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Harmonics Elimination by Two-Leg Hybrid Filter Controlled by Modified Reference Frame in Distorted Load Conditions

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Abstract- In the past few years, specifically after late 2019, a dangerous virus spread in the Republic of China called (SARS-Co This paper presents the performance of three-phase two-leg shunt hybrid power filter (SHPF) for quality improvement with distorted conditions of the nonlinear load. Shunt hybrid power filter (SHPF) are considered an attractive solution to overcome the problem of current harmonics generated by nonlinear loads. The hybrid filter used in this study includes two-leg inverter connected in series with passive filter tuned for 7th harmonic frequency. The passive filter is designed with three phase LC filters. The nonlinear load is a diode rectifier feeding a (R_d, C_d) parallel load. The current control strategy appropriate for filtering harmonics of an unbalanced nonlinear load in a three-phase three-wire power system. It is based on modified reference frame method which combine Self-Tuning-Filter (STF) with unit vector generation instead of Phase-Locked-Loop (PLL) circuit. As the power electronics equipment based non-linear loads generates harmonic currents that are the source of adverse effects, therefore, it is very important to compensate the dominant harmonics and thus Total Harmonic Distortion (THD) below 5% as specified in IEEE 519 standard. For the connection to the network no transformer is needed. Simulation results obtained by the MATLAB Simulink shows the efficiency and effectiveness of the filter to mitigate harmonic distortion and balance of the utility current with power quality improvement.

Keywords: hybrid filter, modified reference frame, modified unit vector, (PLL) circuit, Self-Tuning Filter (STF).

I. Introduction

The large number of computers and other sensitive electrical loads connected to the power system are directly affected by power quality problems. The increasing reliability of power semiconductor devices motivated the development of power electronics solutions to the problem of harmonic currents circulation into the grid. Harmonic restriction standards, such as IEEE 519, have been recommended to limit the harmonics injected into the grid by nonlinear loads. The solution to limit harmonics currents is to filter out these harmonics. There are many filters' topologies present in the literature which can be classified into three types (passive, active and hybrid). The passive filters, although their simplicity and low cost, present some disadvantages as sensitivity to temperature changing, dependence of the filtering characteristic on the grid impedance, parallel resonance. For these reasons, many applications were proposed for the development of the active filters. On the other hand, the cost of active filters in industrial could be very high because of large power rating of the power converter. These cost considerations limit the applications of active filters used in the power systems [1],[2].
Nowadays, various topologies of hybrid filters with different control strategies could be considered as one of the best solutions for improving power quality and as lower cost alternatives to active filtering for harmonic compensation. In this paper, three-phase three-wire hybrid power filter with two-leg is proposed, this hybrid filter configured by a classical active filter consisting of two-leg bridge using two power electronic switches for each leg and two DC capacitors located in the DC side of the power

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converter, this topology uses a smaller number of power electronic switches that allow to reduce the manufacturing cost [3]-[6].

The active filter connected in series with a passive filter. The nonlinear load is a diode rectifier feeding a (R_d, C_d) parallel load. This filter is able to operate in balanced and unbalanced load conditions. A simple and accurate control method is used to calculation and generate the harmonic reference currents which makes it efficient in unbalanced load conditions. This method based in modified reference frame method which based on unit vector generation with STF to generate of references currents. Figure 1, shows the SHPF studied in this paper.

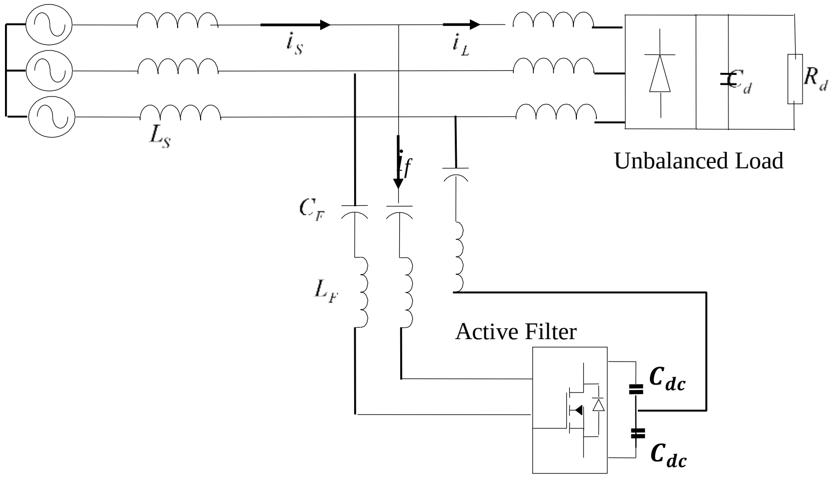

Figure.1. Studied three phase system with two-leg shunt hybrid power filter.

