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Grid Interconnection of Distributed Generation System with Power Quality Improvement Features

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ABSTRACT

This paper presents the modeling and control of grid interfaced Distributed Generation (DG) system with embedded active filter function. The output of the DG is given to the DC side of the Voltage Source Inverter for interfacing to the Grid. In the presented work, the features of Active Power Filter have been incorporated in the control circuit of the current controlled voltage source inverter interfacing the DG to the grid. Thus the same inverter is utilized to inject power generated from DG source to the Grid and also to act as Shunt Active Power Filter to compensate for load current harmonics and reactive power demand. Thus, after compensation, the Grid current is sinusoidal and in-phase with Grid voltage. The entire system is modeled in MATLAB/ SIMULINK environment and simulations carried out to verify the operation and the control principle. Various simulation results are presented for the proposed Grid interfaced DG system.

Keywords: *Active and Reactive Power, Distributed Generation, Utility Grid, Pulse Width Modulated Voltage Source Inverter*

I. INTRODUCTION

The rapidly increasing global energy consumption has become a matter of great concern for both utilities and the end users. The fossil fuels which are the primary sources of electric power cause serious environmental pollution and moreover these fossil fuels are on the verge of extinction. Hence, a transition from conventional energy systems to more cleaner and secure energy is necessary to alleviate energy crisis and to address environmental concerns. Distributed Generation (DG) are rapidly increasing across the globe because they can meet the increasing power demand while complying with the environmental regulations of low emissions [1, 2].

Interfacing the DG to the grid presents a quite different and challenging scenario because unlike the conventional system, the DG cannot be directly connected to the grid. A power conditioning interface between the DG and grid is required to match the characteristics of DG and the requirements of the grid connections such as voltage, frequency, active and reactive power control, harmonic minimization etc [3,4].

The increased use of non-linear devices results in many power quality problems in the power system network. These non-linear devices not only increase the reactive current but also generate significant current harmonics giving rise to non sinusoidal current and voltage waveforms at the point of common coupling (PCC). The increased reactive power and non-sinusoidal supply voltage and current result in many adverse effects such as overheating of distribution transformers, poor system efficiency, instability, disturbance to other consumers and interference with precision instrument and communication equipment etc. The power quality of the DG system is affected by the harmonic content of the current injected to grid by the inverter and also by the harmonic currents produced by non-linear loads connected to the system. Non-linear elements produce harmonics in DG system and affect the quality of electric power [8,9].

In order to solve the above power quality problems, many active power filters have been proposed in the recent years because the conventional passive filters used because of their low cost and high efficiency have demerits of fixed compensation, large size and resonance. The shunt active power filter (SAPF) presents a dynamic solution best suited for the compensation necessities. The SAPF can compensate the unwanted reactive, unbalanced and harmonic load current components under non-sinusoidal supply voltage [5-7,11]. The principle of operation of the SAPF is to supply the undesired harmonics and reactive power to the load, so that the mains current is of improved quality. But the installation of the SAPF requires additional costs. The cost of installing DG system is also large. Thus, the function of SAPF can be implemented with the DG system thus reducing the overall cost [10].

With the objective of reducing the cost and increasing the efficiency, a single-phase, Grid-interactive DG system has been proposed which includes the functionality of SAPF. The function of APF is added in the existing inverter of DG system by making the necessary modification in the control circuit.

Thus, the proposed interface does not require any additional circuit for enabling the existing inverter to also perform APF function. This concept, thus, reduces the overall design cost of the system. The proposed system is capable of injecting DG power to electric Grid while compensating load reactive power and harmonics caused by non-linear loads.

II. GRID INTERFACING/SHUNT ACTIVE POWER FILTER INVERTER CONTROL

Fig. 1 shows the single line diagram of Grid interfaced DG system. Pulse-width modulated (PWM) H-Bridge CC-VSI is used to interconnect the DG system to the utility Grid for power flow and power quality control purposes. A DC-link capacitor on the DC side of the VSI acts as an energy buffer and makes a stable DC voltage for the converter in the steady state condition. This DC-link capacitor decouples the DG from the Grid and also allows independent control of converters on either side of DC-link.

The Grid-interface/SAPF inverter control circuit of proposed Grid-interactive DG system is shown in Fig. 2. The AC-side voltage of the inverter is controlled both in magnitude and phase to control the active and reactive power flow between the DG and the grid. The function of the APF is to maintain the desired source currents to be sinusoidal, and inphase with the fundamental component of source voltages.

