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Power Quality Improvement of Utility Current in a PV Based Shunt Active Filter using P-Q Theory

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ABSTRACT

Nowadays, the active filters represent a viable alternative for controlling harmonic levels in industrial consumers' electrical installations. It must be noted the availability of many different types of filter configurations that can be used but there is no standard method for rating the active filters. This paper focuses on basic principle of SAPF and the theoretical concepts describing the shunt active power Filter structure and design. The filter controller is based on instantaneous power theory (p-q theory) and the circuit performing as an inverter with PWM hysteresis control. To validate the performance of shunt active filters a Matlab-Simulink model was developed. Simulation results are presented which verifies the power quality of the grid is enhanced

Keywords— *Active power _lter (APF), instantaneous power theory, photovoltaic (PV), power quality, renewable energy.*

I. INTRODUCTION

The power quality (PQ) problems in power distribution systems are not new, but only recently the effects of these problems have gained public awareness. Advances in semiconductor device technology have fuelled a revolution in power electronics over the past decade, and there are indications that this trend will continue [1]. However these power equipments which include adjustable-speed motor drives (ASDs), electronic power supplies, direct current (DC) motor drives, battery chargers, electronic ballasts are responsible for the rise in related PQ problems [2]-[4]. These nonlinear loads are constructed by nonlinear devices, in which the current is not proportional to the applied voltage. A simple circuit as shown in Figure 1.1 illustrates the concept of current distortion. In this case, a sinusoidal voltage is applied to a simple nonlinear resistor in which the voltage and current vary according to the curve shown. While the voltage is perfectly sinusoidal, the resulting current is distorted.

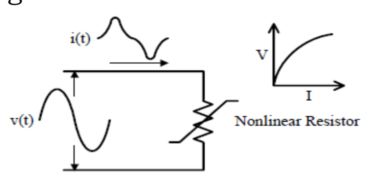

Figure 1.1 Current distortion caused by nonlinear resistance

Nonlinear loads appear to be prime sources of harmonic distortion in a power distribution system. Harmonic currents produced by nonlinear loads are injected back into power distribution systems through the point of common coupling (PCC). These harmonic currents can interact adversely with a wide range of power system equipment, most notably capacitors, transformers, and motors, causing additional losses, overheating, and overloading [2]-[4].

Recently, there is an increasing concern about the environment. The need to generate pollution-free energy has triggered considerable effort toward renewable energy (RE). RE sources such as sunlight, wind, flowing water and biomass offer the promise of clean and abundant energy. They do not generate any greenhouse gases and are inexhaustible. Solar energy, in particular, is especially attractive in a sunshine country like Malaysia. This energy is in DC form from photovoltaic (PV) arrays. It is converted into a more convenient alternating current (AC) power through an inverter system. Efforts have been made to combine the APF with PV array. However, it appears that no attempt has been made to combine a hybrid APF with PV array.

The power demand always exceeds the available power generation in any developing country. Hence, renewable power generating systems such as PV and wind energy conversion systems are used to supplement the fossil fuel based power generation. But due to the non-linearity of the load that is diode bridge rectifier with RL- load, there is harmonics in the load currents. Hence, harmonics reduction and reactive power compensation simultaneously can be done by using a voltage source inverter connected in parallel with the system which acts as a shunt APF for reducing the distortions produced due to non-linear load in the load current. This active filter generates a compensating current which is of equal in magnitude as harmonic current and opposite in phase with it to reduce the harmonics present in the load current.APF is classified as series, shunt or combination both series and shunt but shunt APF is preferred here as the principle of the shunt APF is to produce compensating currents of equal in magnitude but opposite in-phase to those harmonics that are present due to non-linear loads. SAPF is a closed loop structure where non-linear loads act as linear. It can compensate reactive power and can also mitigate harmonics and distortions.