II. MODIFIED REFERENCE FRAME METHOD

The modified synchronous reference frame control method is used in this paper instead of classical one that presented in [7] to generate harmonic reference currents. Figure. 2 shows the modified control scheme.

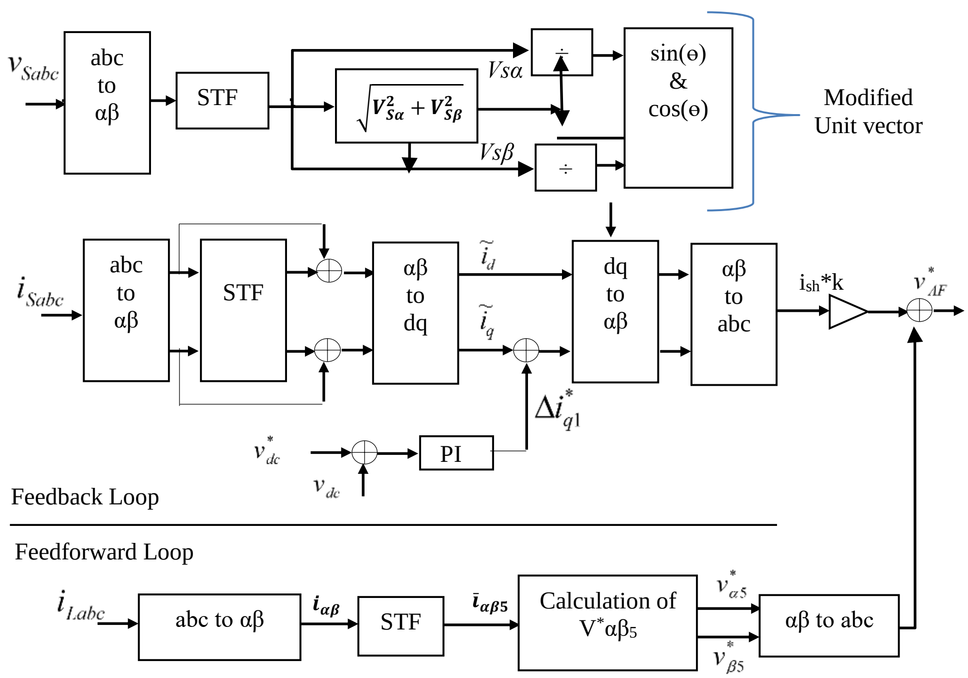

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Figure.2. Modified reference frame control scheme with unit vector and STF.

This study is aimed to modify and simplify the control method by using modified unit vector generation with STF instead of using classical unit with two LPFs. M. Suleiman et al. (2017) in [8], used a unit vector generation for generating the synchronization vector, which is a simple and efficient approach adopted in calculating the output of the unit vector model in the reference frame method. Figure 3 shows the diagram of a unit vector generation. The unit vector with STF allows to eliminate the PLL circuit from the classical scheme used in [8].

As presented in Figure.2, this method combines feedback and feedforward loop. The feedback control is applied to the diode rectifier input harmonic currents, whereas the feedforward loop is applied to the most dominant 5thharmonic current component, to improve filtering characteristics of tow-leg SHPF. The studied topology does not require many involves mathematical computation for generating compensation currents and this is an important choice in this study to reduce many mathematical manipulations. In this unit, the α-β voltages are used for calculating the transformation angle. The STF is used instead of classical harmonics extraction filters in order to more reducing calculation steps and computational times.

