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Improved Methodology for Harmonics Reduction using Shunt Active Power Filter Based on p-q Theory

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Abstract: ***This paper discuss about the problem of harmonics occurring in various power electronic equipments. It proposes a simple method for enhancement of power quality using concept of Shunt Active Power Filter (SAPF). In this paper SAPF is modeled using p-q theory with PI control method so that Total Harmonic Distortion (THD) should be in compliance with IEEE 519 standard. The compensation characteristics of each topology with the respective control scheme are proved by using MATLAB/SIMULINK.***

Keywords: Harmonics Compensation, SAPF, p-q theory, THD, PI controller

1. Introduction

Power quality determines the fitness of electrical power to consumer devices. Synchronization of the voltage frequency and phase allows electrical systems to function in their intended manner without significant loss of performance or life. The term is used to describe electric power that drives an electrical load and the load's ability to function properly. Without the proper power, an electrical device (or load) may malfunction, fail prematurely or not operate at all. There are many ways in which electric power can be of poor quality and many more causes of such poor quality power. Current harmonics produced by non-linear loads, such as switching power supplies and motor speed controllers, are prevalent in today’s power systems. These harmonics interfere with sensitive electronic equipment and cause unnecessary losses in electrical equipment. Harmonics voltages and currents in an electric power system are a result of non-linear electric loads. Harmonic frequencies in the power grid are a frequent cause of power quality problems. Harmonics in power systems result in increased heating in the equipment and conductors, misfiring in variable speed drives, and torque pulsations in motors. Reduction of harmonics is considered desirable. A harmonic of a wave is a component frequency of the signal that is an integer multiple of the fundamental frequency, i.e. if the fundamental frequency is f, the harmonics have frequencies 2f, 3f, 4f . . . etc. The harmonics have the property that they are all periodic at the fundamental frequency; therefore the sum of harmonics is also periodic at that frequency. Harmonic frequencies are equally spaced by the width of the fundamental frequency and can be found by repeatedly adding that frequency.

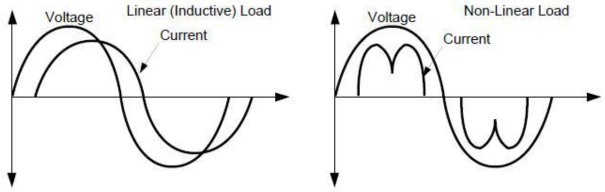


Figure 1: Difference between Linear and Non-Linear Loads

The terms “linear” and “non-linear” define the relationship of current to the voltage waveform. A linear relationship exists between the voltage and current, which is typical of an across-the-line load. A non-linear load has a discontinuous current relationship that does not correspond to the applied voltage waveform.

2. Various Methodologies For Harmonic Mitigation

The presence of harmonics in the power system cause greater power loss in distribution, interference problem in communication system and, sometimes results in operation failure of electronic equipment which are more and more sensitive. In order to reduce this problem various types of filters are used using different methods which are as follows:

A. Passive Filters

Passive implementations of linear filters are based on combinations of resistors (R), inductors (L) and capacitors (C). These types are collectively known as passive filters, because they do not depend upon an external power supply and/or they do not contain active components such as transistors. Passive filters are used to mitigate power quality problems in six pulse ac-dc converter. Apart from mitigating the current harmonics, passive filters also provide reactive power compensation, thereby further improving the system performance. Passive filters have been used as a solution to solve harmonic current problems, but because of the several disadvantage of passive filter like it can mitigate only few harmonics, gives rise to resonance problem, bulky in size and costly they are being used to a certain limit.

B. Active Filters

To overcome drawbacks of passive filters active filters are introduced. They inject harmonic voltage or current with appropriate magnitudes and phase angle into the system and cancel harmonics of non-linear loads. Active filters have the advantage of being able to compensate for harmonic without fundamental frequency reactive power concerns. This means that the rating of the active power can be less than a comparable passive filter for the same non-linear load and the active filter will not introduce system resonances that can move a harmonic problem from one frequency to another. Active filter can be classified based on the connection scheme as:

- Shunt active filter
- Series active filter
- Hybrid active filter.

In this paper harmonic mitigation is done by using shunt active power filter.

