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DG-Grid Interfaced System with Shunt Active Filter Functions

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Abstract— **This paper deals with the control of active and reactive power while compensating voltages of a distributed generation (DG)-grid interfaced with energy storage shunt active power filter (APF). The APF control is based on reference current estimation in d-q reference frame. The proposed APF control system is capable for controlling the active power supplied by the distributed generation system while compensates load power factor and harmonics. The active power exchange is based on phase angle between APF inverter and grid voltages and reactive power control is based on magnitude of their voltages. The wide simulation of the study is carried out under MATLAB /Simulink environment to illustrate the effectiveness of the control algorithm. Various simulation results are offered with integrated mode (forward and reverse power flow) of operation of distribution generation system with utility grid.**

Keywords- Active power filter (APF), current controlled voltage source inverter (CC-VSI), distributed generation (DG), harmonics and power quality.

I. Introduction

The global energy consumption is increasing by leaps and bounds to improve the living standards of mankind's worldwide. Moreover, the requirement of the reliable and quality power supply has become indispensable [1]. Today there has been a growing concern on technological, economical and environmental for a more efficient use of the energy are boosting the interest in expanding electric generating capacities through the use of distributed energy generation (DEG) [2]. Distributed generation encompasses a wide range of prime mover technologies, such as internal combustion (IC) engines, gas turbines, microturbines, photovoltaic cells, fuel cells and wind-power [3]-[4]. A micro grid comprise of low voltage distribution system with integrated distributed energy sources, energy storage devices and controllable loads connected to the main power network or islanded, in a controlled, coordinated way [2]-[5]. This integrated DG along with microgrid system can solve many typical problems of conventional AC system such as energy security, reduces transmission and high voltage equipment cost etc. Nevertheless, a small DG has some significant problems of frequency and voltage variation when it is operated in stand-alone mode [6]-[8]. Consequently, a small DG shall be interconnected with the power system in order to maintain the frequency and the voltage. Further a large penetration of DG may produce different technical problems related to power quality [4]-[7].Therefore; the power quality issue has become important nowadays. Fig.1 shows a general purpose block diagram of DG-grid system with power electronics interface which can be subdivided into four major sections. These include: the DG source input converter module, an inverter module, the output interface module, and the controller module. The unidirectional arrows show the power flow path for the distributed energy sources whereas the bidirectional arrows illustrate the bidirectional power flows for the distributed energy storages. The input converter module can be either used with alternating current (AC) or direct current (DC) DG systems and is most likely to be specific for the type of energy source or storage. The DC-AC inverter module is the most generic of the modules and converts a DC source to grid-compatible AC power. The output interface module filters the AC output from the inverter. The fourth major module is the monitoring and control module that drives the entire interface and contains protection for both the DG source and the utility at the PCC [5]-[10].

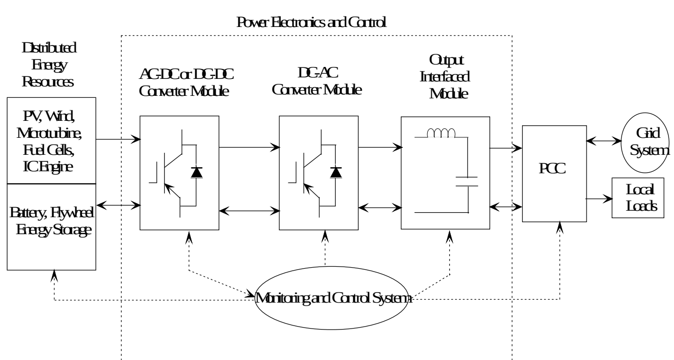

Fig.1 General Purpose block diagram of DG-grid system.

The basic objective of the distribution generation system connected with grid is to control the power that the inverter injects into the grid. According to the grid demands, injected power does not only include the control of the active power, but also the control of the injected reactive power. Several studies proposed an interconnection system for DG with the power system through the inverter because the inverter gives versatile functions for improving the performance of DG [4]-[10]. Chandorkar et al. [7] has studied line interactive inverters to be used as uninterruptible power supplies (UPS), where the inverters do not power the local load and the utility mains simultaneously, and therefore do not contribute to transmission system stability. References [8] and [9] have reported field test results of active filters intended for installation on power distribution systems. Liang et al. [10] have presented a power control method for a grid-connected voltage source inverter which achieves good (P, Q) decoupling and fast response. However, this approach requires knowledge of the value of power system equivalent impedance, which is not viable. Illindala et al. [11] have presented a different power control strategy based on frequency and voltage droop characteristics of power transmission, which allows decoupling of P and Q at steady state. F. Blaabjerg et al. [12] have suggested the applications of power electronics in the integration of DG units, in particularly, wind power, fuel cells and PV generators. This paper presents the combined operation of APF and DG which is connected to a dc-link energy storage system through rectifier. The proposed APF system is capable for compensating harmonics, reactive current and voltage regulation while injecting energy to grid.