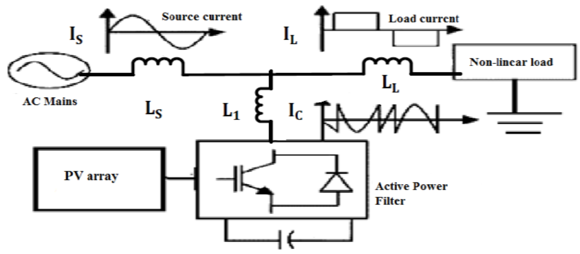

Fig.1.2 Principle of shunt APF

In Fig. 1.2 AC mains is connected to the non-linear load that is diode bridge rectifier with RL-load where,

I_S - Source current
I_L - Load current produced due to non-linear load
IC – Compensating current produced by shunt APF to mitigate harmonics
L_S - Source inductance
L_L - Load inductance
L_1 – Coupling inductance

Here, the shunt APF produced compensating currents of equal in magnitude but opposite in-phase to those harmonics that are present due to non-linear loads which results in mitigation of harmonics at load current. Generally, the voltage source inverters (VSI) are used to convert the power of the PV system to inject it to the distribution system. But here, the VSI act as a multifunctional device which is used for energy conversion and also for harmonics elimination as well as reactive power compensation simultaneously. This control strategy incorporates P-Q solution as in shunt active power filter technique. This control technique is same as technique used in shunt filter to reduce harmonics in the distribution network due to non-linear loads in the system.

II. Literature Survey

Due to the presence of non-linear loads harmonics are generated in the load current. Hence, it is required to reduce the load current harmonics. So, Shunt APF is needed for harmonics reduction and for reactive power compensation.

In 2011 Chaitanya et. al described the PV array mathematical modeling and also the MPPT algorithm implementation on a boost converter to track maximum power during rapid change in environment conditions. The complete PV model is simulated and P-V and I-V curves are drawn using MATLAB/SIMULINK and the results are discussed from which it is clear that the P-V and I-V curves are dependent on temperature and irradiation.

Using MPPT algorithm, a PV system can be operated at maximum efficiency [19].

In 2014 Jeevanathan et. al described that a SAPF is a current control system that is used for reduction of harmonics in current by injecting a current of equal magnitude but opposite in phase of the harmonics in current and also reactive current produced from the non-linear loads such that only fundamental active currents can be supplied from the ac source to the loads. This technique is used for both harmonic reduction along with reactive compensation produced due to non-linear loads. As a result, efficiency of the system is increased with reduced value of THD in source current [18].

In 2014 Remya et. al discovered that due to increase in power demand, the power distribution also increased so Renewable Energy Sources (RES) are connected to the distribution systems where inverter, converter and non-linear loads are present hence, harmonics are present in currents and power quality decreases. So, they used to reduce the harmonics as well as for reactive power compensation. Here, the PV system is connected to the grid through a three-phase inverter which is used as a multi-functional device as it is used as power converter also for harmonics elimination [21].

In 2014 Boukezata et. al presented a paper where active filter is used to compensate the reactive power and to inject active power simultaneously whenever needed by the nonlinear loads. The PV array model with boost converter and MPPT controller is directly connected to the dc-side voltage source inverter(VSI) and the PV system is connected to the grid through this inverter using Direct Power Control Algorithm [10].

In 2013, Belaidi et. al described the analysis and simulation of shunt active filter (SAPF) where a PV system is connected to shunt power active filter and it can be used for the harmonics elimination which is generated by a nonlinear load and also reactive power compensation is done here. For the reference current calculation of Shunt Active Filter We are using the synchronous d-q-o reference frame algorithm (SRF) and the carrier-based PWM modulation is used for gating signal generation for the voltage source inverter. This system produced current in sinusoidal form only in multiples frequency of fundamental and also reactive power compensation occurred [16].

In 2012, Blorfan et. al presented a paper where a hybrid three-phase active power filter(HAPF) is configured and a passive high-pass filter is connected in parallel with an active power filter and then to a photovoltaic system. This configuration is able to improve the filtering capability of an active filter (APF) using sliding mode control and was able to filter out small band as well as wideband harmonics. This sliding mode method track the reference current and also give source current THD at a very lesser value which indicates the effectiveness of the system [4, 15].

III. PV SYSTEM

3.1 Definition

A photovoltaic system is a system which uses one or more solar panels to convert solar energy into electricity. It consists of multiple components, including the photovoltaic modules, mechanical and electrical connections and mountings and means of regulating and/or modifying the electrical output [14].