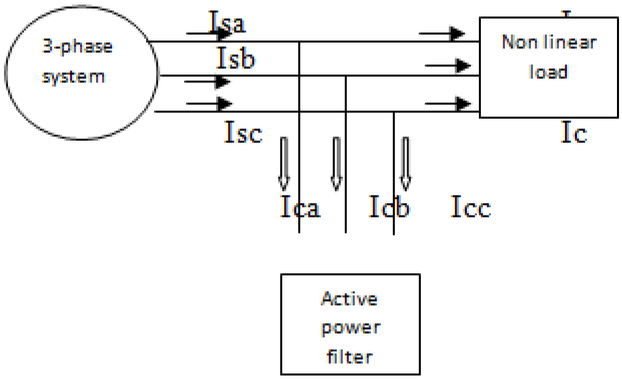


Figure 2: Active Power Filter

3. Shunt Active Power Filter (SAPF)

Shunt active power filter compensate current harmonics by injecting equal but opposite harmonic compensating current. In this case SAPF operates as a current source injecting the harmonic components generated by the load but phase shifted by 180º. This principle is applicable to any type of load considered a harmonic source. Moreover, with an appropriate control scheme, the active power filter can also compensate the load power factor. The shunt active filter has the capability of damping harmonic propagation between an already-existing passive filter and the supply impedance. The current compensation characteristic of SAPF is as shown.

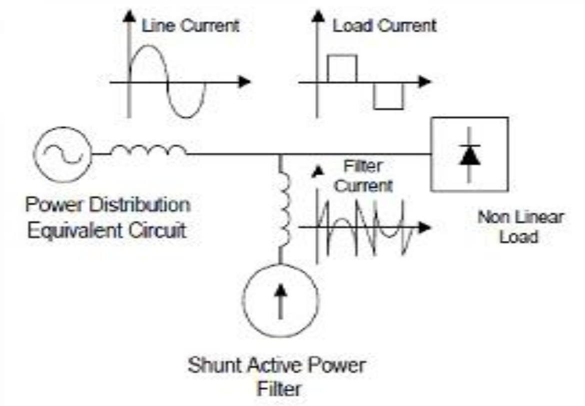


Figure 3: Compensation Characteristics of SAPF

The compensation effectiveness of an active power filter depends on its ability to flow with a minimum error and time delay the reference signal calculated to compensate the distorted load, current finally, the DC voltage control unit must keep the total DC voltage constant and equals to a given reference value. The DC voltage control is achieved by adjusting the small amount of real power absorbed by the inverter from the PCC. This small amount of real power is adjusted by changing the amplitude of the fundamental component of the reference current. The block diagram of a shunt active power filter control scheme is shown and consists of sensing the load currents and the point of common coupling (PCC) voltages, reference current generator, DC voltage control, injected current control and the inverter. The Shunt Active Power Filter analyzed in this paper is designed for 3-phase 4-wire systems and is capable of compensating current harmonics, current unbalance and power factor in 3-phase 4-wire electric systems.

3.1 Concept of P-Q Theory

The research work studied showed that a three phase four wire system i.e. system having three phase with neutral connection has large discrepancies when calculation of neutral current takes place. This problem is identified and can be solved using the concept of shunt active power filter. It has further been seen that the neutral current concept offers a large value when active shunt power filter has not been deployed so validation for this also has to be done. Moreover since the PI controller based system requires a hysteresis control mechanism hence a hysteresis loop must also be incorporated in the design to allow for more robust control system.

An active rectifier based shunt compensator plays a vital role in present-day static power compensation. This includes the conventional compensation features like power factor improvements, harmonic compensation and neutral current elimination in a three-phase four- wire system. The instantaneous power compensation theories have been evolved essentially to execute the compensation or correction in time domain.

