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Research article

Analysis and Simulation of Harmonics Current in Power Electronics Equipment Generated by Nonlinear Loads: Hysteresis Current Control Approach

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Abstract
The present paper demonstrates a novel analysis of harmonic currents in power electronics equipment produced by nonlinear loads. Simulated results are explored using Matlab and Simulink software packages. Shunt active power filters (APF) pay a key role to reduce harmonics current generated by nonlinear loads. Impact of shunt active power filter (APF) for compensating the harmonics current has been examined and analysed by using Hysteresis current control technique. In view of observational fact that the harmonic currents produced by nonlinear loads can interact adversely with a wide range of power electronics equipment causing additional losses, overloading, malfunctioning, overheating and interferences, comprehensive analysis of harmonics current in power electronics equipment has been focused here. In addition, the present analysis finds its application in pure sinusoidal waves. This paper contains several sections and initially description of shunt active power filters (APF) and instantaneous reactive power theory are presented. Subsequently, the principle of Hysteresis approach to control harmonic current produced through nonlinear loads and simulink model of shunt active power filter (APF) have been proposed. Using Matlab/Simulink simulated results have been explored and analysed for its implementation. Various relevant figures including bar representation of load current with and without filter and active and reactive power system with and without APF have also been shown. Finally, some conclusive observations are drawn.

Keywords: Harmonic current, nonlinear load, power electronics equipment, active power filters (APF), Matlab and Simulink, Hysteresis current control, instantaneous reactive power theory, simulation, fast Fourier technique (FFT), matrix equation, Clarke transformation, inverse orthogonal transformations.

1. Introduction

Power electronics equipments such as capacitors, transformers, and motors have their increasing demands in our day-to-day life which causes an increasing harmonics distortion in the ac mains currents. It is an observational fact in field of Electrical and Electronics Engineering that the harmonics mechanism is a severe as well as dangerous problem. In Electric Power System (EPS) mostly nonlinear loads based on solid-state converters are like UPS, SMPS etc. These nonlinear loads draw current that is not sinusoidal and thus create voltage drops in distribution conductors. This harmonic current causes number of adverse effects in power system such as overheating, overloading, perturbation of sensitive control and electronic equipment, capacitor failure, motor vibration, excessive neutral currents, resonances problem and low power factor. As a result, effective harmonic compensation from the system has become an important phenomenon both for the utilities and users as well. Active power filtering constitutes one of the most effective proposed solutions. Active power filter (APF) can solve the problems of harmonic and reactive power, power factor, unbalance, achieved balance, sinusoidal current at source end, with unitary value of power factor. There are two main affects of harmonic current on a distribution power system**.** The first affect is that harmonic currents add to the RMS value of the fundamental current**.** This additional current will increase losses in wire, bus bars, generators, transformers and capacitor banks used in the distribution system**.** The second affect of harmonic current is the additional heating of equipments caused by the harmonic currents**.** Transformers, capacitor banks, motors, circuit breakers, wires and bus bars must be designed to handle the higher frequency currents**.** If these components are not correctly sized, the harmonic currents can cause additional heating in those components**.** This heating can result in premature component failure and the possibility of fire**.** The quality of electric power is deteriorating mainly due to current and voltage harmonics, negative sequence components, voltage sag, voltage swell, flicker, voltage interruption, etc. The literature shows that analysis and simulation of harmonics current produced by nonlinear loads have taken a prominent place in research community. Several noteworthy researchers [1, 2, 3…8, 10, 13, 15,…17] confined their attention in analyzing problems including modelling and simulation of its different versions. In this connection it is noted here that Hysteresis current control method is the most popular method in terms of quick current controllability, versatility and easy implementation, we refer for more details Akagi [2]. Later in 2006 Akagi [1] proposed that shunt active power filter (APF) is one of the custom power devices planned to improve the power quality. So far many theories have been developed for instantaneous current harmonics detection in active power filter such as fast Fourier technique (FFT), neural network, instantaneous p-q theory (instantaneous reactive power theory), synchronous d-q reference frame theory or by using suitable analogue or digital electronic filters separating successive harmonic components, PLL with fuzzy logic controller, neural network etc. Recently, Maurya *et al.* [11] contributed for computational model for performance analysis of photonic band gap structure on defected ground surface with microwave and band stop filter and subsequently Maurya *et al.* [12] succeeded to explore a novel method for analysis of synchronization of GPS and geosynchronous satellite signals using solar braking and intrinsic velocity rectification. Some research works by previous contributors for its other different versions can be found in Capmany and Pastor [6] and references therein.

Although, as revealed here that number of theories for instantaneous current harmonics detection in active power filter are explored by different previous researchers yet out of these theories, p-q theory and d-q theory are mostly used due to their accuracy, robustness and easy calculation. The main sources of voltage and current harmonics are due to control and energy conversion techniques involved in the power electronic devices such as chopper, rectifier, cyclo converter etc. In this connection, Ali and Seyed [4] may be referred for more details. In this paper we are mainly confined to analyze and simulate results of shunt active power filter with hysteresis current control technique for power filtering. Here, it is examined that the compensation principle used for current harmonics suppression and harmonic control method provides a quick and easy response in the system. Matlab and simulink are very much useful software for modelling and simulation of various physical, mathematical and engineering phenomena. In this direction, Maurya and Maurya [9], Maurya *et al.* [14] and Patel *et al.* [15] are worth mentioning.

