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Harmonics Cancelation in 3-Phase 4-Wire System using Modified Reference Frame

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Abstract—**In this paper, A modified synchronous reference frame (SRF) or (d-q theory) with Self-Tuning Filter (STF) for the three-phase four wires system is presented to control of 4-legs shunt active power filter (SAPF) under balanced supply voltages. The main goal of the paper is to apply this control method using unit vector generation with STF instead of PLL circuit. In utility power system, it has been observed that harmonics build a major role in reducing the power quality. These harmonics caused by nonlinear loads. Many consumers appliances demand quality of power continuously for their operation. The performance of the end user equipment is heavily dependent on the quality of power supplied to it. This power is affected by various external and internal factors. They are like voltage and frequency variations, faults, outages etc. The solution to overcome these problems is to filter out these harmonics. For this purpose, there are many filters' topologies and control methods are proposed and studied in the literature to eliminate harmonics currents. In our study, 4-legs shunt active power filter is proposed and controlled by d-q method with modified unit vector generation. The SAPF is proposed to solve problems of line harmonic currents and neutral line currents of three phase 4-wire power distribution system. The use of STF in the modified control method can optimize the performance of this topology regarding to classical one (high pass and low pass filters). The proposed control strategy is simulated in MATLAB Simulink and the results are presented.**

Index Terms: **Modified d-q theory, shunt active filter, self-tuning filter (STF), unit vector generation.**

I. INTRODUCTION

Power quality problems are common in industrial, commercial and utility networks. The increasing use of power electronics in the electrical systems based nonlinear loads continuously deteriorated quality of power. Generally, harmonic currents are mostly generated by AC/DC power conversion units and the power electronic equipments. These harmonics are the source of adverse effects for many types of equipments such as heating in distribution transformer, perturbation of sensitive control equipments and resonances with grid. Therefore, it is very important to compensate the dominant harmonics and thus Total Harmonic Distortion (THD) below 5% specified in IEEE 519 harmonic standard. Many solutions have been studied in the literature to mitigate the harmonic problems with various topologies [1-4]. The passive filter is the simplest solution to eliminate the harmonic distortion in the power system utilities [5].

Passive filter consists of passive elements like capacitor (C), inductor (L) and resistor (R). These are widely used because of their low cost and ease of control. These are classified into two types- low pass filter (LPF) and high pass filter (HPF). Passive filters are used but they are dependent heavily on the system parameters and are suitable for filtering out a particular frequency harmonic. Therefore, to overcome the problems of passive filters, active filters are used.

The use of active power filters for power quality improvement is presented in many papers along with control strategies. Active power filter is a dynamic and flexible solution for the mitigation of harmonic current due to their compact size, no requirement of tuning and stable operation [6-9]. It has the capability to inject harmonic current into the ac system with the same amplitude but in opposite phase of the load. Fig.1 shows the studied system.

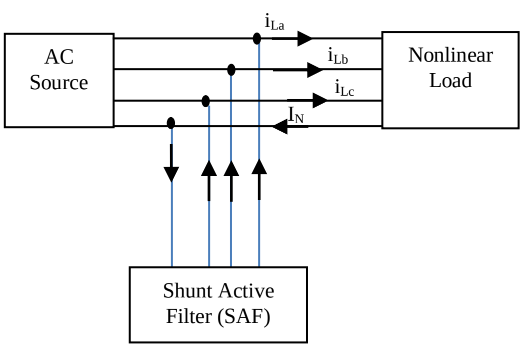

Figure. 1. Studied three phase 4-wire system.

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II. THREE PHASE FOUR WIRE SYSTEM

Three-phase four wire system which means three wires of three phases and fourth wire is neutral connection. For three phase loads like motors, three phase heaters etc, three phase three wire supply is enough. However, if some loads are single phase and some are three phases, four wire system is suitable.

Distribution of electrical energy to consumers is carried out by the three-phase, four-wire system, the voltage between any line and the neutral conductor is 240 V. In a house all the loads are usually single-phase and require a voltage of 240 V. This system can feed both balanced three phase loads as well as unbalanced three loads and single-phase loads. The neutral wire provides a path for out-of-balance current.