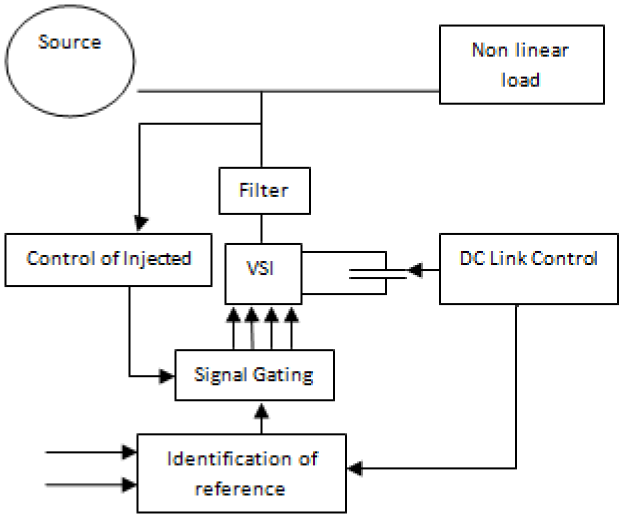


Figure 4: Control Scheme of SAPF

The first instantaneous reactive power compensation theory, popularly known as p-q theory was developed in Japan for a three-phase three-wire system. The p-q theory was further extended for a three-phase four wire system by defining zero sequence power. The Instantaneous Reactive power theory (IRP) p-q theory developed by Akagi, Kanazawa and Nabae in 1983 uses time domain in order to define a set of instantaneous powers. These Instantaneous powers are defined in terms of instantaneous voltages and currents, which are first, transformed from phase R, S and T to α, β, 0 coordinates by using the Clarke Transformation. This transformation produces a stationary reference frame, where coordinates α and β are orthogonal and the co-ordinate 0 corresponds to the zero sequence component. However, this zero sequence coordinate differs from the zero sequence components in the symmetrical component transformation.

3.2 Compensation with p-q Theory

This concept gives an effective method to compensate for the instantaneous components of reactive power for three-phase systems without energy storage. Instantaneous real and imaginary powers have first been defined in the time domain. The three phase voltages are sensed at the PCC and denoted as ea, eb and ec. The resultant load side line currents are sensed and denoted as iaL, ibL and icL. The Clarke transformation for three phase voltages and line currents, therefore are given as follows:

$$\begin{bmatrix} e_\alpha \\ e_\beta \\ e_0 \end{bmatrix} = \sqrt{\tfrac{2}{3}} \cdot \begin{bmatrix} 1 & -1/2 & -1/2 \\ 0 & \sqrt{3}/2 & -\sqrt{3}/2 \\ 1/\sqrt{2} & 1/\sqrt{2} & 1/\sqrt{2} \end{bmatrix} \cdot \begin{bmatrix} e_a \\ e_b \\ e_c \end{bmatrix} \ldots (1)$$

$$\begin{bmatrix} i_{\alpha\_load} \\ i_{\beta\_load} \\ i_{0\_load} \end{bmatrix} = \sqrt{\tfrac{2}{3}} \cdot \begin{bmatrix} 1 & -1/2 & -1/2 \\ 0 & \sqrt{3}/2 & -\sqrt{3}/2 \\ 1/\sqrt{2} & 1/\sqrt{2} & 1/\sqrt{2} \end{bmatrix} \cdot \begin{bmatrix} i_{aL} \\ i_{bL} \\ i_{cL} \end{bmatrix} \ldots (2)$$

According to the p-q theory the set of instantaneous powers in a three-phase system consists of the instantaneous zero sequence power p_0 defined as,

$$p_0 = e_0 i_0 \ldots (3)$$

Instantaneous real power p and the instantaneous imaginary power q defined as,

$$p = e_\alpha i_\alpha + e_\beta i_\beta \;..(4)$$

$$q = -e_\alpha i_\beta + e_\beta i_\alpha \;..(5)$$

These powers can also be written in a matrix form as,

$$\begin{bmatrix} p_0 \\ p \\ q \end{bmatrix} = \begin{bmatrix} e_0 & 0 & 0 \\ 0 & e_\alpha & e_\beta \\ 0 & e_\beta & -e_\alpha \end{bmatrix} \cdot \begin{bmatrix} i_0 \\ i_\alpha \\ i_\beta \end{bmatrix} \;..(6)$$

These quantities written in equation (3), (4) and (5) can be elaborated as follows:

$$p = \bar{p} + \tilde{p} \;..(7)$$

$$q = \bar{q} + \tilde{q} \;..(8)$$

Where,

p0 - Mean value of the instantaneous zero-sequence power – corresponds to the energy per time unity which is transferred from the power supply to the load through the zero-sequence components of voltage and current.

