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RESEARCH ARTICLE

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Power Quality Improvement Using Three Phase Hybrid Filter Controlled by Modified Synchronous Reference Frame

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Abstract. The power system consists of large range of electrical, electronic and power electronic equipment in industrial and commercial applications. The power electronics equipment generates harmonic currents that are the source of adverse effects such as heating in transformers, perturbation of sensitive control equipment and resonances with grid. These problems can deteriorate the power quality in power networks. Therefore, it is very important to compensate the dominant harmonics and thus Total Harmonic Distortion (THD) below 5% as specified in IEEE 519 harmonic standard. Many solutions used to reduce this type of problems such as active filter, passive filter and hybrid filter, at the same time the performance of filters and harmonics elimination can be optimized by control strategy and filters topologies. This paper focuses on the control of shunt hybrid power filter by modified synchronous reference frame method (SRF). It focuses on the use of Self-Tuning-Filter (STF) with unit vector generation instead of Phase-Locked-Loop (PLL) circuit. The studied hybrid active filter consists of an active filter and three phase LC filters tuned for 7th harmonic frequency. The nonlinear load is a diode rectifier feeding a (R, C) parallel load. The use of STF's simplifies the control scheme by reducing the number of extraction filters. The use of STFs instead of classical extraction filters allows extracting directly the voltage and current fundamental components. The effectiveness of this study verified by computer simulation using MATLAB/Simulnk with the power system toolbox under steady-state condition.

Keywords: Modified Reference Frame, Shunt Hybrid Filter, Unit Vector Generation.

1 Introduction

Power quality is very important to certain consumers. For this reason, the most transmission or distribution systems are obliged to improve and supply the electric power. Non-linear loads that connected to the electrical network, such as power electronics equipment in industrial activities and consumers, causes an increase of current and voltage harmonics, and leads to a lower power factor and some of adverse effects in power systems, such as equipment overheating, motor vibration, excessive neutral currents. A clean network has less strain on appliances and their lifespans are lengthened. Nowadays with the advancement of technology, the demand for electric power is increasing at an exponential rate. The performance of the end user equipment is heavily dependent on the quality of power supplied to it. The solution to overcome these problems is to filter out these harmonics [1-3]. Many control methods and filters topologies have been presented in the literature to mitigate currents harmonics. Filters, which classified into three types (passive, active, hybrid), are widely preferred as the best solution to cancel the load harmonics currents.

This study presents three phase hybrid filter and modified control strategy to control the filter in such a way that the harmonics are reduced [3-5]. The hybrid filter is a combination of active filter and passive filter. While the passive filter mitigates load produced harmonics, the active filter helps to enhance filtering properties of passive filter. This shunt hybrid power filter controlled by modified synchronous reference frame method based on combined STF with unit vector generation instead of PLL circuit. This method can achieve general improvement in power quality and ensures a great diminution of harmonics currents.

2 System Configuration

Fig. 1, shows the shunt hybrid filter studied in this paper to improve power quality of the AC mains, it is consisting of a passive filter connected in series with an active filter without any transformer. The passive filter is a three-phase LC filter tuned at 7th harmonic frequency, which absorbs harmonics currents generated by the load, whereas the active filter improves filtering performances of the passive filter. The nonlinear load is a diode rectifier feeding a (R, C) parallel load [5-8].

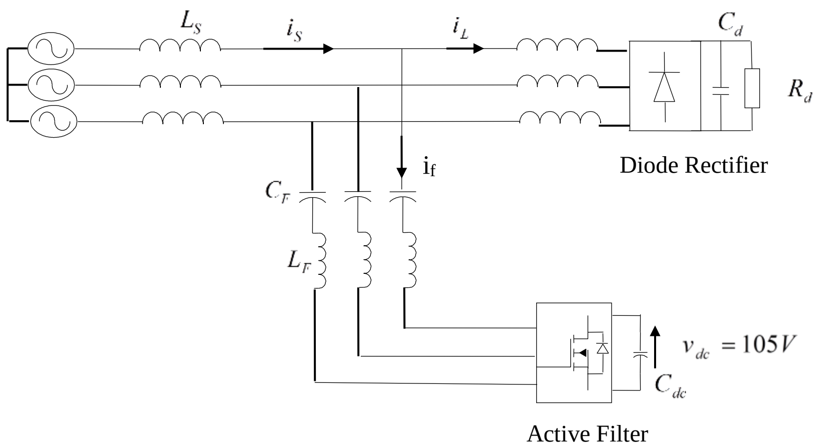


Fig. 1. Three phase hybrid filter system.

