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Microcomputer Control of a Fuel Cell Power System

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Abstract—**Microcomputer-based control of a fuel cell power conditioning system conected directely to the public grid is described. The control functions are implemented using Intel 8XC196KD20 single-chip microcontroller-based hardware and software. The microcontroller is responsible for protection fuel cell, secuencing control, some diagnostics and protections. Moreover, a reactive predictive control has been used in the system to compensate the reactive energy of load in the grid. The controller has been tested in the laboratory with the prototype power conditioner and shows excellent performance.**

I. INTRODUCTION

At present, hydroelectric, thermal and nuclear generating systems are usually used to generate electric power. All of them use rotating machines that generate power through electro-mechanical energy conversion. Fuel cells, in principle, convert chemical energy into electrical energy. A generating system similar to a conventional generating system can also be considered because this system generates electric energy as long as fuel is supplied continuously from outside [1].

In this paper a complete design and implementation of a power conditioning system for a 10 KW PAFC fuel cell is presented. In particular, this prototype has been used as a previous step to study the problems that can appear in the fuel cell conection to the public electrical grid.

The main designing constraints for the power conditioning system have been high efficiency, reduction of space requiered for installation and continuous stable operation. In order to achieve a very high efficiency in the system, it was necessary to use the most optimum component in the power circuit, because the output voltage generated by the fuel cell was low (80V), meaning that the system has to work with strong currents to delivery high power. It has also been very important to avoid high harmonic currents due to the inverter circuit behaviour, so that damage doesn't appear in the fuel cell [2][3].

The control of this system has been implemented by a microcomputer. The microcontroller is responsible for protection fuel cell control, sequencing control, some diagnostics and protections. But there are three additional characteristics of this controller, because the power system conditioning is conected directely to the grid: The first, is that the system is able to compensate the reactive energy of load in the public grid, and the second is that the delay betwen the grid voltage and the generated current can be controlled, achieving, in some cases, a rectification of working conditions in the system, extracting energy from the public grid, and loading some storage devices. The third characteristic is that the power system can be programed to inject current harmonics with its corresponding delay. This will be used to compensate harmonics that it has been generated by non-linear load in the public grid. The control functions are implemented using Intel 8XC196KD20 microcontroller which has been tested in the laboratory with the prototype power conditioner, showing excellent performance. Experimental power results are given, confirming the feasibility of the proposed implementation.

This paper is organized as follows: section II summarizes the description of a power conditioning system and its technological problems in the choice of the components. In section III, the description of the control system and the reactive energy compensation is shown. Finally, section IV shows the electronic implementation of the power conditioning system and experimental results are then presented.

II. POWER CONDITIONING SYSTEM

Fig. 1 shows the block diagram of the conditioning system.

A. *PAFC Power Plant*

The PAFC power plant is base on the use of a steam reformer with a phosphoric acid fuel cell stack. The power plant system concept is shown in Fig. 1(a). Liquid fuel is fed to the reformer. This generates hydrogen which,

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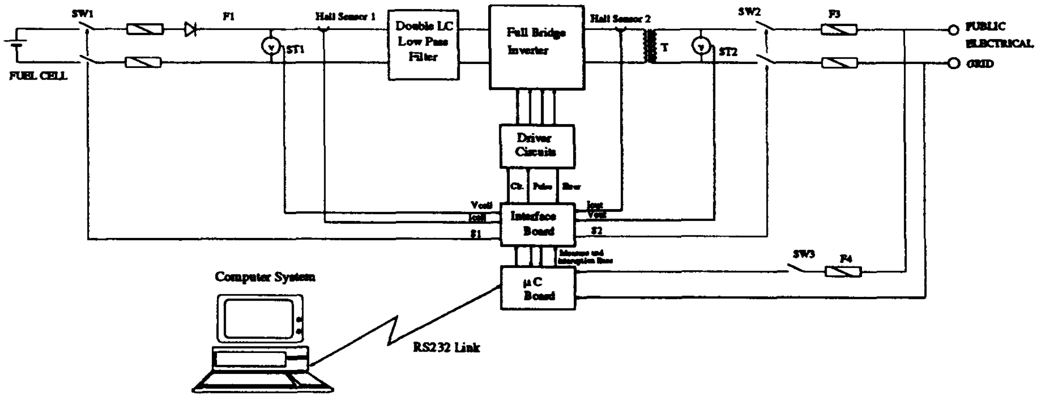

Figure 1: Fuel Cell Conditioning System.