For distribution of electrical power, 3-phase 4-wire circuits are used so as to supply single phase and three phase loads depending on the requirement. While for transmission, power is not supplied to load, but only carried from generating stations towards distribution. So, 4^{th} wire i.e., neutral wire is not required so 3-phase 3-wire circuits are used [10]. In an ideal case when the loads were balanced, the neutral current would be zero, but in 3-phase 4-wire system, the neutral current carries the zero-sequence due to the unbalanced loading among the phase conductors.

Due to the presence of power electronics loads a triplen (3^{th}, 9^{th}, etc.) harmonics are introduced in the system. In most three-phase power system suppling single phase loads, there will be some phase current imbalance and some neutral current. On three phase four wire distribution systems, third harmonic current are increased which cause overheating of the neutral conductors [11].

III. SYSTEM CONFIGURATION AND CONTROL METHOD

The studied system in this paper consists of a three-phase source which is connected to a three-phase nonlinear load. The proposed SAPF is connected at the point of common coupling (PCC) between the three-phase supply and the nonlinear load. The SAPF is composed of a three-phase voltage source inverter and a dc bus capacitor to provide a constant dc voltage and real power necessary to cover the losses of the system, the filter is connected in parallel with the AC three phase four wire system by three inductors L_f.

The objective of the active filters is to generate currents that are equal but opposite to the harmonic currents. The active filter is intended for harmonic compensation of a diode rectifier feeding a (RL) load.
The study of active filter control is divided in two parts. The first part deals with the harmonic isolator which generates the harmonic reference currents and the second part focuses on the generation of the switching pattern of IGBTs of inverter by hysteresis current controller. Various control strategies have been used in the generation of the harmonic reference signal from the load current in the time domain, such as the synchronous reference theory (SRF) or d-q theory, synchronous detection (SD) method, and instantaneous power theory or p-q theory.

The SRF method is extensively used in three-phase systems and is recognized as the simplest technique in harmonic extraction [12-15]. Figure 2, shows the diagram of classical SRF method with PLL circuit.

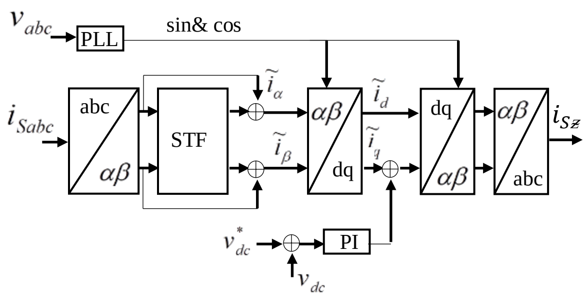

Figure 2. Control scheme with PLL circuit.

In this scheme, the PLL circuit will be replaced by classical unit vector generation presented in figure 3 [16]. 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.

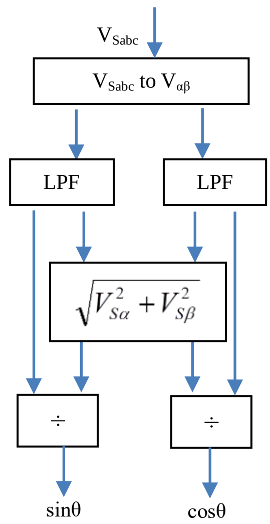

Figure 3. Unit vector generation with two LPFs.

In order to reducing calculation steps and computational times, we propose to modify and simplify the classical unit scheme by using one STF instead of two LPFs as presented in figure 4[17,18].

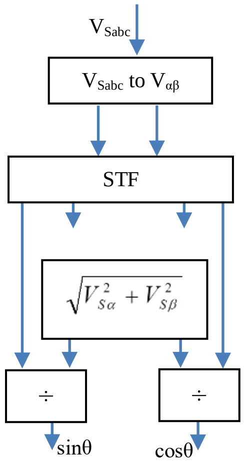

Figure 4. Modified unit vector generation with STF.

In order to transform from the *α-β* plane to the d-q rotating frame, the unit vector circuit is applied to produce sine and cosine signals, as presented in figure 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.

