Design and experimental implementation of single phase power factor correction converter based on fuzzy logic controls techniques

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ABSTRACT—this paper presents an experimental implementation of the single phase power factor corrector PFC based on AC/DC converter with boost chopper. PI, Fuzzy logic and fuzzy adaptive PID controllers for the capacitor voltage are implemented to improve the performance of the boost converter. A self-tuning filter, used to extract the fundamental component from distorted voltage source, is applied to the Phase Locked Loop (PLL) circuit to get better performance. The robustness of the controllers is verified through simulation in MATLAB/Simulink, the results show that the behavior of the PFC with fuzzy controller is better than the conventional proportional integral PI controller and the fuzzy adaptive PID. An experiment is conducted through a test bench based on dSPACE 1103. The experimental results proved that the proposed controller enhanced the performance of the converter under different parameters variations.

Keywords—power factor correction, PFC, PLL, self-tuning filter, fuzzy adaptive PID, PI, Fuzzy logic controller (FLC).

I. INTRODUCTION

In recent years, power quality has become a significant and critical issue, due to industrial and domestic devices using more electronic circuits having a non-linear behavior such as switching power supplies, inverters, single-phase and three-phase rectifiers, they generate in the distribution networks non-sinusoidal currents.

PFC provides rectification of the line current to be a sinusoid and in phase with the grid voltage, with a controlled DC voltage [1]. Due to adoption of IEC 1000-3-2 and the IEEE 519 as a norm in Europe and in USA [2], PFC are increasingly being used in electronic equipment's power supply [3], the basic structure of the AC/DC converter with power factor correction, as well as its working principle, is illustrated in Fig 1. This is a diode bridge rectifier connected to the network and with a correction stage placed between the output of the bridge and the load. This stage of correction of the power factor based on a boost converter structure comprises an inductor, a power switch (IGBT, MOSFET) and

a power diode. This assembly is placed in parallel with the DC bus capacitor. The AC/DC converter is a non-reversible elevating structure, including a single controllable switch. The control objectives are sinusoidal line current with unity power factor and controlling output voltage to a desired reference [4].

Commonly, the traditional regulators PI have been used to control the dc bus voltage of the boost converter [5,6]. These controllers are based on modeling of the system around a nominal point under constant parameters and disturbance, which provide an acceptable performance but if the parameters change, the system loses its performance. For this reason, various intelligent controllers have been introduced to get an optimal performance of the converter regardless of parameters variations. Among these controllers fuzzy logic [7,8] and artificial neural network [9] are used.

In this paper a simulation and real time implementation comparison of PI, fuzzy adaptive PID and fuzzy logic controllers for DC bus voltage in the output of the PFC. an hysteresis controller is used for the current loop, it have an advantage in terms of robustness and implementation simplicity, hysteresis controller doesn't not need a mathematical model [10]. Control algorithms are simulated in MATLAB/Simulink. For the real time implementation a dSPACE DS1103 controller board is used to improve the proposed controls techniques. Finally, controllers' performances are compared.
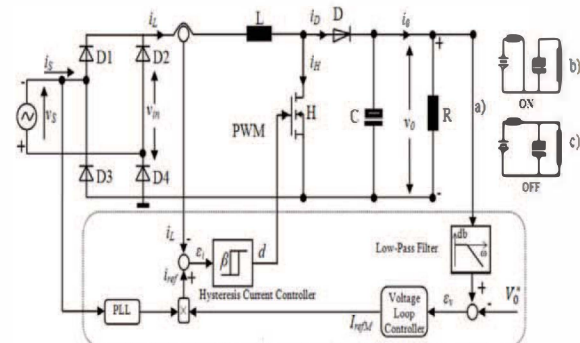

Fig. 1. Power Factor Corrector

II. PHASE LOCKED LOOP (PLL)

The PLL is used as a means to recover the information of the phase and the frequency. The basic form of the P.L.L is shown in Fig. 2, it's based on a feedback system tracking the grid instantaneous phase θ using a controller. However, distorted grid voltages will reduce the performance. This drawback may be overcome by using a filter to eliminate the harmonics components in the voltages.
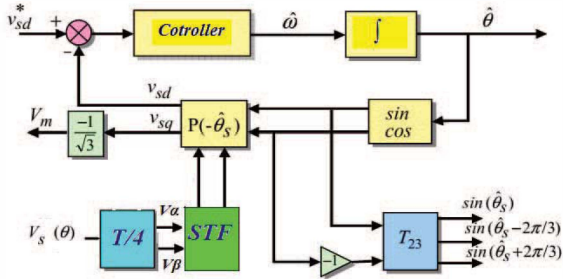