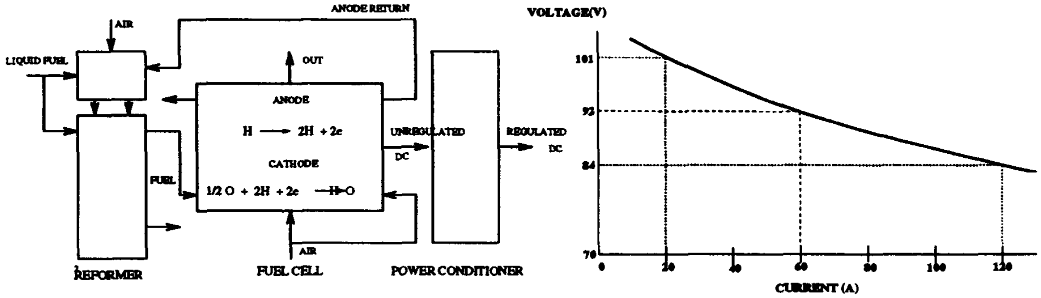

Figure 2: a) Phosphoric Acid Fuel Cell Power Plant Diagram. b)Characteristic DC output behaviour of the fuel cell.

together with water vapor and byproduct carbon dioxide, flows to the fuel cell stack. Most of the hydrogen is converted to DC electricity in the stack. The residual hidrogen is converted to DC electricity in the stack. The stack has an output of 10 KW at 80-100 V DC. The characteristic DC output behaviour of the fuel cell is shown in Fig 2(b).

B. DC/AC Power Converter Circuit

The scheme simplificated of power circuit is shown in figure 3.

Input Filter: The fuel cell has a strong requirement in the output current ripple. When this was applied it was necessary to design a special input filter to avoid ripple (less than 1% in the input DC/AC power current). It consists in two LC low pass filter, found by an analytical method and checked by simulations. The input filter parameters are shown in schematic circuit in Fig. 3. The auxiliary diode D_1 is used to prevent inverse current back tracking to the power supply, because this can damage the fuel cell [4][5][6].

Full-Bridge Topology: Due to the design specifications, the full-bridge topology has been chosen for the inverter circuit [7][9]. The first reason to choose the power switches was the low-voltage and high current in the input bridge so that MOSFETs have been chosen. Furthermore, MOSFETs can operate at higher switching frecuency and the anti-parallel body diode of MOSFET can be employed, thus reducing the number of components needed. A full-bridge was mounted to obtain greater peak power output than 15KVA, to secure reliable operation and nominal power delivered. For these reasons, eight doubles MOSFETs modules (81A, 200V) were used in each branch, mounted on a radiator and then cooled by a fun. Two integrateds drivers were used which secure correct operation until 25KHz. It was necessary to use a link capacitor, mounted on the same radiator to secure correct current delivery for each MOSFET. Finally, polarized snubber circuits (Fig. 3) were required to limit the reapplied dv/dt cross switches and the maximum peak voltage to 200V. [4]

Smoothing Inductor: The rating change of the current slope is determined by the smoothing inductor. For its design, was considered the minimum input voltage in the bridge and the maximum power rating of the inverter. Bearing this in mind, the smoothing inductor value was theoreticly determined.

Output Transformer: The output transformer was designed for a maximum power of 20KVA, and it adapts the bridge ac voltage at the public grid. It also has three different turn ratios in order to compensate tolerance in local ac power supply. It uses a very thin steel plate to achieve minimum loss and best frecuency response. For this design, the minimum voltage of the fuel cell, input ripple voltage and resistances of the active and passives components at high frecuency was considered.

