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PARALLEL HYBRID ACTIVE POWER FILTER FOR STATIC REACTIVE POWER AND HARMONICS COMPENSATION WITH SOGI-PLL

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Abstract- In this paper, according to the lack of relevant studies based on reactive power compensation, the control method related to this subject has been investigated and applied to the Parallel Hybrid Active Power Filter (P-HAPF). Firstly, the dq base control algorithm is applied for harmonic compensation. Then, the reactive power compensation control which is supplied by active filter of hybrid active filter is added. Finally, the static reactive power and harmonic compensation is achieved by P-HAPF. All controllers are written by FORTRAN language in PSCAD/EMTDC.

Keywords: Power Quality, Harmonics, Reactive Power, Hybrid Active Filter.

I. INTRODUCTION

In recent years, with the increase of nonlinear loads in industrial manufacturers, the power quality issue has become more serious. There are various custom power devices to solve these power quality problems. In the past, the passive power filters were often used to solve serious harmonic problems of the grid. Although passive filters were preferred because of its economic and simple structure, new methods are needed due to the disadvantages of passive filter such as requirement of a separate filter for each harmonic current, having limited filtering characteristics, the negative effects caused by parallel and series resonance between grid and filter impedance [1, 2].

The active power filter which is developed to remedy the shortcomings of the passive filter consists of voltage or current source inverter, DC link storage and output filter. When active filter is compared to passive filter, although active filter has complex structure and more costly, today they can solve various power quality problems such as harmonic compensation, reactive power compensation, voltage imbalance, voltage flicker [3, 8, 9]. Even though the active power filter is an effective compensation system, their cost is increasing seriously with the proportion of increasing power capacity [1, 2]. As a solution to this situation, the hybrid active power filters have been developed by using active and passive filters together [3-6].

The main aim in the development of P-HAPF [11, 12] is to reduce the cost and rating of active filter by using passive filter that filters dominant harmonics caused by nonlinear loads and supplies reactive power requirement [2].

In this paper, according to the lack of relevant studies based on reactive power compensation, the control method related to this subject has been investigated and applied to the P-HAPF. Firstly, the dq base control algorithm is applied for harmonic compensation. Then the reactive power compensation control which is supplied by active filter of hybrid active filter is added. Finally, the static reactive power and harmonic compensation is achieved by P-HAPF. All controllers are written by FORTRAN language in PSCAD/EMTDC.

II. PARALLEL HYBRID ACTIVE POWER FILTER

Parallel hybrid power filter which is the main concern of this article is formed by the use of a three phase voltage source PWM converter, and a series connected LC passive filter directly. Thus, there is no need to use transformer. The series connected LC filter is tuned to dominant harmonic component of the load. It compensates the current harmonics caused of the nonlinear load, however, the filtering characteristic of just the passive filter itself does not give satisfactory results. Hence, active power filter is used to develop the filtering performance of the overall system and to remove the resonance risk of the passive filter. The power circuit of the inverter includes an energy storage element of a DC link capacitor and controllable semiconductor switches with their anti-parallel diodes. Active Power Filter (APF) injects compensation currents by operating as a current controlled voltage source. In conventional voltage source active power filter topology, the DC link capacitor voltage must be greater than the peak value of the grid voltage, else the generated compensation currents cannot be injected to the mains. However, the presence of filter capacitor in this topology ensures a reduced DC link voltage and a low rated voltage source converter at the expense of additional fundamental current, passing through the converter. The P-HAPF topology is illustrated in Figure 1.

As a result, for low voltage applications, PWM converter can be formed by power MOSFETs instead of using IGBTs. So that, the initial cost of the converter can be decreased by using MOSFETs instead of IGBTs. Similar to conventional VSC based APFs, P-HAPF does not require a DC power supply for its DC link voltage regulation. To explaining both harmonics and reactive power compensation characteristics of the P-HAPF, the single phase equivalent circuit is shown in (Figure 2). Z_s presents the source impedance and Z_f presents the passive filter impedance. The nonlinear load is indicated as an ideal current source (I_L), and the APF is shown as a voltage source.