A. Feedback Loop

As presented in the feedback loop in Figure. 2, 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 reference frame method. It has an important characteristic of contributing to the balance of the AC voltage network [9]-[11]. Thus, the desired source voltage can be given as:

$$V_{sa} = v_{sm}\, sin\, (\omega t) \quad (1)$$
$$V_{sb} = v_{sm}\, sin\, (\omega t - 120) \quad (2)$$
$$V_{sc} = v_{sm}\, sin\, (\omega t + 120) \quad (3)$$

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

The use of a unit vector for sin (ω_1t) and cos (ω_1t) computation is however necessary. The computation of d-q current components is effectively necessary in this control loop for V_{dc} regulation. 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:

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

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

The three phase supply currents, i_{sa}, i_{sb} and i_{sc} are measured for the feedback loop and transformed into α-β reference frame:

$$\begin{bmatrix} i_{S\alpha} \\ i_{S\beta} \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} 1 & -\frac{1}{2} & -\frac{1}{2} \\ 0 & \frac{\sqrt{3}}{2} & -\frac{\sqrt{3}}{2} \end{bmatrix} \begin{bmatrix} i_{Sa} \\ i_{Sb} \\ i_{Sc} \end{bmatrix} \quad (7)$$

From Figure. 3, the output of STF can be obtained:

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

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$$\hat{v}_\beta = \left(\frac{K}{s}[v_\beta(s)-\hat{v}_\beta(s)] + \frac{\omega_1}{s}\cdot\hat{v}_\alpha(s)\right) \quad (9)$$

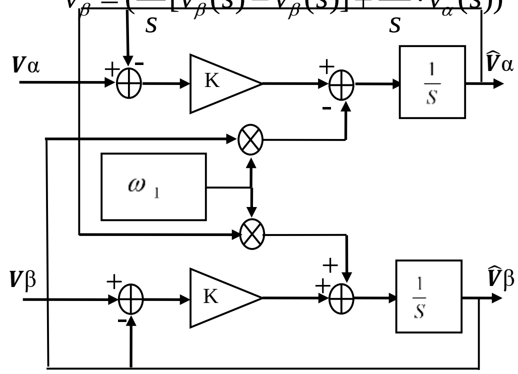

Figure. 3. Self-tuning filter circuit (STF).

Where (ω_1), is the fundamental frequency.

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 i_{sa}, i_{sb} and i_{sc} in the stationary reference frame. Then, after computation based on d-q transformation, we obtained the three-phase harmonic reference currents i_{sha}, i_{shb} and i_{shc}. Each harmonic current i_{sh} is amplified by a gain K in order to produce the three AC voltage references of the feedback loop, given by:

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

B. *Feedforward Loop*

The Feedforward control greatly differs from the classical one presented in. Here, the STF allows to directly and simultaneously extracting $\bar{i}_{\alpha 5}$ and $\bar{i}_{\beta 5}$ components for the 5th 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:

$$i_\alpha = \bar{i}_\alpha + \tilde{i}_\alpha \quad (12)$$

and

$$i_\beta = \bar{i}_\beta + \tilde{i}_\beta \quad (13)$$

The STF was tuned 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:

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

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

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Where (ω_5 = -5ω_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 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.

$$\begin{bmatrix} v^*_{a5} \\ v^*_{b5} \\ v^*_{c5} \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} 1 & 0 \\ -\frac{1}{2} & \frac{\sqrt{3}}{2} \\ -\frac{1}{2} & -\frac{\sqrt{3}}{2} \end{bmatrix} \begin{bmatrix} v^*_{\alpha 5} \\ v^*_{\beta 5} \end{bmatrix} \tag{21}$$

Finally, each voltage reference of the active filter is compared with a triangular waveform (10 KHz) to generate the switching signals for the four 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 0.6 $\Omega^{-1}$and 20 $\Omega^{-1}S^{-1}$ respectively.

III. PERFORMANCE OF THE FILTER WITH DISTORTED LOAD

The control and the performance of two-leg shunt hybrid active filter by modified synchronous reference frame during a transient regime of the load is the main concern of this paper. However, in order to study this situation, we assumed that the suddenly change has been happened to the load by changing the power of the load from 20kW to 10kW by varying of the resistance R_d from 21Ω to 42 Ω as following:

$$U_d = (3\sqrt{2}/\pi) * V = 648 \text{ V} \tag{22}$$

$$R_{d1} = U^2_d / p_1 \tag{23}$$

$$R_{d1} = (648)^2 / (20000) \tag{24}$$

$$R_{d1} = 21\ \Omega \tag{25}$$

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$$R_{d2} = U^2_d / p_2 \quad (26)$$
$$R_{d2} = (648)^2 / (10000) \quad (27)$$
$$R_{d2} = 42\Omega \quad (28)$$

