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Impacts of Harmonics on Power System Equipment and Design of Active Power Filter for Their Compensation

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Abstract: ***This paper presents the analysis and simulation using Matlab/Simulink of a shunt active power filter (APF) for compensating the harmonics current generated by nonlinear loads. Due to increasing the usage of power electronics equipment with linear load, the increase of the harmonics disturbance in the ac mains currents has became a major concern due to the adverse effects on all equipment. In addition, the harmonic currents produced by nonlinear loads can interact adversely with a wide range of power system equipment, mostly capacitors, transformers, and motors, causing additional losses, overloading, malfunctioning and overheating and interferences. Active Power filter eliminates the harmonics which are produced through non-linear loads by generating the opposite phase harmonics which gives pure sinusoidal wave.***

Keywords: Harmonic Distortion, Shunt Active Power Filter, Non-Linear Load, Instantaneous Power Theory, Total Harmonic distortion

1. Introduction

Nowadays, due to wide spread of power conversion units and power electronic equipments, causes an increasing harmonics distortion in the ac mains currents. Harmonics component is a very serious and a harmful problem in Electric Power System. Mostly non-linear loads based on solid-state converters are like UPS, SMPS etc. These Non-linear loads draw current that is not sinusoidal and thus create voltage drops in distribution conductors. This harmonic current causes 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 important for both the utilities and the users.

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 an 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. Hysteresis current control method is the most popular method in terms of quick current controllability, versatility and easy implementation [1].

Shunt active power filter (SAPF) is one of the custom power devices proposed to improve the power quality [2]. Many theories have been developed for instantaneous current harmonics detection in active power filter such as FFT (fast Fourier technique) technique, neural network, instantaneous p-q theory(instantaneous reactive power theory), synchronous d-q reference frame theory or by using suitable analog or digital electronic filters separating successive harmonic components, PLL with fuzzy logic controller, neural network etc.

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 [3].

This paper basically deals with the modelling and simulation of shunt active filter with hysteresis current control for power filtering and then we have studied about the compensation principle used for current harmonics suppression and harmonic control method provides a quick and easy response in the system.

2. Shunt Active Power Filter

The shunt active power filter (APF) is a device that is connected in parallel to a nonlinear load and 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 APFs need to generate enough reactive and harmonic current to compensate the nonlinear load generated harmonics in the AC line. In an SAPF shown in fig.1, a current controlled voltage source inverter is used to generate the compensating current (i_c) and is injected into the line. This cancels the harmonic components drawn by the nonlinear load and then the utility line current (i_s) is sinusoidal.

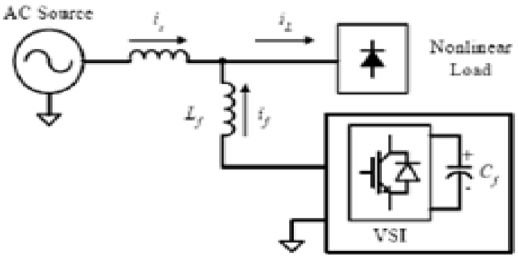

Figure 1: Principle of Shunt Active Filter

3. Instantaneous Reactive Power Theory

In 1983, Akagi et al. [1, 2] have proposed the "The Generalized Theory of the Instantaneous Reactive Power in Three-Phase Circuits", also known as instantaneous reactive power theory or 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 (1) and (2) respectively.

$$\begin{bmatrix} v_\alpha \\ v_\beta \end{bmatrix} = \begin{bmatrix} 1 & -1/2 & -1/2 \\ 0 & \sqrt{3}/2 & -\sqrt{3}/2 \end{bmatrix} \begin{bmatrix} v_a \\ v_b \\ v_c \end{bmatrix} \text{..........} \quad (1)$$

$$\begin{bmatrix} i_\alpha \\ i_\beta \end{bmatrix} = \begin{bmatrix} 1 & -1/2 & -1/2 \\ 0 & \sqrt{3}/2 & -\sqrt{3}/2 \end{bmatrix} \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} \text{............} \quad (2)$$

The clarke transformation is shown in figure 2 below:

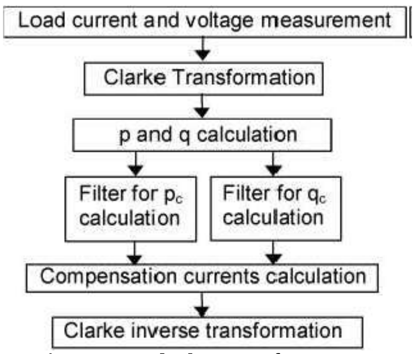

Figure 2: Clarke transformation

The three phase coordinates a-b-c is mutually orthogonal. As a result, the conventional power for three phase circuits can be derived by using the above equations. The instantaneous real power is defined as follows in equation 3.

$$p = v_a i_a + v_b i_b + v_c i_c \text{..........} \quad (3)$$

From above equations, the instantaneous power can be rewritten as shown below:

$$\begin{bmatrix} p \\ q \end{bmatrix} = \frac{\sqrt{2}}{3} \begin{bmatrix} v_\alpha & v_\beta \\ -v_\beta & v_\alpha \end{bmatrix} \begin{bmatrix} i_\alpha \\ i_\beta \end{bmatrix} \text{..........} \quad (4)$$

As the compensator will only compensate the instantaneous reactive power. The reference current equation is given below:

$$\begin{bmatrix} i^*_{s\alpha} \\ i^*_{s\beta} \end{bmatrix} = \frac{1}{v_\alpha^2 + v_\beta^2} \begin{bmatrix} v_\alpha & -v_\beta \\ v_\beta & v_\alpha \end{bmatrix} \begin{bmatrix} p_0 + p_{-loss} \\ 0 \end{bmatrix} \text{..........} (5)$$

These two reference current add in the mux and generate the reference current i^*_{ref}. By deriving from above equations, the compensating reactive power can be identified. The compensating current for each phase can be derived by using the inverse orthogonal transformations as shown below:

$$\begin{bmatrix} i^*_{ca} \\ i^*_{cb} \\ i^*_{cc} \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} 1 & 0 \\ -1/2 & \sqrt{3}/2 \\ -1/2 & -\sqrt{3}/2 \end{bmatrix} \begin{bmatrix} i^*_{s\alpha} \\ i^*_{s\beta} \end{bmatrix} \quad (6)$$

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. Harmonic Current Control Method

The harmonic current control strategies play an important role in fast response current controlled voltage source inverters such as the active power filters. There are different types of current controllers such as three independent hysteresis controllers, ramp comparison controllers, PI controller and predictive controllers. However, the hysteresis control method is the most commonly proposed control method in time domain. This method provides instantaneous current counteractive response, good accuracy and unconditioned stability to the system. Besides that, this method is said to be the most proposed solution for current controlled inverters [5], [6]. 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.

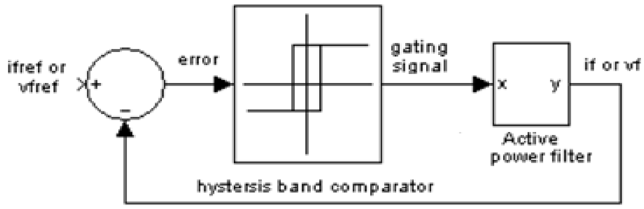

Figure 3: Basic principle of Hysteresis Current Control

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 limit, it is the difference of the reference current and the minimum error. Supposing the value for the minimum and maximum error should be equal. As a result, the hysteresis bandwidth is equal to two times of error.

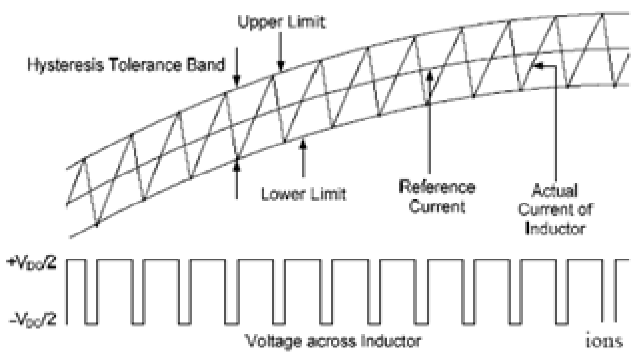

Figure 4: Hysteresis Band

5. Simulink Model of the APF

The overall system model containing the power source, the shunt active power filter and the nonlinear loads is shown in fig. 5.

