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Harmonic Mitigation in Utility Grid with Highly Unbalanced Non-linear Load Using Intelligent Controller: an Experimental Study

***Abstract**. The kind of grid-connected loads and the control strategy of harmonic mitigation system using active power filters (APF) play a very important role in terms of total harmonic distortion (THD) and their performances during dynamic operating conditions. Much research deals with these filtering systems only under nonlinear loads with THD values of the source current not exceeding 30%. However when much distorted loads like LED lighting is chosen, the used control strategy can work unsatisfactorily. In this contribution paper, the indirect current control method (ICC) was examined under an extreme case when involving a very high nonlinear load. For the current control, the hysteresis method is adopted which provides switching signals with a fast response and good accuracy. Without require any accurate mathematical model and based on a linguistic description, a fuzzy logic control scheme (FLC) is also developed for the DC-side capacitor voltage to enhance the undesirable dynamic performances obtained using a conventional proportional-integral controller (PI). Simulations outputs and experimental implementation using dSPACE hardware are done under Matlab/Simulink software. Obtained results demonstrate very good performances of the laboratory platform and the control system has been proved to be effective and in perfect compliance with the standard harmonic limits IEEE 519-1992 even when the load current is highly distorted characterized by a high THD more than 60% and an important amplitude of 5^{th} and 7^{th} harmonics.*

***Streszczenie.** Rodzaj odbiorników podłączonych do sieci oraz strategia sterowania systemem ograniczania harmonicznych za pomocą filtrów mocy czynnej (APF) odgrywają bardzo ważną rolę w zakresie całkowitego zniekształcenia harmonicznych (THD) i ich wydajności w dynamicznych warunkach pracy. Wiele badań dotyczy tych układów filtrujących tylko przy obciążeniach nieliniowych, przy wartościach THD prądu źródłowego nieprzekraczających 30%. Jednak w przypadku wybrania bardzo zniekształconych obciążeń, takich jak oświetlenie LED, zastosowana strategia sterowania może działać niezadowalająco. W niniejszym artykule, pośrednia metoda sterowania prądem (ICC) została zbadana w skrajnym przypadku, przy bardzo dużym obciążeniu nieliniowym. Do regulacji prądu przyjęto metodę histerezy, która zapewnia sygnały przełączające o szybkiej odpowiedzi i dobrej dokładności. Nie wymagający żadnego dokładnego modelu matematycznego i oparty na opisie językowym, opracowano również schemat sterowania logiki rozmytej (FLC) dla napięcia kondensatora po stronie DC w celu zwiększenia niepożądanych osiągów dynamicznych uzyskanych przy użyciu konwencjonalnego sterownika proporcjonalno-całkującego (PI). Wyniki symulacji i eksperymentalna implementacja przy użyciu sprzętu dSPACE są wykonywane w oprogramowaniu Matlab/Simulink. Uzyskane wyniki wskazują na bardzo dobre osiągi platformy laboratoryjnej, a system sterowania okazał się skuteczny i doskonale zgodny z normami dotyczącymi limitów harmonicznych IEEE 519-1992, nawet gdy prąd obciążenia jest silnie odkształcony charakteryzujący się wysokim THD powyżej 60% i ważną amplitudę 5. i 7. harmonicznej. (**Łagodzenie harmonicznych w sieci energetycznej z wysoce niezrównoważonym obciążeniem nieliniowym za pomocą inteligentnego sterownika: badanie eksperymentalne**)*

Keywords: Highly nonlinear load, Fuzzy logic, Indirect current control, Total harmonic distortion.
Słowa kluczowe: harmoniczne, nieliniowe obciążenie, THD, logika rozmyta.

Introduction

The supply of the electricity product is always associated with a notion of quality, the increasing use of power electronics equipment such as converters, adjustable speed drive, and switching power supplies on the electrical networks contributes to a great deal on the degradation of this quality. This pollution has been introduced into power systems by harmonic currents and voltages. Indeed, these called non-linear loads call from the grid a non-sinusoidal current with a content rich in harmonic. These non-linear loads also consume reactive power, which leads to direct consequences on the shape of the voltage and current waves that become non-sinusoidal.

Circulating through the impedances of the electric grid, harmonic currents when they are important in amplitudes cause the malfunction of several sensitive devices connected to the common point of connection such as medical devices, computers, PLCs and rotating machines, they can also cause the malfunction of the network protections and the accelerated aging of the electrical grid elements (cables, transformers ....etc.) [1-2]. Therefore, it is necessary to reduce these dominant harmonics below a THD specified in the IEEE International Harmonic Standard imposed on suppliers and industrial consumers. Many topologies of parallel active power filters have been developed recently [3]. As shown in Fig 1, the harmonics in the line current produces a non-linear voltage drop (ΔV) through the line impedance (R, L) which distorts c (V_L) [4].

