A Fuzzy-Controlled Active Front-End Rectifier with Current Harmonic Filtering Characteristics and Minimum Sensing Variables

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Abstract— **A control strategy which allows conventional voltage-source current-controlled (VSCC) pulsewidth modulation (PWM) rectifiers to work simultaneously as active power filters is presented. The proposed control strategy also allows compensating the system power factor and compensating unbalanced loads. The measurement and/or calculation of the harmonics and reactive power are not required, making the proposed control scheme very simple. The active front-end rectifier acts directly on the mains line currents, forcing them to be sinusoidal and in phase with the mains voltage supply. To improve the dynamic of the system, the amplitude of the current is controlled by a fuzzy system, which adjusts the dc-link voltage of the PWM rectifier. The strategy is based on connecting all the polluting loads between the PWM rectifier and their input current sensors. The main advantages of this approach are the following: 1) there is no need to install a specially dedicated active power filter; 2) it also works simultaneously as power factor compensator; and 3) no special and complicated calculations are required for harmonic elimination. The viability of the proposed active front-end rectifier is proved by simulation and with experimental results obtained from a 2-kVA PWM prototype.**

I. INTRODUCTION

TRADITIONALLY, passive LC filters have been used to eliminate line current harmonics and to improve the load power factor. However, in practical applications these passive second-order filters present many disadvantages such as aging and tuning problems, series and parallel resonance, and the requirement to implement one filter per frequency harmonics that needs to be eliminated. In order to overcome these problems, different kinds of active power filters, based on force-commutated devices, have been researched and developed [1], [2]. Particularly, shunt active power filters, using different control strategies, have been widely investigated. They have gradually been recognized as a viable solution to the problems created by high-power nonlinear loads [3], [4]. These filters operate as current sources, connected in parallel with the nonlinear load, and generate the current harmonic components required by the load. In this form the mains only needs to supply the fundamental, avoiding contamination problems along the distribution lines. However, shunt active filters present the disadvantages that are difficult to implement in large scale, the control is complicated [5], [6], and the cost is high.

To reduce those drawbacks, the solution proposed in this paper is to use a conventional four-quadrant voltage-source current-controlled (VSCC) pulsewidth modulation (PWM) rectifier simultaneously as a shunt active power filter. This is accomplished by simply connecting all the polluting loads between this rectifier and their line current sensors. This solution reduces the cost of the filter to almost zero because there is no need to install a specially dedicated power device for harmonic elimination. Besides, this approach presents the following particular characteristics: 1) the four-quadrant rectifier–inverter system can operate as an active filter and as a power factor compensator simultaneously; 2) it also can operate to compensate unbalanced loads; and 3) the control block is quite simple because there is no need to evaluate and/or to sense the current waveforms of the polluting loads.

II. PRINCIPLES OF OPERATION

Fig. 1(a) shows the schematic of the proposed control strategy, which is being applied to a conventional VSCC PWM rectifier. The control only needs to measure the dc-link voltage ($V_{\rm dc}$) and the mains line currents ($I_{\rm MAINS}$). As it can be observed, neither the polluting load current ($I_{\rm LOAD}$) nor the rectifier ($I_{\rm RECT}$) current need to be measured. This fact is very important because almost any current-controlled PWM rectifier can be used as a shunt active power filter, without the need of additional electronic circuitry. All polluting loads (three-phase polluting loads in Fig. 1) are connected between the rectifier and their current sensors. By doing that, the rectifier behaves as a shunt active power filter, but without loosing its characteristics as a four-quadrant rectifier. The current-controlled rectifier does not detect the proximity of the nonlinear load. It simply try to keep the mains current sinusoidal because the current sensors are located at the mains side, and they follow a sinusoidal template. In this way, there is no need to sense and/or calculate, neither the polluting load current nor the filter current. In this way, the PWM converter can operate as a four-quadrant rectifier, as a power factor compensator, and as an active power filter simultaneously. It can also compensate unbalanced loads. In other words, it works as a multiple-function power converter. The control strategy is conventional in the sense that the dc-link voltage of the rectifier is controlled by adjusting the amplitude of the input ac currents. Due to the multiple capability of this

