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Hybrid Renewable Energy Sources Based Four Leg Inverter for Power Quality Improvement

PALLAGIRI VENKATA DINESH REDDY[1], S. CHANDRA MOULI[2]
[1]PG Scholar, Dept of EEE, Arjun College of Technology & Sciences, Batasingaram, Hayathnagar, Hyderabad, India.
[2]Asst Prof, Dept of EEE, Arjun College of Technology & Sciences, Batasingaram, Hayathnagar, Hyderabad, India.

Abstract: A novel versatile photovoltaic (PV) systems still demand on at least one fuel cell with improved characteristics of robustness and efficiency, which can be achieved using hybrid topologies. In this paper, the boost-inverter topology is used as a building block for a single-phase grid-connected fuel cell (FC) with PV connected through proposed compensation systems which offering low cost and compactness.The compensator is proposed for use with each individual distributed generation (DG) system in the micro grid, and consists of two four-phase-leg inverters (a shunt and a series), optimally controlled to achieve an enhancement of both the quality of power within the micro-grid and the quality of currents flowing between the micro-grid and utility system. An efficient active power filter is implemented with a four-leg voltage-source inverter using a predictive control scheme is presented. The use of a four-leg voltage-source inverter allows the compensation of current harmonic components, as well as unbalanced current generated by single-phase nonlinear loads. A detailed yet simple mathematical model of the active power filter, including the effect of the equivalent power system impedance, is derived and used to design the predictive control algorithm. The compensation performance of the proposed active power filter and the associated hybrid PV/Wind system generation scheme with predictive control scheme under steady state and transient operating conditions is demonstrated to improve the power quality features is simulated using MATLAB/SIMULINK.

Keywords: Active power filter, Current Control, Distributed Generation, Four-Leg Converters, Fuel Cell, PV Cell, Predictive Control Harmonics, and Power Quality.

I. INTRODUCTION

The recent trends in small scale power generation using the with the increased concerns on environment and cost of energy, the power industry is experiencing fundamental changes with more renewable energy sources (RESs) or micro sources such as photovoltaic cells, small wind turbines, and microturbines being integrated into the power grid in the form of distributed generation (DG) [1]. The fuel cells are electrochemical devices that convert chemical energy directly into electrical energy by the reaction of hydrogen from fuel and oxygen from the air without regard to climate conditions, unlike hydro or wind turbines and photovoltaic array. Fuel cells are different from batteries in that they require a constant source of fuel and oxygen to run, but they can produce electricity continually for as long as these inputs are supplied. This can be accomplished mainly by resorting to wind and photovoltaic generation, which, however, introduces several problems in electric systems management due to the inherent nature of these kinds of RESs [2]. In fact, they are both characterized by poorly predictable energy production profiles, together with highly variable rates. As a consequence, the electric system cannot manage these intermittent power sources beyond certain limits, resulting in RES generation curtailments and, hence, in RES penetration levels lower than expected. However, the extensive use of power electronics based equipment and non-linear loads at PCC generate harmonic currents, which may deteriorate the quality of power controlled by HGS.

Generally, current controlled voltage source inverters are used to interface the intermittent RES in distributed system. Recently, a few control strategies for grid connected inverters incorporating PQ solution have been proposed. In [3] an inverter operates as active inductor at a certain frequency to absorb the harmonic current. But the exact calculation of network inductance in real-time is difficult and may deteriorate the control performance. Although active power filters implemented with three-phase four-leg voltage-source inverters (4L-VSI) have already been presented in the technical literature [2]–[6], the primary contribution of this paper is a predictive control algorithm designed and implemented specifically for this application. Traditionally, active power filters have been controlled using pre-tuned controllers, such as PI-type or adaptive, for the current as well as for the dc-voltage loops [7], [8]. PI controllers must be designed based on the equivalent linear model, while predictive controllers use the nonlinear model, which is closer to real operating conditions. An accurate model obtained using predictive controllers improves the performance of the active power filter, especially during transient operating conditions, because it can quickly follow the current-reference signal while maintaining a constant dc-voltage. So far, implementations of predictive control in power converters have been used mainly in induction motor drives [9]–[16].