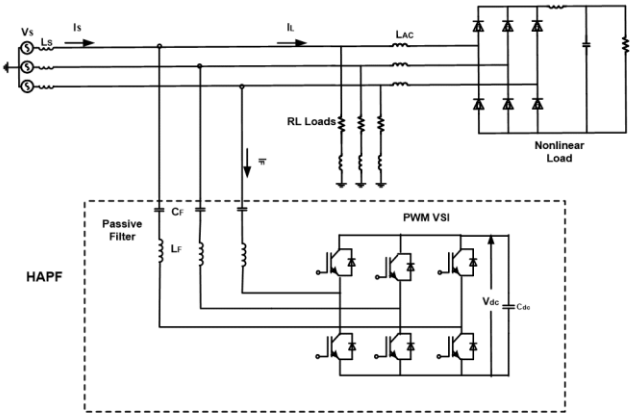
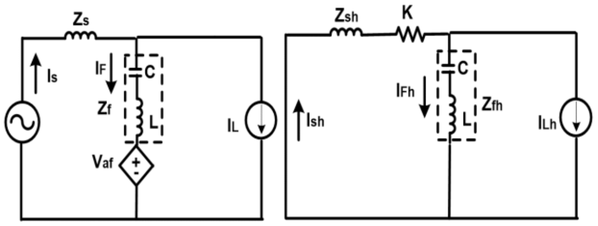


Figure 1. Parallel HYBRID Active Power Filter (P-HAPF)



(a) (b)

Figure 2. (a) Single phase equivalent circuit, (b) Harmonic equivalent circuit [7]

If the terminal voltage does not have no fundamental component, voltage across the PWM inverter can be presented as $K\times I_{sh}$ at harmonic frequencies where '*h*' shows the harmonic components and *K* shows the feedback gain. Therefore, the source voltage can become pure 50 Hz and presenting the current directions as in (Figure 2), the following equations can be obtained by applying Kirchhoff's voltage law [7]:

$$V_{sh} - I_{sh}Z_{sh} - I_{fh}Z_{fh} - V_{af} = 0 \tag{1}$$

where,

$$V_{sh} = 0\,,\ V_{af} = K.x.I_{sh} \tag{2}$$

$$I_{sh} = I_{Lh} + I_{fh} \tag{3}$$

$$I_{sh} = \frac{Z_{fh}}{Z_{fh} + Z_{sh} + K} \times x.I_{Lh} \tag{4}$$

Equation (4) shows that the active part of the filter is connected to the system, feedback gain *K* acts as a damping resistor. *K* protects the resonance between the supply and the passive filter [7]. Theoretically, as *K* goes to infinity, the harmonic content of the source current goes towards zero [7]. However due to stability problems in the control loop, the gain *K* should be limited to certain values [7]. Hence the design procedure of P-HAPF can be divided into two groups as the design of the passive filter and the design of the active filter part. The design of the passive filter is mainly identifying the L_f, C_f parameters considering the harmonic content of the load. It is clear that, tuning frequency of the passive filter is chosen to be the most dominant harmonic component of the nonlinear load. Today's industrial loads generally consist of three phase diode rectifiers as AC/DC converters instead of PWM converters due to their low cost and efficiencies.

As a result, in the case of a diode rectifier, the passive filter should be adjusted to eliminate the 5th or 7th harmonic current content. The 5th harmonic current content of a diode rectifier is higher than its 7th harmonic components, so it is more reasonable to tune passive filter around 250Hz. LC filter for this work is tuned 250 Hz.