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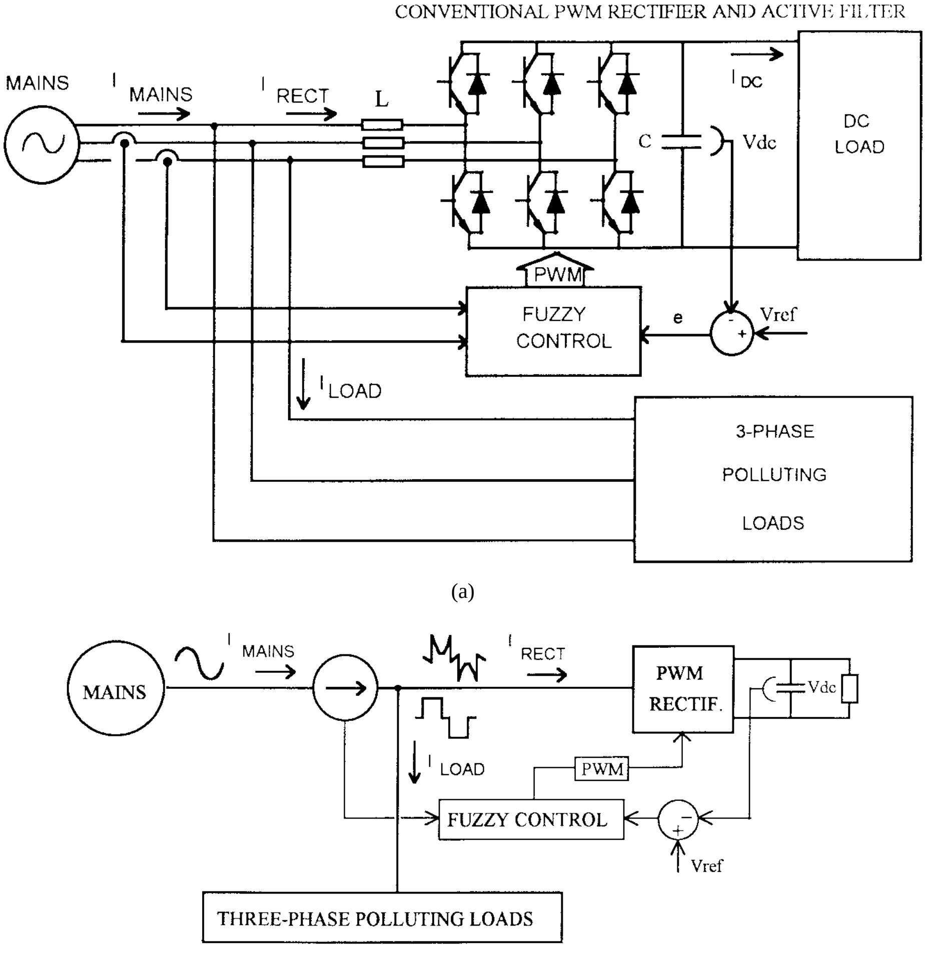


Fig. 1. Active power filter proposed. (a) Physical implementation. (b) Block diagram with current sensor working as sinusoidal current source.

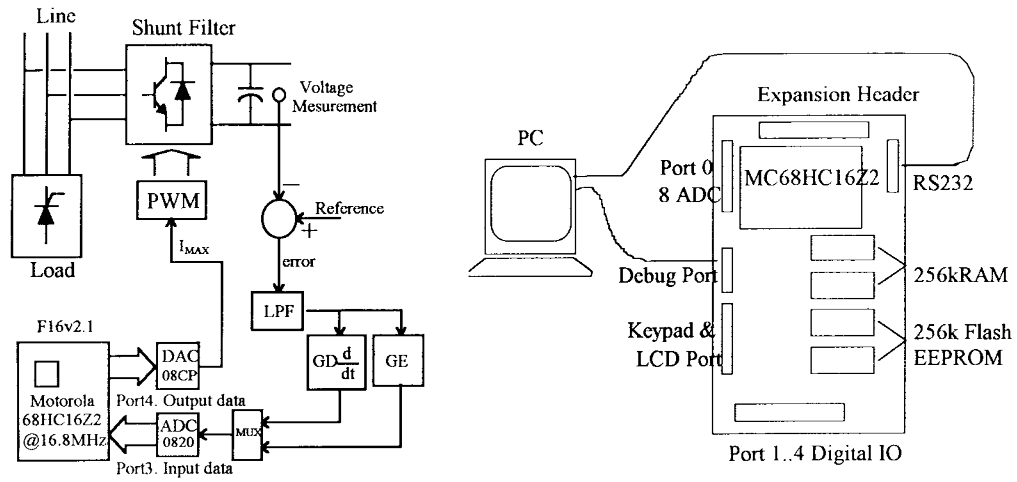
approach, a good dynamic response is required. For this reason, a fuzzy control in the dc link has been implemented, which allows more flexibility and better dynamic response.