II. Active Power Filter an Overview

In active power filters a theory has been established by H. Akagi *et al.* [13] and Gyugyi [15] that a current controlled voltage-source inverter (CC-VSI) may capable to compensate reactive power and harmonics of the nonlinear loads. This concept put forward to formulate a well-known p-q theory of reactive power [15]. According to the p-q theory, the instantaneous reactive power compensator consist of switching device which practically does not require any energy storage components, can compensate fundamental reactive power in transient states along with harmonics currents caused by instantaneous imaginary power of the loads. Apart from reactive power theory there have been several other theories of harmonics compensation. In which some are called the notch filter, flux observer, instantaneous power theory, synchronous reference frame , synchronous detection method, direct and indirect current control techniques and many more [16]-[21].

A. Basic Compensation principle

The basic compensation principle of APF is explained with the help of Fig.2. The instantaneous current of the nonlinear load can be represented as (1)

$$i_L(t) = I_{Lf}\sin(\omega t)\cos(\phi_{Lf}) + I_{Lf}\cos(\omega t)\sin(\phi_{Lf}) + \sum_{h=2}^{\infty} I_{Lh}\sin(h\omega t + \phi_{Lh}) \quad (1)$$
$$= i_{Lfp} + i_{Lfq} + i_{Lh}$$

where, I_{Lf} and I_{Lh} are the peak value and Φ_{Lf} and Φ_{Lh} are the phase angle of the fundamental and harmonic component of the load currents, respectively. A shunt APF is designed to be connected in parallel with the load, to detect its harmonic and reactive current and to inject an identical compensating current into the system. Therefore, Instantaneous supply currents having only fundamental component which is in-phase with their respective voltages.

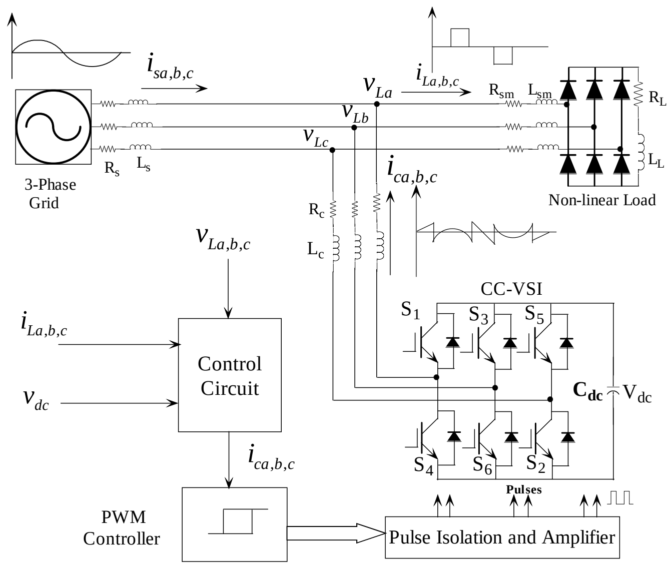

Fig.2. Topology of shunt active power filter.

B. Active Power Filter Parameters Selection

The reference value of dc-link capacitor voltage of APF is mainly depends upon the reactive power compensation capability. For reactive power compensation the primary condition is that the magnitude of reference dc-link capacitor voltage should be higher than the PCC voltage V_L. During reactive power compensation the operation of switches generate a voltage V_c having fundamental component V_{c1} towards AC side of the DC-AC converter (inverter). For proper reactive current compensation (to maintain source fundamental current I_{sp} in-phase with the V_L) the APF generate a current I_{cq} of magnate equal and 180^0 out of phase with load reactive current as shown in Fig.3. The vector diagram represents the reactive power flow in which source fundamental current I_{sp} is in-phase with PCC fundamental voltage V_L and the reactive component of filter current I_{cq} orthogonal to V_L.

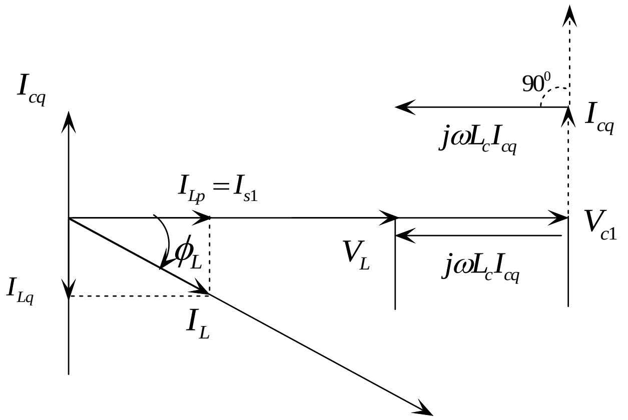

Fig.3. Basic circuit topology of shunt active power filter.

