

# Assessment of Different Compensation Strategies in Hybrid Active Power Filters

Rashed Bahrekazemi

Electrical Engineering Department  
Iran University of Science & Technology (IUST)  
Tehran, Iran  
[rbahrkazemi@ee.iust.ac.ir](mailto:rbahrkazemi@ee.iust.ac.ir)

Alireza Jalilian

Electrical Engineering Department  
Iran University of Science & Technology (IUST)  
Tehran, Iran  
[jalilian@iust.ac.ir](mailto:jalilian@iust.ac.ir)

**Abstract**— In this paper harmonic distortion in power distribution system is considered. Performance of three different compensation strategies (*pq*, *dq* and *dq-pq*) in hybrid active power filter are evaluated in this paper. To simulate the system, four different scenarios for power system mains voltage are considered: ideal, unbalanced, distorted and distorted-unbalanced mains voltage. Simulation results are compared in order to assess the performance of each method. It is demonstrated that in ideal mains voltage condition all the three methods have good performance. However, for a distorted voltage source two methods, *dq* and *dq-pq*, have a satisfactory performance, and when the mains voltage is distorted-unbalanced only *dq-pq* method shows an acceptable compensation performance.

**Keywords**— hybrid active power filter (HAPF), *pq* method, *dq* method, *dq-pq* method, Non-ideal mains voltage.

## I. INTRODUCTION

Widespread increased use of power electronics in industrial, commercial and domestic applications has caused a considerable amount of harmonic current injected to the power system. The problems associated with these distorted currents have made harmonics compensation a priority task. There are several ways to achieve the target of nonlinear currents compensation such as Passive Filters (PF), Active Power Filters (APF), hybrid filters and so on [1]. PF and APF have some advantage and drawback, but hybrid active power filters contain their advantages but not their drawbacks.

There are different models of hybrid filters [2]. The most common of them is formed by connecting APF and PF is shown in Fig. 1. APF generally consists of two distinct main blocks: the active filter controller and the Current-Controlled Voltage-Source Inverter (CCVSI) [3]. APF continuously sensing the load current  $i_L$  with control algorithm, and calculating the instantaneous values of the compensating current reference  $i_c^*$  for the VSI.

The passive filter consists of simple LC filters per phase tuned near the lowest harmonics ( $5^{\text{th}}$  or  $7^{\text{th}}$  or...). It has some main functions: reactive compensation, absorption of harmonic currents produced by the load [4].

Comparison of different APF strategies have been discussed in [1], [5]-[9]. This paper first presents

configuration of HAPF. Then a review of three control strategies including *pq* method [10], *dq* method [4], and *dq-pq* method [3] for extraction of the reference currents for a shunt active power filter connected to a three-phase three-wire source that supplies a nonlinear load. Final section present simulation results that are conducted in MATLAB/Simulink environment and under various non-ideal mains test scenarios. Then a comparison of the methods is made for various conditions.

## II. DIFFERENT CONTROL METHODS' FORMULATION

### A. Instantaneous Reactive Power Theory (*pq* Method)

This method is also known as *pq* method. Most APFs have been designed on the basis of instantaneous reactive power theory or *pq* method to calculate the desired compensation current. This theory was first proposed by Akagi and co-workers in 1984 [10]. A block diagram of the *pq* method is shown in Fig. 2.

In instantaneous power theory, the instantaneous three-phase currents and voltages are easily converted into the  $0\alpha\beta$  orthogonal coordinates that are calculated as [10]:

$$\begin{bmatrix} V_o \\ V_\alpha \\ V_\beta \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} 1/\sqrt{2} & 1/\sqrt{2} & 1/\sqrt{2} \\ 1 & -1/2 & -1/2 \\ 0 & \sqrt{3}/2 & -\sqrt{3}/2 \end{bmatrix} \begin{bmatrix} V_a \\ V_b \\ V_c \end{bmatrix} \quad (1)$$

$$\begin{bmatrix} I_o \\ I_\alpha \\ I_\beta \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} 1/\sqrt{2} & 1 & 0 \\ 1/\sqrt{2} & -1/2 & \sqrt{3}/2 \\ 1/\sqrt{2} & -1/2 & -\sqrt{3}/2 \end{bmatrix} \begin{bmatrix} I_{LPPa} \\ I_{LPPb} \\ I_{LPPc} \end{bmatrix} \quad (2)$$

One advantage of applying the  $0\alpha\beta$  transformation is to separate zero-sequence components from *abc*-phase components. So, no zero-sequence current exists in a three-phase, three-wire system.

