

# Comparison of Shunt Active Power Filter Control Strategies for Harmonic Compensation in a Paper Industrial Factory

Mohamed Aboelkasem Mohamd Abdelaal<sup>1,\*</sup>, Mahmoud Abdelnaby Sayed<sup>1</sup>,  
Essam E. M. Mohamed<sup>1</sup>, Mohamed Mahmoud Hamada<sup>2</sup>

<sup>1</sup>Department of Electrical Engineering, South Valley University, Qena, Egypt

<sup>2</sup>Department of Electrical Engineering, Minia University, Minia, Egypt

## Email address:

Mak200500@yahoo.com (M. A. M. Abdelaal), Mahmoud\_sayed@ieee.com (M. A. Sayed),

esam.mohamed@eng.svu.edu.eg (E. E. M. Mohamed)

\*Corresponding author

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**Abstract:** This paper presents the analysis and evaluates different control strategies of shunt active power filters which are used to reduce harmonic distortion created by an industrial paper factory. The model of the whole system has been carried out by Matlab/Simulink. In order to investigate the accuracy of the simulated model, harmonic analysis of simulation results has been compared with measurements from the electrical networks of a Paper Industrial Factory using harmonic analyzer. The consistency of simulation and measured results proves the accuracy of the system modeling. It also proves the validity of using Shunt Active Power Filters to reduce the harmonic distortion in the factory network. Four different control techniques, namely Unit Vector Template Generation, Instantaneous Active and Reactive theory, Synchronous Reference Frame theory and a proposed control strategy that combines the Synchronous Reference Frame and the Unit Vector Template Generation theories, have been studied. Results of each technique were satisfactory and meet the IEEE-519 Standard, However, when the source voltage is distorted the compensation capability for some control strategies is not equal.

**Keywords:** Harmonics, Power Quality, Total Harmonic Distortion, Variable Frequency Drive, Shunt Active Power Filter

## 1. Introduction

The increase of nonlinear loads such as rectifiers, controlled solid-state devices and variable frequency drives causes an increase of harmonic distortion in industrial and power distribution systems. Harmonics are the sinusoidal voltage and currents at frequencies that are integer multiples of fundamental frequency. They have harmful effects on power distribution systems. Therefore, Shunt Active Power Filters (SAPF) is used to eliminate the current harmonics. Current and voltage harmonics are still present in distribution power systems in spite of all efforts made by the electrical equipment manufactures.

Passive filters as one of the harmonic solution have many problems such as resonance, large size and limitation to few harmonic components. On the other hand, shunt active power filters has a better performance than passive filters.

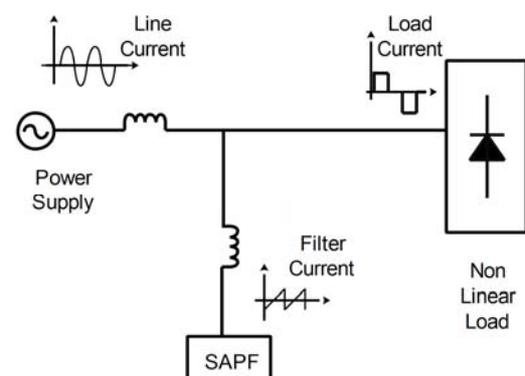


Figure 1. Shunt active filter.

Figure 1 shows operation principle of shunt active filter and how can it compensates the input current by monitoring the distortion of the input current and injects the same distortion

quantities at the input side with 180 degree phase shift. Hence harmonic contained in the load current are cancelled at the source side. Therefore, the load current still has the necessary harmonic contents, whereas the source current remains sinusoidal.

The control scheme of a shunt active power filter usually includes calculation of the reference current required to compensate the input current, maintain constant voltage across the DC (Direct Current) link capacitor, and generate the inverter PWM (Pulse Width Modulation) gate signals.

This paper presents the implementation of shunt active power filters to reduce the harmonic distortion created by a paper industrial factory. The factory model and the shunt active filter have been carried out using Matlab/Simulink. The reference current of the shunt active filter has been calculated using four different control strategies, namely;

- a) Unit Vector Template Generation (UVTG)

- b) Instantaneous Active and Reactive (P-Q) theory
- c) Synchronous Reference Frame (SRF)
- d) proposed control strategy that is combined between P-Q and UVTG theory

Simulation results of the paper industrial factory model have been compared with the actual results to show the accuracy of the simulation model.