2. Design and Functions of Shunt Active Power Filter (APF)

The shunt active power filter (APF) is one of the most important devices in Electronic Power System (EPS) that is connected in parallel to a nonlinear load. Active power filters (APF) utilizes fast switching insulated gate bipolar transistors bridge, which produces an output current of the desired shape such that whenever they are injected into the AC lines, it compensates the reactive and harmonic currents from a nonlinear load. The resulting current drawn from the ac main is sinusoidal. The shunt active power filters (APF) need to generate enough reactive and harmonic current to compensate the nonlinear load generated harmonics in the AC line. Current controlled voltage source inverter is used to generate the compensating current (i_C) and is injected into the line which has been displayed in following figure 1 of shunt active power filter system. This cancels the harmonic components drawn by the nonlinear load and then the utility line current (i_S) is sinusoidal.

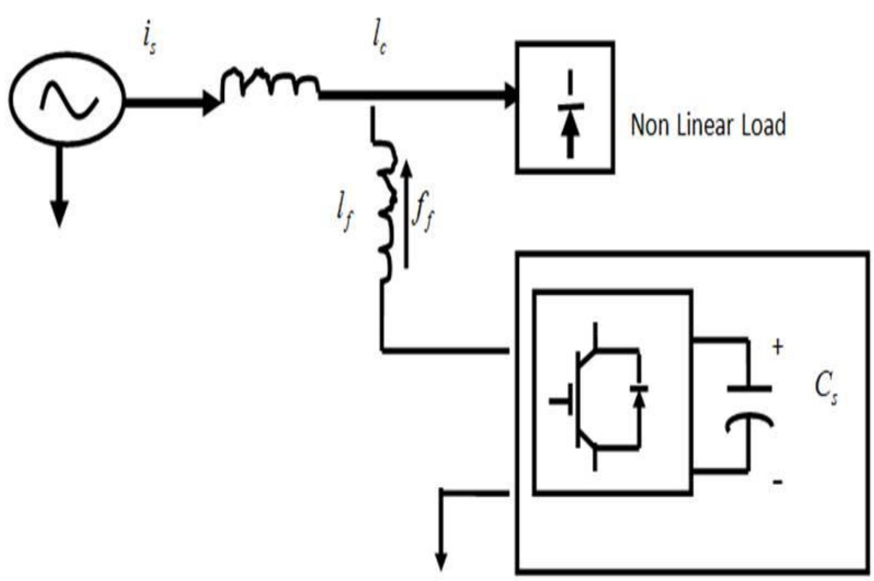

Fig. 1: Principle of shunt active power filter (APF)

3. Generalized Theory of Instantaneous Reactive Power

Several theories for instantaneous current harmonics detection in active power filter are explored by different previous researchers yet out of these theories; p-q theory and d-q theory are mostly used due to their accuracy, robustness and easy calculation. In 1983, Akagi *et al.* [1, 2] contributed to propose a novel theory known as "The Generalized Theory of the Instantaneous Reactive Power in Three-Phase Circuits". By virtue of its internal characteristics, this theory is also known as p-q theory. In this theory, instantaneous three-phase voltages and currents are transformed into α-β coordinates from a-b-c coordinates, known as Clarke transformation as shown in equation (3.1) and (3.2) respectively.

$$\begin{bmatrix} V_\alpha \\ V_\beta \end{bmatrix} = \begin{bmatrix} 1 & -1/2 & -1/2 \\ 0 & \sqrt{3}/2 & -\sqrt{3}/2 \end{bmatrix} \begin{bmatrix} V_a \\ V_b \\ V_c \end{bmatrix} \tag{3.1}$$

$$\begin{bmatrix} i_\alpha \\ i_\beta \end{bmatrix} = \begin{bmatrix} 1 & -1/2 & -1/2 \\ 0 & \sqrt{3}/2 & -\sqrt{3}/2 \end{bmatrix} \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} \tag{3.2}$$

The Clarke transformation is used in instantaneous reactive power theory is shown in figure 2:

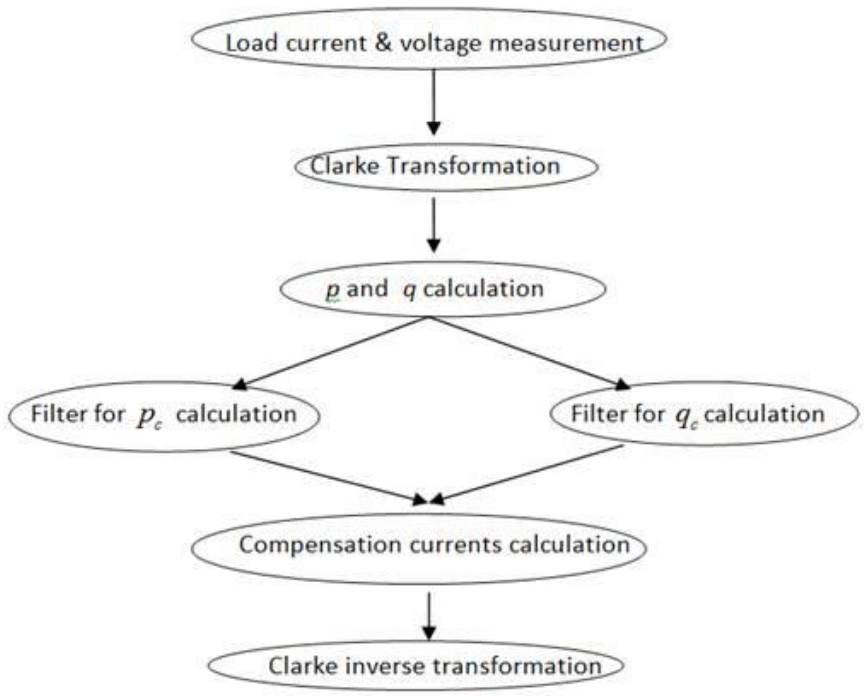

Fig.2: Clarke transformation

In the instantaneous reactive power theory the three phase coordinates a-b-c are mutually orthogonal. As a result, the conventional power for three phase circuits can be derived by using the above matrix equations expressed in (3.1)-(3.2). The instantaneous real power is defined as follows in equation (3.3)

