Single-Stage Fuel-Cell Inverter with New Control Strategy

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***Abstract*- Renewable energy sources has been attracting great interest due to well known environment issues and, hence, the development of power electronics converters to deal with the transformation of these sources into conventional energy forms has been the main challenge faced by many researches working in this area of expertise. Within this subject, this paper focuses the establishment of a simple power structure that based on a new control strategy can provide an amplified sinusoidal output voltage from a fuel cell. The single-stage inverter works based on imposed waveforms of a CSI inductor current and output voltage. The proposed control strategy provides high voltage gain without using high frequency transformer, which contributes to weigh and size reduction of the proposed DC-AC converter structure. Theoretical analysis are presented and corroborated by experimental results of a 180W laboratory prototype.**

***Index Terms*--CSI, dc-ac converter, grid-connected, stand-alone, hybrid control, multistage inverter, single-stage inverter, renewable energy sources.**

I. Introduction

Nowadays the renewable and sustainable energies are a subject of extreme importance in several countries due to the alarming levels of CO_2 presents in the atmosphere that are increasing the global temperature [1]. However, sustainable politics are being applied, in which, renewable energy are a booming sector. In conjunction with the renewable energy growth is the interest associated with static converters development [2].

Due to the efforts of the renewable energy sector Power Electronics are finding a more attractive market. Several systems are used in conjunction with renewable energy such as photovoltaic arrays and full cells. The use of this type of converter is essential to process energy provided by dc voltage such as Photovoltaic Cells, Fuel Cells and others [3].

In static conversion applied to renewable energy there are basically two classes of use: grid-connected and stand-alone.

- Grid-Connected: the power provided by a renewable source is injected into the grid. A grid interface near to the application is required.
- Stand-Alone: the power processed by a renewable source is used to supply an isolated load, such as a house or ordinary equipment like a refrigerator. This type of application is attractive for applications in remote areas, without access to the main supply, or any place that there is a renewable source [4].

Fig. 1 presents a diagram that illustrates the configuration used to process renewable energy. It's seen two examples named A and B. In both cases pre-stages are used to elevate the input voltage amplitude. Within this context many works have been developed to provide ac voltage from a dc source. In several systems is common the presence of a step-up stage provided by a dc-dc converter or a transformer, configuring a multi-stage topology [5]-[8].

In multiple stage inverters, several advantages are accomplished by the freedom of control of each stage. However, this causes some disadvantages like inefficiency and cost. The addition of many stages increases the number of switching elements as well as magnetic and requires power more complexity circuits and more weight. Therefore, lots of efforts have being made towards the development of simple power structures that make all the conversion process (step-up, step-down, inversion…) in a single stage.

Many single-stage inverters systems already have been proposed [9]-[16] and all these works presents a control strategy based on PWM. These inverters have some disadvantages like the non isolation between the source and load and the use of very sophisticated control strategies.

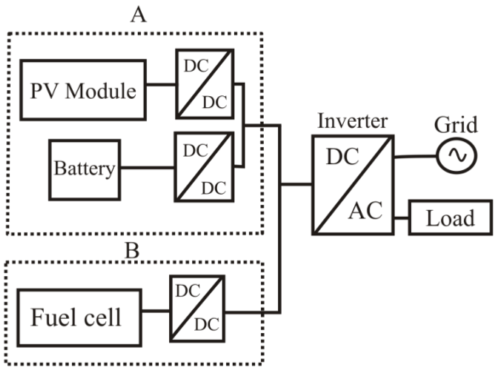

Fig. 1. Block diagram of inverters systems using renewable energies.

Concerning the renewable sources, Fuel Cells are a well know source of clean energy that provides energy by electrochemical process similar to a battery [17]. In this work it is presented a single-stage inverter supplied by a Proton Exchange Membrane Fuel-Cell (PEMFC). The PEMFC presents an inherent characteristic. The output voltage varies depending on the load condition. This happens due to the internal losses, i.e. internal resistance ohmic losses, activation losses and concentration losses [18]. Therefore, simple low cost and robust step-up inverter structure that can deal with input voltage variations is needed.

In this context, single-stage inverter topology is a booming technology and, therefore, this paper presents a novel control strategy applied to a buck-boost inverter structure for full cells applications. This type of inverter was previously presented in [9] where the application of an output filter was needed due to the PWM control strategy. On the other hand, the control strategy proposed in this paper is a non PWM technique that makes possible the elimination of the output filter and uses a small input-inductor as a current source contributing with weight and size reduction. To contribute with weight reduction, it is necessary to operate in the discontinuous conduction mode, however, it increases the input current peak. When operating in continuous conduction mode it can be avoided but it would be unattractive due to the weight increase of the input inductor.