3 Control Strategy

The best control strategy does not require many involves mathematical computation, and for better performance, a good and fast processor must be employed. However, various control strategies have been used in the litterateurs for generating compensation currents requires filters, such as a low pass filter (LPF), high pass filter (HPF), or band pass filter (BPF) to separates of fundamental components from the harmonics. The self-tuning filter (STF) is used in our study instead of classical harmonics extraction filters based on HPFs or LPFs. This is an important choice in this paper to reduce many mathematical manipulations.

Among all these control strategies (synchronous reference frame theory (SRF), synchronous detection (SD) method, and instantaneous power theory [9-13]), the modified method SRF is used to control of hybrid filter in this paper, which is recognized as the simplest and easily implemented technique in harmonic extraction.

Fig. 2, presents the scheme of SRF method, which combines feedback and feedforward loop. The feedback control is applied to diode rectifier input harmonic currents, whereas the feedforward loop is applied to the most dominant 5th harmonic current component to improve filtering characteristics of the hybrid filter.

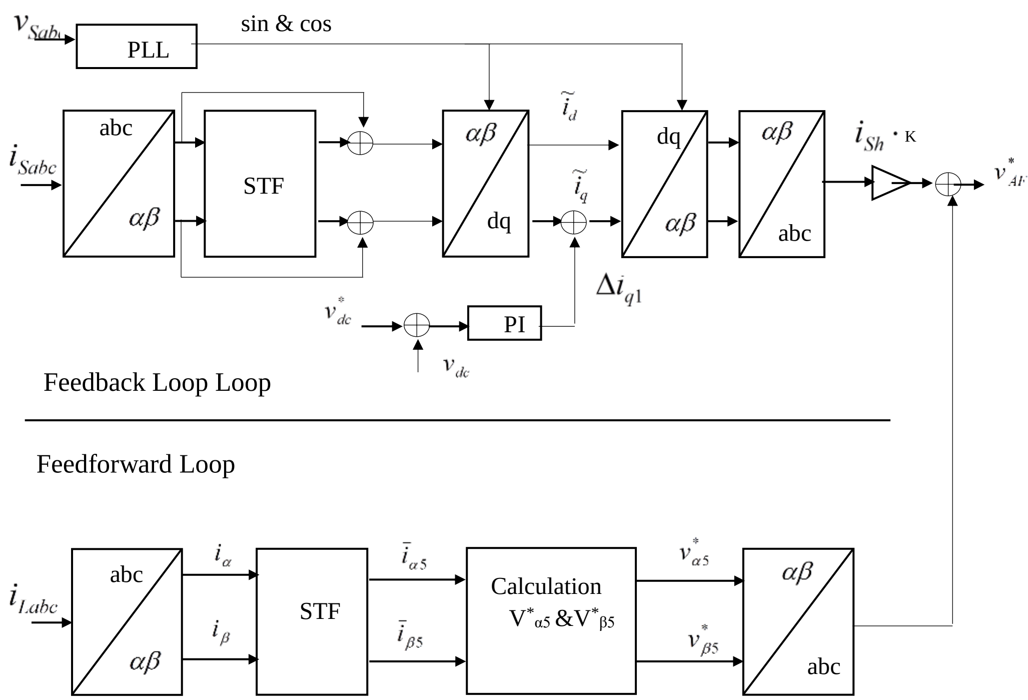


Fig. 2. Control scheme of the hybrid active filter.

This paper is aimed to replace the PLL circuit in the control scheme presented above in feedback loop by classical unit vector generation presented in Fig. 3. [14].

