Mitigation of Harmonics by Hysteresis Control Technique of VSI Based Statcom

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Abstract- Modern industrial equipments are more sensitive to these power quality problems than before and need higher quality of electrical power. Power electronic based power processing offers higher efficiency, compact size and better controllability. But on the flip side, due to switching actions, these systems behave as non-linear loads. This creates power quality problems such as voltages Sag/Swell, flickers; harmonics, asymmetric of voltage have become increasingly serious. At the same time, modern industrial equipments are more sensitive to these power quality problems than before and need higher quality of electrical power. This paper mainly deals with shunt active power filter which has been widely used for harmonic elimination. Active power filter which has been used here monitors the load current constantly and continuously adapt to the changes in load harmonics. The performance of three phase shunt active power filter using three phase two phase transformation with PI and Hysteresis current controller is explained in this paper.

Keywords – Active power filters (APF), composite load, harmonic compensation, linear and non linear load, reactive power, Power Quality, Harmonics, and Voltage Source Inverter.

I. INTRODUCTION

The growing use of non-linear and time-varying loads has led to distortion of voltage and current waveforms and increased reactive power demand in ac mains. Harmonic distortion is known to be source of several problems, such as increased power losses, excessive heating in rotating machinery, and harmonic resonances in the utility, significant interference with communication circuits, flicker and audible noise, incorrect operation of sensitive loads.

Until now, to filter these harmonics and to compensate reactive power at factory level, only capacitor and passive filters were used. More, new PWM based converters for motor control are able to provide almost unity power factor operations. This situation leads to two observations: on one hand, there is electronic equipment which generates harmonics and, on the other hand, there is unity power factor motor drive system which doesn't need power factor correction capacitor. Also, we cannot depend on this capacitor to filter out those harmonics. This is one of the reasons that the research is being done in the area of Active Power Filter (APF) and less pollutant drives. Loads, such as, diode bridge rectifier or a thyristor bridge feeding a highly inductive load, presenting themselves as current source at point of common coupling (PCC), can be effectively compensated by connecting an APF in shunt with the load.

The system configuration under consideration is discussed in chapter II. The proposed control technique based on Hysteresis controller pulse generation is explained in chapter III. A SIMPOWERSYSTEM (SPS) Matlab/Simulink model based on proposed control strategy is given in the chapter IV. The simulation results are discussed in chapter V. The conclusion of the PAPER is summarized in chapter VI.
In a modern power system, the growing use of non-linear loads and time-varying loads are increasing. These nonlinear loads may cause poor power factor, high degree of harmonics and distortion of current and voltage waveforms. These problems are solved by using APF’s. By implementing these for power conditioning, it provides functions such as reactive power compensations, harmonic compensations, negative-sequence current or voltage compensation and voltage regulation. The main purpose of the APF installation by individual consumers is to compensate current harmonics or current imbalance of their own harmonic-producing loads. Besides that, the purpose of the APF installation by the utilities is to compensate for voltage imbalance or provide harmonic damping factor to the power distribution systems. Figure 3.1 shows the basic APF block diagram including non-linear load on three-phase supply conditions.

APF consisting of VSI and a dc capacitor have been researched and developed for improving the power factor and stability of transmission systems. APF have the ability to adjust the amplitude of the synthesized ac voltage or current of the inverter by means of pulse width modulation or by control of dc-link voltage, thus by drawing either leading or lagging reactive power from the supply. APF is an up-to-date solution to power quality problems. Normally, APF can be classified into shunt and series. Both are designed to compensate for reactive power or harmonics. APF consists of an inverter with switching control circuit. The inverter of the APF will generate the desired compensating harmonics based on the switching gates provided by the controller. The APF injects an equal-but-opposite distortion harmonics back into the power line and cancel with the original distorted harmonics on the line. Figure 3.1 shows the basic idea for the compensation principle of an APF, and Figure 3.2 shows the basic idea of operation of APF for a diode rectifier.