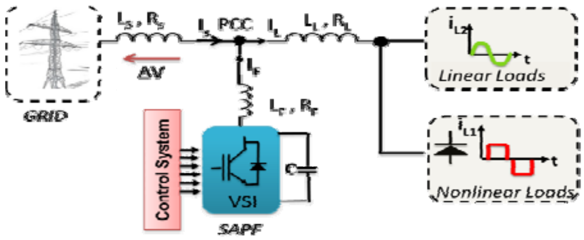


Fig.1. APF and power system with linear and non-linear loads

To extract and generate harmonic currents components of the source current, the indirect current control strategy is used due to its simplicity and easy mathematical model. Firstly, a classical PI controller was used for controlling the

DC-link voltage including generation and estimation of the harmonic reference current. However, many disadvantages of this type of regulator such as speed, precision and response time under dynamic operating conditions have pushed to search another alternative of control [5].

To deal with transient effects, the paper focuses on an intelligent controller based on fuzzy logic, which optimizes and gives improved results compared with the conventional one in terms of THD source current, response time and stability of the DC bus voltage.

A lot of research studies active filtering systems under nonlinear loads characterized by less THD value of the source current not exciding 30% (rectifier feeding RL load). However, the present work testes the ICC under extreme conditions when the waveform of source current is highly deformed and the 5^{th} 7^{th} harmonics present more than 50% of the fundamental component. In the last section of the paper, simulations as well as hardware implementations, have been presented in the main goal is to verify the effectiveness of the proposed control under such conditions.

Topology and Principle of Shunt Active Power Filters

Figure 2 depicts the configuration of the overall system. The APF consists of a voltage source inverter using six IGBT switches, DC bus capacitor, and coupling inductance. The filter is connected in parallel at the (PCC) point of common connection through coupling inductance (L_F). The aim is to obtain a sinusoidal source current and cancel the nonlinear load effects on the power grid. Supply opposing harmonics to the nonlinear load and compensate the reactive power are the main mission of the APF, effectively resulting in sinusoidal source current in phase with source voltage [6-7].

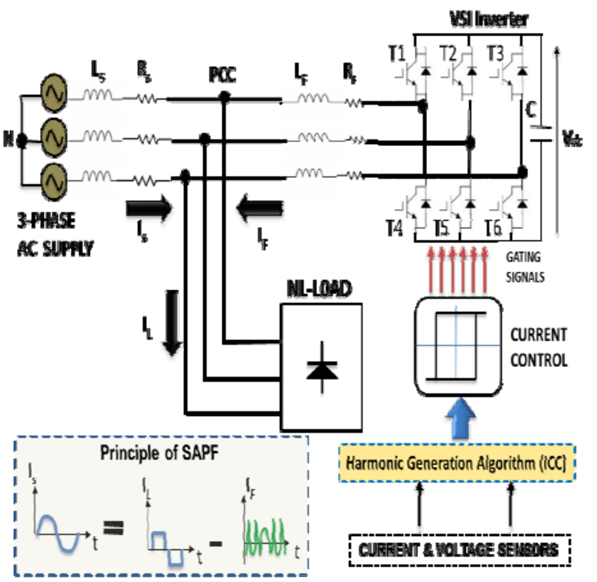


Fig.2. The structure of the active filtering system

Reference Current Generation using the Indirect Current Control Algorithm

The objective of the control part in the SFAP is to perform three main functions [8]:

- The most important is the identification strategy of harmonic currents.
- Tracking the reference currents (in this study by hysteresis control).
- Regulation of the DC- link voltage.

One of the decisive and important control operations of the APF is to extract and generate the reference currents from the power line. The generation of compensating signals is the most important part of the APFs control. It plays a main role in compensation objectives, deciding ratings of the active filter and its transient as well as steady state performance. As shown in Fig.3, an indirect current control algorithm is used for the generation of the reference current. Source voltages are taken for the PLL and source currents to produce the final filter current [9-10].

