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IMPROVED PI BASED CONTROL OF SHUNT ACTIVE POWER FILTER FOR POWER QUALITY MITIGATION

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Abstract— In this paper the Synchronous Reference frame PI-based control method for generating the reference signals for the Voltage Source Converter of Shunt Active Power Filter (SAPF) is presented. The method relies on the performance of the Proportional-Integral (PI) controller for achieving 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 the integrator. Using Reference Frame Transformation, reference signals were transformed from $a-b-c$ stationery frame to $0-d-q$ rotating frame. Using the PI controller, reference signals in $0-d-q$ rotating frame were controlled to get the desired reference signals for the Pulse Width Modulation. Using MATLAB/SIMULINK, the 5th, 7th, and 11th harmonics were used to test the proposed Active Power Filter with improved PI controller resulting in harmonic content down to 3.87%.

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

I. INTRODUCTION

The increase of power electronic converters which are used for power supplies for electrical equipment in industrial and commercial applications is the origin of the AC current distribution network pollution. These power electronic converters typically draw non-sinusoidal currents from the utility causing interference with the adjacent sensitive loads and limiting the utilization of the available electrical supply. The quality of electric current therefore becomes of significant concern for distributors of energy and their customers.

Recent progress in the technology of power electronics brings various possibilities of compensation techniques for harmonic distortion generated by the non-linear loads Fig.1 presents a power system with sinusoidal source voltage v_s operating with a linear and non linear load. The current of the non linear load (I_{L1}) contains harmonics. The harmonics in the line-current i_s produce a non-linear voltage drop (Δv) in the line impedance, which distorts the load voltage (v_L).Since load voltage is distorted; even the current at the linear load I_{L1} becomes non-sinusoidal. Figure 2 shows a shape of a distorted wave to illustrate the fundamental and the third harmonic components. The characteristics of non-sinusoidal waveform of voltage or current in mathematical model can be described as given in expression (1).

$$f(t) = A_0 + \sum_{n=1}^{\infty} A_n \cos(n\omega_0\tau + \theta_n) \qquad (1)$$

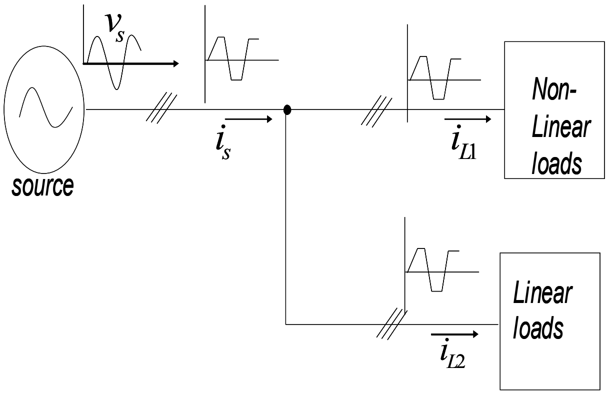


Fig.1 Sinusoidal source voltage operating with linear and linear loads.

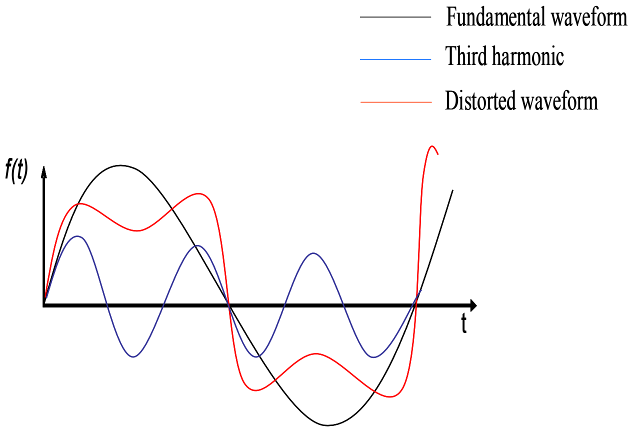


Figure 2. shows a shape of a distorted wave to illustrate the fundamental and the third harmonic components

where
A_0 is the amplitude of dc component.
A_n is the magnitude of n^{th} harmonic
ω is the fundamental frequency
θ_n is the phase angle.

