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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 and stability enhancement devices on the grid. The penetration limit is 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.**

***Index Terms*— Distributed Generation (DG); Grid connected Converter (GCC); PV penetration; Power Oscillation Damping.**

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 only5% 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

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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 than5%. In the new policy scenario, power generated from 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 648MWp plant in Tamil Nadu & 12 MWp in Kerala, resulting in 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-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 System can cause prolonged power oscillations, and this couldcause a complete blackout, which is undesirable [3]. Severalstudies [4] [5] show that the increasing the penetration limitcould induce negative damping. Some authors have concludedthat a 20% PV penetration limit causes relatively large peakovershoot 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 stabilityenhancement using LVRT scheme is investigated in [9] [10].

Existing literature suggest the use of FACTS devices suchas STATCOM, SSSC or SVC for power oscillation dampingto improve the dynamic stability of systems with highPV penetration. Most of the existing works are based onSTATCOM. Superimposing a supplementary power oscillationdamping controller on the automatic voltage control loop [11]of a STATCOM is a useful method of providing dampingalongside the voltage controller; however, this approach assumesthat the remote parameters for the controller are readilyavailable. Fuzzy based controller for STATCOM [12] can alsobe used for power oscillation damping; however, this is notreliable, since network up-gradation may require retuning thefuzzy parameters. Most of other literature use WAMS basedtechnology [13] [14] to provide power oscillation dampingusing STATCOM, this method uses PMU's & PDC's toobtain unknown parameters, such as the tie-line power, forthe controller action. Issues such as time delay, data loss,disordering, and communication failure can affect the poweroscillation damping & performance of the system when usingWAMS technology because the transient period is in order ofseveral seconds. State estimation is also used for determiningthe unknown state variables [15]. Others recommend the useof a separate STATCOM [12] or SSSC for power oscillationdamping, the use of such dedicated power oscillation dampingsystems is highly reliable, but not economic, as the power oscillationson the system do not occur that often and the periodof operation is minuscule. Schemes using remote parametersfor power oscillation damping are not recommended due totheir low reliability and vulnerability to noise [16].

This paper proposes a modified controller to provide poweroscillation damping as an ancillary service by the PV-DGinverter. This method only uses the locally available parameter,i.e. the PV station voltage or the Point of Common Coupling(PCC) voltage. Thus the use of state estimation &WAMS technologycan be avoided. A Grid connected converter (GCC),having two stage converters; .i.e. a DC-DC Boost converterfor MPPT operation and a two-level PWM VSI is used forconverting the DC from PV to AC. The GCC is tied to the gridthrough an LC filter and a transformer. The PV penetrationlimit can be increased with the negligible cost of additionalequipment for stability enhancement.

II. FACTS TECHNOLOGY & DYNAMIC STABILITY

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

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

STATCOMs are VSI which is similar to the operationof a synchronous compensator, and hence the name. TheSTATCOM injects a voltage into the power system therebyproviding voltage regulation. Power oscillation damping isprovided by varying the voltage according to the power of thealternators during the transient period [16]. The voltage of thesystem is increased during the retardation of the alternator andvoltage is decreased during the acceleration of the alternator'srotor, and hence power oscillation damping is provided. SSSCis a VSI connected in series with the system. The operationof a SSSC is similar to the STATCOM and providespower oscillation damping in the same method. STATCOMstands out as a superior device for power oscillation dampingcompared to SSSC, because the cost is high for a SSSC.STATCOM's require tie-line power flow as an observablesignal for feedback. The operation of STATCOM with remotestate variables is not recommended due to their low reliabilityand vulnerability to noise [16]. STATCOM's with locallyavailable signal for feedback is also proposed [17]; howeversuch dedicated equipment for power oscillation damping isrelatively expensive for power oscillations which don't occurvery often.

This paper proposes a modified controller for providingpower oscillation damping using the GCC, rather than theutilization of a STATCOM. The PV-DG system provides poweroscillation damping as an ancillary service, using locallyavailable signal and requires no additional changes in thepower circuit of the existing PV-DG system, and the activepower control is not affected. Thus the cost of providing poweroscillation damping is little, and the PV-DG utilization factoris improved.