3.2 Photovoltaic Arrangements

3.2.1 Photovoltaic Cell

PV cells are made of semiconductor materials, such as silicon. For solar cells, a thin semiconductor wafer is specially treated to form an electric field, positive on one side and negative on the other. When light energy strikes the solar cell, electrons are knocked loose from the atoms in the semiconductor material. If electrical conductors are attached to the positive and negative sides, forming an electrical circuit, the electrons can be captured in the form of an electric current - that is, electricity. This electricity can then be used to power a load[16]. A PV cell can either be circular or square in construction.

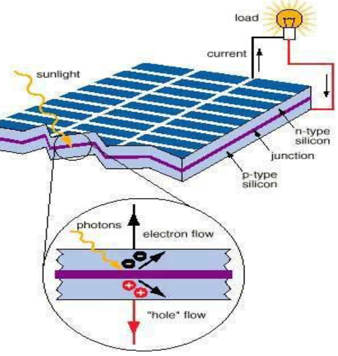

Figure 3.1 Basic Structure of PV Cell

3.2.2 Photovoltaic Module

Due to the low voltage generated in a PV cell (around 0.5V), several PV cells are connected in series (for high voltage) and in parallel(for high current) to form a PV module for desired output. Separate diodes may be needed to avoid reverse currents, in case of partial or total shading, and at night. The p-n junctions of mono-crystalline silicon cells may have adequate reverse current characteristics and these are not necessary. Reverse currents waste power and can also lead to overheating of shaded cells. Solar cells become less efficient at higher temperatures and installers try to provide good ventilation behind solar panels [15].

3.2.3 Photovoltaic Array

The power that one module can produce is not sufficient to meet the requirements of home or business. Most PV arrays use an inverter to convert the DC power into alternating current that can power the motors, loads, lights etc. The modules in a PV array are usually first connected in series to obtain the desired voltages; the individual modules are then connected in parallel to allow the system to produce more current [14].

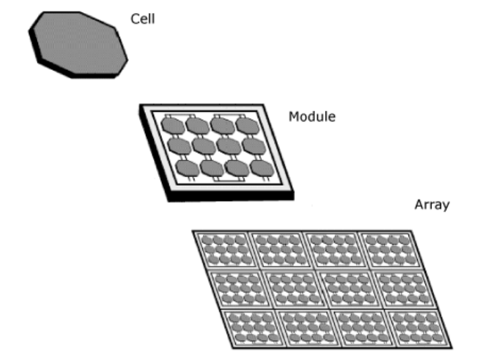

Figure 3.2 Photovoltaic system [16]

III. Shunt Active Power Filter

In the recent years of development the requirement of harmonic and reactive power has developed, causing power quality problems. Many power electronic converters are used in industries as well as in domestic purpose. The power converter loads offer highly nonlinear characteristic in their input currents. These currents drawn by power converters have a wide spectrum that includes: fundamental reactive power, third, fifth, seventh, eleventh and thirteenth harmonics in large quantities and other higher frequency harmonic are in small percentage. These currents at the consumer bus further distort the voltage spectrum thus becoming troublesome problems in AC power lines. As passive power filters doesn't reaches the desired performance a power electronic solution has emerged. Most of the common loads that can be watched in daily life at industries are balanced three phase loads and single-phase loads with different loading on them making the system unbalance.

This chapter basically deals with the modeling and investigation of shunt active power filter for compensation of harmonics and reactive power. Designs of different parameters like power circuit, control circuit, control strategies, EMI / Ripple filters are discussed. The three leg topology shown in fig 4.1 is basically used for three-phase balanced loads.

