

IMPROVING ELECTRICAL POWER QUALITY IN DISTRIBUTION NETWORKS USING A UNIFIED POWER QUALITY CONDITIONER (UPQC) CONTROLLED BY AN ADAPTIVE HYSTERESIS BAND

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Abstract

Recently the use of sensitive electronic devices has increased, and the quality of energy has become an important factor in electrical power systems, where disturbances occurring in the network (harmonics, swell, voltage sag, etc.) affect consumers and lead to technical-economic damages. One of the most prominent solutions to address energy quality problems is the UPQC (Unified Power Quality Conditioner).

Keywords and phrases: unified power quality conditioner, power quality, adaptive hysteresis band, total distortion factor THD%.

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In this paper, the unified power quality conditioner used to improve the electrical power quality in the distribution networks was discussed, where the Park transformations are used to obtain the required reference signals, and also the use of adaptive hysteresis band to generate the electronic switch pulses in both serial and shunt switches, where the pulse width is determined by dependence on fuzzy logic.

The studied system was validated by simulating different distortion cases and comparing the results when using the Sinusoidal Pulse Width Modulation (SPWM) to control the two switches. The results showed improvement in the electrical power quality through the use of an adaptive hysteresis band controller, and that appeared by reducing the total distortion factor (THD%), which resulted in improving the shape of both the voltage and current waveforms.

1. Introduction

Industrial and technical progress has led to the increasing use of advanced electronic equipment, but the operation of these equipment has led to the emergence of many problems in the electrical network, including the emergence of higher harmonics, and thus the deformation of the input voltage waveform. Likewise, the transient cases that occur in the electrical network during the separation and connection of large loads, and the starting of high-power motors, are some of the causes of disturbances in the electrical network, such as voltage sag and swell that negatively affect other loads connected to the network. On the other hand, the use of electrical and electronic equipment sensitive to the quality of electric energy has led to restrictions on the quality of energy provided by the network [1].

The methodology for improving energy quality based on electronic devices is an effective solution to energy quality problems. One of the best solutions to improve electrical power quality is the use of a UPQC unified power quality conditioner that combines the properties of serial and shunt active filters together [1], [2].

Previously, many traditional methods were used to overcome power quality problems; like static capacitors to compensate for the reactive power in the network, also used induction reactors to consume the reactive power in the network during the low load period, and also used Thyristor Switched Capacitor (TSC) & Thyristor Controlled Reactor (TCR) and Static VAR compensators (TCR) Compensator, which gave more flexibility to control the inductive power compensation [3]. Passive filters were used to eliminate the harmonics, but these methods suffer from many disadvantages, such as the magnitude of the size, the possibility of resonant circuits occurrences, and most importantly, the fixed compensation that limits the possibility of performing their functions [4].

Active filters have also been used that are more flexible than inactive filters and are smaller in size, and provide greater control capacity [5]. Shunt Active Filters that are connected in parallel with the load are used to overcome current power quality problems such as harmonics and to compensate reactive power [6]. Series Active Filters, which are connected in series with the load, is used to overcome voltage-related power quality problems (sags, voltage swell, interruptions, etc.) [7]. Mixed filters (serial - shunt) are used which combine characteristics of serial and shunt filters together to treat voltage and current related power quality problems, called the Unified Power Quality Conditioner (UPQC), which is the most effective filter.

2. Unified (Mixed) Power Quality Conditioner (UPQC)

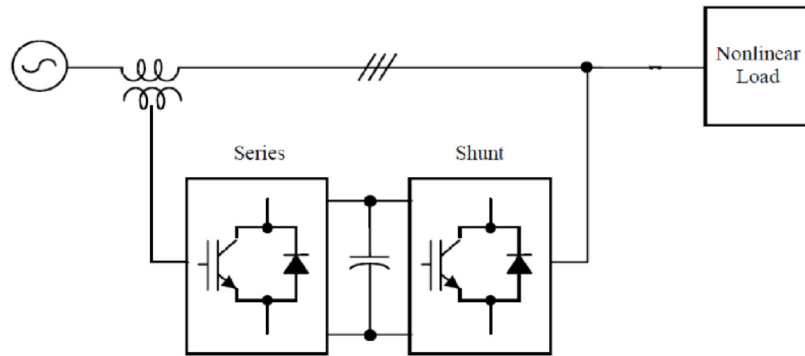


Figure 1. Unified power quality conditioner (UPQC).