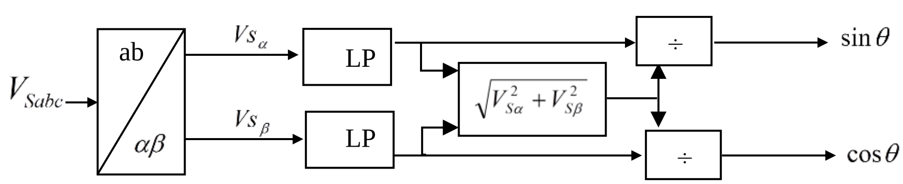


Fig. 3. Classical unit vector generation with two LPFs.

In this unit, the *α-β* voltages are used for calculating the transformation angle, two low pass filters (LPFs) are used in reducing the voltage harmonics of the input signals, and are consequently used in control process. This filter is essential because the method becomes less affected by harmonics from the source voltage [9,16]. Therefore, in order to more reducing calculation steps and computational times, we propose to modify and simplify the classical unit scheme by using one Self Tuning Filter (STF) instead of two LPFs as presented in Fig. 4.

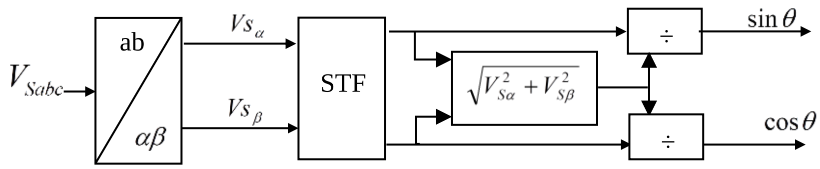


Fig. 4. Modified unit vector generation with STF.

As presented in Fig. 4, three main sinusoidal voltages V_{Sa}, V_{Sb} and V_{Sc} sensed and transformed into *α-β* reference frame by the Clarke transformation in order to generate the synchronization vector, a simple and efficient approach is adopted in calculating the output of the unit vector model in the SRF method. It has an important characteristic of contributing to the balance of the AC voltage network [17]. Thus, the desired source voltage can be given as:

$$V_{sa} = v_{sm} \sin(\omega t) \tag{1}$$

$$V_{sb} = v_{sm} \sin(\omega t - 120) \tag{2}$$

$$V_{sc} = v_{sm} \sin(\omega t + 120) \tag{3}$$

$$\begin{bmatrix} v_{S\alpha} \\ v_{S\beta} \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} 1 & -\frac{1}{2} & -\frac{1}{2} \\ 0 & \frac{\sqrt{3}}{2} & -\frac{\sqrt{3}}{2} \end{bmatrix} \begin{bmatrix} v_{Sa} \\ v_{Sb} \\ v_{Sc} \end{bmatrix} \tag{4}$$

By dividing the output of STF ($V_{\alpha\beta}$ components of the source voltage) with the magnitude of space vector, the unit vector generation is thus defined as [14]:

$$\sin\theta = \frac{v_{s\alpha}}{\sqrt{v_{s\alpha^2} + v_{s\beta^2}}} = \frac{(\sqrt{3}/2)v_{sm}\sin(\omega t)}{(\sqrt{3}/2)v_{sm}} = \sin(\omega t) \tag{5}$$

$$\cos\theta = \frac{v_{s\beta}}{\sqrt{v_{s\alpha^2} + v_{s\beta^2}}} = \frac{(\sqrt{3}/2)v_{sm}\cos(\omega t)}{(\sqrt{3}/2)v_{sm}} = -\cos(\omega t) \tag{6}$$

From Fig. 5, following expressions can be obtained:

$$\hat{v}_\alpha = (\frac{K}{s}[v_\alpha(s) - \hat{v}_\alpha(s)] - \frac{\omega_1}{s} \cdot \hat{v}_\beta(s)) \tag{7}$$

$$\hat{v}_\beta = (\frac{K}{s}[v_\beta(s) - \hat{v}_\beta(s)] + \frac{\omega_1}{s} \cdot \hat{v}_\alpha(s)) \tag{8}$$