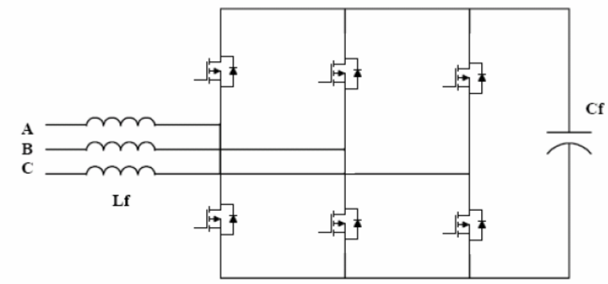

Fig 4.1 Three leg topology of shunt active power filter

4.1 Basic compensation principle of STATCOM

The shunt active power filter, with a self controlled dc bus, has a topology similar to that of a static compensator (STATCOM) used for reactive power compensation in power transmission systems. Shunt active power filters compensate load current harmonics by injecting equal but opposite harmonic compensating current. In this case the shunt active power filter operates as a current source injecting the harmonic components generated by the load but phase shifted by 180o. Fig 4.2 shows the connection of a shunt active power filter and Fig 4.3 shows how active power filter works to compensate the load harmonic currents[4].

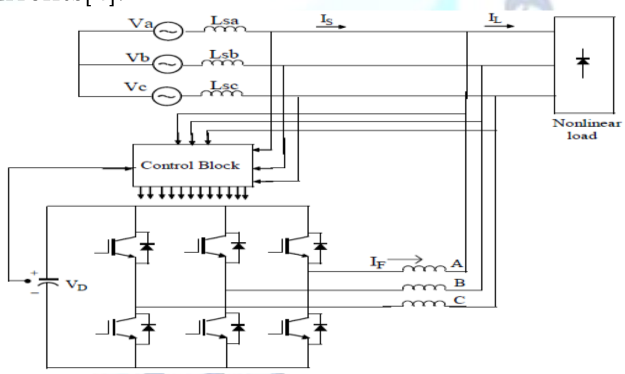

Fig 4.2 Shunt power filter topology

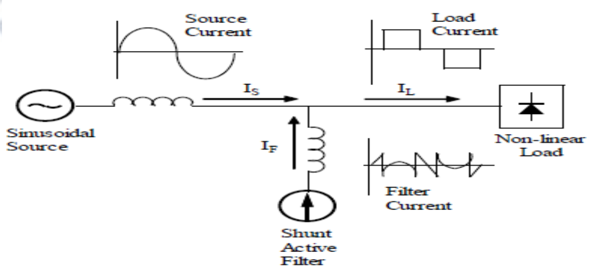

Fig 4.3 Filter current IF generated to compensate load current harmonics

Fig 4.4 shows the basic compensation principle of shunt active power filter. A voltage source inverter (VSI) is used as the shunt active power filter[10]. This is controlled so as to draw or supply a compensating current Ic from or to the utility, such that it cancels current harmonics on the AC side i.e. this active power filter (APF) generates the nonlinearities opposite to the load nonlinearities. Fig 5.5 shows the different waveforms i.e. the load current, desired source current and the compensating current injected by the shunt active power filter which contains all the harmonics, to make the source current purely sinusoidal. This is the basic principle of shunt active power filter to eliminate the current harmonics and to compensate the reactive power.