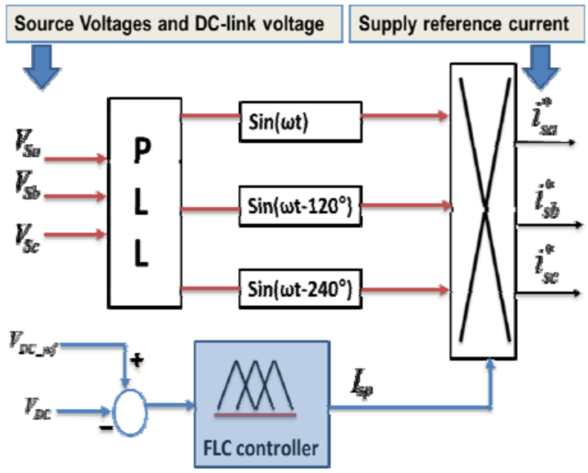


Fig.3. ICC algorithm scheme

In this strategy, the peak value of the reference current is obtained by controlling (DC) link voltage. To obtain an ideal compensation, a sinusoidal wave current in phase with the source voltage is required.

The principle of this estimation reference current is based on a simple model, the instantaneous current at (PCC) can be written as:

(1) $$i_{s(t)} = i_{L(t)} - i_{f(t)}$$

The source voltage can be represented by:

(2) $$v_{s(t)} = V_m \sin(\omega t)$$

If a non-linear load has applied in the distribution grid, the load current will have a non-sinusoidal form which contains of fundamental component and harmonic components. This load current can be represented by Fourier transform as follows:

(3) $$i_{L(t)} = I_1 \sin(\omega t + \phi_1) + \sum_{n=2}^{\infty} I_n \sin(n\omega t + \phi_n)$$

From equations (2) and (3), the instantaneous load power can be defined as [11-12]:

(4)
$$p_{L(t)} = v_{s(t)} * i_{L(t)}$$
$$= V_m I_1 \sin^2(\omega t) \times \cos(\phi_1) + V_m I_1 \sin(\omega t) \times \cos(\omega t) \times \sin(\phi_1) +$$
$$V_m \sin(\omega t) \times \sum_{n=2}^{\infty} I_m \sin(n\omega t + \phi_n)$$

Thereafter, this instantaneous load power can be written as:

(5) $$p_{L(t)} = p_{fun(t)} + p_{r(t)} + p_{h(t)}$$

Next, the real fundamental power drawn by the non-linear load can be deduced using equations (4) and (5):

(6) $$p_{fun}(t) = V_m I_1 \sin^2(\omega t) * \cos(\phi_1) = v_s(t) * i_s(t)$$

The source current after compensation can be given by:

(7) $$i_{s(t)} = \frac{p_{fun(t)}}{v_{s(t)}} = I_1 \cos(\phi_1) * \sin(\omega t) = I_{sm} \sin(\omega t)$$

In addition to the real power demand of the load, there are also some switching losses in the inverter and DC capacitor leakage, the utility must supply more power (small overhead) for compensating these losses [13]. The total peak current (I_{sp}) provided by the source can be expressed by:

(8) $$I_{sp} = I_{sl} + I_{sm}$$

Where, I_{sl} and Ism represent respectively the loss component of source current and the maximum source current.

The aim of the APF is to provide the harmonic currents and reactive power simultaneously. Hence, the source current should be in phase with the utility voltage and purely sinusoidal. At this time, the APF must provide the following filter current:

(9) $$i_{f(t)} = i_{L(t)} - i_{s(t)}$$

After compensation, the desired source currents can be written as follows:

(10) $$\begin{aligned} i^*_{sa(t)} &= I_{sp} \sin(\omega t) \\ i^*_{sb(t)} &= I_{sp} \sin(\omega t - 120^\circ) \\ i^*_{sc(t)} &= I_{sp} \sin(\omega t - 24 \end{aligned}$$

Where the peak current (I_{sp}) is given by the output of the DC voltage control [14-15-16].

DC-link Voltage Control

The DC-link voltage of the inverter is mainly used to ensure two purposes, keeping constant the dc voltage V_{DC} and also it serves as an energy storage element to provide during transients a power difference between load and source. The control of the DC voltage V_{DC} is ensured by the use of one of two controller types: PI controller and fuzzy logic controller. The output DC current I_{sp} of the controller is subsequently added to the identification current control algorithm as shown in Fig. 4 [17-18].

