Decoupled Adaptive Noise Detection control based Three Phase Four-Leg Grid tied PV Inverter (VSC) Using Fractional Order PID Controller

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ABSTRACT: A grid supportive two stage three phase four wire 4-Leg SPV (Solar Photovoltaic) system with Fractional Order PID controller is presented in this paper, wherein a boost converter is used as a first stage to serve the function of MPPT (Maximum Power Point Tracking) and a 4-leg VSC (Voltage Source Converter) is used to feed the extracted SPV energy along with supporting distribution system for improvement in the power quality. The elimination of harmonics, grid currents balancing and compensation for non-active part of the load currents are extra features offered by proposed system other than conventional features of the solar inverter. The true power reflecting part of load current is estimated using FOPID Based decoupled adaptive noise detection (DAND) algorithm approach. The output of which is current component reflected on grid side to instantaneously regulate the DC link voltage using proposed Fractional Order PID. In the proposed approach, the load, PV array and loss contributions are kept decoupled. The feasibility of proposed control algorithm is confirmed via MATLAB/SIMULINK results.

Keywords— Fractional Order PID (FOPID), DAND, Solar PV; Two-stage; Power Quality; MPPT.

I INTRODUCTION

The electricity can be considered as one of the primary needs for human beings. The demand for electricity is increasing day by day. However, the conventional fuels for generation of electricity are getting depleted. Moreover, the environmental pollution is also a prime concern. Therefore, renewable energy based systems are getting importance. Solar thermal, SPV (Solar Photovoltaic), wind power generations are few such renewable energy systems. The SPV is gaining importance as it is reaching the grid parity [1]-[2].

Grid connected solar PV (Photovoltaic) systems do not require a battery energy storage hence these systems are gaining more popularity. Several researchers have proposed grid connected PV inverters [3]-[6]. These systems collect power from solar panel and feed that power into the grid without any big energy storage. A review of topologies for single phase converters is shown in [3]. A single stage topology based PV inverter for grid tied application is shown in [4]. A current source inverter based transformer less PV inverter is proposed in [5], wherein a 4-leg CSI (Current Source Inverter) is proposed for reduction of ground leakage current.

The solar PV characteristics are nonlinear due to which the peak power can be extracted only at a unique voltage from a given PV array. A classification of MPPT (Maximum Power Point Tracking) techniques is presented in [6]. An evaluation of P&O (Perturb and Observe) based MPPT technique is shown in [7]. The P&O based technique is simple and easy to implement, however, it has drawbacks of poor dynamic response and oscillation near MPP point in steady state conditions. An INC (Incremental Conductance) based MPPT technique is used in [8], which is used in here also, as it offers simple and easy to implement structure along with fast dynamic response and high steady state accuracy.

The nonlinear loads using power electronic converter at front-end are getting popular day by day as they offer high efficiency and occupy comparatively low space. However, the harmonics drawn by these systems cause several problems in the distribution system such as derating of transformer, higher distribution losses and distortion of CCP (Common Connection Point) voltage. The D-STATCOM (Distribution Static Compensator) offers a retrofit solution for these power quality problems [9]-[10]. A peak detection and low pass filter based control algorithm is presented in [9]. An adaptive neural network based technique is used in [10], wherein constant learning rate is used.

The grid supportive solar PV generation systems are demonstrated in [11]-[13]. An algorithm shifting true power component to DC for a multifunctional PV generation system is presented in [11]. The grid tied PV generation system under voltage power quality disturbances is shown in [12]-[15]. An ILST (Improved Linear Sinusoidal Tracer) based control approach for single-stage dual functional system is presented in [16]. However, the frequency response for ILST approach shows that the performance of the control approach deviates under frequency disturbances. In SRF theory based control actuality power part of load currents is detected in much coupled manner, leading to second harmonic oscillation underneath load currents unbalance. A low pass filter is employed to suppress this oscillation, which ends up in trade off between performances underneath dynamics and steady state condition. Considering this non stationary behavior with respect to frequency variations an adaptive frequency based approach is presented in [17]. However, in proposed approach, separate frequency estimation is avoided by use of grid voltage unit vectors.

A variable step size based adaptive harmonics detecting algorithm is used for shunt active filter in [19]-[20]. A control of DSTATCOM with adjustable step least mean square based algorithm is shown in [21]. Various decoupled and adaptational techniques used for noise detection within the communication signals. However, in this paper associate application of DAND (Decoupled adaptational Noise Detection) approach is given for grid tied PV systems where as the adaptational detection technique estimates the active power elements of all three section currents on an individual basis, so the detection is decoupled. However, in this paper an improved adjustable step adaptive neuron based control approach is used for grid supportive PV generation system. The proposed control algorithm is called an improved adjustable step neuron adaptive approach as it gives a decoupled estimation of load, loss and solar power contribution. Moreover, the quick response to sudden variation in insolation is managed via a feed-forward term considering active power changes from PV array which ensures a relieved burden on DC link FOPID (Fractional Order PID Controller). The proposed work is simply explained as given below.

1. A decoupled estimation of salient true power reflective components of grid current.
2. A suitable improvement is proposed in the exiting D-STATCOM algorithm to make it suitable for combined operation of distributed generation and power quality improvements.
3. Demonstration of effect of separate PV power contribution.
4. A case study for reduction in distribution losses via such multifunctional system.

The proposed control approach is simulated and verified on MATLAB/SIMULINK. All salient internal signals of proposed control approach are also presented to make this algorithm intuitive. The grid currents are found adhering to an IEEE- 519 standard [22].