## 2. Harmonic Limits

The acceptable levels of harmonics are determined using international standards such as the IEEE 519-2014, which has the permissible voltage and current harmonics in industrial systems applications. The current harmonic limits depend on the ratio of short circuit current ( $I_{sc}$ ) to maximum load current ( $I_{load}$ ) at common coupling point as given in Table 1 [1]:

**Table 1.** Current Harmonic Limits as per IEEE 519-2014 [1].

Individual harmonic order (Odd harmonics)						
$I_{sc} / I_{load}$	$< 11$	$11 \leq h < 17$	$17 \leq h < 23$	$23 \leq h < 35$	$35 \leq h$	TDD
$< 20$	4.0	2.0	1.5	0.6	0.3	5.0
$20 < 50$	7.0	3.5	2.5	1.0	0.5	8.0
$50 < 100$	10.0	4.5	4.0	1.5	0.7	12.0
$100 < 1000$	12.0	5.5	5.0	2.0	1.0	15.0
$> 1000$	15.0	7.0	6.0	2.5	1.4	20.0

Where, h is individual harmonic order and TDD is total demand distortion.

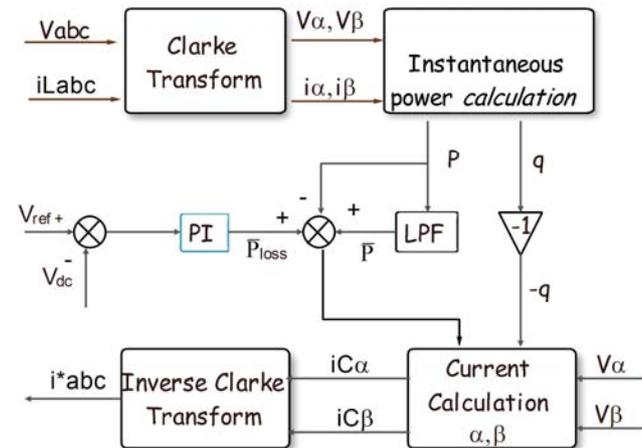
The limitation of even harmonics is 25% of odd harmonic limits in Table 1.

## 3. Control Algorithms

### 3.1. Instantaneous P-Q Theory Control

Figure 2 shows the block diagram of the shunt active filter based on the P-Q theory introduced by Akagi in 1983 [2], [3], [4], [5], [6].

The three phase voltages ( $V_{abc}$ ) and currents ( $i_{Labc}$ ) are transformed from the a-b-c coordinates to  $\alpha$ - $\beta$ -0 coordinates using Clarke transformation as in (1) and (2).



**Figure 2.** Block diagram of the shunt active filter based on the P-Q theory.

$$\begin{bmatrix} v_\alpha \\ v_\beta \end{bmatrix} = [T] \begin{bmatrix} V_a \\ V_b \\ V_c \end{bmatrix} \quad (1)$$

$$\begin{bmatrix} i_\alpha \\ i_\beta \end{bmatrix} = [T] \begin{bmatrix} i_{La} \\ i_{Lb} \\ i_{Lc} \end{bmatrix} \quad (2)$$

Where T is expressed as follows:

$$T = \sqrt{\frac{2}{3}} \begin{bmatrix} 1 & -\frac{1}{2} & -\frac{1}{2} \\ 0 & \frac{\sqrt{3}}{2} & -\frac{\sqrt{3}}{2} \end{bmatrix} \quad (3)$$

The instantaneous active and reactive power can be formulated as (4).

$$\begin{bmatrix} p \\ q \end{bmatrix} = A \times \begin{bmatrix} i_\alpha \\ i_\beta \end{bmatrix} \quad (4)$$

Where,

$$A = \begin{bmatrix} v_\alpha & v_\beta \\ v_\beta & -v_\alpha \end{bmatrix} \quad (5)$$

$$p = \bar{p} + \tilde{p} \quad (6)$$

$$q = \bar{q} + \tilde{q} \quad (7)$$

Where  $\tilde{p}$  and  $\tilde{q}$  represent the oscillating powers and  $\bar{p}$  and  $\bar{q}$  represent the average powers. A low pass filter is used to separate between  $\bar{p}$  and  $\tilde{q}$ .

Compensation current references in the  $(\alpha-\beta)$  reference frame can be expressed as:

$$\begin{bmatrix} ic\alpha \\ ic\beta \end{bmatrix} = \frac{1}{v\alpha_2 + v\beta_2} \times A \times B \quad (8)$$

Where,

$$B = \begin{bmatrix} -\tilde{p} + \bar{p}_{loss} \\ -q \end{bmatrix} \quad (9)$$

$\bar{P}_{loss}$  is the PI (Proportional Integral) controller output of the dc-link capacitor voltage error. It represents the small real power taken continuously from the power supply to maintain the dc capacitor voltage constant. The compensation current references in the three-phase frame can be obtained as follows:

$$\begin{bmatrix} I_a^* \\ I_b^* \\ I_c^* \end{bmatrix} = \sqrt{\frac{2}{3}} \times T_{inv} \times \begin{bmatrix} ic\alpha \\ ic\beta \end{bmatrix} \quad (10)$$

