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A New Design of dSpace Microcontroller-based Real-Time Digital Predictive Controller for Grid Connected Photovoltaic Power Conditioning System

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Abstract: Nowadays, a great deal of research is being carried out to utilize the solar energy effectively through power electronics converters (conditioners) to meet the increasing demand for load. This paper proposes an experimental photovoltaic (PV) power conditioning system with line connection and islanding detection method (IDM). The conditioner consists of a flying capacitors inverter fed by a dc-dc boost converter. The boost converter is designed to step-up the PV voltage to the stable required dc level for direct grid feeding without using a line transformer. A new dSpace microcontroller-based weighted real-time digital predictive controller combined with a Slip Mode phase Shift (SMS) IDM is proposed. The predictive algorithm controls the output inverter current with unity power factor and extracts the maximum power from the PV solar panel. A Slip Mode phase Shift (SMS) IDM is used to detect the islanding. The proposed control algorithm is implemented in C language and computations are performed by a dSpace dS1104 microcontroller board.

Keywords: dSpace Microcontroller Board, Real-Time Digital Predictive Controller, Islanding Detection

I. Introduction

Renewable Energy (RE) technologies play a crucial role in producing energy with low or zero GHGs [1]. Many alternative sources of energy such as renewable energies are being explored for different applications [2]-[5]. Solar photovoltaic (PV) systems are becoming attractive options for isolated and remote locations due to its performance compared to other renewable sources due to the vast availability of its input (solar radiations) especially in the middle-east region. Furthermore, grid interconnection of (PV) power generation systems has the advantage of immediate and efficient utilization of generated power [6].

Islanding phenomenon of grid-connected independent generators like PV system occurs when a section of a utility system is isolated from the main utility voltage source while the PV generator continues to feed the utility lines in the isolated section. This phenomenon can cause safety problems to utility service personnel or related equipment.

However, anti-islanding protection is a requirement for connecting to the utility grid via an anti-islanding inverter (IEEE Std. 929-2000) and has undergone extensive study and discussion.

In order to prevent this phenomenon, various IDMs have been studied. These techniques can be classified as remote and local [7]. Remote techniques are based on communication between the utility and the PV inverter. Local techniques can be divided into two main types; passive IDMs and active IDMs.

Under islanding condition, the magnitude and frequency of the voltage at the Point of Common Coupling (P_{CC}) tend to drift from the rated values.

Thus, passive IDMs rely on the detection of the disturbance in the voltage at the P_{CC}.

But, it has been shown that the larger the power imbalance in local generation and consumption in the islanded system prior to grid disconnection, the larger are the variations in the voltage and frequency of the voltage at the P_{CC}. Therefore, standard methods (passive islanding detection) are effective in preventing islanding in systems with large power imbalances. Conversely, islanding tends to occur for systems with small power imbalances. In this case, the passive IDMs can fail to detect the islanding phenomenon [8].

Active IDMs use a variety of methods to inject a disturbance in the P_{CC} voltage magnitude and frequency.

The non-detection zone (NDZ) is one of the most indexes to assess the effectiveness of the IDMs. This is defined as a range in which the IDMs fail to detect islanding. In the past, the NDZ have been defined in a power mismatch space (ΔP versus ΔQ) [9]. However, the use of NDZs in the power mismatch space is not adequate for assessing the performance of the active IDMs [10] because for a given reactive power mismatch different combinations of R, L and C are possible. Some of these combinations result in islanding whereas others do not.

In this paper an SMS IDM for a grid connected

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photovoltaic power system is discussed.

A dc-dc boost converter feeding a flying capacitors multilevel inverter is proposed to connect the PV solar panel to the local load and the grid.

The effectiveness of the SMS IDM is analysed using the concept of the NDZ in the quality factor Q_f and resonant frequency f_0 (Q_f versus f_0) space. Theoretical analysis, simulation and experimental results are presented.

II. PROPOSED SYSTEM

Fig. 1 shows the circuit of the proposed PV power conditioning system with grid connection and RLC local load. The whole system consists of a PV power supply followed by a boost converter feeding a multilevel inverter.