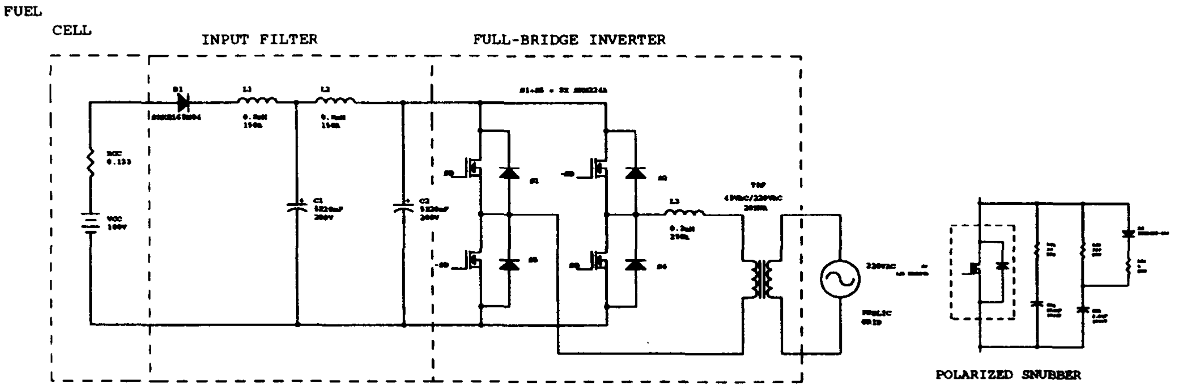

Figure 3: a)DC/AC Power Converter Circuit. b) Snubber circuit.

III. CONTROL CIRCUIT

A. Control Characteristics

The power system is controlled using a Bang-bang current control method, with constant frequency and a null deadband around the reference current to provide a faster transient response. A sinusoidal reference signal has been generated which must then be followed by real current injected by the power system. The sample frequency is fixed by the control system. Each sample step, and injected current in the public grid is read by the microcomputer. Next, it is compared with the reference value that has been internally generated and according to this, the appropiate device is switched on (off), forcing the current to follow the reference. The control specifications are the following:

Active power control: The power system is controlled to inject active power into the public grid. As the reference signal, the value of the current given by the fuel cell is used. This reference is compared with the actual current given by the cell, forcing an increase or decrease of the power injected by the cell, achieving the requirements programed.

Reactive power control: The power system is controlled to inject reactive power in the public grid. Two kinds of controls are used:

Open loop reactive control. In this case, an active power reference signal is commanded to follow the inverter system. Reactive power is then programed to be added to the active power and injected into the public grid. The programed delay could be between 0° and 360° so the system could work injecting or absorbing active and reactive power (if the power is not supplied by a fuel cell).

Close loop reactive control. In this case, a reactive predictive control to compensate the value of the reactive power has been used which has been generated by a non linear load in the public grid. The reactive current is estimated by the control system and is compensated by injecting the necessary reactive power. The way to do this is by reading the delay between the current and the voltage and the value of the RMS current that flows in the public grid. The scheme of this control system is shown in Fig. 4. Fig. 5 shows a sample diagram of the reactive control strategy [10][11].

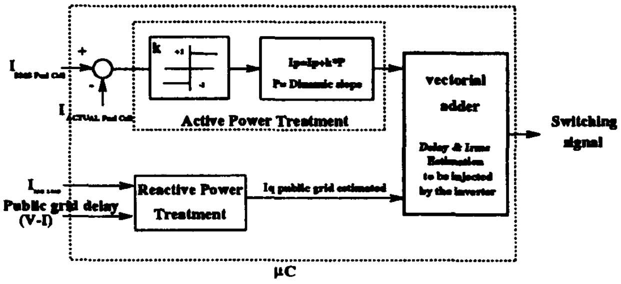

Figure 5: Reactive control strategy diagram.