The harmonic current compensation by the APF is controlled in a closed loop manner. The APF will draw and inject the compensating current, \(i_f\) to the line based on the changes of the load in the power supply system. The supply line current, \(i_s\), is described by the following equation 1

\[ i_s = i_f + i_l \]

The line current, \(i_s\), is shaped to be sinusoidal by adding the compensating current, \(i_f\), into the distorted load current, \(i_l\). The problem of this APF is the suitable design for the controller and the filter configuration. Traditionally, its control techniques were mostly using Pulse Width Modulation (PWM) technique. However, before developing the controller, the configuration of the APF used in the design has to be defined.
Figure 2 Principle of operation of an APF compensating a diode rectifier

Figure 3.3 shows the basic compensation principle of a shunt active power filter. A voltage source inverter (VSI) is used as the shunt active power filter [1]. This is controlled to generate a current wave such that it compensates by cancelling out the nonlinear current waveform generated by the load i.e. this active power filter (APF) generates the nonlinearities opposite to the load nonlinearities. Figure 3.4 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.

Figure 3 Basic Compensation Technique
Total instantaneous power drawn by the nonlinear load can be represented as:

\[ P_L(t) = P_F(t) + P_R(t) + P_H(t) \]  
(2)

Where \( f, r, h \) stands for fundamental, reactive, and harmonic contents.

Real power supplied by the source \( P_s = P_f \)  
(3)

Reactive power supplied by the source \( Q_s = 0 \)  
(4)

Real power drawn by the load \( P_L = P_f + P_h \)  
(5)

Reactive power drawn by the load \( Q_L = Q_f + Q_h \)  
(6)

Real power supplied by the APF \( P_C = P_h - P_{Loss} \)  
(7)

Reactive power supplied by APF \( Q_C = Q_f + Q_h \)  
(8)

Where \( P_{Loss} \) is the loss component of the APF.

From the single line diagram

\( I_S(t) = I_L(t) + I_C(t) \)  
(9)

The utility voltage is given by

\[ V_S(t) = V_m \sin(\omega t) \]  
(10)

The load current will have a fundamental component and the harmonic components which can be represented as

\[ I_L(t) = I_1 \sin(\omega t + \phi_1) + \sum_{n=2}^{\infty} I_n \sin(n \omega t + \phi_n) \]  
(11)

\[ I_L(t) = I_1 \sin(\omega t + \phi_1) + \sum_{n=2}^{\infty} I_n \sin(n \omega t + \phi_n) \]  
(12)

Instantaneous load power \( P_L(t) \) can be expressed as

\[ P_L(t) = V_S(t) I_L(t) \]  
(13)

\[ P_L(t) = V_m \sin(\omega t) I_1 \sin(\omega t + \phi_1) + V_m \sin(\omega t) \sum_{n=2}^{\infty} I_n \sin(n \omega t + \phi_n) \]  
(14)

\[ P_L(t) = V_m I_1 \sin^2(\omega t) \cos(\phi_1) + V_m I_1 \sin(\omega t) \cos(\omega t) \sin(\phi_1) + V_m \sin(\omega t) \sum_{n=2}^{\infty} I_n \sin(n \omega t + \phi_n) \]  
(15)

\[ P_L(t) = P_F(t) + P_R(t) + P_H(t) \]  
(16)

\[ P_L(t) = P_F(t) + P_C(t) \]  
(17)

\[ P_L(t) = P_F(t) + P_R(t) + P_H(t) \]  
(16)

\[ P_L(t) = P_F(t) + P_C(t) \]  
(17)

**Figure 4** Waveforms for the actual load current, desired source current and the compensating current

Where, the term \( P_F(t) \) is the real power (fundamental), the term \( P_R(t) \) represents the reactive power and the term \( P_H(t) \) represents the harmonic power drawn by the load. For ideal compensation only the real power (fundamental) should be supplied by the source while all other power components (reactive and the harmonic) should be supplied by the active power filters i.e. \( P_C(t) = P_R(t) + P_H(t) \) be supplied

\[ P_R(t) = V_m I_1 \sin^2(\omega t) \cos(\phi_1) \]  
(18)
\[ P_R(t) = V_S(t)I_S(t) \]  

i.e. \[ I_S(t) = \frac{P_R(t)}{V_S(t)} = I_{sm} \sin(\omega t) \]  

Where, \( I_{sm} = I_1 \cos \phi_1 \) since, there are some switching losses in the inverter. Therefore, the utility must supply a small overhead for capacitor leaking and inverter switching losses in addition to the real power of load. Hence, total peak current supplied by the source

\[ I_{\text{max}} = I_{sm} + I_{SL} \]  

If active power filter provide the total reactive and harmonic power, then \( I_S(t) \) will be in phase with the utility and pure sinusoidal. At this time, the active filter must provide the following compensation current:

\[ I_S(t) = I_L(t) + I_C(t) \]  

Hence, the accurate value of the instantaneous current supplied by the source, \( I_S(t) = I_{\text{max}} \sin(\omega t) \).