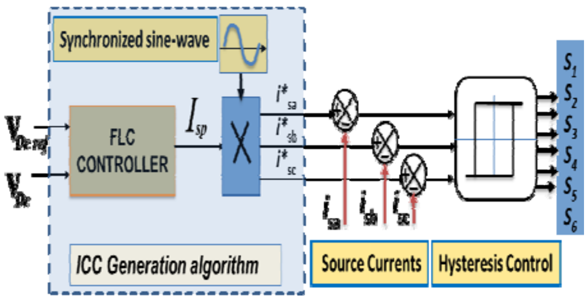


Fig.4. The importance of V_{dc} control in the system

Due to its fixed gains, the main drawback of the conventional PI controller is the incapability to cope with an abrupt change of the signal error Δe of the system. This is a reason to search another alternative approaches. Recently, fuzzy logic controllers FLCs are used in most systems and applications, its principal advantage is that they do not require any mathematical model or system modeling .The FLC concept proposed is shown as Fig.5 [19-20] where the error E and its derivation DE are used as inputs for the fuzzy process and the output represent the peak current I_{sp}. Membership functions for inputs and output are also illustrated in Fig.6.

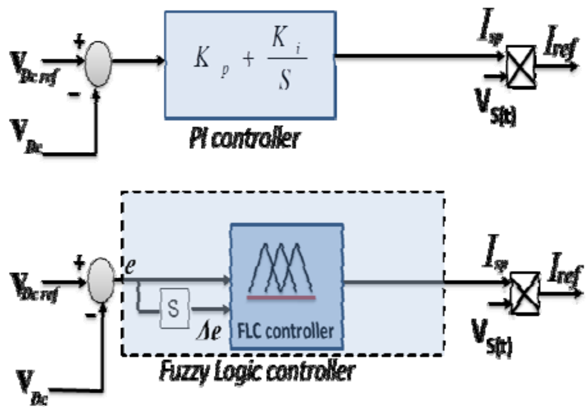


Fig.5. PI and Fuzzy logic control loops

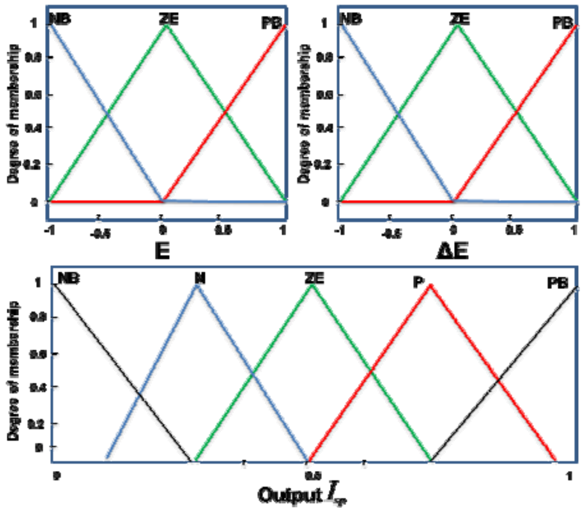


Fig.6. Member ship functions for inputs E/DE and output Isp

As shown in Table 1, the used FLC is characterised by three fuzzy sets in linguistic variable are Negative (N), Zero (ZE), Positive (P),Negative Big (NB) and Positive Big (PB) [21].

Table.1. Fuzzy control rules table

ΔE \ E	N	ZE	P
N	NB	N	PB
ZE	P	ZE	N
P	PB	PB	PB

Hysteresis Current Control

To implement with fast responses, switching gates of the inverter are generated using the hysteresis technique. In the case of the indirect current control, this nonlinear approach uses the error between the reference source current produced by ICC algorithm and the measured source current. This error E is compared between upper and lower tolerance limits called HB band. When the error leaves the lower or upper limit band, switching order will be generated in order to stay inside the HB band [22-23-24].

Simulation and Experimental Results

The proposed system based on the indirect current control algorithm using a PI /fuzzy controller for the DC bus voltage is evaluated and implemented under MATLAB Simulink software and dSPACE1103 AutoBox hardware. The system parameters used both for simulation and experimental implementation are shown in Table 2. Under 230v line voltage, the diode rectifier with RL then RLC load is used as non-linear loads. Note that all experimental results are obtained by a sampling time of 2e-5s resulting in better operation of the inverter with a minimum of losses. Figure 7 illustrates the overall simulated system under MATLAB.