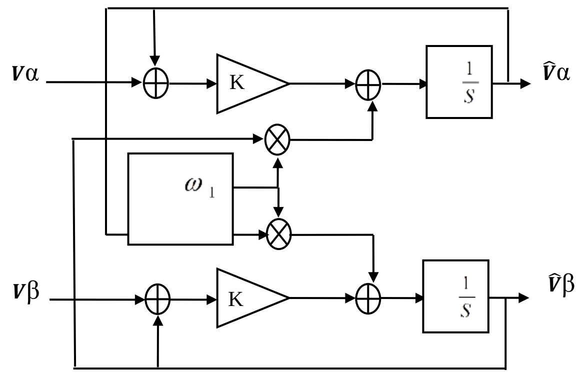


Fig. 5. Self-tuning filter circuit (STF).

where (ω_1), is the fundamental frequency.

For the Feedback loop, the use of a unit vector for sin (θ) and cos (θ) computation is however necessary. The computation of d-q current components is effectively necessary in this control loop for V_{dc} regulation. According to Fig.2, the three phase supply currents, i_{sa}, i_{sb} and i_{sc} are measured and transformed into α-β reference frame [6,7]:

$$\begin{bmatrix} i_{S\alpha} \\ i_{S\beta} \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} 1 & -\frac{1}{2} & -\frac{1}{2} \\ 0 & \frac{\sqrt{3}}{2} & -\frac{\sqrt{3}}{2} \end{bmatrix} \begin{bmatrix} i_{Sa} \\ i_{Sb} \\ i_{Sc} \end{bmatrix} \quad (9)$$

Then, a STF is introduced in feedback loop, which extracts the ac components directly from the current in the α-β axis. This extraction is achieved by substracting the self-tuning filter input signals from the corresponding outputs. The resulting signals are the ac components, $\tilde{i}_\alpha$ and $\tilde{i}_\beta$, which correspond to the harmonic components of isa, isb and isc in the stationary reference frame.

Then, after computation based on d-q transformation, we obtained the three-phase harmonic reference currents isha, ishb and ishc. Each harmonic current ish is amplified by a gain K in order to produce the three AC voltage references of the feedback loop, given by [18,19]:

$$V_{Sh}^{*} = i_{Sh} \times K \quad (10)$$

The Feedforward control greatly differs from the classical one presented in [18]. Here, the STF allows to directly and simultaneously extracting $\bar{i}_{\alpha 5}$ and $\bar{i}_{\beta 5}$ components for the 5^{th} harmonic frequency. The three phase load currents, i_{La}, i_{Lb} and i_{Lc}, are measured and transformed into α-β reference frame by:

$$\begin{bmatrix} i_{L\alpha} \\ i_{L\beta} \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} 1 & -\frac{1}{2} & -\frac{1}{2} \\ 0 & \frac{\sqrt{3}}{2} & -\frac{\sqrt{3}}{2} \end{bmatrix} \begin{bmatrix} i_{La} \\ i_{Lb} \\ i_{Lc} \end{bmatrix} \quad (11)$$

The currents in the stationary frames can be respectively decomposed into dc and ac components, regarding the 5th harmonic frequency, by:

$$i_\alpha = \bar{i}_\alpha + \tilde{i}_\alpha \tag{12}$$

and

$$i_\beta = \bar{i}_\beta + \tilde{i}_\beta \tag{13}$$

We tuned the STF at the 5th harmonic frequency by changing ω_1 to ω_5 in order to compute the dc components $\bar{i}_{\alpha 5}$ and $\bar{i}_{\beta 5}$ at the output of the self-tuning filter, as follows:

$$\bar{i}_{\alpha 5} = (\frac{K}{s}[i_\alpha(s) - \bar{i}_{\alpha 5}(s)] - \frac{\omega_5}{s} \cdot \bar{i}_{\beta 5}(s)) \tag{14}$$

$$\bar{i}_{\beta 5} = (\frac{K}{s}[i_\beta(s) - \bar{i}_{\beta 5}(s)] + \frac{\omega_5}{s} \cdot \bar{i}_{\alpha 5}(s)) \tag{15}$$