It is important to explain how the rectifier can manage the filtering and compensation requirements without measuring the load harmonics. First, with the help of current sensors connected in the mains lines, the line currents $(I_{\rm MAINS})$ are being forced to follow a sinusoidal reference template. This template is followed using a current-hysteresis controller (or other current control method), which is driving the transistors of the PWM rectifier. In this way, if a nonlinear load is connected after the point where the current sensors are located, their harmonics will not be allowed to go through the power distribution system. This situation happens because the current sensors force the lines to behave as sinusoidal current sources connected in series to the mains, as shown in Fig. 1(b). Then, the mains behaves as a high-impedance circuit for harmonics, and hence these currents are forced to flow through the PWM rectifier. This behavior is similar to that of a series active filter which presents a very high-impedance path for the harmonics going to the power system. In other words, the control strategy proposed not only make the PWM rectifier work as a shunt active filter, but also as a series active filter simultaneously. The fact that the harmonic currents are forced to flow through the PWM rectifier makes the filtering requirements more stringent in the dc bus of the rectifier $(V_{\rm dc})$ because their input currents are now contaminated. That means more dc capacitors at the dc-link rectifier. However, the harmonics flowing into the system have been eliminated, and the power factor has been compensated, without the need of a specially dedicated active power filter.

III. Power Circuit Implementation

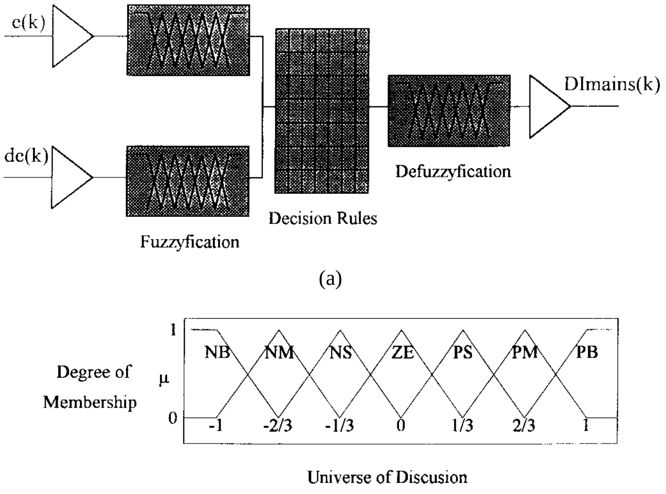
The proposed front-end rectifier prototype was implemented with a 2-kVA four-quadrant current-hysteresis-controlled insulated gate bipolar transistor (IGBT) converter. As a polluting load, a three-phase diode rectifier with an input inductance and an "RL" dc load was connected. The block called fuzzy control in Fig. 1 generates the three sinusoidal templates to control the magnitude of the mains current $I_{\rm MAINS}$. These magnitudes are controlled by adjusting the error between the dc-link voltage $V_{\rm dc}$ of the PWM rectifier and a preestablished reference voltage $V_{\rm ref}$ as shown in Fig. 1. The sinusoidal template is synchronized with the phase to neutral mains voltage, and can be adjusted to be "in phase" with the mains voltage supply. In this way, the mains will see a noncontaminated and balanced load, operating at unity power factor.

In the first experiments after the hardware was finished, a proportional–integral (PI) control was implemented. Despite this control, it worked fine, but the dynamics were not as



(a) (b)

Fig. 2. (a) Fuzzy control loop. (b) PC interface for programing and debugging.



(a)

(b)

Fig. 3. (a) Fuzzy control block. (b) Unitary discussion universe.

good as required. For this reason, a fuzzy controller was tested, which showed to be superior in performance than PI control, even considering that until now only a few characteristics of this controller have been investigated. This means that there is a lot of room for research in this option waiting for better results, and then this is a very good reason to adopt the fuzzy system in this proposed scheme. Even more, a final adjustment can been reached using dedicated hardware for the fuzzy sets, such as EPROM's or PLA's.