III. CONTROL METHODS

A. Harmonic Compensation

In parallel hybrid filter topology, PWM converter generates compensation voltages by operating as a current controlled voltage source. So, the performance of the system is highly dependent on the accurate measurement and the calculation of the compensation current references. Once the current references are obtained, voltage reference for each phase is produced by an appropriate control method in which the gate signals of semiconductor switches are also produced in modulation part.

Synchronous reference frame method is based on the transformation of vectors into synchronously rotating direct (d), and quadrature axis (q) reference frames. In order to calculate the harmonic components of the mains current, initially three phase supply current vectors are mapped into synchronously rotating reference frame in Equation (5). The phase angle θ defines the fundamental frequency phase information of the utility voltage and it is obtained from a phase locked loop circuit which is investigated.

$$\begin{bmatrix} i_d \\ i_q \\ i_0 \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} \cos\varphi & \cos(\varphi - \frac{2\pi}{3}) & \cos(\varphi + \frac{2\pi}{3}) \\ -\sin\varphi & -\sin(\varphi - \frac{2\pi}{3}) & -\sin(\varphi + \frac{2\pi}{3}) \\ \frac{\sqrt{2}}{2} & \frac{\sqrt{2}}{2} & \frac{\sqrt{2}}{2} \end{bmatrix} \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} \tag{5}$$

$$\begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} \cos\varphi & -\sin\varphi & \frac{\sqrt{2}}{2} \\ \cos(\varphi - \frac{2\pi}{3}) & -\sin(\varphi - \frac{2\pi}{3}) & \frac{\sqrt{2}}{2} \\ \cos(\varphi + \frac{2\pi}{3}) & -\sin(\varphi + \frac{2\pi}{3}) & \frac{\sqrt{2}}{2} \end{bmatrix} \begin{bmatrix} i_d \\ i_q \\ i_0 \end{bmatrix} \tag{6}$$

Once the current vectors are transformed into synchronously rotating dq reference frame, the fundamental component of the mains current converts to be a DC signal, and the harmonic components which are still AC signals are rotating with a corresponding angular frequency.

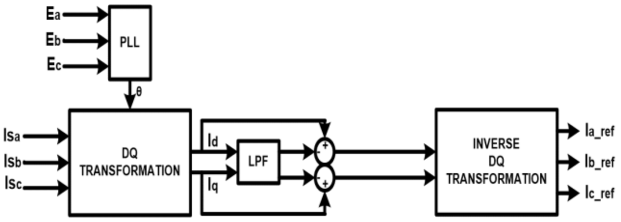


Figure 3. Current reference calculation based on SRF method [7]

The harmonic current control is based on the calculation of voltage reference by utilizing the source current harmonic references. In this method, 50 Hz component of the source current is extracted and the remaining oscillating part in dq reference frame is treated as reference compensation currents.

In this control, dq reference frame method is used to calculate the harmonic components of the source current. The block diagram based on SRF method is indicated as Figure 3. The phase angle (θ) of the supply voltage is required which affects the performance of the control method. Hence, an accurate phase tracking system is the key point of the control method to transform the measured current vectors into synchronously rotating d-q reference frame. So SOGI-PLL is selected for extracting the phase angle (θ).

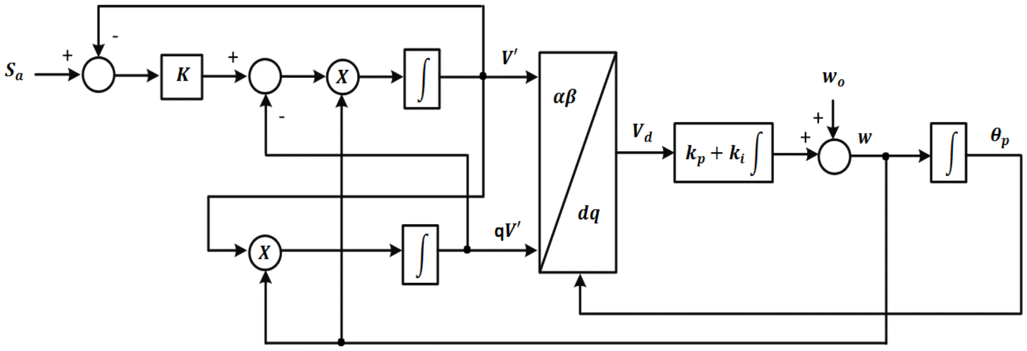


Figure 4. Block diagram of the SOGI-PLL [10]

