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Harmonic Mitigation Techniques for Shunt Active Power Filter using Synchronous Reference Frame

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ABSTRACT
A shunt active filter injects a suitable non-sinusoidal current (compensating current) into the system at the point of common coupling and makes the source current sinusoidal. This paper presents a method for obtaining the desired reference current for Voltage Source Converter (VSC) of the Shunt Active Power Filter (SAPF) using Synchronous Reference Frame Theory. The method relies on the performance of the Proportional-Integral (PI) controller for obtaining the best control performance of the SAPF. To improve the performance of the PI controller, the feedback path to the integral term is introduced to compensate the winding up phenomenon due to integrator. Using Reference Frame Transformation, reference signals are transformed from $a - b - c$ stationery frame to $0 - d - q$ rotating frame. Using the PI controller, the reference signals in the $0 - d – q$ rotating frame are controlled to get the desired reference signals for the Pulse Width Modulation. The synchronizer, the Phase Locked Loop (PLL) with PI filter is used for synchronization, with much emphasis on minimizing delays. The system performance is examined with Shunt Active Power Filter simulation model. The use of active power filters is widely accepted and implemented as a solution to the power quality problems in utility, industry and commercial applications. In this paper, three of the three-phase shunt active filtering algorithms in time-domain have been compared for a non-linear load. The non-linear load chosen here is a soft-start for a three-phase induction motor. The comparison of the simulation results show the effectiveness of both the algorithms although the time domain current detection modified algorithm is more complex in terms of its implementation aspects.

***Keywords*—**Phase Locked Loop (PLL), Voltage Source Converter (VSC), Shunt Active Power Filter (SAPF), PI, Pulse Width Modulation (PWM).

I INTRODUCTION

The proliferation of power electronic converters has led to the degradation of the power quality. The performance of SAPF depends on the method of extraction of the reference compensating current. This reference current and the actual SAPF current is given to a hysteresis based, carrier-less PWM current controller to generate the switching signals of the inverter. Figure 1 shows the SAPF, which is controlled to supply a compensating current ic at the point of common coupling (PCC) and cancels current harmonics on the supply side.

Now, the source current is will be sinusoidal and in-phase with the supply voltage Vs. The organization of this paper is as follows. The different methods of estimating reference compensating current are discussed and their performance is compared under ideal and non ideal mains voltage at different load conditions.

THE ever increasing use of power semiconductor switching devices in power supply for DC motors, computers and other microprocessor based equipment causes harmonics in electric power system. Harmonics may cause serious problems such as excessive heating of electric motors and malfunction of sensitive electronic gadgets. Filtering of harmonics can be effected by using either passive or active power filters.

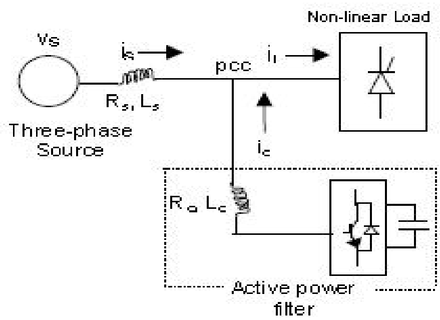


Fig. 1 Basic compensation principle of SAPF

Traditionally, passive filters have been used for harmonic mitigation purposes. Active filters have been alternatively proposed as an adequate alternative to eliminate harmonic currents generated by nonlinear loads as well as for reactive power compensation. Active Power Filter consists of Voltage Source Converter operating at relatively high frequency to give the output which is used for cancelling low order harmonics in the power system network. With Shunt Active Power Filter, crucial part involves generation of the reference signal used to generate gating signals for the VSC. Fig. 2 shows Block Diagram of PWM Controlled VSC operated as APF.

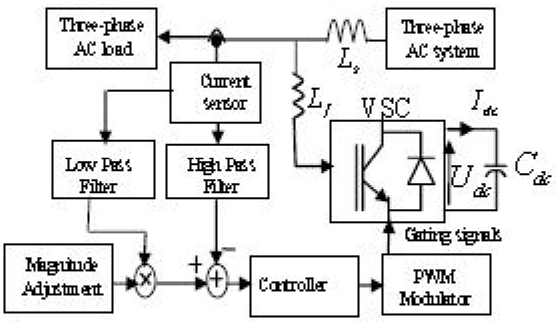


Fig.2 Block Diagram of PWM Controlled VSC operated as APF

II HARMONIC CURRENT REFERENCE

To get the reference harmonic current, first the load current is measured. The load current consists of fundamental component 1 i and harmonic component h i . Using the band pass filter, with appropriate cut-off frequencies the fundamental current is extracted from the measured system load current. Using comparator, as shown in Fig.3, the load current is compared to the fundamental component and the

error is the reference harmonics signals.

