Mitigation of Power Quality Problems in Grid-Interactive Distributed Generation System

C. N. Bhende[1], A. Kalam[2], S. G. Malla[3]

[1,3]Indian Institute of Technology Bhubaneswar, India-751013

[2]College of Engineering and Science, Victoria University, Melbourne, Australia

Abstract: Having an inter-tie between low/medium voltage grid and distributed generation (DG), both exposes to power quality (PQ) problems created by each other. This paper addresses various PQ problems arise due to integration of DG with grid. The major PQ problems are due to unbalanced and non-linear load connected at DG, unbalanced voltage variations on transmission line and unbalanced grid voltages which severely affect the performance of the system. To mitigate the above mentioned PQ problems, a novel integrated control of distribution static shunt compensator (DSTATCOM) is presented in this paper. DSTATCOM control helps in reducing the unbalance factor of PCC voltage. It also eliminates harmonics from line currents and makes them balanced. Moreover, DSTATCOM supplies the reactive power required by the load locally and hence, grid need not to supply the reactive power. To show the efficacy of the proposed controller, several operating conditions are considered and verified through simulation using MATLAB/SIMULINK.

Keywords: Distributed generation, power quality conditioner, voltage variations, non-linear and unbalanced load compensation and reactive power compensation.

---

[1]**Corresponding author - Tel/Fax**: +916742306248**, E-mail**: cnb@iitbbs.ac.in

1. INTRODUCTION

The continuously increasing energy demand, along with the necessity of higher reliability requirements, are driving the modern power systems towards distributed generation (DG) as an alternative source. Wind turbines, Fuel cells (FC), Photovoltaic (PV), Batteries, etc. are nowadays the most commonly available DGs for generation of power mostly in peak times or in rural areas [1]. The hybrid system (i.e., combination of DGs) offers the strengths of each type of sources that complement one another and provides more reliability and also cost effective [2-3]. Usually, DGs are connected near the local load and are connected to the grid through a short/medium transmission line for the low/medium voltage network. To deliver high quality and reliable power, DGs should appear as a controllable unit that responds to changes in the system [4]. DG should preferably tie to the utility grid so that any surplus energy generated within them can be channelled to the grid. Similarly, any shortfall can be replenished from the grid. However, due to inter-tie connection between DG and grid, they are exposed to each other's inner disturbances such as: harmonics, voltage unbalance, voltage variations and other power quality (PQ) problems [5]. These PQ problems can be arose from three sides

- Loads connected at DG end
- Transmission line connected between grid and DG
- Grid side

Local loads connected at DG end are usually unbalanced and non-linear in nature which results in injection of harmonic and negative sequence currents into the grid [6]. The presence of harmonic current increases the losses in ac power lines, transformers and rotating machines. The load imbalance causes oscillatory torque leading to mechanical stress and malfunctions of sensitive equipment.

Another major issue associated with DG connection is the voltage variation on transmission line connected between grid and DG. The voltage variations mainly result from impedance of transmission lines, loading types and uneven distribution of single-phase loads. The scenarios become much severe in the low-voltage microgrid system due to reverse power flow contributed by distributed generations in either three or single phase connection [7]. Voltage fluctuations cause system losses, capacity reduction, transformer overloading and motor overheating. Moreover, voltage variation results in output limitation of DGs, nuisance tripping of protected devices and malfunction of sensitive equipment. According to IEEE Std. 1547.2-2008 [8], voltage fluctuations are limited to ±5% as renewable energy sources are paralleled to low-voltage systems. The voltage unbalance factor (VUF) below 2.0%–3.0% is acceptable for both manufactures and utility, where %VUF is defined as the ratio of the negative-sequence voltage to the positive sequence voltage [9]. Further, in practice, usually upto 5% unbalance occurs in grid voltages and due to this VUF at PCC voltage increases further. Therefore, voltage regulation is absolutely needed to allow more DGs to join for grid connected operation. In such a system, distribution static shunt compensator (DSTATCOM) and active power filter (APF) are suitable for power quality improvement of the distribution system [5, 10, 11]. Hence, to mitigate the above mentioned PQ problems a PQ conditioner is recommended at DG side [5, 10-13].

In [10], authors used DSTATCOM to mitigate the voltage fluctuations at microgrid-bus (i.e., PCC) due to unbalanced load and reactive power demand. However, the above approach did not consider the unbalance in grid voltages since in practice grid voltages may vary upto 5%. In [12-13], authors considered that each DG is connected to two converters, one in series and other in parallel. By controlling those two inverters, authors claimed the enhancement of both quality of power within microgrid and quality of current flowing between microgrid and utility system. However, such systems may not be cost effective and control will be complex in case of multiple DGs. Moreover, the important control configuration i.e., control of DC-link voltage of micro-source is missing in the above mentioned literature. In [14], authors considered a new configuration in which DG is connected to DC-link of unified power quality conditioner (UPQC). The reported system in [14] can compensate voltage sag and swell, voltage interruption, harmonics and reactive power in both interconnected mode and islanding mode. However, in [14], authors did not consider unbalance in grid voltage which is a common phenomenon in distribution networks. Moreover, configuration proposed in [14] may be critical since DG is connected to DC-bus of UPQC and UPQC being a power electronic device is susceptible for faults. Hence, DG owners may have limitations to accept such configuration due to various technical limitations.