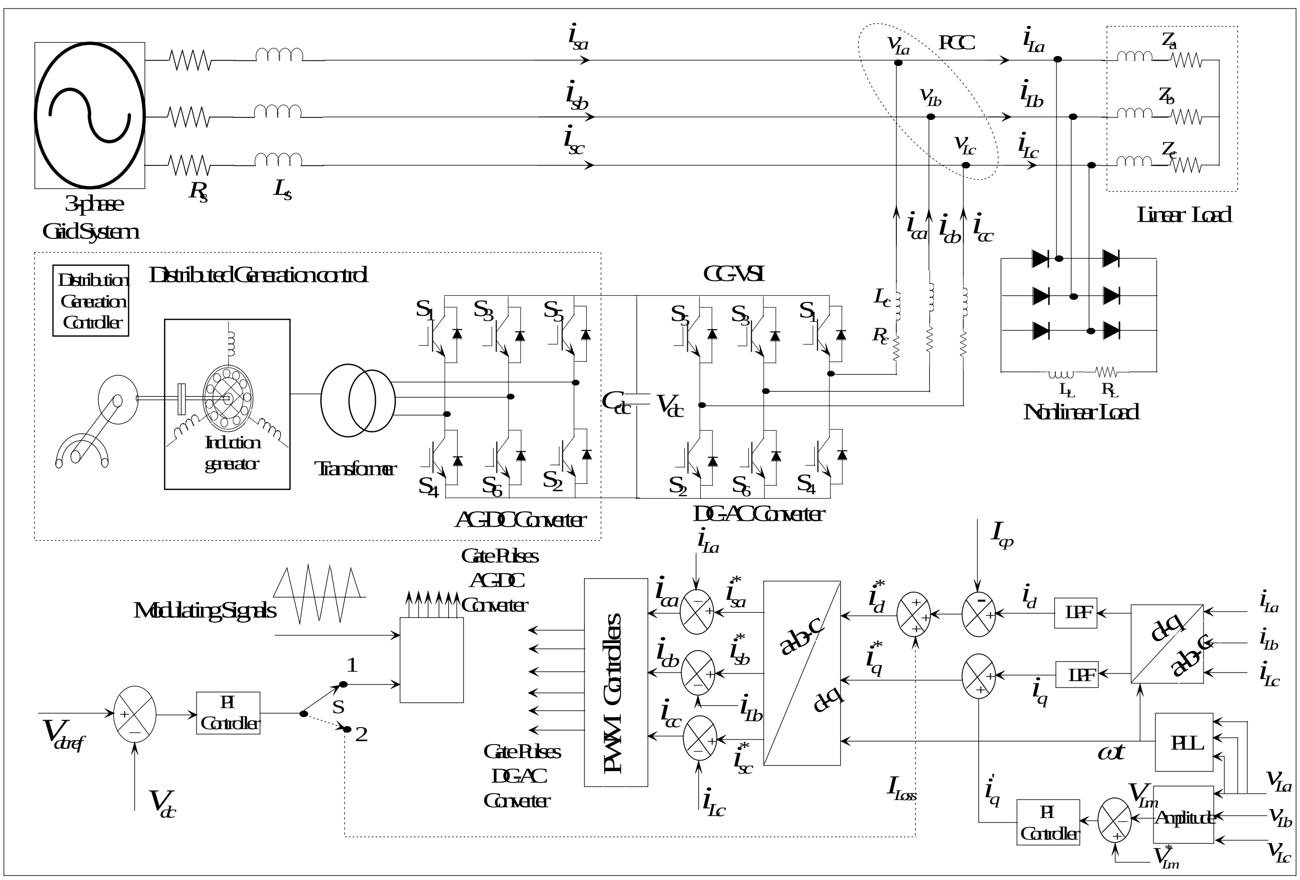

Fig.4. Schematic diagram of power and control circuit of the proposed DG-Grid system interfaced with active power filter.

From vector diagram shown in Fig.3

$$V_{c1} = V_L + j\omega L_c I_{cq} \qquad (2)$$

From (2) I_{cq} is

$$I_{cq} = \frac{V_{c1} - V_L}{j\omega L_c} = \frac{V_{c1}}{\omega L_c}(1 - \frac{V_L}{V_{c1}}) \qquad (3)$$

Three-phase reactive power delivered by the APF is equal to the three-phase reactive power requirement of the nonlinear load, hence from vector diagram.

$$Q_{cq} = Q_L = 3V_L I_{cq}$$

$$= 3V_s\left(\frac{V_{c1}}{\omega L_c}\right)\left(1 - \frac{V_L}{V_{c1}}\right) \qquad (4)$$

From (4) it is obvious that the APF can compensate the load reactive current only when $V_{c1} > V_L$ and for this case value Q_{cq} is positive. For the case when $V_{c1} < V_L$, the Q_{cq} is negative and

