Harmonic Compensation Using Active Power Filter

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Abstract: ***Nonlinear loads inject harmonic current into the power system and cause harmonic related problems such as harmonic interactions between utility system and loads. Active power filter is used to eliminate current harmonics and also for reactive power compensation. The objective of the shunt active filter is to supply harmonic current to the nonlinear load effectively resulting in a net sinusoidal current. Simple single phase model (simulation and hardware) for harmonic compensation using shunt active power filter is presented. In this work single-phase shunt active power filter is implemented to compensate harmonics and reactive power using FFT (Fast Fourier Transform) analysis and P-Q control technique. It is based on instantaneous values, allowing excellent dynamic response. Various simulation results are presented under steady state conditions. PWM pattern generation based on hysteresis based current control is used to obtain the switching signals to the PWM converter. Evaluation based on Simulation and Hardware setup using PIC microcontroller are shown. MATLAB is used for simulating the results.***

Keywords: Harmonic Compensation, FFT, PQ Theory, PWM

1. Introduction

The use of semiconductor devices is responsible for harmonic and reactive power disturbances. The harmonics and reactive power cause various problems which includes overheating of transformers, excessive neutral current, distortion of feeder voltage, low power factor, damages to power electronic devices and malfunction of sensitive equipment [2]. The use of active power filters (APFs) to mitigate harmonic problems has drawn much attention since 1970's, and it has gradually been recognized as a feasible solution of the problems created by nonlinear loads. APF is a power electronic device used to compensate harmonic and reactive power required for loads. The objective of the APF is to detect the load harmonic and reactive current and to inject an equal but opposite current to cancel out the load harmonic and reactive current, and thus, only fundamental current to be supplied by the source [4]. Though APFs are widely used in three phase system, by little modification in the control strategy it can be implemented in the single phase system, thus harmonic pollution can be reduced at low voltage system. An important component of APF system is the current controller, which maintains the output current at the imposed reference value [4].

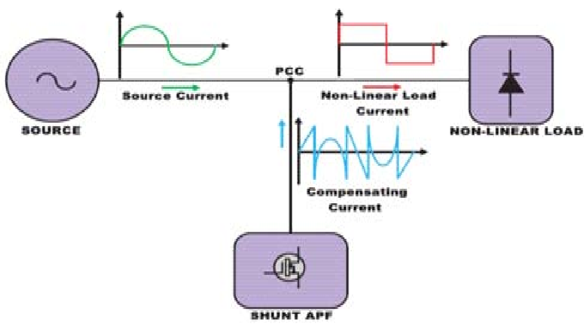

Figure 1.1: Principle of Shunt connected SPAPF

2. Compensation Techniques

2.1 Generation of Gating Signals to the Devices of the AF

The third stage of control of the AF's is to generate gating for the solid-state devices of the AF based on the derived compensating commands, in terms of voltages or currents. A variety of approaches, such as hysteresis-based current control, PWM current or voltage control, deadbeat control, Adaptive hysteresis control, sliding mode of current control, fuzzy-based current control, Neural networks current control etc. are implemented, either through hardware or software to obtain the control signals for the switching devices of the AF's. PWM is the most popular method for producing a controlled output for inverters [4]. They are quite popular in industrial applications.

2.2 Generation of reference compensation current

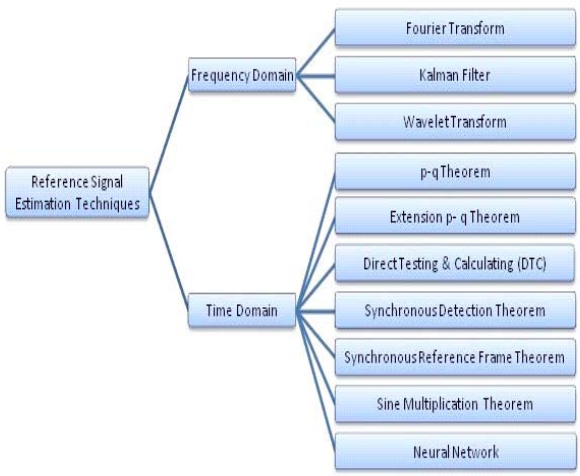

Figure 2.1: Instantaneous reactive power theory [9]:

In general, when the load is nonlinear the real and imaginary powers can be divided in average and oscillating components, as shown below.
real power - p
imaginary power - q

From these oscillating powers, it is possible to calculate the compensating currents in the α-β reference frame. Then, by using the Clarke inverse transformation, it is possible to calculate the currents to be injected by the active filter to compensate for these harmonic components in the load. This technique has proven to be very efficient and practical [9]. However, the compensated currents are not sinusoidal if the voltage used in the control algorithm is not balanced and purely sinusoidal. This problem may happen if the voltage at the point of common connection (PCC) is distorted or unbalanced and used in the control algorithm.