Where,

$$T_{inv} = \begin{bmatrix} 1 & 0 \\ -\frac{1}{2} & \frac{\sqrt{3}}{2} \\ -\frac{1}{2} & -\frac{\sqrt{3}}{2} \end{bmatrix} \quad (11)$$

### 3.2. Unit Vector Template Generation Technique

Figure 3 shows the block diagram of the shunt active filter based on the UVTG theory [7], [8], [9], [10]. In this strategy the supply voltage is sensed and given to the Phase Locked Loop (PLL) and with a proper phase delay the outputs of the Unit Vector Templates ( $X_a$ ,  $X_b$  and  $X_c$ ) can be expressed as (12).

$$\begin{aligned} X_a &= \sin(\omega t) \\ X_b &= \sin(\omega t - 120) \\ X_c &= \sin(\omega t + 120) \end{aligned} \quad (12)$$

The PI control is used to maintain the dc-link voltage constant by comparing the DC voltage reference and the actual dc-link voltage. The output error is multiplied by the output of Unit Vector Templates, which gives the reference source current signals as (13).

$$\begin{bmatrix} I_a^* \\ I_b^* \\ I_c^* \end{bmatrix} = \text{Im} \begin{bmatrix} X_a \\ X_b \\ X_c \end{bmatrix} \quad (13)$$

The actual source current is compared with the reference current signal and the output is applied to a hysteresis current controller that generates the switching signals of the shunt active filter inverter.

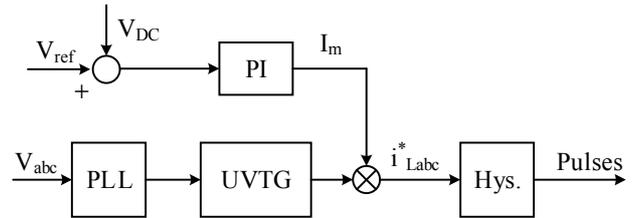


Figure 3. Control block of the shunt active filter based on UVTG theory.

### 3.3. Synchronous Reference Frame Technique

Figure 4 shows the block diagram of the shunt active filter based on synchronous reference frame theory or d-q theory [11], [12], and [13]. In this technique, the load current is transformed to the d-q synchronous reference coordinate using Park Transform as per the following equation:

$$\begin{bmatrix} id \\ iq \\ i0 \end{bmatrix} = \frac{2}{3} \times K \times \begin{bmatrix} iLa \\ iLb \\ iLc \end{bmatrix} \quad (14)$$

Where,

$$K = \begin{bmatrix} \cos(\omega t) & \cos(\omega t - \frac{2\Pi}{3}) & \cos(\omega t + \frac{2\Pi}{3}) \\ -\sin(\omega t) & -\sin(\omega t - \frac{2\Pi}{3}) & -\sin(\omega t + \frac{2\Pi}{3}) \\ \frac{1}{2} & \frac{1}{2} & \frac{1}{2} \end{bmatrix} \quad (15)$$

Low Pass Filter (LPF) is used to separate the harmonic reference current from the load current. The PI controller is used to maintain the dc-link voltage constant.

PLL is applied to develop the electrical position ( $\theta$ ) which helps to maintain synchronism of the supply voltage and current.

The current source reference can be obtained in three-phase system using inverse Park Transform as per the following equation:

$$\begin{bmatrix} I_a^* \\ I_b^* \\ I_c^* \end{bmatrix} = K_{inv} \times \begin{bmatrix} id \\ iq \\ i0 \end{bmatrix} \quad (16)$$

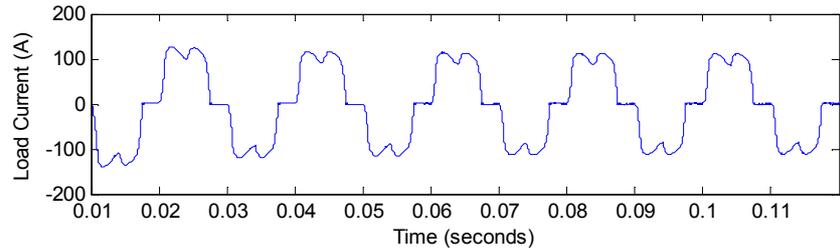
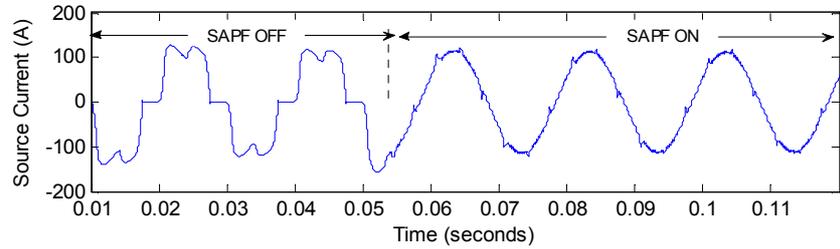
Where,