III. SYSTEM DESCRIPTION

The PV-DG systems are available from ranges of 50kWand above. Usually, PV-DG systems consist of several stringsof inverters combined to form a large PV system. Theseinstallations are integrated into the grid at distribution ortransmission levels. Without any loss of generality these canbe considered as a single large capacity PV-DG system or onlya Centralized PV-DG system (CPV), and hence this is used tostudy the impact of PV penetration on system stability.

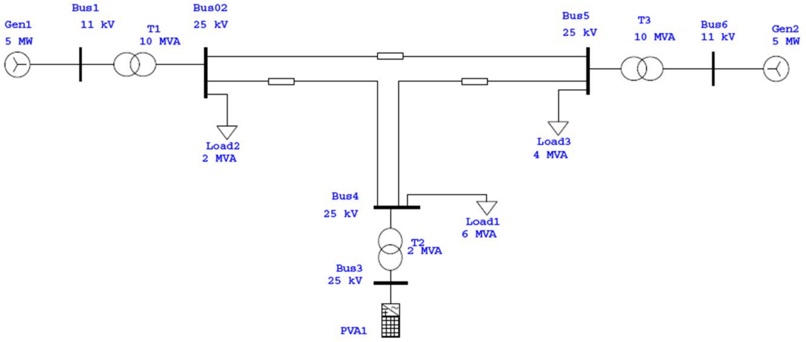

Fig 1. Two machine system with double transmission line, with large PVpenetration, used for study

The proposed system is a simple two machine system, eachhaving a 5MW capacity; one is selected to be the swingbus and the other as the PV bus. The system also has aPQ bus, the PV-DG system is connected to the third bus, atthe center of the second transmission line. The two machinesare connected by a double transmission line as in figure 1.Similar systems are used for the study of system stability andprotection coordination etc. [18]. The alternators are supportedby their Load frequency control (LFC) and Automatic voltageregulator (AVR) with Power system stabilizers (PSS). The PV-DGsystem of 1MW capacity is used (20% penetration) andconnected to the center of the transmission line. The inverterof PV-DG system is designed for 30% additional capacity. Theexcess capacity is meant for reactive power component [16].

In this paper, the alternator one is selected as the PVbus, providing constant voltage and real power; the alternatortwo is chosen as the swing bus, providing constant voltageand floating power control, so as to achieve power balanceunder steady state. The PV-DG system is typically designedto operate at unity power factor [16], but here reactive poweris injected during the transient period. Also, it is assumed noother 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]. Energyfunction analysis is an easy method to comment on the stabilityof the system, without the need for determining the solution ofthe system equations. Structure Preserving Energy Functions(SPEF) is a form of Energy function which has several advantagescompared to standard energy functions [20]. The majoradvantage is the ability to modify the Energy function afterthe addition of a system element [20]. A considerable amountof work is available with SPEF for FACTS technology [21].This paper proposes SPEF method to determine the controllaw for PV-DG system, to provide stability enhancement. TheSPEF model of a system is given by,

$$V(\widetilde{\omega},\widetilde{\phi},\widetilde{V}) = \frac{1}{2}\sum_{i=1}^{m} M_i\widetilde{\omega}_i{}^2 - \sum_{i=1}^{m} P_{mi}(\widetilde{\phi}_i - \widetilde{\phi}_{i(s)}) +$$

$$\sum_{i=1}^{n} P_i(\widetilde{\phi}_i - \widetilde{\phi}_{i(s)}) + \sum_{i=1}^{n}\int_{V_{i(s)}}^{V_i}\frac{Q_i(V_i)}{V_i}dV_i + \frac{1}{2}\sum_{1}^{line} Q_{series} \quad (1)$$

The SPEF is provided as a function of angular velocity ’ω’,phase angle ’φ’ and the voltage ’V ’, and ’m’ is the numberof PV buses and ’n’ is the number of PQ buses. ’Q_{series}’ isthe 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 variousbuses and reactive power controlling devices such as DVR,STATCOM, SSSC, etc. The SPEF equation is formulated inthe Center ofAngle (COA), and Center of Inertia (COI)references [20].