So, instantaneous real and imaginary powers are calculated as following equations:

$$\begin{bmatrix} p \\ q \end{bmatrix} = \begin{bmatrix} V_\alpha & V_\beta \\ -V_\beta & V_\alpha \end{bmatrix} \begin{bmatrix} I_\alpha \\ I_\beta \end{bmatrix} \quad (3)$$

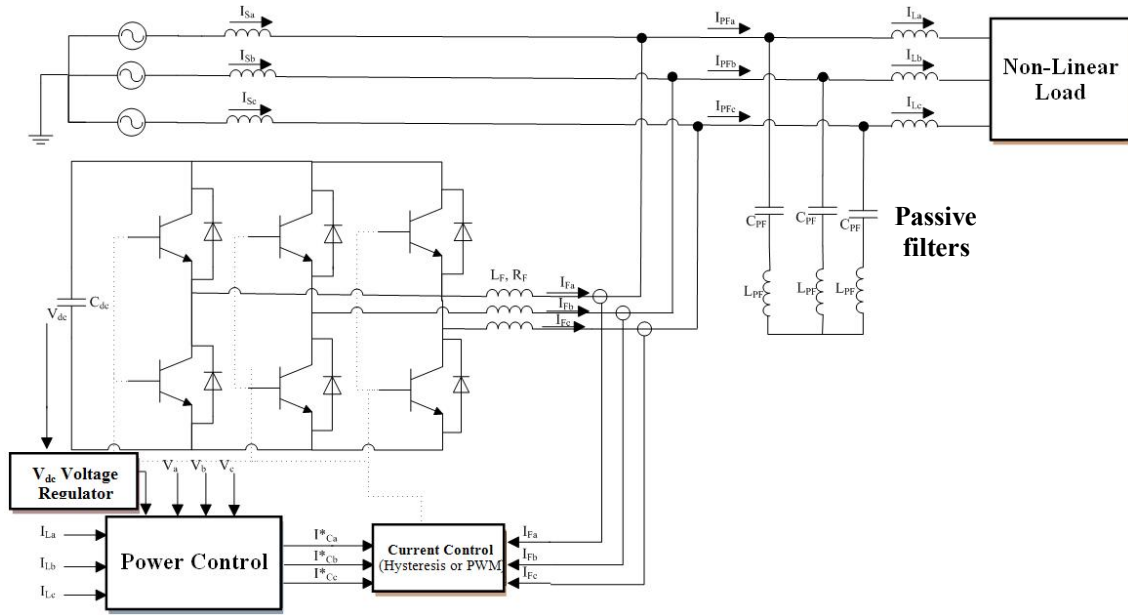


Figure 1. Configuration of Hybrid Active Power Filter

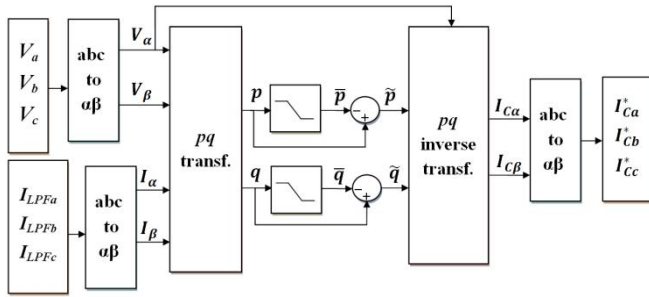


Figure 2. Block diagram of pq method

In (3),  $V_\alpha I_\alpha$  and  $V_\beta I_\beta$  are instantaneous real ( $p$ ) and imaginary ( $q$ ) powers [4].

The instantaneous active and reactive power includes AC and DC values and can be expressed as follows:

$$\begin{aligned} p &= \bar{p} + \tilde{p} \\ q &= \bar{q} + \tilde{q} \end{aligned} \quad (4)$$

$\bar{p}$ , the mean value of the instantaneous real power.  $\tilde{p}$ , alternated value of the instantaneous real power.  $\tilde{q}$ , instantaneous imaginary power, corresponds to the power that is exchanged between the phases of the load.  $\bar{q}$ , the mean value of the instantaneous imaginary power that is equal to the conventional reactive power.