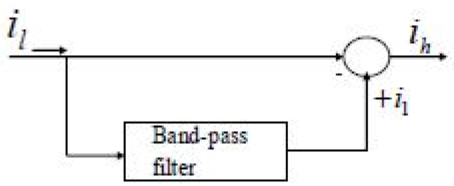


Fig. 3 Harmonic reference extraction

Where $i_h = \sqrt{i_{ha}^2 + i_{hb}^2 + i_{hc}^2}$, the instantaneous magnitudes of the three phase harmonic currents. i_l = load current and i_1 = fundamental component of the load current.

III REFERENCE FRAME TRANSFORMATION

Reference Frame transformation is the transformation of coordinates from a three-phase $a - b - c$ stationery coordinate system to the $0 - d - q$ rotating coordinate system as shown in Fig.4

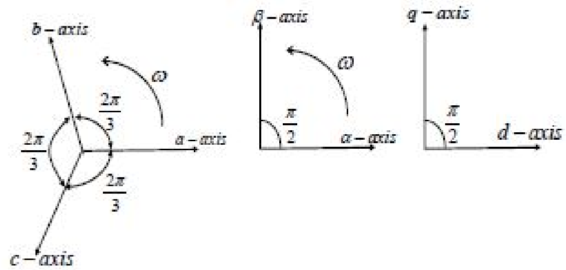


Fig. 4 Reference Frame Transformation

This transformation is important because it is in $0 - d - q$ reference frame the signal can effectively be controlled to get the desired reference signal. Transformation is made in two steps: First a transformation from the three-phase stationery coordinate system to the two-phase so-called $0 -\alpha - \beta$ stationery coordinate system is done. Load currents and voltages at Point of Common Coupling (PCC) are transformed to $0 -\alpha - \beta$ coordinates. The three-phase signal with maximum voltage $V m$, at 120 degrees apart from each other is as given by (1):

$$f_{abc} = V_m \begin{bmatrix} \cos \omega t \\ \cos\left(\omega t - \frac{2\pi}{3}\right) \\ \cos\left(\omega t + \frac{2\pi}{3}\right) \end{bmatrix} \quad (1)$$

TABLE I
NOMENCLATURE

L_s, L_f	Line inductance, filter inductance
I_{dc}, V_{dc}	Dc current, dc voltage
$i_{load}, i_{harmonics}$	Load current, harmonics current
i_{sa}, i_{sb}, i_{sc}	Three-phase currents
i_d, i_q	Component currents in $dq-frame$
$v_{aref}, v_{bref}, v_{cref}$	Three-phase reference voltage
K_p, K_i	Proportional constant, integral constant
e_s	Error signal
u_c, u	Controller output, actuator output
T_i, T_t	Integral time constant, tracking time constant
D_1, D_2	Anti-parallel diodes
T_1, T_2	Switches
p, n, z	Positive rail, negative rail and neutral point respectively.
ω_0	Target output frequency
θ_0	Arbitrary output phase

The signal f abc in the $a - b - c$ stationery frame is rotating with the frequency of ω in radians /sec. The signals in $0 -\alpha - \beta$ stationery frame are obtained using (2). Fig. 5 shows the reference signal calculation using the Synchronous Reference Frame Theory. The desired controlled signals obtained are used for PWM processes to generate the switching signals for the VSC.

$$f_{0\alpha\beta} = V_m\sqrt{\frac{2}{3}}\begin{bmatrix} \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} \\ 1 & -\frac{1}{2} & -\frac{1}{2} \\ 0 & \frac{\sqrt{3}}{2} & -\frac{\sqrt{3}}{2} \end{bmatrix}\begin{bmatrix} \cos\omega t \\ \cos\left(\omega t-\frac{2\pi}{3}\right) \\ \cos\left(\omega t+\frac{2\pi}{3}\right) \end{bmatrix} \quad (2)$$