Fig. 2.   The block diagram of the PLL with STF

The self tuning filter (STF) is used to extract the fundamental sinusoidal voltage wave from the distorted and asymmetrical grid voltage in α-β axes [11]. The STF, shown in Fig. 3, is represented by the transfer function defined as:

$$H(s) = \frac{\hat{x}_{\alpha\beta}(s)}{x_{\alpha\beta}(s)} = k\frac{(s+k)+jw_c}{(s+k)^2 + w_c^2} \quad (1)$$
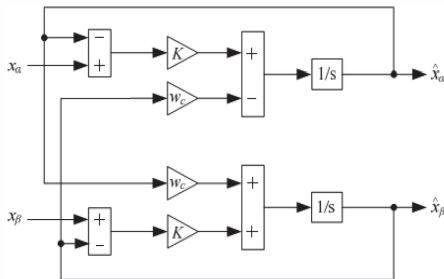

Fig. 3.   Self tuning filter STF

This technique works well if the harmonics components are at high frequencies and the filter do not change the voltage angular phases. In this paper, the conventional PLL has been improved by adding a self-tuning filter STF in the output of the abc/αβ transformation block.

III. VOLTAGE-LOOP CONTROLLER

The DC bus voltage control loop maintains the voltage at a constant reference value by controlling the process of charging and discharging of the capacitor. The causes of the variation are substantially the losses in the switches of the converter, in the coupling inductance and the variation of the load connected to the DC bus. The regulation of this voltage is effected by adjustment of the reference amplitude of the current taken to control the active power flow between the network and the DC bus. For this purpose, it is intended to compensate for any interference from the inverter side and the load side, causing a variation of the energy stored in the capacitor. This loop has as input the reference voltage V_o^* and the measured voltage V_o as shown in Figure 1.

The components of the boost chopper (transistor and diode) are considered ideal, absorbed instantaneous power is zero; this hypothesis with a power balance is independent of the presence of the DC-DC converter assuming that:

$$i_L \cong i_{ref} \quad (3)$$

$$P(1 - \cos(2wt)) = v_0 i_D = v_0\left(\frac{dv_0}{dt} + \frac{v_0}{R}\right) \quad (4)$$

Supposing $i_L \approx i_{ref}$; to satisfy the constraint form i_L, it is certain that the ripples of 50Hz to DC bus voltage do not affect the calculation of the voltage whose bandwidth is very low. We therefore consider that equation (4) can be reduced to that of the average power. The main difference concerns the disappearance of 50Hz ripples due to power fluctuation. Controller role is to maintain the average voltage of the DC bus and not the instantaneous value, equation (4) becomes:

$$\frac{V_{sM}I_{ref\,dc}}{2} \cong C\frac{dv_{0dc}^2}{dt} + \frac{v_{0dc}^2}{R} \quad (5)$$

The *dc* indication is used to remind that only the average value of V_o is expressed in this equation. As shown in (5), the control of V_{Odc} is made possible by action on I_{refdc}. To calculate the controller parameters, we can linearize equation (5) around an operating point defined by (V_{Odcc} and I_{refdcc}).

Tf(s) is the transfer function of the system:

$$Tf(s) = \frac{\delta v_{0dc}}{\delta I_{dcref}} = \frac{V_{sM}}{4v_{0dc}}\frac{R}{1 + RC\,s} = \frac{k_s}{1 + \tau_s\,s}$$
$$= \frac{21.78}{1 + 0.2844\,s} \quad (6)$$

1)   PI-Controller :

As shown in Fig. 1, the dc-bus voltage v_0 is compared to a reference value v_{oref}. The error is the input of the PI controller; the output of the controller is multiplied by |*sin wt*| of the PLL. This gives the reference current iref. Calculation of PI controller is determined conventionally by compensating the dominant pole and the imposition of a dynamic closed-loop, we can deduce the two parameters of the PI controller as follows:

$$K_{PI} = \frac{RC}{T_{PI}} = 0.6091 ; T_{PI} = \frac{BRV_{sM}}{8\pi(f_{cv})v_{0dc}} = 0.3858 \quad (7)$$

B: attenuation of the measured DC bus voltage,

f_{CV}: the closed loop cutoff frequency of the DC bus voltage $f_{cv}=45Hz$.