Recently in [11], a new control algorithm of PQ conditioner for DG system is proposed to mitigate the effect of unbalanced and non-linear load connected at DG. In this paper, we further extended the work presented in [11] for the regulation of PCC voltage due to unbalanced grid voltages and unbalanced loads connected at transmission line between grid and DG. Hence, in this paper, many usually occurring PQ problems due to interconnection of DG and grid are considered and integrated control is proposed for the mitigation of those PQ problems.

The main inverter associated with DG (i.e., which connects DG to PCC) works for active power transfer from DG to PCC. The purpose of DG inverter control is to coordinate active power sharing with grid which depends on DG’s available power and load demand. The PQ problem of non-linear and unbalanced load (connected at DG-side) can be mitigated by DG inverter [15]. However, it is not wise to burden the DG inverter since it is the main interface between DG source and remaining power network. Therefore, in this paper, DSTATCOM is connected at PCC (refer Fig. 1) for the mitigation of PQ problems. Across the transmission line, assume that unbalanced loads are connected at different load buses as shown in Fig. 1. Due to this, unbalanced currents flow the in transmission line which causes unbalance voltages at PCC. This unbalance increases further when grid voltages are unbalanced. The proposed DSTATCOM control helps in reducing VUF at PCC voltage. Moreover, DSTATCOM control is developed in such a fashion that it should provide reactive power demand of DG-side load locally and hence, neither inverter nor grid should supply the reactive power.

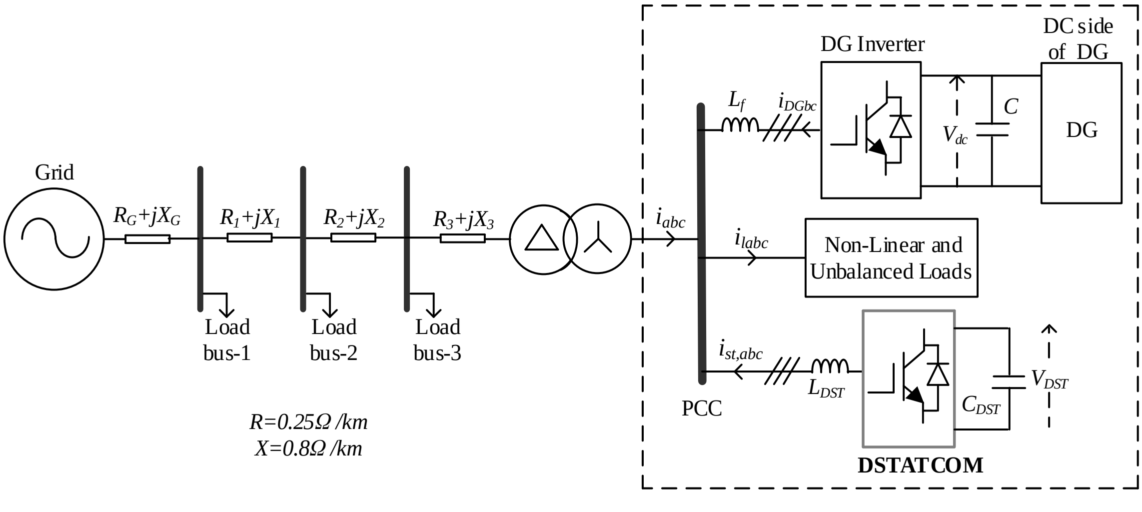

Fig. 1: Schematic of DG connected to utility grid through medium transmission line

2. CONTROL OF DG INVERTER AND DSTATCOM

The control schemes for DG inverter and DSTATCOM are mentioned as follows:

2.1) *DG Inverter Control*

The main aim of DG inverter control is to coordinate active power sharing with grid which depends on available power of DG and load demand. Once power balance among DG, load and grid is achieved, the dc-link voltage of inverter (V_{dc}) is maintained at its reference value which in turn helps in maintaining ac voltage of inverter [16].

The control scheme for inverter is presented in Fig. 2. The proposed control strategy for inverter is realized in synchronous rotating frame [17]. The synchronous rotating frame angle (Θ) is generated through phase locked loop (PLL) by sensing PCC voltages as shown in Fig. 2. Using Θ, inverter output currents and PCC voltages are decomposed into d-axis and q-axis components. The d-axis component corresponds to the real power and q-axis component relates to the reactive power. The output power of renewable sources always fluctuates because of weather condition, for example solar irradiance in case of photovoltaics depends on weather condition. Due to this, there is always power mismatch between generation and load. Mismatch of real power changes the dc side voltage (V_{dc}) of DG. Therefore, error between V_{dc} and reference dc-link voltage (V_{dc}^*) is fed to the proportional plus integral (PI) controller to obtain i_d^* which corresponds to the reference component of real power which DG supplies to PCC. Since, DG inverter is not designed for reactive power supply, i_q^* is made zero. After generating i_d^* and i_q^*, the PWM pulse for DG inverter are generated by well-known method proposed by Schauder *et. al.* [17] as shown in Fig. 2.