Total Harmonic Distortion of current (THD_I) in percentage is calculated as shown in equation (2).

$$TDH_I = \frac{\sqrt{\sum_{h=2}^{\infty} I_h^2}}{I_{1RMS}} * 100\%. \qquad (2)$$

Where, I_h is the current magnitude of the h^{th} harmonic and I_I is the fundamental current magnitude [1]

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. Traditionally, passive filters have been used for harmonic mitigation purposes. Active filters have been proposed as an adequate alternative to eliminate harmonic currents generated by nonlinear loads as well as for reactive power compensation. Various control methods with various control strategies as discussed in [2]-[13], were implemented for minimizing harmonics in the electric power network. However, to date the Shunt Active Power Filter is still extensively used. Shunt 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.

TABLE 1. NOMENCLATURE

L_s, L_f	Line inductance, filter inductance
I_{dc}, V_{dc}	Dc current, dc voltage
$i_{liad}, i_{harmonics}$	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

Several control methods involved in generating reference signals have been discussed in [2]-[14] among them being the Synchronous Reference Frame method. Many control strategies have been proposed, for example [14] discussed about taking care of delays which when not taken care off, may cause the controller to be unstable hence the whole system becoming unstable. However, where control is concerned, the integral component of the PI controller can lead to integrator windup resulting into instability of the controller and hence poor performance of the shunt active power filter. In order to improve performance, this paper presents a method to effectively compensate the windup of the integral term of the PI controller. It is an integrator anti-windup circuit.

An extra feedback path is provided by using the output of the saturator model and forming an error e as the difference between the estimated actuator output u and the controller output c_u feeding this error back to the integrator through an appropriate gain. The error signal is zero when the actuator is not saturated. Emphasis is placed on choosing the gain, that it should be large enough that the anti-windup circuit keeps the input to the integrator small under all error conditions. The performance of the proposed method is examined with an active filter simulation model and the results are compared with the SAPF without anti-windup scheme
Fig. 3 shows the principal components of the three-phase power system with an inverter based Shunt Active Power Filter

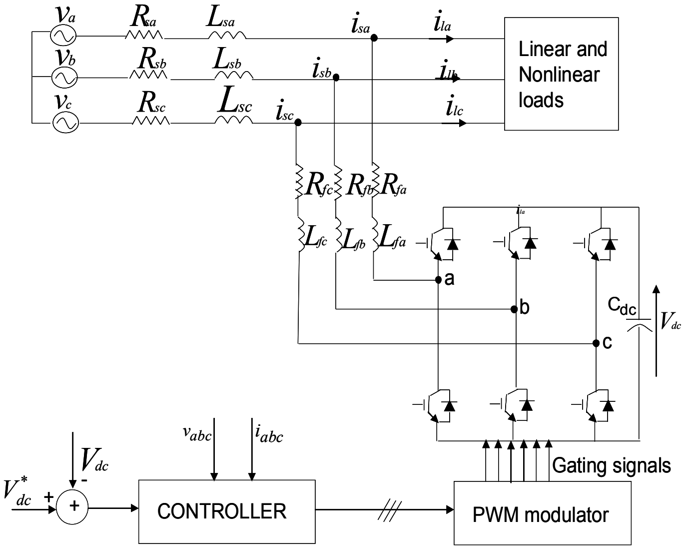


Figure.3 The principal components of the three-phase power system with an inverter based Shunt Active Power Filter.

II. 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. 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 given in "(3)".

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

The signal f_{abc} in the $a-b-c$ stationery frame is rotating with the frequency of ω in radians /sec. The signals $0-\alpha-\beta$ in stationery frame are obtained using (4)

$$f_{0\alpha\beta} = V_m \sqrt{\frac{2}{3}} \begin{bmatrix} \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} \\ 1 & -\frac{1}{2} & -\frac{1}{2} \\ 0 & \frac{\sqrt{3}}{2} & -\frac{\sqrt{3}}{2} \end{bmatrix} \begin{bmatrix} \cos \omega t \\ \cos\left(\omega t - \frac{2\pi}{3}\right) \\ \cos\left(\omega t + \frac{2\pi}{3}\right) \end{bmatrix} \quad (4)$$

a transformation from the $0-\alpha-\beta$ stationery coordinate system to the $0-d-q$ rotating coordinate system is performed as given in (5).

$$f_{0dq} = \begin{bmatrix} \cos \omega t & \sin \omega t \\ -\sin \omega t & \cos \omega t \end{bmatrix} \begin{bmatrix} f_{0\alpha\beta} \end{bmatrix} \quad (5)$$

Fig.4 and Fig.5 shows the block diagram and overall algorithm for calculation of the reference signals using Synchronous Reference Frame Theory respectively.