The closed loop transfer function is by:

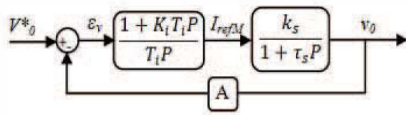$$\frac{v_0}{v_{0ref}} = \frac{k_f}{1 + \tau_f\,s} \quad (8)$$

Fig. 4.   Voltage loop controller for PFC

TABLE I.   DESIGN SPECIFICATION AND CIRCUIT PARAMETERS

Magnitude of supply voltage (Vmax)	72V
DC-Bus reference output voltage	100V
Output voltage ripples	5%
Load resistance	161 Ω
Input Inductance	5mH
Output Capacity	4700μF
Line Inductance	5mH

2)   Fuzzy-Controller:

In recent years, the fuzzy logic control is increasingly used for controlling the static converter. Most non-linear control approaches require the availability of a mathematical model of the system. Control performance will be directly related to the accuracy of the used model. It allows for better performance and to compensate for nonlinearities and the various constraints on the modeling of the process [12]. In this part, the conventional PI controller is substituted by a fuzzy logic controller.

The advantage of fuzzy logic lies firstly in its similarity to human reasoning. Indeed, the operator decision is based on several variables described qualitatively and not through specific numerical values. Second, this logic is interesting because it allows the decision despite the absence of a complex system modeling upstream such nonlinear systems or variable structure systems. A fuzzy system realizes a no linear correspondence between a vector and a scalar output [13]-[14], through the steps shown in Fig 5.

The global structure of the voltage regulation, with a fuzzy controller of the DC bus voltage, is illustrated in Figure 6.

The fuzzy controller developed in this section is PI .The two input variables are discretized with a sampling period Ts and normalized using normalization gains (Ge for error and GΔe for the variation of the error) .They are defined by the following expressions:

The input error $e(k)=v_{0ref}(k)-v_0(k)$

Error variation $\Delta e(k)= e(k)- e(k-1)$.

The dc bus voltage is controlled by adjusting the reference current i^*.

The table II shows the set of fuzzy rules used in the design of this controller. Human perception of the control system is so translated.

3)   Fuzzy Adaptive PID Controller :

PID controller is simple, stable, easy adjustment and high reliability, it is widely used in control processes but, most industrial processes have a nonlinear behavior, parameter variability with times and reduced mathematical model.
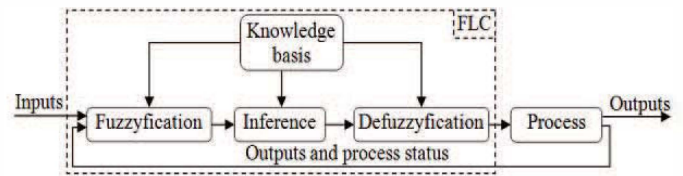

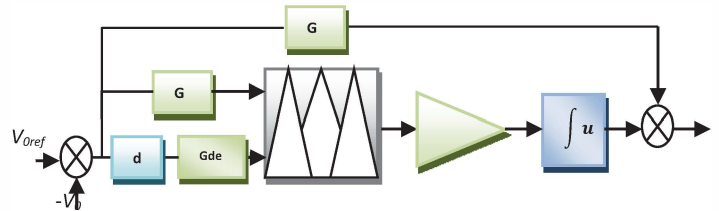Fig. 5.   Fuzzy logic controller scheme and the controlled process.

Fig. 6.   Fuzzy logic controller for DC bus.