According to the Lyapunov’s stability criteria, for the systemto be stable, the SPEF function should be positive definite andthe derivative with respect to time of the SPEF function shouldbe negative. The stability criteria do not provide the necessarycondition for stability; however, the sufficient condition forstability can be achieved. The derivative of equation (1) withrespect to time yields the following.

$$V'(\widetilde{\omega},\widetilde{\phi},\widetilde{V}) = \sum_{i=1}^{m} M_i\widetilde{\omega}_i\widetilde{\omega}_i{}' - \sum_{i=1}^{m} P_{mi}\widetilde{\phi}_i{}' + \sum_{i=1}^{n} P_{gi}\widetilde{\phi}_i{}' +$$

$$\sum_{i=1}^{n} P_i\widetilde{\phi}_i{}' + \sum_{i=1}^{n}\frac{Q_i(V_i)}{V_i} + \frac{d}{dt}\int_{V_{i(s)}}^{V_i}\frac{-I_{Qg}V_g}{V_g}dV_g +$$

$$\frac{d}{dt}\frac{1}{2}\sum_{1}^{line} Q_{series} \quad (2)$$

The above equation (2) can be modified for the systemunder study, where $IQg$is the PV station reactive powercomponent [16]. The various terms in the equation (2) on theRHS, can be equated to zero, owing to the real and reactivepower balances in the buses. The last term on the RHS ofthe equation can also be related to zero if the network isassumed to be lossless [19]. The only term remaining is thesixth term on the RHS. Using Lyapunov’s stability criteria, i.e$V(\widetilde{\omega},\widetilde{\varphi},\widetilde{V}) > 0$ and $V'(\widetilde{\omega},\widetilde{\varphi},\widetilde{V}) \leq 0$. The sufficient conditionfor effectively damping the electromechanical oscillations isthat the time derivative of the total energy function mustbe negative. The energy released during a disturbance mustdecrease with time to ensure damping of power oscillations[16]. Hence the following can be derived from equation (2).

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

The active damping of electromechanical oscillations can beachieved if equation (3) is incorporated into the control lawas below,

$$I_{Qg} = K_g\frac{dV_g}{dt} \tag{4}$$

The term $Vg$is the PV station voltage in the SynchronouslyRotating Reference Frame (SRRF). From the above equation(4), the electromechanical oscillations during a disturbance canbe curbed by controlling the reactive current from the PV-DGsystem, as in a STATCOM. Since the locally availablesignal,$Vg$is used the process of state estimation and WAMStechnology can be eliminated. The gain Kg can be tuned toobtain optimum performance.

B. GCC Control

A Grid connected converter (GCC) is used to interfacebetween DC and AC in a PV-DG system. Here a two stageconverter is used, i.e. DC-DC Boost converter for MPPTand two level PWM VSI for DC-AC conversion. The MPPTalgorithm is implemented in the boost converter to extractthe maximum power available and ensure maximum availablepower flows into the DC link [22] [23].

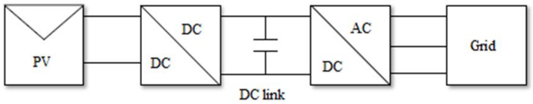

Fig 2. Two stage converter topology of a PV-DG system

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

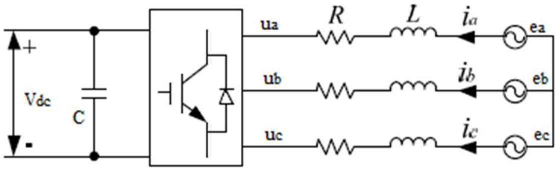

Fig 3. Grid connected converter with L filter

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

The real power injection does not interfere with the reactivepower control; this is achieved by the decoupling termsbetween active and reactive power components of the currentsin the VSI control [25]. Thus the performance of a vectorcontrol is improved. The mathematical model of a GCC isgiven by the equations (5, 6) as per figure (3).

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

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

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

$$u_d^* = e_d - \omega_s L i_q + \tilde{u}_d \quad (7)$$

$$u_q^* = e_q + \omega_s L i_q + \tilde{u}_q \quad (8)$$

The term $\tilde{u}_d \& \tilde{u}_q$in the equation (7,8) are the controlleroutputs. The output energy and power factor can be controlledvia changing d-axis current and q-axis current. Hence, usingthe DCC vector control, it is possible to regulate the real andreactive powers independently. The reactive power componentof current injected by the PV-DG system into the grid ismodulated by the control law, equation (4).