The fuzzy controller has been implemented with a microcomputer called "Freedom16," v2.1 from Intec Inoventures, Inc. [8]. This board is built around Motorola's 16-b 68HC16 microcontroller. This device not only has more computer capabilities than a PC-AT, but also features digital signal processing (DSP) capabilities, and a host of specific features such as pulse counting, high-speed inputs and outputs, and eight channels of ten analog–digital (A/D) conversion. The board has the advantage that it can be programmed in "C" language through a PC serial interface and can be debugged through the parallel port. Once the program is finished, the Freedom16 can be programed in a ROM for a stand alone operation.

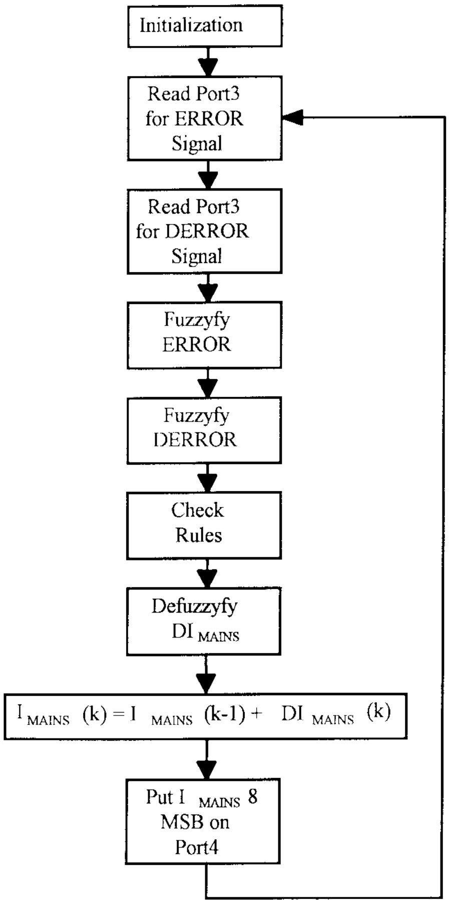
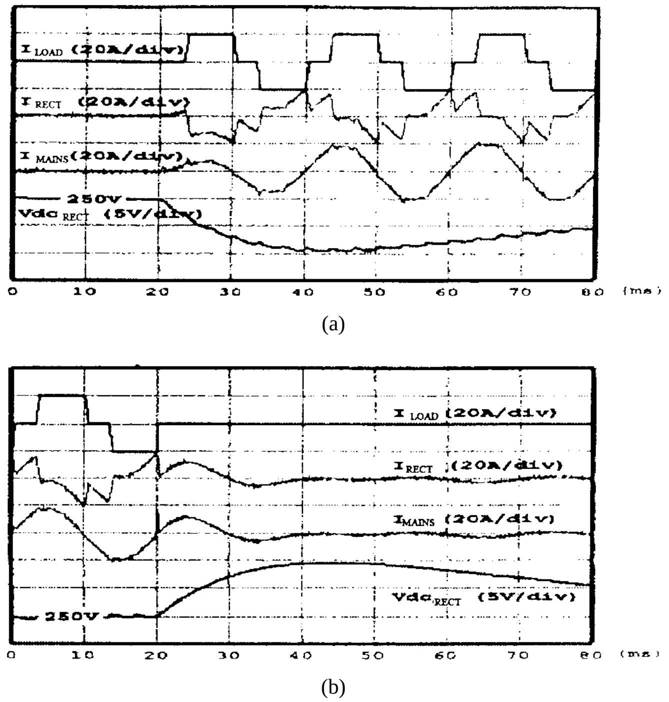


Fig. 4. Flowchart of the fuzzy control.