$$p = V_a i_a + V_b i_b + V_c i_c \tag{3.3}$$

In view of above equations, it is fairly easy to express the instantaneous power in following equation (3.4):

$$\begin{bmatrix} p \\ q \end{bmatrix} = \sqrt{2}/3 \begin{bmatrix} V_\alpha & V_\beta \\ -V_\beta & V_\alpha \end{bmatrix} \begin{bmatrix} i_\alpha \\ i_\beta \end{bmatrix} \tag{3.4}$$

As the compensator will only compensate the instantaneous reactive power, the real power is always set to zero. The reference current equation is given below:

$$\begin{bmatrix} i^i_{s\alpha} \\ i^i_{s\beta} \end{bmatrix} = \frac{1}{V_\alpha^2 + V_\beta^2} \begin{bmatrix} V_\alpha & -V_\beta \\ V_\beta & V_\alpha \end{bmatrix} \begin{bmatrix} p_0 + p_{-loss} \\ 0 \end{bmatrix} \tag{3.5}$$

These two references current add in the mix and generate the reference current i_{ref}. By deriving from above equations, the compensating reactive power can be identified. Using the inverse orthogonal transformations the compensating current of each phase can be derived by following matrix equation as shown in (3.6):

$$\begin{bmatrix} i^i_{ca} \\ i^i_{cb} \\ i^i_{cc} \end{bmatrix} = \sqrt{2/3} \begin{bmatrix} 1 & 0 \\ -1/2 & \sqrt{3}/2 \\ -1/2 & -\sqrt{3}/2 \end{bmatrix} \begin{bmatrix} i^i_{s\alpha} \\ i^i_{s\beta} \end{bmatrix} \tag{3.6}$$

The instantaneous reactive power theorem performs instantaneously as the reactive power is detected based on the instantaneous voltages and currents of the three phase circuit. This will provide better harmonics suppression as the response of the harmonics detection phase is in small delay.

4. Principle of Hysteresis Current Control Technique

The harmonic current control strategies play a key role in fast response current controlled voltage source inverters such as the active power filters (APF). There are different types of current controllers such as three independent hysteresis controllers, three dependent hysteresis controllers, ramp comparison controllers, PI controller and predictive controllers. However, the hysteresis current control method is the most commonly proposed control method in time domain. This method provides instantaneous current corrective response, good accuracy and unconditioned stability to the power system. In 1988, Peng *et al.* [16] considered this technique as the most suitable solution for current controlled inverters. Of late, Grady *et al.* [8] confined their attention for survey of active line conditioning methodologies and proposed that the hysteresis current control method is the most suitable among others. With the hysteresis current control method, limit bands are set on either side of a signal and generate the required triggering pulses by comparing the error signal with that of the hysteresis band and it is used for controlling the voltage source inverter so that the output current is generated from the filter will follow the reference current waveform is shown in fig. 3.

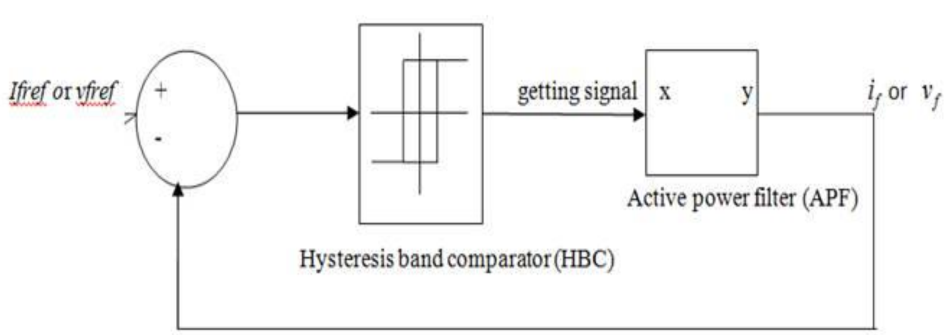

Fig.3: Basic principle of Hysteresis current control

Fig. 4 illustrates the ramping of the current between the two limits where the upper hysteresis limit is the sum of the reference current and the maximum error or the difference between the upper limit and the reference current and for the lower hysteresis limit, it is the subtraction of the reference current and the minimum error. Supposing the value for the minimum and maximum error should be the same. As a result, the hysteresis bandwidth is equal to two times of error.