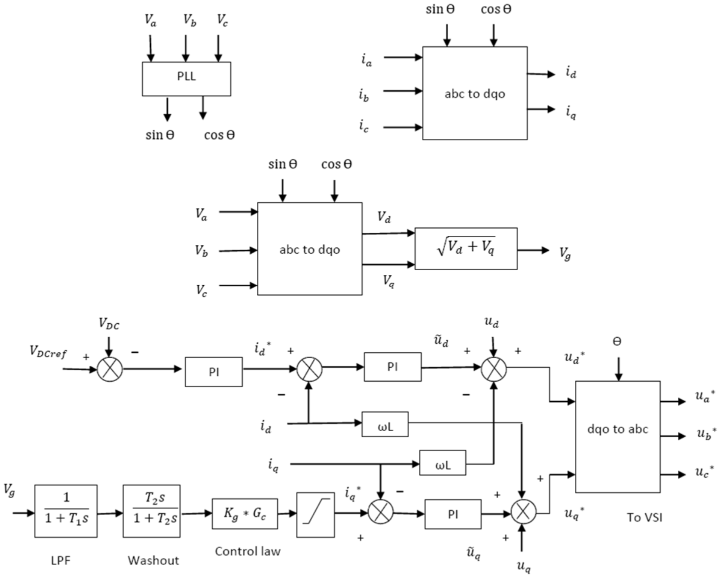

Fig 4. Proposed control strategy for enhancing the dynamic stability (POD)of a power system during high level penetration from a CPV system

The modified DCC vector control of GCC is shown infigure (4), here a washout filter (High pass) prevents thecontroller from responding to the DC offset and steady stateDC components of the voltage, whereas the Low pass filter(LPF) is used to eliminate noise in the PV station voltagesignal. A limiter is usedto limit the amount of reactive power being injected into thegrid, to prevent overloading the GCC. The various elements used for the GCC were designedaccording 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 theMATLAB-Simulink software. Two types of transients weresimulated, i.e. the load switching and faults, to trigger disturbances.The response of the system with and without theproposed controller for power oscillation damping is studied.Based on the type of transients, the study is classified into twocases.

A. Load switching at the PV bus

A load of several MW was switched on during the steadystate of the system, i.e. t=6s, to trigger the disturbance and the corresponding change in load angle of the machine, voltageand reactive power on the grid, was studied with and withoutthe proposed controller.

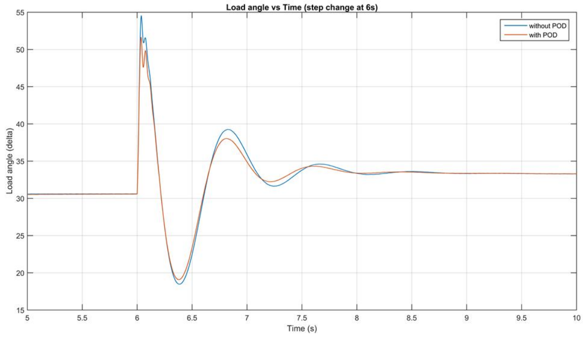

Fig 5. Load angle of the PV bus with and without the proposed POD

1. Without proposed controller:

The load is switched att=6s and disturbance is introduced into the system. The typicalPV-DG system is operating at unity power factor withoutreactive power injection. This transient causes hunting of the alternator. The load angle increases sharply and settles down gradually. The transient period lasts for fewseconds until the system reaches a steady state.

2. With proposed controller:

The control strategy is activatedand dynamic stability enhanced. During the instanceof switching at t=6s, the reactive power is injected into thegrid. A voltage is injected into the grid to retard the motionof machine during acceleration and vice versa. The proposedcontroller has improved damping capability, the load angle ofthe machine is damped, and the peak overshoot of the loadangle was reduced figure (5). The settling time is cut by asmall fraction compared to the conventional controller. Theactive power is not affected during the transient period as perfigure (6). The PV station voltage figure (7) shows oscillationscorresponding to the disturbance; this verifies the use of PVstation voltage (PCC) as the feedback signal.