IV. SIMULATION RESULTS

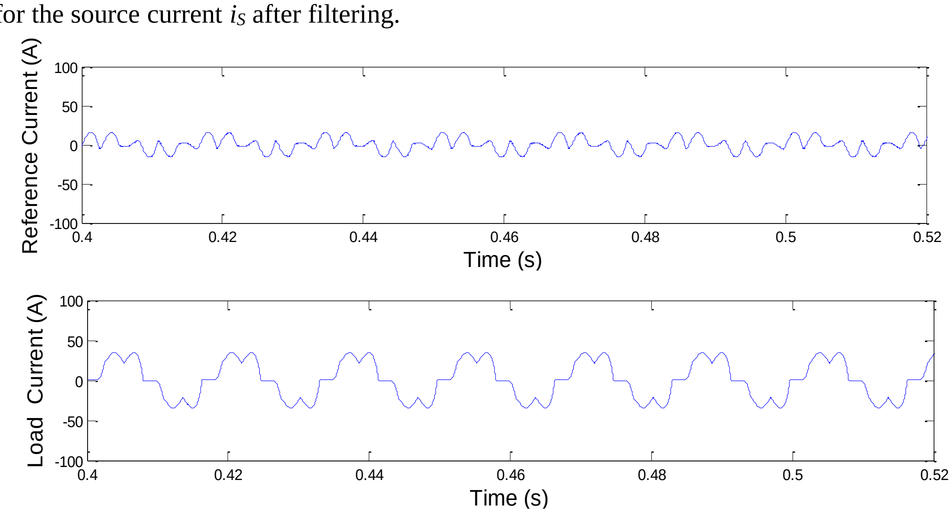
In this paper, the effectiveness of the modified control method based on unit vector generation with STF has been demonstrated. Simulation model of the system is formed and examined by MATLAB and associated toolboxes "Simulink" and "SimPower System Blockset". The performance of two-leg SHPF and its behavior to harmonic compensation is studied and verified under two aspects (steady state conditions and transient conditions) of the load. The system parameters used in these simulations are given in Table I.

Table I: Simulation Parameters

Capacitor: C_F	57.6 µF
Inductor: L_F	2.5 mH
Inductor: L_S	0.15 mH
DC bus voltage	210 V
Capacitor: C_d	1500 µF
Resistor: R_{d1}	21 Ω
Resistor: R_{d2}	42 Ω
Capacitor: C_{dc}	1500 µF
System voltage	1500, 60 Hz

A. Under normal conditions

The simulation results show an excellent performance of SHPF under steady state conditions. As presented in Figure 4, the THD of the non-linear load i_L is equal to 27.7% before filtering because of the large amount of the harmonic current while it is equal to 4.4% for the source current i_S after filtering.



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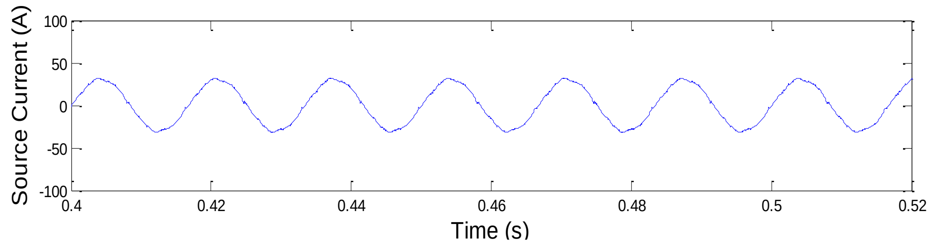

Figure 4. Simulation results under normal conditions of the system
From top to bottom: Reference current i_f (A), Load current i_l (A) and Source current i_s(A).

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 210V for both control schemes. This enables the hybrid filter to use low-voltage MOSFETs which are less expensive.

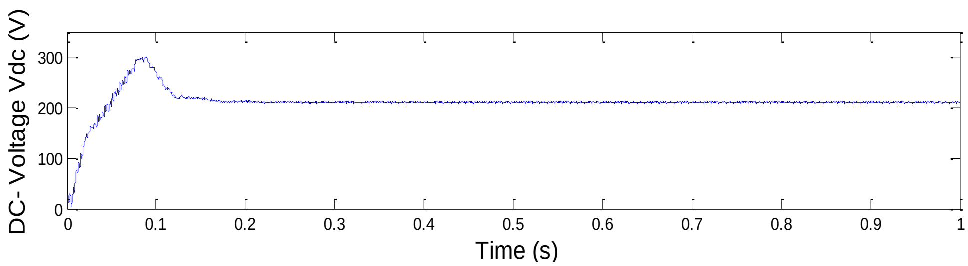

Figure 5. Simulation results for DC-Bus voltage V_{dc} (V) under normal conditions.