Harmonic Compensation. The power system can be programed to inject third, fifth, seventh and ninth current harmonics with its corresponding delay. This can be used to try and compensate harmonics that were generated by non-linear load in the pubic grid.

B. Hardware and Software Implementation

An Intel 8XC196KD20 microcontroller has been used to implement the power conditioning control system. It was necessary to design an electronic interface between the power circuit and the microcontroller to establish the current comparation. The sinusoidal reference, internally generated by the microcontroller, takes place each 50 μs, generating the switching signal to the appropriate power semiconductor so that the frecuency used was 20 KHz. A complete scheme of the system control is shown in Fig. 1, where it is possible to observe the control variables. An RS232-c serial communication has been programed to monitor the system variables (including alarm levels to provide the system a security margin operation) and to command the system (go and stop signals, to set requiered control and the reactive power and harmonics reference in open control loop working conditions) To avoid any kind of damage to the power system, the control system has

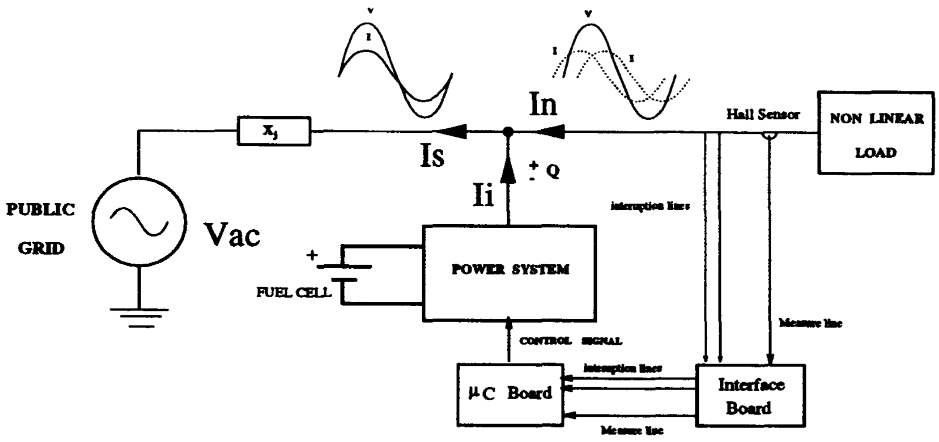

Figure 4: Reactive Predictive Control Diagram.

been provided with many kinds of software protection to detect any abnormal behaviour. The control program has been developed using interruptions to provide sincronicity between the power system and the public grid.

C. Interface

The input and output voltages and currents are measured and transfered to the microcomputer input voltage level using galvanic isolation, *RMS* and operational amplification level conversion (Fig. 6). Another design characteristic is the zero cross detection in the interface board. The output is optoisolated with a Schmitt Trigger circuit isolator. This is shown in Fig 7. The level conversion interface board is possible to adapt to all rating voltages and currents. This task is made by changing the current sensor to another range and the divisor resistors to the voltage measured. The primary current of the transformer is fed back to the microcontroller in order to perform, with constant frecuency and Bang–Bang current control. The driver circuits, interface, and microcontroller boards can be integrated becoming a low cost industrial version controller.

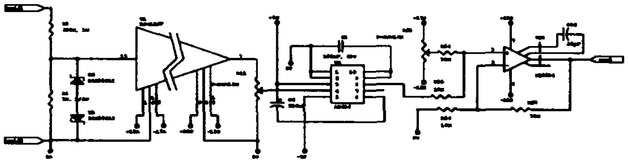

Figure 6: RMS measure.

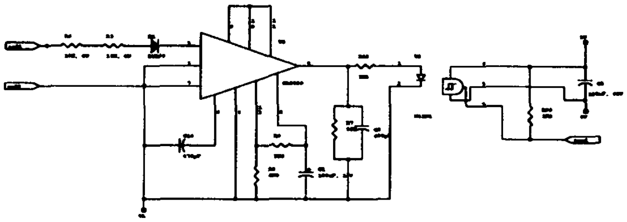

Figure 7: Zero cross detection.