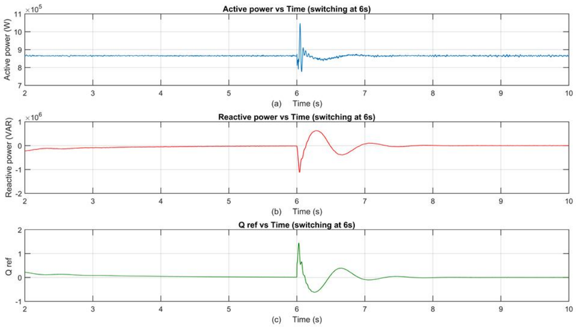

Fig 6. Simulation results of the system corresponding to a switching transient at t=6s, (a) active power (b) reactive power (c) reference to VSI (iq)

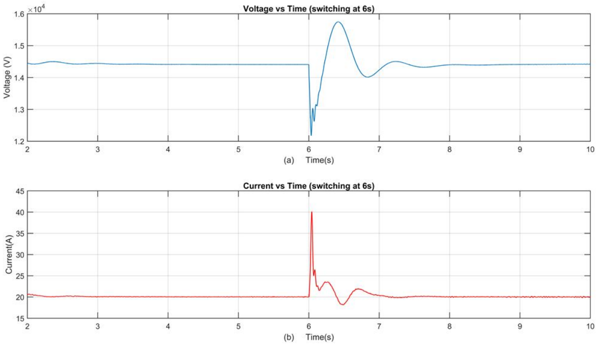

Fig 7. Simulation results of the system corresponding to a switching transient at t=6s, (a) voltage at PCC, (b) current at PCC

B. Symmetrical fault on bus 4

In this case, a 3 phase fault is simulated from t=4s to t=4.1s. The fault causes short circuit current to flow in the system, causing all the sources to feed the fault. The breaker action prevents the system from falling out of step,thus ensuring synchronism. This system is studied with andwithout the proposed controller.

1. Without proposed controller:

The power at the correspondingbus is examined figure (9). The fault occurs at the midpoint of the transmission line. The power becomes zero from t=4s to t=4.1s (fault period). The reclosing action of the circuit breaker results in switching the entire load instantly. This causes significant oscillation on the alternators because the power of alternators cannot be varied instantaneously. The power has higherpeak overshoot as well as larger settling time.

2. With proposed controller:

The proposed controller providessufficient damping compared to the typical system. Thepower at the bus four is studied. The peak overshoot is reducedsufficiently and the settling time is much shorter in comparing.Thus the controller provides power oscillation damping similarto a STATCOM.

From the simulation results, it is clear that the proposedcontroller for Centralized PV-DG systems provides Poweroscillation damping, this then offers additional PV penetrationmargin, despite the inertia-less nature of the PV-DG system.

VI. CONCLUSION

The future power system is considered to be highly deregulated.The deregulated system would lead to high-level PVpenetration in the system causing problems with stability andinducing a penetration limit on the grid. The proposed controllercan enhance the dynamic stability with PV-DG systemsthereby producing additional margin for PV penetration, thattoo with little cost for stability enhancement. The proposedmethod can provide sufficient damping in weak grids. This approachrequires no modification in the existing power circuit ofPV-DG systems. The locally available signal used for feedbackeliminates the requirement for state estimation and WAMS technology, thereby making the system more economical.