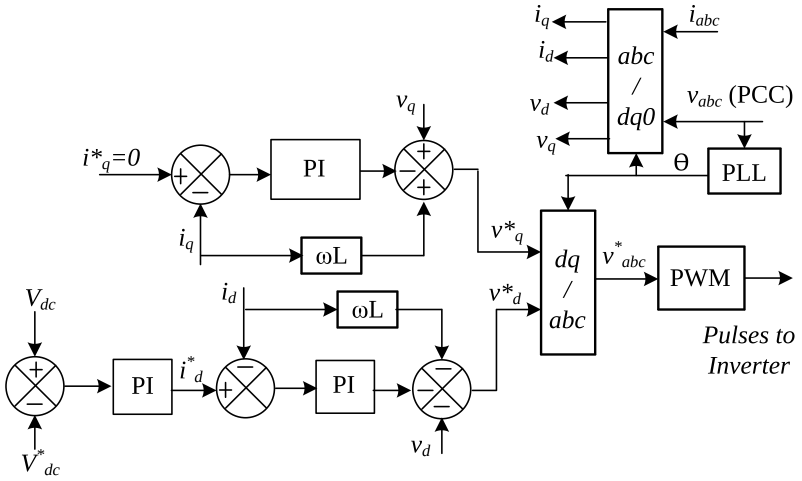

Fig. 2: Control scheme for DG inverter

2.2) ***DSTATCOM Control***

DSTATCOM controller is developed to achieve the following objectives:

- To eliminate harmonics from transmission line currents.
- To make transmission line currents balanced (arise from unbalanced loads).
- To maintain VUF below 3% at PCC during unbalanced load condition as well as unbalanced grid voltage condition.
- To compensate the reactive power required by the local load so that neither grid nor DG inverter should supply the reactive power demand.
- To provide the voltage support during fault condition by supplying the reactive power.

The control scheme for DSTATCOM is shown in Fig. 3. Due to non-linear and unbalance loads, the transmission line currents (i.e., i_{abc}) consist of harmonics and negative sequence components. Therefore, when they are transformed through *abc/dq0* transformation, the real (*d*) and reactive (*q*) components consist of dc part and oscillating part as given below [18].

$$i'_d = \bar{i}'_d + \tilde{i}'_d \tag{1}$$

$$i'_q = \bar{i}'_q + \tilde{i}'_q \tag{2}$$

In order to compensate for unbalanced and harmonic currents, a STATCOM has to supply $\tilde{i}'_d$ and i'_q [19]. Hence, to get $\tilde{i}'_d$, the dc part i.e., $\bar{i}'_d$ is removed from i'_d using low pass filter (LPF) as shown in Fig. 3.

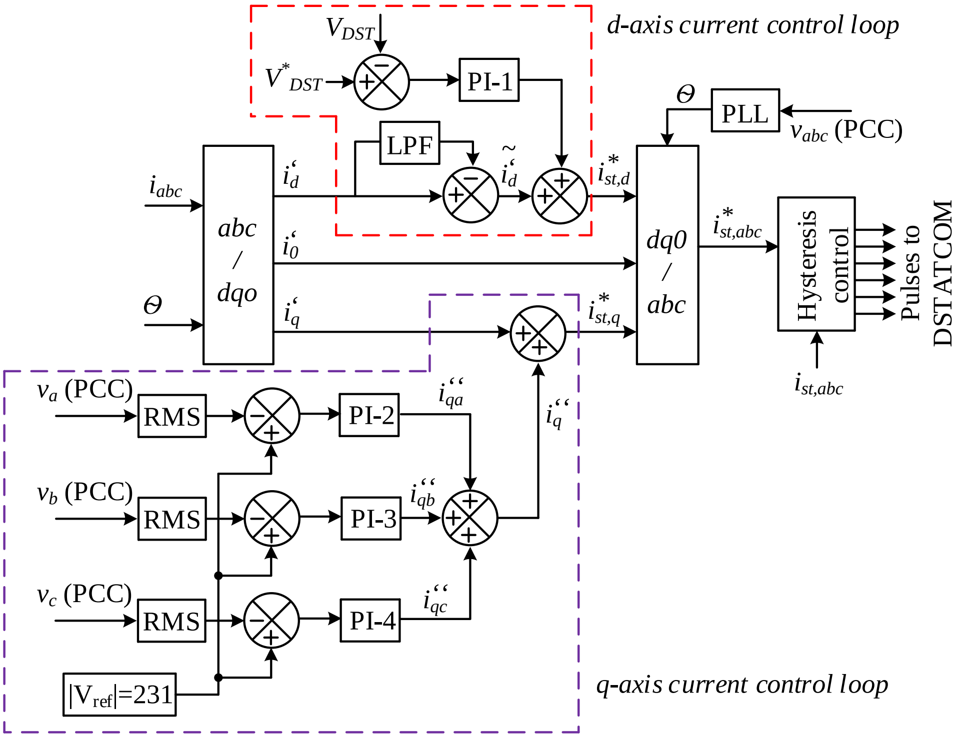

Fig. 3: Control scheme for DSTATCOM

In order to overcome the losses in DSTATCOM circuit, a small portion of real power should flow to DSTATCOM from PCC. This can be achieved by maintaining dc voltage of DSTSTCOM (V_{DST}) at its reference value. Hence, V_{DST} is compared with reference dc voltage and error is fed to PI-1 controller. The output of PI-1 controller is then added with $\tilde{i}_d^{'}$ and thus reference *d*-axis current component of DSTATCOM ($i_{st,d}^{*}$) is generated as shown in Fig. 3.

