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Operation and Control of Converter Based Single Phase Distributed Generators in a Utility Connected Grid

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Abstract: ***The operation and control of converter based single phase distributed generators (DG) in a utility connected grid is proposed in this paper. A common utility practice is to distribute the household single-phase loads evenly between the three phases. The voltage unbalance between the phases remains within a reasonable limit. The single phase sources are operated to deliver available maximum power generated while the rest of the power demands in each of the phases are supplied by the utility (and if available, three phase DG sources). However, the voltage unbalance can be severe if single-phase rooftop mounted PVs are distributed randomly among the households. Moreover, there can also be single-phase nonlinear loads present in the system. The cumulative effect of all these will cause power quality problem on the utility side. The problem can be macabre if three-phase active loads (e.g., induction motors) are connected to the utility feeder.***

Keywords: Distribution Generation, DSTATCOM, Point of common coupling, Grid.

1. Introduction

Today everyone is aiming at a reduction in greenhouse gas emissions, the requirements for adding new generation capacity can no longer be met by traditional power generation methods of burning the primary fossil fuels such as coal, oil, natural gas, etc [1]. This is why distributed generators (DG) have a significant opportunity to the evolving power system network. Both consumers and power utilities can benefit from the widespread deployment of DG systems which offer secure and diversified energy options, increase generation and transmission efficiency, reduce greenhouse gas emissions, improve power quality and system stability, cut energy costs and capital expenditures [2].

A distribution static compensator (DSTATCOM) can compensate for unbalances and nonlinearities while providing reactive power support. The size of the dc capacitor determines how much reactive power support the DSTATCOM can provide without any drop in voltage [3]. The choice of this capacitor is thus a trade-off between the reactive support and system response distribution static compensator is connected to the utility bus to improve the power quality [4]. The DSTATCOM only supplies reactive power and no real power. Alternatively, a three phase DG-compensator can be connected at the point of common coupling (PCC) to share the real and reactive power with utility and to compensate for the unbalance and nonlinearities in the system.

The imbalance in three phase power is compensated two ways –either through a DSTATCOM or through a DG-compensator. With the proposed structure of distribution system, it is possible to operate single phase DG sources in a utility connected grid and this might become a useful tool as their penetration in distribution systems increases.

Application of single phase converter based DGs are very common in distribution level and with the increasing number of single phase, micro sources in a utility connected grid have raised concern about power quality [5]. For a microgrid, a common practice is to isolate the micro grid from the utility grid by an isolator if the voltage is seriously unbalanced. Howeverwhen the voltages are not critically unbalanced, the isolator will remain closed, subjecting the microgrid to sustained unbalanced voltages at the PCC, if no compensating action is taken. Unbalancedvoltages can cause abnormal operation particularly for sensitive loads and increase the losses in motor loads [6].

This paper proposes the operation and control of single phase micro-sources (DG) in a utility connected grid. While the DGs supply their maximum generated power, rest of the power demand of each phase is supplied by the utility and three phase DG connected at the PCC, if any. To counteract this problem, we have proposed two different schemes. In the first scheme, a DSTATCOM is connected at the PCC to compensate the unbalance and nonlinear nature of the total load current and to provide the reactive power support. In the second scheme, a three phase DG, connected at the PCC, in place of the DSTATCOM to share both real and reactive power with the utility. The DG also compensates the system and makes the PCC voltage balanced [7]. The efficacies of the controllers and improvement in power quality have been validated through simulation for various operating conditions using Matlab.

2. Distributed Generation

Distributed generation, also called on-site generation, dispersed generation, embedded generation, decentralized generation, decentralized energy or distributed energy generates electricity from many small energy sources. Currently, industrial countries generate most of their electricity in large centralized facilities, such as fossil fuel (coal, gas powered) nuclear or hydropower plants [8]. These plants have excellent economies of scale, but usually transmit electricity long distances and negatively affect the environment.

Most plants are built this way due to a number of economic, health & safety, logistical, environmental, geographical and geological factors. For example, coal power plants are built away from cities to prevent their heavy air pollution from affecting the populace. In addition, such plants are often built near collieries to minimize the cost of transporting coal. Hydroelectric plants are by their nature limited to operating at sites with sufficient water flow. Most power plants are often considered to be too far away for their waste heat to be used for heating buildings.

Low pollution is a crucial advantage of combined cycle plants that burn natural gas. The low pollution permits the plants to be near enough to a city to be used for district heating and cooling.

Distributed generation is another approach. It reduces the amount of energy lost in transmitting electricity because the electricity is generated very near where it is used, perhaps even in the same building. This also reduces the size and number of power lines that must be constructed. Typical distributed power sources in a Feed-in Tariff (FIT) scheme have low maintenance, low pollution, and high efficiencies. In the past, these traits required dedicated operating engineers and large complex plants to reduce pollution. However, modern embedded systems can provide these traits with automated operation and renewable, such as sunlight, wind and geothermal. This reduces the size of a power plant that can show a profit [9].

3. Distribution Static Compensator

A D-STATCOM, which is schematically depicted in Fig.1, consists of a two-level Voltage Source Converter (VSC), a dc energy storage device, a coupling transformer connected in shunt to the distribution network through a coupling transformer. The VSC converts the dc voltage from the storage device into a set of three-phase AC output voltages [10]. These voltages are in phase and coupled with the AC system through the reactance of the coupling transformer. Suitable adjustment of the phase and magnitude of the D-STATCOM output voltages allows effective control of active and reactive power exchanges between the D-STATCOM and the AC system. Such configuration allows the device to absorb or generate controllable active and reactive power [11].