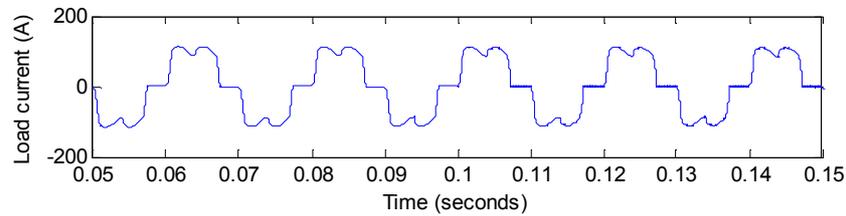
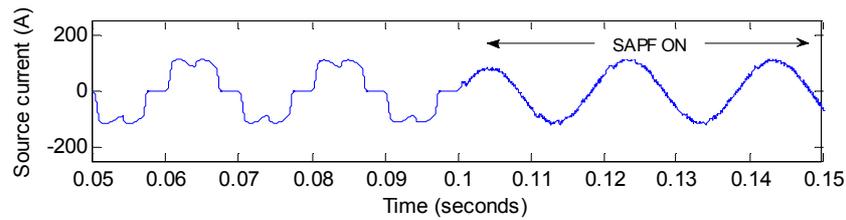
## 5. Simulation Results

Table 3. THD of Case (A).

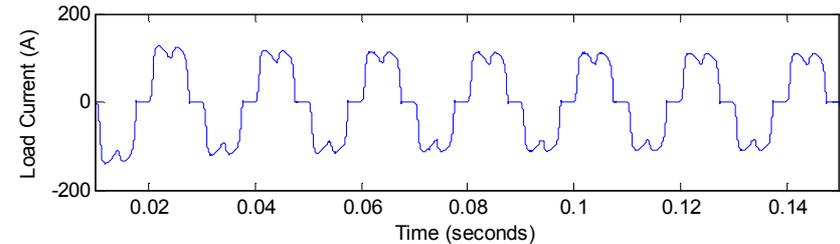
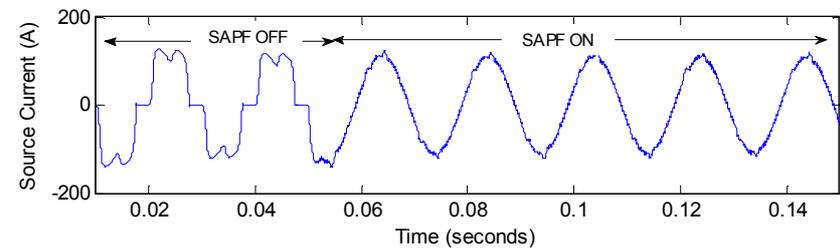
Control strategy	P-Q	UVTG	SRF	Combined P-Q and UVTG Theory
THD%	3.32	4.31	4.05	1.24



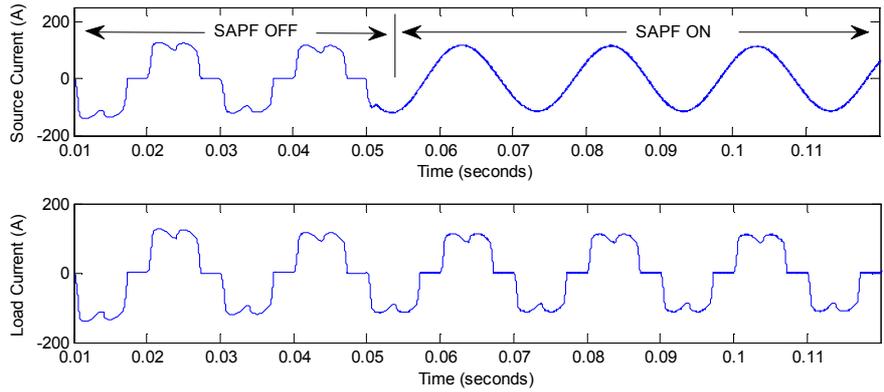
(a) P-Q theory



(b) UVTG theory



(c) d-q strategies



(d) Combined P-Q and UVTG Theory

Figure 8. Simulation Results for case (A) source and load current.

The complete model of shunt active filter is shown in Appendix 1. For comparison between different control strategies, simulation under ideal and distorted voltage source have been carried out.

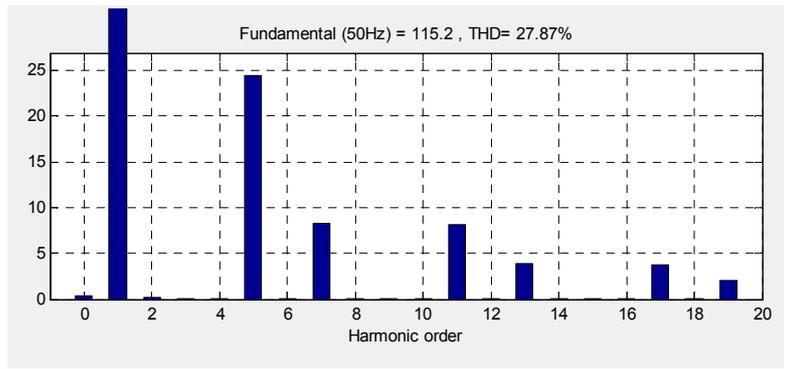
Case (A): Ideal Source Voltage

The Ideal source Voltage case happens at the factory when it is connected to its own power plant.