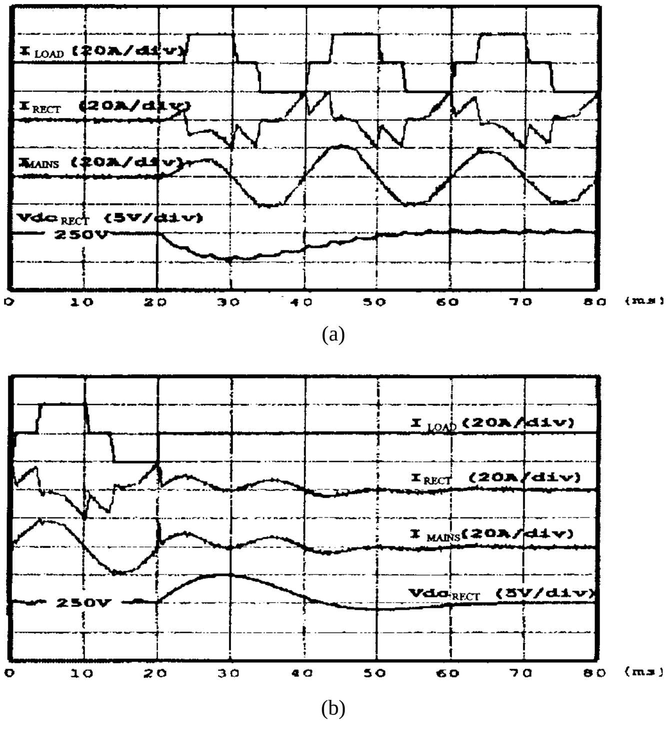
Despite the F16 has eight A/D converters, the control was implemented with an external 8-b converter. In this form, was possible to increase the conversion time and produce a faster response in the control loop. As the F16 does not support digital–analog (D/A) conversion, the output was also implemented with an external 8-b D/A converter. The Fig. 2(a)



(a)

(b)

Fig. 5. Transient response with PI control. (a) From 0 to 20 [A] load current. (b) From 20 to 0 [A] load current.



(a)

(b)

Fig. 6. Transient response with fuzzy control. (a) From 0 to 20 [A] load current. (b) From 20 to 0 [A] load current.

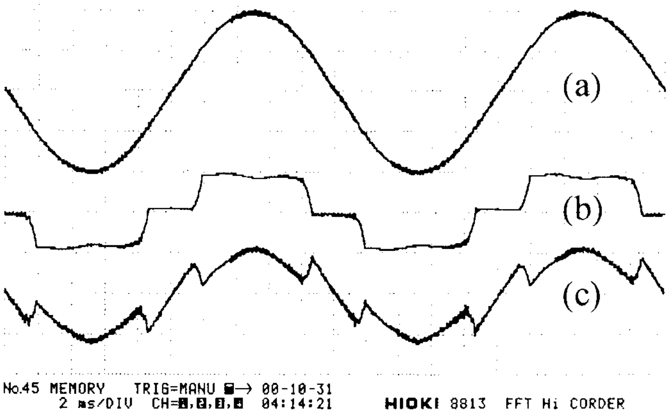


Fig. 7. Steady-state operation. (a) Line current I_{MAINS} (4 A/div). (b) Load current I_{LOAD} (4 A/div). (c) Filter current I_{RECT} (4 A/div).

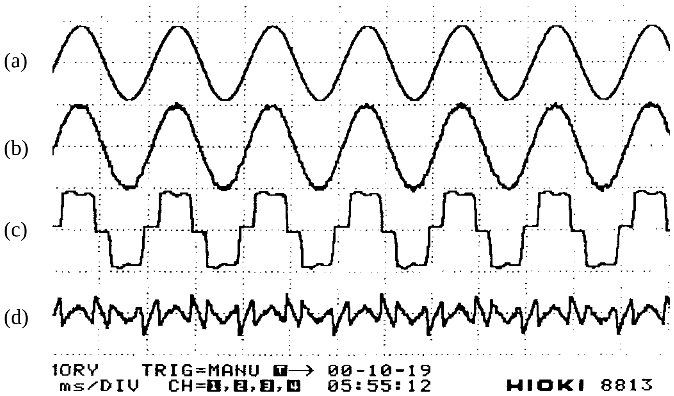


Fig. 8. In-phase operation of the system. (a) Phase-to-neutral source voltage [50 V/div]. (b) Source current I_{MAINS} [4 A/div]. (c) Current through the nonlinear load I_{LOAD}. (d) Current through the active power filter I_{RECT}.

shows the hardware implementation for the fuzzy control loop, and Fig. 2(b) shows the PC interface for programing and debugging in F16.