However, these kinds of applications present disadvantages related to oscillations and instability created from unknown load parameters [15]. One advantage of the proposed algorithm is that it fits well in active power filter applications, since the power converter output parameters are well known [17]. These output parameters are obtained from the converter output ripple filter and the power system equivalent impedance. The converter output ripple filter is part of the active power filter design and the power system impedance is obtained from well-known standard procedures [18], [19]. In the case of unknown system impedance parameters, an estimation method can be used to derive an accurate R–L equivalent impedance model of the system [20]. This paper presents the mathematical model of the 4L-VSI and the principles of operation of the proposed predictive control scheme, including the design procedure. The complete description of the selected current reference generator implemented in the active power filter is also presented. Finally, the proposed active power filter and the effectiveness of the associated control scheme compensation, power quality improvement is simulated using MATLAB/SIMULINK.

II. FOUR-LEG CONVERTER MODEL

Fig1 shows the configuration of a typical power distribution system with renewable power generation. It consists of various types of power generation units and different types of loads. Renewable sources, such as wind and sunlight, are typically used to generate electricity for residential users and small industries. Both types of power generation use ac/ac and dc/ac static PWM converters for voltage conversion and battery banks for long term energy storage. These converters perform maximum power point tracking to extract the maximum energy possible from wind and sun.

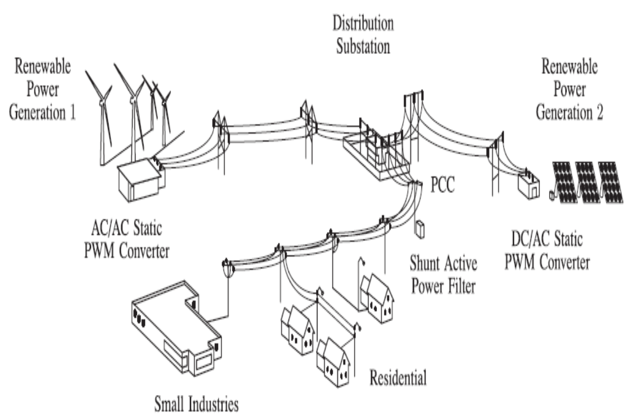

Fig. 1 Stand-alone hybrid power generation system with a shunt active power filter.

The electrical energy consumption behavior is random and unpredictable, and therefore, it may be single- or three-phase, balanced or unbalanced, and linear or nonlinear. An active power filter is connected in parallel at the point of common coupling to compensate current harmonics, current unbalance, and reactive power. It is composed by an electrolytic capacitor, a four-leg PWM converter, and a first-order output ripple filter, as shown in Fig. 2. This circuit considers the power system equivalent impedance Zs , the converter output ripple filter impedance Zf , and the load impedance ZL. The four-leg PWM converter topology is shown in Fig. 3. This converter topology is similar to the conventional three-phase converter with the fourth leg connected to the neutral bus of the system. The fourth leg increases switching states from improving control flexibility and output voltage quality [19], and is suitable for current unbalanced compensation.

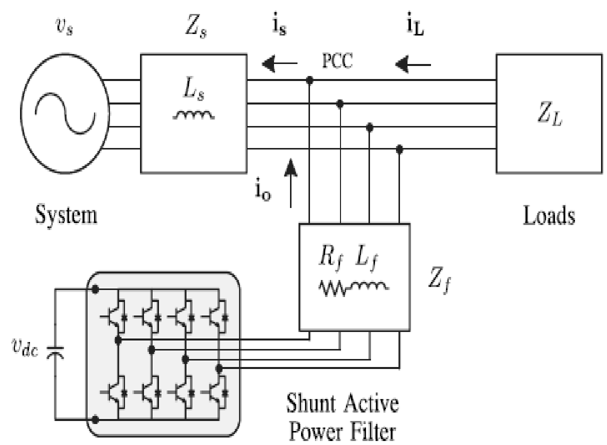

Fig. 2. Three-phase equivalent circuit of the proposed shunt active power filter.

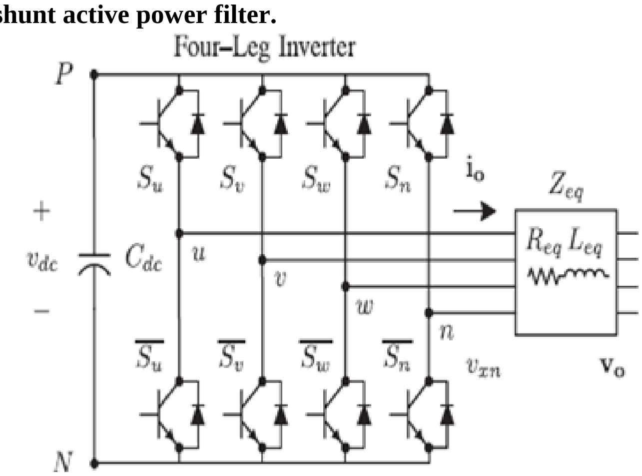

Fig. 3. Two-level four-leg PWM-VSI topology

The voltage in any leg x of the converter, measured from the neutral point (n), can be expressed in terms of switching states, as follows:

$$v_{xn} = S_x - S_n \, v_{\mathrm{dc}}, \quad x = u,\, v,\, w,\, n. \tag{1}$$

The mathematical model of the filter derived from the equivalent circuit shown in Fig. 2 is

$$\mathbf{v_o} = v_{xn} - R_{\mathrm{eq}}\, \mathbf{i_o} - L_{\mathrm{eq}} \frac{d\,\mathbf{i_o}}{dt} \tag{2}$$

Where Req and Leq are the 4L-VSI output parameters expressed as Thevenin’s impedances at the converter output terminals Zeq . Therefore, the Thevenin’s equivalent impedance is determined by a series connection of the ripple filter impedance Zf and a parallel arrangement between the system equivalent impedance Zs and the load impedance ZL.

$$Z_{\mathrm{eq}} = \frac{Z_s Z_L}{Z_s + Z_L} + Z_f \approx Z_s + Z_f \tag{3}$$

For this model, it is assumed that ZL _ Zs , that the resistive part of the system's equivalent impedance is neglected, and that the series reactance is in the range of 3–7% p.u., which is an acceptable approximation of the real system. Finally,

Req = Rf and Leq = Ls + Lf . (4)

III. REFERENCE CURRENT GENERATION SCHEME

A dq-based current reference generator scheme is used to obtain the active power filter current reference signals. This scheme presents a fast and accurate signal tracking capability. This characteristic avoids voltage fluctuations that deteriorate the current reference signal affecting compensation performance [20]. The current reference signals are obtained from the corresponding load currents as shown in Fig. 4. This module calculates the reference signal currents required by the converter to compensate reactive power, current harmonic, and current imbalance. The displacement power factor (sin φ(L)) and the maximum total harmonic distortion of the load (THD(L)) defines the relationships between the apparent power required by the active power filter, with respect to the load, as shown

$$\frac{S_{\mathrm{APF}}}{S_L} = \frac{\sqrt{\sin\phi_{(L)} + \mathrm{THD}_{(L)}{}^2}}{\sqrt{1 + \mathrm{THD}_{(L)}{}^2}} \tag{5}$$

Where the value of THD(L) includes the maximum compensable harmonic current, defined as double the sampling frequency fs. The frequency of the maximum current harmonic component that can be compensated is equal to one half of the converter switching frequency. The dq-based scheme operates in a rotating reference frame; therefore, the measured currents must be multiplied by the sin(wt) and cos (wt) signals. By using dq-transformation, the d current component is synchronized with the corresponding phase-to-neutral system voltage, and the q current component is phase-shifted by 90◦. The sin(wt) and cos (wt) synchronized reference signals are obtained from a synchronous reference frame (SRF) PLL [21].

$$\begin{bmatrix} i_d \\ i_q \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} \sin\omega t & \cos\omega t \\ -\cos\omega t & \sin\omega t \end{bmatrix} \begin{bmatrix} 1 & -\frac{1}{2} & -\frac{1}{2} \\ 0 & \frac{\sqrt{3}}{2} & -\frac{\sqrt{3}}{2} \end{bmatrix} \begin{bmatrix} i_{Lu} \\ i_{Lv} \\ i_{Lw} \end{bmatrix} \tag{6}$$

The SRF-PLL generates a pure sinusoidal waveform even when the system voltage is severely distorted. Tracking errors are eliminated, since SRF-PLLs are designed to avoid phase voltage unbalancing, harmonics (i.e., less than 5% and 3% in fifth and seventh, respectively), and offset caused by the nonlinear load conditions and measurement errors [3], the relationship between the real currents iLx(t) (x = u, v,w) and the associated dq components (id and iq). A low-pass filter (LFP) extracts the dc component of the phase currents id to generate the harmonic reference components id . The reactive reference components of the phase-currents are obtained by phase-shifting the corresponding ac and dc components of iq by 180◦. In order to keep the dc-voltage constant, the amplitude of the converter reference current must be modified by adding an active power reference signal ie with the d-component. The resulting signals i*d and i*q are transformed back to a three-phase system by applying the inverse Park and Clark transformation, The cut off frequency of the LPF used in this paper is 20 Hz.