The peak value of the reference current \( I_{\text{max}} \) can be estimated by controlling the DC link voltage. The ideal compensation requires the mains current to be sinusoidal and in phase with the source voltage irrespective of load current nature. Hence, the desired source currents after compensation can be given as

\[ I_{sa}^* = I_{\text{max}} \sin(\omega t) \]  

\[ I_{sa}^* = I_{\text{max}} \sin(\omega t - 2\pi/3) \]  

\[ I_{sa}^* = I_{\text{max}} \sin(\omega t - 4\pi/3) \]  

Where, \( I_{\text{max}} = I_{sm} + I_{SL} \) is the amplitude of the desired source currents so, these currents are taken as the reference currents for the shunt APF.

### III. The Proposed Control Technique

The STATCOM has received widespread application these years. Among which, the transformer less cascaded multilevel converter based configuration has excellent performance. For example, the converters do not need high voltage stress switches, and produce few harmonics. This type STATCOM needs many power cells, which are composed by two levels full bridge and one DC capacitor. The capacitor voltage varies in the duration of charge or discharge process, and because of the discrete characteristics of these devices, the capacitors voltages cannot retain symmetry, which deteriorate the STATCOM performance and some switches should endure higher voltage than others, which does harm to these switches and generates severe faults.

There are two classes of unbalance capacitors voltage. The three phases current that flow into/out the capacitors could not be ideally symmetry, so the three phase DC voltages are asymmetry. Moreover, when the cascaded converters are working, some cells produce zero voltage, so their DC voltage keep constant, meanwhile other cells produce ±E voltage, so these capacitors are in charge/discharge states. Obviously the different working condition should result in the unbalance capacitors voltage of one single phase. To avoid these problems, a great number of methods for capacitors voltage balance are proposed. Some papers adjust the phase angle of the STATCOM output voltage, but this method need complex modulation. It presented one imaginary d-q decoupled control method to equilibrate the three phase voltages. Some researchers proposed voltage balance control strategy for single phase, and they use current loop or PWM adjusting methods to regulate each capacitor voltage. However, these methods do not consider these two types unbalance problems together.

This project presented one current control strategy to maintain all capacitors voltage equilibrium, and it includes three stages. The decoupled control is implemented to adjusting the active and reactive power of the STATCOM, which directly control the current with fast response. The q-axis current controller regulates the reactive power, so it does less influence on the DC voltage. On the other side, the d-axis current controller regulates the active power restored in STATCOM, which leads DC capacitors to charge or discharge. The DC voltage loop generates the reference active current and the current loop produces the reference voltage for converter. One voltage angle adjusting method is proposed to balance the three phases voltages, which regulate the power restored in each phase capacitors slightly. The theory analysis displays that the angle between the source and the converter voltages \( \delta \) has greatly influence on the charge/discharge process. So the angle is regulated separately for different phase to balance...
the three phase voltages. To balance the capacitors voltages in each single phase, one simple PWM based method is
introduced. This method dose not modify the reference voltage of each cells but exchange the power cells outputs,
and the converter could generates the same voltage determined by the decouple control and phase balance control.
But when the current is small, because the energy exchange is under low level, the balancing process is too slow.
One new current control is designed to speed up the equilibrium process, which increase the reactive current to
enlarge the current meanwhile to avoid influencing the dc voltage.
This chapter describes how STATCOM is operated in hysteresis control mode to regulate the load reactive power
and eliminate harmonics from the supply currents. Mainly design includes capacitor, Hysteresis controller based PI
controller. [6-7]