$\tilde{p}_0$ -Alternated value of the instantaneous zero-sequence power – it means the energy per time unity that is exchanged between the power supply and the load through the zero-sequence components. The zero-sequence power only exists in three-phase systems with neutral wire.

p - Mean value of the instantaneous real power – corresponds to the energy per time unity which is transferred from the power supply to the load.

$\tilde{p}$ - Alternated value of the instantaneous real power – It is the energy per time unity that is exchanged between the power supply and the load.

q - Instantaneous imaginary power – corresponds to the power that is exchanged between the phases of the load. This component does not imply any transference or exchange of energy between the power supply and the load, but is responsible for the existence of undesirable currents, which circulate between the system phases.

This theory, unlike other theories does not only consider each phase of the three phase system separately but also defines them in terms of other phases. Moreover, this gives us flexibility of using the theory for three-wire systems.

3.3 Instantaneous p-q theory for three-wire systems

Since, three-wire power systems do not contain zero sequence current components, the zero sequence components and in IRP p-q theory can be considered as zero. As a result, the three-wire system can be represented in terms of reduced vector Clarke coordinates. The reduced Clarke coordinates are nothing but the representation of IRP p-q theory for three-wire systems by neglecting the zero sequence components. The reduced vectors for three phase Clarke voltages and currents are determined as,

$$\begin{bmatrix} e_\alpha \\ e_\beta \end{bmatrix} = \begin{bmatrix} 1 & -1/2 & -1/2 \\ 0 & \sqrt{3}/2 & -\sqrt{3}/2 \end{bmatrix} \cdot \begin{bmatrix} e_a \\ e_b \\ e_c \end{bmatrix} \;..(9)$$

The active and reactive power is written as:

$$\begin{bmatrix} p \\ q \end{bmatrix} = \begin{bmatrix} e_\alpha & e_\beta \\ -e_\beta & e_\alpha \end{bmatrix} \cdot \begin{bmatrix} i_\alpha \\ i_\beta \end{bmatrix} \;..(10)$$

3.4 PI Controller

In this paper the proportional-integral (PI) controller is used in SAPF. The control scheme comprises of PI controller, limiter, and three phase sine wave generator for reference current generation and generation of switching signals. The peak value of reference currents is studied by regulating the DC link voltage. The definite capacitor voltage will be compared with a set reference value. The error signal is then fed through a PI controller, which gives to zero steady error in tracking the reference current signal. The schematic representation of the control circuit is as shown:

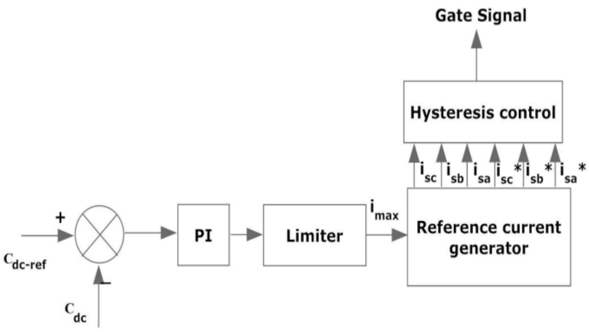
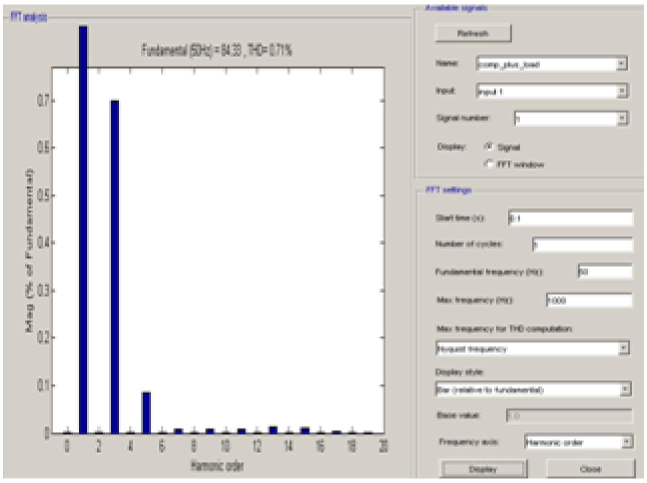