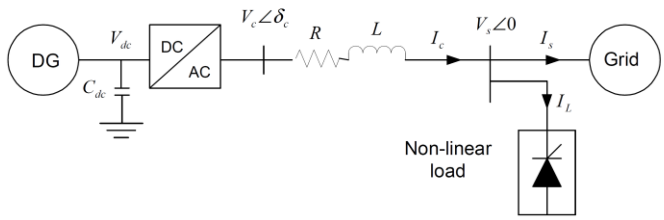

Fig 1 Single line diagram of Grid interfaced DG system.

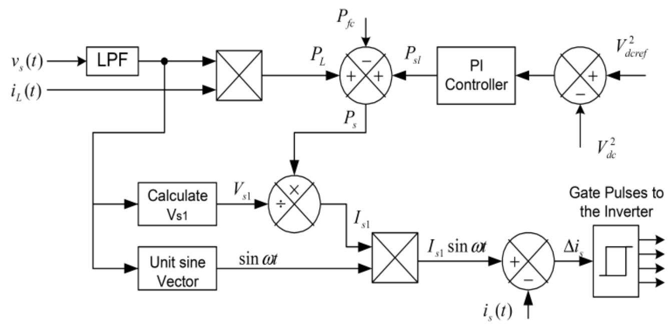

Fig 2 Control circuit of Grid-interfacing/ SAPF Inverter

The average value of active power supplied by the Grid is:

$$P_S = P_L + P_{sl} - P_{dg} \qquad (1)$$

where P_L is the load active power, P_{sl} is the active loss power of the inverter and P_{dg} is the active power supplied by the DG source. The inverter consumes a small amount of active power to maintain the DC-link voltage and to overcome the losses associated with the inverter. The losses in the inverter are because of the switching loss in the devices, iron and copper losses in the circuit components, etc. Discrete PI controller is used to maintain a constant DC-link voltage under varying conditions.

III. RESULTS AND DISCUSSIONS

The entire DG circuit is simulated in MATLAB/Simulink using power system block sets to validate its performance.

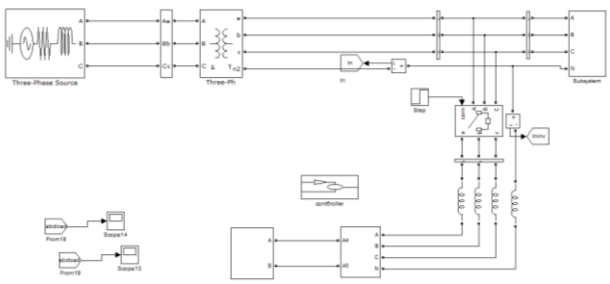

Fig. 3 MATLAB/Simulink model of the system

The simulation results are presented for two different modes of operation. In the first mode of operation there is no power generation from the DG source. Thus in this mode of operation, the grid-interfacing inverter is working as a SAPF, thus improving the power quality at PCC. In the second mode of operation, apart from working as a SAPF, the inverter is also injecting active power from DG to the grid. The grid current waveforms have been analyzed to obtain their total harmonic distortions (THDs) before and after compensation in different modes of operation under varying load conditions.

Mode 1: Power quality enhancement mode-No supply from DG

In this mode of operation, there is no power generation from the DG source. Thus the grid interfacing inverter is operating as a SAPF. In other words, the grid-interfacing inverter is utilized as SAPF when there is no power generation from DG source.

In the SAPF mode of operation, the inverter consumes a small amount of active power from the grid to maintain the DC-link voltage and to overcome the losses associated with the inverter and most of the load reactive power need is provided by inverter effectively.

Case 1(a) Reactive compensation

In this case a linear load is connected at PCC. Thus both source voltage as well as source current is sinusoidal but not in phase. The APF is required to compensate the reactive power only. At t=0.1, the inverter is switched on. At this instant the inverter starts injecting the compensating current so as to compensate the phase difference between the source voltage and current.

Figure 4 shows the waveforms of grid voltage Vs and load current I_L, grid current Is, APF inverter compensating current Iv and DC-link capacitor voltage Vdc. The grid voltage Vs and grid current is in Figure 5.

At time t=0.1s, when the inverter is switched on, there is a significant improvement in the power factor. Thus the APF compensates the phase difference between the grid voltage and grid current. The DC-link voltage is maintained at 150V. The linear load is changed at times t=0.4s and t=0.8s. The results confirm the good dynamic performance of the SAPF for a rapid change in the linear load current. The corresponding grid, load and inverter active Pgrid, Pload and Pinv) and reactive powers (Qgrid, Qload and Qinv) is shown in Figure 6.