IV. SOFTWARE IMPLEMENTATION

To implement the fuzzy control strategy, a PI fuzzy control with 49 rules was selected [7], [9]. The inputs are the error voltage $\mathbf{e}(\boldsymbol{k})$ and its incremental variation $\mathbf{de}(\boldsymbol{k})$. The output is the amplitude of the mains current $\mathbf{I}_{\mathbf{mains}}(\boldsymbol{k})$. In order to compensate the ac system power factor (power factor compensator), the mains currents are kept in phase with the respective phase to neutral mains voltage. Fig. 3(a) shows the fuzzy control scheme implemented.

The main characteristics of the fuzzy control are the following:

1) seven fuzzy sets for each of the two inputs;
2) seven fuzzy sets for the output;
3) triangular membership functions;
4) fuzzyfication using continuous universe of discourse;
5) implication using the "*min*" operator;
6) inference mechanism based on fuzzy implication;
7) defuzzyfication using the "*centroid*" method.

All fuzzy variables have the same partition and membership functions. The fuzzy control has seven membership functions called from negative big (NB) to positive big (PB). The Fig. 3(b) shows a unitary discussion universe which can be modified by simple gain on each variable. The idea of this partition is to simplify the number of calibration variables, reducing them to one gain for each variable: GE for error, GD for error derivative (derror), and finally GU for DI_{mains}. The final output of the system is calculated as $I_{\mathrm{mains}}(k) = GU * DI_{\mathrm{mains}}(k) + I_{\mathrm{mains}}(k-1)$. Fig. 4 shows the flowchart for the software implementation.

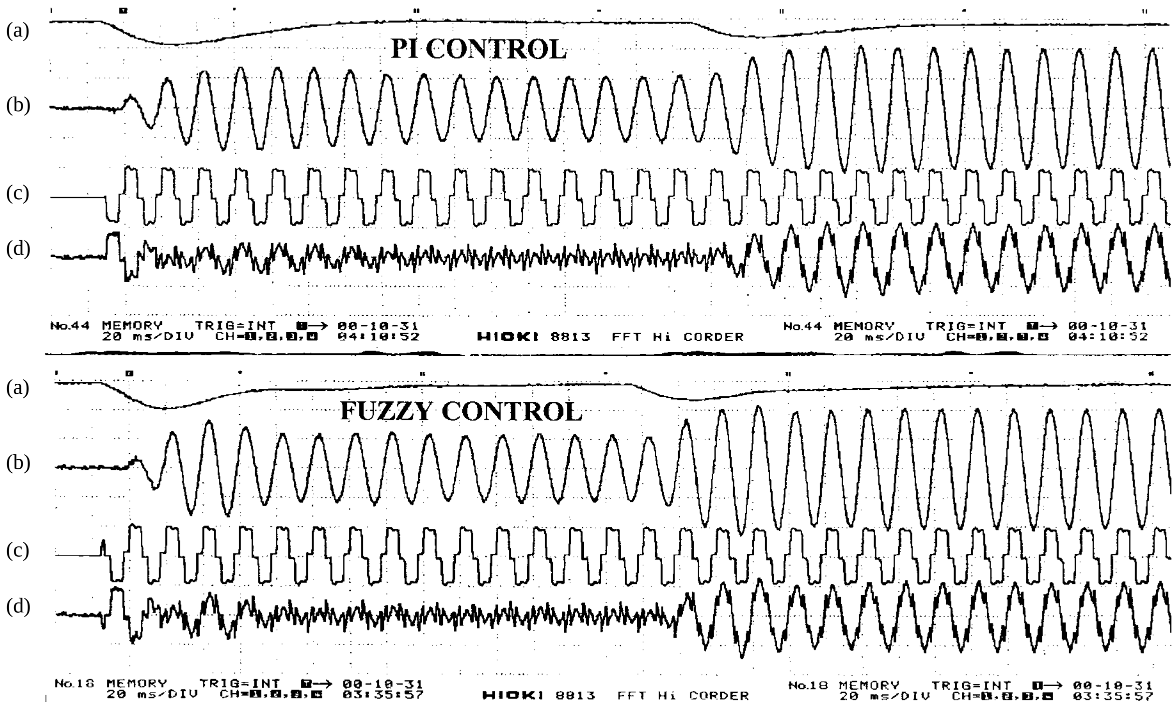


Fig. 9. Comparison between PI control (upper signals) and fuzzy control (lower signals). (a) The dc-voltage drop in $V_{\rm dc}$ [25 V/div]. (b) Source current $I_{\rm MAINS}$ [4 A/div]. (c) Nonlinear load current $I_{\rm LOAD}$ [4 A/div]. (d) Filter current $I_{\rm RECT}$ [4 A/div].