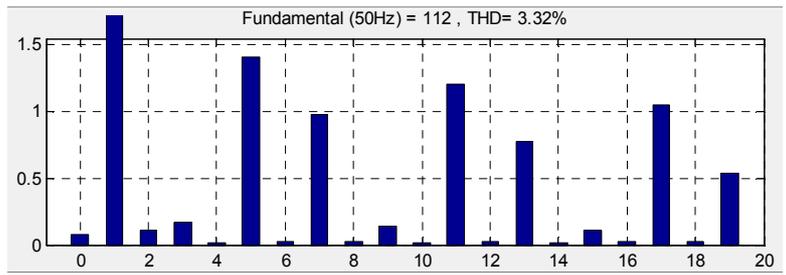
Figure 8 show the simulation results for source and load

current of SAPF control before and after compensation.

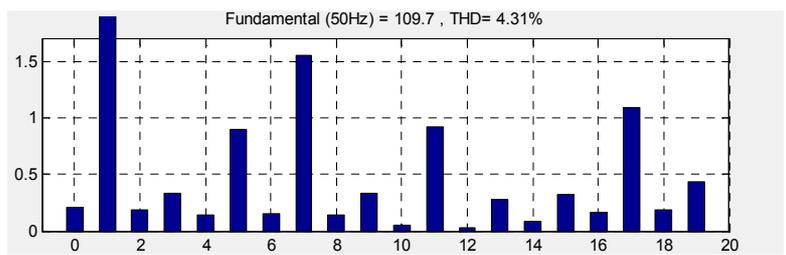
Figure 9 shows Frequency spectrum. THD (Total Harmonic Distortion) levels of the source current after applying the SPAF is given in Table 3. It can be seen that the THD has been reduced from 27.87% to the IEEE 519-1992 Limits when the SAPF is applied for all the studied techniques, however the combined P-Q and UVTG theory exhibits the lowest THD of 1.24%.



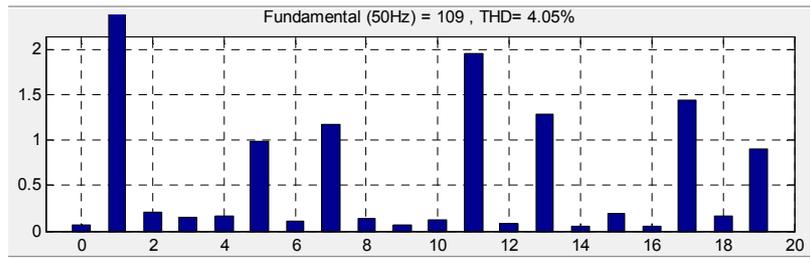
(a) Load Current



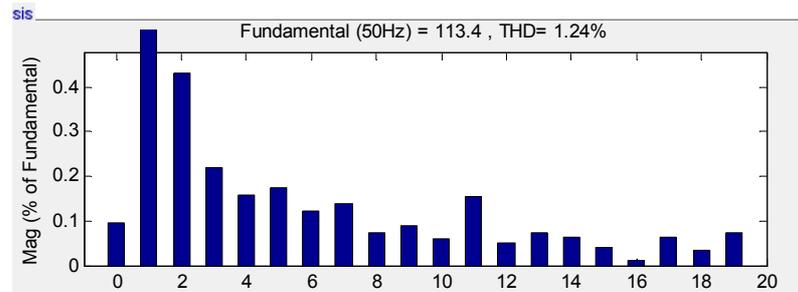
(b) P-Q theory



(c) UVTG theory



(d) d-q theory



(e) Combined P-Q and UVTG Theory

Figure 9. Case (A) Frequency spectrum.

Case (B): distorted voltage source

The distorted supply voltage case is happened when the factory is connected to the Electrical network in case of its own power plant is under maintenance or breakdown which observed that it has mainly harmonic orders 5<sup>th</sup> and 7<sup>th</sup>.

The simulation of distortion in supply voltage at this condition with a value of harmonic order 5<sup>th</sup> (20% of the

fundamental input) and 7<sup>th</sup> (5% of fundamental input) harmonic voltage sources was done as shown in Figure 10.

Figures 11 show the simulation results for source and load current of SAPF control before and after compensation.

Figure 12 shows Frequency spectrum.

A summary of the results are shown in Table 4.