$$\begin{bmatrix} i_{ou}^* \\ i_{ov}^* \\ i_{ow}^* \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} \frac{1}{\sqrt{2}} & 1 & 0 \\ \frac{1}{\sqrt{2}} & -\frac{1}{2} & \frac{\sqrt{3}}{2} \\ \frac{1}{\sqrt{2}} & -\frac{1}{2} & -\frac{\sqrt{3}}{2} \end{bmatrix} \times \begin{bmatrix} 1 & 0 & 0 \\ 0 & \sin\omega t & -\cos\omega t \\ 0 & \cos\omega t & \sin\omega t \end{bmatrix} \begin{bmatrix} i_0 \\ i_d^* \\ i_q^* \end{bmatrix} \tag{7}$$

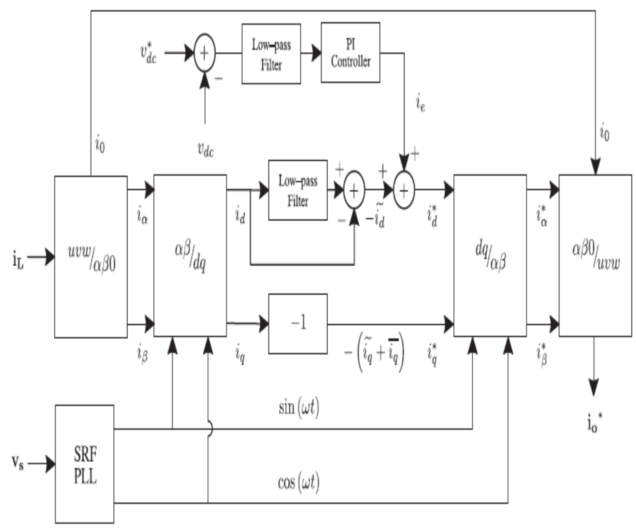

Fig.4. dq-based current reference generator block diagram.

The current that flows through the neutral of the load is compensated by injecting the same instantaneous value obtained from the phase-currents, phase-shifted by 180◦, as shown next.

$$i_{on}^* = -\left(i_{Lu} + i_{Lv} + i_{Lw}\right) \tag{8}$$

One of the major advantages of the dq-based current reference generator scheme is that it allows the implementation of a linear controller in the dc-voltage control loop. However, one important disadvantage of the dq-based current reference frame algorithm used to generate the current reference is that a second order harmonic component is generated in id and iq under unbalanced operating conditions. The amplitude of this harmonic depends on the percent of unbalanced load current (expressed as the relationship between the negative sequence current iL,2 and the positive sequence current iL,1). The second-order harmonic cannot be removed from id and iq , and therefore generates a third harmonic in the reference current when it is converted back to abc frame [17]. Since the load current does not have a third harmonic, the one generated by the active power filter flows to the power system.

A. DC Link Voltage Control

The dc-voltage converter is controlled with a traditional PI controller. This is an important issue in the evaluation, since the cost function is designed using only current references, in order to avoid the use of weighting factors. Generally, these weighting factors are obtained experimentally, and they are not well defined when different operating conditions are required. Additionally, the slow dynamic response of the voltage across the electrolytic capacitor does not affect the current transient response. For this reason, the PI controller represents a simple and effective alternative for the dc-voltage control. The dc-voltage remains constant (with a minimum value of sqrt of 6vs(rms)) until the active power absorbed by the converter decreases to a level where it is unable to compensate for its losses. The active power absorbed by the converter is controlled by adjusting the amplitude of the active power reference signal ie , which is in phase with each phase voltage. In the block diagram shown in Fig. 5, the dc-voltage vdc is measured and then compared with a constant reference value v*dc. The error (e) is processed by a PI controller, with two gains, Kp and Ti . Both gains are calculated according to the dynamic response requirement. Fig. 5 shows that the output of the PI controller is fed to the dc-voltage transfer function Gs which is represented by a first-order system.