IV. EXPERIMENTAL RESULTS

A prototype has been used in the laboratory for performance testing Figs. 8 and 9. Fig. 10 shows the current measured in the inverter output, and the AC voltage measured in the grid terminal with unity power factor.

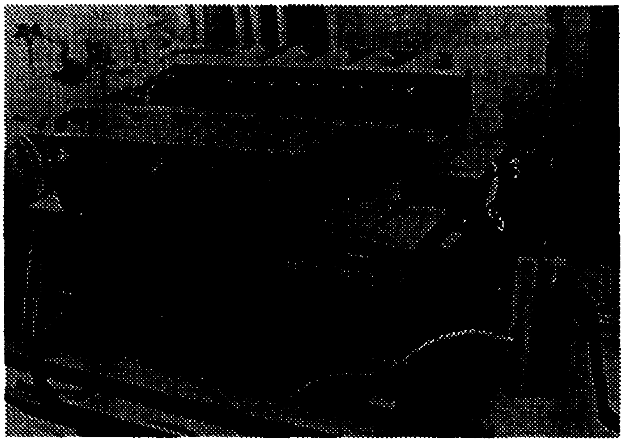

Figure 8: Photograph of the prototype (Inversor).

In the reactive control mode, the circuit operates with a delay in the current. Fig. 11 shows the current delayed by 90°. The inverter can be required to work as a rectifier during the time of low load of the public grid. Fig. 12 shows an excellent controlled rectification without disturbing the public grid. It can be seen in Fig. 12 that the input current is controlled with unity power factor and very low harmonic distortion. The power system conditioning is conected directely to the grid, and so the system is to able to compensate reactive energy of load in the public grid. In Fig 13 is shown the AC voltage and the injected current I_S for a load of (4KVA) without

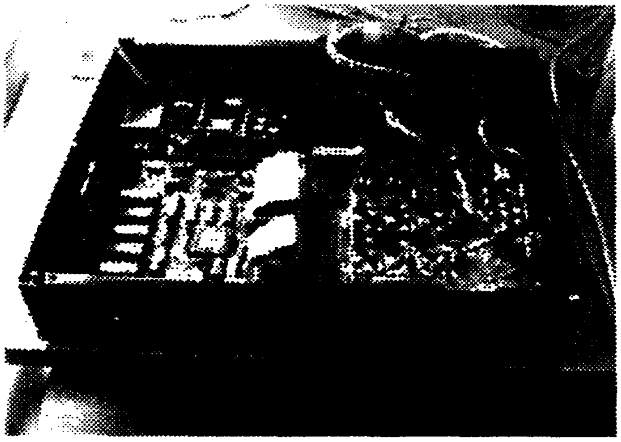

Figure 9: Photograph of the prototype (Control System).

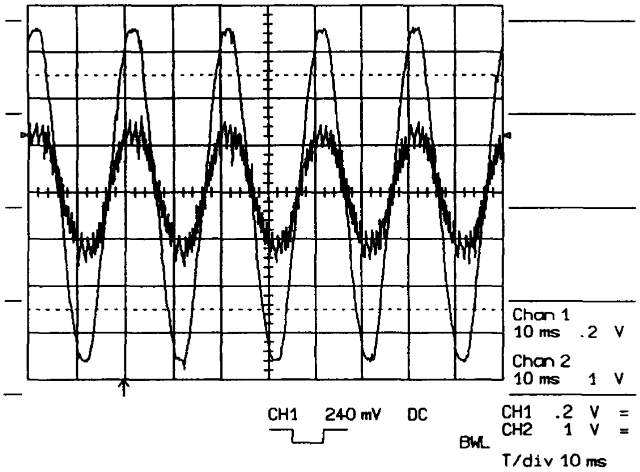

Figure 10: Experimental curve showing AC voltage and Injected current I_S with unity power factor ($\phi = 0$).