The VSC connected in shunt with the AC system provides a multifunctional topology which can be used for up to three quite distinct purposes:

1. Voltage regulation and compensation of reactive power;
2. Correction of power factor; and
3. Elimination of current harmonics.

Here, such device is employed to provide continuous voltage regulation using an indirectly controlled converter.

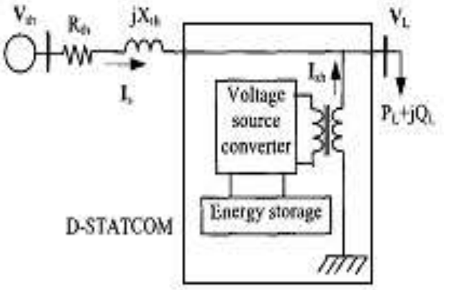

Figure 1: D-STATCOM Schematic diagram

In Fig. 1, the shunt injected current I_{sh} corrects the voltage sag by adjusting the voltage drop across the system impedance Z_{th}. The value of I_{sh} can be controlled by adjusting the output voltage of the converter.

The shunt injected current I_{sh} can be written as,

$$I_{sh} = I_L - I_s = I_L - \frac{V_{Th} - V_L}{Z_{Th}}$$

$$I_{sh}\angle\eta = I_L\angle-\theta - \frac{V_{th}}{Z_{th}}\angle(\delta-\beta) + \frac{V_L}{Z_{th}}\angle-\beta$$

The complex power injection of the D-STATCOM can be expressed as,

$$S_{sh} = V_L I_{sh}^*$$

It may be mentioned that the effectiveness of the D-STATCOM in correcting voltage sag depends on the value of Z_{th} or fault level of the load bus [12]. When the shunt injected current I_{sh} is kept in quadrature with $V_{L,}$ the desired voltage correction can be achieved without injecting any active power into the system. On the other hand, when the value of I_{sh} is minimized, the same voltage correction can be achieved with minimum apparent power injection into the system. The control scheme for the D-STATCOM follows the same principle as for DVR. The switching frequency is set at 475 Hz.

4. Basic Structure of the Proposed System

The structure of the system studied in this paper is shown in Fig.2.The utility is connected to the PCC through a primary feeder with an impedance of *Rs*, *Ls*. The supply side contains three single phase DGs and one three phase DG or DSTATCOM. The single phases DGs are connected through secondary feeders to the PCC. The three phases DG or DSTACOM is also connected at the PCC. Since both these devices are used for improving power quality, they will be commonly called as the compensator. It is assumed that all the DG are inertia less and VSC-interfaced. Six single phase loads are denoted by *Ld*1 to *Ld*6. The secondary feeder impedances are denoted by *Z*. The DG output voltages are denoted by $Ei\llcorner\delta i$, $i = 1\ldots3$. Each single phase DG is connected to the grid through external inductors as shown in the figure. A three-phase induction motor is connected at the PCC to study the impact of poor power quality on its operation. The system data used for the studies are given in Table.

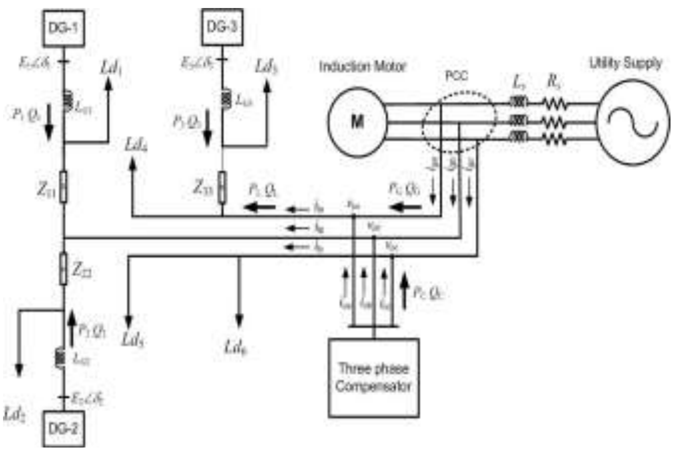

Figure 2: Structure of the grid system under consideration.

TABLE 1: GRID SYSTEM PARAMETERS

[1] **System Specifications**	[2] **Ratings**
[3] System frequency, f	[4] 50 Hz
[5] Feeder impedance, Z	[6] Z_{12}, Z_{23}, Z_{34}, Z_{45}, Z_{56}, Z_{67}, Z_{78}, Z_{89} = 1.03+j 4.71 Ω
[7] Load ratings	[8] L_1= 4.2 kW and 3.2 kVAr, [9] L_2= 4.2 kW and 3.2 kVAr, [10] L_3= 8.4 kW and 6.4 kVAr, [11] L_4= 4.2 kW and 3.2 kVAr, [12] L_5= 8.4 kW and 6.4 kVAr, [13] L_6= 8.4 kW and 6.4 kVAr, [14] L_7=4.2 kW and 3.2 kVAr
[15] DG rating	[16] DG-1= 5.2 kW, [17] DG-2= 7.5 kW, [18] DG-3= 3.0 kW
[19] Output inductance, L_G	[20] L_{G1}= L_{G2}=L_{G3}=L_{G4}=75 mH
[21] DC voltages (Vdc1 to Vdc4)	[22] 0.5 kV
[23] Transformer rating	[24] 0.350kV/0.350kV, 0.25 MVA,2.5%L_f
[25] VSC losses, R_f	[26] 1.5Ω
[27] Filter capacitance, C_f	[28] 50 µF
[29] Hysteresis constant, h	[30] 10^{-5}