It is one of the best solutions to deal with power quality problems. It consists of two switches, one connected in series and the other connected in parallel with the load and they share a common DC link. Figure 1 shows the most common structure of UPQC - there are several possible connection methods for UPQC which differ according to the desired function of UPQC [8].

UPQC is divided into:

- Capacitor voltage regulation;
- Control of shunt and serial switches.

2.1. Capacitor voltage regulation

Many methods have been used to regulate the capacitor voltage, such as proportional- integral controller PI, and proportional integral differential controller (PID), but they need a linear mathematical model, and according to studies, PI is better than PID because the differential element is very sensitive to measuring noise [9], and it fails to regulate capacitor voltage at dynamic operating conditions. Artificial intelligence methods, such as neural networks [10] and fuzzy logic [11] have also been used. These methods are characterized by rapid response, and they do not require mathematical models [12].

We will use fuzzy logic to regulate capacitor voltage because it performs better than a PI controller and does not require a mathematical model.

Seven fuzzy groups represented by organic functions of the trigonometric type were selected to characterize the output as shown in Table 1.

Table 1. Fuzzy rules for the fog controller used to control capacitor voltage

e Ce	NB	NM	NS	ZE	PS	PM	PB
NB	NB	NB	NB	NB	NM	NS	ZE
NM	NB	NB	NM	NM	NS	ZE	PS
NS	NB	NM	NS	NS	ZE	PS	PM
ZE	NB	NM	NS	ZE	PS	PM	PB
PS	NM	NS	ZE	PS	PS	PM	PB
PM	NS	ZE	PS	PM	PM	PB	PB
PB	ZE	PS	PM	PB	PB	PB	PB

2.2. Switch control (reference signals generation)

There are several methods used to generate reference signals (generation of reference voltages for the serial switches, generation of reference currents of the shunt switches), some of which depend on the frequency field such as the fast Fourier transformation and the discontinuous Fourier transformation. However, considerations regarding performing the calculations (long time and large memory required) limited their use [13]. Some of them depend on the time domain, such as the theory of instantaneous active and reactive power (p & q), and the synchronous reference frame theory (SRF), as these two methods are characterized by the basic components of the active and reactive power components related to p & q . And the primary voltage or current component of the SRF are continuous quantities that can be easily

extracted with suitable filters. However, the theory p - q cannot function properly if the voltages are unbalanced. The unbalance of voltage leads to failure of control, requiring additional control loops, which complicates the control system [14].

2.2.1. Serial switches control

We will use the SRF theory to generate reference voltages, whereby the single band method we generate three amplitude rays of 1pu each with an angle of 120° from each other as shown in Equations (0), where the initial voltage angle (θ) is obtained in coordinates (d - q), and obtained through a Phase Locked Loop (PLL) [15].

$$V_a = \sin(\omega t + \theta),$$

$$V_b = \sin(\omega t + \theta - \frac{2\pi}{3}),$$

$$V_c = \sin(\omega t + \theta + \frac{2\pi}{3}). \quad (0)$$

Figure 2 shows the control diagram for the serial active filter.