Let us now consider the *q*-axis current control loop. DSTATCOM compensates both harmonic and reactive power required by the DG-side load. Hence, reactive power component of current i.e., $i_q^{'}$ is used in the DSTATCOM control. Due to unbalanced load and unbalanced grid voltages, the PCC voltage becomes unbalanced. Therefore, one of the objectives of DSTATCOM control is to maintain balanced voltages at PCC. As change in voltage reflects the change in reactive power, the PCC voltages are taken into the *q*-axis control loop. In order to compensate for unbalanced voltages, individual phase voltages are sensed and compared with reference voltage and corresponding errors are fed to the three PI controllers (PI-2, PI-3, PI-4) as shown in Fig. 3. The outputs of those three PI controllers are added together to get reactive power component ($i_q^{''}$) related to the voltage change. The current components $i_q^{'}$ and $i_q^{''}$ are then added to generate reference *q*-axis current component of DSTATCOM ($i_{st,q}^{*}$). After generating $i_{st,d}^{*}$ and $i_{st,q}^{*}$, the reference currents of DSTATCOM ($i_{st,abc}^{*}$) are generated from *dq0/abc* transformation. The gate pulses are generated through hysteresis controller by comparing actual DSTATCOM currents ($i_{st,abc}$) and $i_{st,abc}^{*}$ as shown in Fig. 3.

3. RESULTS AND DISCUSSIONS

The parameters of the system and their ratings are given in Table-1. The rating of DG inverter and DSTATCOM are determined based on 500 kW DG and load power. Details are mentioned in the Appendix. Moreover, design of DSTATCOM capacitance (C_{DST}) and inductance (L_{DST}) is also mentioned in the Appendix.

Table-1: System Parameters

Sr. No.	**Components**	**Rating**
1	Nominal voltage at PCC (i.e., output voltage of DG inverter)	400 V (ph-ph)
2	V_{dc}^{*}	666 V
3	Transformer	400V / 25kV
4	Length of transmission line	50 km
5	Grid	25 kV (ph-ph), $X_G/R_G=10$
6	V_{DST}^{*}	660 V
7	C_{DST}	1100 μF
8	L_{DST}	7.5 mH

The performance of inverter and DSTATCOM control techniques is tested by considering the following cases:

Case-1: *Condition of unbalanced grid voltages and load*

To show the efficacy of the proposed controller, the simulation is carried out by considering the unbalanced loads. Next, the grid voltages are maintained at balanced state upto 1.02 sec. and after that they are made unbalanced as shown in Fig. 4. Due to unbalanced grid voltages, the PCC voltages become more unbalanced after 1.02 sec. as shown in Fig. 5 and VUF is found to be 8.97%. This unbalance nature of voltages can be compensated with proposed DSTATCOM control and PCC voltages with DSTATCOM operation are shown in Fig. 6. From Fig. 6, it can be observed that PCC voltages become balanced (after 1.02 sec.) with DSTATCOM control and the VUF factor of PCC voltage becomes 1.04%. Hence, DSTATCOM helps in keeping VUF within limit irrespective of unbalanced grid voltages and unbalanced loads.