In one hand, the PV output voltage V_{pv} has a wide range of variations, and the dc–dc converter is boost type to step up the PV voltage to a constant level greater than the maximum line voltage.

On the other hand, for the flying capacitors inverter, the load current and capacitor voltages must be jointly controlled. Continuous control approach is conventionally used for this type of converters. In this paper, a hybrid control is proposed by taking into account the hybrid nature of the system. The control variables are directly the converter switching states [11][12], so any modulation strategy is necessary. Moreover, the real-time constraint is important. This constraint leads us to propose a control based on a simplified state-space model. The model allows predicting the state vector evolution for every converter configuration. The control directly determines the converter switching state which minimizes a simple cost function. A normalization of the state variables is proposed for the cost function calculation in order to insure a trade-off between the tracking of the load current and the tracking of the capacitor voltages.

In addition, the output inverter current must be controlled to be in phase with the voltage at the point of common coupling V_{Pcc}, so that the system works with unity power factor. Furthermore, the inverter is controlled to detect islanding when the grid is disconnected. In this case, it stops supplying the load and the grid. This technique is based on the detection of the V_{Pcc} frequency f_{Pcc} for each zero crossing [9]. An Under/Over voltage and Under/Over frequency protection block is used to compare the rms and the frequency values of the voltage at the Pcc to the thresholds values corresponding to the IEEE standards (IEEE std 929-2000). As a result, this block generates a fault signal when the f_{Pcc} or the rms values exceed the fixed limits. However, the islanding phenomenon can occurs while the mentioned parameters are within the fixed limits. In this case, the inverter fails to detect islanding which is the major drawback of passive IDMs [8]. In this paper, an active IDM is proposed to decrease the NDZ and to take into consideration the load parameters. This technique named SMS is based on the detection of the voltage frequency at the P_{CC} and the injection of a phase shift in the output inverter current in order to cause an abnormality at the P_{cc}. Thus, this method increases the islanding detection possibilities. The effectiveness of this method is tested using the concept of the NDZ in the (Q_f versus f_0) load parameter space.

Furthermore, in order to achieve maximum utilization efficiency, the MPPT control technique, which extracts the maximum possible power from the PV array, was performed by the flying capacitors inverter in order to output the current reference to control the line current for unity power factor.

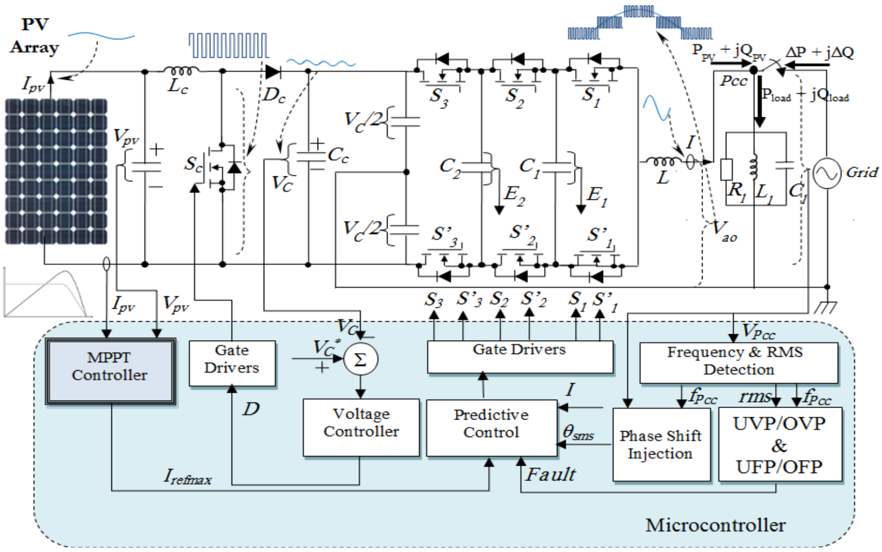

Fig. 1 The proposed controller for the PV power conditioning system connected to the grid with SMS islanding detection method

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A. PV Panel and MPPT Algorithm

Photovoltaic arrays present a nonlinear I-V characteristic with several parameters that need to be adjusted from experimental data of practical devices. The mathematical model of the photovoltaic array, which depends on many factors like temperature of the environment around the panel and irradiation of the sunlight, is useful in the study of the dynamic analysis of converters, in the study of maximum power point tracking algorithms and mainly to simulate the photovoltaic system and its components using circuit simulators [13].
This characteristic as well as the P-V characteristic are shown in Fig. 2.