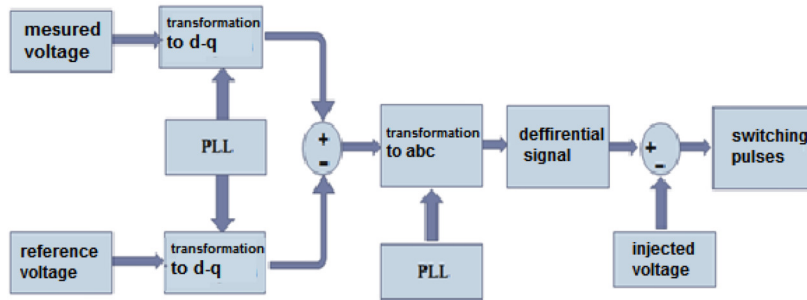


Figure 2. The control diagram for the serial active filter.

The conversion from the abc coordinates to the $d-q$ coordinate was carried out using the park transformation depending on the Equation (1).

$$\begin{bmatrix} u_d \\ u_q \\ u_0 \end{bmatrix} = \frac{2}{3} \begin{bmatrix} \cos(\theta) & \cos(\theta - \frac{2\pi}{3}) & \cos(\theta + \frac{2\pi}{3}) \\ -\sin(\theta) & -\sin(\theta - \frac{2\pi}{3}) & -\sin(\theta + \frac{2\pi}{3}) \\ \frac{1}{2} & \frac{1}{2} & \frac{1}{2} \end{bmatrix} \begin{bmatrix} u_a \\ u_b \\ u_c \end{bmatrix}. \quad (1)$$

Then the $d-q$ compounds are filtered, and the $d-q$ coordinate is converted to the abc coordinate using the reverse park transformation shown by Equation (2).

$$\begin{bmatrix} u_a \\ u_b \\ u_c \end{bmatrix} = \begin{bmatrix} \cos(\theta) & -\sin(\theta) & 1 \\ \cos(\theta - \frac{2\pi}{3}) & -\sin(\theta - \frac{2\pi}{3}) & 1 \\ \cos(\theta + \frac{2\pi}{3}) & -\sin(\theta + \frac{2\pi}{3}) & 1 \end{bmatrix} \begin{bmatrix} u_d \\ u_q \\ u_0 \end{bmatrix}. \quad (2)$$

2.2.2. Shunt switch control

The shunt active filter handles current power quality problems and compensates for the reactive power. The reference signals required for the operation of the filter are generated through Park transformations where the transition is made from (ABC) coordinates to the coordinate $d-q$, where the initial voltage angle is obtained through the Phase Locked Loop (PLL) as shown in Figure 3, and then starts the process of filtering $d-q$ compounds using a suitable filter, and finally, through reverse Park transformations the reference signals are obtained by the transition from the $d-q$ coordinate to the ABC coordinate.

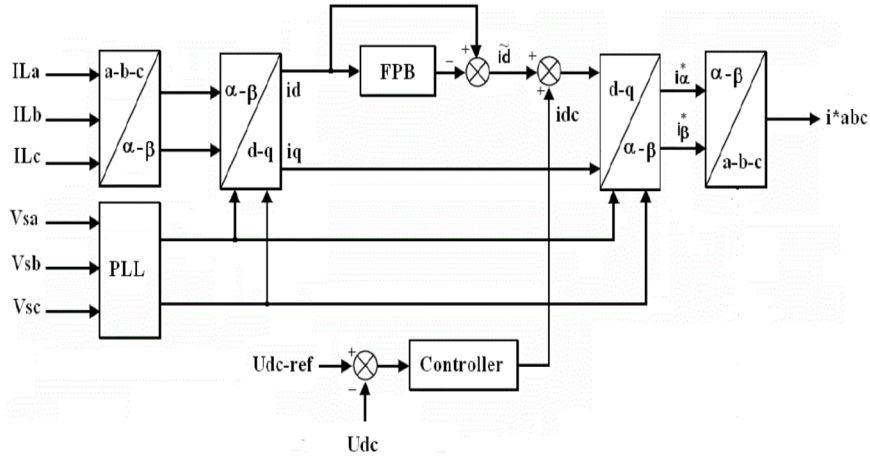


Figure 3. The control diagram for the shunt active filter.