II SYSTEM DESIGN

The power architecture of suggested grid supportive SPV system is demonstrated in Fig. 1. It consists of two power stages, which are the boost converter for MPPT and a 4-leg grid tied VSC to transfer active power to a distribution system and to support it by providing harmonics mitigation, reactive power compensation and grid currents balancing. The connections of VSC and the distribution system are established via current smoothening inductors. The grid, smoothening inductors and shunt high pass filter are connected at a CCP. The shunt high pass filter absorbs the switching noise generated because of VSC.

III PROPOSED CONTROL METHODOLOGY

The control of proposed system in terms of block diagram is presented in Fig. 2. The control approach consists of two main parts corresponding to two power converters. The control approach for boost converter generates duty ratio such that the voltage across PV array reaches MPPT.

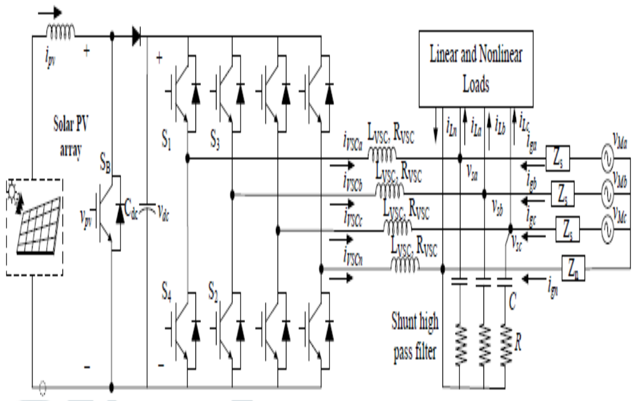

Fig.1 System configuration

The DAND control approach for grid interfaced VSC maintains the balance of true power among the grid, load and VSC. The VSC acts as a three phase currents source in which currents for all the phases are adjusted such that the overall load reflection at CCP is a resistive. In order to achieve this objective, the VSC circulates the unbalanced currents are decoupled to achieve grid currents balancing feature along with supplying inactive part of load currents means the I_{LAPC} for all three phases are estimated in a decoupled it will not affect one phase current in other phase. The control approach for both power converters are discussed here.

A. Control Approach for Boost Converter

An InC MPPT approach is used here [8]. The InC provides PV array voltage reference which finally generates reference duty cycle, using MPPT output and sensed output voltages of boost converter. The duty ratio to perform MPPT is as,

$$d_r(k) = 1 - \frac{V_{pvref}(k)}{V_{DC}(k)} \qquad (1)$$

This duty ratio is used for calculation of pulse width for controlled switch of the boost converter.

B. Control Approach of Grid Connected VSC

The grid tied VSC within the planned system serves for compensation of reactive power, elimination of harmonics current, equalization of grid currents and elimination of neutral current within the grid conductor along with basic options of grid tied PV electrical converter. The DAND algorithm is very simple and using two multipliers, one integrator and one summer per phase for the estimating useful component load current.

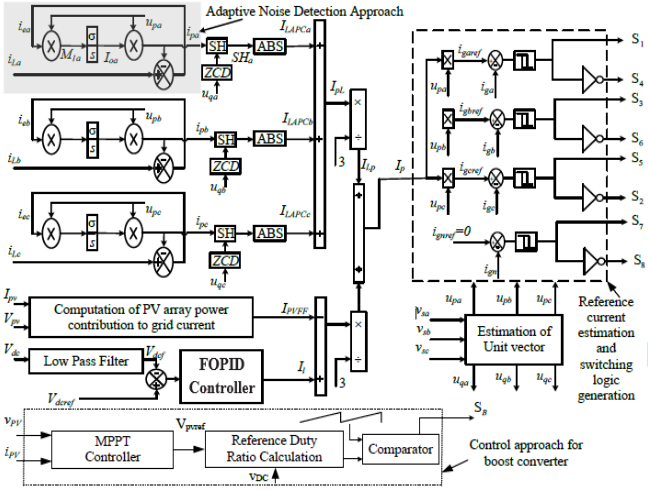

Fig.2 Block diagram for control approach of the system

The VSC is controlled as per block diagram shown in Fig. 2 (a). The CCP voltages (v_{sab}, v_{sbc}), grid currents (i_{ga}, i_{gb}), load currents (i_{La}, i_{Lb}), DC bus voltage (v_{DC}), solar voltage (v_{pv}) and current (i_{pv}) are sensed and processed according to block diagram shown in Fig. 2. The overall control approach for complete system is shown in Fig. 2 (a). The phase voltages are estimated using sensed line voltages [22]-[23], which are then used to calculate the peak value using formula as follows,

$$\begin{bmatrix} v_{sa} \\ v_{sb} \\ v_{sc} \end{bmatrix} = \frac{1}{3}\begin{bmatrix} 2 & 1 \\ -1 & 1 \\ -1 & -2 \end{bmatrix}\begin{bmatrix} v_{sab} \\ v_{sbc} \end{bmatrix} \quad (2)$$

$$V_A = \sqrt{\frac{2\,(V_{sa}{}^2+V_{sb}{}^2+V_{sc}{}^2)}{3}} \quad (3)$$

The PV power contribution is incorporated in reference grid currents using feed forward term. The feed-forward term is based on PV array power and amplitude of CCP voltage. The simulation study for effect of PVFF term is shown in Appendix B. The reflection of PV array power on grid current is estimated in form of a feed-forward (IPVFF) term given as,

$$u_{pa} = \frac{V_{sa}}{V_A}, u_{pb} = \frac{V_{sb}}{V_A}, u_{pa} = \frac{V_{sc}}{V_A} \quad (4)$$