Table 4. Simulation result in case B distorted supply Voltage.

Control strategy	P-Q	UVTG	d-q	Combined P-Q and UVTG Theory
THD	22.10%	4.81%	24.07%	3.87%

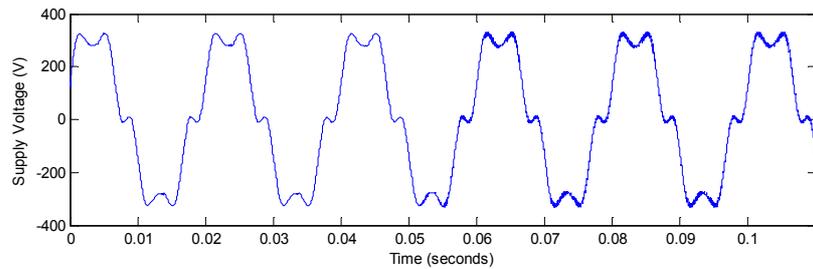
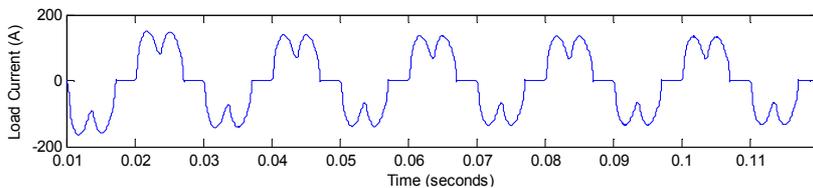
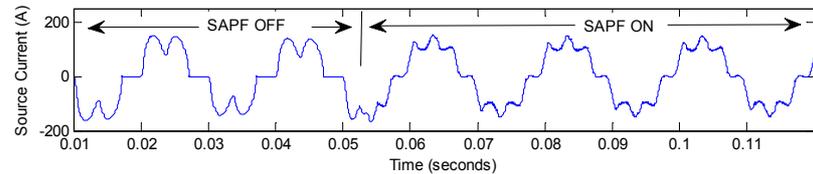
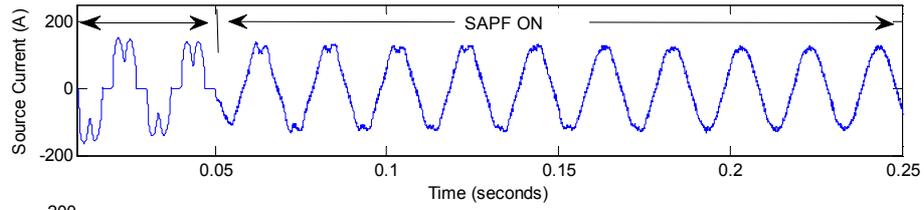


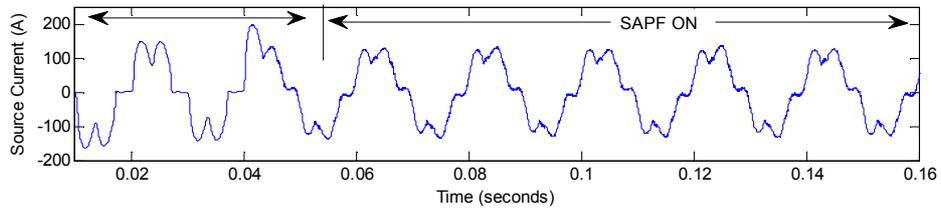
Figure 10. Distorted Supply voltage.