TABLE II.   CONTROL RULE TABLE OF THE FLC

	NG	ZE	PG
NG	NG	NG	ZE
ZE	NG	ZE	PG
PG	ZE	PG	PG

TABLE III.   FUZZY LOGIC CONTROLLER GAINS

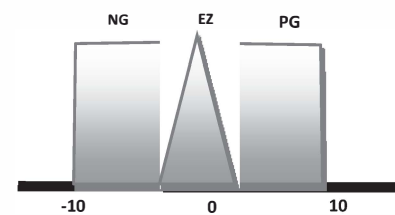| Ge	Gde	Gu	G1
0.03	0.002	0.0005	0.01

Fig. 7.   Membership functions for Error, dError and output of FLC

TABLE IV.   RULE TABLE OF THE ADAPTIVE FUZZY LOGIC CONTROLLER

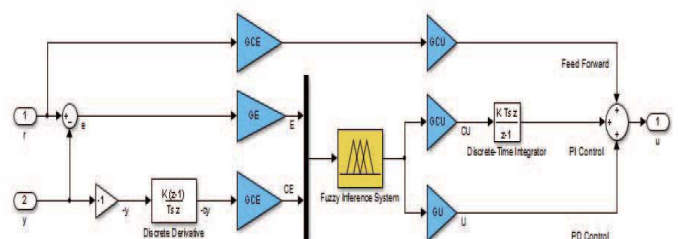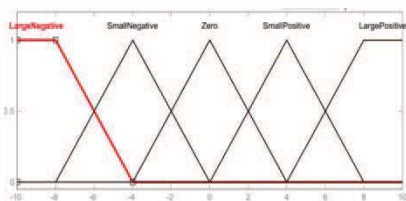|	NG	NP	ZE	PP	PG
NG	NG	NG	NG	NP	ZE
NP	NG	NP	NP	ZE	PP
ZE	NG	NP	ZE	PP	PG
PP	NP	ZE	PP	PP	PG
PG	ZE	PP	PG	PG	PG

Fig. 8.   Adaptive fuzzy PID controller.

Fig. 9. Membership functions for Error,dError and output of AFLC

Tuning PID parameters is very difficult, poor robustness. The controllers based on the concepts of artificial intelligence, fuzzy logic and neural networks are attractive alternatives, and can improve the robustness of the process to be controlled, [15]. In this part, an Adaptive fuzzy PID controller is used to control the DC bus voltage in PFC. PID parameters are adjusted in real time under adaptive fuzzy control. Hence, the controller can be adapting to any change of parameter.

Fuzzy adaptive PID controller used in this paper has two inputs and one output. The structure of this controller is shown in Fig. 8. In Fuzzy adaptive PID controller only one output which is connected to Kp, Ki and Kd gains. The inputs of fuzzy inference system are the error (e), error change (de) and control signal respectively. Membership functions of inputs and output are shown in Fig. 9. Table IV shows the rule used in the fuzzy adaptive PID controller.

IV. SIMULATION AND RESULTS

The performance of the proposed control techniques has been analyzed and compared with the conventional control. In the first case the proposed control technique applied to the PLL have been simulated and compared under distorted voltage without connecting the PFC. The simulation results were carried using Matlab/Simulink. To validate the robustness of the new PLL, it is evaluated with the same voltages applied to the Conventional structure.
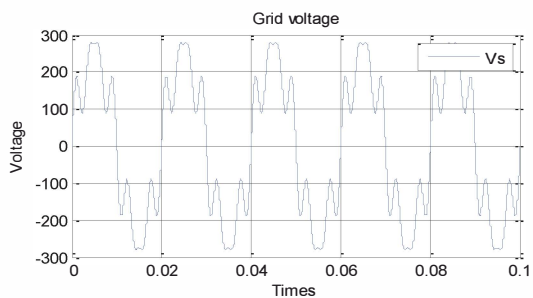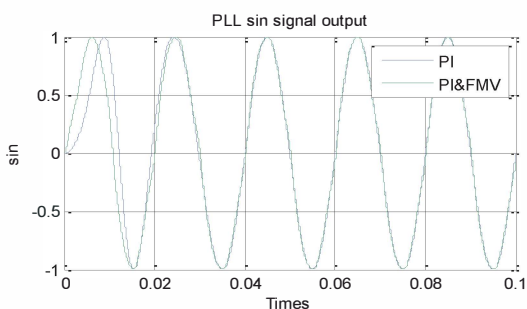