2.2.3. Pulse generation system

There are several techniques for generating pulses for electronic switches, including linear techniques (PWM-SPWM-SVPWM), non-linear techniques, neural networks, fuzzy logic, and the Hysteresis Band (HB) delay.

In this paper, we will present the Adaptive Hysteresis Band (AHB) to control the output of the switches in the UPQC, which is characterized by a fast response, accuracy in tracing the signal, and less ripple of the wave. It is worth noting that the bandwidth is variable and can be calculated mathematically or through artificial intelligence methods, where a comparison is made between the source voltage (V_s) and the reference signal differential (ref), where the resulting signal is fed to the fuzzy logic controller, thus the output of this controller is the bandwidth, as well. As shown in Figure 4. The results will be compared when using the (SPWM) system that depends on comparing the reference signal (V_{ref} , I_{ref}) with the sawtooth signal (carrier signal) (V_{car} , I_{car}) to generate control impulses for the electronic switches as shown in Figure 5(a).

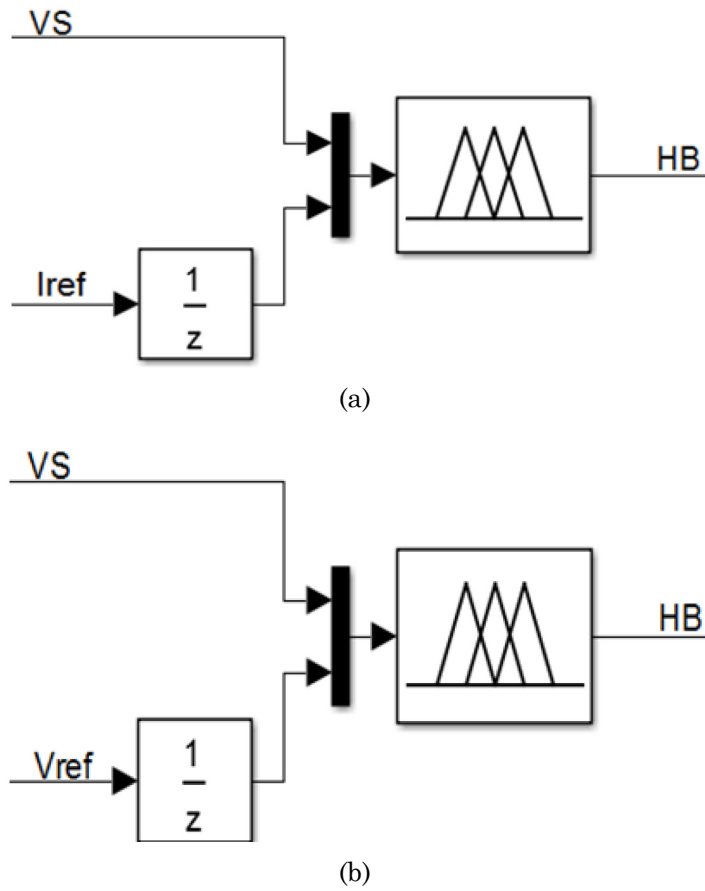


Figure 4. Calculation of the adaptive hysteresis band width (HB) using fuzzy logic (a) for current (b) for voltage.

The adaptive Hysteresis Band method is shown in Figure 5(b) where pulses are obtained for both the voltage and current switches by comparing the actual value with the reference signal, where the beamwidth is variable (2HB), and it was calculated through fuzzy logic.

