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Voltage Harmonic Compensation Control for a Stand-Alone Single Phase Inverter-Based Fuel Cell

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***Abstract*—In recent years, Fuel Cells (FC) have gained interest as energy source for stand-alone and grid connected applications, because they are very high-efficiency and multi-fuel power generators that require neither the burning of conventional fuels nor the mechanical equipment of conventional power generators. When FC are used with inverters for supplying AC loads, harmonic distortion in the supply voltage results in increased heating losses in loads, excite resonances and overload customer power factor correction equipment. Sensitivity of customer equipment to voltage distortion may be dependent on both the magnitude of the distortion levels and the specific harmonic components. For these reasons, it is important to keep the voltage harmonics within recommended levels.**

This paper presents a new method for voltage harmonic compensation of a stand-alone single phase inverter-based FC. The system under study is composed of: 1) Proton-Exchange-Membrane (PEM) FC including a unidirectional DC/DC converter, which converts the DC voltage delivered by the FC to the DC bus voltage; 2) single-phase pulse width modulated (PWM) inverter; 3) transformer; 4) L passive filter; and 5) linear and non-linear loads. The dynamic model of this system and the control applied to the PWM inverter for voltage regulation and harmonic compensation are detailed in this paper. Simulation results show the effectiveness of the purposed method for voltage harmonic compensation to acceptable levels defined in grid codes.

***Index Terms*—Control, fuel cell, harmonics, pulse width modulated inverter.**

I. INTRODUCTION

Nowadays distribution generation (DG) is changing the classic concept of power generation. It is a complementary infrastructure that is approaching the generation to consumption sites using renewable energies sources. Thus, DG is related to sustainability, environment-friendly and pollution reduction. In recent years, the FC power systems have attracted a lot of attention because of their increased efficiency than other types of renewable sources [4].

Uses and potential uses include on-site electric power for households and commercial buildings; supplemental or auxiliary power to support car, truck and aircraft systems; power for personal, mass and commercial transportation; and the modular addition by utilities of new power generation closely tailored to meet growth in power consumption [1].

Sensitivity of customer equipment to voltage distortion may be dependent on both the magnitude of the distortion levels and the specific harmonic components [2,3]. For these reasons, it is important to keep the voltage harmonics within recommended levels.

Although grid-connected DG systems has drawn considerable attention, their operation in stand-alone mode (as much as in islanded mode), where a local AC bus connects the renewables sources to local loads, have been discussed in literature [5]. The system performance in stand-alone mode is more sensitive to factors such as the control scheme, interface, types of loads, etc., compared to grid-connected operation [6].

Most of renewable sources generate DC power which is transformed into AC power by means of a power conversion unit. This unit is typically composed by a PWM voltage source inverter (VSI), fulfilling the grid voltage and frequency requirements. In stand-alone mode, when non-linear loads are tied up to the output AC voltage, one of the issues of the inverter is to eliminate harmonics, in order to meet the specified total harmonic distortion (THD) limitations and improve power quality [7].

A stand-alone micro grid with a FC power source is proposed in this paper, in order to study a novelty harmonic compensation method based on operating the inverter using a non-sinusoidal PWM (NSPWM).

II. CONFIGURATION OF THE SYSTEM UNDER STUDY

The proposed stand-alone micro grid structure is depicted in Fig. 1, which is composed of: 1) FC power system, including a DC/DC converter; 2) single-phase inverter; 3) transformer; 4) L passive filter; and 5) loads.

A. Power Source

A small FC of 1.2 kW is considered in this paper, which uses a unidirectional DC/DC boost converter to adjust the DC bus voltage to 60 V. Among the types of FC, PEM FC is one of the best options for DG because of its high-power density, specific power, low operating temperature, longevity, efficiency, good dynamic behavior, and relative ability to rapidly adjust to changes in power demand. The behavior of this FC is represented by a reduced model as shown in [8, 9].