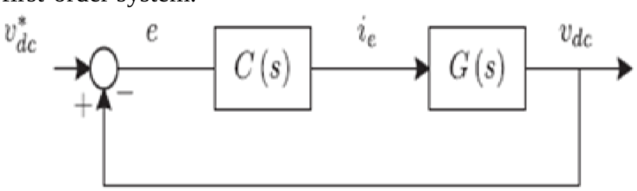

Fig. 5. DC-voltage control block diagram.

$$G(s) = \frac{v_{dc}}{i_e} = \frac{3}{2}\frac{K_p v_s \sqrt{2}}{C_{dc} v^*_{dc}} \tag{9}$$

The equivalent closed-loop transfer function of the given system with a PI controller

$$C(s) = K_p\left(1 + \frac{1}{T_i \cdot s}\right)$$

$$\frac{v_{dc}}{i_e} = \frac{\frac{\omega_n^2}{a}\cdot(s+a)}{s^2 + 2\zeta\omega_n \cdot s + \omega_n^2} \tag{10}$$

Since the time response of the dc-voltage control loop does not need to be fast, a damping factor ζ = 1and a natural angular speed ωn = 2π · 100 rad/s are used to obtain a critically damped response with minimal voltage oscillation. The corresponding integral time Ti = 1/a (13) and proportional gain Kp can be calculated as

$$\zeta = \sqrt{\frac{3}{8}\frac{K_p v_s \sqrt{2} T_i}{C_{dc} v^*_{dc}}}$$

$$\omega_n = \sqrt{\frac{3}{2}\frac{K_p v_s \sqrt{2}}{C_{dc} v^*_{dc} T_i}}. \tag{11}$$

IV. ABOUT HYBRID GENERATION SCHEME

The photovoltaic (PV) power generation systems are renewable energy sources that expected to play a promising role in fulfilling the future electricity requirements. The PV systems principally classified into stand-alone, grid connected or hybrid systems. The grid-connected PV systems generally shape the grid current to follow a predetermined sinusoidal reference using hysteresis-band current controller, which has the advantages of inherent peak current limiting and fast dynamic performance. The model of grid connected photovoltaic system to control active and reactive power injected in the grid is presented. The proposed multilevel power converter uses two single-phase voltage source inverters and a four wire voltage source inverter. The structural design of this new power converter allows a seven level shaped output voltage wave at the output of multilevel inverter.

A. Photovoltaic Array Modeling

Numerous PV cells are connected in series and parallel circuits on a panel for obtaining high power, which is a PV module. A PV array is defined as group of several modules electrically connected in series-parallel combinations to generate the required current and voltage. The building block of PV arrays is the solar cell, which is basically a p-n semiconductor junction that directly converts solar radiation into dc current using photovoltaic effect. The simplest equivalent circuit of a solar cell is a current source in parallel with a diode, shown in Fig. 6. The series resistance RS represents the internal losses due to the current flow. Shunt resistance Rsh, in parallel with diode, this corresponds to the leakage current to the ground. The single exponential equation which models a PV cell is extracted from the physics of the PN junction and is widely agreed as echoing the behavior of the PV cell. The grid integration of RES applications based on photovoltaic systems is becoming today the most important application of PV systems, gaining interest over traditional stand-alone systems. This trend is being increased because of the many benefits of using RES in distributed (aka dispersed, embedded or decentralized) generation (DG) power systems.

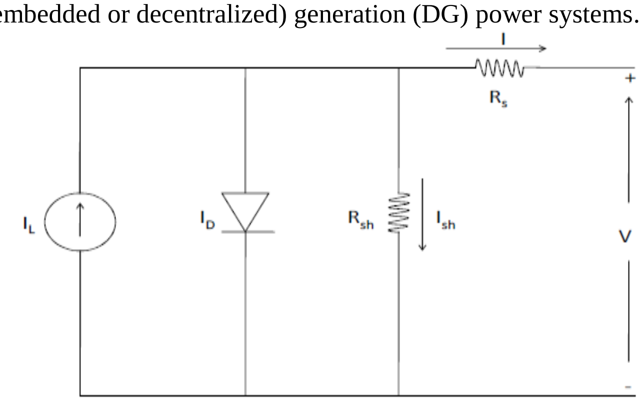

Fig.6. Circuit Diagram of a Solar Cell.

B. Wind Energy System

Wind turbines transform wind energy into electricity. The wind is a highly variable source, which cannot be stored, thus, it must be handled according to this characteristic. The principle of operation of a wind turbine is characterized by two conversion steps. First the rotor extract the kinetic energy of the wind, changing it into mechanical torque in the shaft; and in the second step the generation system converts this torque into electricity. In the most common system, the generator system gives an AC output voltage that is dependent on the wind speed. As wind speed is variable, the voltage generated has to be transferred to DC and back again to AC with the aid of inverters. However, fixed speed wind turbines are directly connected to grid.