5. Converter Structure and Control

The converter structure that is connected to the single-phase DGs is shown in Fig. 3

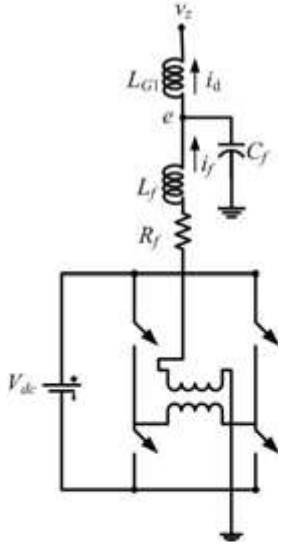

Figure 3: Single-phase converter structure.

Here the DG is assumed to be an ideal dc voltage source supplying a voltage of *Vdc* to the VSC. The converter contains one H-bridges. The output of the H-bridge is connected to a single-phase transformer. The resistance *Rf* represents the switching and transformer losses, while the inductance *Lf* represents the leakage reactance of the transformers. The filter capacitor *Cf* is connected to the output of the transformers to bypass switching harmonics. The inductance *LG* is physically connected to represent the output inductance of the converter-DG source combination. The same converter structure is used for all the single phase DG sources. The three phase compensator contains three such H-bridges. However, it is connected to the PCC without any output inductance. The schematic diagram is shown in Fig. 4.

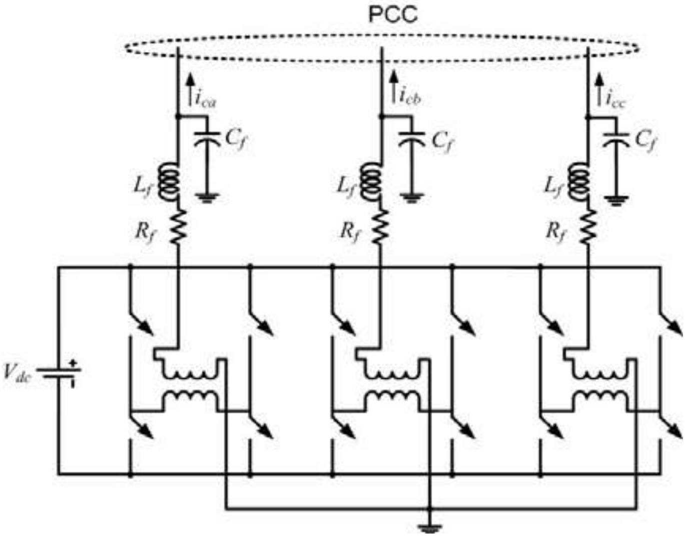

Figure 4: Three-phase converter structure for the compensator.

It is to be noted that for a DSTACOM, the dc bus contains a dc capacitor, while for a DG compensator; the dc bus is supplied by an ideal voltage source.

6. Simulation Results and Discussion

In order to understand the performance of operation and control of converter based single phase distributed generators in a utility connected grid, a power system network as shown in Fig.5 is implemented. There are different cases like without compensator, DSTATCOM Connected at PCC, DG-Compensator Connected at PCC and non-linear loads are simulated using MATLAB/SIMULINK software. Simulation studies are carried out in Matlab. The DGs are considered as inertia-less DC sources supplied through the VSCs.

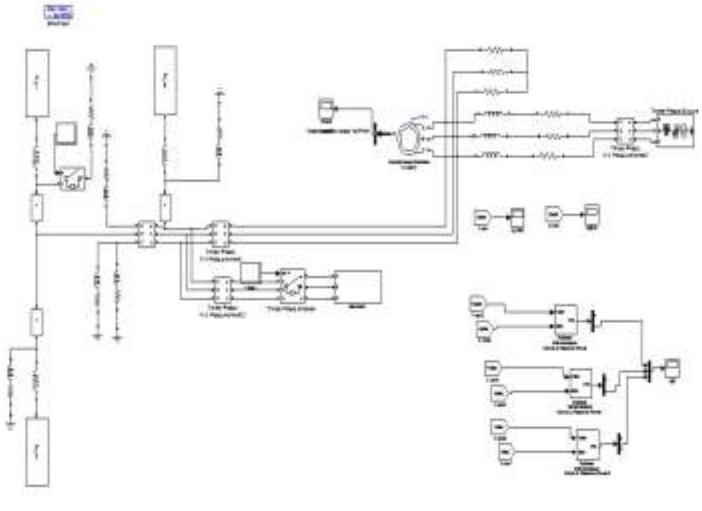

Figure 5: MATLAB/Simulink Model

6.1. Case-I: Without Compensator

It is assumed that all the single phase DGs are able to supply their maximum rated power. As is evident from Table that the total load demand is more than the total maximum generation. Thus the rest of the power requirement has to be supplied from the utility. It is assume that the system is operating in the steady state in which DG-2 is supplying 3 kW and load *Ld*1 is not connected. Suddenly at 0.45 s, the power output of DG-2 increase to 7 kW. Furthermore, at 0.7 s, the load L_{d1} gets connected drawing real and reactive power of 4.2 kW and 3.2 kVAr respectively. The system response is shown in Fig.6.