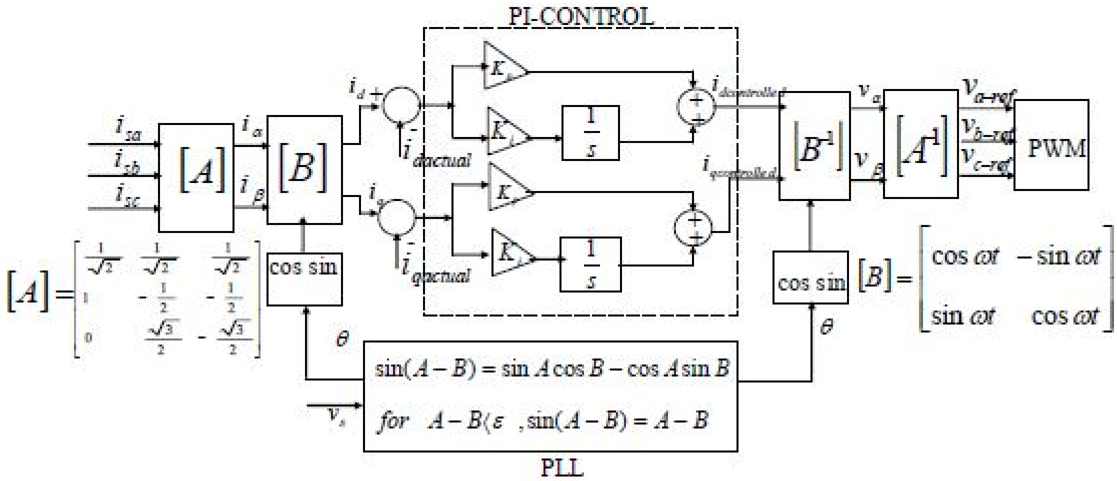


Fig. 5 Block diagram of reference signals calculation for the PWM

The axes a, *b*, and *c* are fixed on the same plane and are separated from each other by ⅔ π radians. $0-\alpha-\beta$ are orthogonal axes with the $\alpha-axis$ being synchronized with the $a-axis$ of $a-b-c$ plane and the $\beta-axis$ being orthogonal to the $\alpha-axis$. $f0\alpha\beta$ in (2) is still rotating with the frequency of ω radians/second. To eliminate this frequency, a step further is taken, a transformation from the $0-\alpha-\beta$ stationery coordinate system to the $0-d-q$ rotating coordinate system is performed using (3)

$$\begin{bmatrix} B \end{bmatrix} = \begin{bmatrix} \cos\omega t & \sin\omega t \\ -\sin\omega t & \cos\omega t \end{bmatrix} \quad (3)$$

Equation (3) is assigned such that when it is multiplied by $f0\alpha\beta$, the $0-\alpha-\beta$ coordinates which are in stationery frame achieves the same frequency as that in $0-d-q$ rotating frame as given in (4)

$$f_{0dq} = \begin{bmatrix} \cos\omega t & \sin\omega t \\ -\sin\omega t & \cos\omega t \end{bmatrix}\begin{bmatrix} f_{0\alpha\beta} \end{bmatrix} \quad (4)$$

IV THE PROPORTIONAL INTEGRAL (PI) CONTROLLER

The PI controller is very important part for the SAPF. It consists of proportional term and integral term. With this element, the best control performance of the SAPF is obtained. PI focuses on the difference (error) between the process variable (PV) and the set-point (SP), the difference between harmonics current reference signal *ih* and the filter current *i f* . In this paper the PI controller has been implemented. PI controller algorithm involves two separate parameters; the Proportional and the Integral. The Proportional value determines the reaction to the current error; the Integral determines the reaction based on the sum of recent errors.

V PHASE LOCKED LOOP (PLL)

The PLL circuit with the PI control scheme controls the oscillation frequency of the VCO with the sum of a voltage proportional to the error signal and a voltage proportional to the time integral of the error signal as shown in Fig 6.