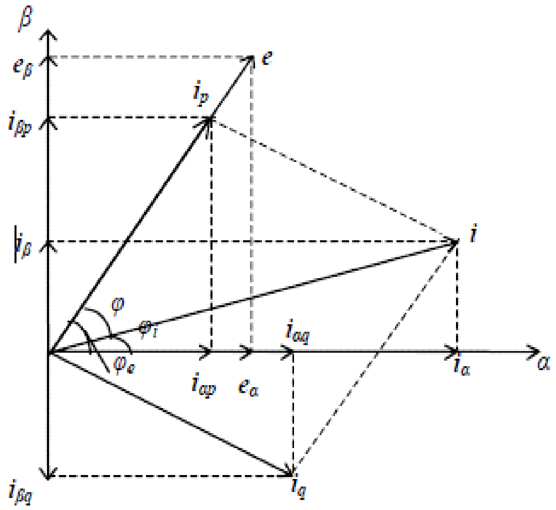

Figure 2.2: Vector diagram of voltage and currents

In 3-phase circuits with balanced voltage, instantaneous currents and voltages are converted into instantaneous space vectors. The traditional definitions of the power components are all based on the direct quantities of 3-phase voltages and currents vectors: e_a, e_b, e_c and i_a, i_b, i_c. In instantaneous reactive power theory, the instantaneous 3-phase currents and voltages are expressed as the following equations. These space vectors are easily converted into α-β coordinates known as Clarke transformation

$$S = V^* i^* = (v_\alpha + jv_\beta)^*(i_\alpha - ji_\beta) = (v_\alpha i_\alpha + v_\beta i_\beta) + j(v_\beta i_\alpha - v_\alpha i_\beta)$$

From this active and reactive power components are

$P = v_\alpha i_\alpha + v_\beta i_\beta$

$q = v_\alpha i_\beta - v_\beta i_\alpha$

For systems that do not have a neutral connection, the zero sequence does not exist and the mathematical equation will be presented in matrix form

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

And

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

This active and reactive power in matrix form is given below

$$\begin{bmatrix} p \\ q \end{bmatrix} = \begin{bmatrix} V_\alpha & V_\beta \\ -V_\beta & V_\alpha \end{bmatrix} \begin{bmatrix} i_\alpha \\ i_\beta \end{bmatrix}$$

Active and reactive powers can be separated into two parts which are AC part and DC part as shown below.

$$P = \bar{p} + \tilde{p}$$
$$q = \bar{q} + \tilde{q}$$

In order to get the DC part of the active and reactive power, the signals need to be filtered using low pass filter. The low pass filter will remove the high frequency component and give the fundamental part.

The reference currents required by the shunt active power filters are calculated with the following expression:

$$\begin{bmatrix} i^*_{C\alpha} \\ i^*_{C\beta} \end{bmatrix} = \frac{1}{V_\alpha^2 + V_\beta^2} \begin{bmatrix} V_\alpha & V_\beta \\ V_\beta & -V_\alpha \end{bmatrix} \begin{bmatrix} -\bar{p} \\ -\bar{q} \end{bmatrix}$$

The final compensating current components in a, b, c reference frame in terms of α-β are given as

$$\begin{bmatrix} i^*_{Ca} \\ i^*_{Cb} \\ i^*_{Cc} \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} 1 & -\frac{1}{2} & -\frac{1}{2} \\ 0 & \frac{\sqrt{3}}{2} & -\frac{\sqrt{3}}{2} \end{bmatrix} \begin{bmatrix} i^*_{C\alpha} \\ i^*_{C\beta} \end{bmatrix}$$

These are the compensating current injected by the shunt active filter to reduce harmonics in three phase systems[7] .

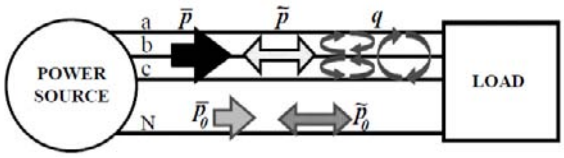

Figure 2.3: Components of p-q theory

It allows two control strategies: constant instantaneous supply power and sinusoidal supply current.