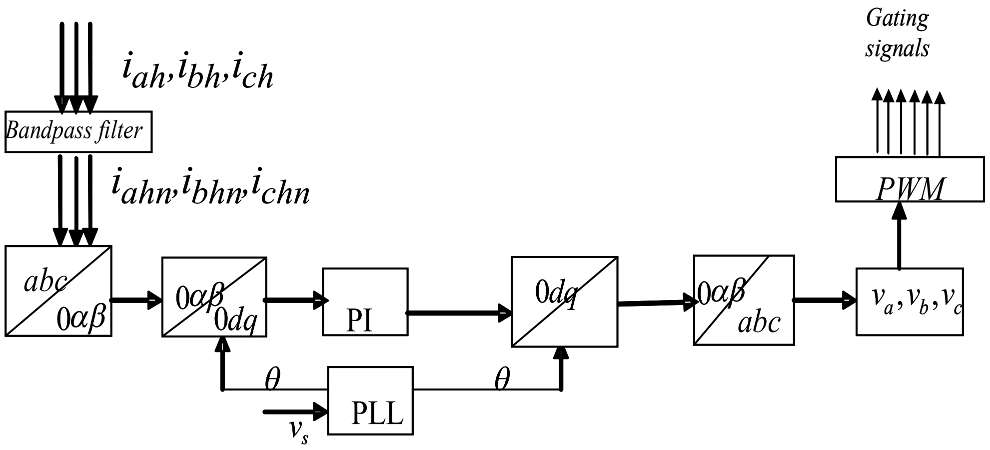


Figure.4 Block diagram of overall algorithm for calculation of the reference signals using Synchronous Reference Frame theory.

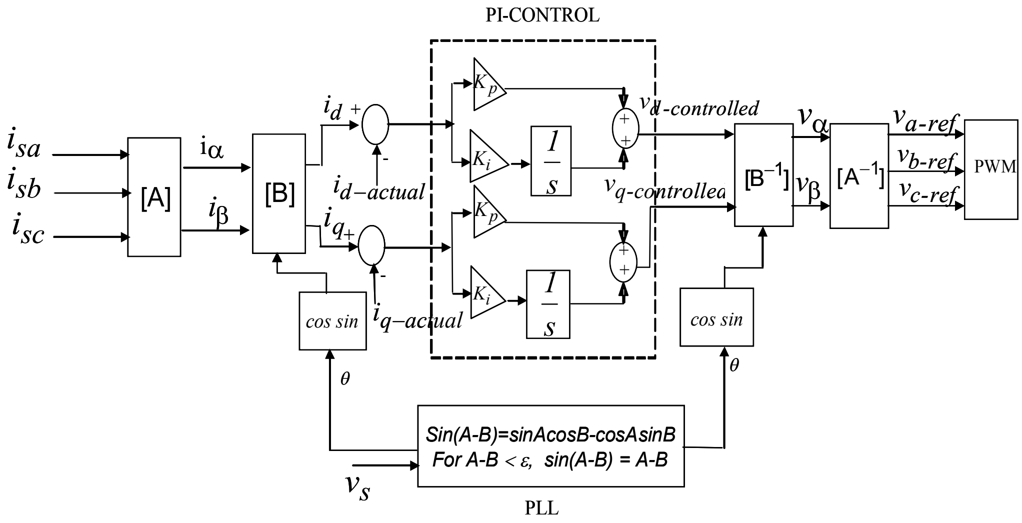


Figure. 5 Overall algorithm for calculation of the reference signals using synchronous Reference Frame theory

In MATLAB/SIMULINK the Overall algorithm for calculating reference signals using synchronous Reference Frame theory is done using algorithm shown in figure 6, the phase mixer; an algorithm for computing from $0-\alpha-\beta$ stationery frame to $0-d-q$ rotating frame and vice versa.