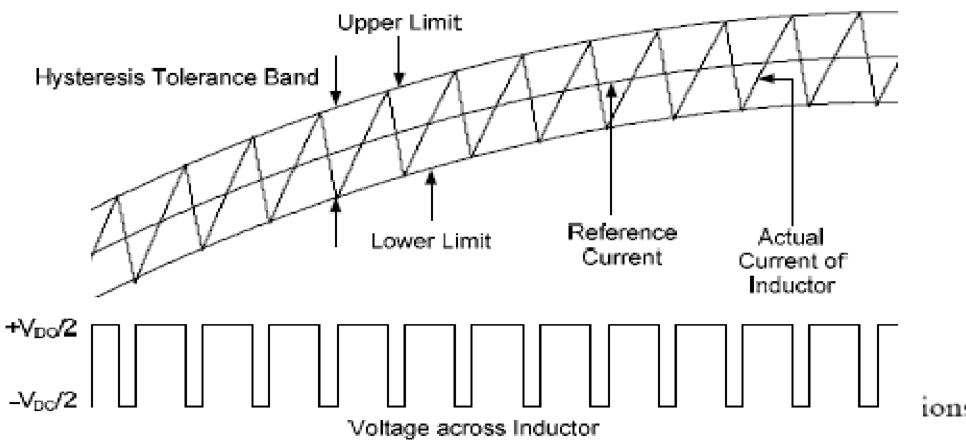

Fig. 4: Hysteresis Band

5. Simulation Model of Shunt Active Power Filter (APF)

In this section, simulation model of the shunt active power filter (APF) has been briefly described. The main components of the system are shown in the following overall system model containing the power source, the shunt active power filter and the nonlinear loads is shown in fig. 5.

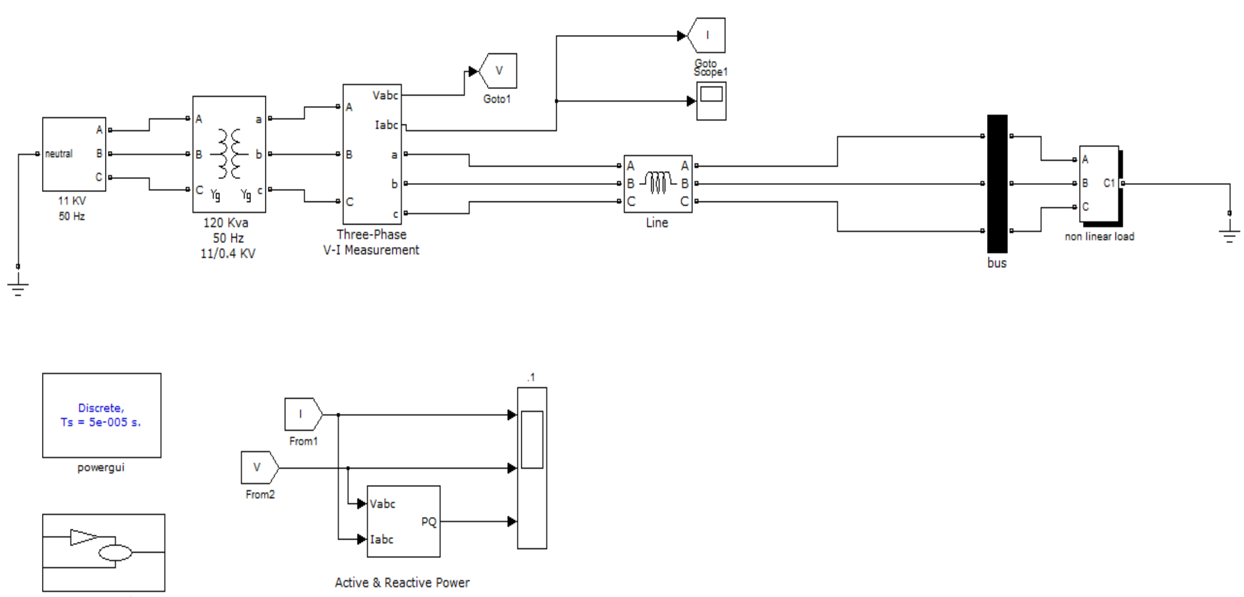

Fig. 5: System model without active power filter (APF)

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The main components of the system are described as below:

- The power source, which was designed as a three-phase 11KV/50Hz voltage sources connected together in a Y configuration with neutral and a three phase L branch.
- The single-phase nonlinear loads are containing a single phase uncontrolled diode rectifier supplying a series RL load for phase A, a single-phase uncontrolled diode rectifier supplying a parallel RC load for phase B, a single phase uncontrolled diode rectifier supplying a series RL loads for phase C.
- The three phase non-linear load is containing a three phase uncontrolled diode rectifier supplying a series RL load.