A. Under transient conditions

Figure 6, presents simulated waveforms of SHPF under load variation from 20 kW to 10 kW. It confirms the effectiveness of hybrid power filter for dynamic compensation. The source current was distorted nearly for one cycle following the occurrence of the load change and it reaching his sinusoidal form quickly with 3.5% THD after this transient period. Also, a small deviation can be observed during the distorted regime but does not produce any bad effect on the performance of the hybrid filter.

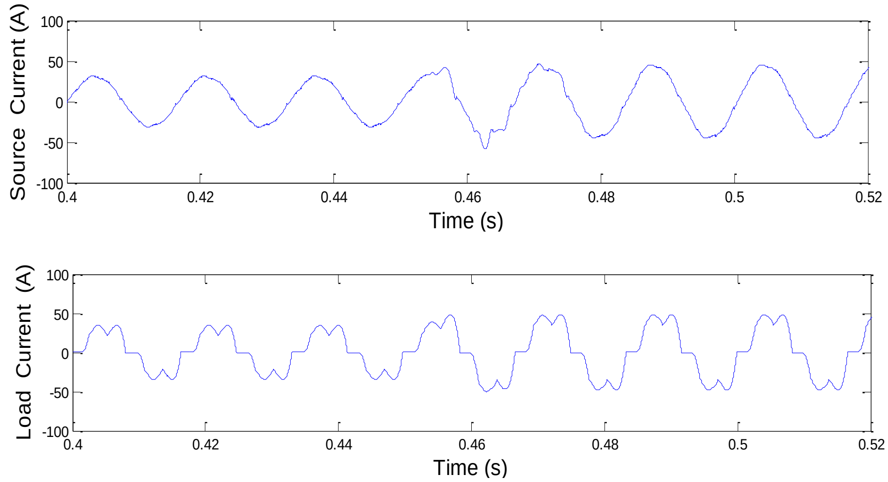

Figure 6. Influence of transient regime on the Source currents i_S (A) and Load currents i_L(A).

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Figure 7, shows the influence of transient regime on the Dc-voltage waveform V_{dc}. A small deviation in dc bus voltage is observed which is recovered quickly and stabilize again around its initial value of 210V, maximum voltage of V_{dc} during this period was 218 V, the increase is 8 V.

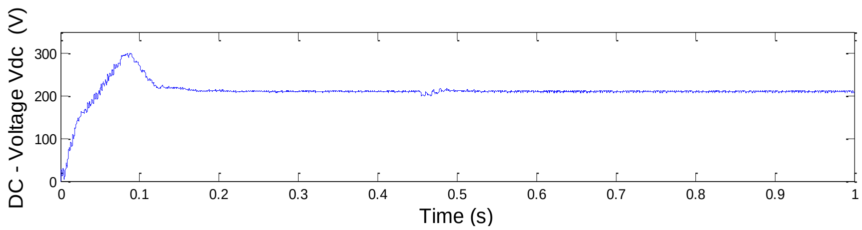

Figure 7. Influence of transient regime on the DC-Bus voltage waveform V_{dc} (V).

V. CONCLUSION

This paper has studied by computer simulation the performance of shunt hybrid power filter with two legs and a midpoint capacitor intended for suppress harmonics currents caused by nonlinear load. This topology with two legs allows to reduce the number of power electronic switches which led to reduction of the cost. Modified synchronous reference frame with unit vector generation and STFs used to control this filter. The continuity of service of SHPF is studied under normal and transient conditions of the load. The transient regime has a consequence of an increase in energy loss. It may affect the performance of sensitive equipment, and reducing the useful life of the equipment. The value R_d has been changed from 21Ω to 42Ω for transient regime. We noted clearly that source current, load current and dc voltage waveforms have been deformed during this transient. It has been observed through simulations that the hybrid power filter offers an excellent performance resulting in 4.4 % THD and 3.5%THD in the source current for the normal and transient regime respectively. The hybrid filter is transiently influenced by this change of the load but quickly found its effectiveness at the end of this transient regime.

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