3.1 DESIGN OF CAPACITOR
The reference value of the capacitor voltage V_{dc ref} is selected mainly on the basis of reactive power compensation
capability. For satisfactory operation the magnitude of V_{dc ref} should be higher than the magnitude of the source
voltage V_S. By suitable operation of switches a voltage V_S having fundamental component V_{C1} is generated at the ac
side of the inverter. This results in flow of fundamental frequency component I_{s1}, as shown in Figure 3.1. The phasor
diagram for V_{C1}>V_S representing the reactive power flow is also shown in this Figure. In this I_{s1} represent
fundamental component.

\[ I_{C1} = \frac{V_{C1} - V_S}{\omega L_f} = \frac{V_{C1}}{\omega L_f} \left( 1 - \frac{V_S}{V_{C1}} \right) \]  (27)

\[ Q_{C1} = Q_{L1} = 3 V_S I_{C1} \]  (28)

\[ Q_{C1} = Q_{L1} = 3 V_S \frac{V_{C1}}{\omega L_f} \left( 1 - \frac{V_S}{V_{C1}} \right) \]  (29)

\[ V_{dc} = 2 \sqrt{2} V_{C1} \]  (30)

Figure 3.1 Single line and vector diagrams for STATCOM

3.2 AXES TRANSFORMATION
Consider a symmetrical three-phase Supply with stationary as-bs-cs axes at 2\pi/3-angle apart, as shown. Our goal is to
transform the three-phase stationary reference frame (as ~ bs ~ cs) variables into two-phase stationary reference frame
(d‘-q‘) variables and then transform these to synchronously rotating reference frame (d’-q’), and vice-versa.

Figure 3.2 Stationary frame a-b-c to d‘-q‘ axes transformation
Assume that the dˢ-qˢ Axes are oriented at θ angle, as shown in Figure 3.2. The voltages $V_{ds}$ and $V_{qs}$ can be resolved into as bs cs components and can be represented in the matrix form as

$$
\begin{bmatrix}
V_{ax} \\
V_{bx} \\
V_{cx}
\end{bmatrix} =
\begin{bmatrix}
\cos \theta & \sin \theta & 1 \\
\cos(\theta - 120^0) & \sin(\theta - 120^0) & 1 \\
\cos(\theta + 120^0) & \sin(\theta + 120^0) & 1
\end{bmatrix}
\begin{bmatrix}
V_{qs} \\
V_{ds} \\
V_{cs}
\end{bmatrix}
$$

(31)

The corresponding inverse relation is

$$
\begin{bmatrix}
V_{qs} \\
V_{ds} \\
V_{cs}
\end{bmatrix} =
\frac{2}{3}
\begin{bmatrix}
\cos \theta & \cos(\theta - 120^0) & \cos(\theta + 120^0) \\
\sin \theta & \sin(\theta - 120^0) & \sin(\theta + 120^0) \\
0.5 & 0.5 & 0.5
\end{bmatrix}
\begin{bmatrix}
V_{ax} \\
V_{bx} \\
V_{cx}
\end{bmatrix}
$$

(32)

The corresponding Matlab Simulink model is as shown in Figure 3.3 Where $V_{qs}$ is added as the zero sequence component, which may or may not be present. We have considered voltage as the variable. The current and flux linkages can be transformed by similar equations. It is convenient to set $\theta = 0$, so that the qˢ-axis is aligned with the as-axis. Ignoring the zero sequence components, the transformation relations can be simplified as

$$
V_{ax} = V_{qs}
$$

(33)

$$
V_{bx} = -\frac{1}{2}V_{qs} - \frac{\sqrt{3}}{2}V_{ds}
$$

(34)

$$
V_{cx} = -\frac{1}{2}V_{qs} + \frac{\sqrt{3}}{2}V_{ds}
$$

(35)

And inversely

$$
V_{qs} = \frac{2}{3}V_{ax} - \frac{1}{3}V_{bx} - \frac{1}{3}V_{cs} = V_{ax}
$$

(36)

$$
V_{ds} = -\frac{1}{\sqrt{3}}V_{bx} + \frac{1}{\sqrt{3}}V_{cs}
$$

(37)

### 3.3 DESIGN OF PI CONTROLLER

The controller used is the discrete PI controller that takes in the reference voltage and the actual voltage and gives the maximum value of the reference current depending on the error in the reference and the actual values [8]. The mathematical equations for the discrete PI controller are:

The voltage error $V(n)$ is given as:

$$
V(n) = V^*(n) - V(n)
$$

(38)

The output of the PI controller at the nth instant is given as:

$$
I(n) = I(n-1) + K_p [V(n) - V(n-1)] + K_i V(n)
$$

(39)

When the DC link voltage is sensed and compared with the reference capacitor voltage, to estimate the reference current, the compensated source current will also have sixth harmonic distortion for three-phase system and second harmonics distortion for single phase system. A low pass filter is generally used to filter these ripples which introduce a finite delay and affect the transient response. To avoid the use of this low pass filter the capacitor voltage is sampled at the zero crossing of the source voltages.
3.4 HYSTERESIS CONTROLLER

With the hysteresis control, limit bands are set on either side of a signal representing the desired output waveform [8]. The inverter switches are operated as the generated signals within limits. The control circuit generates the sine reference signal wave of desired magnitude and frequency, and it is compared with the actual signal. As the signal exceeds a prescribed hysteresis band, the upper switch in the half-bridge is turned OFF and the lower switch is turned ON. As the signal crosses the lower limit, the lower switch is turned OFF and the upper switch is turned ON. The actual signal wave is thus forced to track the sine reference wave within the hysteresis band limits.
A controlled current inverter is required to generate this compensating current. Hysteresis current control is a method of controlling a voltage source inverter so that an output current is generated which follows a reference current waveform. This method controls the switches in an inverter asynchronously to ramp the current through an inductor up and down so that it tracks a reference current signal. Hysteresis current control is the easiest control method to implement.

3.5 PULSE GENERATION

A hysteresis current controller is implemented with a closed loop control system and is shown in diagrammatic form in Figure 3.6 An error signal, $e(t)$, is used to control the switches in an inverter. This error is the difference between the desired current, $I_{ref}(t)$, and the current being injected by the inverter, $I_{actual}(t)$. When the error reaches an upper limit, the transistors are switched to force the current down. When the error reaches a lower limit the current is forced to increase. The minimum and maximum values of the error signal are $e_{min}$ and $e_{max}$ respectively.

![Figure 3.6 Basic principle of hysteresis controller](image)

Figure 3.6 Basic principle of hysteresis controller

![Figure 3.7 Pulse generation diagram](image)

Figure 3.7 Pulse generation diagram

Figure 3.6 block diagram the range of the error signal, $e_{max} - e_{min}$, directly controls the amount of ripple in the output current from the inverter and this is called the Hysteresis Band. The hysteresis limits, $e_{min}$ and $e_{max}$, relate directly to an offset from the reference signal and are referred to as the Lower Hysteresis Limit and the Upper Hysteresis Limit. The current is forced to stay within these limits even while the reference current is changing. So these switching
pulses S1, S2, S3, S4, S5 and S6 are given to the voltage source inverter that will produce harmonic current to compensate the harmonic current produced by non linear load.

Pulse generation is main and important part of this technique. Here we have used hysteresis technique for switching. The actual current and the reference current are given to the summer and it is given to the combination of relay to limit the extent of fault current and NOT gate to produce 6 pulses for the STATCOM using AND gate in a suitable manner and a step signal is given to the AND gate to differentiate the change in current waveform before and after the control technique Figure 3.7 shows the pulse generation diagram

**IV. SIMULATION MODEL**

The simulation model of proposed technique is shown in Figure 4.1. First the capacitor voltage is sensed which is compared with the reference voltage and the error signal is given to the PI controller for processing to obtain the maximum value (I_m) of the reference current [9-10]. This signal is now delayed by 120° for getting the reference current for phase b, which is further delayed by 120° to get the reference current for the phase c. these reference currents are now compared with the actual source currents and the error is processed in the hysteresis controller to generate the firing pulses for the switches of the inverter.