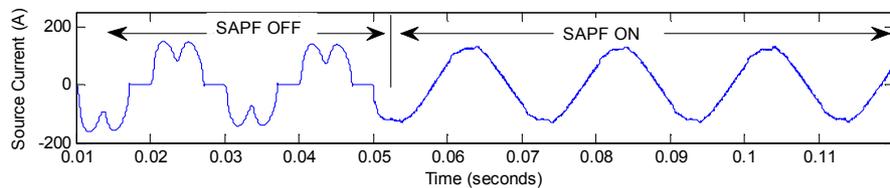
(a) P-Q theory



(b) UVTG theory

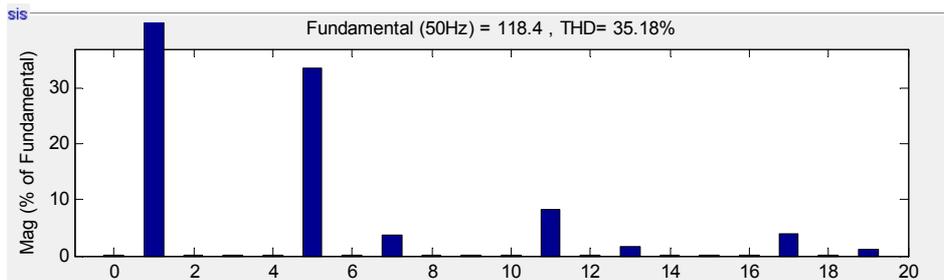


(c) d-q strategies

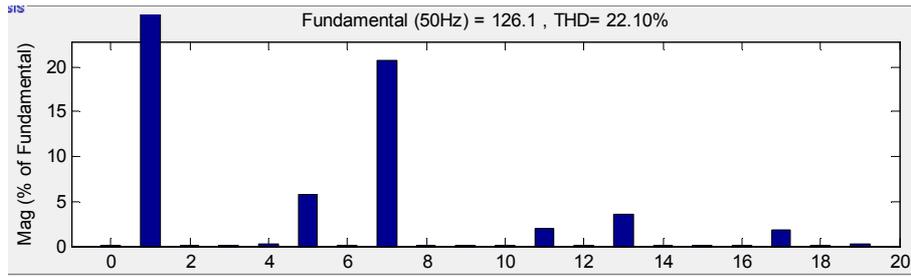


(d) Combined P-Q and UVTG Theory

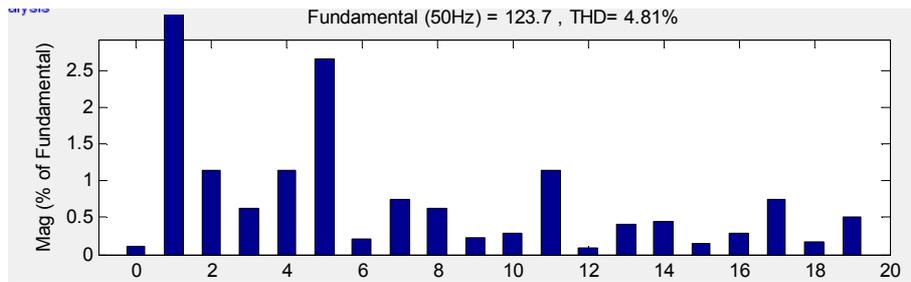
**Figure 11.** Simulation Results for case (B) source and load current.



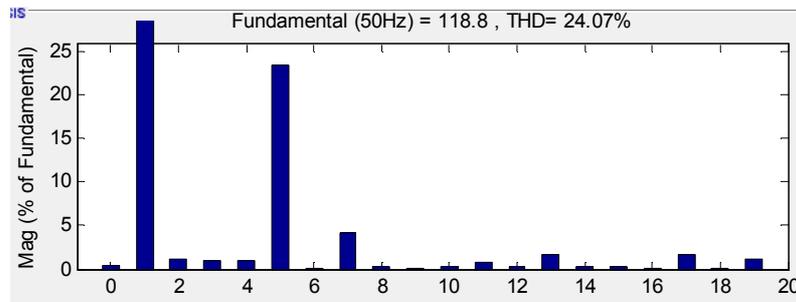
(a) Load Current



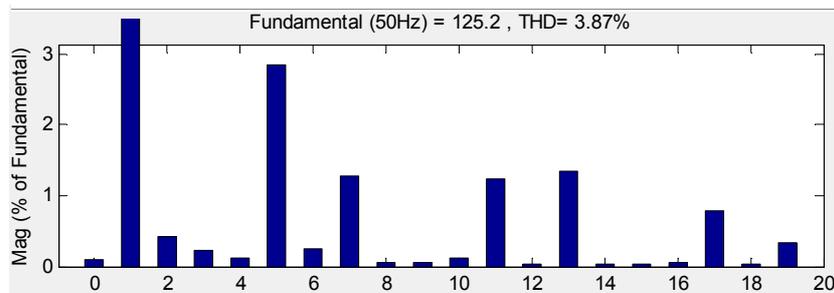
(b) P-Q theory



(c) UVTG theory



(d) d-q theory



(e) Combined P-Q and UVTG Theory

**Figure 12.** Case (B) Frequency spectrum.

The THD level of the source current was reduced from 35.18% to 22.10%, 4.81%, 24.07% and 3.87% by using P-Q, UVTG, SRF and combined (P-Q and UVTG) control strategy respectively.

It is clear that from the simulation results that in the presence of distorted mains voltage P-Q and d-q control strategy are given poor results in terms of THD, however UVTG and the proposed topology Combined P-Q and UVTG Theory are given satisfactory results, and The proposed control strategy combined P-Q and UVTG strategy has the least THD value result for the source current.