APF will draw the reactive power from the utility. The upper limit of V_{c1} is calculated on the basis of maximum compensation capacity of the APF, calculated as follows:

$$\frac{dQ_{c1}}{dV_L}=0; \quad \frac{d}{dV_L}\left(\frac{3V_LV_{c1}}{\omega L_c}-\frac{3V_L^2}{\omega L_c}\right);\ V_{c1}=2V_L$$

Thus the maximum capacity of APF can be obtained as:

$$Q_{cq\max}=\frac{3V_L^2}{\omega L_c} \tag{5}$$

Hence, the value of reference dc-link capacitor voltage of the APF must be according to the reactive power requirement of the system. From above relations the range of V_{c1} will be

$$V_L < V_{c1} \leq 2V_L$$

If it is assumed that the PWM converter operates in the linear modulation mode ($0\leq m_a \leq 1$) [27] then,

$$m_a=\frac{2\sqrt{2}\,V_{c1}}{V_{dc}}, \quad for\ m_a=1,\ V_{dc}=2\sqrt{2}V_{c1} \tag{6}$$

Due to switching of the converter there will be ripples in the output current of the converter. To control the level of ripple current a filter inductor L_c is used to attune the ripples of the filter current. Hence, the design of the filter inductor L_c is based on the principle of harmonic current reduction. For sinusoidal PWM converter that operates in the linear modulation mode $0\leq m_a \leq 1$, the maximum harmonic voltage occurs at the frequency ωm_f where, m_f is the frequency modulation ratio of the PWM converter [23]. Considering only this harmonic content, the ripple of the converter current can be given as:

$$I_{ch} \cong I_{ch}(\omega m_f)=\frac{V_{ch}(\omega m_f)}{\omega m_f L_c} \tag{7}$$

where h denotes the harmonic components.

For qualitative representation, ratio of I_{ch} and $I_{chrated}$ is defined as ripple attenuation factor (RAF);

$$RAF=\frac{I_{ch}}{I_{ch_{rated}}} \tag{8}$$

Solving equations (4) and (8) simultaneously will give V_{dcref} and filter inductance L_c.

III. System Description

The schematic diagram of the proposed DG-grid system interfaced with energy storage active power filter for compensating harmonics and reactive current of load while regulating the PCC voltages is shown in Fig.4. A Three-phase grid with source resistance R_s, and inductance L_s per phase, supplying power to nonlinear load. A current controlled 3-phase shunt active power filter with energy storage capacitor C_{dc} is connected in parallel with load and grid. The APF consists of an inductor L_c and a resistance R_c (equivalent resistance of the inverter circuit) per phase and a three-phase IGBT bridge current-controlled voltage source inverter (CC-VSI). A fixed speed distributed generation unit is connected to the dc-link of APF through AC-DC converter. A smoothing inductor of resistance R_{sm} and inductance L_{sm} per phase is also connected in series with nonlinear load. The APF can compensate the current harmonics, load power factor and voltage regulations while the DG supplying power to the source and loads or only loads.

III.The Proposed Control Technique

The proposed controller for the DG-grid interconnected system with active power filter is shown in Fig.4. The system works in interconnected mode when both the DG and the grid supply power to the load. But it works in islanding mode when the voltage interruption on grid occurs. Once the voltage interruption is removed, the system operation transfers from the islanding mode to the interconnected mode. The control of inverter involved the control of active power supplied by DG and reactive power requirement of load in such a way that reactive power supplied by the main source remains zero. The ac-side voltages of the active power filter interfaced inverter are controlled both in magnitude and phase to control the active and reactive power.

The synchronous reference frame theory based method is used for reference current generation. The load currents, PCC voltages and dc-link capacitor voltage of the APF are sensed as feedback signals for the controller. In order to examine the compensation mechanism let's assume that distribution generation uses a constant speed induction generator and the grid voltages of vector $\vec{v_s}$ and load currents of vector $\vec{i_L}$ consist a set of harmonic components h are expressed in (9) and (10) respectively, where H = {1, 2, 3……..N} and where N is the highest order of harmonics under considerations.

$$\vec{v_s}=\begin{bmatrix} v_{sa}=\sum_{h\in H}^{H} V_{sha}\sin(h\omega t+\alpha_{ha}) \\ v_{sb}=\sum_{h\in H}^{H} V_{shb}\sin(h(\omega t-2\pi/3)+\alpha_{hb}) \\ v_{sc}=\sum_{h\in H}^{H} V_{shc}\sin(h(\omega t+2\pi/3)+\alpha_{hc}) \end{bmatrix} \tag{9}$$

$$\vec{i_L}=\begin{bmatrix} i_{La}=\sum_{h\in H}^{H} I_{Lha}\sin(h\omega t+\alpha_{ha}-\phi_{ha}) \\ i_{Lb}=\sum_{h\in H}^{H} I_{Lhb}\sin(h(\omega t-2\pi/3)+\alpha_{hb}-\phi_{hb}) \\ i_{Lc}=\sum_{h\in H}^{H} I_{Lhc}\sin(h(\omega t+2\pi/3)+\alpha_{hc}-\phi_{hc}) \end{bmatrix} \tag{10}$$

where $V_{sha,b,c}$ and $I_{Lha,b,c}$ are the peak value of supply voltages and load currents corresponding to h^{th} order harmonics, $\alpha_{ha,b,c}$ and $\Phi_{ha,b,c}$ are the arbitrary and phase angles. The load currents are converted into the d-q-0 frame using park's transformation as:

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$$\begin{bmatrix} i_d \\ i_q \\ i_0 \end{bmatrix} = \frac{2}{3} \begin{bmatrix} \sin(\omega t) & \sin\left(\omega t - \frac{2\pi}{3}\right) & \sin\left(\omega t + \frac{2\pi}{3}\right) \\ \cos(\omega t) & \cos\left(\omega t - \frac{2\pi}{3}\right) & \cos\left(\omega t + \frac{2\pi}{3}\right) \\ \frac{1}{2} & \frac{1}{2} & \frac{1}{2} \end{bmatrix} \begin{bmatrix} i_{La} \\ i_{Lb} \\ i_{Lc} \end{bmatrix} \quad (11)$$

The three-phase source voltages are applied to three-phase phase locked loops (PLL) for synchronizing the current signals the voltages at PCC. The d-q components of load currents are then passed through low pass filters to extract the dc components. The error between the actual dc capacitor voltage and reference capacitor voltage of the APF is sensed and is given to PI (proportional-integral) controller. The output of PI controller is given to PWM controller (switch S in Fig. 4 is at position 1) to generate the gate pulses for AC-DC converter. For APF operation without DG the output of PI controller (switch S in Fig.4 is at position 2) is added with the direct axis component (i_d) of the load currents. Similarly, another PI controller is used to regulate the PCC voltages. The amplitude of the PCC voltages and their reference value are fed to a PI controller and whose output is added with the quadrature axis component (iq) of the load currents. Active component of DG current I_{cd} is also subtracted from the direct axis component (i_d) of the load currents. The resultant currents are again converted into the reference currents using the reverse park's transformation as:

$$\begin{bmatrix} i_{sa}^* \\ i_{sb}^* \\ i_{sc}^* \end{bmatrix} = \begin{bmatrix} \sin(\omega t) & \cos(\omega t) & 1 \\ \sin\left(\omega t - \frac{2\pi}{3}\right) & \cos\left(\omega t - \frac{2\pi}{3}\right) & 1 \\ \sin\left(\omega t + \frac{2\pi}{3}\right) & \cos\left(\omega t - \frac{2\pi}{3}\right) & 1 \end{bmatrix} \begin{bmatrix} i_d^* \\ i_q^* \\ i_0 \end{bmatrix} \quad (12)$$

The desired source currents are now compared with the actual load currents to obtain the compensating currents which include both active current supplied by the DG unit and reactive current requirement of the load. The compensating currents are now applied to the hysteresis controllers to obtain the switching pulses to switch the devices used in APF inverter (DC-AC converter) configuration.

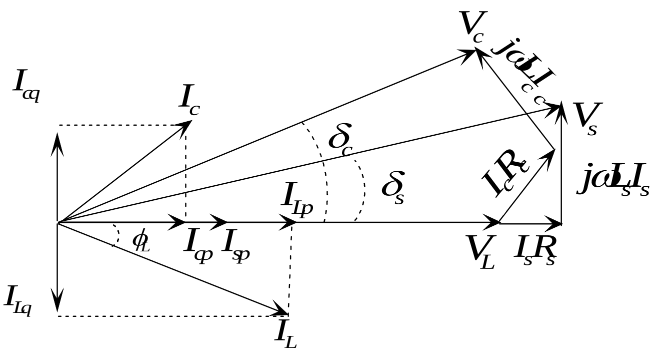
The active power transfer from DG to grid is the function of power angle δ_c and the reactive power transfer is the function of voltage magnitude difference between the inverter voltages and the grid voltages.

$$P_{cp} = \frac{V_c V_l \sin\delta_c}{\omega L_c} \quad (13)$$

$$Q_c = \frac{V_c}{\omega L_c}(V_c - V_L \cos\delta_c) \quad (14)$$

where V_L and V_c are the voltages of grid and inverter and δ_c is the phase angle between them. The APF reference current is the function of exchange of power among load and both the supply sources. Fig.5-8 shows the vector diagrams of active power flow at unity power factor with and without voltage regulation for forward and reverse interconnected mode of operation. In which I_{sp}, I_{Lp}, and I_{cp} are the active fundamental currents of the grid, load and DG (ac-side of the inverter) respectively. And V_s, V_L, and V_c are the voltages at grid, load and ac side of the DC-AC converter. The Φ_L is the load power factor angle and δ_s is the power angle between grid and load voltage and δ_c is the power angle between inverter and load voltage. I_{Lq} and I_{cq} are the reactive current component of load and filter respectively.