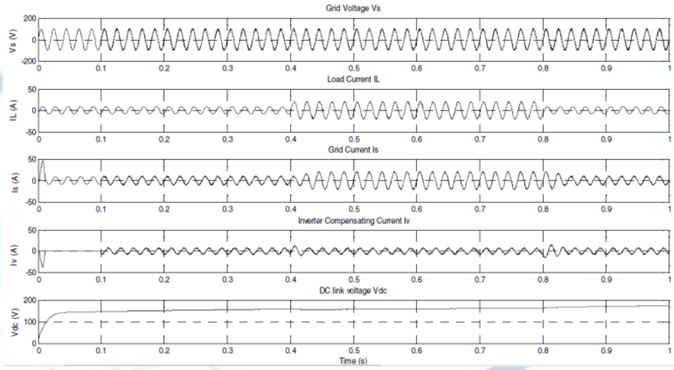

Fig 4 Grid Voltage Vs, Load Current IL, Gridcurrent Is, Inverter Compensating Current Iv and DC-Link Voltage Vdc for Case 1(a)

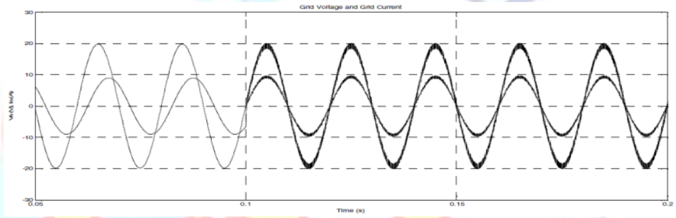

Fig 5 Grid voltage Vs (scaled by factor 0.1) and current Is

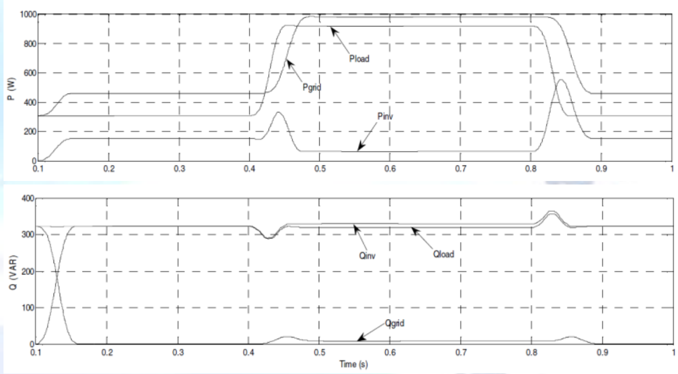

Fig 6 Grid, Load and Inverter active powers (Pgrid, Pload and Pinv), reactive powers (Qgrid, Qload and Qinv)

Case 1(b) Reactive and harmonic compensation

In this case, the source voltage is sinusoidal and the load current is non-sinusoidal because of the non-linear load connected at PCC. The load in this case is a diode bridge rectifier load followed by an inductor in series with a resistor. Fig 7 shows the waveforms of grid voltage Vs, load current I_L, grid current Is, APF inverter compensating current Iv and DC-link capacitor voltage Vdc. The APF inverter is switched on at t=0.1s. The grid current at t=0.1s become pure sinusoidal and in phase with the grid voltage as shown in figure 8. The FFT of the grid current before and after compensation is carried out. The current THD is reduced from

30.58% to 2.70% as shown in Figure 9. The non-linear load is changed at the time t=0.4s and t=0.8s to verify the dynamic performance of APF. The corresponding grid, load and inverter active powers (Pgrid, Pload and Pinv) and reactive powers (Qgrid, Qload and Qinv) is shown in Figure 10.