Fig. 10. Line voltage

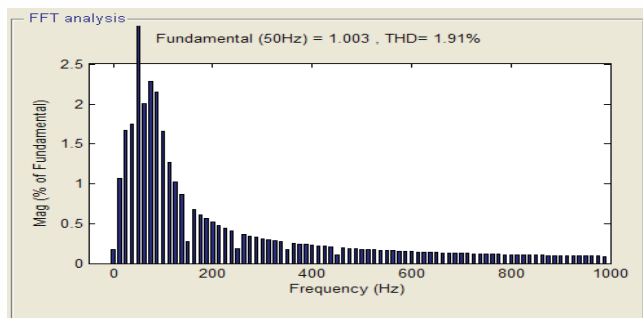Fig. 11. PLL SIN signal output

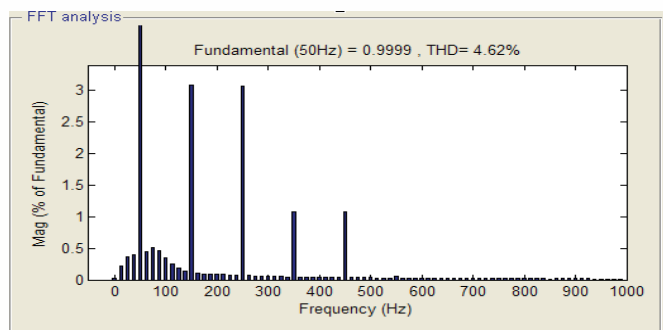Fig. 12. PLL based on self tuning filter Sin signal output THD

Fig. 13. Conventional PLL Sin signal output THD.

Figure 11, 12 and 13 shows the results of the PLL for voltages source which contain harmonics 5, 7 and 11. It is noted that the STF based PLL structure enables us to obtain a linear and periodic phase angle, and that the presence of STF improves the voltage signals quality in the (α,β) axes. The Proposed PLL provides a much reduced THD. Therefore, we get a unit sinusoids and very good qualities in the output of the PLL.

To show the effectiveness of fuzzy control based power factor correction boost converter, simulation has been carried out. The reference output voltage is taken as 100V. Figures 14, 15 and 16 illustrate the line current simulated waveforms, for the proposed methods at nominal load and constant voltage of 100 V. From this figures, it can be seen that the obtained results with the fuzzy control techniques are excellent. The grid current is sinusoidal and in phase with the line voltage. The total harmonic distortion (THD) is found less than 5%. Figures 17, 18 and 19 show that the output voltage is maintained constant at desired value for a steady-state error of 0.5 V.

TABLE V.   PARAMETERS OF SIMULATION

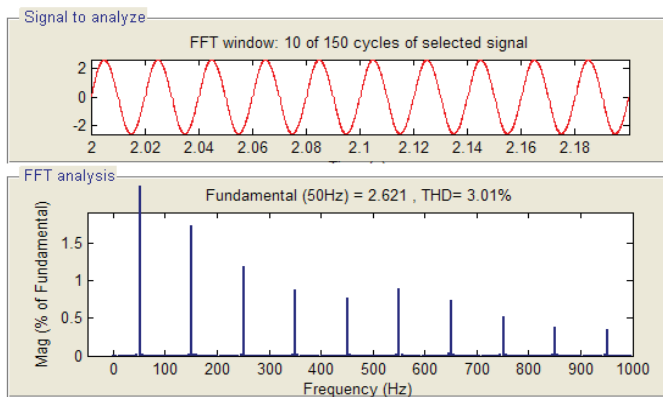| Parameters	Value
DC bus voltage	100V
Line inductance	5mH
PFC inductance	2mH
DC link capacitor	4700μF
Load resistance	121Ω
Sampling time	1e-5 s

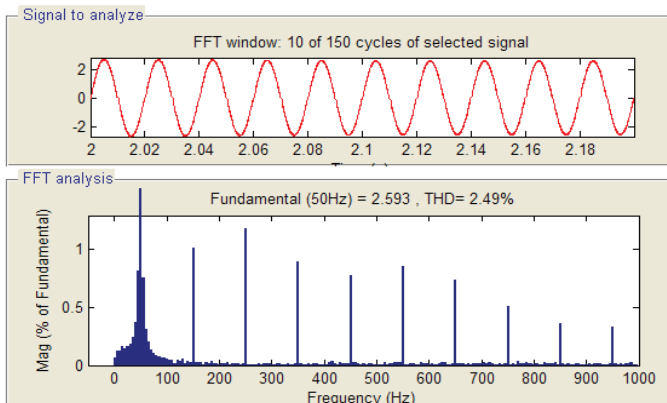Fig. 14. Line Current using PI controller for DC bus.