Calculate quadrature unit sinusoid signals by using phase synchronizing signals. The governing equations are as,

$$u_{qa} = -\frac{u_{pb}}{\sqrt{3}} + \frac{u_{pc}}{\sqrt{3}} \quad (5)$$

$$u_{qb} = \frac{\sqrt{3}u_{pa}}{2} + \frac{u_{pb}-u_{pc}}{2\sqrt{3}} \quad (6)$$

$$u_{qc} = -\frac{\sqrt{3}u_{pa}}{2} + \frac{u_{pb}-u_{pc}}{2\sqrt{3}} \quad (7)$$

$$\mathrm{I_{PVFF}} = \mathrm{I_{PVg}} = \frac{2\mathrm{P_{PV}}}{3\mathrm{V_Z}} \quad (8)$$

This method runs through a real time and also the loop settles once a stable average value of I_{oa} is achieved. The convergence of this scheme is reliant on a value of the internal parameter σ. The high value of σ leads to quick convergence however, giant steady state oscillations, leading to a negotiation in between steady state and dynamics responses. The sample and hold of output of adaptive noise detection technique at zero crossings of quadrature unit vector (u_{qa}) gives positive and negative peaks at alternate samplings. The absolute of output of sample and hold logic is I_{LAPC}. Similarly, I_{LAPC} of other two phases of load currents are estimated. The output of this algorithm is not affected by change in grid frequency and the magnitude of I_{LAPC} is also adaptively adjusted with load current variations. The fast convergence and the simple structure are the key features of this algorithm. In order to calculate the PV array contribution to the reference grid currents, a feed forward term is estimated. The feed-forward term is based on PV array power and amplitude of CPI voltage. It should be noted that the PV array voltage and currents are already sensed for MPPT purpose and addition of this feed-forward term does not need any additional sensor. The reflection of PV array power on grid current is calculated in kind of a feed-forward (I_{PVFF}) term given as,

$$\mathrm{I_{PVFF}} = \frac{2\mathrm{V_{PV}}\times\mathrm{I_{PV}}}{\mathrm{V_Z}} \quad (9)$$

Where V_Z=Voltage across the PV panel

By using a FOPID (Fractional order Proportional Integral Derivative Controller) on the DC link voltage of VSC, the loss element of grid current is calculated. The output of FOPID (I_l) is implicit as a loss element of the system as other two components are already calculated in feed-forward manner. The magnitude of reference grid current is estimated taking into account all three elements as,

$$I_P = \left[\sum_{i=a,b,c} I_{LAPCi} + I_l - I_{PVFF}\right]\Big/3 \quad (10)$$

where I_p is magnitude of balanced reference grid currents at unity power factor with respect to CPI. It ought to be noted the active power elements from various power generation and consumption nodes are added and equally divided amongst the three phases of the grid, which makes it common amplitude for all three phases of reference grid currents. The product of phase locking unit vectors and estimated amplitude (Ip) are designated as reference grid currents. The governing equations are as,

$$i_{garef} = I_p u_{pa}, i_{gbref} = I_p u_{pb}, i_{gcref} = I_p u_{pc} \quad (11)$$

The reference grid current for neutral conductor is set to zero for neutral current mitigation by neutral leg of VSC. Hence the reference neutral current is as,

$$i_{gnref} = 0 \quad (12)$$

The current controller generates the logic to IGBT switches of a four-leg VSC as shown in Fig. 1. A common demonstration of a conventional PV inverter with its control approach is shown in Fig. 2, where as the sensed load currents are processed with the decoupled adaptation Noise detection based technique. In this conventional approach, a PI controller is used to maintain the DC link voltage to the desired value. A close inspection reveals that in this case, the output of PI controller consists of loss component of VSC and contribution of solar power in the grid current. Therefore, while setting the gains of the PI there is a coupling in loss and solar power component. Since the contribution of the solar power changes throughout the day, the output of the PI controller varies in a wide range. Moreover, due to sudden cloud or change in climatic condition, the solar power contribution changes rapidly. Therefore, it is difficult to tune the DC link PI controller to provide good steady state and dynamic performances under all operating conditions. Therefore, in the proposed system, an extra term for contribution from solar array is derived using PV array power and sensed grid voltages. It should be noted here that no extra sensor is used to deduce this information. The PV array voltage and current are being already sensed for MPPT operation and the grid voltage for grid synchronization.

The model for DC link voltage control loop is shown in Fig. 3, where the FOPID bears the burden for loss and solar power contribution. However, the model for DC link voltage control for the proposed approach is shown in Fig. 5. It is clearly visible from the overall control loop in the Fig. 5 that the extra added solar array contribution cancels the PV array input power and the load term cancels the power drawn by the loads. Therefore, the feed-forward term instantaneously cancels effect of changes in the PV array power and the load power which leads to fast dynamic response and limited DC link voltage overshoot. These feed-forward terms also relieve the burden on the FOPID such that the changes in the PV array power and load power are not dealt with the PI controller. Therefore, from DC link voltage control point of view, the burden on the FOPID is reduced and it has to bear only the loss component of the power. By using FOPID controller the error is measured involuntary and tune the parameters accordingly, so the error is reduced to zero and the three loss components is reduced So that we prefer FOPID controller. Here error is stored for future reference.

IV. Fractional Order PID Controller for DC-Link Voltage Regulation

The FOPID used as the DC-link Voltage regulator in this proposed system. A PID controller is a generic control loop feedback mechanism widely used in industrial control systems. The PID controller attempts to correct the error between a measured process variable and a desired set point by calculating and then outputting a corrective action that can adjust the process accordingly. An integer order PID controller has the following transfer function:

$$G_c(s) = K_p + T_i\, s^{-1} + T_d\, s \quad (13)$$

The Fractional order Proportional Integral Derivative controller (FOPID) is derived from the PID controller by simply changing over it into fractional request from the whole number request, proposed in 1999 by Igor Podlubny. It furnishes better flexibility with option of two more parameter which can also be used to accomplish the extra specification for the design of control system.