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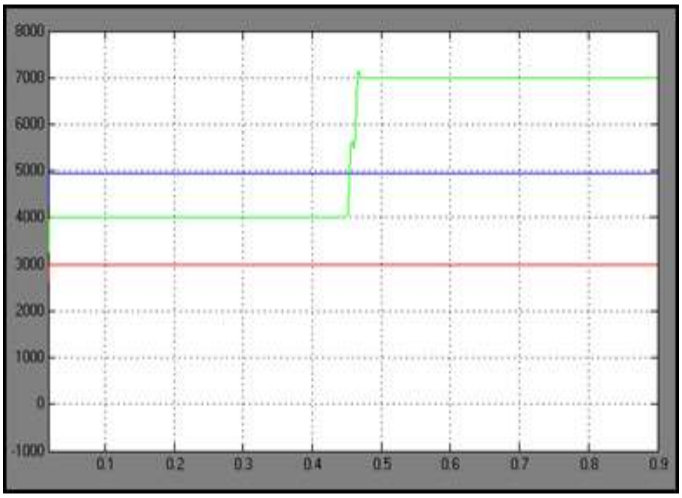
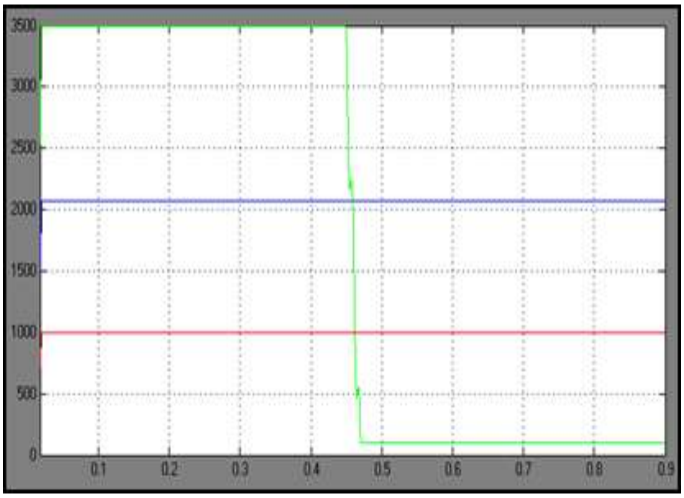


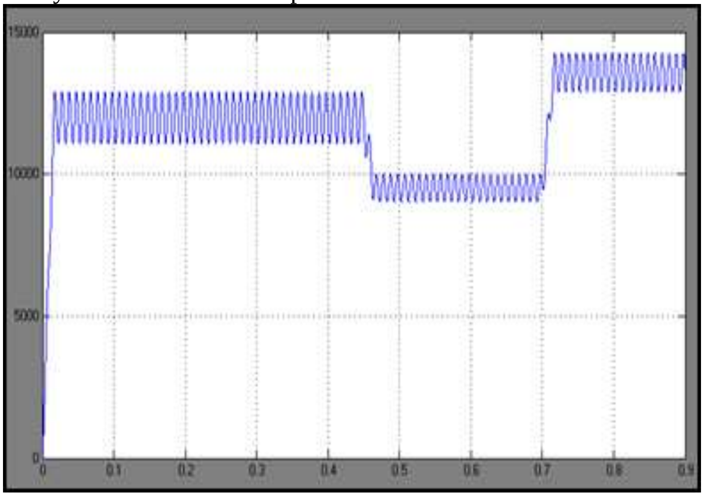
(a) Active power supply of single-phase DGs



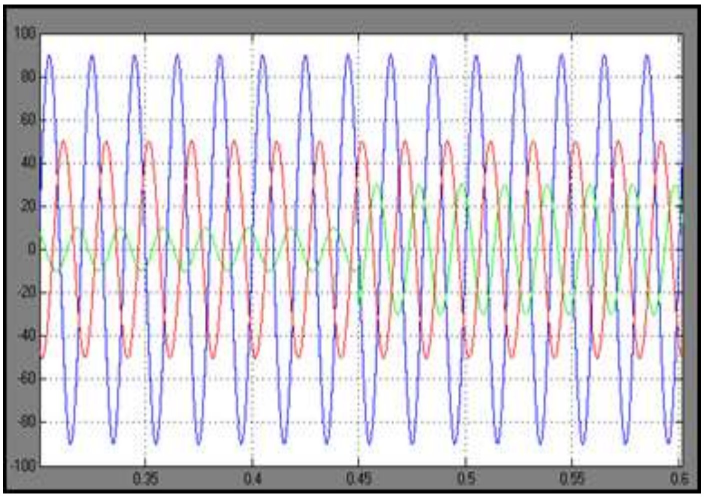
(b) Reactive power supply of single-phase DGs

Figure 6: Real and reactive power sharing for Case-1

It can be seen that the maximum power supply by DG-2 increase, while the load change has not impact on the maximum power supplied by any of the DGs. Fig. 7(a) shows the power supplied by the utility. The oscillation in the power level is due to the imbalance in the three phases. At 0.45 s the utility power decreases as the power generation in DG-2 is increased, while at 0.7 s the utility supply is increased to supply the load change in phase b. Fig. 7(b) shows the unbalanced utility currents in the three phases.