The proposed control strategy makes possible the step-up and/or step-down operation in one single-stage and consists in the input-inductor current and output voltage imposition. The proposed control strategy was applied to a stand-alone device that converts 12-48Vdc in sinusoidal 127 Vac *rms* with a reduced THD.

In order to present the results of the proposed research, this paper is organized as follows: Section II presents the control strategy and a detailed circuit description; Section III shows an example of project of the CSI Inductor and the experimental results of a stand-alone application of a 180W prototype; Finally, the main conclusions are presented in Section IV.

II. Principle of Operation

A. Review of Single-stage Inverter

The power structure consists basically in 3 stages illustrated in Fig. 2. This topology was previously presented in [6-9]. In [6] the output voltage gain is obtained using a push-pull converter. The amplified voltage is used as dc-input to supply a *Current Source Inverter* - CSI. Therefore, the control strategy is based on the imposition of a sinusoidal rectified current in the CSI input-inductor. The alternating output voltage is accomplished by the normal operation of the inverter.

In [9] the authors proposed the most similar topology compared to the one presented in this paper since the only difference resides on the applied control strategy. In the converter proposed in [9], the input-inductor current is imposed as well as in [6] , but the step-up operation is done without any other stage and it is is accomplished by the control of the inverter switch. Based on the operational states of the inverter switches the power structure operates like a Boost, Buck or Buck-Boost converter. The reference current in the CSI inductor defines the state of the converter, and the output voltage is control by PWM technique requiring an LC output filter.

In this context the main advantage of the single-stage inverter proposed in this paper is to provide an amplified output voltage with low THD without a LC output filter. The input current and output voltage imposing are obtained using a new modulation technique. The output voltage can assume any waveform depending on the desired THD. Therefore, a non sinusoidal output voltage can be achieved providing higher efficiency, which is very attractive mainly for renewable energy systems.

B. Principle of Operation

The principle of operation of the proposed converter is based on the imposition of two variables:

- I_{REF} : Reference current for the CSI Inductor L.
- V_{REF} : Reference voltage for the output voltage.

The CSI inductor current is compared to I_{REF} and the output voltage is compared to V_{REF}, providing the gate-drive signals to the switches. The current imposed on the inductor L presented in the Fig. 3 is named I_L and the output voltage is named V_O. In order to impose the current I_L the converter must assume two configurations (Buck + Boost), depending on the switches states. This mode of operation is described in Section *C.1 Current Control*. The output voltage V_O is controlled by the inverter switches that force the voltage capacitor to follow the reference signal V_{REF}. This mode of operation is described in Section *C.2 Voltage Control*. The safety operation of the inverter switches is assured since the applied control strategy always provides a path for the inductor current discharge. This mode of operation is described in Section *C.3 Cycle Control*.

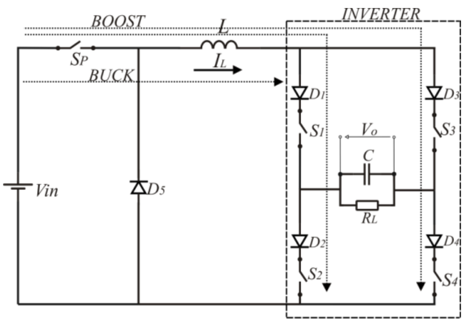

Fig. 2. Power inverter structure.

C. Control Strategy

The circuit and logic schematic are shown in the Fig. 3. The control code is based in three sub-routines which are described in *C.1*, *C.2* and *C.3*.

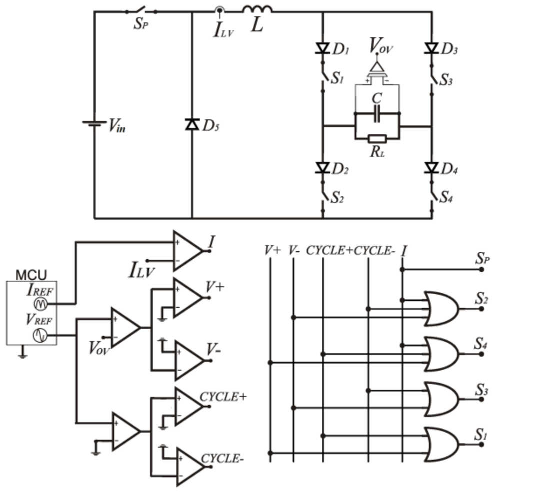

Fig. 3. Control strategy.