The PID controller calculation (algorithm) involves three separate parameters; the Proportional (K_p), the Integral (T_i) and Derivative (T_d) time-constants. The Proportional gain determines the reaction to the current error, the Integral determines the reaction based on the sum of recent errors and the derivative determines the reaction to the rate at which the error has been changing. The weighted sum of these three actions is used to adjust the process via a control element such as the position of a control valve or the power supply of a heating element. The block diagram of a generic closed loop control system with the PID controller is illustrated in Figure 5.

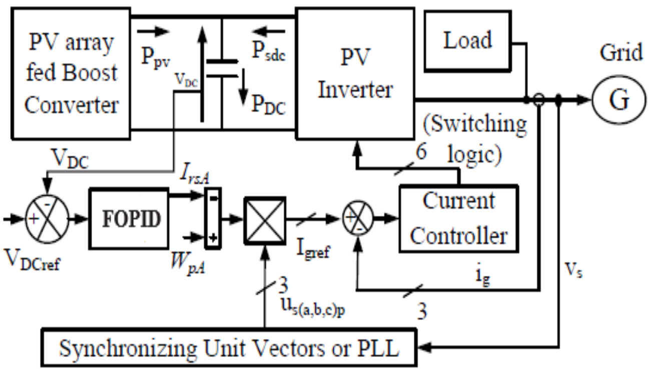

Fig.3 Grid Supporting PV Inverter system with FOPID controller

The real objects or processes that we want to control are generally fractional (for example, the voltage-current relation of a semi-infinite loss RC line). However, for many of them the rationality is very low. In general, the integer-order approximation of the fractional systems can cause significant differences between mathematical model and real system. The main reason for using integer-order models was the absence of solution methods for fractional-order differential equations. PID controllers belong to dominating industrial controllers and therefore are objects of steady effort for improvements of their quality and robustness. One of the possibilities to improve PID controllers is to use fractional-order controllers with non-integer derivation and integration parts. Following the works of Podlubny [6] we may go for a generalization of the PID-controller, which can be called the $PI^{\lambda}D^{\mu}$ controller because of involving an integrator of order and a differentiator of order μ. The continuous transfer function of such a controller has the form:

$$G_c(s) = K_p + T_i s^{-\lambda} + T_d s^{\mu}, (\lambda, \mu > 0) \quad (14)$$

All these classical types of PID-controllers are the special cases of the fractional $PI^{\lambda}D^{\mu}$-controller. As depicted in Figure 4, the fractional order PID controller generalizes the integer order PID controller and expands it from point to plane. This expansion adds more flexibility to controller design and we can control our real world processes more accurately. Here the FOPID is not only used for voltage regulation but also loss contribution is reduced and the burden on error regulation is reduced by the automatic tuning FOPID controller and the power supplied by PV inverter is increases.

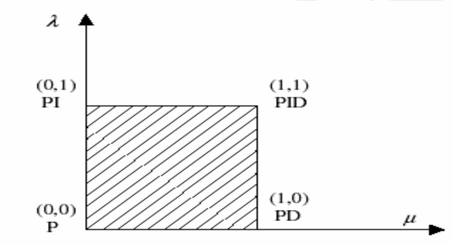

Fig.4 Generalization of the FOPID Controller: From point to plane

IV MATLAB SIMULATION RESULTS

A prototype of the system is developed in the MATLAB/SIMULINK. Simulation results including equilibrium state and system dynamics condition are demonstrated in this section in order to validate the feasibility of the concept.

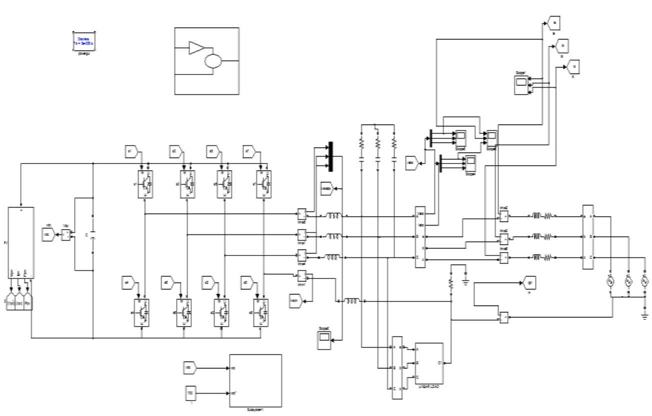

Fig.5 MATLAB SIMULINK model for the Proposed Grid Connected PV System with FOPID

A. Behaviour under Linear Loads

The simulation waveforms at linear load at CPI or CCP are shown in Fig6. A 15 kW, 0.85 lag balanced three-phase star connected linear load is attached at CPI. Prior to t = 0.35 s, the method is working beneath balanced load currents and reactive power part of the load is supplied by SECS is accumulation to PV array power. The load currents are unbalanced between t = 0.35 s to 0.5 s, but grid currents stay balanced sinusoids. The VSC currents are so adjusted that it circulates the active power such that the grid currents are balanced. In case of unbalanced loading condition, a considerable amount of load current in neutral wire is detected, however, VSC extra fourth leg reduce the load current in neutral conductor and about to zero current in grid neutral conductor is ascertained. The power is supplied to both load and grid from VSC, after load thrown increased grid currents which shows that grid share of power which increases once load thrown and vice versa. Maintain DC link voltage as 700 V.