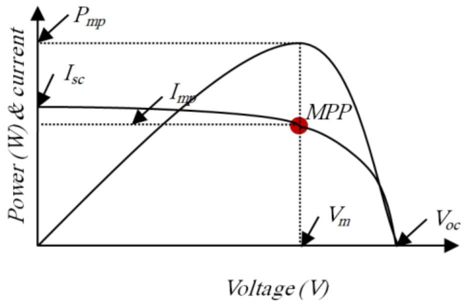

Fig. 2 I-V and P-V characteristics of practical PV cell

P_{mp} is the maximum power, I_{mp} and V_{mp} are the current and voltage at the MPP, V_{oc} is the open-circuit voltage and I_{sc} is the short-circuit current.
As the PV panel operates at its highest efficiency at the MPP, a method should be applied on the PV panel control system to extract the maximum power. Usually, the nature of these methods is based on an algorithm which takes measurement and does some actions to extract as much power as possible from PV panel. In this paper, the Perturb and Observe (P&O) method was applied in order to track the MPP. The MPPT algorithm generates the amplitude of the current at MPP. This amplitude is used as the peak of the reference current of the predictive controller (
Fig. 1).

B. IDM Control Loop

1) Frequency and Rms Detection:
The islanding can be detected using the feedback from the P_{CC} voltage at the previous cycle. When islanding occurs, the voltage frequency and magnitude deviate from the rated values. Therefore, the voltage frequency f_{Pcc} for each zero crossing is detected and the rms value is calculated [9].

2) UVP/OVP and UFP/OFP
According to the IEEE standards mentioned above, the voltage frequency and magnitude should not exceed the fixed thresholds values. Thus, for each zero crossing, the f_{Pcc} and rms parameters, at the previous cycle, are compared to the thresholds values. In case of limits exceeding, the block generates a fault signal in order to shut down the inverter.

3) Phase Shift Injection:
In some cases, although the variations of voltage and frequency are within the fixed limits, the islanding can occur and the inverter fails to detect it [9].
To overcome this problem, the SMS IDM is applied. Thus, the phase angle of the inverter output current is modified to increase the disturbance at the P_{cc} with keeping a unity power factor and a tolerable THD.
The SMS rely in the injection of a phase shift in the inverter output current to create an abnormality in the P_{cc}. Fig. 3 shows the load and the SMS phase responses. When the grid is connected, the load line intersects the SMS line (inverter output current) at the rated grid frequency (50Hz) and the zero phase. When the grid is disconnected, a small perturbation on the f_{Pcc} causes a shifting on the inverter output current. This phenomenon causes instability in the system.
This instability leads the inverter to reinforce the perturbation and drive the system to a new operating stable point. At this point, f_{Pcc} exceeds the threshold value and the islanding can be detected.
In another hand, the phase angle of the inverter output current (θ_{sms}) is a function of the variation between f_{Pcc} (calculated at the previous cycle) and the nominal operating frequency of the utility (50Hz). In case of positive variation, θ_{sms} is positive when it's negative in the other case.
Therefore, the expression of the reference current is given by:

$$I_{ref} = I_{refmax}\, sin(2\pi f t + \theta_{sms}) \quad (1)$$

The phase angle θ_{sms} is given by:

$$\theta_{sms} = \frac{2\pi}{360}\theta_m sin\left(\frac{\pi}{2}\frac{f_{Pcc} - f_g}{f_m - f_g}\right) \quad (2)$$

where:

- θ_m Maximum phase shift in degree (°)
- f_m Frequency at the maximum phase shift
- f_g Grid frequency
- f_{Pcc} P_{cc} voltage frequency