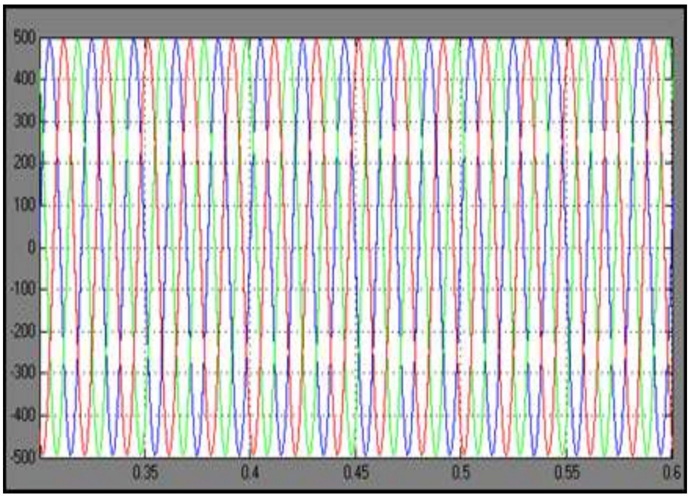
(a) Real power supply by the utility



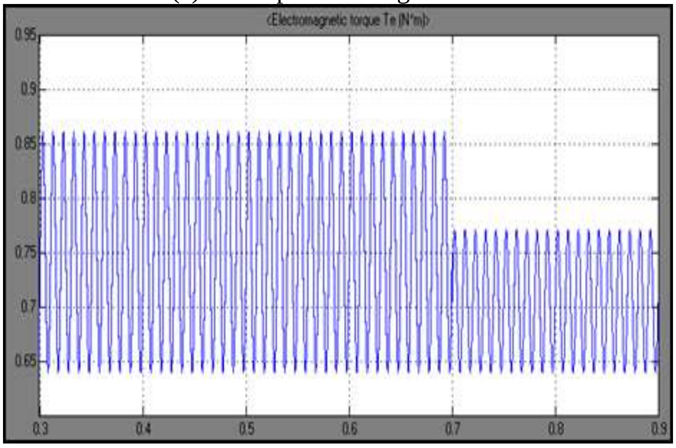
(b) Three phase current from the utility

Figure 7: Real power and three -phase current from utility

Let now investigate the impact of unbalanced currents on the induction motor that is connected at the PCC for the same test. Fig. 8(a) shows the three phase PCC voltage while Fig. 8 (b) shows the electrical torque of the induction machine. The unbalanced voltage at PCC creates the torque pulsation. High torque pulsation is totally undesirable for the operation of the induction motor.



(a) Three phase voltage at PCC

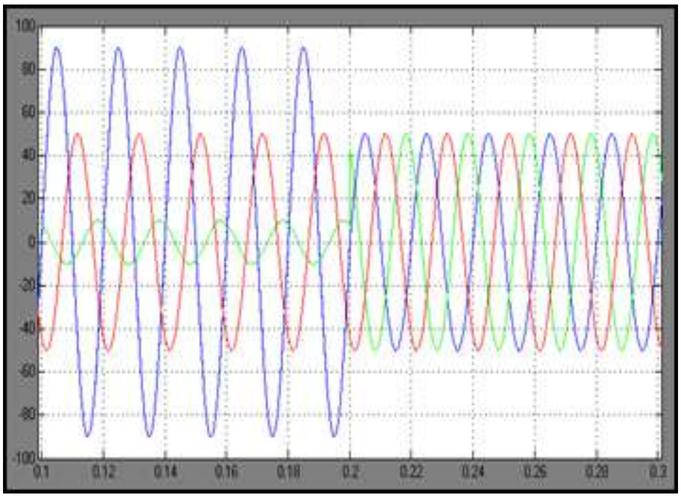


(b) Induction motor electrical torque

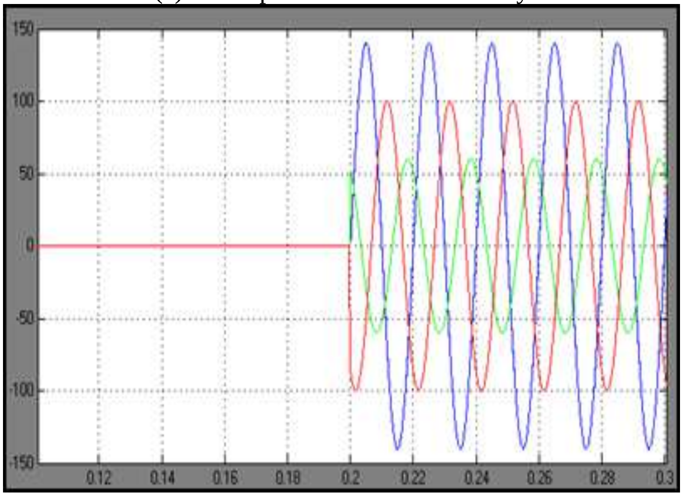
Figure 8: Voltage at PCC and induction motor torque

6.2. Case-II: DSTATCOM Connected at PCC

To compensate the imbalance among the phases, at first a DSTATCOM is connected as a three phase compensator. As discussed previously, DSTATCOM can share the reactive power requirement with utility in a pre-specified ratio. With the initial starting condition as in Case-1, the DSTATCOM is connected to the system at 0.2 s and it is desired that DSTATCOM supply the 70% of the reactive power while balancing the utility currents. The system responses are shown from Fig. 9(a) to. Fig. 9(b) shows the utility and DSTATCOM current. It can be seen that the utility currents gets balanced after the DSTATCOM connection. However, the DSTATCOM supplies unbalanced currents to compensate for the downstream unbalance.