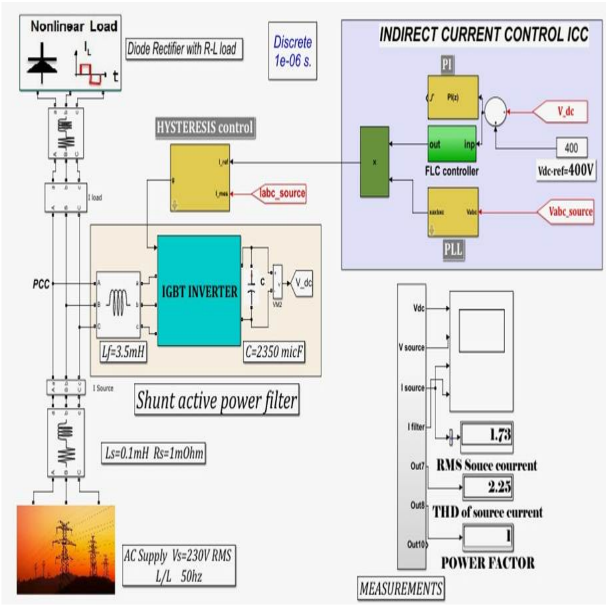


Fig.7. A detailled simulink block of the system

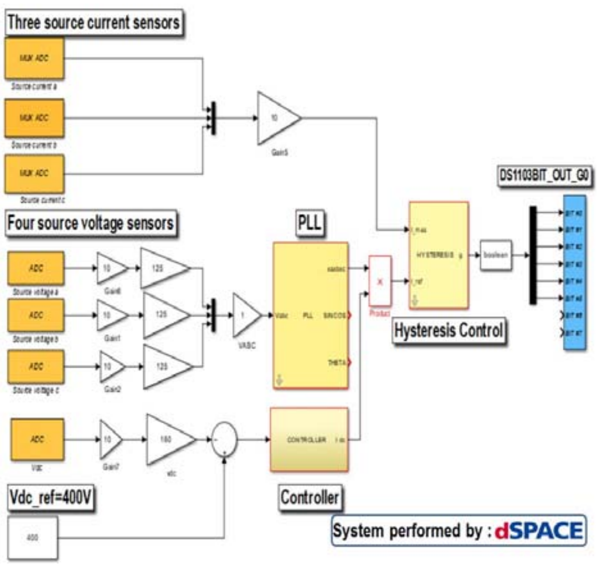


Fig.8. MATLAB model of the overal system for hardware implementation

Figure 8 shows the hardware model under MATLAB performed using dSPACE1103 and Control Desk 5.1 interface. An experimental setup is done in the laboratory as the Fig.9 illustrated, the principal elements in the test bench are indicated to provide more understanding of the real-time implementation.

Figures from 10 to 17 depict both simulation and experimental results of the system where two scenarios are considered:

- Firstly under nonlinear load with THD<30%.
- Secondly under nonlinear load with high THD>60%.

Table.2. System parameters

Description	Parameters	Values
AC Supply	Nominal Line Voltage Frequency R_s,L_s Source Voltage	230 V 50 Hz 0.1Ω, 0.1mH
DC Bus	DC Inverter Voltage DC Capacitor C_{dc}	400 V 2350 μF
NL Load (Diode Rectifier PD3)	RL Load RLC Load (RL parallel with C)	110Ω, 2mH 110Ω, 2mH, 1100 μF
Inverter (VSI)	Coupling inductance L_F	3.5mH
DC-link Controller	PI	Kp= 0.05 Ki=1
Inverter Current Control	Hysteresis Band	0.01 (1%)
Sampling Time	Ts with experiment Ts with simulation	2e-5 S 1e-6 S

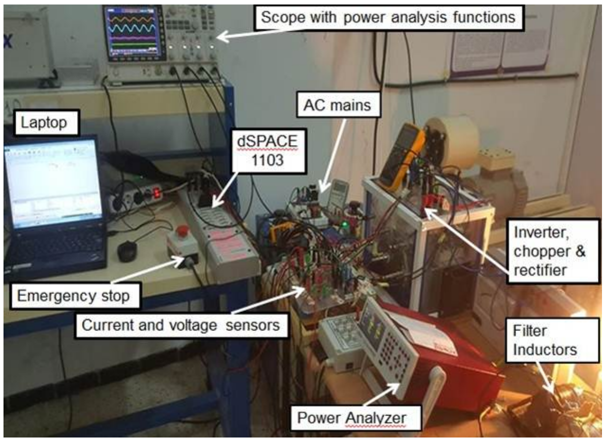


Fig.9. Experimental test bench designed in the laboratory

Responses under Nonlinear Load : Diode Bridge Rectifier with RL Load (THD<30%)