The output FC voltage is calculated from the Nernst's

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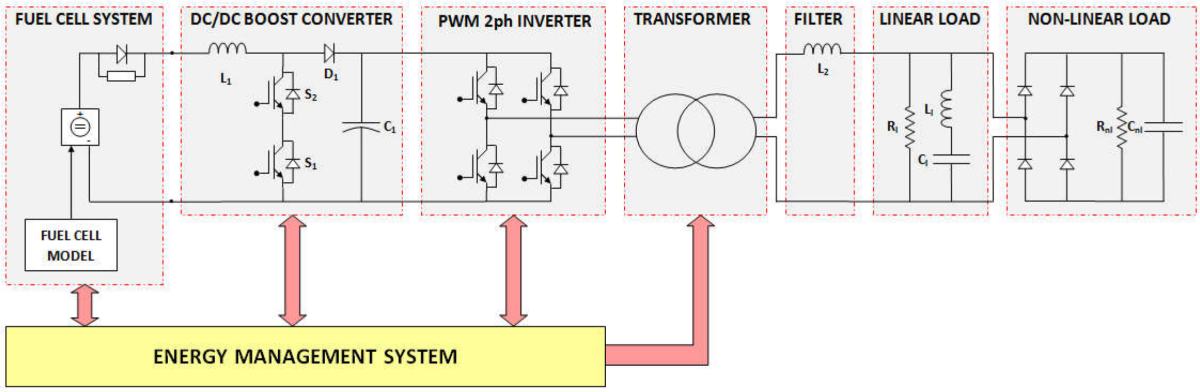

Fig. 1. Configuration of the system under study.

equation and the sum of the irreversible voltage drop (activation, ohmic, and concentration voltage drop) [8].

Otherwise, the FC model is completed with the anode and cathode models, in which the hydrogen partial and the oxygen partial pressure are calculated; a compressor whose dynamic response is modeled by a first order system; and a hydrogen valve located upstream of the anode, which controls the input hydrogen flow to make equal the anode and cathode pressures.

Components as the humidifier and air cooler are regarded as ideal so that the FC operates at an optimum temperature (80 ºC) and a constant relative humidity [10].

Finally, the DC/DC converter is composed of a high-frequency inductor L_1, an output filtering capacitor C_1, a diode D_1 and a main switch S_1, as shown in Fig. 1.

B. Single-Phase Inverter

A detailed model of an IGBT single-phase inverter is used to convert 60 V DC voltage from FC to low 34 AC bus voltage. A PI-controlled NSPWM is adopted in the inverter control module in order to adequate the voltage magnitude to the desired reference at 50Hz at the point of common coupling (PCC), where the linear and non-linear loads are connected. In addition, a voltage harmonic compensation control distorts the sinusoidal reference of the inverter PWM module, assuring PCC voltage distortion levels below the standard limits. This control system will be explained further on.

C. Transformer

Although the proposed scheme does not need extra transformer as compensating device, it is necessary because the FC output voltage is at low 60 V DC level, as usual in residential power generation [11]. In fact, the transformer is used to raise the voltage from the low inverter output AC voltage to 230 V standard AC voltage.

D. L passive filter

A small series inductance is used as filter to eliminate the switch harmonic of the load-side voltage, helping the control and protection of the system.

E. Loads

As usual in voltage harmonic reduction studies, three types of loads have been implemented, two linear loads R_1-L_1 y L_2-C_2, and a non-linear load comprised of a single-phase bridge rectifier with R_3-C_3 load (a large filter capacitor is supplying the resistive load).

III. VOLTAGE HARMONIC COMPENSATION

A significant part of the equipment use today, especially electronic and computer devices, requires a sinusoidal voltage. However, the same equipment often causes distortion of the voltage supply, because of its non-linear characteristics. These loads draw a non-sinusoidal current with a sinusoidal supply voltage. Maintaining a quality voltage waveform is a joint responsibility for the supply company and the electricity user. The cost of distorted supply voltage at the PCC exceeds the cost of measures required for improvement, and therefore, it is necessary to limit the presence of harmonics.

The main document dealing with requirements concerning the supplier's side is the standard EN 50160 [3], which characterize the voltage parameters of electrical energy in public distribution systems. Limits for voltage harmonics are shown in Table I for low and medium voltage.

TABLE I. VALUES OF INDIVIDUAL HARMONIC VOLTAGES AT THE SUPPLY TERMINALS

Odd harmonics				Even harmonics	
Not multiples of 3		Not multiples of 3			
Order h	Relative voltage (%)	Order h	Relative voltage (%)	Order h	Relative voltage (%)
5	6	3	5	2	2
7	5	9	1.5	4	1
11	3.5	15	0.5	6 ... 24	0.5
13	3	21	0.5		
17	2				
19	1.5				
23	1.5				
25	1.5				

The term that has come into common usage to define either voltage or current distortion is the total harmonic distortion (THD). The recommended voltage distortion limits by IEEE Std 519-1992 [2] for low voltage systems is 5% for THD and 3% for the rest of individual voltage distortion, that should be used as system design values in the "worst case" with normal operation. These values decrease when the voltage level increases. The EN 50160 limit for voltage THD is 8%. Comparison of the IEEE Std 519 limits with the limits from EN 50160 show that the harmonic distortion limits in Europe are considerably relaxed compared to the IEEE limits.