Where (ω_5 = -5 ω_1) is the 5th-harmonic frequency and the minus sign is for the negative sequence. The output signals of the STF tuned at the 5th harmonic frequency are the components $\bar{i}_{\alpha 5}$ and $\bar{i}_{\beta 5}$ corresponding to the 5th harmonic frequency. To calculate the feedforward voltage references at the fifth harmonic frequency, we note:

$$V_{\alpha\beta 5} = V_{\alpha 5} + jV_{\beta 5} \tag{16}$$

The complex impedance of the passive filter is given by:

$$Z_F = R_F + j\omega_5 L_F + \frac{1}{j\omega_5 C_F} \tag{17}$$

and the voltage is expressed by:

$$V_{\alpha\beta 5} = Z_F \times I_{\alpha\beta 5} \tag{18}$$

with:

$$I_{\alpha\beta 5} = I_{\alpha 5} + jI_{\beta 5} \tag{19}$$

Consequently, the references voltages at 5th harmonic are expressed by:

$$\begin{bmatrix} V_{\alpha 5}^* \\ V_{\beta 5}^* \end{bmatrix} = \begin{bmatrix} R_F & -\omega_5 L_F + \frac{1}{\omega_5 C_F} \\ \omega_5 L_F - \frac{1}{\omega_5 C_F} & R_F \end{bmatrix} \begin{bmatrix} \bar{i}_{\alpha 5} \\ \bar{i}_{\beta 5} \end{bmatrix} \tag{20}$$

When applying the α-β inverse transformation, we obtained the three-phase feedforward voltage references. Those references are added to the output voltage references established by the feedback loop to define the total voltage references for the active filter.

$$\begin{bmatrix} v_{a5}^* \\ v_{b5}^* \\ v_{c5}^* \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} 1 & 0 \\ -\frac{1}{2} & \frac{\sqrt{3}}{2} \\ -\frac{1}{2} & -\frac{\sqrt{3}}{2} \end{bmatrix} \begin{bmatrix} v_{\alpha 5}^* \\ v_{\beta 5}^* \end{bmatrix} \quad (21)$$

Finally, each voltage reference of the active filter is compared with a triangular waveform (10 KHz) to generate the switching signals for the six MOSFETs. A dc bus controller is required to regulate the dc bus voltage V_{dc} and to compensate the inverter losses. The measured dc bus voltage V_{dc} is compared with its reference value V^*_{dc}.

The resulting error is applied to a Proportional Integral (PI) regulator. The proportional and integral gains are set to $0.2\,\Omega^{-1}$ and $20\,\Omega^{-1}s^{-1}$ respectively.

4 Simulation Results

The efficiency of the proposed control scheme has been examined by computer simulation using MATLAB and associated toolboxes "Simulink" and "Power System Blockset". The parameters of the system are given in Table1.

Table 1. Simulation Parameters.

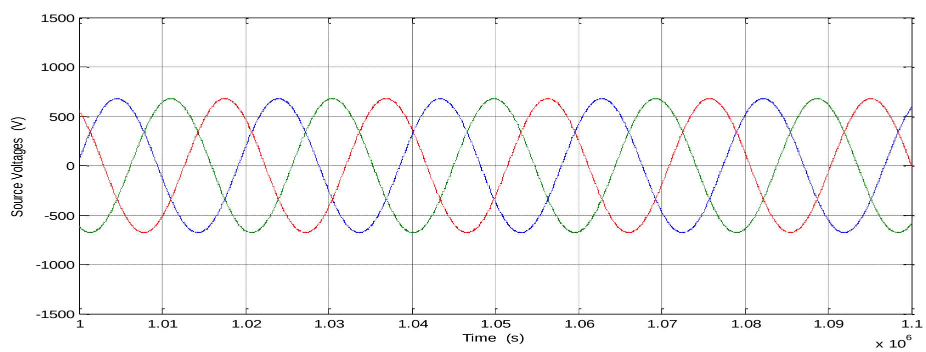
Parameter	Value
Capacitor : C_F	57.6 μF
Inductor : L_F	2.5 mH
Inductor: L_S	0.15 mH
Quality factor: Q	22
DC bus voltage	105 V
Capacitor: C_d	1500 μF
Resistor: R_d	21Ω
Capacitor: C_{dc}	1500 μF
System frequency	60 Hz
System voltage	480 V

Table 2, shows THD values for different choices of the gain value K for the feedback loop of the active filter. The optimal value is equal to 20Ω, which provides better filtering characteristics.