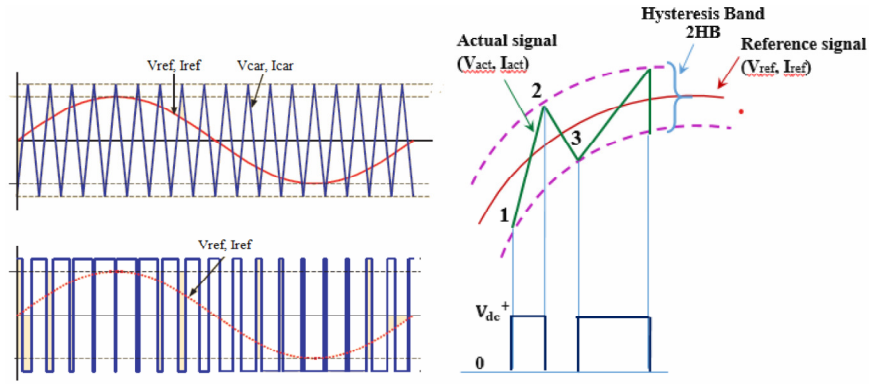


Figure 5. Pulse generation (a) using SPWM, (b) using an adaptive Hysteresis Band.

The bandwidth was determined by fuzzy logic. Five blurry groups represented by organic functions of the triangular type were chosen to characterize the output as shown in Table 2.

Table 2. Fuzzy groups to determine the bandwidth

V_s $\frac{di_c}{dt}$	NL	NM	ZE	PM	PL
NL	PVS	PS	PS	PM	PM
NM	PS	PS	PS	PM	PM
ZE	PL	PL	PVL	PL	PL
PM	PM	PM	PS	PS	PS
PL	PM	PM	PS	PS	PVS

The voltage bandwidth was similarly determined by fuzzy logic by selecting five fuzzy groups represented by organic functions of the triangular type to characterize the output of the serial filter.

3. Simulation and Modelling the Studied System

Figure 6 shows a simulation of the studied system, where both the serial and shunt filters were simulated and combined with each other through the DC link.

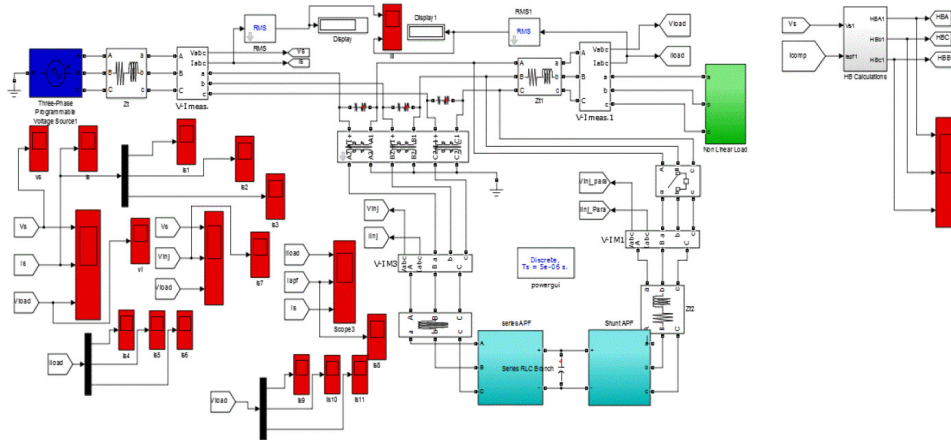


Figure 6. Simulation of the studied system.

Table 3 shows the values of the elements of the used model.

Table 3. The nominal values of the elements in the system

380V	Liner voltage
219.3V	Phase voltage
310.2V	Maximum value of the phase voltage
50Hz	Frequency
$L = 30\text{mh}$ $R = 15\Omega$	Load resistance
1:1	Transformer conversion ratio
800V	DC voltage
$L_L = 10\mu\text{h}$ $R_L = 0.1\Omega$	Line resistance

4. Simulation Results

Several cases of voltage and current disturbances were performed and values of the total distortion factor were determined for both voltage and current waveforms.

4.1. Voltage sag (the voltage value drops to 60% of its nominal value)

Figure 7 shows the input voltage waveform in the event that it falls 40% of its nominal value, where the value of the total distortion factor of the voltage is 15.15%.