If the DG sources operate in grid-connected mode, the quality and magnitude of the voltage waveform at the PCC is entirely imposed by the grid, so that the presence of nonlinear loads does not affect the performance of other loads connected. However, in stand-alone mode, in which the DG source has to supply different loads, it is necessary to compensate the harmonics generated by the inverter and non-linear loads connected at the PCC.

Harmonic compensation can be done with external compensating device, such as transformers or passive filters, or operating the inverter using a NSPWM control [12]. The most commonly used NSPWM technique for harmonic reduction is the selective harmonic elimination (SHE) PWM method. Several algorithms have been considered in the technical literature concerning methods of solving the resultant nonlinear transcendental equations, which describe the SHEPWM problem. However, this method becomes complex and computation intensive with the increase of harmonics number to be eliminated [13].

In this paper, a novelty harmonic compensation method based on NSPWM is used. This method considers and manages harmonics globally, generating an output voltage with a higher number of harmonics under the values specified in the grid codes than those achieved by a typical SHEPWM method, and resulting less complex and computation intensive.

Fig. 2 shows the control implemented in the inverter in order to obtain the 4 pulses PWM generator reference signal. The control scheme comprises two basic loops: 1) the main control loop, that fixes the amplitude and frequency of the voltage wave; and 2) the secondary control loop, dedicated to the voltage harmonic compensation.

The voltage control loop, shown in the top of Fig. 2, uses a conventional SPWM technique to generate a sinusoidal signal with desired reference level. A PI controller handles the error between the RMS voltage reference ($V_{1,ref}$), fixed at rated value, and the measured voltage at PCC ($V_{load,rms}$). A PLL block is in charge of generating the sinusoidal reference of frequency 50 Hz.

The lower loop, depicted in Fig. 2, is the voltage harmonic controller. This control loop uses a waveform containing all voltage harmonics measured at the PCC. This waveform is obtained by removing the fundamental voltage (V_1) from the whole measured waveform (V_{load}). A PI controller decreases the error between the RMS value of the voltage harmonic waveform and the reference value ($V_{H,ref}$). In this case, the reference is set to 0.06 in order to obtain a THD close to 6%. A rate limiter prevents fluctuations above 0.5 volts per second, enabling the PI controller to operate properly. The output is multiplied with the harmonic waveform to obtain a rescaled signal as harmonic reference waveform.

Finally, this harmonic reference waveform, obtained by the compensation loop, is subtracted from the fundamental reference wave provided by the voltage control loop, and thus, generating the non-sinusoidal reference waveform to the 4 pulses PWM generator.

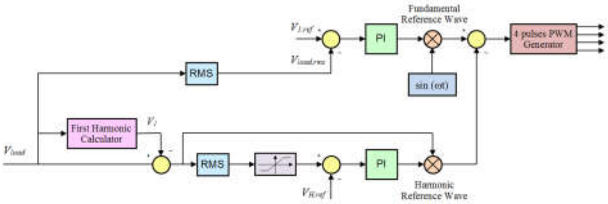

Fig. 2. Control implemented in the inverter.

IV. SIMULATION RESULTS

A model of the proposed stand-alone single phase inverter-based FC was implemented in MATLAB-Simulink, and a suitable energy management system was applied in order to provide the FC power at 60 V DC voltage to the single-phase inverter and at 230 V AC voltage at the PCC with low distortion levels. The loads considered in the simulations are depicted in Fig. 1 and their values are defined in Table II.

TABLE II. DETAILS OF LOADS CONNECTED AT PCC

Load Type	Value
Resistive load	R_l= 150 Ω
LC load	L_l= 0.01 mH, C_l=0.72 μF
Non-linear load	R_{nl}=150 Ω, C_{nl}=100μF

To evaluate the new method for voltage harmonic compensation presented in this paper, two simulations were performed, in which the responses of system (supplying linear and non-linear loads) with and without voltage harmonic compensation control were compared.

In both simulations, the FC operates at rated power, maintaining constant inverter input voltage at 60 V DC. Moreover, the inverter connected to the transformer tries to maintain a voltage of 230 V AC at the PCC.

As seen in Fig. 3a, the FC is made to operate at constant power, around its rated power along the whole simulation, providing the power consumed by the load. Furthermore, the energy management system of the FC controls the incoming voltage to the DC/DC bus converter in order to eliminate abrupt DC bus voltage changes that can influence the behavior of the inverter. In fact, the current supplied to the converter is almost constant, as shown in Fig. 3b, and thus the input voltage fluctuation is limited to 2%.