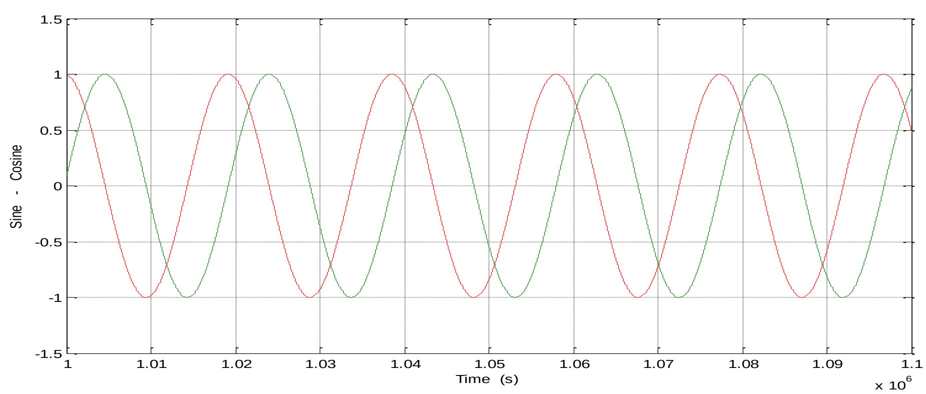
Table 2. Feedback gain (K) and THD (%).

Feedback gain (K)	THD
10	4.3
15	4.7
20	3.2
25	4.9
30	5

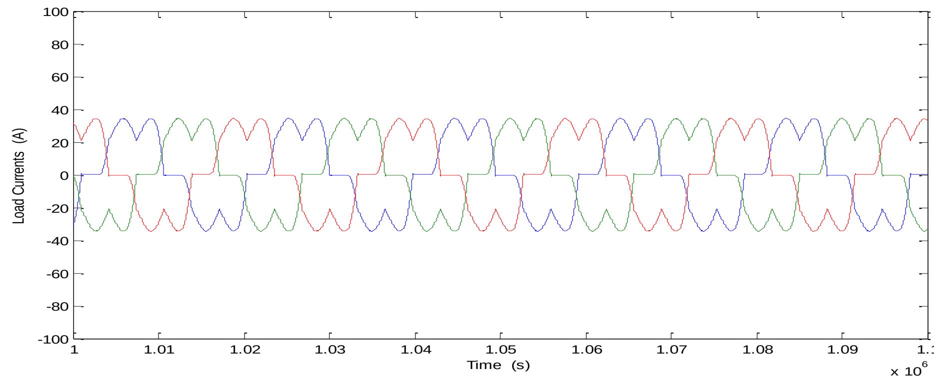
Fig. 6 and Fig. 7, shows simulation results for the modified SRF control scheme. The major aims of this paper were to simplify the unit vector generation and to validate the efficiency of the modified control scheme. The THD of the non-linear load i_L is equal to 27.8 % because of the large amount of the 5th harmonic current while it is equal to 3 % for the source current i_s. The results we obtained demonstrated an efficiency of modified unit vector with STF instead PLL and low of the THD values by using the new control studied in this paper. The V_{AF} waveform is not sinusoidal because the large amount of switching-ripple voltage. The LC filter is tuned at the 7th-harmonic frequency and absorbs the voltage of the network at the fundamental frequency. Consequently, the dc voltage of the inverter V_{dc} can be reduced as low as 105V. This enables the hybrid filter to use low-voltage MOSFETs which are less expensive.