(a) Three phase current from utility



(b) Three phase currents from utility and DSTATCOM

Figure 9: Three-phase currents from utility and DSTATCOM

The reactive power sharing between *QG*, *QC*, and *QL* is shown in Fig. 10. It can be seen that the DSTATCOM and the utility share the reactive power in 7:3 ratio as desired. Also, the DSTATCOM reactive power oscillates in sympathy with *QL*, while *QG* becomes flat.

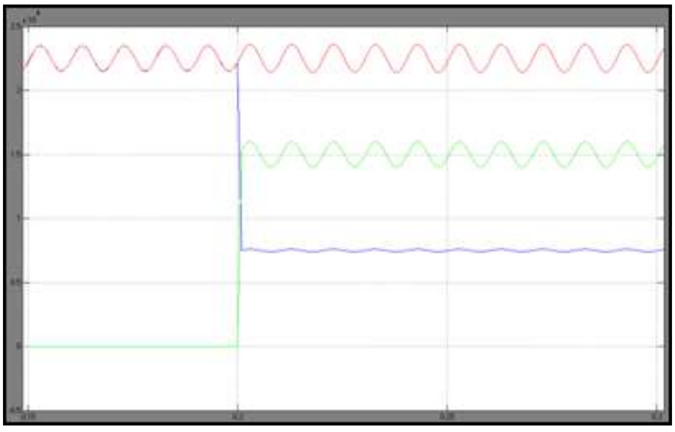
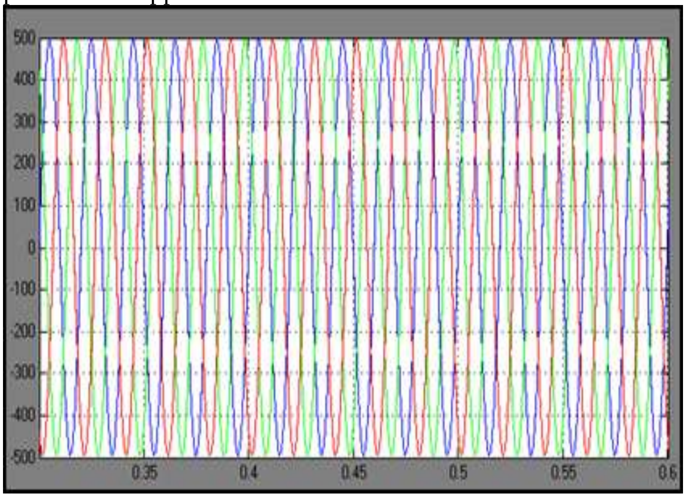
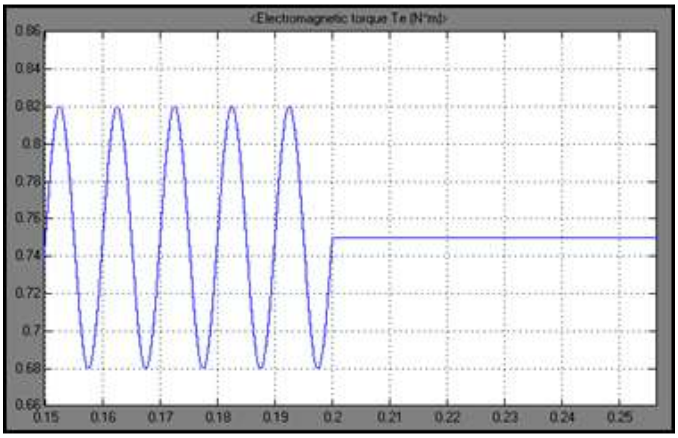


Figure 10: Reactive power sharing with DSTATCOM

The three-phase PCC voltages are shown in Fig. 11(a) the induction motor torque is shown in Fig. 11(b). The PCC voltages become balanced within 3-4 cycle after the DSTATCOM is connected to the system and the motor torque pulsation disappears and it becomes constant.