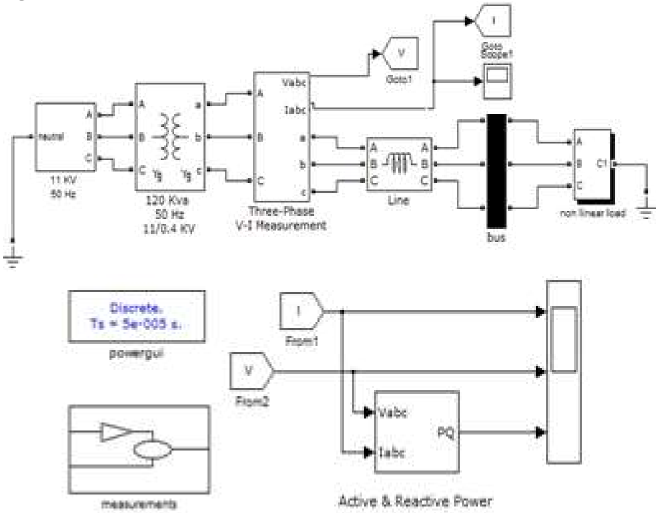

Figure 5: System model without filter

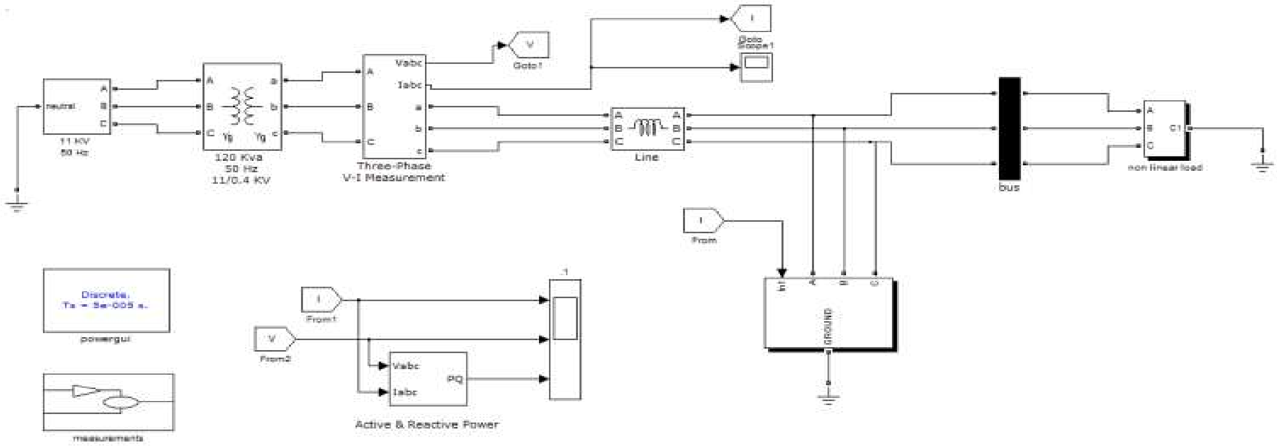

Figure 6: System model with APF

The main components of the system describe 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
- The PWM IGBT voltage source inverter, which contains a three-leg voltage source inverter with neutral clamped DC capacitors and the control scheme, is shown in fig.