(a)



(b)

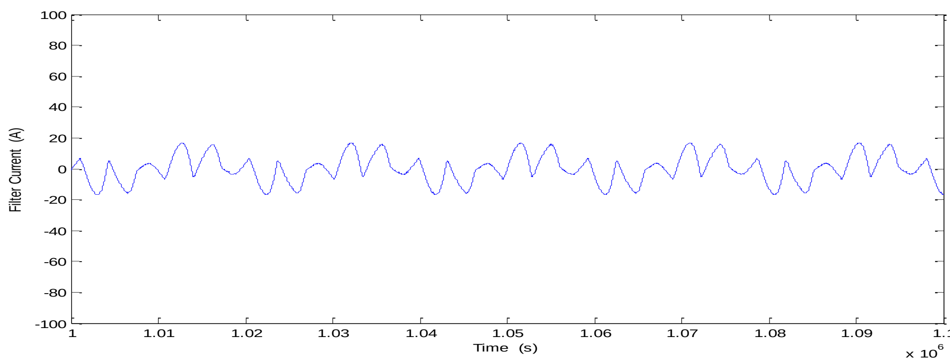


(c)

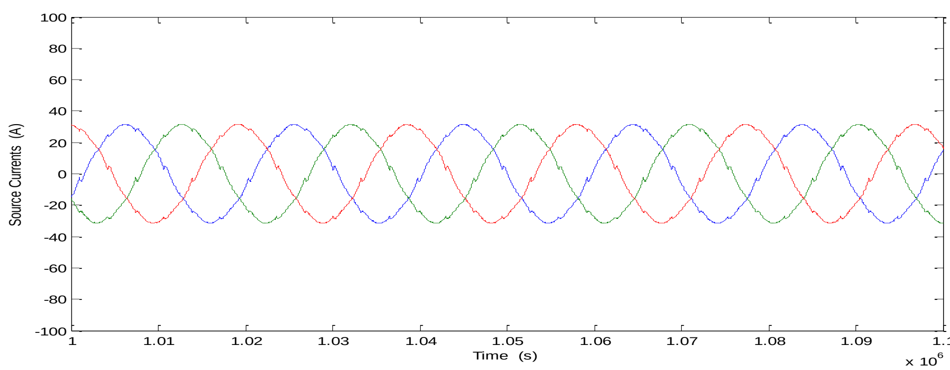
Fig. 6. (a) Three source voltages V_{Sabc} (V),

(b) output of unit vector (sine and cosine waves),

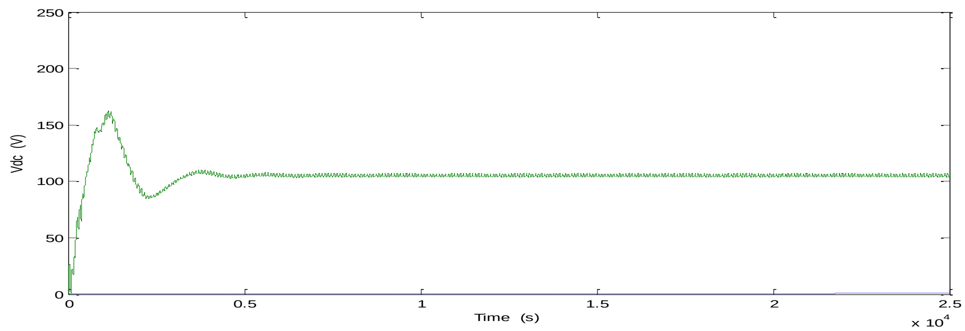
(c) Three load currents i_{Labc},



(a)



(b)



(c)

Fig. 7. (a) : Filter current i_F (A),
(b) : Three source currents i_{Sabc} (A),
(c) : DC-Bus voltage V_{dc} (v).

5 Conclusion

This paper validates by computer simulations the efficiency of modified control scheme to suppress the harmonic currents produced by nonlinear loads. Modified unit vector generation with STF is used instead PLL circuit. Self-tuning filters also have been introduced instead of high pass and low pass filters in the feedback and feedforward loops respectively. The new scheme presented the filtering performances of the shunt hybrid filter and achieved high quality filtering. Simulation results demonstrate the major advantages of using STF in the control system. Morever, we can tune this STF at any frequency by using the same method as the one used for the 5th harmonic frequency. By this way, complementary feedforward control can be added for other harmonics without major complication of the global control.

Conflict of Interest

The author declare no conflicts of interest.

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