(a) Three phase voltage at PCC

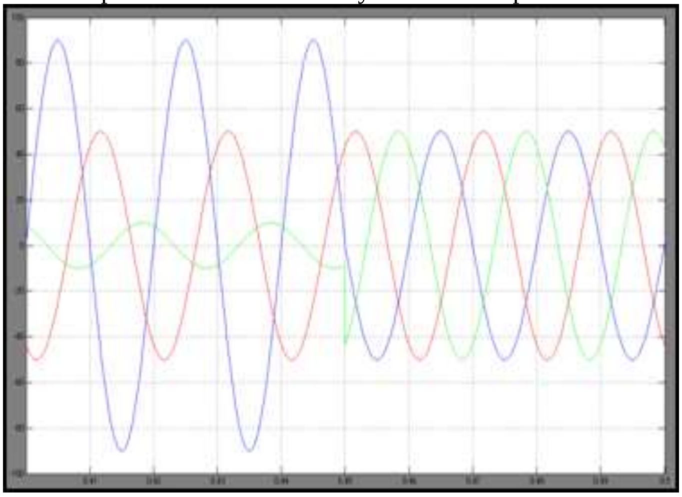


(b) Electrical torque of Induction motor

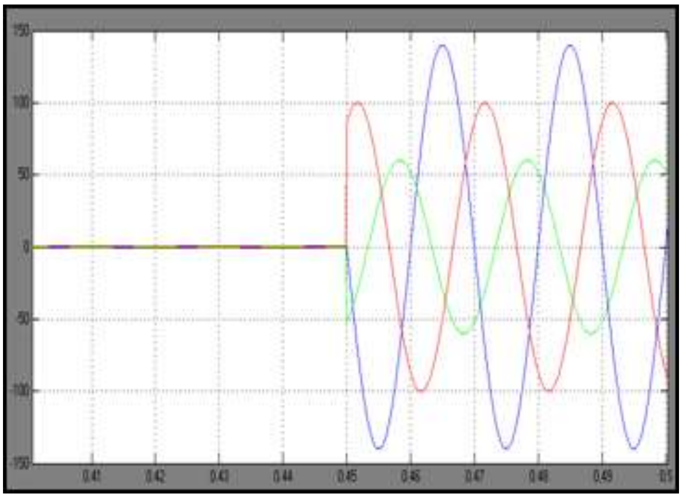
Figure 11: Voltage at PCC and induction motor torque

6.3. Case-III: DG-Compensator Connected at PCC

While the DSTATCOM can only provide the required reactive power, a compensator connected with DG can also share the real power burden of the utility. Let us assume that the DG-compensator supplies 30% of the real and reactive power demand (*PL*, *QL*), when it gets connected to the system at 0.45s. The system responses in Fig. 12(a) and Fig. 12(b) shows the three phase current from utility and DG compensator.



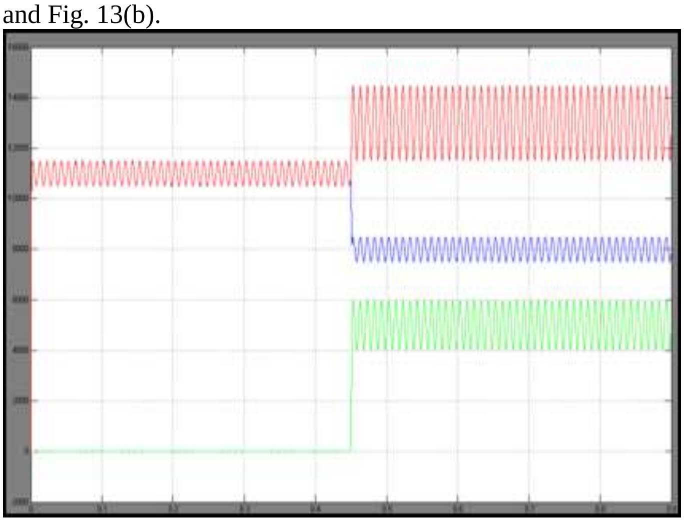
(a) Three phase current from utility



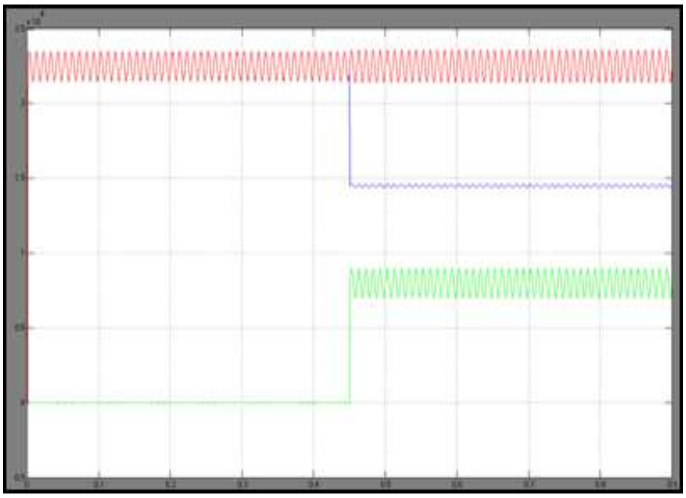
(b) Three phase current from utility and DG-compensator

Figure 12: Three phase current from utility and DG-compensator

The real and reactive power sharing are shown in Fig. 13(a) and Fig. 13(b).