This concept is very popular and, basically consists of a variable transformation from a, b, c, reference frame of the instantaneous power, voltage, and current signals to the α, β reference frame. The transformation equations from the a, b, c, reference frame to the α, β,0 coordinates can be derived from the phasor diagram shown in Fig.2.4

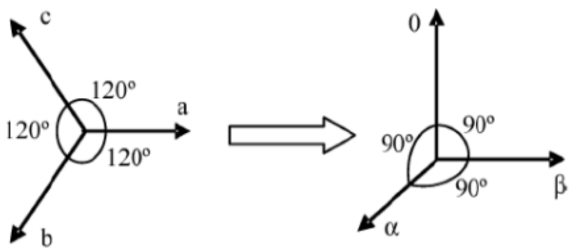

Figure 2.4: Transformation from the phase reference system (a, b, c) to (α, β, 0) system

2.3 Hysterisis Control technique for Shunt Active Filter:

There are various current controlled pulse width modulation (PWM) techniques available. Among all of them, hysteresis controllers offer inherent simplicity in implementation, quick current controllability, easy implementation, unconditioned stability and excellent dynamic performance. The control circuit generates the sine reference current wave of desired magnitude and frequency and it is compared with actual current wave.

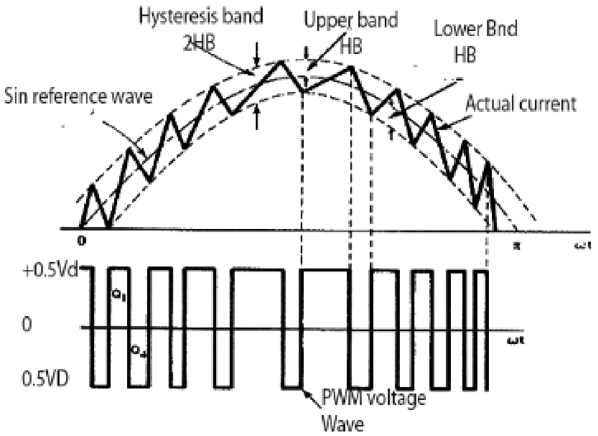

Figure 2.5: Hysteresis Current control technique

The main disadvantage of this method is variable switching frequency. To solve the problem of variable switching frequency, adaptive hysteresis current control technique is applied [8]. The hysteresis band current control is robust, provides excellent dynamics and fastest control with minimum hardware [8].

3. Simulation Model

3.1 Single Phase Active Power Filter

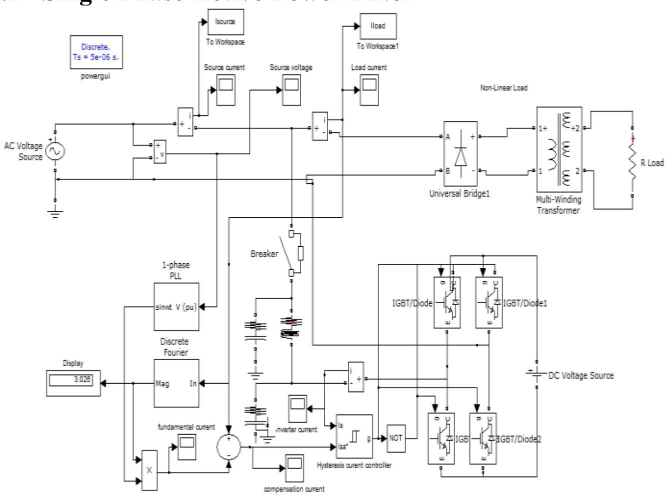

Figure 3.1: Single Phase Active Power Filter

3.2 Three Phase Active Power Filter

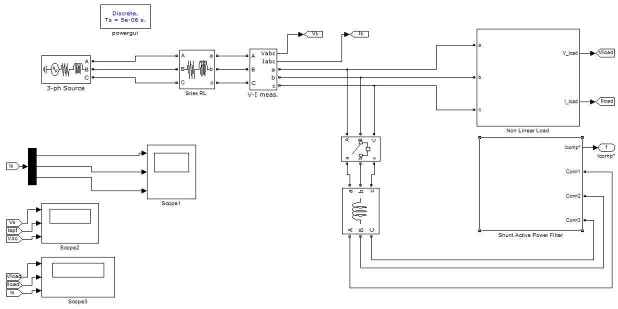

Figure 3.2: Three Phase Active Power Filter

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 output of the PI controller is presumed as peak value of the supply current (I_{max}), 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 (I_{max}) so found, will be multiplied by the unit sine vectors in phase with the individual source voltages to obtain the reference compensating currents [8].