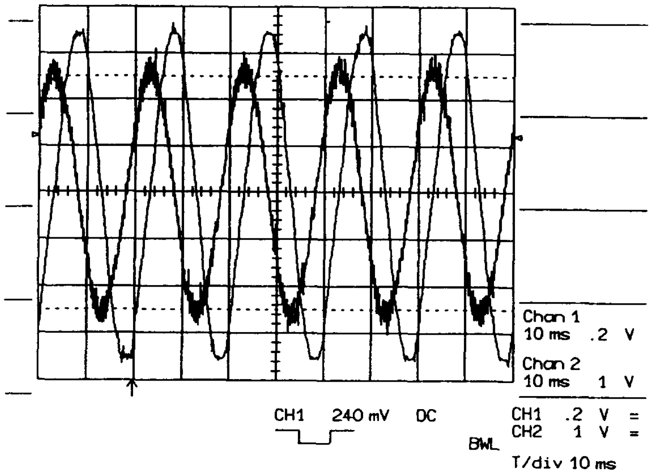

Figure 11: . Experimental curve showing AC voltage and injected current I_S with a zero power factor ($\phi = -90$)

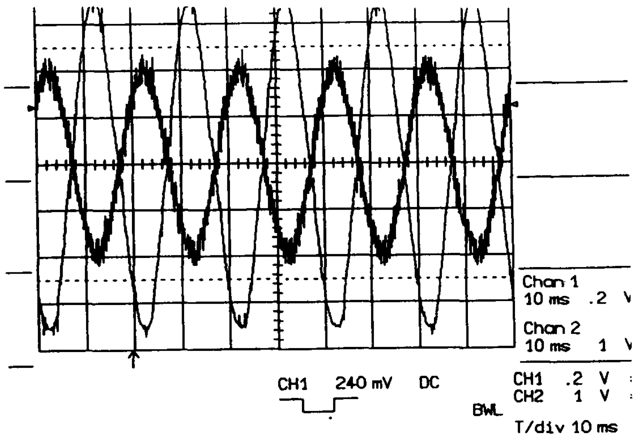

Figure 12: Experimental curve showing AC voltage and injected current I_S working as a controlled rectifier ($\phi = -180$)

reactive power compensation. In next Fig. 14 we can see the injected current I_S when reactive power compensation control is working with the same load. In this case, the AC votage and injected current I_S have unity power factor. In Fig 15 the injected current I_S is shown when the reactive power compensation is working but not the harmonic compensation. This figure also shows the harmonic spectrum of injected current in the public grid. The amplitude of the third, fifth, seventh and ninth of injected current harmonics are high. These harmonics can be compensated injecting a suitable current by the inversor I_I. Fig. 16 represents the same injected current I_S when the harmonic compesnation is working. Its spectrum shows a large improvement in the reduction of these harmonics, confirming the validity of the proposed compensation.

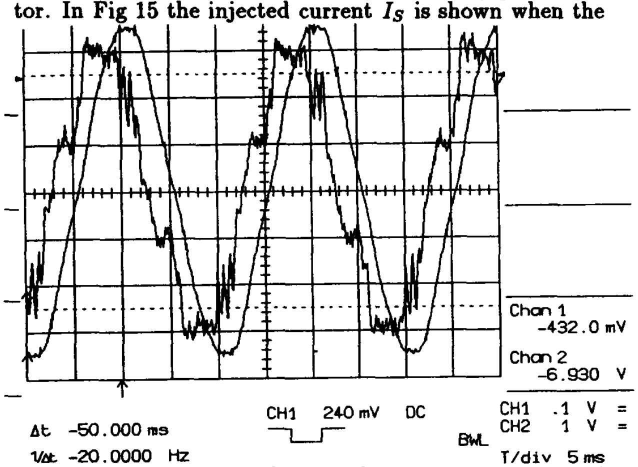

Figure 13: Experimental curve showing AC voltage and injected current I_S working without reactive power compensation control.