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

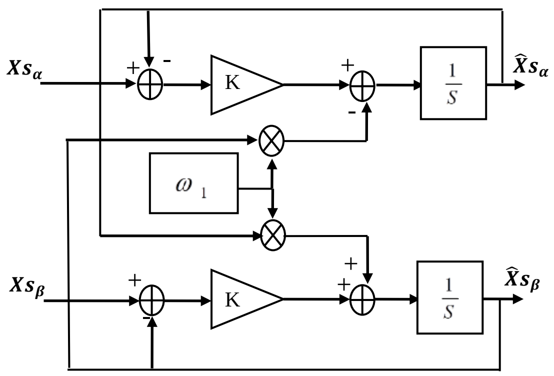

Figure 5: Self tuning filter circuit (STF).

From figure 5, following expressions can be obtained:

$$\hat{X}_{s\alpha} = \left(\frac{K}{s}[X_{s\alpha}(s) - \hat{X}_{s\alpha}(s)] - \frac{\omega_1}{s} \cdot \hat{X}_{s\beta}(s)\right) \qquad (2)$$

$$\hat{X}_{s\beta} = \left(\frac{K}{s}[X_{s\beta}(s) - \hat{X}_{s\beta}(s)] + \frac{\omega_1}{s} \cdot \hat{X}_{s\alpha}(s)\right) \qquad (3)$$

where:

(ω_1), is the fundamental frequency (f_c=50Hz).

Xs_α , Xs_β , are the input signals (voltage or current).

$\hat{X}_{s\alpha}$, $\hat{X}_{s\beta}$, are the output signals (voltage or current).

K, is a constant.

Note that the extraction of ac and dc components depends on the method of connection of this filter (STF) in the control scheme [17].

By dividing the output of STF ($V_{\alpha\beta}$ components of the source voltage) with the magnitude of space vector we can obtains sine and cosine signals:

$$\sin\theta = \frac{\hat{v}_{s\alpha}}{\sqrt{v_{s\alpha^2} + v_{s\beta^2}}} \qquad (4)$$

$$\cos\theta = \frac{\hat{v}_{s\beta}}{\sqrt{v_{s\alpha^2} + v_{s\beta^2}}} \qquad (5)$$

Then, as presented in figure 6, the three phase supply currents, i_{sa}, i_{sb} and i_{sc} are measured and transformed into *0-α-β* reference frame, as follows:

$$\begin{bmatrix} i_\alpha \\ i_\beta \\ i_0 \end{bmatrix} = C \begin{bmatrix} i_{sa} \\ i_{sb} \\ i_{sc} \end{bmatrix} \qquad (6)$$

$$C = \sqrt{\frac{2}{3}} \begin{bmatrix} 1 & -\frac{1}{2} & -\frac{1}{2} \\ 0 & \frac{\sqrt{3}}{2} & -\frac{\sqrt{3}}{2} \\ \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} \end{bmatrix} \qquad (7)$$

$$i_N = i_{sa} + i_{sb} + i_{sc} \qquad (8)$$

$$i_0 = 1/\sqrt{3} * (i_{sa} + i_{sb} + i_{sc}) = 1/\sqrt{3} * i_N \qquad (9)$$

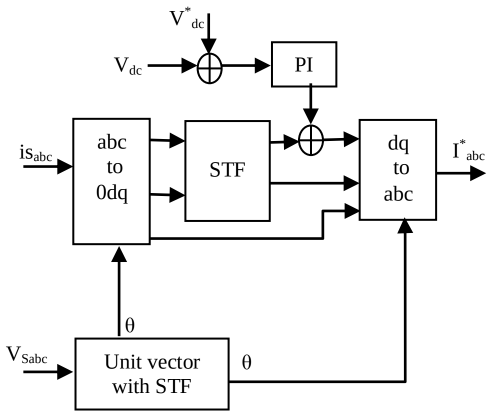

Figure 6. Control method scheme with modified unit vector.