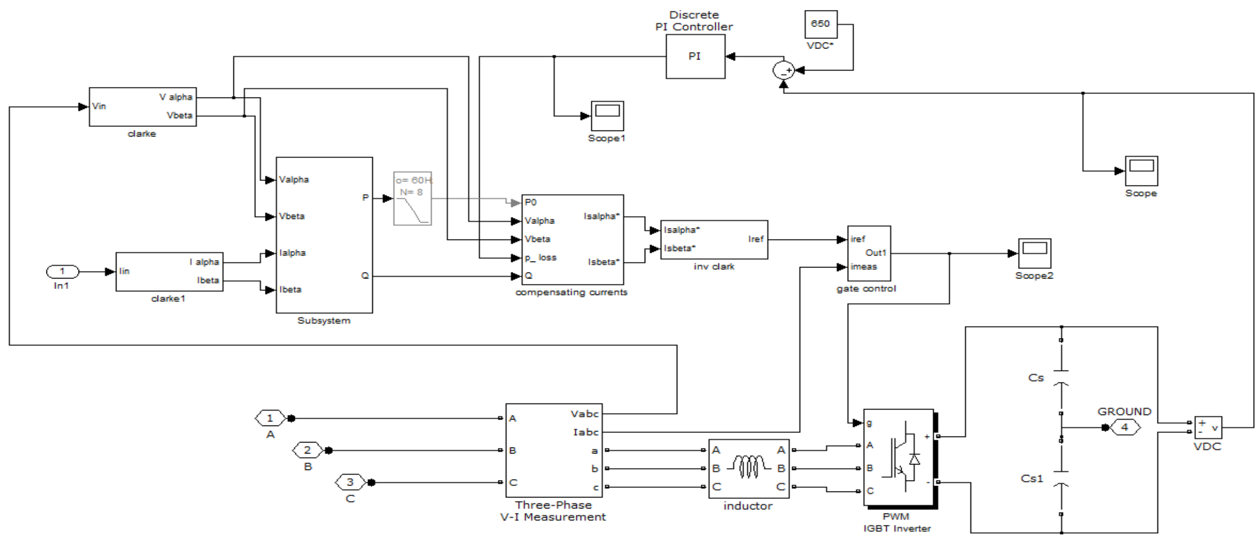

Figure 7: Model of APF

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. The sum of the voltages of the DC capacitors (V_{DC}) is maintained nearly constant to the reference DC voltage value (V_{DC}*) by PI controller and then added to the alternative power $P_{\_loss}$.

6. Simulation Result

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 5th and 7th order, representing 25.14% and 8.25% of the fundamental respectively.

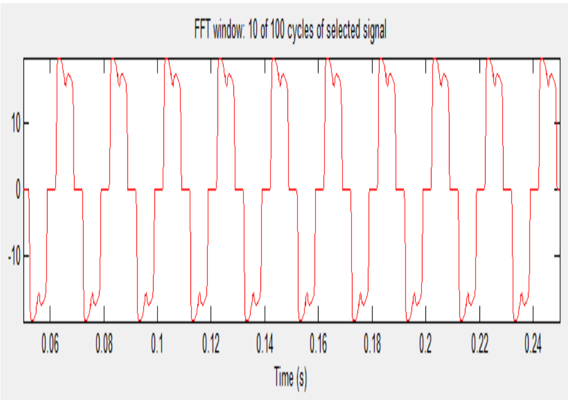

Figure 8: Load Current (System without APF)

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

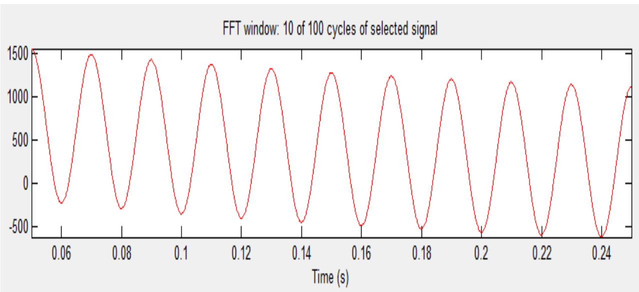

Figure 9: Source Current (System with APF)

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 at a standstill 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. 8and fig. 9 respectively. This shows the difference in total harmonic distortion between the system with and without active power filter.