The phase tracking system indicated above includes the transformation of utility voltages into d-q reference frame and a PI controller. The system is a closed loop controller in which the transformation of the utility voltage is performed by using the θ output of the PI controller. The output signals consists of two sine waves (v' and qv'). These waves has a phase shift of 90°. The sine wave V' is in phase and has same magnitude as the fundamental of the input signal (v).

The equations are based on second order generalized integrator (SOGI), which is defined as:

$$GI = \frac{ws}{s^2 + w^2} \tag{7}$$

where, w represents the resonance frequency of the SOGI. The closed-loop transfer functions ($H_d = v'/v$ and $H_q = qv'/v$) of the structure presented in Figure 4 are defined as:

$$H_{d(s)} = \frac{kws}{s^2 + kws + w^2} \tag{8}$$

$$H_{q(s)} = \frac{kw^2}{s^2 + kws + w^2} \tag{9}$$

where, k affects the bandwidth of the closed-loop system.

The input signal is filtered. The filtering results give two orthogonal voltage signals v *and* qv'. The filtering ability can be tuned by changing k. If k is selected smaller value, the system has heavy filtering, however the dynamic response will be slower.

B. Reactive Power Compensation

When the loading reactive power Q_{Lxf} is greater than Q_{cxfPF}, in order to generate a larger I_{cxf}, the inverter should output *a* negative inverter fundamental active voltage ($V_{invxf} < 0$) [13]. The reactive power equivalent circuit is shown in Figure 5. The related equations as follows:

$$V_{invxf} = V_{sx} - Z_{PPFf} I_{cxf} \tag{10}$$

$$I_{cxf} = \frac{V_{inxf} - V_{sx}}{Z_{PPFf}} \tag{11}$$

$$X_{PPFf} = -\left| X_{cf} - X_{Lf} \right| \tag{12}$$

The reactive power provided by the passive part

$$Q_{cxfPF} = -\frac{V_{sx}^2}{\left| X_{cf} - X_{Lf} \right|} < 0 \tag{13}$$

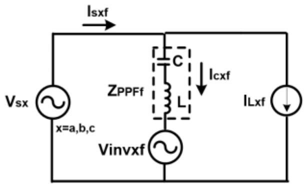


Figure 5. Reactive power equivalent circuit [13]

C. DC Link Control

Proportional plus integral (PI) controller is used for dc link control of PHAPF. The PHAPF is not used any external supply to regulate or charge dc link capacitor. Thus, the PI controller is important to stability of dc link voltage.

The dc link voltage amount directly effects to reactive power and harmonics compensation ability of P-HAPF. For only harmonic compensation, the dc link voltage value is decreased compared to both reactive power compensation and harmonics compensation.

The current reference (ΔI_{q1}) obtained in this control loop is added to the dc link control signal $V_{dc\text{-}pi}$. The dc link control block diagram is presented in Figure 6.

D. Proposed Control Block

The proposed control block consists of four parts which represents as Figure 6:

a. Determination of harmonic reference current
b. Determination of reference reactive power current
c. DC link voltage control
d. Voltage reference PWM control