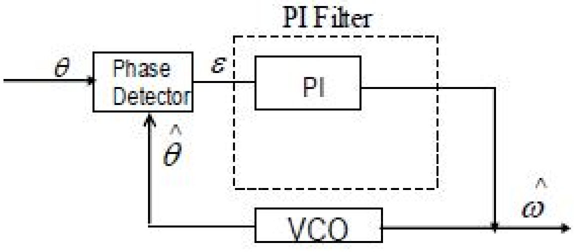


Fig 6 Conventional PLL

When the source for synchronization, i. e. the phase of the input signal frequency of the PLL is lost, a control voltage corresponding to a difference between the input signal frequency and the self-running frequency of the VCO must be memorized as the output voltage signal of an integrator so as to maintain the output frequency of the VCO despite absence of the input signal. Therefore the PI control scheme of the conventional PLL is provided with the second integrator which helps to minimize delays that may affect synchronization.

VI THE P-Q THEORY APPLIED TO ACTIVE FILTERS

It is also possible to see in Fig. 7 that the active filter capacitor is only necessary to compensate $\tilde{p}$ and $\tilde{p}$ 0 , since these quantities must be stored in this component at one moment to be later delivered to the load. The instantaneous imaginary power (q), which includes the conventional reactive power, can be compensated without any capacitor.

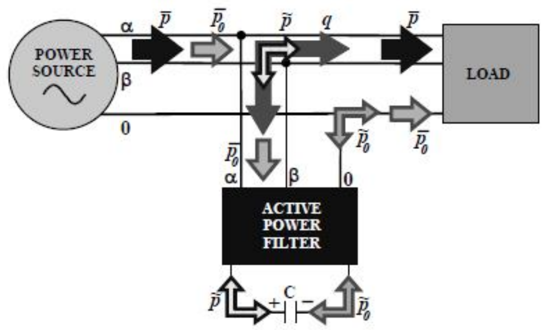


Fig.7 - Compensation of power components $\tilde{p}$, q, $\tilde{p}$ 0 and p0 in α-β-*0* coordinates.

VII SINUSOIDAL PULSE WIDTH MODULATION (SPWM) SCHEME

SPWM scheme is used to determine the switching instants of the VSC for the purpose of maintaining Input/Output linearity especially for Active Power Filter Applications. Fig. 8 shows the basic principle of SPWM . All modulation schemes in principle aim to create trains of switched pulses which have the same fundamental volt-second average (i.e. the integral of the voltage waveform over time) as a target reference waveform at any instant. There are several ways in which switching instants can be decided, at the same time maintaining the minimum harmonics content for the switched waveform. In this paper natural sampling is used, where the switching instants are determined by the intersection of the carrier waveform and the reference waveform. The more common form of naturally sampled PWM uses a triangular carrier instead of saw-tooth carrier to compare against the reference waveform. Naturally sampled PWM compares a low frequency target reference waveform *V ref* (usually a sinusoid) against a high frequency carrier waveform *V tri* . Fig. 9 shows one phase leg of an inverter driven by a triangular wave carrier. The phase leg is switched to the upper DC rail when the reference waveform is greater than the triangular carrier and to the lower DC rail when the carrier waveform is greater than the reference waveform.

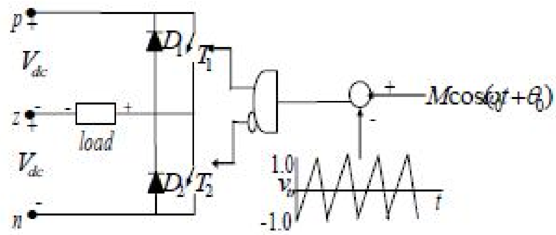


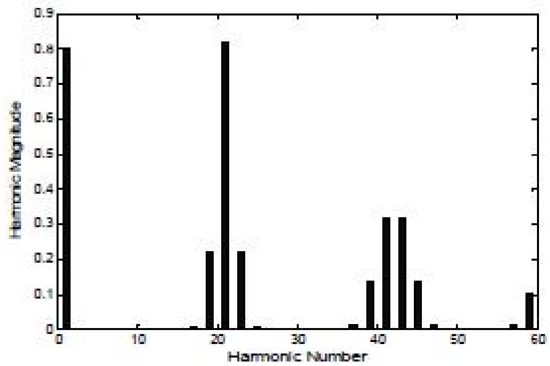
Fig. 8 Double-edge naturally sampled PWM with half bridge (one phase leg) voltage source converter

VIII SIMULATION TOOLS

Simulation is a powerful way to reduce development time and ensure the proper fulfilment of critical steps.