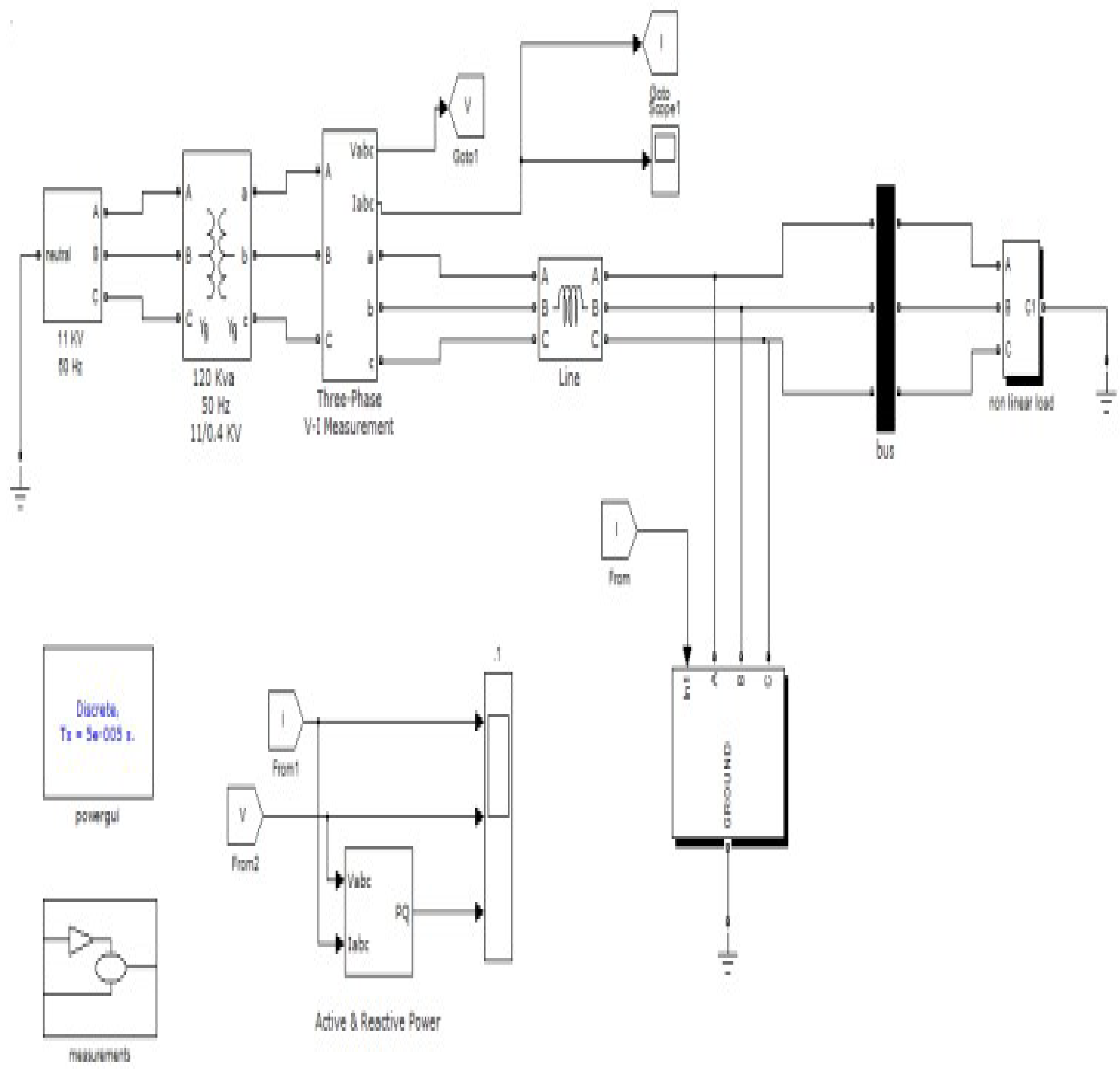

Fig.6: System model with active power filter (APF)

The PWM IGBT voltage source inverter, which contains a three-leg voltage source inverter with neutral clamped DC capacitors and the control scheme, as shown in fig. 7.

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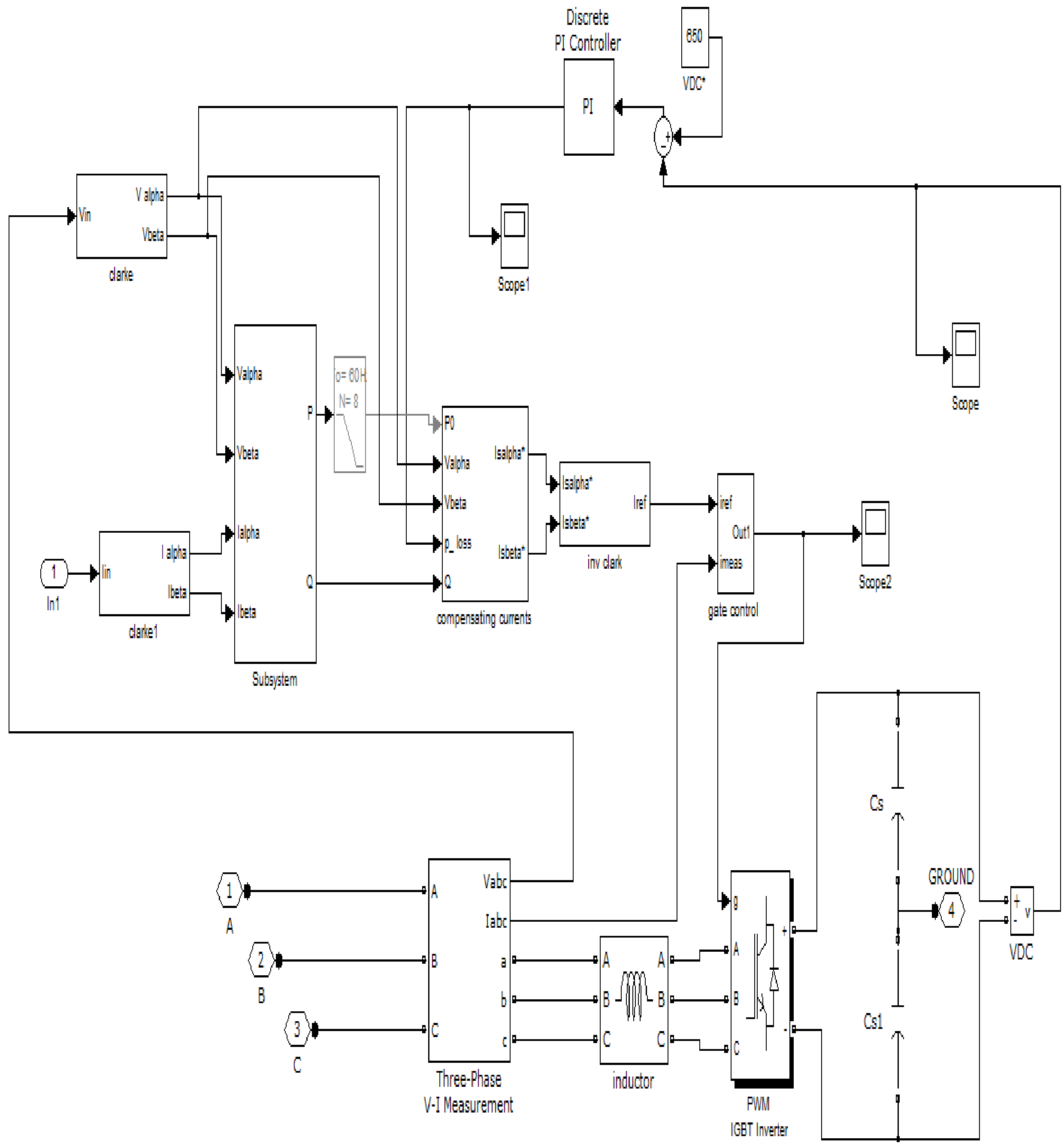