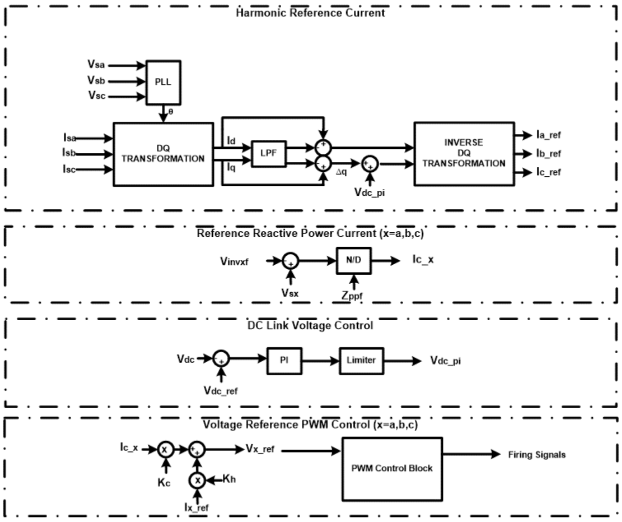


Figure 6. Proposed control block diagram of P-HAPF

IV. SIMULATION AND RESULTS

In this work, simulation model of the system is formed by using EMTDC/PSCAD 4.2.0 Professional software. The Parallel Hybrid Active Power Filter is modeled, simulated and analyzed in PSCAD 4.2.0 environment. The control methods are developed in FORTRAN language. The simulation power system is shown in Figure 1. Table 1 shows simulation parameters.

Harmonic content of the supply current is obtained by dq frame method and DC link voltage control as described previously. The phase information of the supply voltage is obtained by a SOGI-PLL system. As can be seen from Figure 7, the phase angle information (ωt) is locked to the supply voltage between 0-2π which is utilized in the transformation matrices.

Table 1. Simulation parameters

Line Voltage	380 V
Line frequency	50 Hz
Supply inductance (L_s)	0.00005 H
Filter Capacitor, Inductance (C_F, L_F)	170 µF, 2.39 mH
Tuned freq. of series filter (f_{tuned})	250 Hz
DC link capacitor (C_{DC})	3000 µF
Load Resistances(R_{load1}, R_{load2}, R_{load3})	9.75 Ω, 50 Ω,30 Ω
Load Inductances($L_{load1,2,3}$)	65 mH
Load Inductances(L_{ac1})	1.3 mH

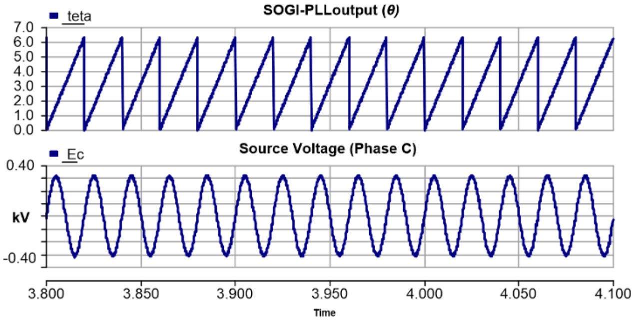


Figure 7. SOGI-phase locked loop output (θ) at steady state

A. Case 1: R_{load1}, L_{load1}, R_{load2}, L_{load2} Connected

In the first case, R_{load1}, L_{load1}, R_{load2} , L_{load2} are connected to the power system. The THD value of load is nearly 23%. When the P-HAPF is operated, the THD value of the source is decreased and equal to 2-3%. The waveform of source voltages, source currents, P-HAPF currents and load currents are shown in Figure 8.

In addition, the reactive power compensation ability is added to active part of P-HAPF with this proposed controller. The passive part reactive power compensation ability is nearly 8 kVar. The loads reactive power is nearly 9 kVar. When the P-HAPF operates, the active part compensates 1 kVar reactive power. Thus, the reactive power could not be seen the source part of the system. The source active and reactive power, load active and reactive power, P-HAPF active and reactive power waveforms are represented as Figure 9. The dc link voltage value is selected 100 V. The dc link waveform is shown in Figure 10.