DC values of the  $p$  and  $q$  ( $\bar{p}$ ,  $\bar{q}$ ) are created from positive-sequence component of the load current. AC values of the  $p$  and  $q$  ( $\tilde{p}$ ,  $\tilde{q}$ ) are produced from harmonic and unbalance components of the load current [8].

In order to compensate harmonics and reactive power the instantaneous real power is filtered and instantaneous compensating currents ( $I_{Ca}$  and  $I_{Cb}$ ) on  $\alpha$  and  $\beta$  coordinates are calculated by using  $\tilde{p}$  and  $q$  as given below:

$$\begin{bmatrix} I_{Ca} \\ I_{Cb} \end{bmatrix} = \frac{1}{v_\alpha^2 + v_\beta^2} \begin{bmatrix} V_\alpha & V_\beta \\ V_\beta & -V_\alpha \end{bmatrix} \begin{bmatrix} \tilde{p} \\ q \end{bmatrix} \quad (5)$$

In order to obtain the reference compensation currents in the  $abc$  coordinates the inverse of the transformation is applied [6]:

$$\begin{bmatrix} I_{Ca}^* \\ I_{Cb}^* \\ I_{Cc}^* \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} 1 & 0 \\ -\frac{1}{2} & \frac{\sqrt{3}}{2} \\ -\frac{1}{2} & -\frac{\sqrt{3}}{2} \end{bmatrix} \begin{bmatrix} I_{Ca} \\ I_{Cb} \end{bmatrix} \quad (6)$$

### B. Synchronous Fundamental dq Frame

This method is also known as  $dq$  method and Synchronous Reference Frame (SRF) [8]. A block diagram of the  $dq$  method is shown in Fig. 3.

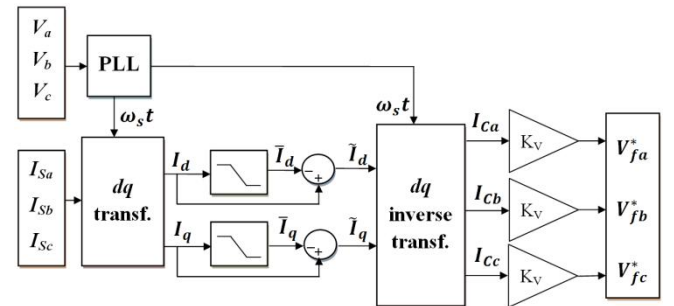


Figure 3. Block diagram of dq method

First, the three-phase supply currents ( $I_{Sa}$ ,  $I_{Sb}$ ,  $I_{Sc}$ ) are transformed into the instantaneous active ( $I_d$ ) and reactive ( $I_q$ ) components using a rotating frame synchronous with the positive sequence of the system voltage [4]:

$$\begin{bmatrix} I_d \\ I_q \\ I_0 \end{bmatrix} = \frac{2}{3} \begin{bmatrix} \sin(\omega_s t) & \sin(\omega_s t - \frac{2\pi}{3}) & \sin(\omega_s t + \frac{2\pi}{3}) \\ \cos(\omega_s t) & \cos(\omega_s t - \frac{2\pi}{3}) & \cos(\omega_s t + \frac{2\pi}{3}) \\ \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} \end{bmatrix} \begin{bmatrix} I_{sa} \\ I_{sb} \\ I_{sc} \end{bmatrix} \quad (7)$$

where  $\omega_s t$  is the phase of the positive sequence of the system voltage and it is provided by a phase-locked loop. The system under study is a three-wire system where the zero sequence is neglected. So, only  $I_d$  and  $I_q$  are considered. The active and reactive currents can also be decomposed in their DC and AC values:

$$\begin{bmatrix} I_d \\ I_q \end{bmatrix} = \begin{bmatrix} \bar{I}_d \\ \bar{I}_q \end{bmatrix} + \begin{bmatrix} \tilde{I}_d \\ \tilde{I}_q \end{bmatrix} \quad (8)$$

The mean values of the instantaneous active and reactive currents ( $\bar{I}_d, \bar{I}_q$ ) are the fundamental active and reactive current components. The ac components of both currents ( $\tilde{I}_d, \tilde{I}_q$ ) correspond to the contribution of active and reactive harmonic components.