Then, by the modified unit vector we can generate the signals sin(θ) and cos(θ) in order to apply 0-d-q theory.

$$\begin{bmatrix} id \\ iq \\ i_0 \end{bmatrix} = \begin{bmatrix} 0 & sin(\theta) & -cos(\theta) \\ 0 & cos & sin(\theta) \\ 1 & 0 & 0 \end{bmatrix} \begin{bmatrix} i_0 \\ i_\alpha \\ i_\beta \end{bmatrix} \qquad (10)$$

The resulting signals are the AC components which correspond to the harmonic components of i_{sa}, i_{sb} and i_{sc} in the stationary reference frame. After computation based on d-q inverse transformation, the three-phase harmonic reference currents can be obtained, as follows:

$$\begin{bmatrix} i_{refa} \\ i_{refb} \\ i_{refc} \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} 1 & 0 & \frac{1}{\sqrt{2}} \\ -\frac{1}{2} & \frac{\sqrt{3}}{2} & \frac{1}{\sqrt{2}} \\ -\frac{1}{2} & -\frac{\sqrt{3}}{2} & \frac{1}{\sqrt{2}} \end{bmatrix}^{-1} \begin{bmatrix} i_{ref\alpha} \\ i_{ref\beta} \\ i_{ref0} \end{bmatrix} \quad (11)$$

Finally, each reference current is compared with filter currents by hysteresis technique to generate the switching signals for the inverter [19]. 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} (700V). The resulting error is applied to a Proportional Integral (PI) regulator [20].

IV. SIMULATION AND RESULTS

In this work, simulation model of the system is formed and examined by MATLAB and associated toolboxes “Simulink” and “SimPower System Blockset”. The parameters of the studied system are given in Table 1.

Table 1. Simulation parameters

Inductor: L_L	105.98 mH
Resistor: R_L	$12.87*10^{-3}\Omega$
Resistor: R_F	$5*10^{-3}\Omega$
Inductor: L_F	100 mH
Inductor: L_S	104 mH
DC bus voltage	700 V
Capacitor: C_d	$8*10^{3}$ μF
System frequency	50 Hz
System voltage	240√2 V

Table 2, presents load current and source current THD as the harmonic-to-fundamental current ratio in (%). It demonstrates the effectiveness of the control scheme by using modified unit vector.

Harmonic content of the supply current is obtained by d-q method.

Table 2.THD values for load and source currents and harmonic-to-fundamental current ratio (%)

	5^{th}	7^{th}	11^{th}	13^{th}	17^{th}	19^{th}	THD (%)
i_L (A)	14.8	8.85	3.31	1.98	1.06	0.94	33.41
i_S (A)	0.8	0.46	0.11	0.09	0.02	0.02	2.17

Figure 7, shows simulation waveform for the load current and its harmonic spectrum. Before compensation, load current and source current are the same. As presented in Table II, the simulation results obtained showed the THD of the non-linear load i_L is equal to 33.41% before compensation, because of the large amount of the 5^{th} and 7^{th} harmonic currents.

When the SRF scheme with modified unit vector is applied to the three-phase four-leg shunt active filter, the active filter can reduce the supply current total harmonic distortion (THD) and it becomes a sinusoidal waveform. Figure 8, presents the compensation current injected by the SAPF to the system in order to eliminate harmonic currents.

The source current and its harmonic spectrum is shown in Figure 9, after filtering, it can be seen that the grid current harmonics were reduced to 2.17% for the source current i_S.

Figure 10 shows how neutral current is compensated. The DC bus voltage has been regulated to its reference value 700V as shown in Figure 11.

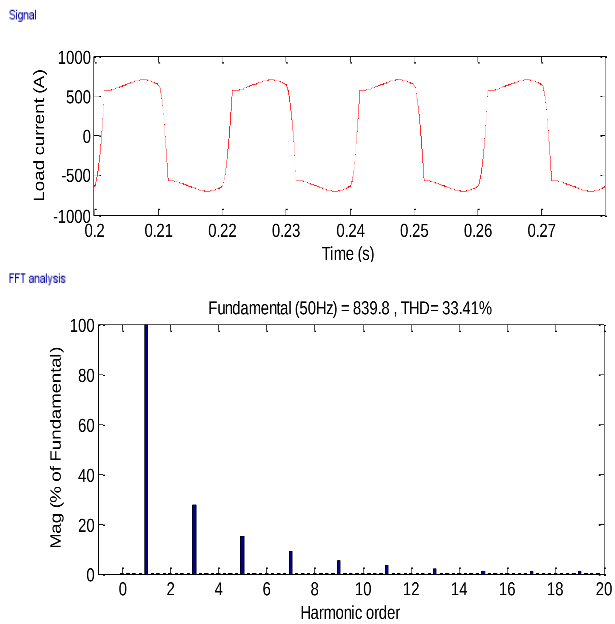

Figure 7. Simulation waveform for Load current i_L (A) and its harmonic spectra.