Case 1: Inverter controlled without harmonic reduction. In this first simulation, the inverter is controlling by means of a SPWM control, without harmonic reduction. Only the main controller provides the sinusoidal waveform reference to the PWM generator. Fig. 4 shows the model response to the proposed load. The voltage at the PCC is represented in Fig. 4a, where it can be seen that it is highly distorted due to the non-linear load connected. The current provided to the loads is shown in Fig. 4b.

Fig. 5 shows the evolution of voltage THD along the simulations (Fig. 5a) and the harmonic spectrum of the load voltage at the end of the simulation (Fig. 5b). As there is not harmonics reduction along the simulation, the THD remains at the same value, over 20.8%, along the whole simulation.

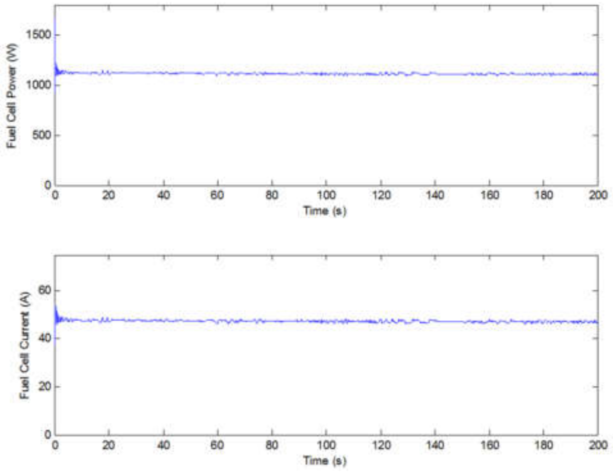

Fig. 3. Fuel cell response of the proposed model: a) Power; b) Current.

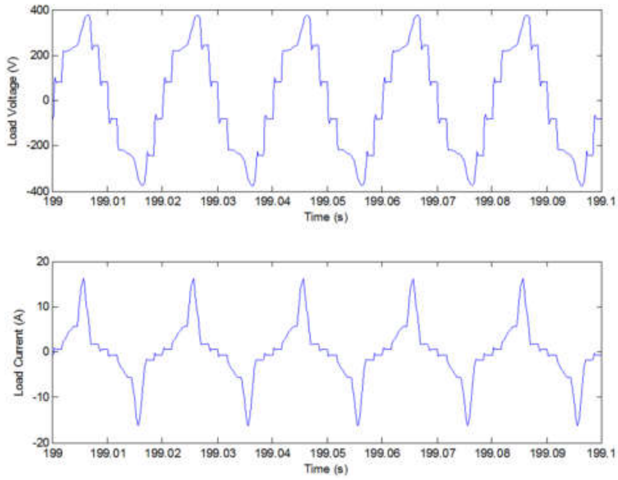

Fig. 4. Response of the system without harmonic reduction (case 1): a) Load voltage; b) Load current.

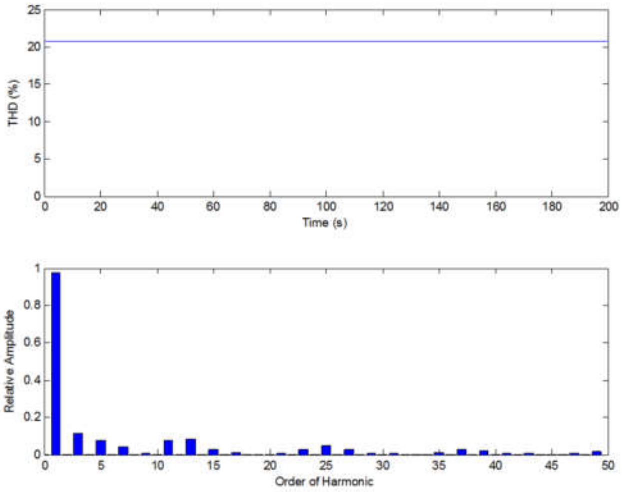

Fig. 5. Response of the system without harmonic reduction (case 1): a) Load voltage THD, b) Load voltage harmonic spectrum at 200s.

The harmonic voltage spectrum, in this case, mainly consists of odd harmonics, as usual in current load with quarter-wave symmetry. Table III shows the dominant harmonics in the spectrum.