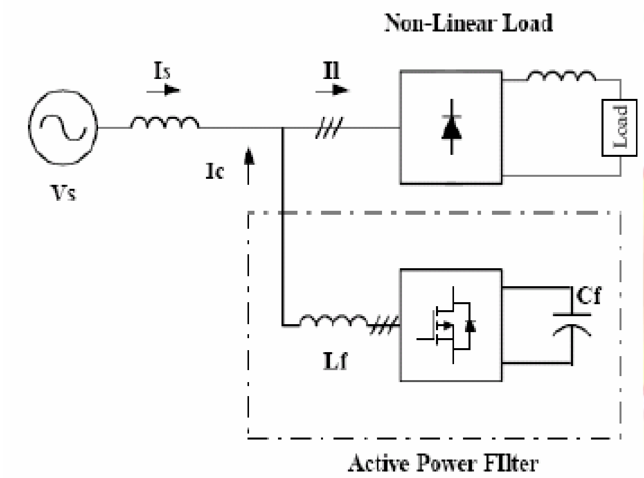

Fig 4.4 Basic compensation principle

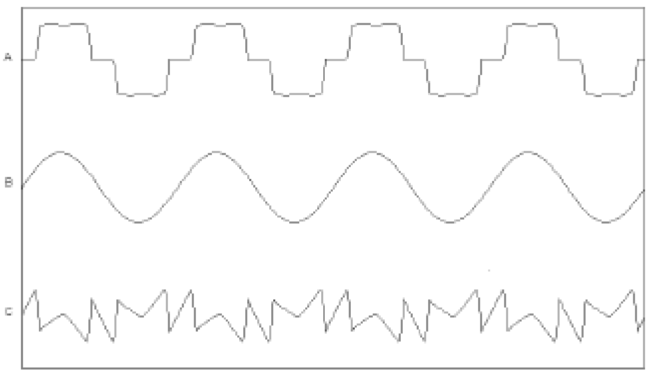

Fig 4.5 Actual load, desired source and the compensating current

IV. Grid Connected PV System with Active Power Filter

A Shunt Active Filter (SAPF) is the bidirectional current converter with six switches having combination of both switching network and filter-components. Structure of this power filter is dependent on the control technique of VSI having a capacitor for the purpose of DC energy storage and the inverter output has been connected to Non-linear load having diode rectifier bridge with a RL-load. In each of the switches the diodes are connected in anti-parallel arrangement with the IGBTs to permit current flow in either direction. For compensation of reactive power the PV interconnected shunt APF injects real PV power to a distribution line at PCC and also reduces harmonic in load currents caused by nonlinear loads by injecting compensating current. This filter is connected in shunt that means in parallel with the nonlinear load. This active filter has capability of detecting the harmonic currents caused by the nonlinear loads and then injects a current of equal magnitude and opposite in phase with the non-linear load current which is called compensating current to reduce the harmonics present in load currents due to Non-linear load. Hence, the resulting current is in form of a fundamental frequency sinusoidal current which is drawn at PCC in distribution network.

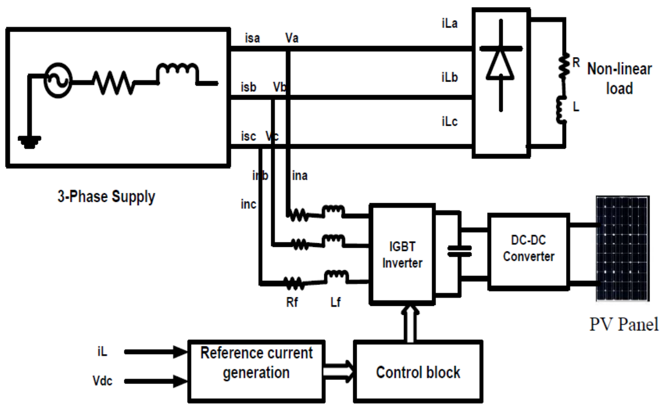

Fig.5.1 Schematic diagram of a PV system connected to a Shunt APF

p–q theory Based Control

Akagi et al in 1983 [3] developed P-Q theory or “instantaneous active-reactive Power theory” for controlling *the* active filters. This can be achieved by transforming the voltage and load current into α-β co-ordinates.

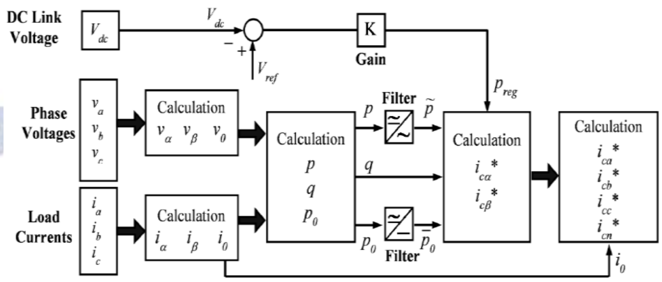

Fig.5.2 Block diagram of p-q compensation theory

P-Q theory can be achieved by transforming the voltage and load current into α-β co-ordinates as following

$$\begin{bmatrix} V_\alpha \\ V_\beta \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} 1 & \frac{-1}{2} & \frac{-1}{2} \\ 0 & \frac{\sqrt{3}}{2} & \frac{-\sqrt{3}}{2} \end{bmatrix} \begin{bmatrix} V_a \\ V_b \\ V_c \end{bmatrix}$$

$$\begin{bmatrix} i_{L\alpha} \\ i_{L\beta} \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} 1 & \frac{-1}{2} & \frac{-1}{2} \\ 0 & \frac{\sqrt{3}}{2} & \frac{-\sqrt{3}}{2} \end{bmatrix} \begin{bmatrix} i_{La} \\ i_{Lb} \\ i_{Lc} \end{bmatrix}$$