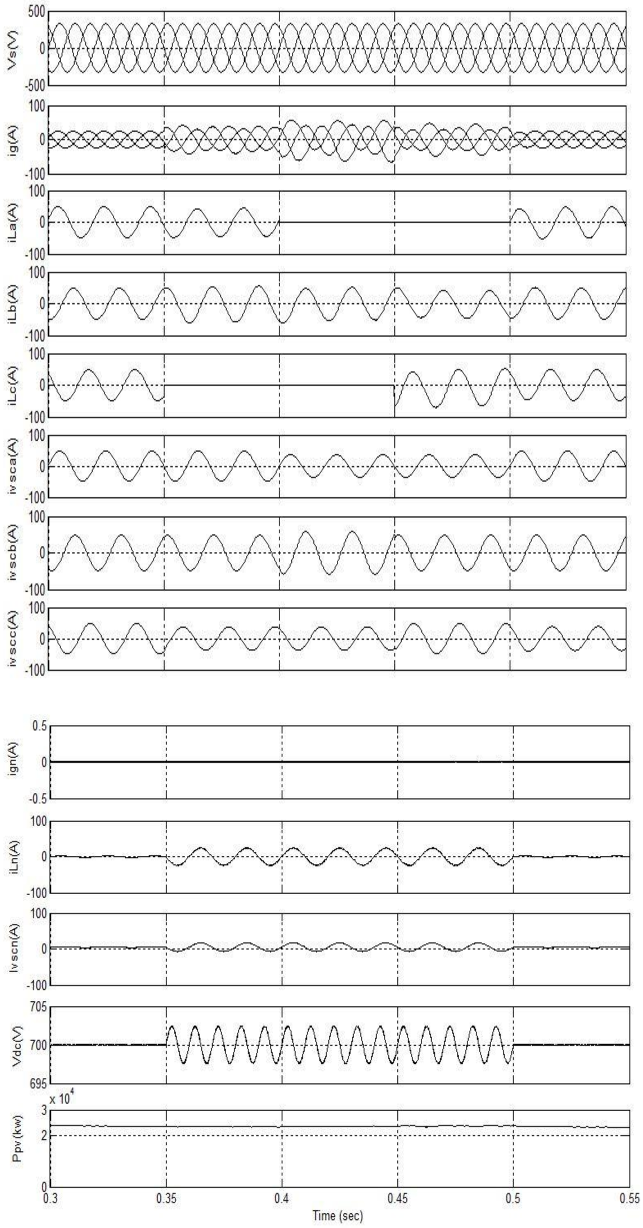

Fig.6 Salient system parameters of SPV generation system operating under linear load

B. Behaviour under Nonlinear Loads

Three single-phase uncontrolled bridge rectifiers (5 kW each) are used to evaluate balanced nonlinear load. Simulation results at nonlinear loads at CPI are shown in Fig.7. Before t = 0.35 s, the load is nonlinear and balanced. The SECS sends harmonics content of the load and PV array power. The load neutral current is nonzero even under balanced loads as it provides path to zero sequence currents. The mitigation of neutral current are simply determined from grid neutral conductor which is zero all the time. The grid currents are balanced and sinusoidal. The load currents are unbalanced between t = 0.35 s to 0.5 s, however the grid currents stay balanced sinusoids.

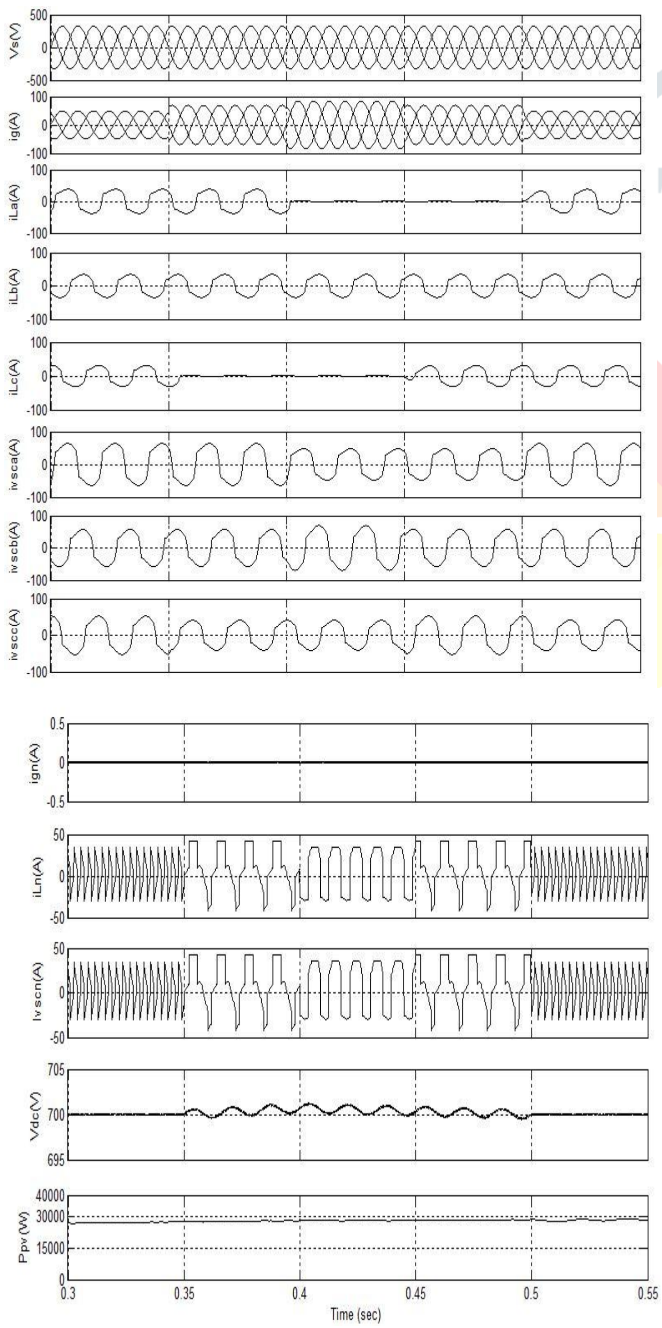

Fig.7 Salient system parameters of SPV generation system operating under nonlinear load