Fig.5 shows the vector diagram of active power flow at unity power factor in forward interconnected mode (DG and grid both supply power to load). In this case the load active current is higher than the DG active current and hence the grid will support to meet the load active power requirement. The grid currents in the case will be in-phase with the respective grid voltages.



$$I_{sp} = I_{Lp} - I_{cp},\ I_{sp} = I_s,\ I_{Lq} = I_{cq}, I_{sq} = 0, I_{Lp} > I_{cp}$$

Fig.5.Phasor diagram at unity power factor in forward interconnected mode.

Fig.6. shows the phasor diagram of active power flow with zero voltage regulation in forward interconnected mode. In this mode the compensator injects additional reactive current to regulate the PCC voltages in such a manner that PCC and grid voltages lie on the loci of same circle. Fig.7 shows the phasor diagram of active power flow at unity power factor in reverse interconnected mode in which DG supply power to load and grid. The active component of load current I_{Lp} in this case is lower than the active current component of DG and hence the DG will supply extra power to grid. The grid currents in the case will be 180^0 out of phase with the respective grid voltages. Fig.8. shows the phasor diagram of active flow with zero voltage regulation in reverse interconnected mode.

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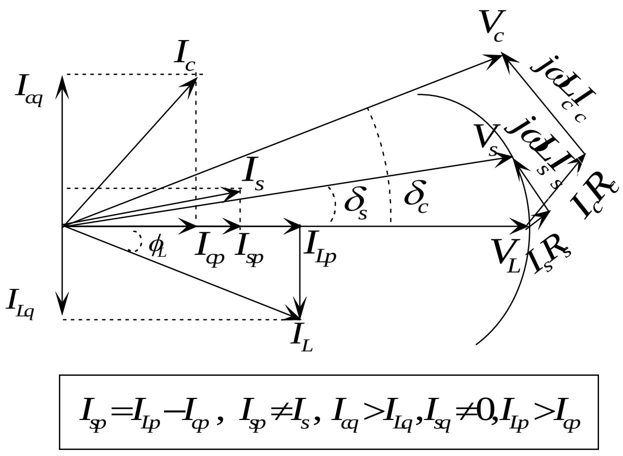

Fig.6. Phasor diagram at zero voltage regulation in forward interconnected mode.

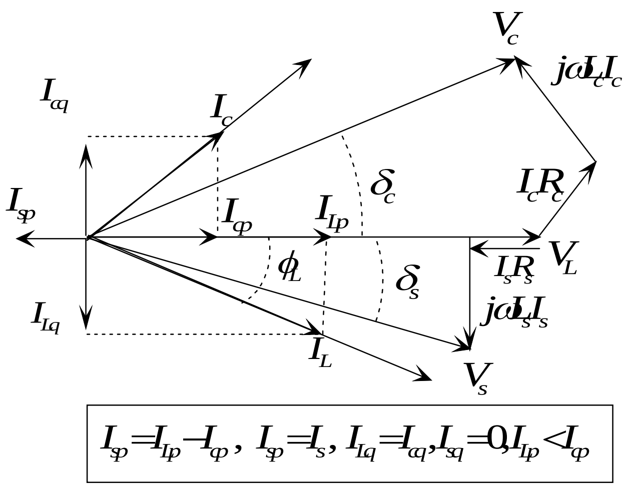

Fig.7. Phasor diagram at unity power factor in reverse interconnected mode.

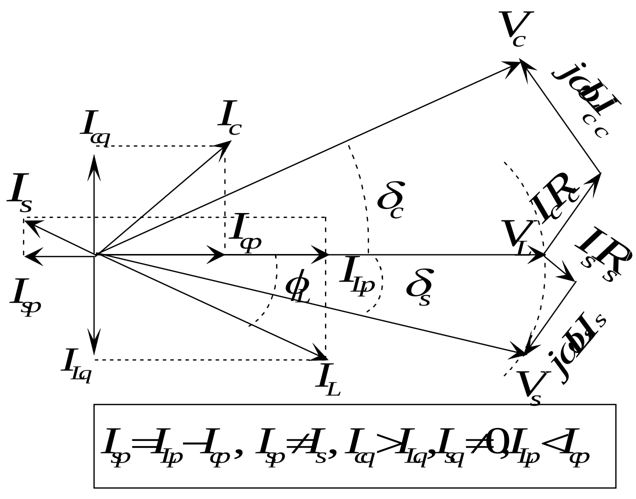

Fig. 8. Phasor diagram at zero voltage regulation in reverse interconnected mode.

IV. Results and Discussions

The performance of the proposed APF controller for DG-Grid interfaced system as per Fig. 4 is simulated under MATLAB/Simulink environment.The APF performance is analyzed under interconnected mode of operation for forward and reverse power flow.