Fig. 7: Model of shunt active power filter (APF)

Despite the fact that the load currents are distorted, with the help of SAPF, the source currents are balanced sinusoids and in phase with their respective voltages. There is a path from the neutral of loads and midpoint of the DC capacitors, the zero sequence current will be appropriately compensated. By using a PI controller, the sum of the voltages of the DC capacitors (VDC) is maintained nearly constant to the reference value (VDC*) and then added to the alternative power P_ loss.

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6. Simulated Results

The complete model of active power filter is presented in fig.7 and result were obtained by using MATLAB/Simulink Simpowersystem Toolbox software for a three phase neutral clamped APF compensating harmonics, reactive power produced by nonlinear loads.

Fig. 8 shows the simulation results obtained in harmonic distortion analysis of the load current, for each phase with nonlinear load. Without APF, the total harmonic distortion (THD) is 30.25%. The highest harmonics are the 5_{th} and 7^{th} order, representing 25.14% and 8.25% of the fundamental respectively.

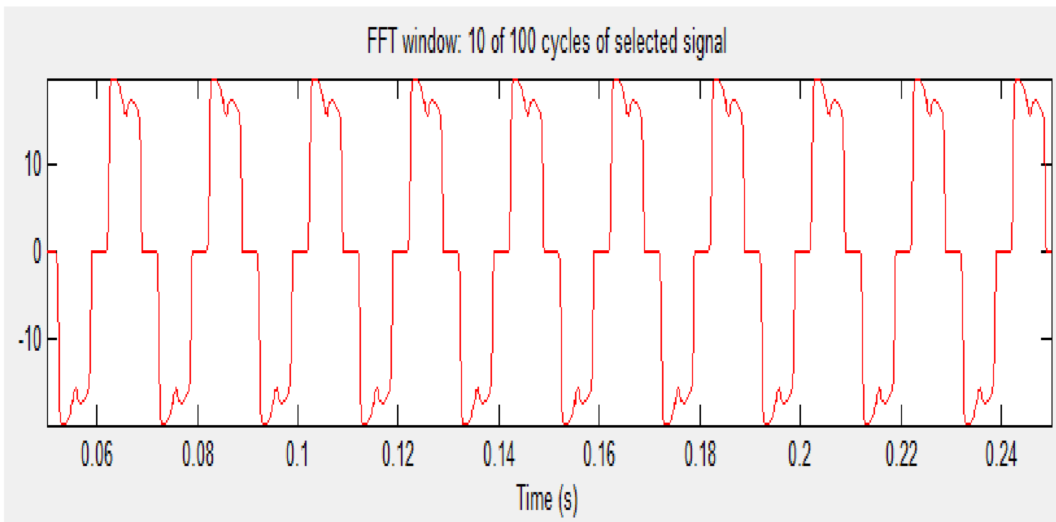

Fig. 8: Load current system without active power filter (APF)

Fig. 9 shows the simulation result of the source current obtained using APF to compensate harmonics created by nonlinear load.