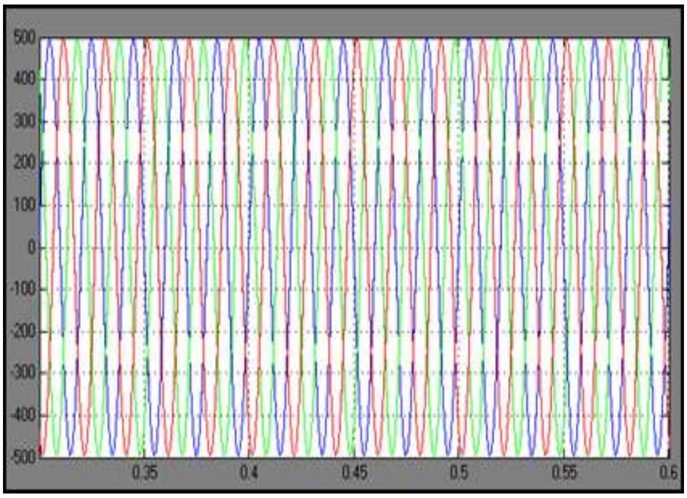
(a) Real power from sharing



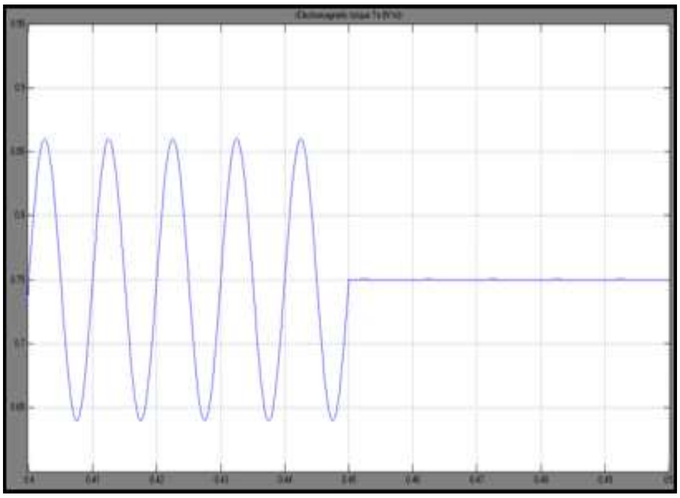
(b) Reactive power sharing

Figure 13: Real and reactive power from utility and DG-compensator

While utility provides balanced real and reactive power, the DG supplies the oscillating component alone in the desired ratio. The three-phase PCC voltages and the induction motor torque are shown in Fig. 14.



(a) Three phase voltage at PCC

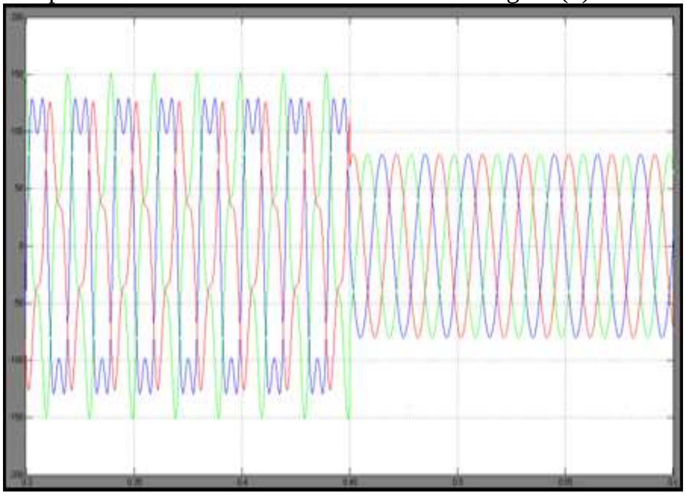


(b) Electrical torque of induction motor

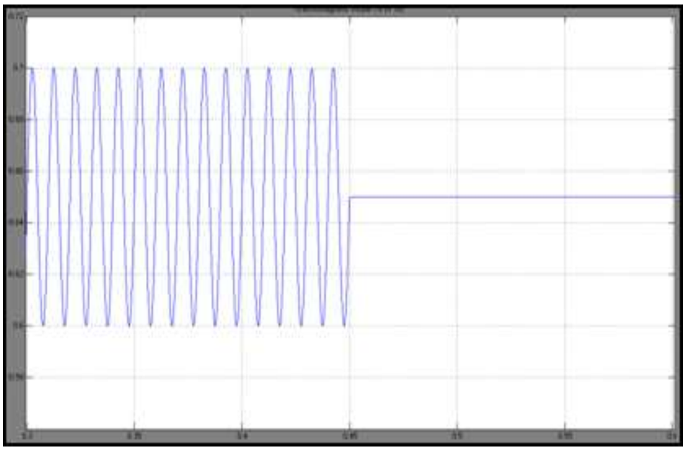
Figure 14: Voltage at PCC and induction motor torque

6.4. Case-IV: Nonlinear Loads

To investigate the efficacy of the DG-compensator further, nonlinear loads are added to the linear loads *Ld*1, *Ld*4, and *Ld*5. It is assumed that the power consumed by these nonlinear loads is 20% of their linear counterparts. The results are shown in Fig. 15 where is DG-compensator is connected at 0.45 s. It can be seen from Fig. 15(a) that the utility currents get balanced as soon as the DG-compensator is connected. The induction motor torque pulsation also ceases due to the DG-compensator connection as can be seen from Fig. 15(b).



(a) Three phase current from utility



(b) Electrical torque of induction motor

Figure 15: System response with nonlinear loads

The total harmonic distortion (THD) has been computed for this case. The THD of the grid voltage is about 10 % and the negative and zero sequence components are around 5 % of the positive sequence component before DG-compensation connection. These are then reduced such that the THD becomes less than 0.5 %, whereas, negative and zero sequence components of the voltages remain below 0.02 % once the DG compensator is connected.

7. Conclusion

In this paper, the operation and control of single phase DG sources are considered in a three-phase utility connected grid. The single phase sources are operated to deliver available maximum power generated while the rest of the power demands in each of the phases are supplied by the utility (and if available, three phase DG sources). The imbalance in three phase power is compensated two ways –either through a DSTATCOM or through a DG-compensator. A DSTATCOM can compensate for unbalances and nonlinearities while providing reactive power support. The size of the dc capacitor determines how much reactive power support the DSTATCOM can provide without any drop in voltage. The choice of this capacitor is thus a trade-off between the reactive support and system response. Alternatively a three phase DG-compensator can be connected at the PCC to share the real and reactive power with utility and to compensate for the unbalance and nonlinearities in the system. The efficacy of the compensation is validated through extensive simulations and calculation of THD. With the proposed structure of distribution system, it is possible to operate single phase DG sources in a utility connected grid and this might become a useful tool as their penetration in distribution systems increases.

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