V. MATLAB MODELEING AND SIMULATION RESULTS

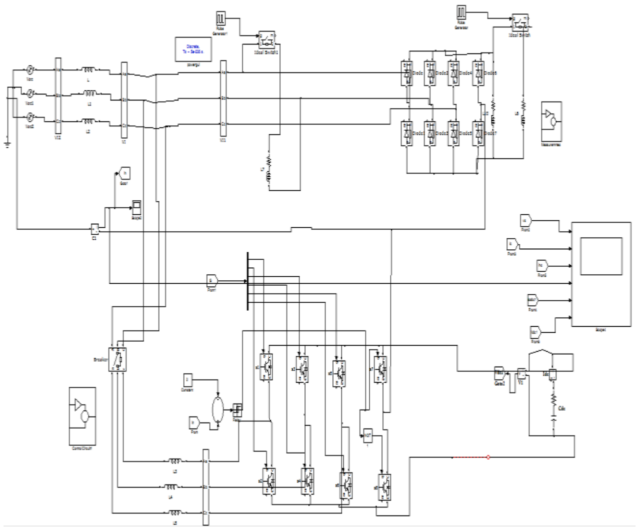

Fig.7. Matlab/Simulink Model of Proposed RES Fed 4-Leg APF system with formal DC Link Capacitor.

A. Proposed RES Fed APF with Conventional DC Link Capacitor.

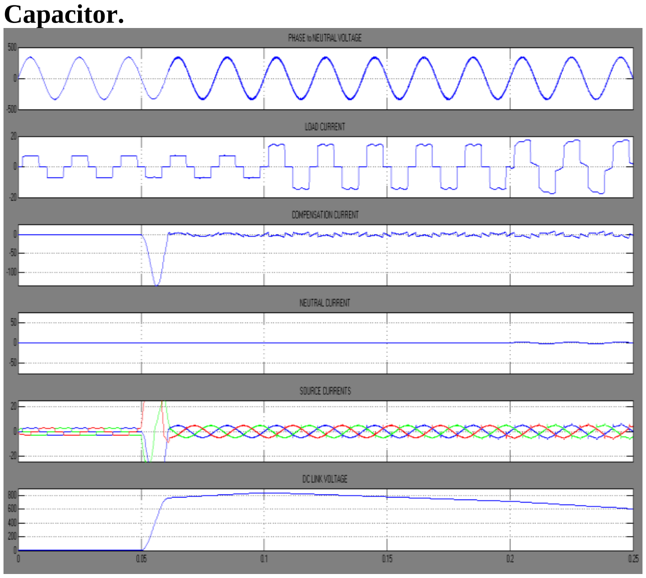

Fig.8. Simulation results for APF with Formal PI Controller (a) Source Voltage. (b) Load current. (c) Compensator Current. (d) Neutral Current, (e) Source Current (f) DC Link Voltage.

Here (fig 8) compensator is turned on at 0.05 seconds, before we get some harmonics coming from non-linear load, then distorts our parameters and get sinusoidal when compensator is in on.

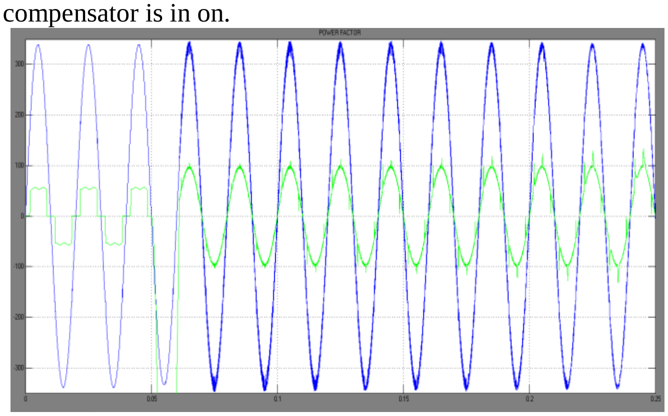

Fig.9 Power Factor for APF with Conventional PI Controller.