Figure 5: Block representation of PI controller

The output of the PI controller is presumed as peak value of the supply current (Imax), which is composed of two components: (a) fundamental active power component of load current, and (b) loss component of APF; to preserve the average capacitor voltage to a constant value. Peak value of the current (Imax) so found, will be multiplied by the unit sine vectors in phase with the individual source voltages to obtain the reference compensating currents. These expected reference currents (Isa*, Isb*, Isc*) and detected actual currents (Isa, Isb, Isc) are equated at a hysteresis band, which delivers the error signal for the modulation technique. This error signal chooses the operation of the converter switches. In this current control circuit configuration the source/supply currents Isabc are made to follow the sinusoidal reference current Iabc, within a fixed hysteretic band. The width of hysteresis window regulates the source current pattern, its harmonic spectrum and the switching frequency of the devices. The DC link capacitor voltage is always preserved constant during the operation of the converter. In this scheme, each phase of the converter is measured independently. To increase the current of a particular phase, the lower switch of the converter related with that particular phase is turned on while to decrease the current the upper switch of the corresponding converter phase is turned on.

4. Simulation Results

The simulation of the project was carried out in Matlab 8.1 and the project uses the simpower system library of SIMULINK, the total harmonic distortion and fft analysis was performed using power gui tool provided in sim power systems, the results are as shown:



Name: comp_plus_load
Input: input 1
Signal number: 1
Display: ● Signal ○ FFT window
Start time (s): 0.1
Number of cycles: 1
Fundamental frequency (Hz): 50
Max frequency (Hz): 1000
Max frequency for THD computation: Nyquist frequency
Display style: Bar (relative to fundamental)
Base value: 1.0
Frequency axis: Harmonic order