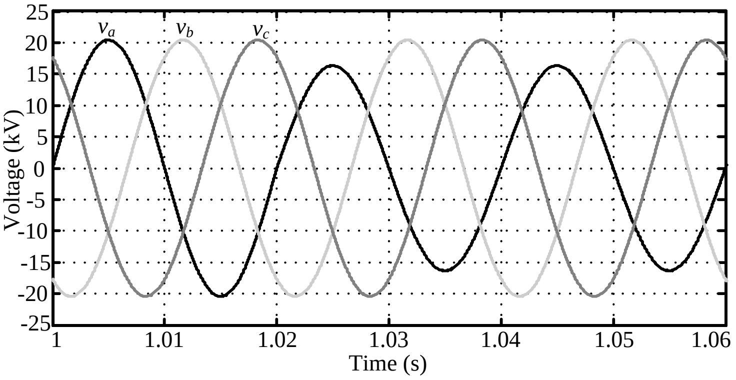

Fig. 4: Instantaneous grid voltages {Case-1}

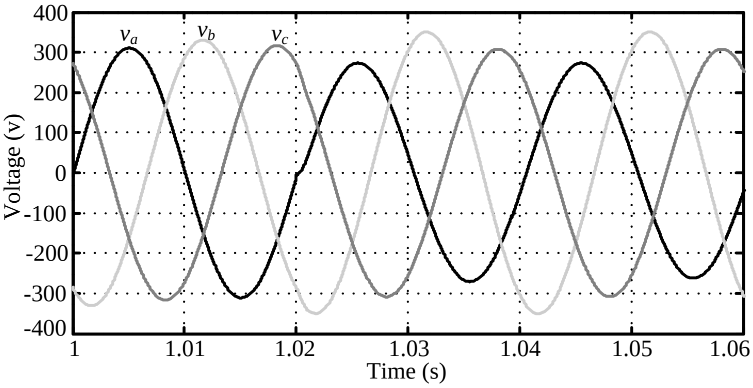

Fig. 5: Instantaneous voltages at PCC without DSTATCOM {Case-1}

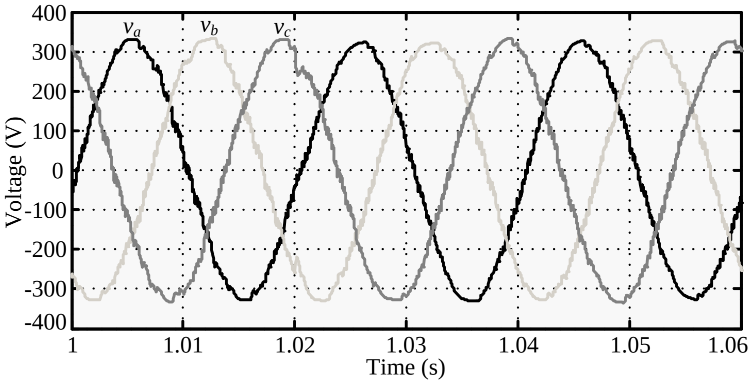

Fig. 6: Instantaneous voltages at PCC with DSTATCOM {Case-1}

Case-2: *Active power sharing between grid and DG*

Consider the photovoltaic (PV) system as a distribution generation (DG) source connected to utility grid through transmission line as shown in Fig. 1. Considering that load demand is 28 kW and PV system is producing 16.9 kW, the remaining load power requirement is fulfilled by the grid as shown in Fig. 7. Now assume that solar irradiance is reduced from 900 W/m^2 to 800 W/m^2 at t= 0.5 sec. (Fig. 7). As solar irradiance reduces, the PV power reduces and hence, grid supplies more power to meet the load demand as shown in Fig. 7. As PV power reduces, the dc-link voltage of inverter also reduces momentarily. However, due to control action of DG inverter (Fig. 2), the dc voltage stabilizes at its reference value as shown in Fig. 8.

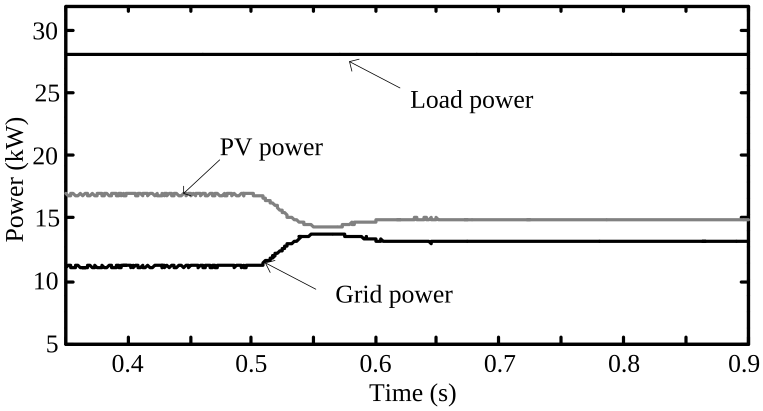

Fig. 7: Active power sharing between grid and DG system {Case-2}

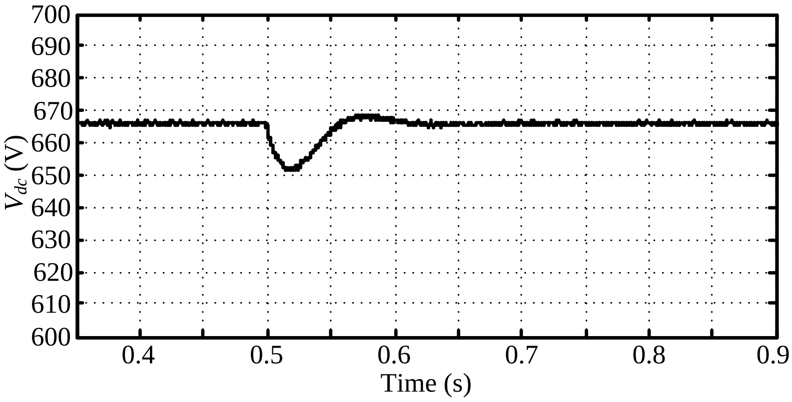

Fig. 8: Dc-link voltage of inverter {Case-2}

Case-3: *Compensation of harmonic and unbalanced currents*

Consider that non-linear and unbalanced load is connected at DG-bus (i.e., PCC) as shown in Fig. 9. Due to this, transmission line currents become unbalanced and non-sinusoidal in nature. Total harmonic distortion (THD) in load current is found to be 27%. With the operation of DSTATCOM and its proposed control scheme, DSTATCOM injects currents at PCC in such a fashion that transmission line currents become sinusoidal and balanced as shown in Fig. 10. THD in line currents becomes 2.6% which is well below the acceptable limit. The injected currents by DSTATCOM are shown in Fig. 11. Hence, with the help of DSTATCOM operation, not only harmonics are eliminated from line currents but also they become balanced.