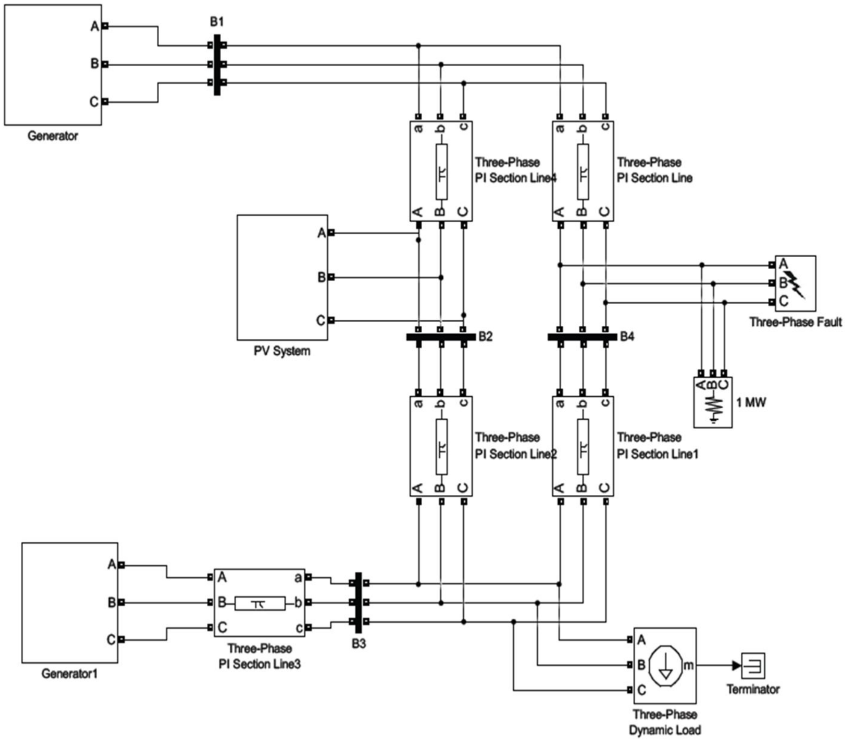

Fig 8. Simulation model of the system under study

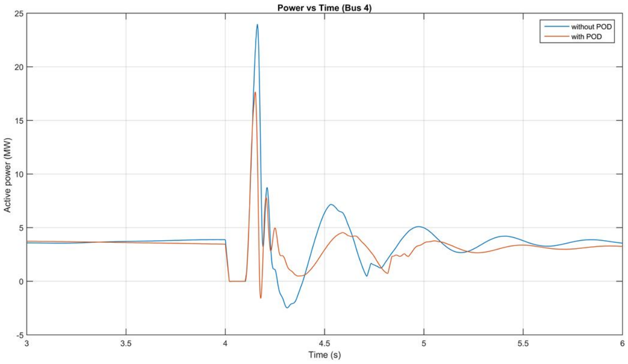

Fig 9. Power at the bus 4, during the fault period at t=4s to t=4.1s. Thesystem with POD and without POD is shown

REFERENCES

[1] S.Sumathi, L.Ashok and P.Surekha, Solar PV & Wind Energy conversion systems, 1st edition, Springer publications, 2015.

[2] The Energy crisis and climate change- Global economic symposium, Chicago 2009.

[3] Y. Tan and D. Kirschen, “Impact on the power system of a large penetration of photovoltaic generation,” in Proc. Power Eng. Soc. Gen. Meet., Tampa, FL, USA, Jun. 2007, pp. 1–8.

[4] W. Du, H.Wang, and R. Dunn, “Power system small-signal oscillation stability as affected by large-scale PV penetration,” in Proc. Sustain. Power Gener. Supply Conf., Nanjing, China, Apr. 2009, pp. 1–6.

[5] S. Eftekharnejad, V. Vittal, G. Heydt, B. Keel, and J. Loehr, “Impact of increased penetration of photovoltaic generation on power systems,” IEEE Trans. Power Syst., vol. 28, no. 2, May 2013, pp. 893–901.

[6] P. McNutt, J. Hambrick, and M. Keesee, “Effects of photovoltaics on the distribution system voltage regulation,” in Proc. 34th IEEE Photovoltaic Specialist Conf. (PVSC), Philadelphia, PA, USA, pp. 1914–1974, Jun. 2009.

[7] Charles P. Steinmetz, “Stability of high power generating stations”, Journal of American Institute of Electrical Engineers, vol. 39, issue. 6, pp. 554-556, 1920.

[8] Narain G. Hingorani, Laszlo Gyugyi, Understanding FACTS: Concepts and technology of AC transmission systems, Wiley IEEE Press, December 1999.

[9] Masaki Yagami; Naohito Kimura; Masanori Tsuchimoto and Junji Tamura, “Power system stability analysis in the case of high-penetration photovoltaics” in Proc. IEEE PowerTech Conf. (POWERTECH), Grenoble, France, Jun. 2013, pp. 1-6.

[10] Masaki Yagami; Seiichiro Ishikawa; Yoshihiro Ichinohe; Kenji Misawa and Junji Tamura, “Power system stability analysis in the case of high-penetration photovoltaics part (2)”, in Proc. IEEE PowerTech Conf. (POWERTECH), Eindhoven, Netherlands, July 2015, pp. 1-6.