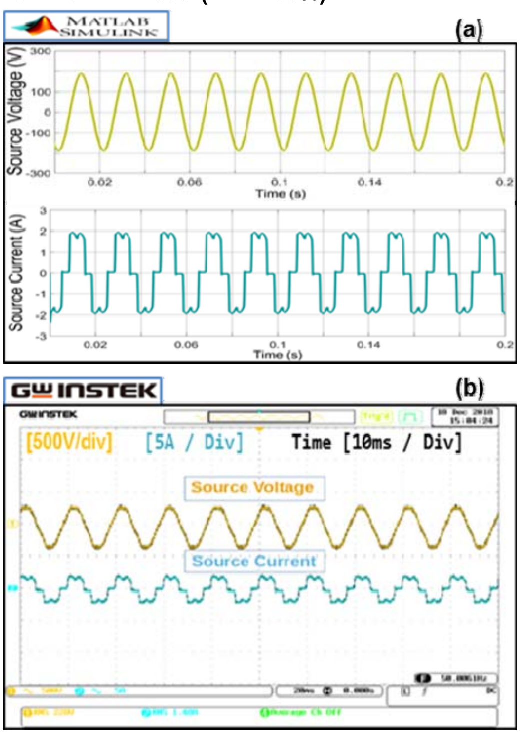


Fig.10. Results before compensation (a) with simulation (b) with experimental

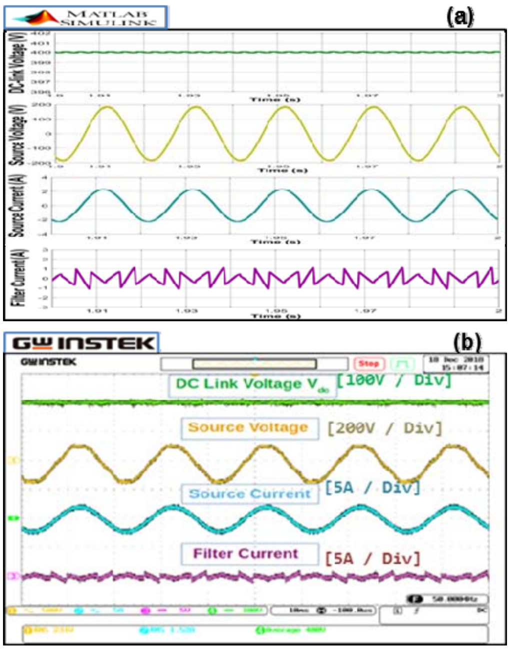


Fig.11. Responses under nonlinear load (THD=28%) with PI Controller (a) with simulation (b) with experiment

Responses under Highly Nonlinear Load:Diode Bridge Rectifier with RL // C Load (THD>60%)

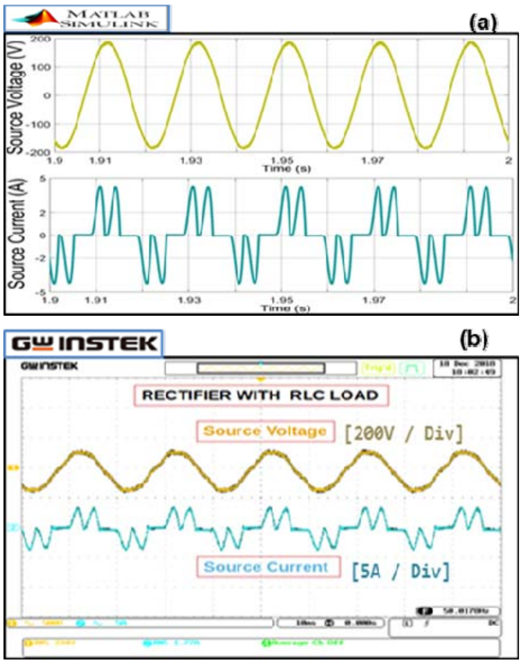
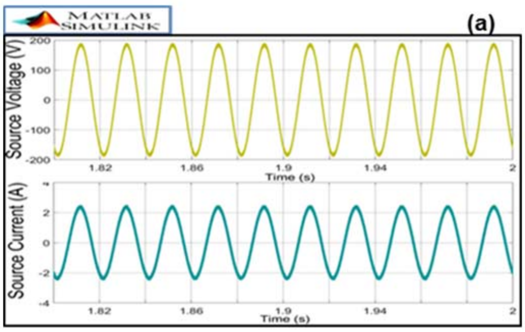


Fig.12. Responses under highly nonlinear load without compensation (a) with simulation (b) with experiment