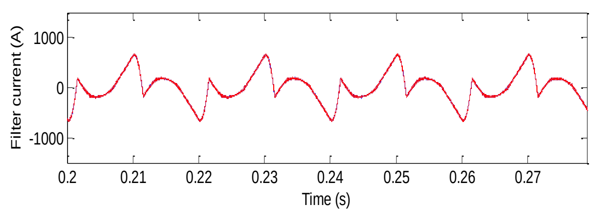

Figure 8. Simulation waveform for filter current (A)..

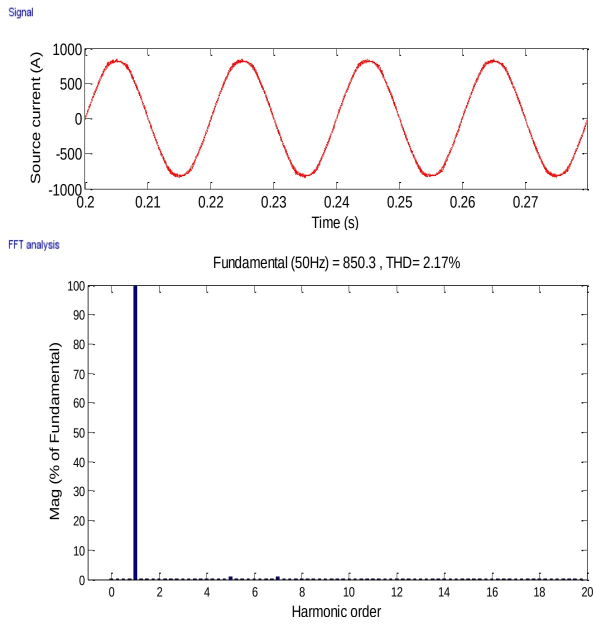

Figure 9. Simulation waveform for Source current i_S (A) and its harmonic spectra after compensation.

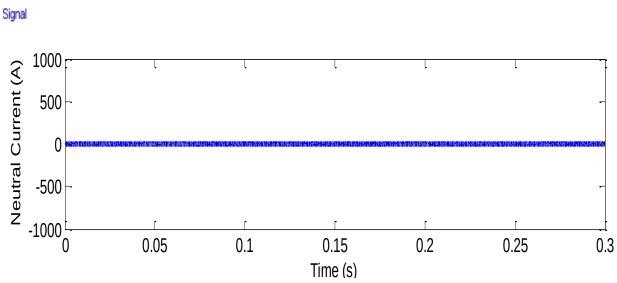

Figure 10. Simulation result for Neutral current iN (A).

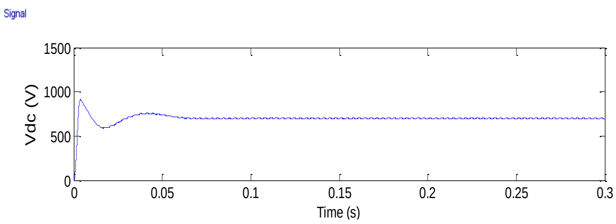

Figure 11. Simulation waveform for DC-Bus voltage Vdc(V).

VI. CONCLUSION

This paper has discussed the control and performances of a three-phase four-leg shunt active power filter (SAPF), to suppress the harmonic currents produced by nonlinear loads under normal voltage conditions. The studied power system is three-phase four-wire system. The control method (SRF) of active filter is divided in two parts. The first part deals with the harmonic isolator which generates the harmonic reference currents, and the second part focuses on the generation of the switching pattern of IGBTs of inverter by hysteresis current controller. Self-tuning-filter has been introduced in the d-q theory instead of classical extraction filters. The simulation results have demonstrated and conforted the major advantages of using modified unit vector with STF and hysteresis current controller in the filter control.

The effectiveness of SAPF, validates by computer simulation. Simulation results demonstrate the major advantages of using STF in the control system. Morever, we can tune this STF at any frequency.

The achieved results proved the proper operation of the presented three-phase four legs active power filter. The proposed control system of the SAPF allowed us to compensate most current harmonics.

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