C.1. Current Control

The operation stage of the proposed converter referent to the control of I_L is presented in the Fig. 5. The current I_{LV} has to follow the I_{REF} signal that is formed by a rectified sinusoidal wave, as presented in Fig. 4. The signal I_{LV} is compared with I_{REF} and the result of this operation is a pulse signal named *I*, that is send to the logic control circuit. Therefore:

- $I_{REF} > I_{LV}$: *I* is a high logic level.

This stage of operation activates switches S_P, S_2 and S_4 forcing two different paths depending on the half-cycle of the output voltage. If the cycle control is forcing the positive half-cycle, current I_L will have a linear increase due to the path formed by S_P, S_1 and S_2 as portrayed in Fig. 5. In this stage the capacitor that is charged with the same polarity of V_O is a high impedance circuit. Then, capacitor *C* supplies energy to the load R_L. In the negative half-cycle of the capacitor voltage, current I_L increases by the path formed by S_P, S_3 and S_4.

- $I_{REF} < I_{LV}$: *I* is a low logic level.

This stage operation is done by deactivating S_P (Figs. 6 and 7). The command done by this stage has no direct influence on the turning-off of S_2 and S_4 once these switches receive commands from others two logic controls, i.e. *voltage control* and *cycle control*. Fig. 3 shows the logic control scheme.

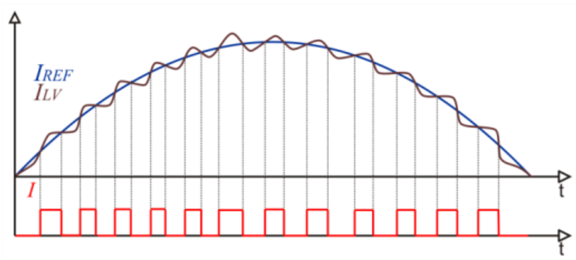

Fig. 4. Modulation strategy of the CSI inductor current.

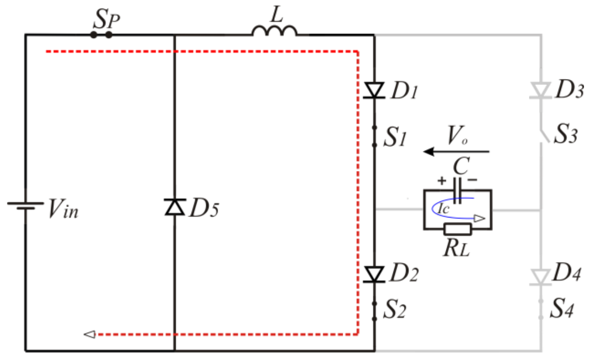

Fig. 5. CSI inductor current during the positive half-cycle of the output voltage (Boost stage).

C.2 Cycle Control

The main objective of this logic control is to protect the inverter switches and avoid high frequency switching loss activating S_1 or S_3 at low frequency (60 Hz) even if the voltage control is activated.

This protection is necessary to avoid over voltage phenomena caused by opening an inductive circuit. The CSI inductor generates an induced voltage forcing the current flow through the body capacitance of the switch that is turned-off causing overvoltage across it.

The logic of this control consists in the comparison between V_{REF} zero, therefore, two pulses are generated, i.e. *Cycle+* and *Cycle–*, which are complementary. Thus,

- $V_{REF} > 0$: *Cycle+* is high logical level
  Cycle- is low logical level

- $V_{REF} < 0$: *Cycle+* is low logical level
  Cycle- is high logical level

Cycle+ is kept in high logical level for the positive half-cycle activating S_1 and S_4 and *Cycle-* is kept in high logical level during the negative half-cycle activating S_3 and S_2.

C.3 Voltage Control

This control logic is responsible for imposing the correct shape of the output voltage waveform. This is done by the constant comparison process between V_{REF} and V_{OV}. V_{REF} is a sinusoidal signal. V_{OV} is the voltage acquired by a voltage sensor circuit connected to the output capacitor (load).

The voltage control doesn't accomplish the output voltage gain just by increasing V_{REF}. To obtain a voltage gain the input current must be controlled in order to assured the perfect match between the input power and the output power and, therefore, guarantee the output voltage step-up. Thus, the current control is a priority task.