It is desired that the network supplies the DC value of the active current, while its AC component, as well as the reactive current, is supplied by the SHAPF. The instantaneous active and reactive currents are filtered in order to separate both components and generate the correct references to the PWM modulator:

$$\begin{bmatrix} \tilde{I}_d \\ \tilde{I}_q \end{bmatrix} = \begin{bmatrix} I_d \\ I_q \end{bmatrix} - \begin{bmatrix} \bar{I}_d \\ \bar{I}_q \end{bmatrix} \quad (9)$$

These current components are amplified by a gain  $K_i$ . Then, the reference currents in the  $abc$  frame are:

$$\begin{bmatrix} I_{ca}^* \\ I_{cb}^* \\ I_{cc}^* \end{bmatrix} = \begin{bmatrix} \sin(\omega_s t) & \cos(\omega_s t) \\ \sin(\omega_s t - \frac{2\pi}{3}) & \cos(\omega_s t - \frac{2\pi}{3}) \\ \sin(\omega_s t + \frac{2\pi}{3}) & \cos(\omega_s t + \frac{2\pi}{3}) \end{bmatrix} \begin{bmatrix} \bar{I}_d^* \\ \bar{I}_q^* \end{bmatrix} \quad (10)$$

Each current component is amplified by a gain  $K_V$  which corresponds to the voltage gain of the PWM inverter. The resultant signal  $v_{af}^*$  is the voltage reference produced by the control which should be synthesized by the power inverter.

### C. dq-pq Method

The conventional pq theory is ineffective under non-ideal mains voltages scenarios. In order to improve the compensating performance, a supplementary algorithm is expressed in this paper.

If the mains voltages are distorted and/or unbalanced, AC values of the instantaneous real and imaginary power have current harmonics and voltage harmonics. The shunt APF does not generate compensation current equal to current harmonics, since the APF compensating currents include source and load harmonics. Consequently, APF injects more current harmonics than required. In order to overcome this problem and to decrease Total Harmonic Distortion (THD)

to desired level, the instantaneous reactive and active powers have to calculate after filtering of mains voltages.

In order to increase the performance of the theory in the distorted and unbalanced system, the measured mains voltages are passed from a low-pass filter in a synchronous reference  $dq$  frame. Hence, the non-ideal mains voltages are converted to ideal sinusoidal shape by using the fifth-order 50 Hz cutoff frequency low pass filters in  $dq$  coordinates [9]. The block diagram of  $dq$  section is shown in Fig. 4.

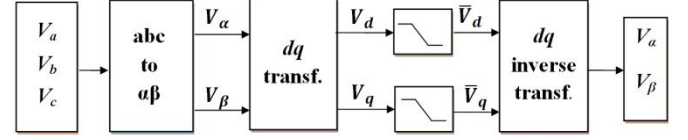


Figure 4. Block diagram of  $dq$  section in  $dq$ - $pq$  method

In this method, instantaneous voltages are first converted to  $\alpha\beta$  coordinates and then to stationary  $dq$  coordinates. The produced  $dq$  components of voltages are filtered and reverse converted  $\alpha\beta$  coordinates (similar to (12)). The filtered  $dq$  components of the voltages ( $V_d$  and  $V_q$ ) are converted to voltages in  $\alpha\beta$  coordinates as given in Fig. 4.

Hence, the non-ideal mains voltages are converted to ideal sinusoidal shape by using low pass filter in  $dq$  coordinates. The time constant of the low pass filter is  $12e^{-3}$ . So, the mains voltages assumed to be an ideal source in the calculation process. Then, similar to  $pq$  method the three-phase reference currents, which the active power filter configuration should supply to the three-phase actual power system, should be obtained.

## III. SIMULATION RESULTS

The presented simulation results are obtained by using MATLAB/Simulink Power System Toolbox software, for a three-phase power system with a shunt hybrid active power filter and a three-phase nonlinear that is shown in Fig. 1. The design specifications and the essential parameters of the system used in the simulation are indicated in Table I.