4. Simulation Results

4.1 Single Phase Active Power Filter

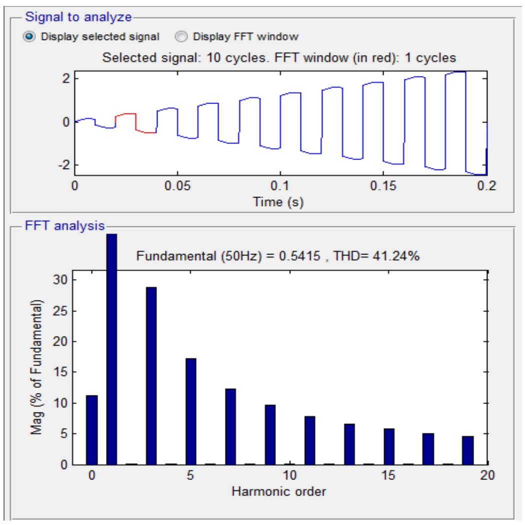

Figure 4.1: THD measurement without APF

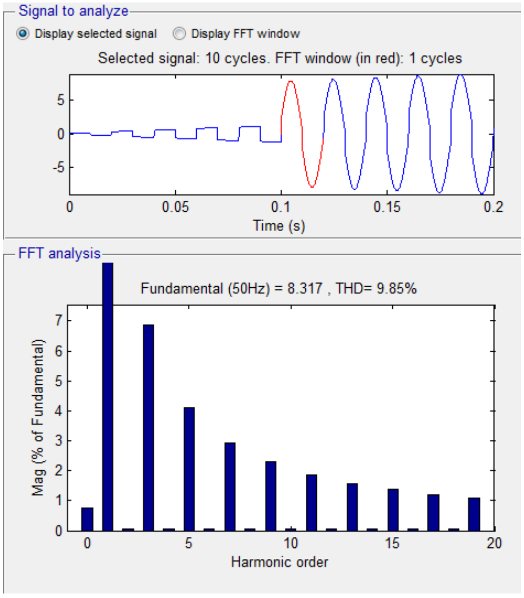

Figure 4.2: THD measurement with APF

4.2 Three Phase Active Power Filter

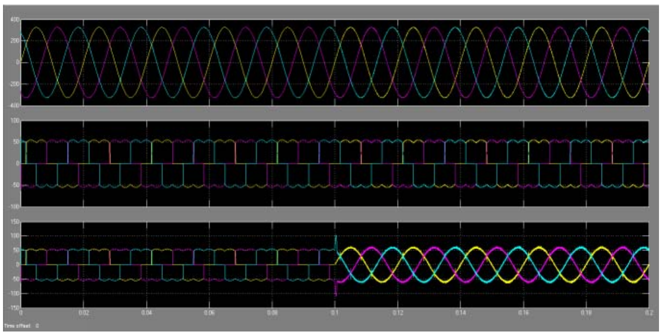

Figure 4.3: Load voltage(Vload), load current(Iload) and source current(Is)