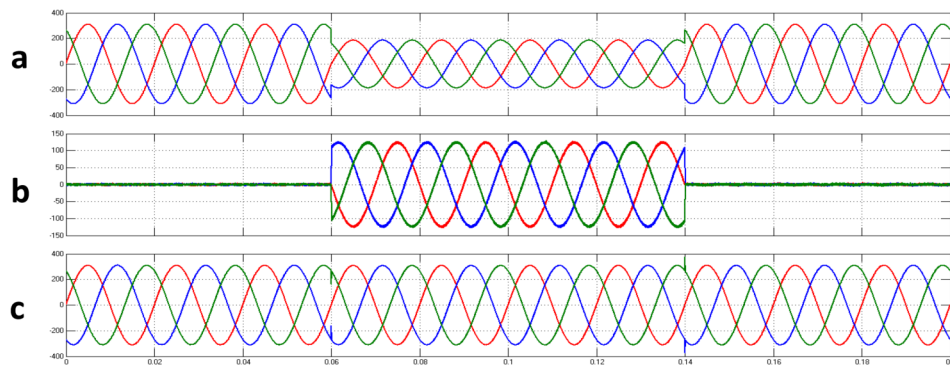


Figure 7. Voltage sag (a) input voltage, (b) injected voltage, and (c) load voltage.

By conducting a Fourier transformation to calculate the THD% for all phases before and after using the serial active filter as shown in Table 4, which shows the comparison of the value of the total distortion factor when using the Fourier transformation for all phases when using the serial active filter led by AHB, SPWM to compensate for the voltage sag.

Table 4. The THD% value in case of voltage sag

Phase	Source THD%	THD% when SPWM is used	THD% when AHB is used
a	15.15%	1.92%	1.63%
b	15.5%	1.96%	1.69%
c	15.32%	1.97%	1.7%

We notice from the previous table the large value of the total distortion factor before entering the filter, and its decrease to a small value after entering the filter, which shows the importance and effective role of the effective serial filter in general and the quality of the AHB delay beam controller in particular in treating the voltage sag and eliminating its effects.

4.2. Voltage swell (increasing the voltage value to 140% of its nominal value)

Figure 8 shows the input voltage waveform if it increases by 40% of its nominal value, where the total distortion factor value is 10.97%.

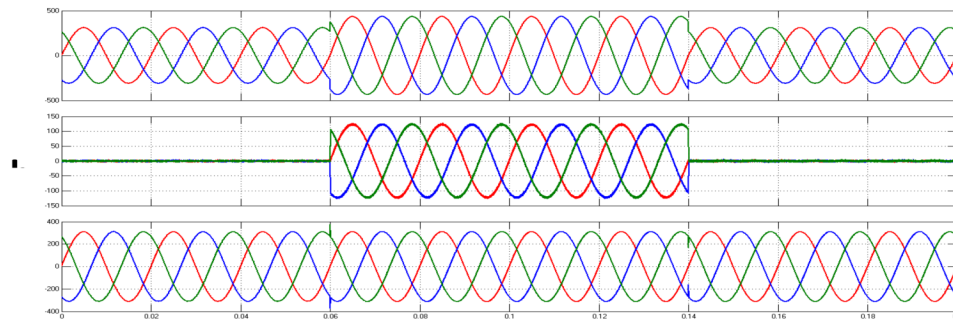


Figure 8. Voltage swell (a) input voltage, (b) injected voltage, and (c) load voltage.

Table 5 shows a comparison of the total distortion factor value when using a Fourier transformation for all phases when using the serial active filter driven by SPWM, AHB to compensate for voltage swell.

Table 5. The THD% value in the case of voltage swell

Phase	Source THD%	THD% when SPWM is used	THD% when AHB is used
a	%10.97	1.75%	1.29%
b	%11.02	1.76%	1.31%
c	10.98%	1.78%	1.32%

Thus, through the low values of THD%, we conclude the ability of the serial active filter in general and the serial active filter led by AHB in particular to treat the voltage swell that may occur in the network.