C. Behaviour under Nonlinear Loads

Fig.8 shows the salient parameters of the system for sudden change in SPV insolation level from 1000 W/m2 to 300 W/m2. The load currents are maintained as constant throughout. Sudden change of insolation at t = 0.5 s. Before t = 0.5 s, the active power is fed into the grid as the SPV generation is more than local consumption of the load. However, this situation reverses after a decrease in SPV insolation resulting in phase reversal of grid currents. Moreover, it should be noted that balanced and sinusoidal grid currents are maintained irrespective of direction of power flow.

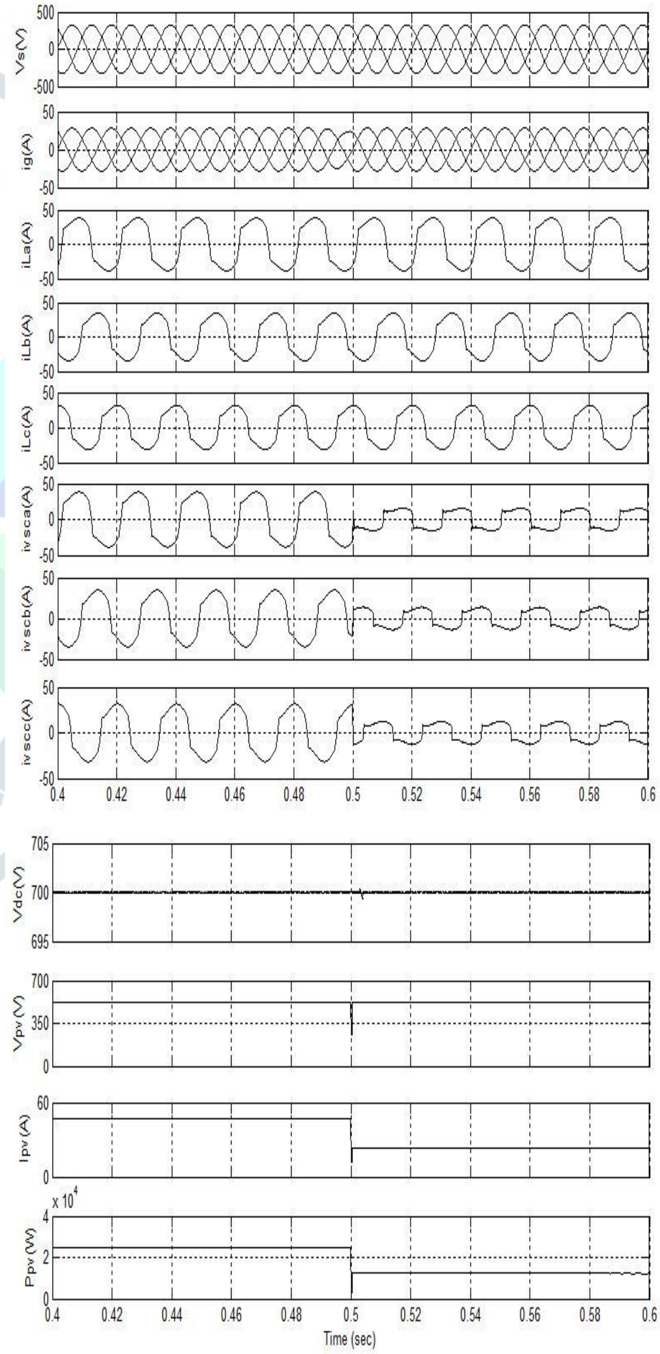

Fig.8 Salient system parameters of SPV generation system operating under change insolation level.