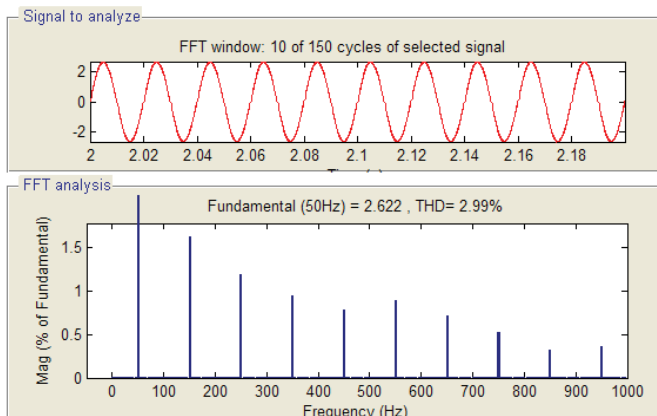Fig. 15. Line Current using fuzzy controller for DC bus.

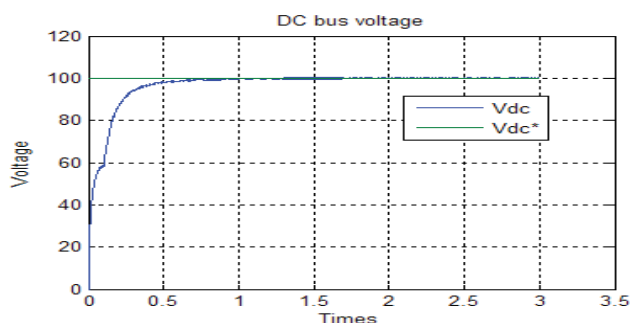Fig. 16. Line Current using fuzzy adaptive PID controller for DC bus.

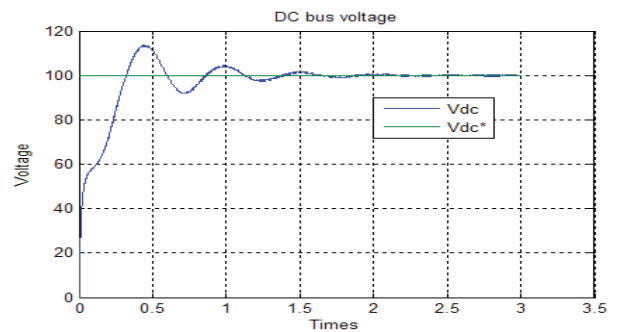Fig. 17. DC bus voltage based on PI controller .
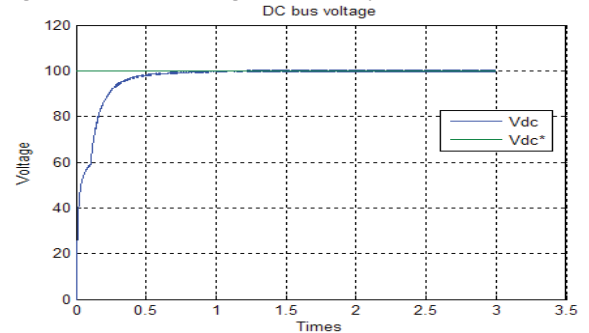

Fig. 18.   DC bus voltagebased on fuzzy controller .

Fig. 19. DC bus voltagebased on fuzzy adaptive PID controller .

V. EXPERIMENTAL VALIDATION

In order to examine the robustness of the proposed controls, a real times implantation setup using the dSPACE 1103 (digital signal processor) controller board is done in LREA laboratory and shown in Fig. 20. For the real time implementation of the proposed controller, an inverter (SEMIKRON, 40KVA, 1200 V, 100A) used as a rectifier.