4.3. Treatment of current harmonic

Given that the load is non-linear, the harmonics will appear in the current waveform, Figure 9 shows the current waveform before and after the current harmonics' compensation, where the harmonics are compensated by the active filter, where the shunt filter is entered at a time of 0.08sec.

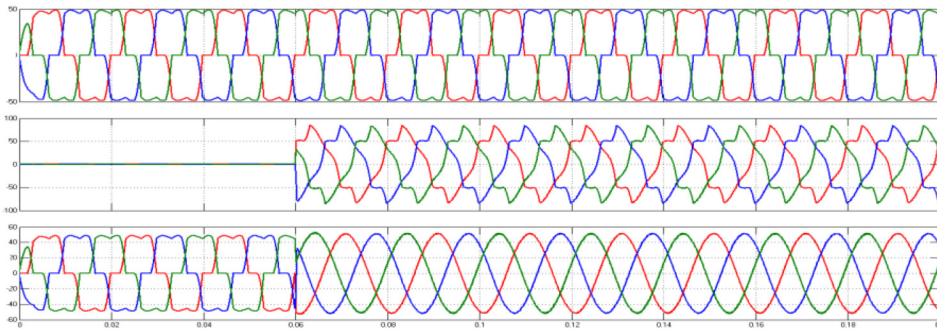


Figure 9. Current waveforms before and after compensation (a) load current, (b) filter current, and (c) input current.

By conducting a Fourier analysis of the three phases to calculate the total distortion factor THD% in the two cases of the filter (two-level and multi-level) as shown in Table 6.

Table 6. Total distortion factor of the two-level and multi-level filter in case of balanced loading

Phase	Source THD%	THD% when SPWM is used	THD% when AHB is used
a	20.97%	3.72%	2.49%
b	23.1%	3.76%	2.5%
c	24.04%	3.77%	2.5%

4.4. Treating the unbalanced loading problem

When loading the first and second phases with a reactive load, the load will draw from the source unequal currents between the three phases. Figure 10 shows the current waveforms in the case of unbalanced loading between the three phases.

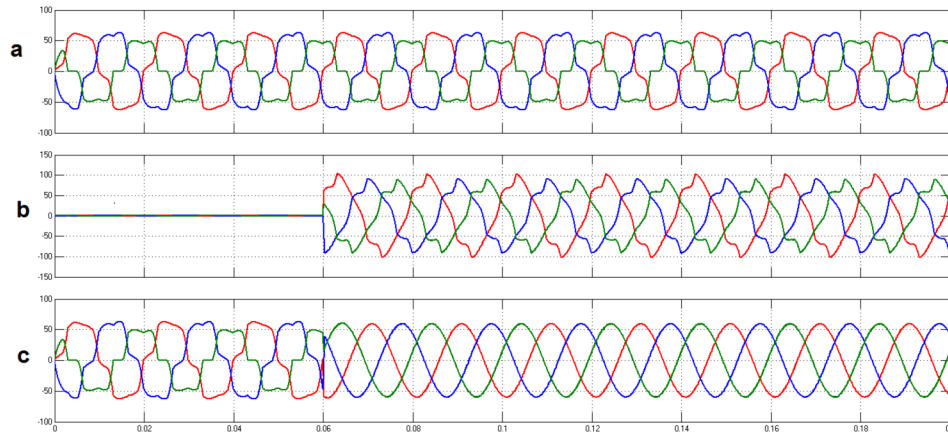


Figure 10. Current waveforms (a) input current, (b) shunt filter current, and (c) load current.

The two previous figures show the ability of the shunt active filter to treat unbalanced disturbances as well. We notice a significant decrease in the total distortion factor from 15.2% (before entering the filter) to 0.43% after entering the filter.

By conducting a Fourier analysis of the three phases to calculate the total distortion factor THD in both cases of the filter when using the serial active filter led by AHB, SPWM to compensate the harmonics of current as shown in Table 7.