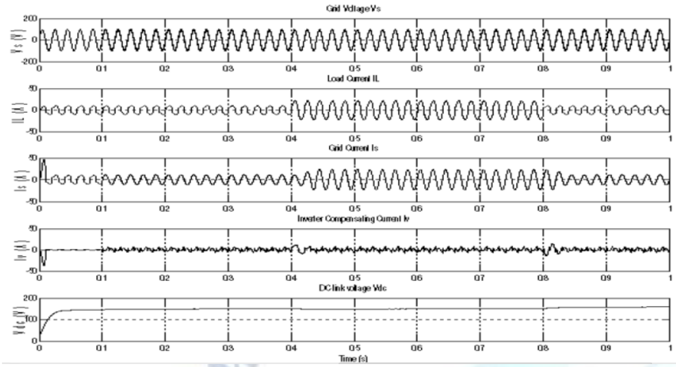

Fig 7 Grid Voltage Vs, Load Current IL, Grid current Is, Inverter Compensating Current Iv and DC-Link Voltage Vdc for Case 1(b)

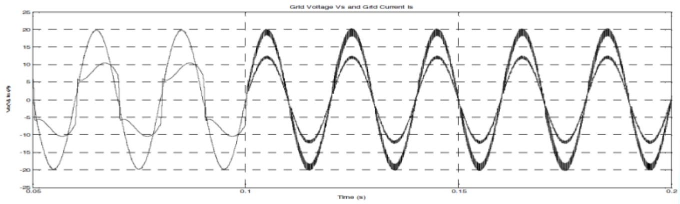

Fig 8 Grid voltage Vs (scaled by factor 0.1) and current Is

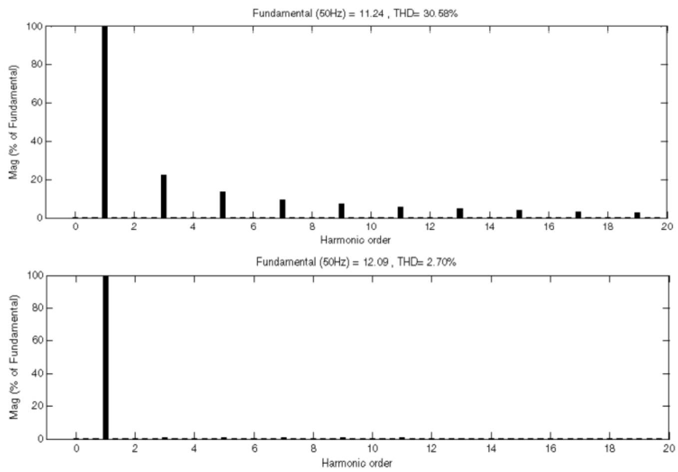

Fig 9 THDs of Grid Current (a) before compensation and (b) after compensation

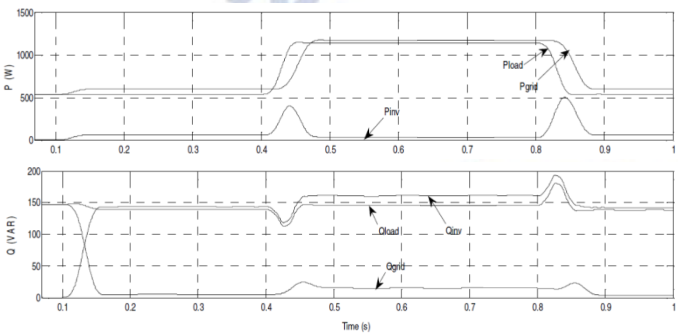

Fig 10 Grid, Load and Inverter active powers (Pgrid, Pload and Pinv), reactive powers (Qgrid, Qload and Qinv)

Mode 2: DG feeding power, Non-linear load

In this mode of operation, the DG is supplying power to the grid and the load. Thus the inverter is also injecting active power from DG to the PCC apart from working as a SAPF. The AC-side voltage of APF inverter is controlled both in phase and magnitude to further control the active and reactive power, respectively.

The inverter is switched on at t=0.05s. Thus at t=0.05s the inverter starts injecting active power generated from DG source. Since the DG power is more than the load active power demand Pload, after meeting the load power demand, additional power of the DG flows to the grid. The PCC voltage Vs, load current IL, grid current Is and inverter current Iv is shown in Figure 11.

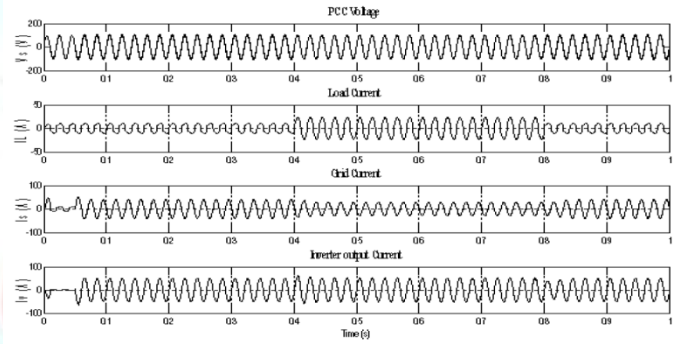

Fig 11 Grid Voltage Vs, Load Current IL, Grid current Is, Inverter Compensating Current Iv and DC-Link Voltage Vdc for Case 2