The result of the comparison process generates two variables *V+* and *V-*, that are complementary. Thus:

- $V_{REF} > V_{OV}$: *V+* is high logical level
  V- is low logical level

- $V_{REF} < V_{OV}$: $V+$ is low logical level
  $V-$ is high logical level

These variables represent the modulation method for V_O imposition. $V+$ activates S_1 and S_4; $V-$ activates S_3 and S_2. Figs. 6 and 7 are presented, showing the current paths in red. To simplify the explanation, a detailed description is given concerning the positive half-cycle of the output voltage. The operation is complementary for the negative half-cycle. Fig. 6 shows the equivalent circuit related to the positive half-cycle operation and with $V_{REF} < V_{OV}$. Thus:

- $Cycle+ = 1$
- $V- = 1$

In this stage of operation the capacitor voltage has the same polarity that V_O and the circuit, in the inverter, was at first, with the current passing through S_1, capacitor C and S_4. When $V-$ activates S_3 and S_2 the inductor current finds the lowest impedance path through the output capacitor, forcing its voltage reduction.

In this process of voltage control, an expected loss of current control can occur. The capacitor C, due to its instant voltage polarity, acts like a source supplying energy to the inductor and the inductor current increases naturally. It is important to note that this process does not have influence on the main converter source, since S_P will be deactivated by the current control logic during this stage of operation ($I_{REF} < I_{LV}$).

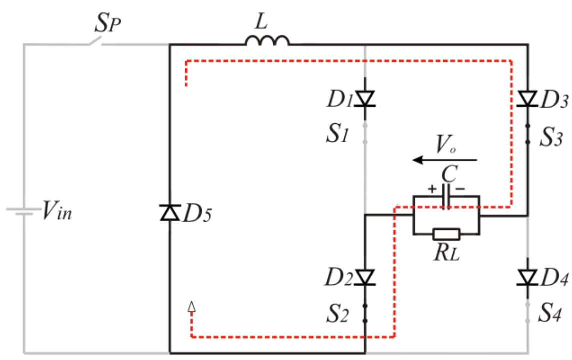

Fig. 6. Capacitor voltage decrease during positive half-cycle ($Cycle+ = 1$; $V- = 1$).

Fig. 7 shows the converter operating stage during the positive half-cycle and with $V_{REF} > V_{OV}$. Thus:

- $Cycle+ = 1$
- $V+ = 1$

In this stage of operation the converter is only stepping-up the output voltage by transferring the inductor energy. The variable $V+$ performs a redundant operation sending commands to activate S_1 and S_4 which are already being activated by $Cycle+$ command.

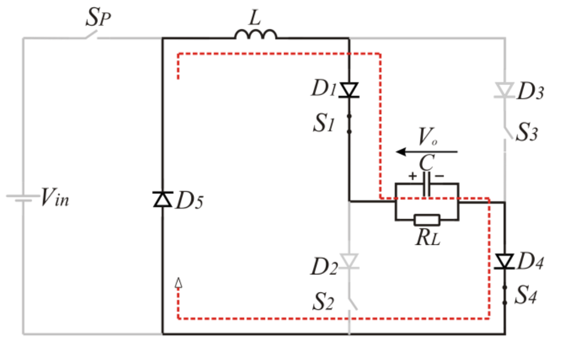

Fig. 7. Capacitor voltage increase during positive half-cycle ($Cycle+ = 1$; $V+ = 1$).

D. *Microcontroller Module*

This module generates the reference signals to the converter. These signals are emitted by a microcontroller in serial pulses using SPI to a multiple output D/A converter. Then the signals pass through a gain circuit and are sent to the controls circuit.

The V_{REF} signal consists in a sinusoidal waveform synchronized with I_{REF} which is a rectified sinusoidal waveform at two times the V_{REF} frequency. The use of a microcontroller allows several waveforms modulations are even a DC voltage reference in order too generate a DC output voltage.

The closed-loop control can be implemented using a feedback output voltage signal to vary the I_{REF} vector and hence, to increase or decrease I_{REF} in order to keep the output voltage with constant magnitude. It is also possible to take into account current phase-angle by monitoring the load current.

III. Experimental Results

A prototype of the single-stage fuel-cell inverter was developed and the project specifications are presented in Table I. The major issue is the design of the CSI Inductor and it was done based on the design guideline presented in [6]. The capacitor value was set by simulation analysis and its value has a linear relationship with the CSI Inductor once it has to supply energy for the load during the inductor energy storage period.