[11] G. Shahgholian, S. Eshtehardiha, H. Mahdavi-Nasab, and M. Yousefi, “A novel approach in automatic control based on the genetic algorithm in STATCOM for improvement power system transient stability,” in Proc. 4th IEEE Conf. Intell. Syst., Sep. 2008, vol. 1, pp. 14–19.

[12] S. Qu and C. Chen, “Low frequency oscillations damping by STATCOM with a fuzzy supplementary controller,” in Proc. IEEE Power System Technol., Oct. 2002, vol. 1, pp. 60–70.

[13] X. Xie, J. Li, J. Xiao, and Y. Han, “Inter-area damping control of STATCOM using wide-area measurements,” in Proc. IEEE Electric Utility Deregulation, Restructuring. Power Technol. (DRPT), Apr. 2004, vol. 1, pp. 222–227.

[14] Xinran Zhang, Chao Lu, Shichao Liu and Xiaoyu Wang, “A review on wide-area damping control to restrain inter-area low frequency oscillation for large-scale power systems with increasing renewable generation”, in Elsevier Journal of Renewable and sustainable Energy reviews, vol. 57, May 2016, pp. 45-58.

[15] Komkrit Prasertwong, Mithulananthan Nadarajah, and Devbratta Thakur, “Understanding Low frequency oscillations in power systems”, in International Journal of Electrical engineering, July 2010.

[16] Rupesh G. Wandhare and Vivek Agarwal, “Novel stability enhancing control strategy for Centralized PV-Grid systems for smart grid applications” in IEEE Trans. on smart grids, vol. 30, issue. 7, pp. 1389-1396, Feb. 2014.

[17] Armin Teymouri; S. Hamid Fathi and Gevork B. Gharehpetian, “An advanced fuzzy control method to improve dynamic stability of power systems with PV units” in IEEE 5th International conference on computer and knowledge engineering (ICCKE), Oct.2015, pp. 319-324.

[18] Paul M. Anderson, A. A. Fouad,Power system control and stability, 2nd edition, Wiley-IEEE Press, 2002.

[19] M. Pai, Energy Function Analysis for Power System Stability. London, U.K.: Kluwer Academic, 1989.

[20] K.R. Padiyar, Structure Preserving Energy Functions in Power systems: Theory and Applications, CRC Press.

[21] R. Mihalic and U. Gabrijel, “A structure-preserving energy function for a static series synchronous compensator,” IEEE Trans. Power Syst., vol. 19, no. 3, pp. 1501–1507, Aug. 2004.

[22] Moacyr A. G. de Brito; Leonardo P. Sampaio; G. Luigi; Guilherme A. e Melo and Carlos A. Canesin, “Comparative analysis of MPPT techniques for PV applications”, in IEEE International Conf. on Clean electrical power (ICCEP), Jun. 2011, pp. 99-104.

[23] Preti Tyagi and V.C. Kotak, “DC to DC converter in Maximum power point tracking” in International Journal of Advanced Research in Electrical, Electronics and Instrumentation Engineering, vol. 2, issue, 12, Dec. 2013.

[24] Shuhui Li; Michael Fairbank; Cameron Johnson; Donald C. Wunsch; Eduardo Alonso and Julio L. Proao, “Artifical neural networks for control of grid connected Rectifier/Inverter under disturbance, dynamic and power converter switching conditions” in IEEE Trans. on Neural networks and learning systems, vol. 25, issue. 4, Sep. 2014.

[25] Shuhui Li’ , Timothy A. Haskew, Yang-Ki Hong and Ling Xu, “Direct current vector control of three phase grid connected rectifier-inverter” in Elsevier Journal of Electrical power systems research, vol. 81, issue 2, Feb. 2011, pp. 357-366.

[26] Bhim Singh; Shailendra Dwivedi; Ikhlaq Hussain and Arun Kumar Verma, “Grid integration of solar PV power generating systems using QPLL based algorithm” in IEEE 6th Power India Conf. (PIICON), Dec. 2014, pp. 1-6.

[27] Ahmed Abdalrahman, Ahmed Alshazly and Abdelhalim Zekry Ain, “Simulation and implementation of grid-connected inverters” in International Journal of computer applications, vol. 60, no. 4, Dec. 2012.