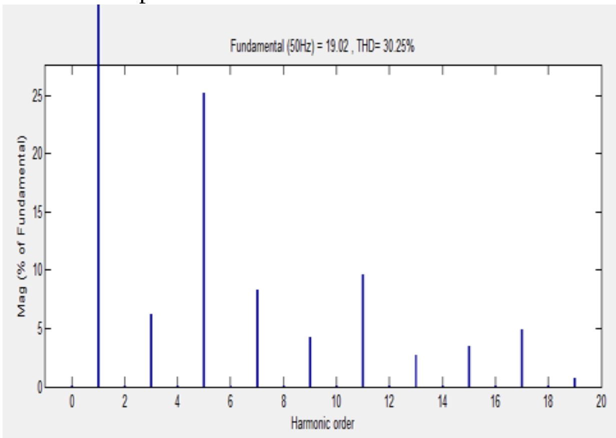

Figure 10: Bar representation of load current (without filter)

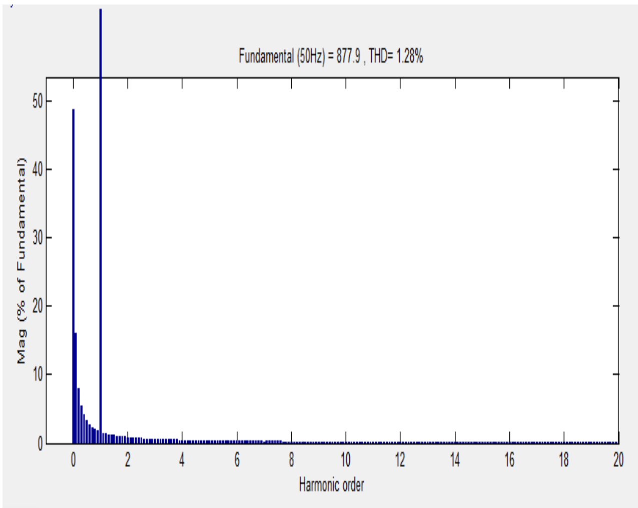

Figure 11: Bar representation of source current (with filter)

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

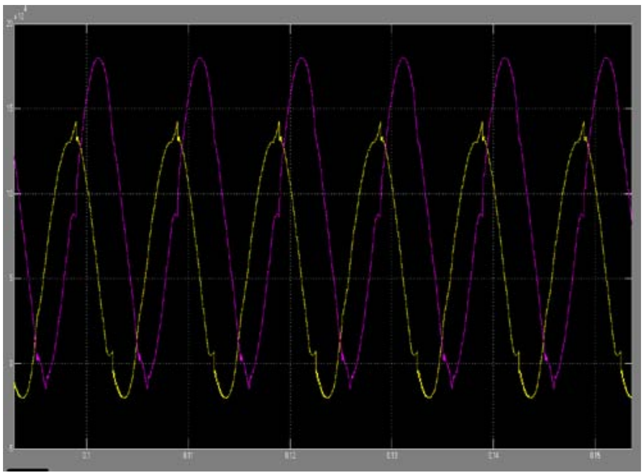

Figure 12: Active and Reactive power (system without APF)

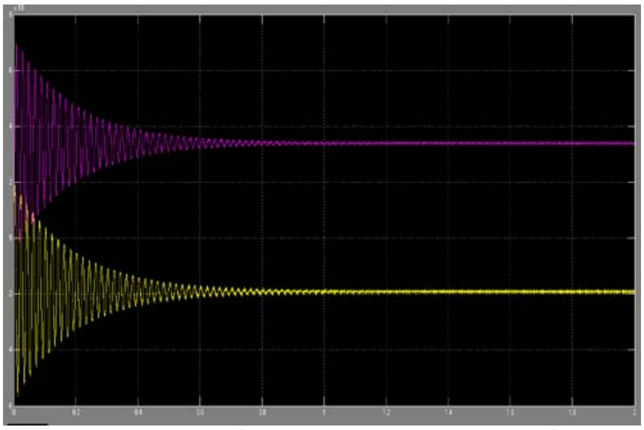

Figure 13: Active and Reactive Power (system with APF)

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. Conclusion

A MATLAB based model of the shunt active power filter has been simulated for nonlinear load using the hysteresis current control technique. The simulation results show that 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. The simulation carried out, the voltage and current harmonic distortions created by a non linear load have been obtained.

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