$V_{IN} = 48V$	DC INPUT VOLTAGE
$F = 20$ kHz	SWITCHING FREQUENCY
$\Delta I_L = 3A$	INDUCTOR CURRENT
$L = \frac{Vin}{4 \times F \times \Delta IL} = 200\mu H$	CSI INDUCTOR

TABLE I
PROTOTYPE SPECIFICATIONS

DESIGN SPECIFICATIONS
$V_{IN} = 48\text{V}_{DC}$
$V_O = 127\text{V}_{AC\,RMS}$
$P_O = 180\text{W}$
SINGLE-STAGE INVERTER
CSI INDUCTOR $L = 300\mu\text{H}$
CAPACITOR $C = 10\mu\text{F}$ +-10%, 650 VAC, 50..60HZ
SWITCHES (MOSFET), $S_P - S_4$: IRFP4668PBF
DIODES, $D_1 - D_5$:STTH200L04TV
MICROCONTROLLER: ATMEGA32
D/A CONVERTER: MAX 509
ANALOG COMPARATORS: LM318

The experimental results were obtained from a PEMFC used as a power supply for the single-stage inverter. For the correct use of a fuel cell some considerations must be done. This single-stage inverter has an inherent operational characteristic represented by the input pulsed current. This pulsed current results in an inappropriate operation of the fuel cell. Therefore a large capacitor (2000µF) was used between the fuel cell and the CSI inverter in order to supply the pulsed current for the converter assuring the correct operation of the fuel cell. Fig. 8 illustrates the laboratory setup outlining the fuel cell, the hydrogen tank, and CSI inverter. Fig. 9 shows a picture of the prototype in detail. The switches and diodes are fixed in a heat sink located under the circuit board and the control circuit is above. The experimental results, shown from Figs. 10 to 13 and were obtained using a *Tektronics®* Oscilloscope TPS2024.

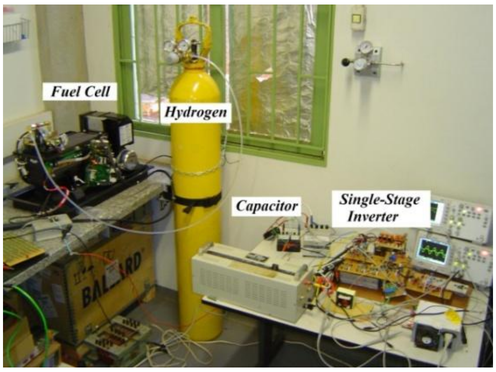

Fig. 8. Laboratory setup - Single-stage inverter connected to a Fuel Cell.

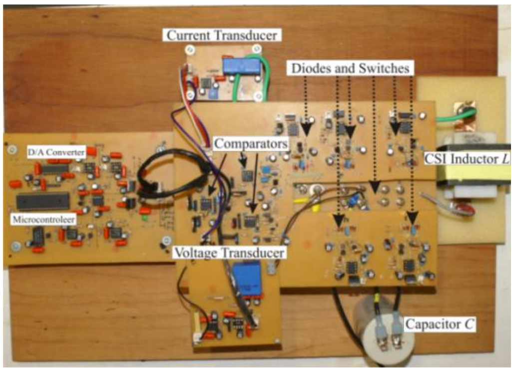

Fig. 9. Single-stage inverter prototype.

Fig. 10 shows the *current control* operation characterized by the current increase through the CSI inductor even when S_P is turned off, as described in the voltage control section. The inductor current increases by the energy provided by the capacitor due to the operation of the voltage control. The signal I_{LV} is different of the real inductor current value due to the action of a low-pass filter used to avoid external noise. This technique was used because it is not necessary to use an identical sinusoidal rectified current for inductor-current imposition. Fig. 11 shows real inductor current where one can observe the high current ripple and the rectified sinusoidal waveform.

Fig. 12 shows the voltage and the current provided by the fuel cell. It is seen that despite the input current ripple, the input voltage is stable. The current in the fuel cell represents a similar shape of the current demanded from the single-stage inverter. Thanks to the input capacitor this current is more stable with a low frequency ripple that contributes to assure the lifetime of the fuel cell. Fig. 13 shows the output voltage and current for a resistive load. The voltage control, in this condition, produced a sinusoidal voltage with a THD of 3.9%.