TABLE I. HAPF AND SYSTEM DESIGN PARAMETERS

Section	Parameter	Value
Main System	$V_s(\text{rms})$ (V)	220
	$f$ (Hz)	50
	$L$ (mH)	1
APF	$V_{dc}$ (V)	700
	$C_{dc}$ ( $\mu\text{F}$ )	1500
	$L_c$ (mH)	1
PF	$Q_{PF}$ (MVar)	4.8
	$f_i$ (Hz)	250
	$C_{PF}$ ( $\mu\text{F}$ )	80.2
	$L_{PF}$ (mH)	5.05
Non-Linear Load	$R_L$ (ohm)	10
	$L_L$ (mH)	10

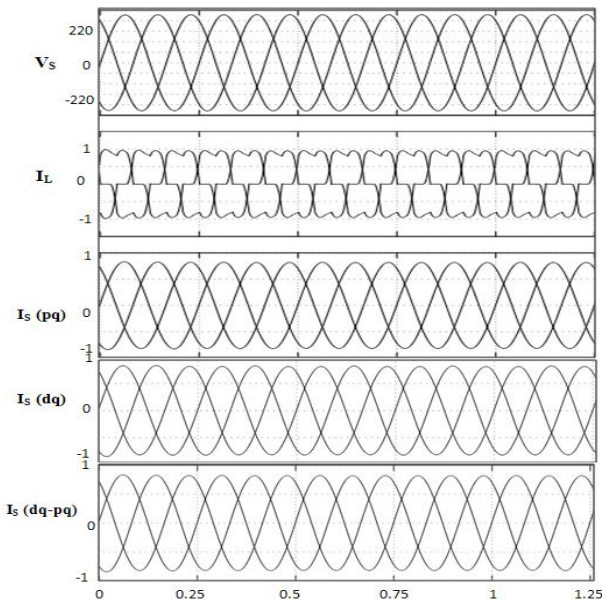


Figure 5. Simulation result for ideal mains voltages with three methods

Non-linear load is including diode rectifier with ohmic-inductive load. Three methods have been simulated under four scenarios, including ideal mains voltages, unbalanced three-phase mains voltages, distorted mains voltages and distorted-unbalanced mains voltages conditions, in each scenario, three method  $pq$ ,  $dq$  and  $dq-pq$  is explained. Voltage values in four operating conditions indicated in Table II. These algorithms performances under such dynamic conditions are investigated by detailed simulation study. The simulation results are discussed below:

#### A. Ideal Mains Voltage

Fig. 5 shows simulation results for ideal mains voltages with three methods. After compensation, three-phase source currents are balanced and sinusoidal and in phase with the three-phase voltages. Hence, with ideal mains voltages, the behavior of APF with all the strategies is equivalent.

#### B. Distorted Mains voltage

If the three-phase mains voltages are distorted, the mains voltages have harmonic components. For this case, the distorted three-phase mains voltages are expressed in Table II.

Fig. 6 shows simulation results of distorted mains voltages scenario with  $pq$ ,  $dq$  and  $dq-pq$  methods, respectively. As said in subsection C of section III and see in results,  $pq$  method is not qualified for distorted mains voltages. In this method, three-phase source current has 14.09% THD level in phase “a”. But for  $dq$  method and  $dq-pq$  method, three-phase source currents have sinusoidal waveform and 1.9 and 1.87% THD level in phase “a”. Therefore, the performance of  $dq$  and  $dq-pq$  methods is better than that of the  $pq$  method.

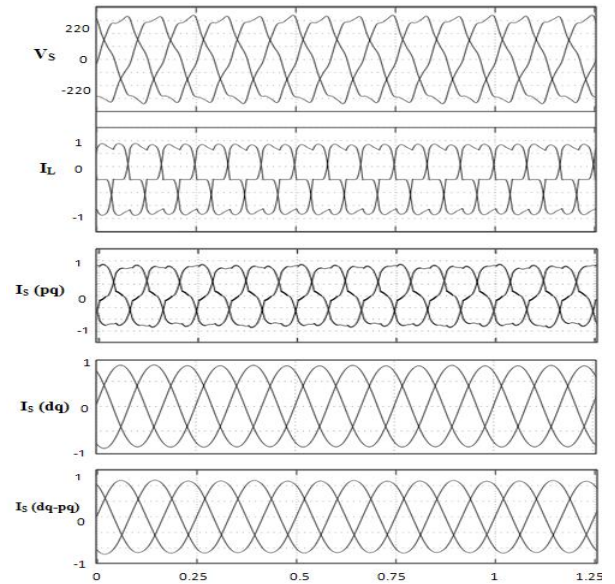


Figure 6. Simulation result for distorted mains voltages with three methods

#### C. Unbalanced Mains Voltage

When the three-phase mains voltages are unbalanced, the mains voltages can be expressed as positive and negative sequence components. For this case, the unbalanced three-phase mains voltages are expressed in Table II.