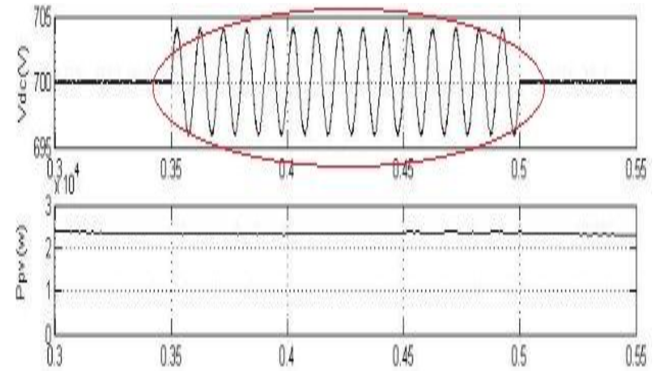

Fig.9 conventional DC link voltage and PV power for Linear load

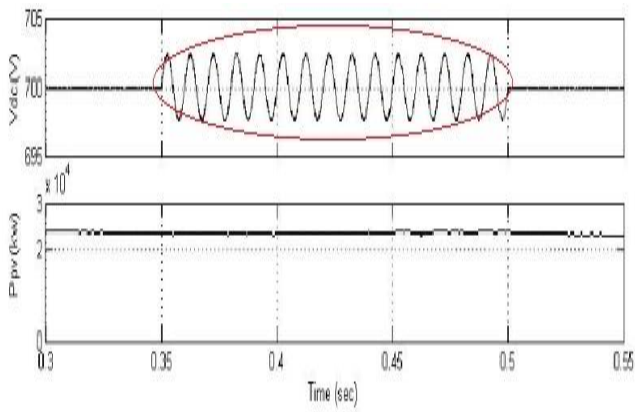

Fig.10 Proposed DC link voltage and PV power for linear load

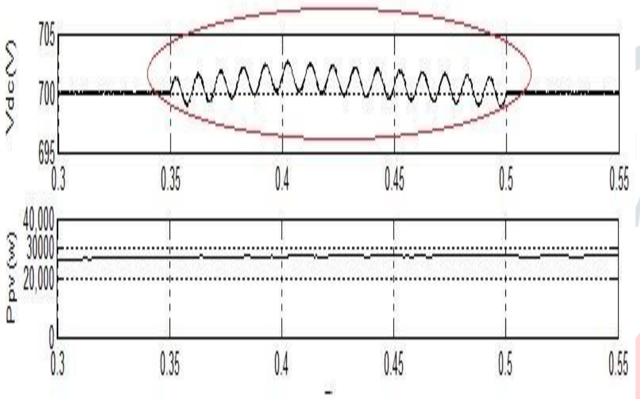

Fig.11 conventional DC link voltage and PV power for Nonlinear load

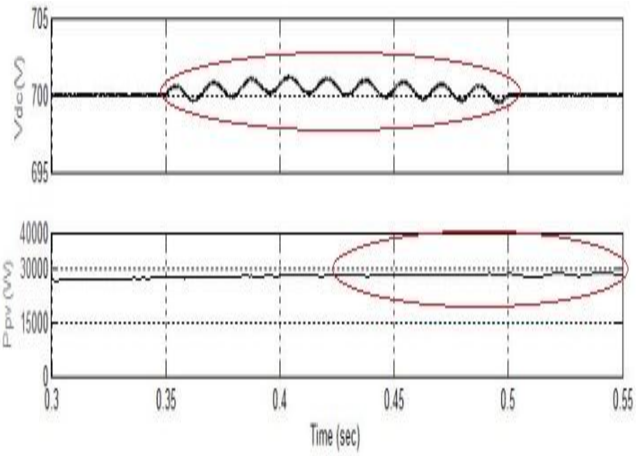

Fig.12 conventional DC link voltage and PV power for Nonlinear load

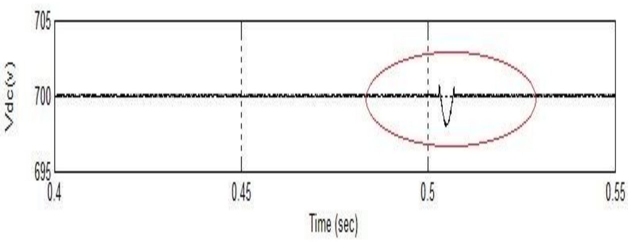

Fig.13 conventional DC link voltage and PV power for sudden changed insolation

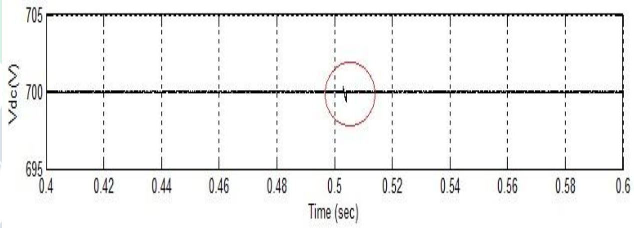

Fig.14 Proposed DC link voltage and PV power for sudden changed insolation

In the above figures shows how the DC link voltage and PV power is changed at various loads. The DC link voltage Regulation at linear load produces high magnitude of oscillations due to using of PI controller, by replacing PI controller with FOPID controller high magnitude oscillations is reduced to low value. It is clearly observes in Fig.9 &Fig.10 and also power also increases slightly. At Nonlinear loads conventional approach regulation of dc link voltage error produces high magnitude of oscillations due to using of PI controller. In case of PI controller the error is not automatically detected to correction so that it produces high amount of oscillations and abrupt change of DC link voltage shown in Fig.11 at Nonlinear load, these effects can be reduced by using FOPID (Fractional Order PID Controller). The FOPID is not only Regulation of DC link voltage but also under the unbalanced loads the PV Power also increased that one is clearly observes in Fig.11&12 shown in above

In case of Nonlinear load if insolation is changed suddenly from 1000 w/m^2 to 300 w/m^2 causes large dip in DC link Voltage and this dip can be reduces to small amount due to using FOPID controller for DC link voltage regulation (DC link voltage Error) this situation clearly observes in Figures 13 and 14.

V CONCLUSIONS

A grid supportive SPV generation system with Fractional Order PID Controller has been proposed for combined aim of distributed SPV generation and power quality improvement. The proposed system not only transfers the SPV power to the distribution system but additionally compensates harmonics and reactive power components of load currents alongside with neutral current reduction, thereby reducing losses in the distribution system. . A DAND based control used for 4-Leg VSC. DAND based control is simple approach and true power currents is detected in a decoupled manner A FOPID approach is used for regulating the DC link voltage. The FOPID controller reduces the oscillations to least possible amount and DC link voltage is stabilized. The comparison between performance results and discussions are presented in above sections. The SIMULINK model is designed and verified under MATLAB/SIMULINK environment. The grid currents are found within the limits of IEEE-519 standards even under unbalanced loads.

REFERENCES

[1] N Y Dahlan, Mohd Afifi Jusoh and W N A W Abdullah, “Solar grid parity for Malaysia: Analysis using experience curves,” *IEEE Power Engineering and Optimization Conference* (PEOCO), 2014, pp.461-466.