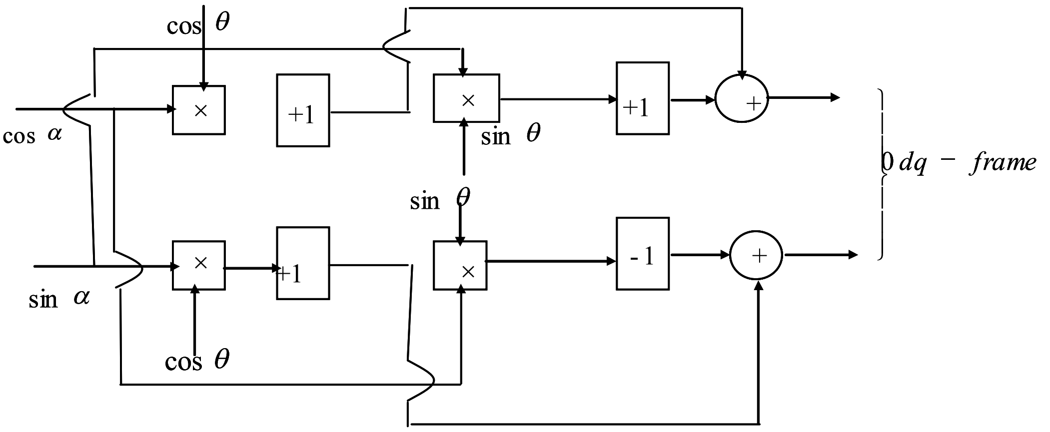


Figure 6: The Phase Mixer; algorithm for computing from $0-\alpha-\beta$ stationery frame to $0-d-q$ rotating frame and vice versa

III. THE PROPORTIONAL INTEGRAL (PI) CONTROLLER

A. Integrator wind-up

The response of the controller can be described in terms of the responsiveness of the controller to an error, the degree to which the controller overshoots the set- point and the degree of system oscillation. Fig. 7 shows PI controller configuration [15]. There are several ways to avoid integrator windup. In this paper a method to effectively compensate the windup of the integral term of the PI controller is presented by an anti-wind up method illustrated in Fig. 8.

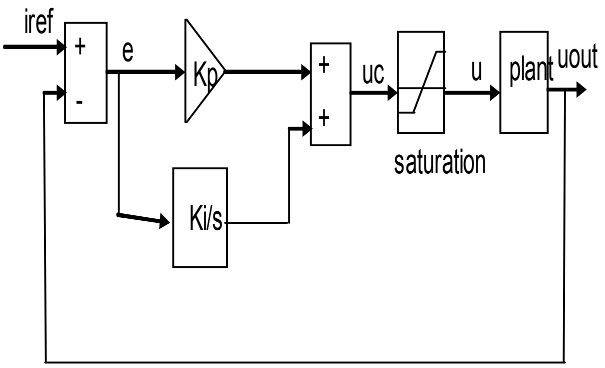


Figure. 7 PI controller without anti-windup scheme

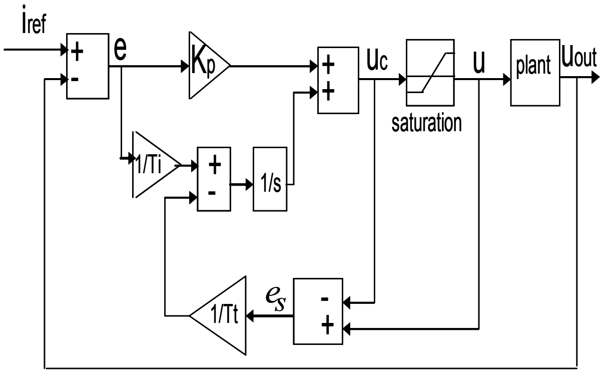


Figure. 8 PI controller with anti-windup scheme

Common choices of T_t is as expressed in (6).

$T_t \le T_i$, T_i, T_t are the integral time constant and tracking time constants (6)

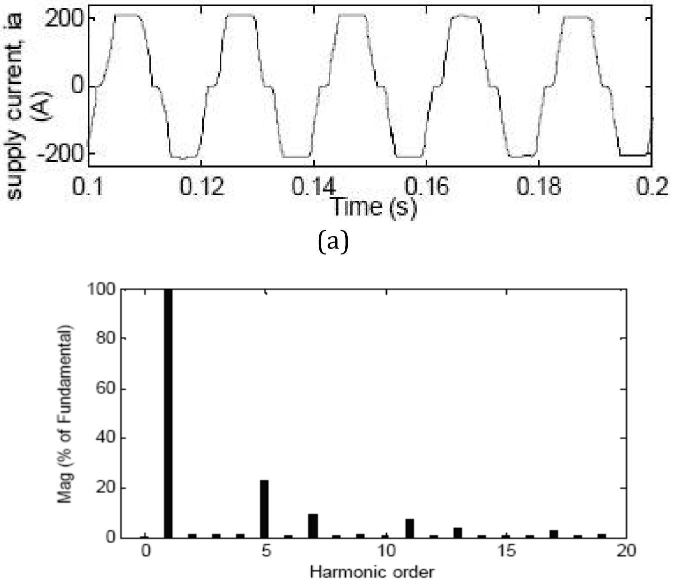
If $0 < T_t \le T_i$, then the integrator state $I(t)$ becomes sensitive to the instances when $e_s \neq 0$, as given in (7)

$$I(t)=\int_0^t\left[\frac{Ke(\tau)}{T_i}+\frac{e_s(\tau)}{T_t}\right]d\tau \approx \frac{1}{T_t}\int_0^t e_s(\tau)d\tau \quad (7)$$