Fig. 7 shows simulation results of 10% unbalanced mains voltages scenario with  $pq$ ,  $dq$  and  $dq-pq$  methods, respectively. The three-phase compensated mains currents are not balance in  $pq$  and  $dq$  methods, and are sinusoidal and balance in  $dq-pq$  method in unbalanced mains voltages case. THD levels of source current after compensation is 1.54% in phase “a” with  $dq-pq$  method. The  $dq-pq$  method has very good harmonic limit imposed by the IEEE-519 standard [11].

#### D. Distorted-Unbalanced Mains Voltage

If the three-phase mains voltages are distorted and unbalanced, the mains voltages have harmonic components and unbalanced. For this case, the distorted and unbalanced three-phase mains voltages are expressed in Table II.

Fig. 8 shows simulation results of distorted-unbalanced mains voltages scenario with  $pq$  theory,  $dq$  and  $dq-pq$  algorithm, respectively. The performance of  $pq$  and  $dq$  algorithms for this case are shown not qualified. The three-phase compensated mains currents have high THD level in  $pq$  and  $dq$  method. But for  $dq-pq$  method, these currents have sinusoidal waveform and have 1.68% THD level in distorted-unbalanced mains voltages scenario.

THD levels of a, b and c phase currents in load and different operating conditions by using different approach are shown in Table III. The harmonic magnitudes of phase currents in load and different operating conditions are shown in Tables IV and V. The results from above comparisons are summarized in Tables III–V.

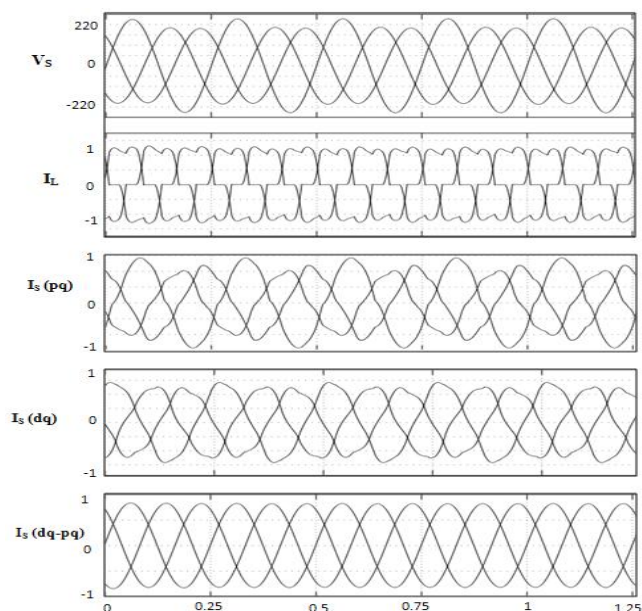


Figure 7. Simulation result for unbalanced mains voltages with three methods

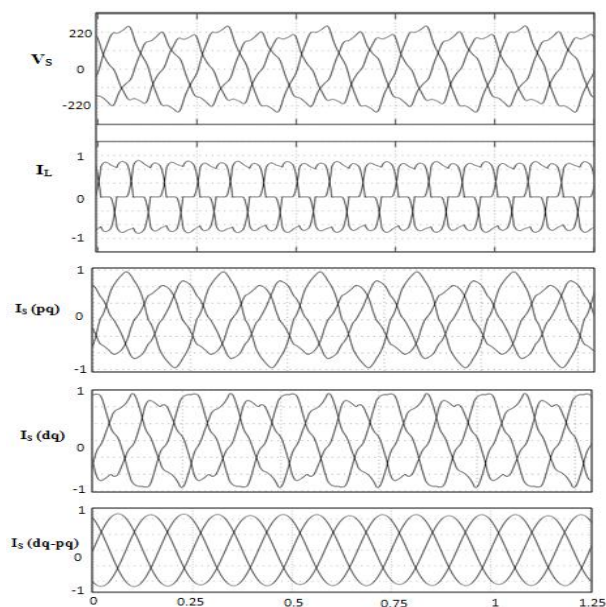


Figure 8. Simulation result for distorted-unbalanced mains voltages with three methods