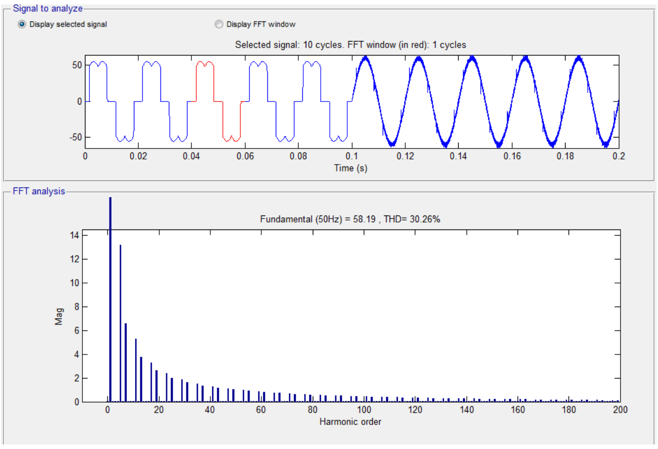

Figure 4.4: FFT Analysis without APF

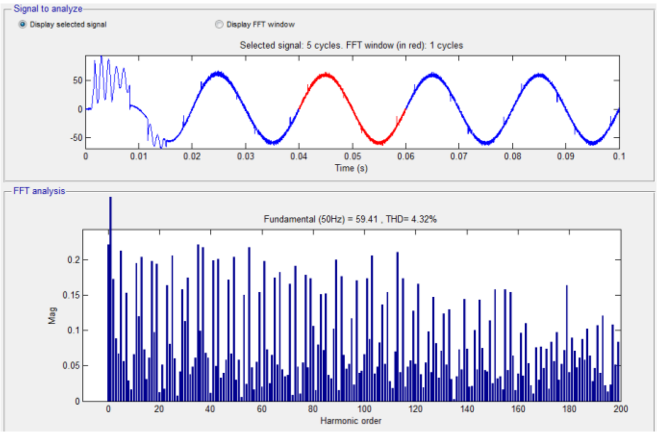

Figure 4.5: FFT Analysis with APF

As shown in above FFT analysis THD without active power filter is 30.26% and it reduced to 4.32% with active power filter in the circuit.

5. Hardware Setup and Results

5.1 Block Diagram

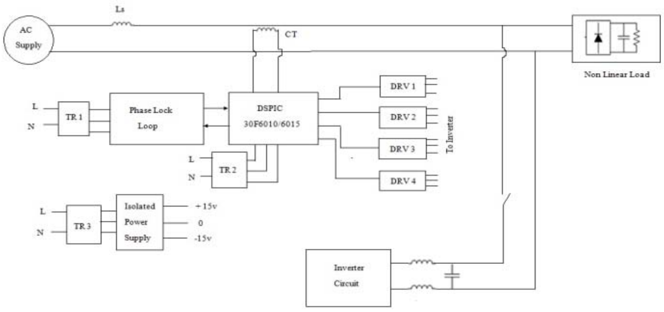

Figure 5.1: Active Power Filter

Fig.5.1 shows the configuration of a single-phase active power filter including the structure of proposed controller. The controller has two current sensors for measuring the load current and the active power filter current, and two voltage sensors for measuring the voltage at the common connection point and the DC voltage of active power filter. The inverter of active power filter has a structure of a full- bridge configuration, and the controller is implemented with software based on the DSP. [3]

The voltage at the common connection point measured with PT(potential transformer) is converted into digital value and sent to the PLL(phase locked loop) module in the DSP. The load current measured with CT(current transformer) is converted into digital value and sent to the FFT module in the DSP. The harmonic components are extracted from the load current and its phase-angle delays are compensated to generate an accurate reference signal. A control algorithm balancing the DC voltage of active power filter is included to cover the system losses. The output of this algorithm is added to the extracted reference signal to generate the final reference signal for the inverter output current. The final reference signal is compared with the actual inverter output current, and passed through the current control to generate the PWM pulses for gating.[3].

5.2 Hardware Results

Parameter	Without APF	With APF	%Reduction
Current (I)	1.2 A	0.7A	55.56
THD %	24.5	2.5	89.80
3rd Har%	23.3	1.5	93.56
5th Har%	7.3	2.2	69.86
7th Har%	0.9	0	100.00
9th Har%	1.3	0	100.00
11th Har%	0.9	0	100.00
13th Har%	1.1	0	100.00
15th Har%	0	0	

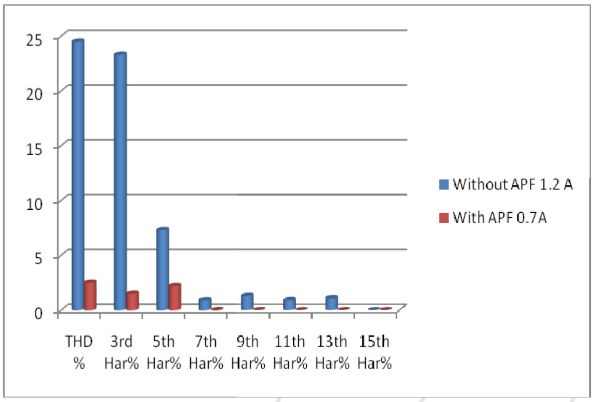

Figure 5.2: Graph of Without and with Active Power Filter

6. Conclusion

Active power filters used over here provide a cost-effective, reliable, and flexible solution for harmonic compensation. When model is simulated in MATLAB and FET analysis is carried out for calculation of THD, the THD of the source current after compensation is less than 5%, which is well within the harmonic limit imposed by the IEEE-519 & IEC-6000. In the hardware circuit as well, source current reduces from 1.2A to 0.7A. So THD of source current reduces from 24.5% to 2.5%.

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