[28] Ahmed Abdalrahman and Abdalhalim Zekry, “Control of the grid-connected inverter using dsPIC Microcontroller” in IEEE 2nd International Japan-Egypt Conf. on Electronics, Communication and Computers (JEC-EEC), Dec. 2013, pp. 159-164.

[29] M. Prodanovic and T. C. Green, “Control and filter design of three phase inverters for high power quality grid connection” in IEEE Trans. on Power electronics, vol. 18, issue. 1, pp. 373-380, 2003.

[30] K. H. Ahmed; S. J. Finney and B. W. Williams, “Passive filter design for three phase inverter interfacing in distributed generation” in IEEE Conf. on Compatibility in Electronics, Jun. 2007, pp. 1-9.

[31] Kannan Moudgalya, Digital control, Wiltshire, U.K.: Wiley, 2007.

[32] Remus Teodorescu, Marco Liserre and Pedro Rodriguez , Grid converter for Photovoltaic and wind power systems, Wiley-IEEE Press, Jan. 2011.

[33] Agam Kumar Tyagi, MATLAB and Simulink for Engineers, Oxford University Press, 2012.

[34] Allen J. Wood, Bruce F. Wollenberg, Power generation, Operation and Control, Wiley Press, 2000.

[35] Rao V. Dukkipati, Analysis and Design of control systems using MATLAB, New Age Science publications.

[36] Rao V. Dukkipati, MATLAB Introduction & Application, New Age Science publications.

[37] M. Yagami; S. Ishikawa; Y. Ichinohe; K. Misawa and J. Tamura, “Transient stability of power system with photovoltaics installed” in Proc. 3rd Renewable power generation conference (RPG 2014), pp. 1-6, Sep. 2014.

[38] Masaki Yagami; Seiichiro Ishikawa; Yoshihiro Ichinohe; Kenji Misawa and Junji Tamura, “Transient stability assessment of synchronous generator in power system with high-penetration photovoltaics part(2)”, in Proc. IEEE International conference on Electrical machines & systems (ICEMS), pp. 401-404, Mar. 2013.

[39] Maryam Hasheminamin, Vassilios G.Agelidis, Vahid Salehi, Remus Teodorescu, and Banislav Hredzak, “ Index-Based Assessment of Voltage Rise and Reverse Power Flow Phenomenon in Distribution Feeder Under High PV Penetration ” in IEEE Journal of Photovoltaics, vol.5, issue. 4, pp. 1158-1168, June 2014.

[40] Danling Cheng, Barry A.Mather, Richard Seguin, Joshua Hambrick and Robert B.Broadwater, “ Photovoltaic (PV) Impact Assessment for Very High Penetration Levels “ in IEEE Journal of Photovoltaics, vol.6, issue. 1, pp. 295-300, Oct. 2014.

[41] Mesut E.Baran, Hossein Hooshyar, Zhan Shen, and Alex Huang, “Accommodating High PV Penetration on Distribution Feeders” in IEEE Trans. on Smart Grid, pp. 1039-1046, June 2013.

[42] Shichao Liu, Peter Xiaoping Liu and Xiaoyu Wang, “Stochastic Small-signal stability Analysis of grid connected photovoltaic systems ” in IEEE Trans. of Industrial Electronics, vol.63, issue.2, pp. 1027-1038 ,Jan 2016.

[43] Baran, M.E. Hosshyar, Zhan Shen and Huang A, “Accommodating High PV Penetration on Distribution Feeders” in IEEE Trans. on Smart Grid, vol. 3, issue.2, pp. 1039-1046, June 2013.

[44] Mohamed A. Eltawil, Zhengming Zhao “Grid-connected photovoltaic power systems: Technical and potential problems—A review “ in Elsevier Journal of Renewable and Sustainable Energy Reviews,vol.13, issue.2, pp. 112–129, Jan 2010.

[45] Ashwini Patil, Rucha Grigonkar and Shravana Kumar Musunuri ., “Impacts of Increasing Photovoltaic Penetration on Distribution Grid- Voltage Rise Case Study” in IEEE International Conf. on Advances in Green Energy (ICAGE), Trivandrum , Dec 2014, pp. 100-105.

[46] Qi Luo,K. B. Ariyur andA. K. Mathur “Will the smart grid be stable: Approaches for supply demand Imbalances” in IEEE Trans. on Smart grid, vol.5, issue.3, pp. 1361-1368, May 2015.