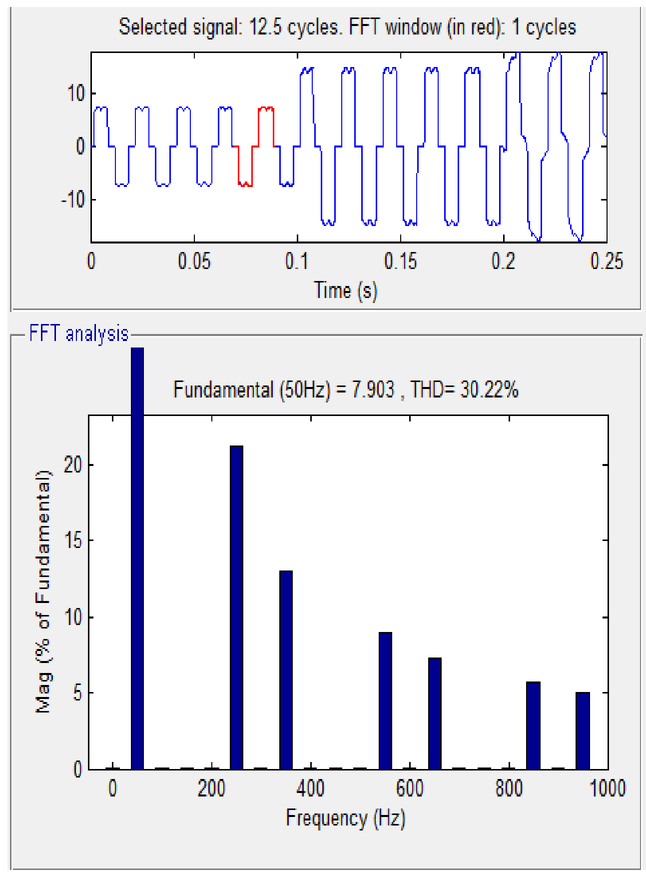

Fig. 10 FFT Analysis of Phase-A Source Current for without compensation scheme.

Fig. 9 shows the power factor it is clear from the figure after compensation power factor is unity. Fig.10 shows the FFT Analysis of Phase-A Source Current without any compensation, here we get 30.22%. Fig.11 shows the FFT Analysis of Phase-A Source Current with PI Controlled APF, here we get 2.52%.

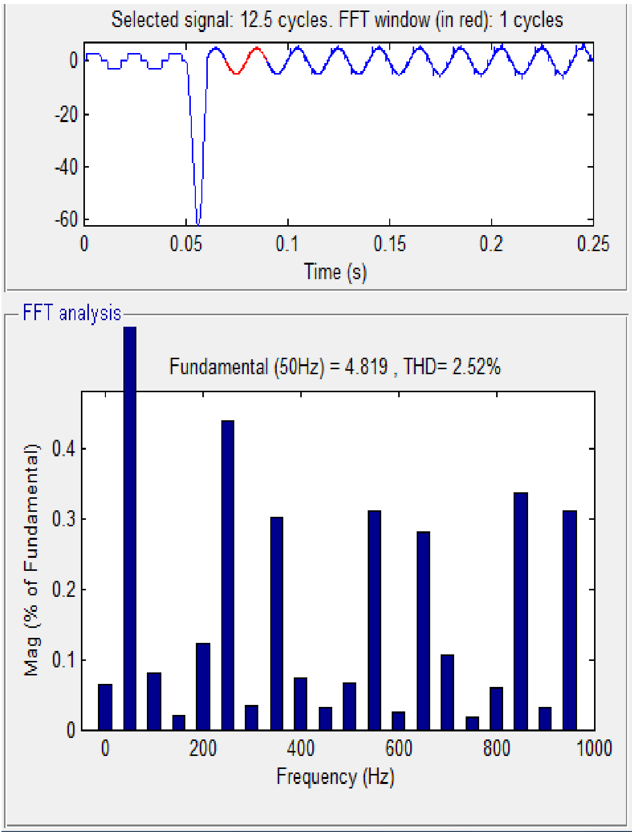

Fig.11.FFT Analysis of Phase-A Source Current with PI Controlled APF.