The instantaneous active power pL and reactive power qLcan be expressed as

$$\begin{bmatrix} p_L \\ q_L \end{bmatrix} = \begin{bmatrix} V_\alpha & V_\beta \\ V_\beta & -V_\alpha \end{bmatrix} \begin{bmatrix} i_{L\alpha} \\ i_{L\beta} \end{bmatrix}$$

These $pL$and qL power can be divided into oscillatory and average terms as following

$pL=\bar{P}+p$

$qL=\bar{Q}+q$

where,

$\bar{P}$= Instantaneous real power Mean value and is treated as desired power component that can be transferred from source to load.

p= Instantaneous real power alternated value and has to be compensated as it is not involve in power transfer between the source to load.

$\bar{Q}$= Instantaneous imaginary power mean value and it is related to the exchanges of power between the load phases which results in undesired current, so it has to be compensated.

q= Instantaneous imaginary power alternated value and is same as conventional reactive- power that has been compensated by using the APF.

In p-q theory assumed voltages are sinusoidal in nature so the power is to be calculated using these sinusoidal voltages.

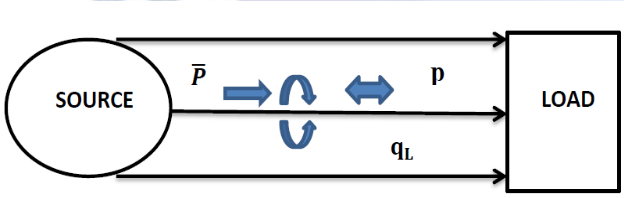

Fig.5.3 p-q theory power components

The powers that have to be compensated are described as below

$pc=-p+p_{loss}$

$qc=-q_L$

where,

p_{loss} = desired active power for compensating filter loss and for desired dc link voltage. By inverting the matrix we can obtain the reference compensation currents as follows

$$\begin{bmatrix} i_{c\alpha} \\ i_{c\beta} \end{bmatrix} = \frac{1}{V_\alpha^2 + V_\beta^2} \begin{bmatrix} V_\alpha & V_\beta \\ V_\beta & -V_\alpha \end{bmatrix} \begin{bmatrix} -p + p_{loss} \\ -q_L \end{bmatrix}$$

$$\begin{bmatrix} i_{ca}* \\ i_{cb}* \\ i_{cc}* \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} 1 & 0 \\ \frac{-1}{2} & \frac{\sqrt{3}}{2} \\ \frac{-1}{2} & \frac{-\sqrt{3}}{2} \end{bmatrix} \begin{bmatrix} i_{c\alpha} \\ i_{c\beta} \end{bmatrix}$$

- For separation of the instantaneous power direct term from alternating one a Low Pass Filter (LPF) with feed-forward effect is used.
- DC-link voltage regulator is responsible for compensation as well as for transient response.

Hence, the actual value of DC-capacitor voltage has to be compared with the reference one and the Differential error is fed to a PI-control.