Experimental Test 1-System without PFC: In this test, no PFC controller was implemented, the experimental results are shown in Fig. 21, it is observed that the performance of the system without PFC is not satisfactory since a THD more than 64% is observed in the line current having a low power factor around 0.8, it haven't a sinusoidal waveform. These results confirm the importance of PFC for the quality of energy in the power converters.
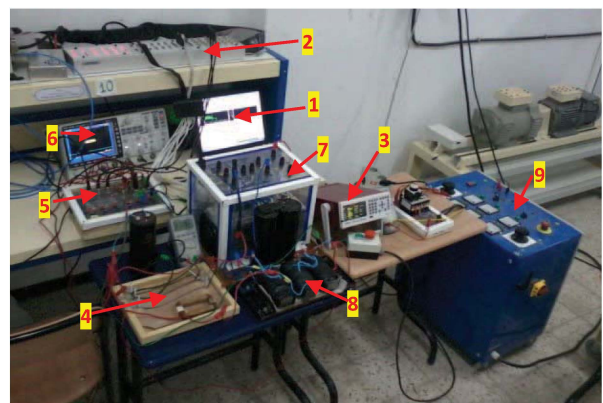

Fig. 20. Experimental test bench: 1: PC, 2: dSPACE 1103 I/O connectors, 3: Power analyzer,4: Load, 5: Current,voltage sensors, 6: Scope, 7: Inverter, 8: Inductors, 9: Transformer.
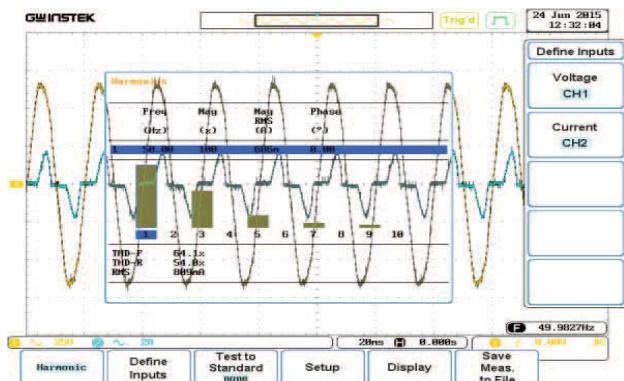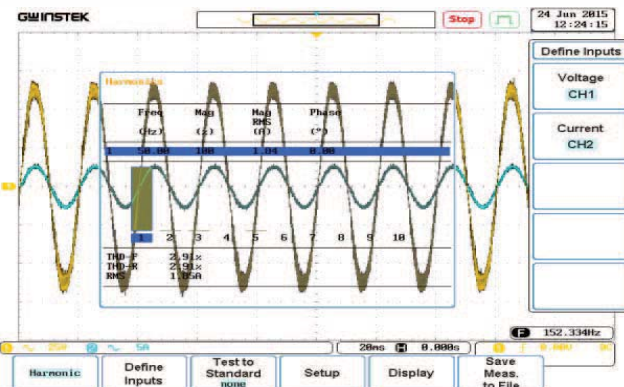
Fig. 21. Experimental results in steady state without PFC.
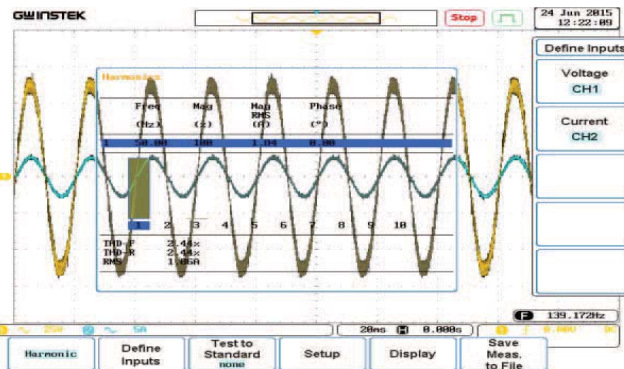

Fig. 25. PFC Output voltage using PI controller.

Fig. 22. Experimental results with PFC unsig PI controller

Fig. 26. PFC Output voltage using FLC controller.