Thus the grid-connected inverter provides the entire load power demand i.e. active reactive and harmonic load power and feeds the additional active power to the grid. The grid current and voltage together is shown in Figure 12. The 180 degree phase shift between the grid voltage and the grid current suggests that the additional power is fed to the grid at unity power factor. The exchange of active and reactive powers between grid, load and DG source is shown in Figure 13. The active powers of grid, load and DG source are represented as Pgrid, Pload and Pdg and the reactive powers of grid, load and DG stack by Qgrid, Qload and Qdg respectively. Thus in this case the grid interfacing inverter is simultaneously utilized to inject the power generated from DG to PCC and to improve the power quality at PCC.

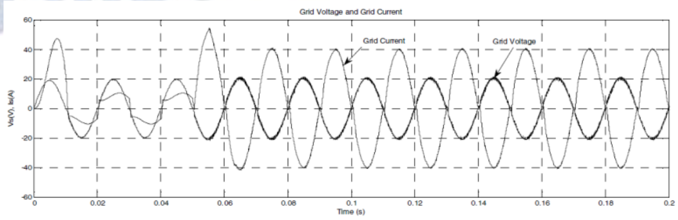

Fig 12 Grid voltage Vs (scaled by factor 0.1) and current Is

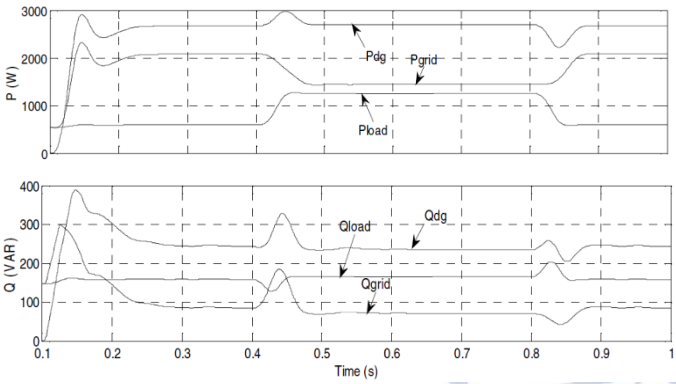

Fig 13 Grid, Load and DG active powers (Pgrid, Pload and Pinv), reactive powers (Qgrid, Qload and Qinv)

Table 1 results

Cases	Supply Current THD (%)	Load Current THD (%)	Power factor of load	Power factor of ***grid***
Case 1(a)	1.94	18.65	0.977	1
Case 1(b)	2.34	18.65	0.977	1
Case 2	1.80	18.65	0.977	1

Thus from the simulation results, it is evident that the grid-interfacing inverter can be effectively used to compensate the load reactive power, current unbalance and current harmonics in addition to active power injection from RES.

This enables the grid to supply/ receive sinusoidal and balanced power at UPF.

IV CONCLUSIONS

This paper has presented a novel control of an existing grid interfacing inverter to improve the quality of power at PCC for a 3-phase 4-wireDGsystem. It has been shown that the grid-interfacing inverter can be effectively utilized for power conditioning without affecting its normal operation of real power transfer. The grid interfacing inverter with the proposed approach can be utilized to:

I) Inject real power generated from RES to the grid, and/or,

II) Operate as a shunt Active Power Filter (APF).

This approach thus eliminates the need for additional power conditioning equipment to improve the quality of power at PCC. Extensive MATLAB/Simulink simulation as well as the DSP based experimental results have validated the proposed approach and have shown that the grid-interfacing inverter can be utilized as a multi-function device.

It is further demonstrated that the PQ enhancement can be achieved under three different scenarios. The current unbalance, current harmonics and load reactive power, due to unbalanced and non-linear load connected to the PCC, are compensated effectively such that the grid side currents are always maintained as balanced and sinusoidal at unity power factor. Moreover, the load neutral current is prevented from flowing into the grid side by compensating it locally from the fourth leg of inverter. When the power generated from RES is more than the total load power demand, the grid-interfacing inverter with the proposed control approach not only fulfills the total load active and reactive power demand (with harmonic compensation) but also delivers the excess generated sinusoidal active power to the grid at unity power factor.

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