TABLE II. VOLTAGES VALUES IN DIFFERENT OPERATING CONDITIONS

Operating condition	3-Phase Voltages Values (rms)					
	Fundamental positive sequence	Fundamental negative sequence	3 Harmonic	5 Harmonic	7 Harmonic	11 Harmonic
Ideal mains voltage	220	0	0	0	0	0
Distorted mains voltage	220	0	2.83	12.73	3.25	2.19
Unbalanced mains voltage	220	22	0	0	0	0
Distorted-Unbalanced mains voltage	220	22	2.83	12.73	3.25	2.19

TABLE III. THD LEVEL OF THREE-PHASE CURRENTS IN DIFFERENT OPERATING CONDITIONS

Operating condition	Load THD Level (%)			The pq method THD Level (%)			The dq method THD Level (%)			The dq-pq method THD Level (%)		
	Phase "a"	Phase "b"	Phase "c"	Phase "a"	Phase "b"	Phase "c"	Phase "a"	Phase "b"	Phase "c"	Phase "a"	Phase "b"	Phase "c"
Ideal mains voltage	24.55	28.01	27.96	1.65	1.5	1.45	1.13	1.45	1.72	1.65	1.5	1.45
Distorted mains voltage	23.01	22.82	23.19	14.09	13.83	15.56	1.90	1.57	1.30	1.87	1.52	1.65
Unbalanced mains voltage	22.79	29.25	31.56	8.14	9.79	10.59	5.95	8.42	6.85	1.54	1.05	1.64
Distorted-Unbalanced mains voltage	22.61	27.04	29.97	12.76	13.82	15.70	6.25	7.05	7.28	1.68	1.87	2.16

TABLE IV. 1, 3 AND 5 HARMONIC MAGNITUDES OF CURRENTS IN LOAD AND THREE METHODS

Operating condition	1 Fundamental current magnitude (A)				3 Harmonic current magnitude (A)				5 Harmonic current magnitude (A)			
	Load	pq method	dq method	dq-pq method	Load	pq method	dq method	dq-pq method	Load	pq method	dq method	dq-pq method
Ideal mains voltage	94.00	76.22	95.25	83.48	0.2	≈ 0	0.19	≈ 0	15.52	0.68	0.91	1.35
Distorted mains voltage	91.12	76.67	85.61	78.88	1.88	0.27	0.22	0.60	18.43	7.25	1.07	1.26
Unbalanced mains voltage	105.13	74.20	83.40	80.25	5.98	2.60	3.29	0.31	16.74	6.86	4.52	0.1
Distorted-Unbalanced mains voltage	98.96	75.87	74.80	83.48	7.25	3.07	1.07	0.52	16.20	7.64	5.09	1.35

TABLE V. 7, 9 AND 11 HARMONIC MAGNITUDES OF CURRENTS IN LOAD AND THREE METHODS

Operating condition	7 Harmonic current magnitude (A)				9 Harmonic current magnitude (A)				11 Harmonic current magnitude (A)			
	Load	pq method	dq method	dq-pq method	Load	pq method	dq method	dq-pq method	Load	pq method	dq method	dq-pq method
Ideal mains voltage	7.99	0.91	0.24	≈ 0	0.46	≈ 0	≈ 0	≈ 0	1.8	0.14	≈ 0	≈ 0
Distorted mains voltage	8.62	2.30	0.15	0.22	0.84	0.38	≈ 0	≈ 0	4.20	0.18	0.11	0.12
Unbalanced mains voltage	11.74	1.48	0.38	0.11	6.80	1.49	0.11	≈ 0	2.42	1.16	0.65	≈ 0
Distorted-Unbalanced mains voltage	10.82	1.73	1.29	0.23	6.10	2.21	≈ 0	≈ 0	2.01	2.07	0.87	0.14

#### IV. CONCLUSION

In this paper, three different control method schemes have been simulated in order to survey the performance of HAPF under non-ideal mains voltages conditions. Based on simulation results performed in MATLAB/Simulink environment, the following conclusions are drawn:

- Although all the three methods are proper for ideal mains voltages, *pq* method is simpler than other two methods.
- *dq* method is proper for ideal and distorted mains voltages but is not appropriate for unbalanced mains voltages.
- The third method, *dq-pq*, shows an acceptable performance to compensate nonlinear loads, even when the power system voltage are unsymmetrical and distorted. Furthermore, the control circuit needed to implement the *dq-pq* method is simpler than other non-ideal mains voltages compensation strategy algorithms.

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