[2] S. Reichelstein and M. Yorston, “The prospects for cost competitive solar PV power special section: Long run transitions to sustainable economic structures in the European Union and beyond,” *Energy Policy*, vol. 55, pp. 117–127, 2013.

[3] S.B. Kjaer, J.K. Pedersen and F. Blaabjerg, “A review of single-phase grid-connected inverters for photovoltaic modules,” *IEEE Trans. on Industry Applications*, vol.41, no.5, pp.1292-1306, Sept.-Oct. 2005.

[4] Yang Chen and K.M. Smedley, “A cost-effective single-stage inverter with maximum power point tracking,” *IEEE Trans. on Power Electronics*,vol.19, no.5, pp.1289-1294, Sept. 2004.

[5] S. Anand, S. K. Gundlapalli and B. G. Fernandes, “Transformer-Less Grid Feeding Current Source Inverter for Solar Photovoltaic System,” *IEEE Trans. Indus. Electron.*, vol. 61, no. 10, pp. 5334-5344, 2014.

[6] Bidyadhar Subudhi and Raseswari Pradhan, “A comparative study on maximum power point tracking techniques for photovoltaic power systems,” *IEEE Trans. Sus. Energy*, vol. 4, no. 1, pp.89-98, Jan. 2013.

[7] M. A. Elgendy, B. Zahawi and D. J. Atkinson,“Evaluation of perturb and observe MPPT algorithm implementation techniques,” *IET Renewable Power Generation Conference*, 2011, pp.1-6.

[8] G. J. Kish, J. J. Lee and P. W. Lehn, “Modelling and control of photovoltaic panels utilising the incremental conductance method for maximum power point tracking,” *IET Renewable Power Generation*, vol.6, no.4, pp.259-266, July 2012.

[9] B. Singh, S. R. Arya, C. Jain, “Simple peak detection control algorithm of distribution static compensator for power quality improvement,” *IET Power Electronics*, vol.7, no.7, pp.1736-1746, 2014.

[10] B. Singh, S. R. Arya, C. Jain, S. Goel, “Implementation of four-leg distribution static compensator,” *IET Generation, Transmission & Distribution*, vol.8, no.6, pp.1127-1139, 2014.

[11] Chinmay Jain and Bhim Singh “A Frequency Shifter Based Simple Control for Multifunctional Solar PV Grid Interfaced System” 37th *National System Conference*, 2013, pp 1-6.

[12] Chinmay Jain and Bhim Singh “A Single-Phase Single-Stage Multifunctional Grid Interfaced Solar PV System under Abnormal Grid Conditions,” *IET Generation, Trans. and Distribution*, vol.9, no.10, pp.: 886 - 894, 2015.

[13] Chinmay Jain and Bhim Singh, “A Three-Phase Grid Tied SPV System with Adaptive DC Link voltage for CPI Voltage Variations,” *IEEE Transactions on Sustainable Energy*, vol.7, no.1, pp.337-344, Jan. 2016.

[14] C. Jain and B. Singh, “An Adjustable DC Link Voltage Based Control of Multifunctional Grid Interfaced Solar PV System,” in *IEEE Journal of Emerging and Selected Topics in Power Electronics*, Early Access.

[15] Chinmay Jain and Bhim Singh, “A PEF Based Control for Single-Phase Multifunctional SECS with Adaptive DC Link Structure for PCC Voltage Variations,” in *Proc. of* 30th *Annual IEEE Applied Power Electronics Conference & Exposition*, 2015, pp. 1722-1729.

[16] B. Singh, Chinmay Jain and Sagar Goel “ILST Control of Single-Stage Dual Purpose Grid Connected Solar PV System,” *IEEE Transactions on Power Electronics*, vol.29, no.10, pp.5347-5357, 2014.

[17] Bhim Singh, Chinmay Jain, Sagar Goel, Ambrish Chnadra and Kamal Al-Haddad, “A Multifunctional Grid Tied Solar Energy Conversion System with ANF Based Control Approach,” *IEEE Transactions on Industry Applications*, Accepted for publication.

[18] S. Janpong, K.L. Areerak and K.N. Areerak,“A literature survey of neural network applications for shunt active power filters,” *Journal of World Academy of Science, Engineering and Technology*, vol. 60,pp.392-398, 2011.

[19] Changhe Li, Zhengguo Wu and Fei Liu, "A Novel Variable Step size Adaptive Harmonic Detecting Algorithm Applied to Active Power Filter," *IEEE International Conference on Industrial Technology*, 2006, pp.574-578.

[20] B. Singh, C. Jain, A. Bansal, “An improved adjustable step adaptive neuron based control approach for grid supportive SPV system,” in Proc. 2015 Annual IEEE India Conf. (INDICON), New Delhi, India, pp. 1 - 6.

[21] S.R. Arya, B. Singh, A. Chandra and K. Al-Haddad, "Control of DSTATCOM using adjustable step least mean square control algorithm," *IEEE 5th Power India Conference*, 2012, pp.1-6.

[22] Bhim Singh, Ambrish Chandra and Kamal Al-Haddad, *Power Quality: Problems and Mitigation Techniques*, John Wiley and Sons, UK, 2015, p.117.

[23] H. Akagi, E. H. Watanabe, and M. Aredes, *Instantaneous Power Theory and Applications to PowerConditioning*, John Wiley & Sons, Inc., Hoboken, NJ, 2007.

[24] IEEE Recommended Practices and requirement for Harmonic Control on Electric Power System, IEEE Std. 519, 1992.