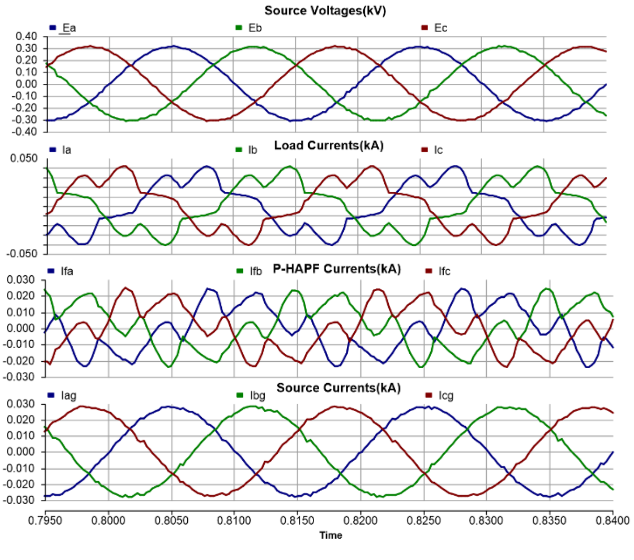


Figure 8. Supply voltages, load currents, P-HAPF currents, supply currents (P-HAPF operates, Loads: R_{load1}, L_{load1}, R_{load2}, L_{load2})

B. Case 2: R_{load1}, L_{load1}, R_{load3}, L_{load3} Connected

In the second case, R_{load1}, L_{load1}, R_{load3}, L_{load3} are connected to the power system. The THD value of load is nearly 22%. When the P-HAPF is operated, the THD value of the source is decreased and equal to 2-3%. The wave form of source voltages, source currents, P-HAPF currents and load currents are shown in Figure 11.

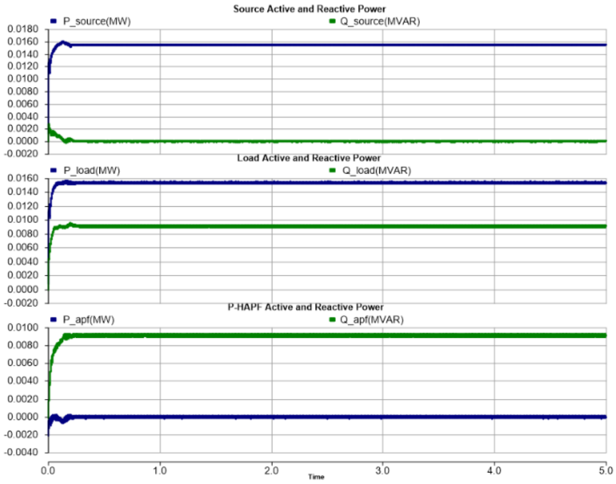


Figure 9. Source active and reactive power, load active and reactive power, P-HAPF active and reactive power (Loads: R_{load1}, L_{load1}, R_{load2}, L_{load2})

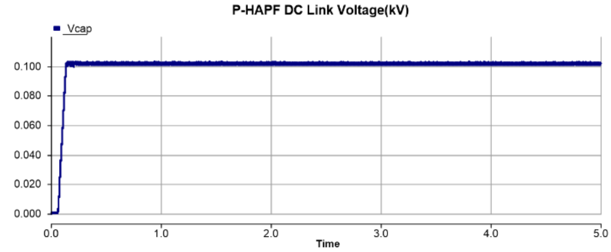


Figure 10. DC-Link voltage of P-HAPF - (Loads: R_{load1}, L_{load1}, R_{load2}, L_{load2})