A. Proposed APF with Hybrid Generation Scheme

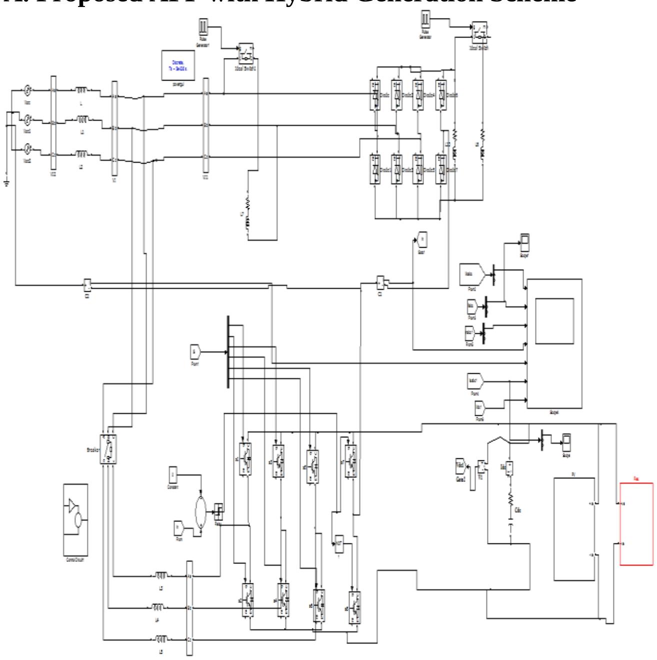

Fig.12 Matlab/Simulink Model of Proposed RES Fed 4-Leg APF system with Hybrid Generation Scheme.

In fig 13 compensator is turned on at 0.05 seconds, before we get some harmonics coming from non-linear load, then distorts our parameters and get sinusoidal when compensator is in on.

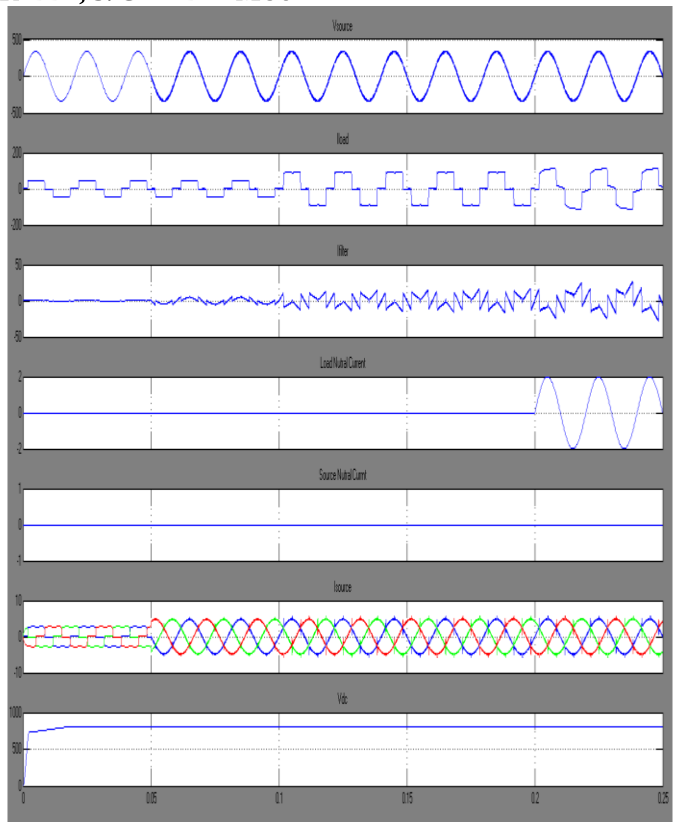

Fig.13 Simulation results for APF with Hybrid Generation Scheme (a) Source Voltage. (b) Load current. (c) Compensator Current. (d) Neutral Current, (e) Source Current (f) DC Link Voltage.

VI. CONCLUSION

This proposed model is implemented using Matlab Simulink software and the obtained resultant waveforms were evaluated and the effectiveness of the system stability and performance of power system have been established. Improved dynamic current harmonics and a reactive power compensation scheme for power distribution systems with generation from renewable sources has been proposed to improve the current quality of the distribution system. Advantages of the proposed scheme are related to its simplicity, modeling, and implementation. This paper has presented a novel control of an existing RES interfacing APF using hybrid generation scheme to improve the quality of power at PCC for a 3-phase 4-wire system. By using hybrid generation scheme, maintains constant voltage condition at PCC level by using DG interfaced Inverter with optimal control scheme, improve the grid stability, minimize the fluctuations in the grid system, and mainly increase the power transfer capability in between grid to load system, through proposed compensation scheme. It has been shown that the APF system can be effectively utilized for power conditioning without affecting its normal operation of real power transfer.

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