The active filter does not need to provide any real power to cancel harmonic currents from the load. The harmonic currents to be cancelled show up as reactive power. Reduction in the harmonic voltage distortion occurs because the harmonic currents flowing through the source impedance are reduced. Therefore, the dc capacitors and the filter components must be rated based on the reactive power associated with the harmonics to be cancelled and on the actual current waveform (rms and peak current magnitude) that must be generated to achieve the cancellation. The inverter in the Shunt Active Power filter is a bilateral converter and it is controlled in the current Regulated mode i.e. the switching of the inverter is done in such a way that it delivers a current which is equal to the set value of
current in the current control loop. Thus the basic principle of Shunt Active Filter is that it generates a current equal and opposite to the harmonic current drawn by the load and injects it to the point of coupling there by forcing the source current to be pure sinusoidal. This type of Shunt Active Power Filter is called the Current Injection Type APF.

V SIMULATION RESULTS

Figure 5.1 shows the supply voltage, supply current and injected current wave forms of the line current before the shunt current and after the shunt current injection. The overall simulation run time is 0.2 sec. the control strategy is started after 0.1 sec. After 0.1 sec the PI controller acted to settle the reference DC link voltage and current from the shunt converter injected to make the supply current sinusoidal. It is observed that after the control strategy started the wave shape of the line current at the input side is improved in term of the harmonic distortion. It is also observed that the supply voltage does not get affected. Figure 5.2 shows the Load voltage and current remain unaffected throughout the operation. Figure 5.7 shows the current on the main line side before injection and frequency contain in it. Fast Fourier Transformation (FFT) analysis of the same current is carried out and the Total Harmonic Distortion (THD) in this case is 28.93%. Figure 5.8 shows the current on the main line side after injection and frequency contain in it. FFT analysis of the same current is carried out the THD in this case is 3.97% for R Load.

6.2.1 Simulation results for R Load:

Figure 6.3 shows the output voltage waveform and output current for R load. On X-axis time is taken and on Y- axis Voltage and Current are taken.

Scale:
On X-axis 1 unit = 0.02secs
On Y-axis 1 unit = 100V
On Y-axis 1 unit = 10A
Figure 5.3 shows the waveforms of the source current before and after control for each phase with a step signal at 0.1 secs.

Figure 5.4 shows the waveforms of the source current before and after control for all the three phases with a step signal at 0.1 secs.
Figure 5.4 source current before and after control for all the three phases.

Figure 5.5 shows the waveforms of the injected current before and after control for each phase with a step signal at 0.1 secs.

Figure 5.5 Injected current before and after control for each phase.

Figure 5.6 shows the waveforms of the injected current before and after control for all the three phases with a step signal at 0.1 secs.

Figure 5.6 Injected current before and after control for all the three phases.
Figure 5.7 Shows the FFT Analysis of the source actual load current before control for 2 cycles by taking the following parameters.

**In FFT window:**
Start time=0.14secs  
Number of cycles = 2  
Fundamental Frequency = 50Hz

**In FFT Settings:**
Display style= Bar (relative to fundamental. 
Frequency axis = Harmonic order  
Maximum Frequency (Hz) = 1000 Hz

![FFT analysis of supply current before control](image)

Figure 5.7 FFT analysis of supply current before control

Figure 5.8 Shows the FFT Analysis of the source actual load current after control for 2 cycles by taking the following parameters.

**In FFT window:**
Start time=0.14secs  
Number of cycles = 2  
Fundamental Frequency = 50Hz

**In FFT Settings:**
Display style= Bar (relative to fundamental. 
Frequency axis = Harmonic order  
Maximum Frequency (Hz) = 1000 Hz
VI. CONCLUSION

An extensive review of AF’s has been presented to provide a clear perspective on various aspects of the AF to the researchers and engineers working in this field. The substantial increase in the use of solid-state power control results in harmonic pollution above the tolerable limits. The utilities in the long run will induce the consumers with nonlinear loads to use the AF’s for maintaining the power quality at acceptable levels. A large number of AF configurations are available to compensate harmonic current, reactive power, neutral current, unbalance current, and harmonics. The consumer can select the AF with the required features.

Static compensation (STATCOM) has low cost and concentrates the research interests; however, the capacitors voltage unbalance problem will deteriorate its performance with more harmonics and over current/voltage faults. A very simple hysteresis current controller based control technique with help of instantaneous power theory is proposed for STATCOM. A MATLAB/Simulink based model has been simulated. Simulation result shows the input current harmonics produced by nonlinear load is reduced after using the control strategy. FFT analysis shows the reduction in THD is remarkable.

REFERENCES