V. CONCLUSION

In this paper a complete design and implementation of a power conditioning system conected directely to the public grid for a 10 KW PAFC fuel cell is presented. The control functions are implemented using Intel

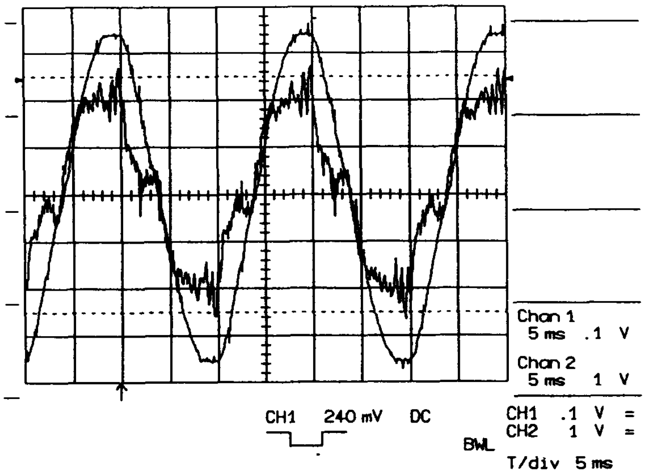

Figure 14: Experimental curve showing AC voltage and injected current I_S working without reactive power compensation control.

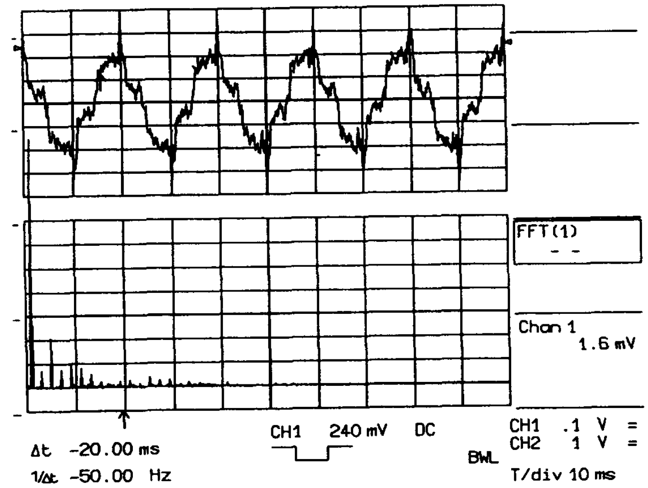

Figure 15: Experimental curve showing injected current I_S and its spectrum when the reactive power compensation is working but not the harmonic compensation.

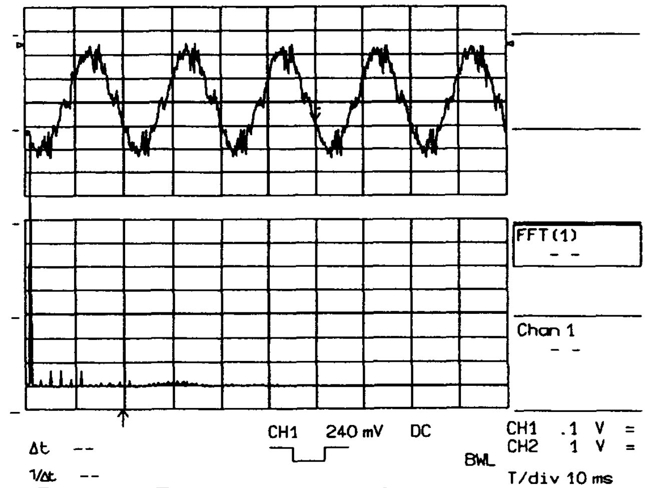

Figure 16: Experimental curve showing injected current and its spectrum when the reactive power compensation is working and harmonic compesation too.

8XC196KD20 single-chip microcontroller-based hardware and software. Moreover, a reactive predictive control has been used in the system to compensate the reactive energy of load in the grid. An additional characteristic has been introduced, which is the power system can be programed to inject current harmonics that can be used to compensate harmonics that have been generated by nonlinear load in the public The controller has been tested in the laboratory with the prototype power conditioner and shows excellent performance.

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