A. Only Reactive power Control Mode (without DG)

Fig.9 shows the phasor diagram for reactive power control in which I_{Lp} and I_{Lq} are the fundamental and reactive component of load currents and Φ_L is the load power factor angle. In this mode of operation the DG unit is disconnected and the APF compensates the reactive and harmonic currents which are the basic functions of APF. Fig. 10 shows the grid voltages and currents before and after compensation. The APF is switched-on at t = 0.1 s with R-L load on dc-side of a six pulse rectifier. The source currents after compensation are in-phase with respective voltages (scaled with a factor of 0.3).The grid current THD before and after compensation of each phases are measured which trim down from 19.77% to 0.8% shows that APF works satisfactorily.

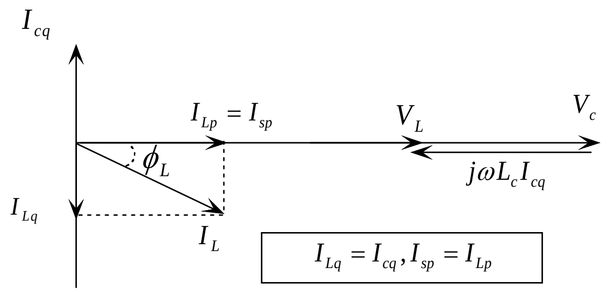

Fig. 9. Reactive power control (The grid alone is supplying total power to load).

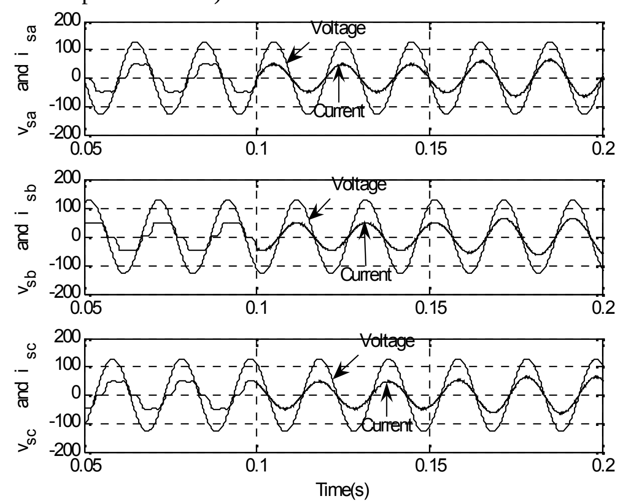

Fig. 10. Grid voltages and currents before and after compensation without DG.

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B. Forward Interconnected Mode

In this case the active power requirement of load is more than DG capacity, and hence, grid also supplies active power to load. The compensator is switched on at t = 0.05 s and further load is changed at t = 0.25 s and t = 0.5 s. The load, grid and DG active power in this case are shown in Fig.11. It is assumed that DG and grid provides 10 kW power to load during 0.05s < t < 0.25 s, 11.8 kW during 0.25 s < t < 0.5 s, and 12.2 kW during t > 0.5 s in which DG will supply 5 kW power. The APF energy storage capacitor is supplies extra power during transient as shown in Fig. 11. The three-phase grid voltages and currents are shown in Fig.12 in which the gird currents are in-phase with the respective phase voltages proves that grid is supporting to meet out the load active power demand. The grid currents THD after compensation are well within the recommended limits shows the harmonic compensation capabilities of the controller.

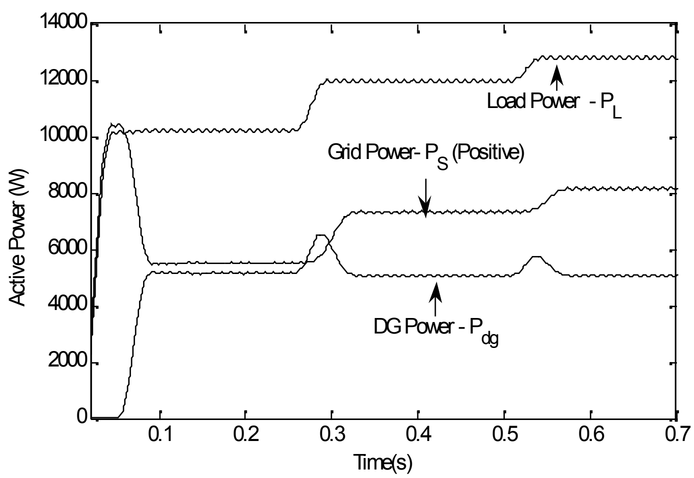

Fig.11. Grid, load and DG active powers in forward interconnected mode of operation.

