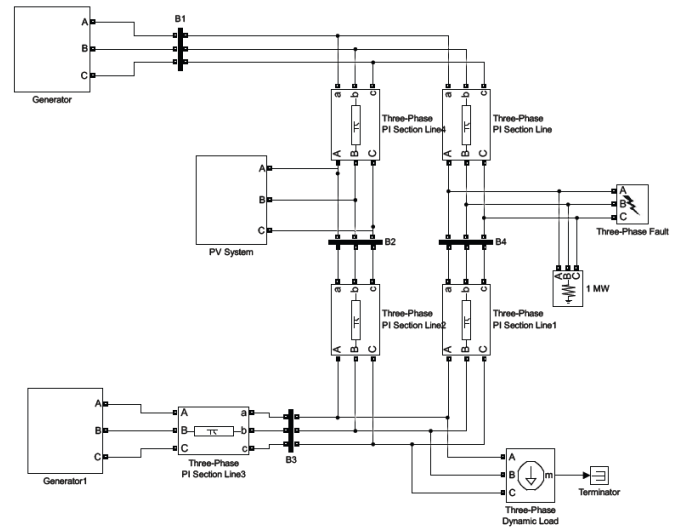


Fig.8 Simulink model of the system under study.

1) Without proposed controller

The power at the corresponding bus is examined figure (9). The power has higher peak overshoot as well as larger settling time.

2) With proposed controller

The proposed controller provides sufficient damping compared to the typical system. The power at the bus four is studied. The peak overshoot is reduced sufficiently and the settling time is much shorter in comparing. Thus the controller provides power oscillation damping similar to a STATCOM.

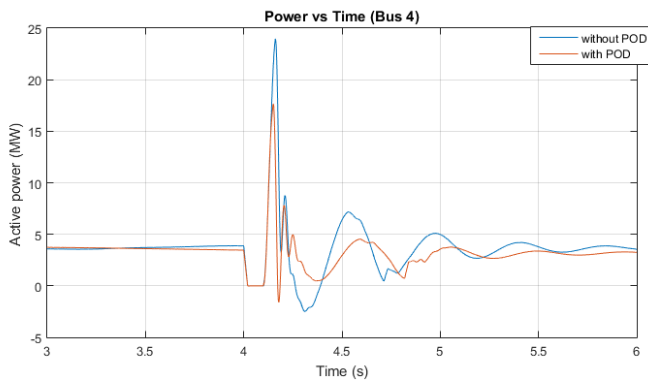


Fig 9. Power at the bus 4, during the fault period at $t=4s$ to $t=4.1s$. The system with POD and without POD is shown

From the simulation results, it is clear that the proposed controller for Centralized PV-DG systems provides Power oscillation damping, this then offers additional PV penetration margin, despite the inertia-less nature of the PV-DG system.

CONCLUSION

The future power system is considered to be highly deregulated. The deregulated system would lead to high-level PV penetration in the system causing problems with stability and inducing a penetration limit on the grid. The proposed controller can enhance the dynamic stability with PV-DG systems thereby producing additional margin for PV penetration, that too with little cost for stability enhancement. The proposed method can provide sufficient damping in weak grids. This approach requires no modification in the existing power circuit of PV-DG systems. The locally available signal used for feedback eliminates the requirement for state estimation and WAMS technology, thereby making the system more economical.

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