V. Simulation Results

Simulated results were obtained using Pascal 7.0 Borland. Some simulations were performed with a thyristor rectifier as a nonlinear load, with different firing angles, and different voltage and current levels. However, the simulations shown in this paper have been programmed to match with the ratings and characteristics of the experimental prototype. Figs. 5 and 6 show a comparison between simulated results obtained with the PI control and fuzzy control. The nonlinear load is a diode rectifier, and the parameters of the simulated filter are: $V_{\rm dc} = 150$ [V], $L = 2.5$ [mH], and $C = 7,400$ [uF]. In 1), a step change from 0 to 3 [A] in the load current (diode rectifier) is displayed. In 2) the opposite situation (from 3 to 0 [A]) has been simulated. It is clear that the transient response in the mains current and in the dc-link voltage is faster with the fuzzy control scheme. With fuzzy logic, the dc voltage in the filter $(V_{\rm dc})$ is recovered in less than 40 [ms] (two cycles), but with conventional PI, the same situation takes more than 60 [ms]. The parameters of the PI control were $K_p = 6$ and $K_i = 167$. For the fuzzy system, the calibration variables were adjusted to the following values: $GE = 3$, $GD = 40$, and $GU = 1$.

VI. Experimental Results

For the experiments, a 2-kVA four-quadrant current-controlled PWM rectifier, such as the one shown in Fig. 1, was used. In order to prove that the four-quadrant rectifier can operate simultaneously as rectifier and as active power filter, a resistor was connected at $V_{\rm dc}$ (dc load). On the other hand, the "three-phase nonlinear load" of Fig. 1 was implemented with a diode rectifier connected to the mains. The PWM rectifier was implemented with IGBT's, and their main components were: $C = 7400$ μF and $L = 2.5$ mH. The dc-link voltage $(V_{\rm dc})$ was adjusted to 150 V. The settings for the PI and fuzzy control were adjusted to be almost the same as the simulations.

Fig. 7 shows the waveforms obtained for steady-state operation. The first oscillogram [see (a)] shows the mains (source) current. The second [see (b)] shows the current through the nonlinear load (diode rectifier), and the third [see (c)] shows the current through the active power filter (four-quadrant PWM rectifier). It can be observed that the waveform of the mains current is quite sinusoidal, proving the good performance of the proposed control strategy.

Fig. 8 shows the in-phase operation of the input current respect to the mains voltage supply (unity power factor operation). The first oscillogram [see (a)] shows the source voltage. The second [see (b)] shows the source current. The third [see (c)] shows the current through the nonlinear load (diode rectifier), and the fourth [see (d)] shows the current through the active power filter (four-quadrant PWM rectifier).

Fig. 9 shows a comparison between PI control (upper signals), and fuzzy control (lower signals). The first oscillogram of each experiment [see (a)] shows the dc-voltage drop when $V_{\rm ref} = 100$ V. The callouts (b)–(d) show the source current $(I_{\rm MAINS})$, the nonlinear current $(I_{\rm LOAD})$, and the filter current $(I_{\rm RECT})$, respectively. In this experiment, two step changes were generated. In the first step, a dc load at the diode rectifier output terminals is connected. This situation simulates the sudden connection of a *nonlinear load*. In the second step, a dc load is directly connected at the dc link of the active power filter (conventional PWM rectifier and active filter). The oscillograms prove that the fuzzy control recovers the steady state in a shorter time, which justifies the utilization of such a control method. The scales are: $V = 25$ V/div and $I = 4$ A/div. The maximum switching frequency in the current-hysteresis controller is 16 kHz. The source frequency is 50 Hz.