Table 7. Total distortion factor of the two-level and multi-level filter in the case of unbalanced loading

Phase	Source THD%	THD% when SPWM is used	THD% when AHB is used
a	15.2%	2.89%	2.43%
b	15.22%	2.9%	2.44%
c	18.06%	2.94%	2.43%

4.5. Treating voltage harmonics

When there are harmonics in the input voltage waveforms as shown in Figure 11, where the figure shows both the input voltage and the injected voltage from the series switch and the voltage connected to the load.

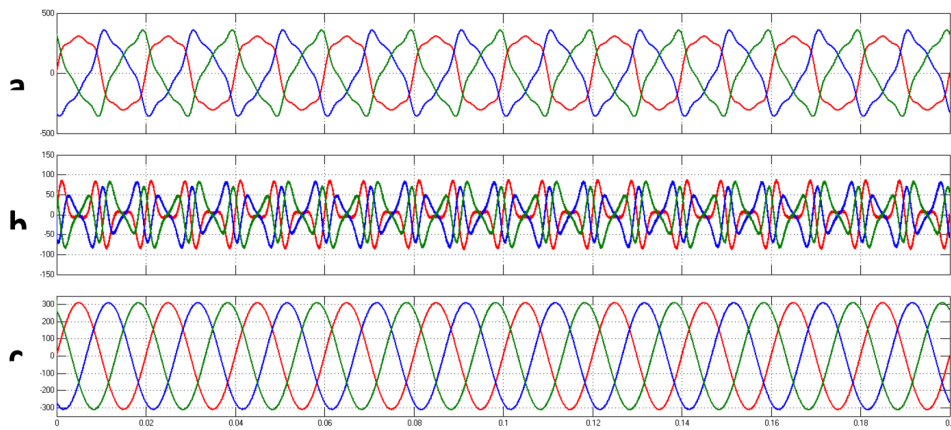


Figure 11. (a) The input voltage, (b) the injected voltage, and (c) the load voltage.

By conducting a Fourier transformation of phase voltage, we note that the total distortion factor decreased from 17.67% to 0.6%. Table 8 shows the comparison of the total distortion factor value when using a Fourier transformation for all phases when using SPWM guided by AHB, UPQC for processing voltage harmonics.

Table 8. The THD% value in the case of voltage harmonics compensation

Phase	Source THD%	THD% when SPWM is used	THD% when AHB is used
a	17.67%	2.11%	1.55%
b	17.69%	2.14%	1.58%
c	17.7%	2.12%	1.56%

Thus, through the low values of the total distortion factor, we have seen the ability of UPQC in general and UPQC led by AHB in particular to process the voltage harmonics that may occur in the network, thus eliminating the harmful effects of the presence of harmonics and the technical and economic problems they cause on consumers.

5. The Results Discussion

(1) A Unified Power Quality Conditioner (UPQC) has been proposed, where each part of the switches works separately to compensate for voltage (serial) and current (shunt) problems.

(2) The proposed system was simulated and different perturbations were studied before and after compensation to verify the effectiveness of the proposed Unified Power Quality Conditioner.

The results showed that the voltage and current problems could be overcome by using the Unified Power Quality Conditioner. Through Park transformation, accurate reference signals were extracted. Also, the Adaptive Hysteresis Band using fuzzy logic had good results for the generation of the electronic switches pulses. It was also observed that the

total distortion factor of both the current and the voltage waveforms decreased to less than 3%. This positively affects the shape of the input current waveforms and the load voltage waveforms.

6. Recommendations

(1) Use of UPQC to compensate for voltage and current problems in electrical power systems.

(2) Using the proposed system in FACTS systems as advanced compensators through which we can dispense with the traditional compensators TSC and TCR as a distinct compensation device that achieves a lower deformation coefficient.

(3) During periods of instantaneous outage (transient state), higher harmonics can arise that lead to distortion of the output waveforms. Therefore, we recommend multi-level switches or Uninterruptible Power Supplies (UPS) that are in a state of permanent readiness (stand by) to operate during periods of instantaneous outage.

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