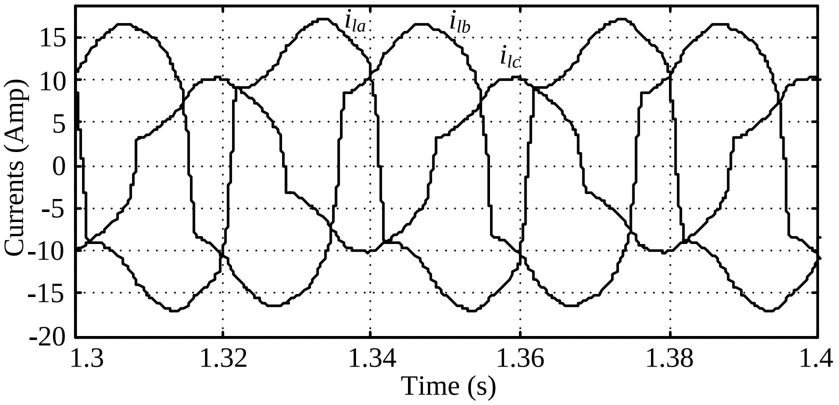

Fig. 9: Non-linear and unbalanced load connected at PCC {Case-3}

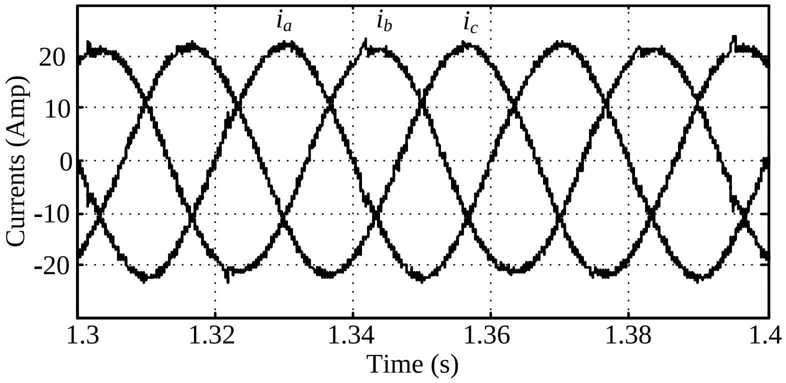

Fig. 10: Transmission line currents at PCC after DSATCOM operation {Case-3}

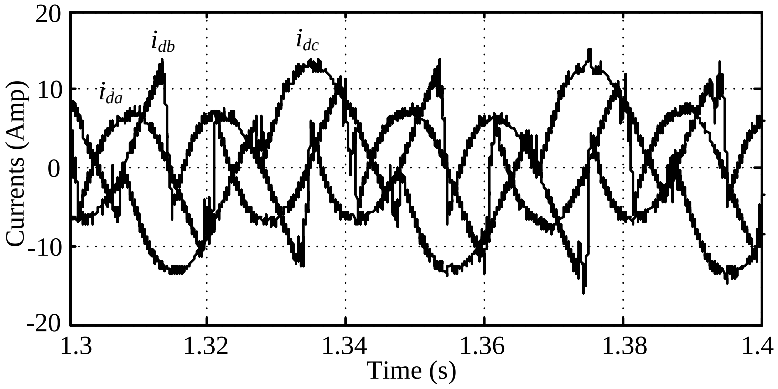

Fig.11: DSTATCOM currents {Case-3}

Case-4: *Reactive power compensation*

Now let us examine the performance of DSTATCOM control for reactive power compensation. Consider the reactive power demand of load is 6 kVAR. Fig. 12 shows the reactive power of various components of power system. In Fig. 12, it is assumed that initially DSTATCOM was switched OFF and it is switched ON at t=1.0 sec. From Fig. 12, it can be seen that when DSTATCOM was OFF, the reactive power demand of the load was met by the grid. The reactive power supplied by the DG inverter is zero as per the control command mentioned in Fig. 2. When DSTATCOM is switched ON at t=1.0 sec., the reactive power requirement of the load is met by DSTASTCOM and hence, reactive power flow from grid becomes zero as shown in Fig. 12. Hence, with the help of proposed DSTATCOM control it can supply the reactive power demand locally and neither the inverter nor grid supplies the reactive power demand of load.

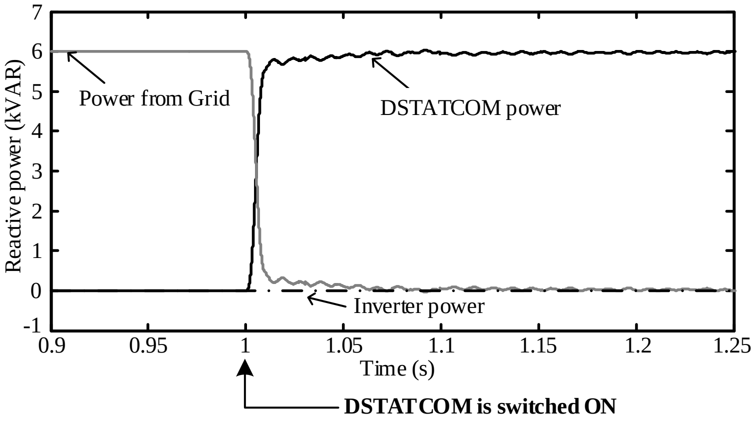

Fig. 12: Reactive power compensation by DSTATCOM {Case-4}

Case-5: C*ondition of fault at 'Load bus-1'*

Consider that phase-A to ground (LG) fault occurred at 'Load bus 1' at t=1.0 sec. (Fig. 13). Assume that CB is taking time of two cycles to open the faulty feeder after occurrence of fault. During this period, voltage of faulty phase (i.e., phase-A) reduces to large extent (Fig. 13) since large current flows through faulty feeder. Sensitive load connected to PCC may get affected by dip in PCC voltages. After incorporating DSTATCOM control, it supplies the reactive power so that PCC voltages are maintained near to rated value as shown in Fig. 14. Hence, DSTATCOM plays an important role under this condition. With DSTATCOM, dip in faulty phase voltage reduces to about 6.8%. Similarly rise in healthy phase also reduces. Hence, DSTATCOM provides voltage support during fault and quality of voltage is improved at PCC during fault.