During the development process of the shunt active filter, simulations were performed, which allowed the study of its behaviour under different operation conditions, and permitted the tuning of some controller parameters together with the optimisation of the active filter components values. There are not many simulation tools that allow working with electrical systems, power electronics and control systems, in the same integrated environment. *Matlab/Simulink* and the *Power System Blockset* were used as simulation tools in this case .

Fig 9 shows simulation results for single-phase full bridge, using the triangular carrier method. The theoretical phase leg "a" voltage harmonics are shown in Fig. 9 (a) together with the l-l output voltage in Fig 9(b) for particular operating conditions of a carrier ratio of 21 and modulation index M of 0.8.



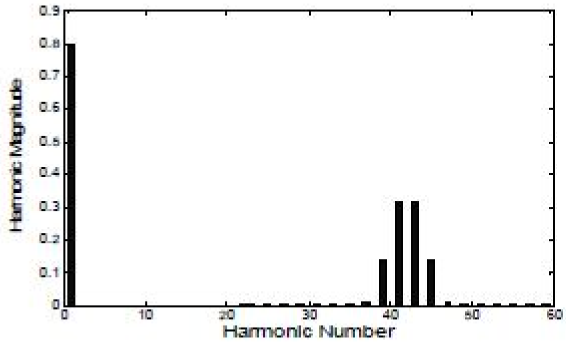
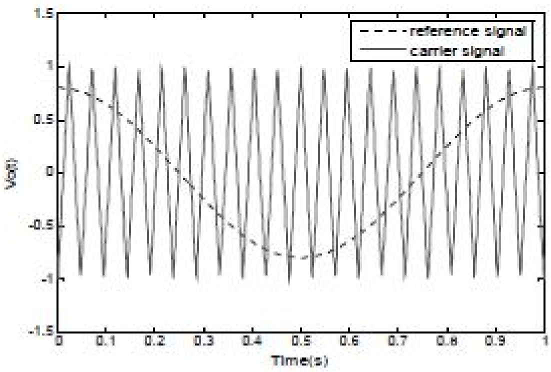


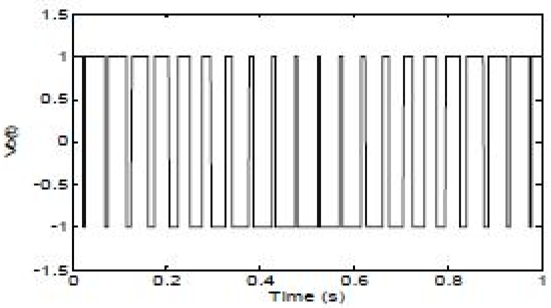
Fig 9 Harmonic spectra during PWM process

(a) Spectrum of the phase to neutral voltage
(b) Spectrum of line to line voltage

MATLAB/SIMULINK software has been used to generate the switching signals. Simulation results for SPWM process is shown in fig 10. Fig.10 (a) shows the comparison between the sinusoidal reference voltage with triangular carrier signal and Fig 10 (b) shows the switching signals generated as a result of
comparison between the carrier signal and reference signal.



(a)



(b)

Fig. 10 PWM Process

(a) Simulation Results- Simulations based on MATLAB/SIMULINK were implemented to verify the proposed Shunt Active Power Filter with anti-windup scheme. The circuit parameters of the equivalent power system based on Fig. 1 are as follows: Vrms = 380V, Vdc = 450V, Ls = 1.0 mH, Lf = 0.3 mH. The power converter is switched at a frequency of 10 kHz. The 5th, 7th, and 11th harmonics were used to test the proposed Active Power Filter.

IX CONCLUSION

This paper presents a shunt active power filter as a reliable and cost-effective solution to power quality problems.

The filter presents good dynamic and steady-state response and it can be a much better solution for power factor and current harmonics compensation than the conventional approach (capacitors to correct the power factor and passive filters to compensate for current harmonics). Besides, the shunt active filter can also compensate for load current unbalances, eliminating the neutral wire current in the power lines. Therefore, this active filter allows the power source to see an unbalanced reactive non-linear load, as a symmetrical resistive load.

The proposed low-cost solution allows the use of a large number low-power active filters in the same facility,close to each problematic load (or group of loads), avoiding the circulation of current harmonics, reactive currents and neutral currents through the facility power lines. This solution reduces the power lines losses and voltage drops, and avoids voltage distortions at the loads terminals.

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