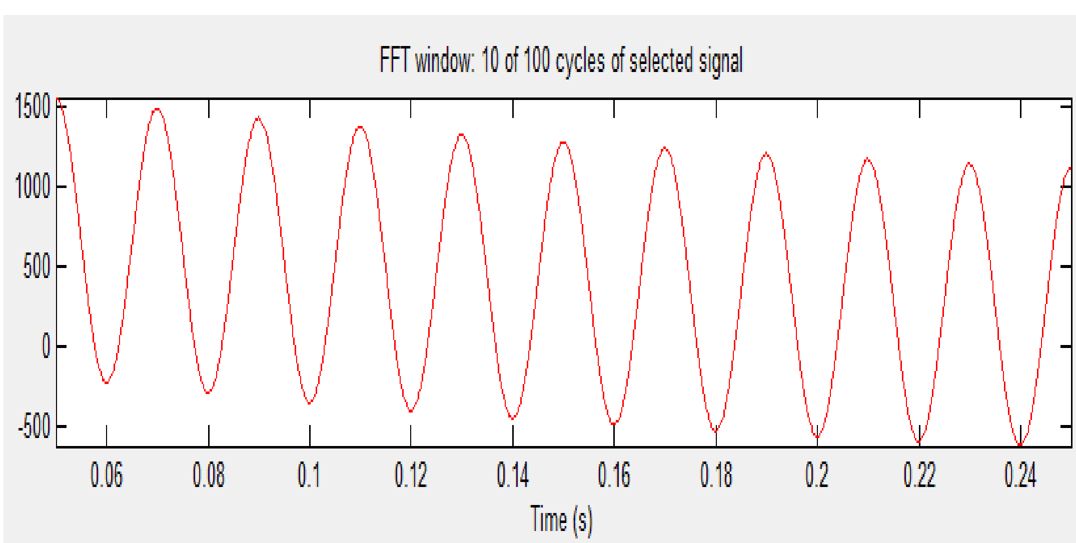

Fig.9: Source current system with active power filters (APF)

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By using APF, the THD of the source current is now 1.28% and magnitude of 5th and 7th harmonics are respectively 0.38% and 0.21% of the fundamental value, thus meeting the limit of harmonic standard of IEEE STD. 519-1992. The highest harmonics are still the 5th and 7th, but now they represent only 0.38% and 0.21% of the fundamental, which meets the harmonic standard of (IEEE STD. 519-1992).

Fig. 10 and fig.11 show the Bar representation of signals of fig. 8 and fig. 9 respectively. This shows the difference in total harmonic distortion between the system with and without active power filter.

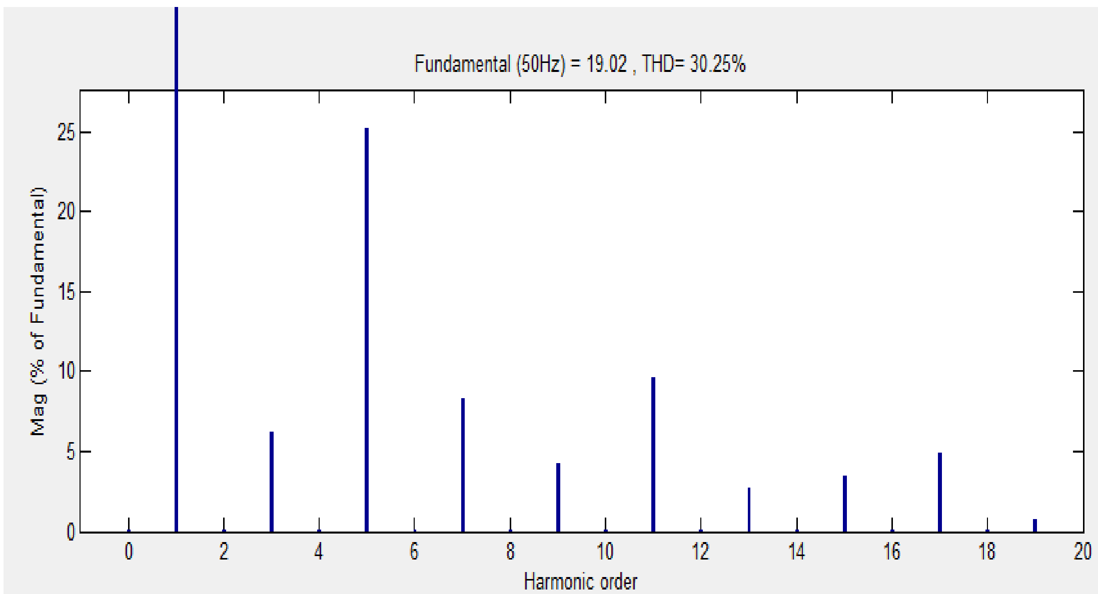

Fig.10: Bar representation of load current without active power filter (APF)