VI. SIMULATION RESULTS

6.1 Conventional Simulation Circuit

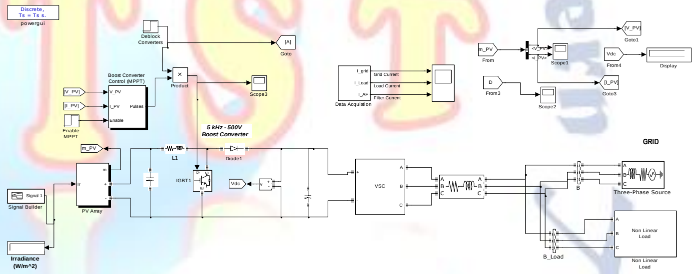

Fig 6.1 Conventional Simulation Circuit

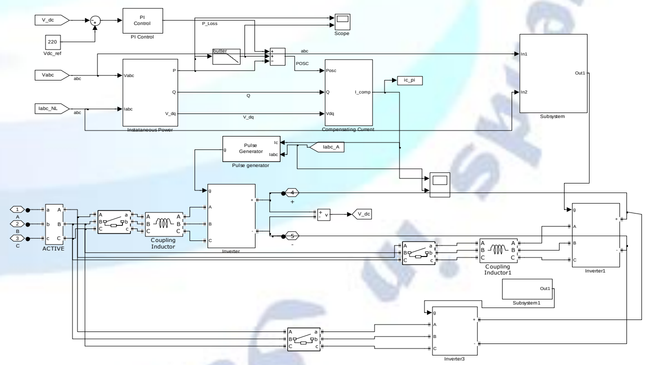

Fig 6.2 VSC with Filter

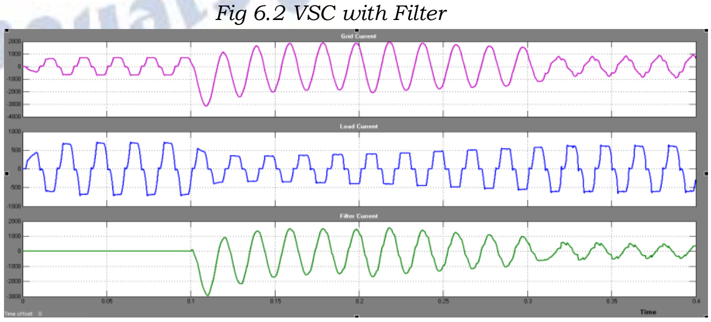

Fig 6.3Grid Current, Load Current, Filter Current

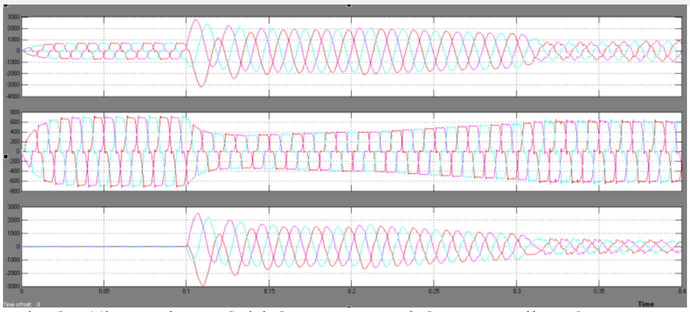

Fig 6.4 Three phase Grid Current, Load Current, Filter Current

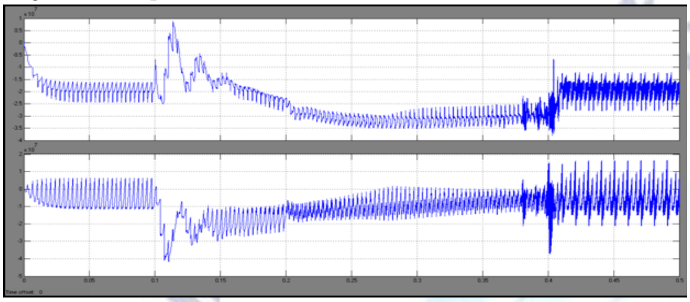

Fig 6.5Active Power and Reactive Powers

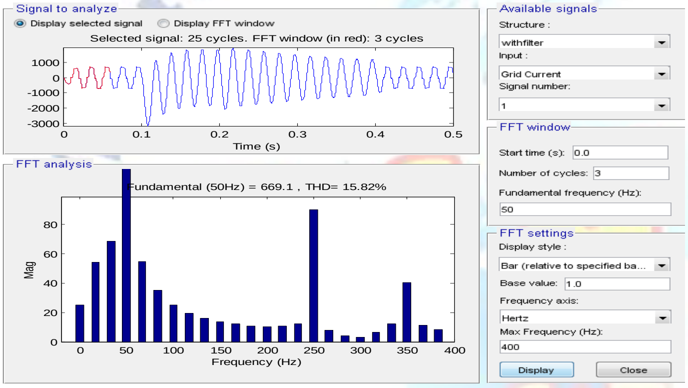

Fig 6.6THD Without Filter

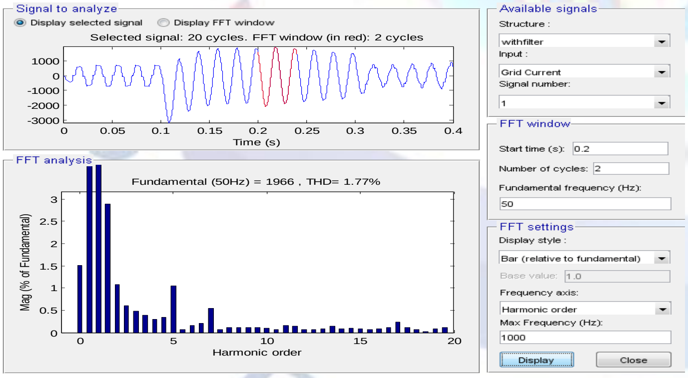

Fig 6.7 THD with Filter

Proposed Simulation Circuit

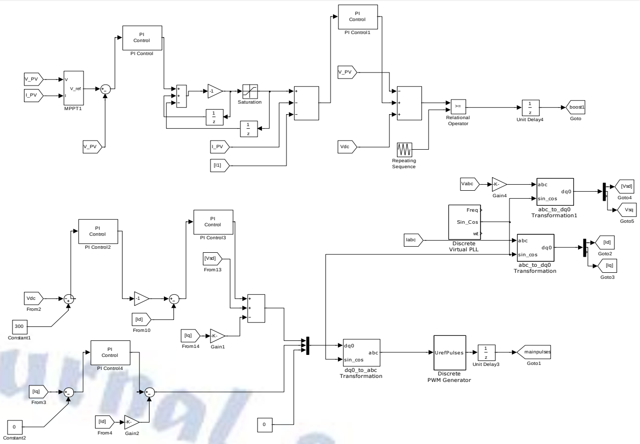

Fig 6.8Proposed P-Q control theory

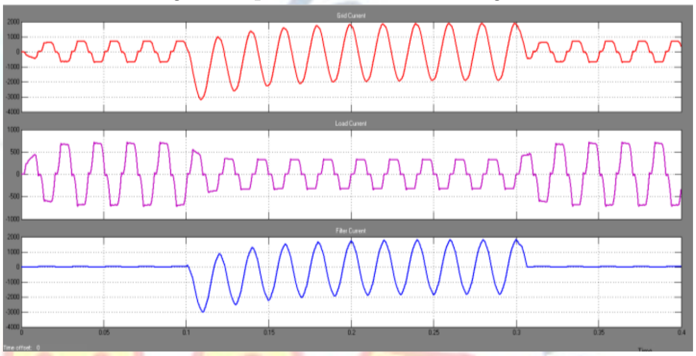