B. Simulation results

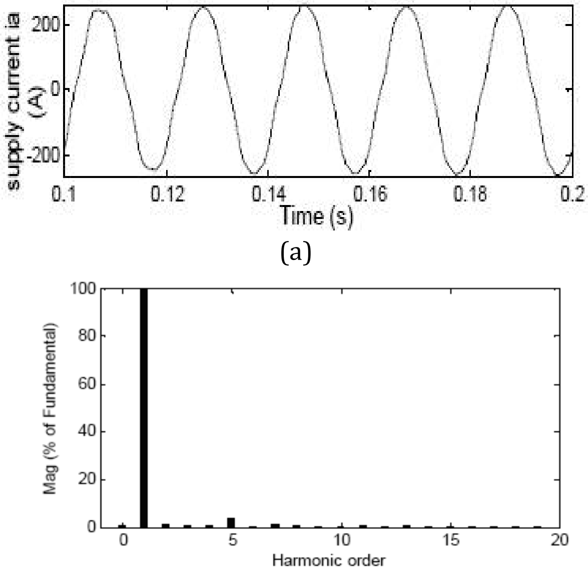
Simulations based on MATLAB/SIMULINK were implemented to verify the proposed Shunt Active Power Filter with anti-windup scheme. The circuit parameters of the equivalent power system based on Fig. 1 are as follows: Vrms = 380V, V_{dc} = 450V, L_s = 1.0 mH, L_f = 0.3 mH. The power converter is switched at a frequency of 10 kHz. The 5th, 7th, and 11th harmonics were used to test the proposed Active Power Filter. Using the Fast Fourier Transform (FFT), supply current was analyzed to obtain the Total Harmonic Distortion. Simulations to verify the performance of the Shunt Active Power Filter were performed for different loads as follows: (a) resistive load of R= 2Ω, (b) Inductive of L= 65e-3 Henry and (c) R-L load of R= 0.7Ω and L=20e-3 Henry; is shown in figures 12.1 through 12.3.

Figures 12.1to 12.3 show the waveforms and corresponding harmonic spectra of the supply current before and after compensation for non linear loads consisting thyristor converter feeding resistive, inductive and R-L loads respectively.



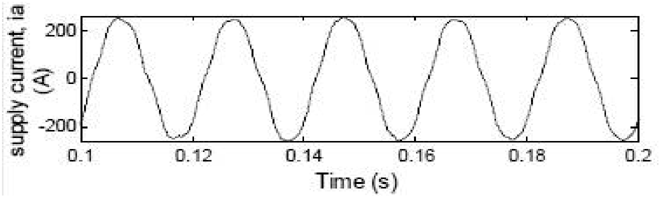
(b)

Figure 12.1 (a): The source current before compensation (b) Spectra of source current having THD of 26.35% before compensation



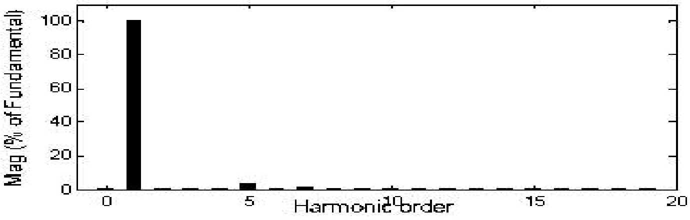
(b)

Figure 12.2 (a) shows the source current, when the Shunt active power filter was modelled without anti-windup scheme (b) Spectra of supply current having THD of 4.32% after compensation.



(a)

Figure 12.3 (a): source current when the shunt active power filter was modelled with anti-windup scheme



(b)

(b) Spectra of supply current having THD of 3.60%after compensation

IV. CONCLUSIONS

The Shunt Active power filter with SRF based-PI controller was examined in this paper using the SRF theory. The SAPF with PI controller was modeled in two modes (i) without anti-windup circuitry, (ii) with anti-windup circuitry. The performance of the Shunt Active Power Filter with both proposed controller circuits for reference current generation were examined with a simulation model and the results were compared. The results show that with both algorithms the THD meets the recommended harmonic standards such as IEEE 519, where, the one with the anti-windup scheme achieved the best performance in terms of Active Filtering

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