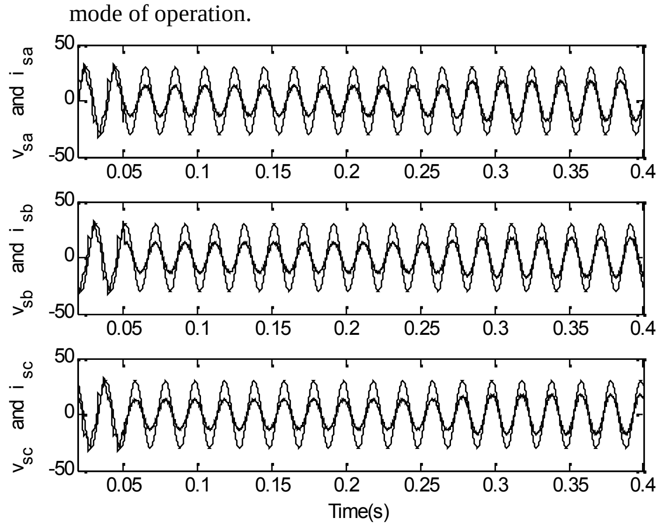

Fig. 12. Three-phase grid voltages (scaled by a factor of 0.1) and currents in forward interconnected mode.

C. Reversed Interconnected Mode

In this case the load active power demand (P_L) is less than DG capacity (P_{dc}), and hence, DG supply active power to load as per load requirement and the balance power is injected into the grid. The compensator is switched on at t = 0.05 s and further load is changed at t = 0.25 s and t = 0.5 s. The load, grid and DG active power in this case are shown in Fig.13. It is assumed that out of 5kW power DG provides 1.1 kW power to load during 0.05 s < t < 0.25 s, 2.2 kW during 0.25 s < t < 0.5 s, and 3.3 kW during t > 0.5 s. The rest of the power in the above mentioned durations are injected into the grid. The three-phase grid voltages and currents are shown in Fig. 14 in which the grid currents are 180^0 out of phase with respective phase voltages proves that DG system injecting extra power into the grid. The grid currents THD after compensation are well within the recommended limits shows the harmonic compensation capabilities of the controller. The reactive power injected by APF is equal to the reactive power requirement of load for unity power factor compensation.

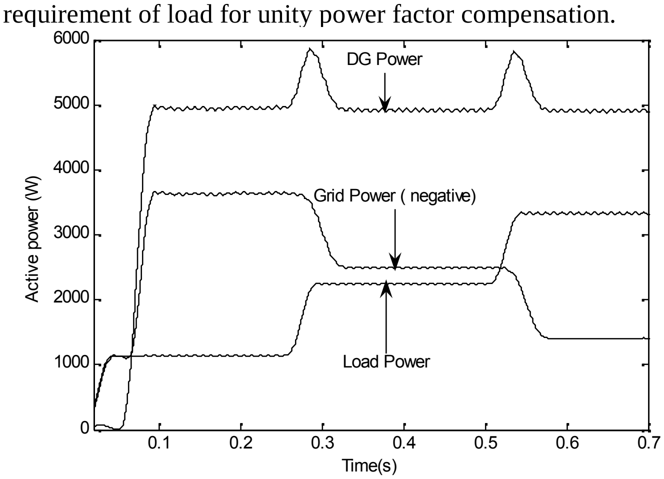

Fig.13.Grid, load and DG active powers in reverse interconnected mode of operation.

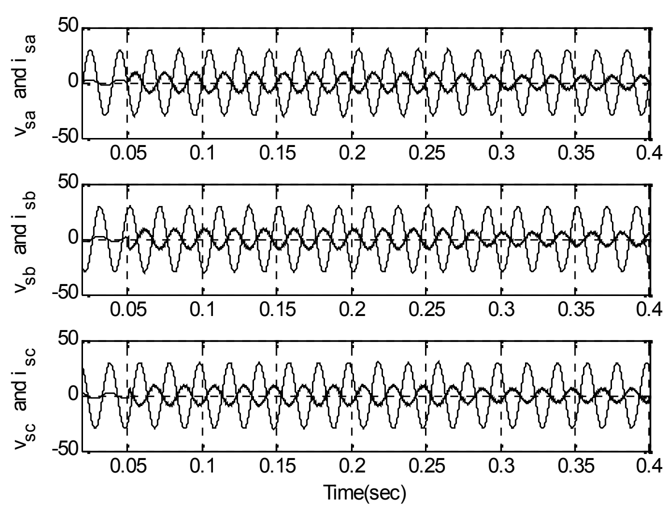

Fig. 14. Three-phase grid voltages (scaled by a factor of 0.1) and currents in reverse interconnected mode.

Conclusion

This paper presents an accurate behavioral model and control of a Grid-interactive system with active filter functions. The proposed APF system is able for injecting energy to electric grid while compensating load power factor, harmonics and voltage regulation. The grid system currents are sinusoidal and in-phase with their respective voltages. The grid current THD after compensation are well within the IEEE 519-1992 recommended limits. The proposed controller is suitable for integrated connected for both forward and reverse mode of operation under unbalanced and distorted grid voltages conditions.

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