Fig 6.9Grid Current, Load Current, Filter Current

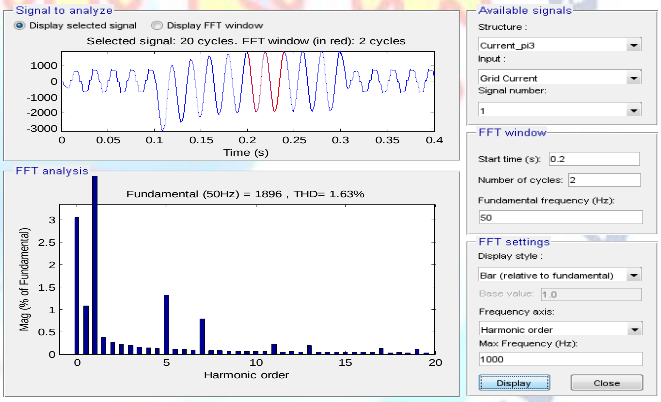

Fig 7.0THD of Grid Current for Proposed circuit

Table: Comparison of THD for conventional and proposed methods

Conventional circuit without filter	15.82%
Conventional circuit with filter	1.77%
Proposed circuit with filter	1.63%

CONCLUSION

On the basis of simulation results, the paper utilizes the P-Q theory to detect the load, source& harmonic current. The compensation of the Harmonics in the load current is effectively done by reshaping the source current to that similar to sine wave. The active & reactive power graphs after & before activation of filter reveals the reactive power compensation.

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