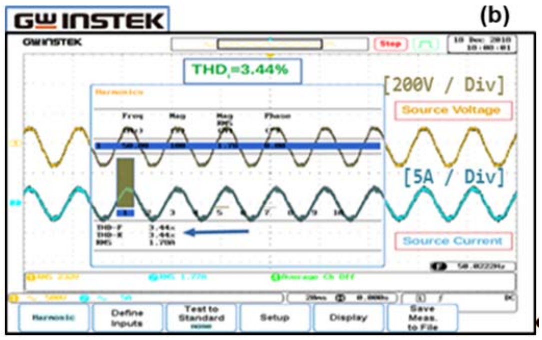


Fig.13. Responses under highly nonlinear load after compensation (a) with simulation (b) with experiment

Dynamic Enhancement using Fuzzy Logic Controller

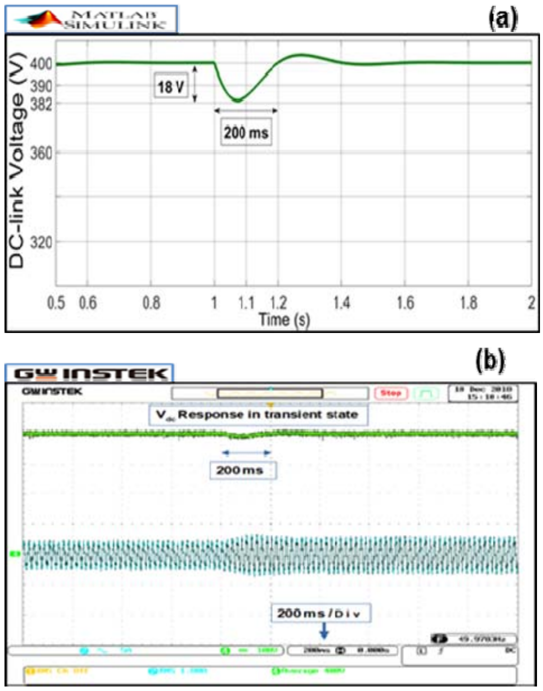


Fig.14. Dynamic responses using PI controller (a) with simulation (b) with experiment

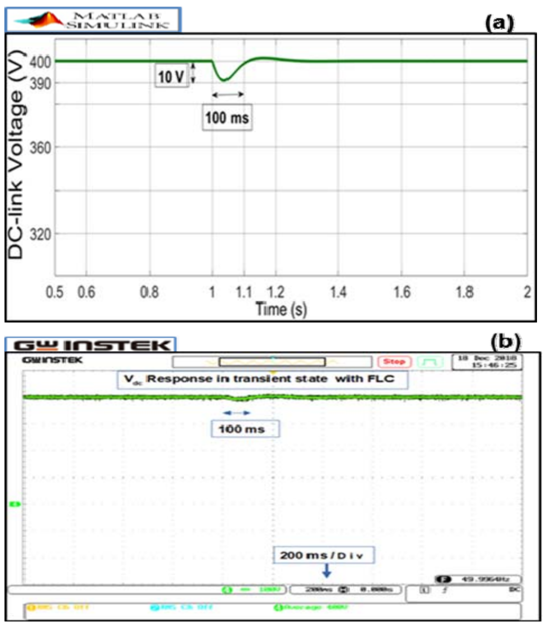


Fig.15. Dynamic responses using FLC (a) with simulation (b) with experiment

Figures 16 and 17 summarize all obtained THD values which clearly indicate that THD is less than 5% in all cases.

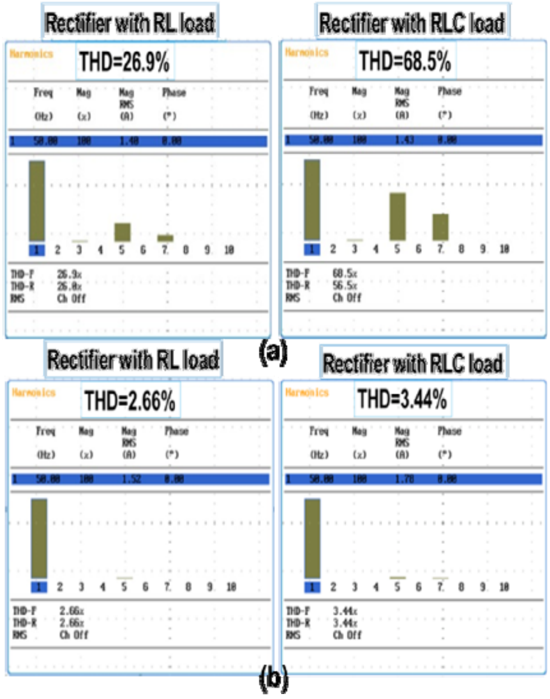


Fig.16. THD values with experiment (a) before compensation (b) after compensation