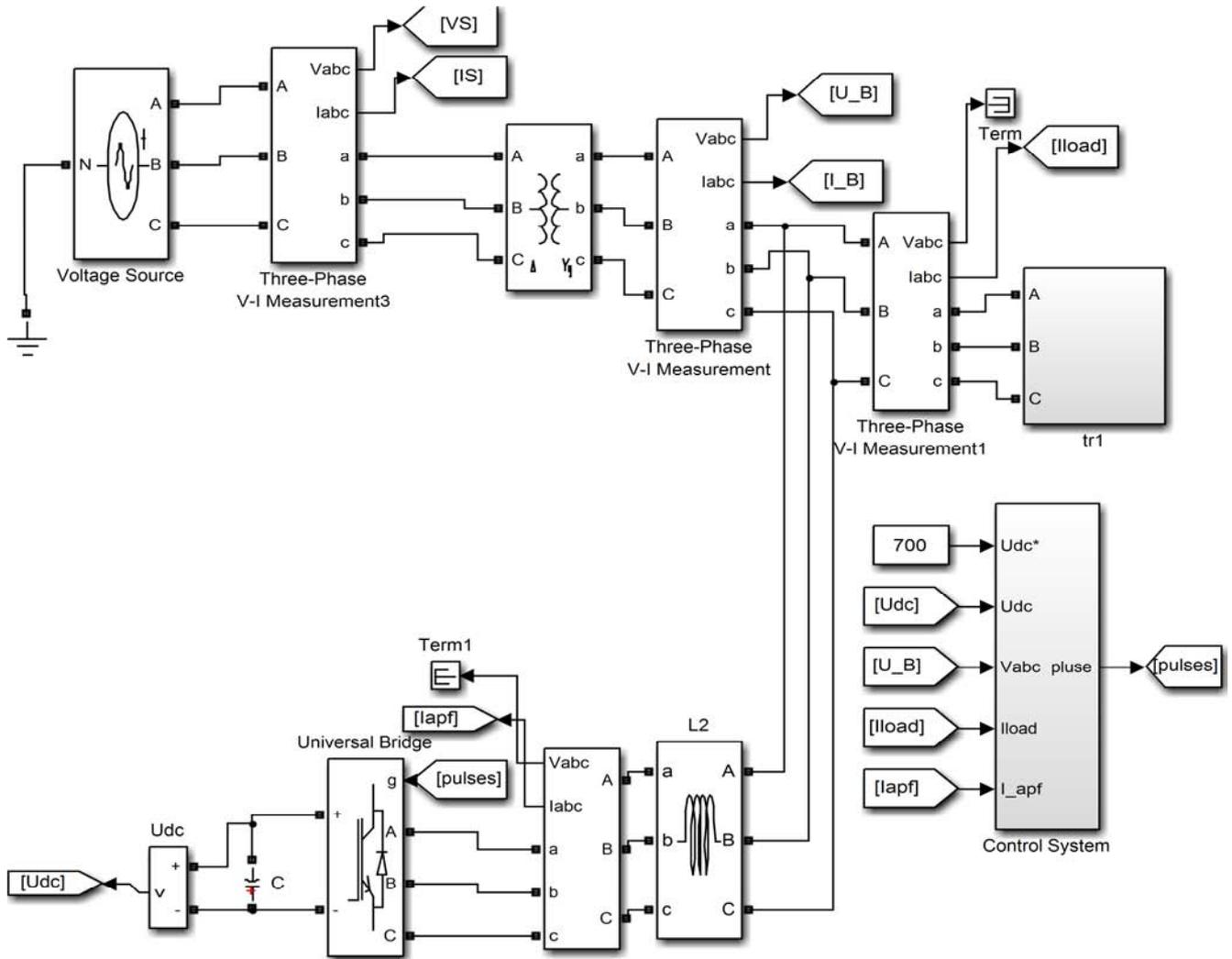
## 6. Conclusion

This paper presents modeling and design of shunt active filter along with different control techniques for minimizing harmonics of Qena Paper Industry factory. Shunt active power filter based on four different control strategies namely, the P-Q theory, the Unit Vector Template Generation theory, the Synchronous Reference Frame theory and the proposed combined P-Q and UVTG theory has been simulated under ideal and distorted supply voltage

conditions. The simulation results show that the fur techniques effectively compensate the harmonics. The THD of Qena Paper Industry factory is reduced to the permissible limits according to the IEEE-519 Standards under ideal supply voltage condition for all the control strategies. The P-Q and SRF control strategies are very

sensitive to the distortion in the supply voltage. The UVTG theory and the combined P-Q and UVTG strategy are capable of compensating harmonic currents under the two cases; however the combined P-Q and UVTG strategy has the lowest THD for the source current.

### Appendix



Appendix 1. System Model with Shunt Active Power Filter.

H.	MODULE	H.	MODULE
DC	1.55%	21	0.76%
3	2.61%	23	1.12%
5	29.21%	25	1.55%
7	7.43%	27	0.20%
9	0.36%	29	0.73%
11	5.37%	31	0.34%
13	3.56%	33	0.35%
15	0.72%	35	0.52%
17	1.23%	37	0.35%
19	1.12	39	0.99%

PF:0.957  
F:49.9 HZ  
V:405V  
I :166A  
THD :29.81%

**print**  
**10:31**

Appendix 2. Print out of the harmonic analyzer.

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