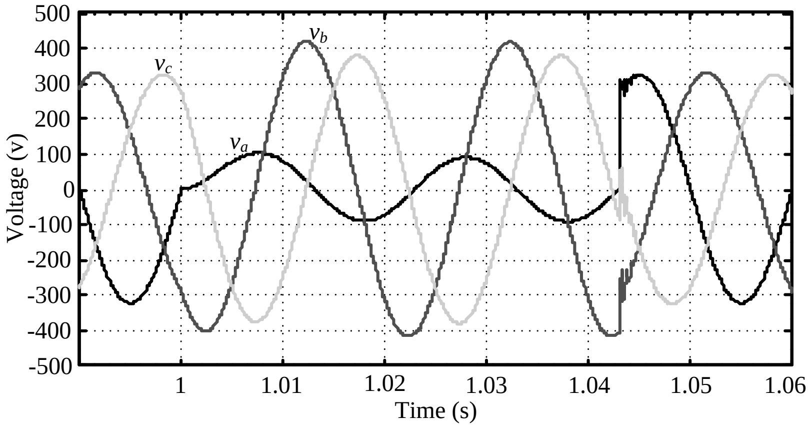

Fig. 13: Instantaneous voltages at PCC during fault at ‘load bus-1’ without DSTATCOM {Case-5}

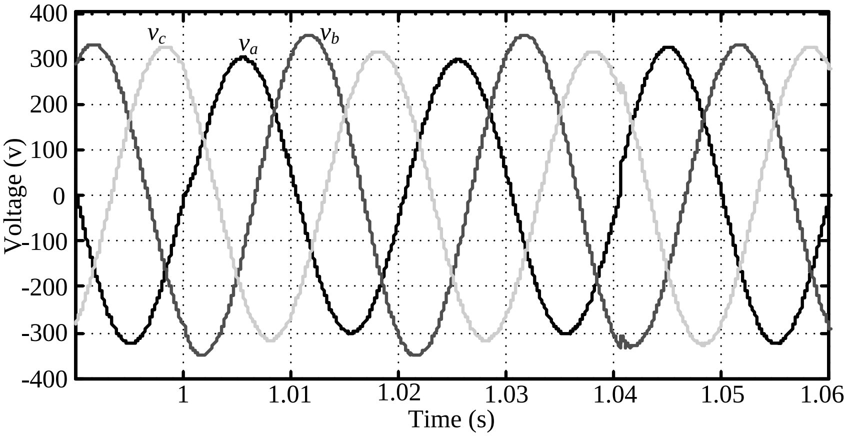

Fig. 14: Instantaneous voltages at PCC during fault at ‘load bus-1’ with DSTATCOM {Case-5}

Case-6: *Increase in R/L ratio of transmission line*

In low voltage systems, the feeder with high *R/L* ratio is very common. In this case, the performance of DSTATCOM is evaluated where the *R/L* ratio is increased by two times. As can be seen from Table-2, %VUF increases to 6.93% when *R/L* ratio is made double as compared to normal value. However, with the operation of DSTATCOM the VUF reduces to 1.06%. Hence, DSTATCOM keeps the VUF within limit even though *R/L* ratio of line increases.

Table-2: VUF for different *R/L* ratio of transmission line

	% VUF at PCC	
	Normal *R/L* ratio	***R/L* ratio increased by two times**
DSTATCOM OFF	4.84	6.93
DSTATCOM ON	1.04	1.06

4. CONCLUSIONS

Having an inter-tie between grid and DG, both exposes to PQ problems created by each other such as current harmonics, unbalanced load and voltage variations. In this paper, the novel coordinated control of DG inverter and DSTATCOM is presented for the mitigation of various PQ problems. DG inverter coordinates the active power sharing among DG, grid and load. DSTATCOM is connected at PCC where DG is connected and it acts as DG power quality conditioner. DSTATCOM operation compensates the unbalanced currents flowing in the transmission line and hence, keeps the VUF of PCC voltage within limit irrespective of unbalanced grid voltages and unbalanced loads. The injection of harmonic currents in the transmission line arose due to non-linear load is eliminated by DSTATCOM control. Moreover, control of DSTATCOM is designed in such a fashion that it provides reactive power demand of load locally and hence, neither grid nor DG inverter supplies the reactive power. DSTATCOM regulates the voltage at PCC by supplying reactive power during the condition of faults. Various practical case studies are discussed and simulation results are presented to validate the performance of proposed controllers for the mitigation of PQ problems.

5. APPENDIX

A. Ratings of Inverter

For 500 kW DG is considered, hence inverter is designed only based on DG active power (i.e., reactive power supplied by DG = 0). Inverter consists of six IGBT devices. The current rating of device is calculated is approximately 750 A.

B. Ratings of DSTATCOM

For 500 kW load, considering that power factor needs to be maintained at 0.9, the VAR rating of DSTATCOM will be 242.2kVAR. Required reactive power during voltage sag (for no. of cycles = 6 and % dip = 40) is calculated as 22.6kVAR [20]. Hence, total rating of DSTATCOM is considered as 297.49kVAR (242.2 + 55.29).

C. Design of C_{ds} *,* L_{ds} *of DSTATCOM*

Dc side capacitor and interfacing inductance of DSTATCOM are given by [21]

$$C_{ds} = \frac{(2X - X/2)\,nT}{(1.8V_m)^2 - (1.4V_m)^2} \tag{3}$$

$$L_{ds} = \frac{1.6V_m}{4h\,f_{sw}} \tag{4}$$

where

V_m (peak value of the source voltage) $= 231\sqrt{2}$,

X (rating of the DSTATCOM) = 297.49 kVA,

n (no. of cycles considered for voltage sag) = 9,

T (time period of the each cycle) =20 msec.,

h (constant) =16, and

f_{sw} (switching frequency) = 1050 Hz.

From (1) and (2), the values of C_{ds} and L_{ds} are calculated and given as, C_{ds} =1100 μF, L_{ds} = 7.5 mH.

ACKNOWLEDGEMENT

This work was supported by INSA, Govt. of India under "Indo-Australia Science and Technology Visiting Fellowship Programme - 2013".