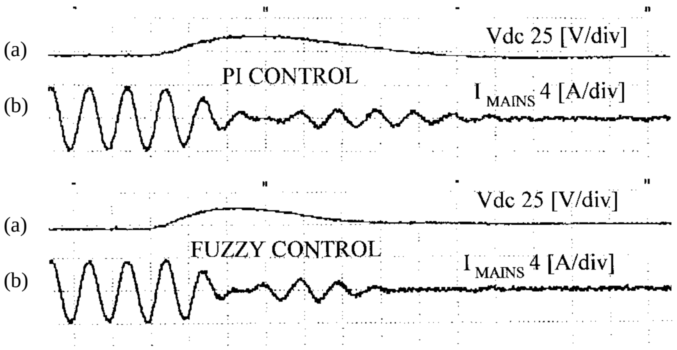


Fig. 10. Transient response for a sudden disconnection of the load at the active filter dc link. (a) The dc-link voltage for $V_{\mathrm{ref}} = 100$ V. (b) Line current I_{MAINS}.

Finally, Fig. 10 shows the transient response obtained for a sudden disconnection of the load at the active power filter dc link. The upper oscillograms are for PI control, and the lower correspond to fuzzy control. Again, it is possible to realize that fuzzy has better dynamic behavior than PI control. It can be noticed that there is a power reversal in the load current to allow fast recovery of the dc-link capacitor voltage. The oscillograms show: 1) the dc-link voltage error (25 V/div) and 2) the input source current (4 A/div). The diode rectifier was not connected, but the transient response in that case is quite similar.

VII. CONCLUSIONS

Power factor and harmonic compensation can be done without additional equipment. A control strategy which allows a conventional PWM rectifier to operate simultaneously as active power filter has been presented. The proposed active front-end rectifier also can compensate the system power factor. The measurement and/or calculation of harmonics and reactive power is not required, making the control proposed very simple. The sensors acts directly on the mains line currents, forcing them to be sinusoidal and in phase with the mains voltage supply. Two kinds of controllers have been evaluated to command the dc-link voltage of the PWM rectifier (active power filter): conventional PI control and fuzzy control. The fuzzy control demonstrates better dynamic behavior than conventional PI control and for this reason was chosen as a good alternative for the stringent requirements of dynamic response of this multiple-function converter. The main advantages of this approach are the following: 1) the control block becomes simpler because there is no need to sense or evaluate the current template for filtering requirements and 2) the equipment costs are minimized because the same four-quadrant rectifier–inverter system can operate simultaneously as an active power filter, as a power factor compensator, and as a compensator for unbalanced loads.

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REFERENCES

[1] H. Akagi, Y. Kanazawa, and A. Nabae, "Instantaneous reactive power compensators comprising switching devices without energy storage components," *IEEE Trans. Ind. Applicat.*, vol. IA-20, pp. 625–630, May/June 1984.

[2] H. Akagi, A. Nabae, and S. Atoh, "Control strategy of active power filters using multiple-voltage source PWM converters," *IEEE Trans. Ind. Applicat.*, vol. IA-20, pp. 460–465, May/June 1986.

[3] W. M. Grady, M. J. Samotyj, and A. H. Noyola, "Survey of active power line conditioning methodologies," *IEEE Trans. Power Delivery*, vol. 5, pp. 1536–1542, July 1990.

[4] L. Malesani, L. Rosseto, and P. Tenti, "Active filters for reactive power and harmonic compensation," in *Proc. IEEE PESC'86*, June 1986, pp. 321–330.

[5] J. Dixon, J. García, and L. Morán, "Control system for three phase active power filter, which simultaneously compensates power factor and unbalanced loads," *IEEE Trans. Ind. Electron.*, vol. 42, pp. 636–641, Dec. 1995.

[6] S. Tepper, J. Dixon, G. Venegas, and L. Morán, "A simple frequency independent method for calculating the reactive and harmonic current in a nonlinear load," *IEEE Trans. Ind. Electron.*, vol. 46, pp. 647–654, Dec. 1996.

[7] B. K. Bose, "Expert system, fuzzy logic, and neural network applications in power electronics and motion control," *Proc. IEEE*, vol. 82, pp. 1303–1323, Aug. 1994.

[8] *Freedom 16 Advanced 16 bit Controller, User's Manual.*, Intec Inoventures, Inc., Victoria, B.C., Canada.

[9] R. Dorf, *Modern Control Systems*. Reading, MA: Addison-Wesley 1989.

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