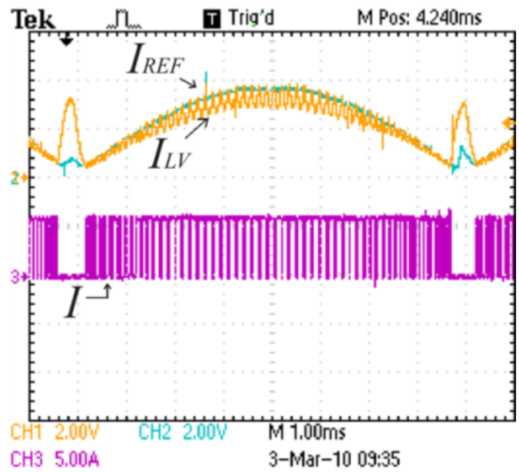

Fig. 10. I_{LV} , I_{REF} and I command.

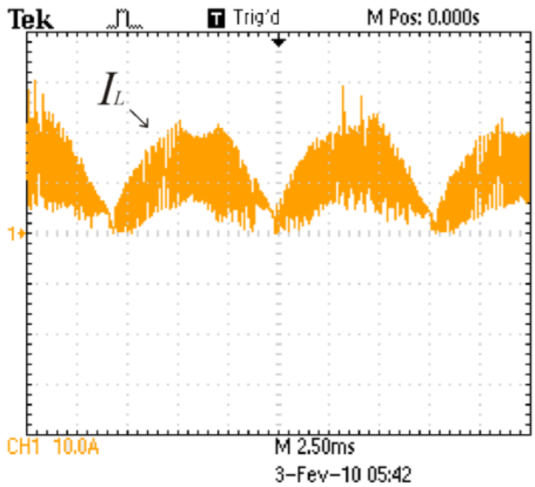

Fig. 11. CSI Inductor current I_L.

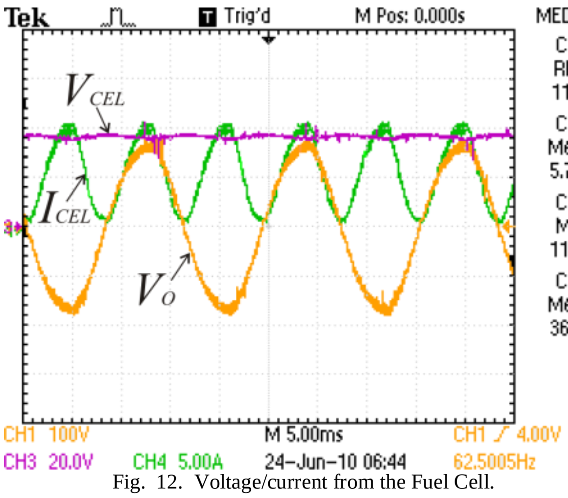

Fig. 12. Voltage/current from the Fuel Cell.

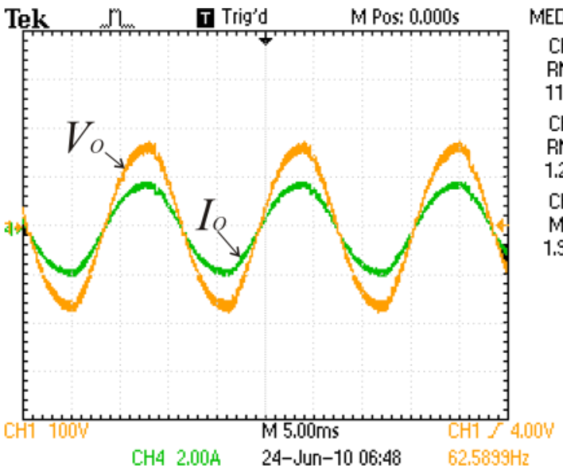

Fig. 13. Output voltage/current.

IV. Conclusion

A 180W step-up/step-down single-stage fuel cell inverter prototype with a CSI Inductor current and output voltage totally controlled was presented in this paper. This converter provides an elevated voltage gain in a single-stage circuit without using a boost stage circuit or a transformer. The output voltage with low THD was achieved what makes it an attractive grid-connected system.

This paper showed the applicability of this type of inverter with a fuel cell for Stand-alone as well as Grid-connected applications. The experimental result corroborates with the proposed structure operational description and with the proposed control strategy, which provides high voltage gain and low THD without using LC filters.

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