REFERENCES

[1] D. Menniti, C. Picardi, A. Pinnarelli and D. Sgro, "Power management by grid connected inverters using a voltage and current control strategy for microgrid applications", in *Proc. of International Symp. on Power Electronics, Electrical Drives, Automation and Motion (SPEEDAM)*, pp. 1414-1419, 2008.

[2] C. Wang and M.H. Nehrir, "Power Management of a Stand- Alone Wind/Photovoltaic/Fuel Cell Energy System", *IEEE Transactions on Energy Conversion*, Vol. 23, No. 3, pp. 957 - 967, Sept. 2008.

[3] F. Katiraei, M. Iravani, "Power management strategies for a microgrid with multiple distributed generation units", *IEEE Trans. on Power Systems*, Vol. 21, No.4, pp. 1821-1831, Nov. 2006.

[4] T. Kaipia, P. Peltoniemi, J. Lassila, P. Salonen and J. Partanen, "Power electronics in smart grids-impact on power system reliability", in *Proc. of CIRED Int. Conf.*, Germany, June 2008.

[5] J. M. Guerrero, P. C. Loh, T. L. Lee and M. Chandorkar, "Advanced Control Architectures for Intelligent Microgrids—Part II: Power Quality, Energy Storage,

and AC/DC Microgrids”, *IEEE Transactions on Industrial Electronics,* Vol. 60, No. 4, pp. 1263 – 1270, April 2013.

[6] IEEE Application Guide for IEEE Std. 1547™, IEEE Standard for Interconnecting Distributed Resources with Electric Power Systems, 2011.

[7] C. L. Masters, “Voltage rise: The big issue when connecting embedded generation to long 11 kV overhead lines,” *Inst. Elect. Eng. Power Eng. J.*, Vol. 16, No. 1, pp. 5–12, Feb. 2002.

[8] *IEEE Standard for Interconnecting Distributed Resources With Electric Power Systems,* IEEE Std. 1547.2-2008, 2008.

[9] A. V. Jouanne and B. Banerjee, “Assessment of voltage unbalance,” *IEEE Trans. Power Del.*, Vol. 16, No. 4, pp. 782–790, Oct. 2001.

[10] Tzung-Lin Lee, Shang-Hung Hu and Yu-Hung Chan,“ D-STATCOM With Positive-Sequence Admittance and Negative-Sequence Conductance to Mitigate Voltage Fluctuations in High-Level Penetration of Distributed-Generation Systems”, *IEEE Transactions on Industrial Electronics,* Vol. 60, No. 4, pp. 1417-1428, April 2013.

[11] C. N. Bhende and A. Kalam, “Power Quality Conditioner for Microgrid”, *Australasian Universities Power Engineering Conference (AUPEC),* Hobart, TAS, Australia, 29 Sept.-3 Oct. 2013.

[12] Y. W. Li, D. M. Vilathgamuwa and P. C. Loh, “Microgrid Power Quality Enhancement Using a Three-Phase Four-Wire Grid-Interfacing Compensator”, *IEEE Transactions on Industry Applications,* Vol. 41, No. 6, pp. 1707-1719, Nov/Dec. 2005.

[13] Y. W. Li, D. M. Vilathgamuwa and P. C. Loh, “A Grid-Interfacing Power Quality Compensator for Three-Phase Three-Wire Microgrid Applications”, *IEEE Transactions on power electronics*, Vol. 21, No. 4, pp. 1021-1031, July 2006.

[14] B. Han, B. Bae, H. Kim and S. Baek, “Combined Operation of Unified Power-Quality Conditioner with Distributed Generation”, *IEEE Transactions on Power Delivery*, Vol. 21, No. 1, pp. 330-338, Jan. 2006.

[15] X. Tang, K. M. Tsang, and W. L. Chan, “A Power Quality Compensator with DG Interface Capability Using Repetitive Control”, *IEEE Transactions on Energy Conversion*, Vol. 27, No.2, pp. 213 - 219, June 2012.

[16] C. N. Bhende, S. Mishra and Siva Ganesh Malla, “Permanent Magnet Synchronous Generator-Based Standalone Wind Energy Supply System”, *IEEE Transactions on Sustainable Energy*, Vol. 2, No. 4, pp. 361-373, Oct. 2011.

[17] C. Schauder and H. Mehta, “Vector analysis and control of advanced static VAR Compensators”, *IEE Proceedings-C*, Vol. 140, No. 4, pp. 299-306, July 1993.

[18] C. Salim and B. M. Toufik, “Intelligent Controllers for Shunt Active Filter to Compensate Current Harmonics Based on SRF and SCR Control Strategies”, *International Journal on Electrical Engineering and Informatics*, Vol. 3, No. 3, 2011.

[19] M. Aredes, J. Hafner and K. Heumann, “Three-Phase Four-Wire Shunt Active Filter Control Strategies”, *IEEE Transactions on Power Electronics*, Vol. 12, No. 2, pp. 311-318 , March 1977.

[20] S. B. Karanki, N. Geddada, M. K. Mishra and B. Kalyan Kumar, “A DSTATCOM Topology with Reduced DC-Link Voltage Rating for Load

Compensation with Nonstiff Source”, *IEEE Transactions on Power Electronics*, Vol. 27, No. 3, pp. 1201-1211, March 2012.

[21] Hendri Masdi *et al*, “Design of a Prototype D-Statcom for Voltage Sag Mitigation”, *National Power & Energy Conference (PECon) Procedings*, Kuala Lumpur, Malaysia, pp. 61-66, 2004.