Fig. 23. Experimental results with PFC unsig FLC controller

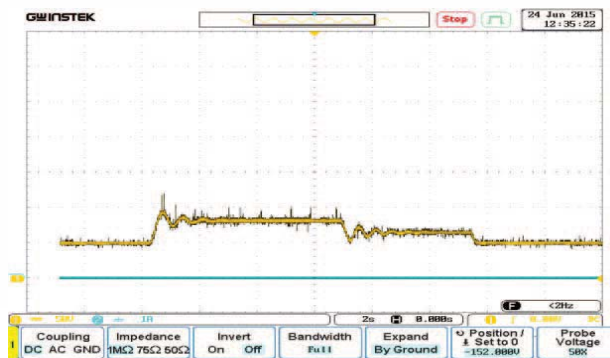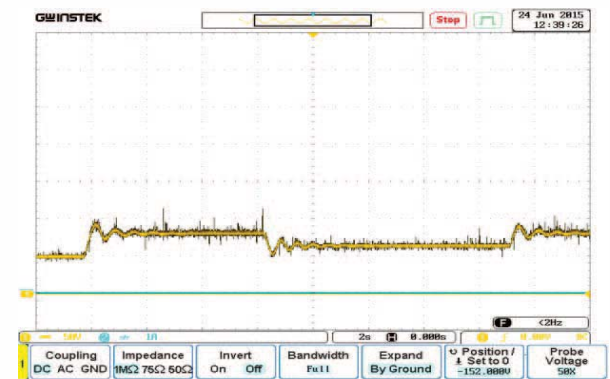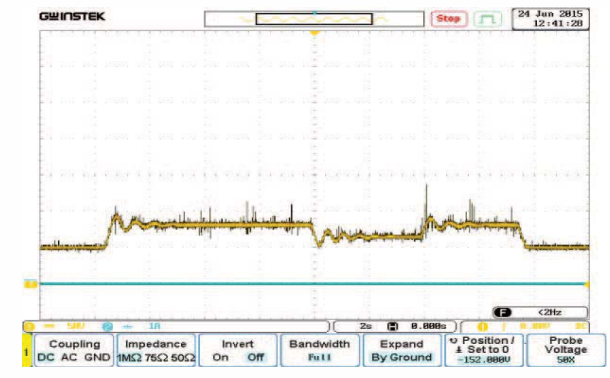Fig. 27. PFC Output voltage using fuzzy adaptive PID controller.

Experimental Test 2-System with PFC: In this test, first step the PFC was implemented at nominal loading condition with nominal output voltage (121 ohm, 100 V), Figs. 22 and 25 show the system responses with PI controller. Reduction of the THD around 2.9%, the power factor is PF=0.984. The capacitor voltage is maintained close to its reference after a short transient. In the second step, the PFC was implemented with fuzzy controller, Figs. 23 and 26 show the responses of the system, the system exhibits excellent results with PFC. Reduction of the THD around 2.44%, the power factor is PF=0.98. The dc bus voltage is maintained close to its reference after a short transient, the line current has a sinusoidal waveform and in phase with the grid voltage. In the third step, the PFC was implemented with fuzzy adaptive

Fig. 24. Experimental results with PFC unsig Fuzzy adaptive PID controller.

Condition(THD)	PI	AFLC PID	FLC
Simulation	3.01%	2.99%	2.49%
Experimental	2.91%	2.60%	2.44%

controller, Figs. 24 and 27 show the responses of the system, Reduction of the THD around 2.6%, the power factor is PF=0.98. The dc bus voltage is maintained close to its reference 100 V.

It is clear, from these results that the fuzzy control gives better performance than a conventional PI or fuzzy adaptive PID.

VI. CONCLUSION:

In this paper, the control of AC/DC converter which has a power factor near to the unit with sinusoidal line current was presented. The role of the DC bus voltage control loop is to maintain this voltage at a constant reference value by controlling the process of charging and discharging of the capacitor, by using conventional PI controller, fuzzy adaptive PID and fuzzy logic controller. The proposed controllers were simulated and experimental implemented. The results show that the FLC is more performance than the classical control (dc-bus voltage error equal to 0.9V and THD of line currents is 2.44%). The absorbed current is sinusoidal and in phase with the grid voltage with a near unity power factor. The experimental implementation show that the fuzzy controller performance is excellent, a good rejection of load variation disturbance and an excellent robustness are verified.

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