Figure 6: Result of THDi for the SIMULINK model

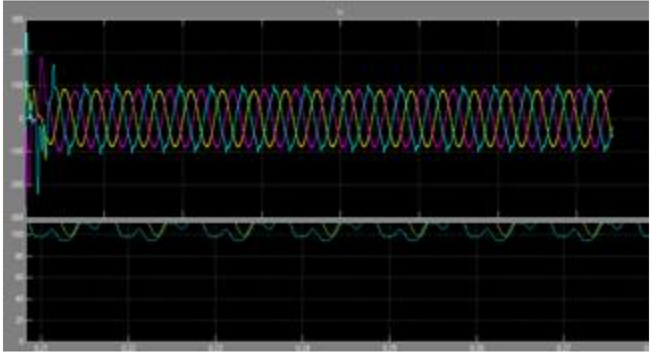


Figure 7: Graph of source current and THD without apf

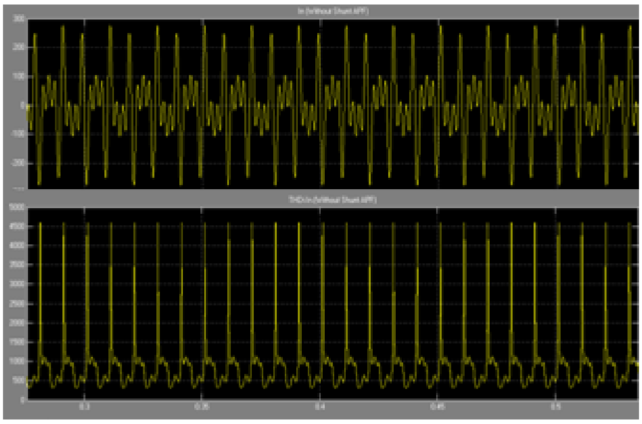


Figure 8: Graph of neutral current and THD without apf

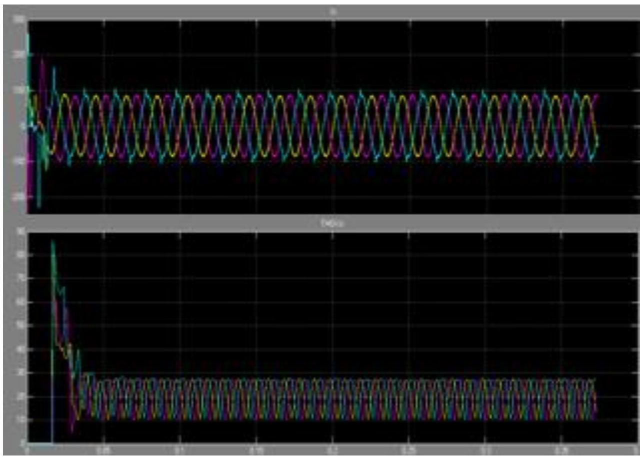


Figure 9: Graph of source current and THD in presence of apf

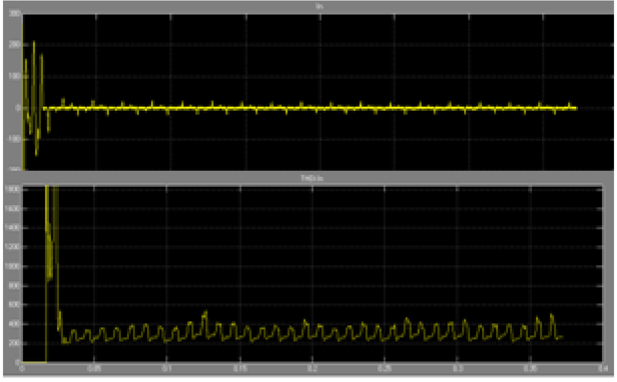


Figure 10: Graph of neutral current and THD in presence of apf

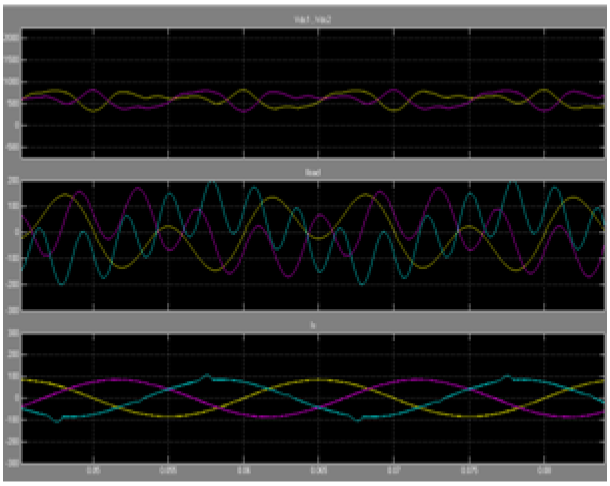


Figure 11: Graph showing PI controller operation

4.2 Comparison of Different Methodologies Adopted for Harmonic Reduction

Parameters	1st	2nd	3rd	4th	Our Work
SAPF implementation method	pq theory with PI controller	SRF theory	pq theory	pq theory with MRC	pq theory with PI controller
Supply system	Single phase	Not specified	Single phase	3-phase3-wire	3-phase 4-wire
Load used	Non linear (6 IGBT bridge)	Not specified	Single phase00diode rectifier	Not specified	Three phase bridge
THDi	1.10%	1.01%	1.85%	Not specified	0.71%
Tools used	PSCAD	Simulink	Simulink	Simulink	Simulink

5. Conclusion

In this paper an Active filter based on the instantaneous active and reactive power component p-q method is studied. Current harmonics consist of positive and negative sequence including the fundamental current of negative sequence can be compensated. Therefore, it acts as a harmonic and unbalance current compensator. The analysis of IRP p-q theory for non-sinusoidal conditions such as distorted supply voltage and harmonic-generating loads also provides us with an evaluation of performance of the p-q theory. For an instance, it shows that the values of instantaneous powers in a 3pN system with a balanced harmonic generating load (HGL) supplied by a sinusoidal and symmetrical voltage does not change with the harmonic order. In other words, the values of instantaneous powers do not change when a 5th order current harmonic generating load is replaced by a 7th order current HGL. The total harmonic reduction for current at the point of common coupling turns out to be 0.7% which is way below the specification provided by IEEE 519 standard which specifies a nominal total harmonic distortion to be under 5% , in this way the efforts put in to work are aptly rewarding and the results were in compliance with industrial standard.

6. Future Work

Experimental analysis can be done on Shunt Active Power Filter based on instantaneous active and reactive power component (p-q) method by developing prototype model in the laboratory to verify the simulation result based on (p-q) method with PI controller. It is important to develop this system in laboratory because the field test of the theory promises to give exciting results , although every care has been taken to model the simulation as close as as possible to the real world but the testimony of the project will remain incomplete without the field testing of the model.

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