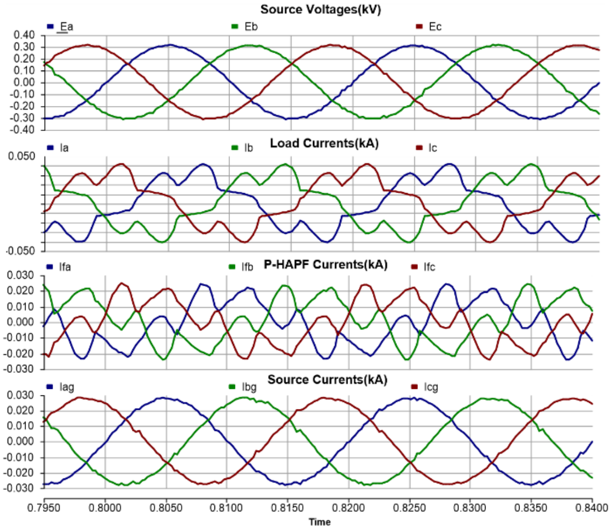


Figure 11. Supply voltages, load currents, P-HAPF currents, supply currents (P-HAPF operates, Loads: R_{load1}, L_{load1}, R_{load3}, L_{load3})

Furthermore, the reactive power compensation ability is added to active part of P-HAPF with this proposed controller. The passive part reactive power compensation ability is nearly 8 kVar. The loads reactive power is nearly 10 kVar. When the P-HAPF operates, the active part compensates 2 kVar reactive power. Thus, the reactive power couldn't see the source part of the system. The source active and reactive power, load active and reactive power, P-HAPF active and reactive power waveforms are represented as Figure 12. The dc link voltage value is selected 150 V. The dc link waveform is shown in Figure 13.

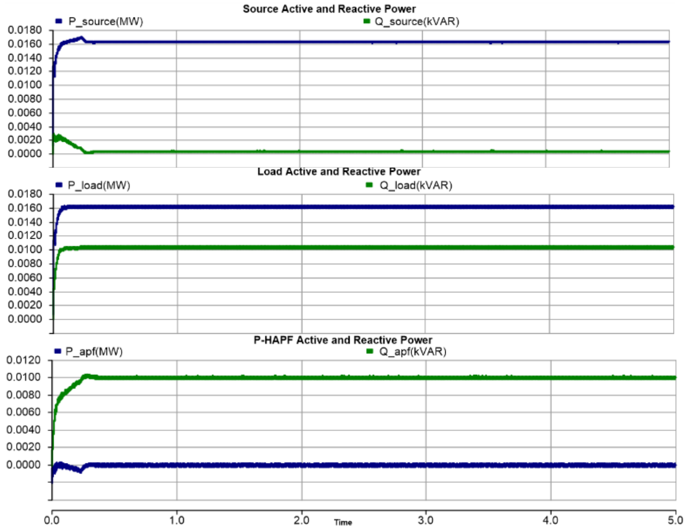


Figure 12. Source active and reactive power, load active and reactive power, P-HAPF active and reactive power (Loads: R_{load1}, L_{load1}, R_{load3}, L_{load3})

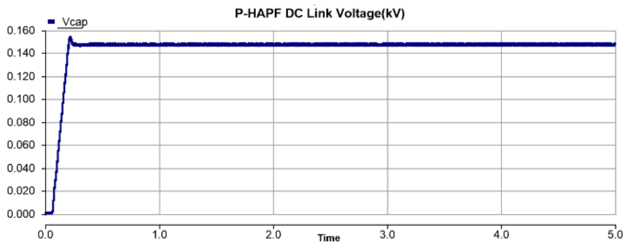


Figure 13. DC-Link voltage of P-HAPF (Loads: R_{load1}, L_{load1}, R_{load3}, L_{load3})

V. CONCLUSIONS

This paper represents a control algorithm applied to parallel hybrid active power filter to compensate harmonics and reactive power by statically. The results shows the effectiveness of the proposed control algorithm. With this control method, P-HAPF compensates reactive power with APF part not passive filter part.

When the linear load is increased, APF DC link voltage is also increased. So by tuning K_c values, the reactive power compensation capability is increased. The validity of the proposed algorithm and the whole behavior of the parallel P-HAPF is demonstrated through PSCAD simulation program.

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BIOGRAPHIES

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