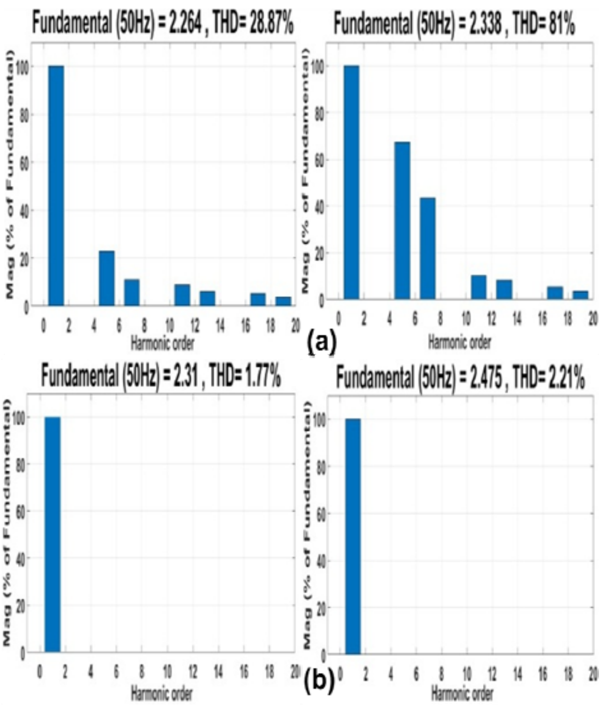


Fig.17. THD values with simulation (a) before compensation (b) after compensation

Results Discussion

Many simulations have been carried out in order to test the viability of the proposed algorithm. Initially before compensation, the source current is non-sinusoidal with THD values of 28.87% and 81% in the case of diode bridge rectifier with RL and RLC load respectively as shown in Fig.16-(a). Figures 10-(a) and 12-(a) show clearly the initial waveform of the deformed source current before compensation.

After compensation, with a low THD value of 1.77 % in the case of nonlinear load and 2.21 % for highly one, the source current becomes perfectly sinusoidal and in phase with the source voltage resulting in almost unity power factor as shown in Figures 11-(a) and 13-(a) .A step-change in the load current at t=1s is made for testing the dynamic performance. Figures 14-(a) and 15-(a) display respectively the PI and FLC results in the transient state. It can be observed that the response time and the overshoot using FLC is better compared with a conventional one.

For further evaluation of both steady state and transient performance, a hardware prototype is done for verifying the results with their corresponding simulation outputs. For the first case without APF, the results are shown in Figures 10-(a) and 10-(b) which indicate an undesired source current waveform. After compensation, the system works satisfactory in steady state as indicated in Figures 11-(b) and 13-(b). But in transient state using PI controller, the result of Figure14-(b) demonstrates unsatisfactory when considering a sudden increase of load current. As shown in Figures 14-(b) and 15-(b), FLC thus appears to be an effective alternative approach to deal with the high overshoot and response time during the dynamic state.

From obtained results for both simulation and experimental tests, it can be noticed that there is a good closeness between results and are found quite satisfactorily according to IEEE International Harmonic Standard. Table 3 illustrates all obtained results through simulation and hardware implementations where NLL represents the nolinear load and HNLL represents the highly nonlinear load.

Table.3. Simulation and experimental results

	Grid without APF		THD Source current		Dynamic performances	
Load kinds	NLL	HNLL	NLL	HNLL	PI	FLC
Simulation	28.8%	81%	1.77%	2.21%	200ms	100ms
Experiment	26.9%	68.5%	2.66%	3.44%	200ms	100ms

Conclusion

The paper assessed the algorithm of harmonic mitigation under extreme conditions when highly nonlinear load and dynamic operating conditions are applied. Whereas the PI regulator is capable of compensating harmonic currents in the steady state, it can be seen that the Fuzzy logic controller has a better quality of compensation that improves the dynamic behavior in the case of abrupt load evolution. The system using the indirect current control has been proved to be effective even when the load is highly nonlinear having a high value of THD with important amplitude of 5^{th} and 7^{th} harmonics. Simulations outputs and experimental results verify the effectiveness of the proposed algorithm and also confirm that the APF is capable to eliminate harmonic currents and compensate reactive power components of load current under an extreme perturbed grid.

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