TABLE III. DOMINANT HARMONICS IN THE SPECTRUM WITHOUT HARMONIC REDUCTION

Order of harmonic	1st	3rd	5th	7th	11th	13th	25th
Relative amplitude (%)	98	11.3	7.9	4.3	8.0	8.6	4.96

Case 2: Inverter controlled with harmonic reduction. In the second simulation, the inverter is controlled by means of a NSPWM in order to reduce the harmonic spectrum. Besides the main controller, it includes a second controller that supplies the necessary mixture of harmonics to modify the sinusoidal reference waveform, as mentioned previously. Thus, a non-sinusoidal variable reference is modulated to obtain the reference to the PWM generator. The reference of the harmonic controller is set to 6%, in order to reduce the PCC voltage THD to this value.

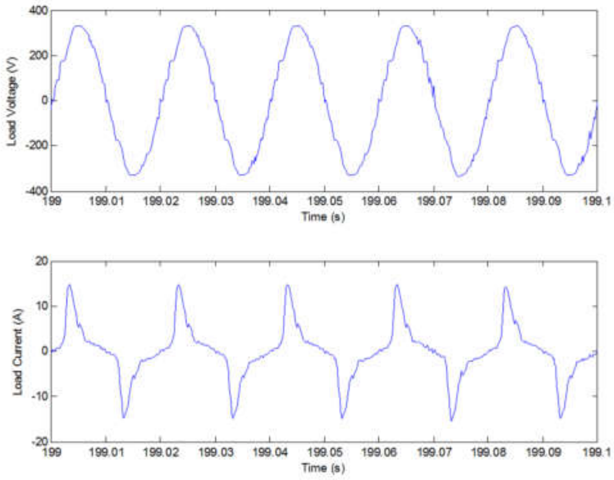

Fig. 6. Response of the system with harmonic reduction (case 2): a) Load voltage; b) Load current.

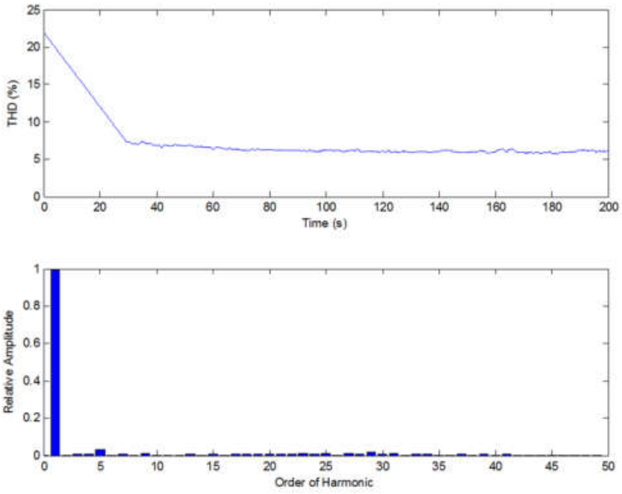

Fig. 7. Response of the system with harmonic reduction (case 2): a) Load voltage THD, b) Load voltage harmonic spectrum at 200s.

As can be seen in Fig. 6, the voltage distortion is clearly reduced to acceptable values, due to the harmonics controller action, although the non-linear load is connected to the PCC.

The better way to see the effectiveness of the harmonics reduction is to show the evolution of the voltage THD along the simulation. Fig. 7a depicts this evolution, with a fast reduction during the first 30 seconds, reaching a value of 7%. Then, the reduction is slower, achieving a THD of 6% to the end the simulation.

In this case, the harmonic spectrum shows the great reduction achieved with the proposed method, as can be seen in Fig. 7b and Table IV.

TABLE IV. DOMINANT HARMONICS IN THE SPECTRUM WITH HARMONIC REDUCTION

Order of harmonic	1st	3rd	5th	7th	11th	13th	25th
Relative amplitude (%)	98.9	1.6	2.4	1.6	0.4	0.7	1.1

The comparison of the simulation results show the effectiveness of the purposed method for voltage harmonics compensation to acceptable levels, achieving that the FC provides the power consumed by the loads.

V. CONCLUSIONS

This paper has presented a novelty control to reduce voltage harmonics produced by non-linear loads in a stand-alone system based on PEM FC power source. A NSPWM controller manages the voltage at the PCC in order to obtain a global reduction of harmonic level. The proposed model was evaluated by comparing the response of the system without harmonic reduction controlled by means of a SPWM controller and the response of the system with the harmonic reduction obtained from the proposed NSPWM control. The simulation results show the effectiveness of the purposed method for voltage harmonics compensation to acceptable levels, when the FC provides the power consumed by the loads.

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