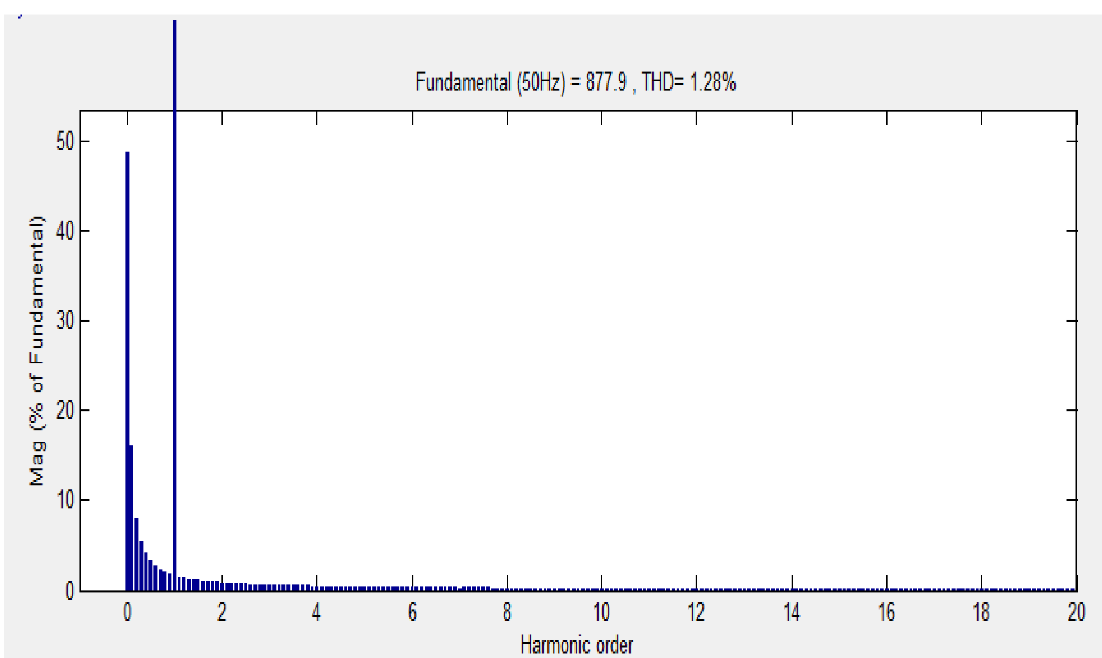

Fig.11: Bar representation of source current with active power filter (APF)

Fig. 12 and fig. 13 shows the waveform of active and reactive power of system without and with APF respectively.

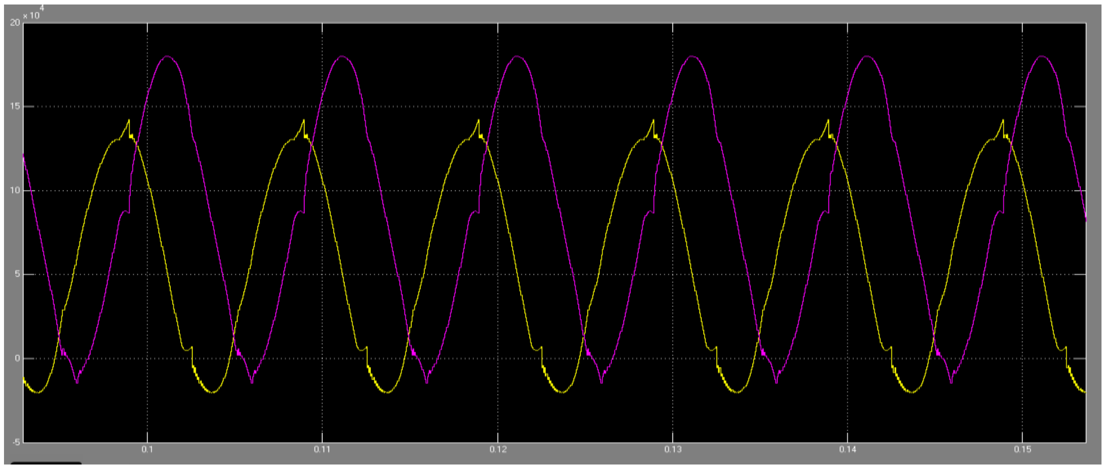

Fig. 12: Active and reactive power system without active power filter (APF)

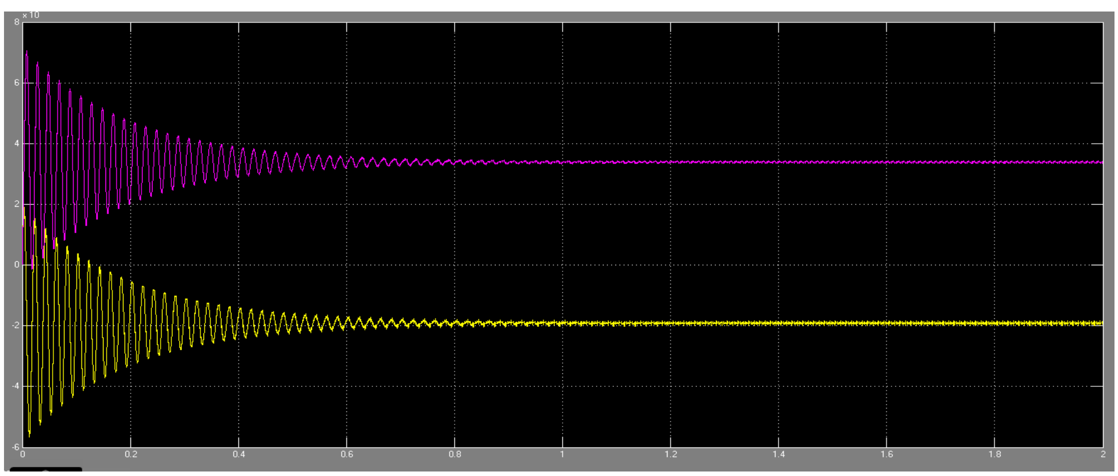

Fig.13: Active and reactive power system with active power filter (APF)

Fig. 13 shows that when connecting the APF to the system, the reactive power decreases below to Zero. This is proven that APF is a very effective tool to compensate reactive power.

7. Conclusive Observations

Harmonics current generated by nonlinear loads in power electronics equipments has been successfully analysed using Hysteresis current control technique. Simulated results for the present model are explored using Matlab/Simulink softwares. Relevant figures and graphs have been shown to understand the conclusive results for the simulation model in appropriately. A few more observations found based on the simulated results which are as following:

- The source current harmonics are compensated very effectively by using the shunt active power filter.
- The THD of the source current is reduced below the 5% limit imposed by (IEEE STD. 519-1992) standard for non linear load using the APF.

- Besides, active filters with different rated values can be simulated in order to analyse different reductions of the harmonic distortion.
- By means of the simulation results carried out herein, the voltage and current harmonic distortions created by a non linear load have been obtained.

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