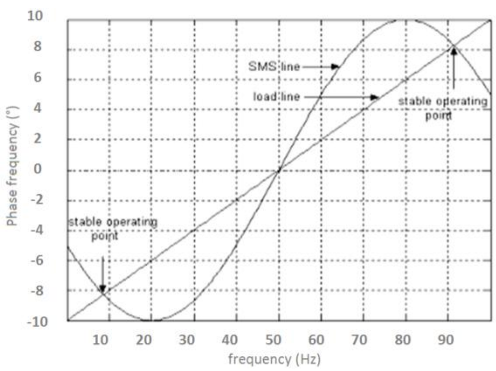

Fig. 3 SMS and load line response curves

4) Real-time Predictive Controller Loop:
The two flying capacitors voltages $E_1(t)$, $E_2(t)$ and the load

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current $I(t)$ are chosen as three state variables noted $X(t) = [E_1(t) \quad E_2(t) \quad I(t)]^T$, and the switching states of the commutation cells $U(t) = [u_3 \quad u_2 \quad u_1]^T$ are selected as the control vector.

As the real-time constraint is important for the considered system, a simplified model is mandatory. If the sample time is sufficiently small, the state trajectories in the state space can be considered as rectilinear. With this hypothesis, the 8 states at time (k+1) in the state space can be approximated, for each sampling time T_s [11], by:

$$X_i(k+1) = X(k) + \dot{X}_i(t).T_s \qquad (3)$$

From a measured state X(k), by using (3), the 8 possible directions in the state space after T_s can be determined.

The proposed control proceeds as follows during each sampling period:

- Measure capacitors voltages $E_1(k)$, $E_2(k)$ and load current $I(k)$.
- Predict the state vector $X_i(k+1) = [E_{1i}(k+1) \quad E_{2i}(k+1) \quad I_i(k+1)]^T$ for the 8 possible control vectors by using (3).
- From the desired reference state $X_c = [E_{1ref} \quad E_{2ref} \quad I_{ref}]^T$, the control selects the configuration which gives the smallest distance $dist_i$ between $X_i(k+1)$ and X_c.

At each sampling period, the control algorithm calculates the distance between the reference point and the reached point of each configuration. The configuration which corresponds to the minimal distance (minimum error) is selected. This control strategy does not allow optimal tracking capabilities of the reference state variables. Furthermore, the state variables are not homogeneous (Ampere and Volt) and the variation ranges are also different (hundreds Volt for voltages and a few Ampere for current). Due to these facts, the state variables are normalized. Then the predictive control algorithm is designed to minimize the following weighted (μ is a weighting factor) cost function $dist_i$.

$$dist_i = \sqrt{\left(\frac{E_{1ref} - E_{1i}}{\Delta E_1}\right)^2 + \left(\frac{E_{2ref} - E_{2i}}{\Delta E_2}\right)^2 + \left(\frac{I_{ref} - I_i}{\square\Delta I}\right)^2} \qquad (4)$$

where:

$$\begin{cases} \Delta E_1 = |max(E_{1i}(k+1)) - min(E_{1i}(k+1))| \\ \Delta E_2 = |max(E_{2i}(k+1)) - min(E_{2i}(k+1))| \\ \Delta I = |max(I_i(k+1)) - min(I_i(k+1))| \end{cases}$$

μ allows a trade-off between the current tracking and the voltages tracking performance. Indeed, a good tracking of the capacitor voltages leads to oscillations on the load current and vice-versa. For better current tracking, voltage tracking performance must be reduced. The factor μ is determined experimentally and is kept constant during the running of the algorithm. When μ is small, the priority is given to the current tracking. When μ is large, it favours the voltages tracking.

III. Simulation Results

Simulations results are presented to verify the effectiveness of the combined predictive-SMS controller to give a better quality output voltage and current and its capability to detect islanding. The simulation parameters are given by Table I.

TABLE I
SIMULATION PARAMETERS

Variables	Designation
V_g=120 V	Grid voltage
f_g=50Hz	Grid frequency
P_{load}=1kW	Active power consumed by load
Q_f=2.5	Quality factor of load
f_0=50Hz	Resonant frequency of load
θ_m=10°	Maximum phase shift

The PV output voltage is boosted to the required DC link voltage as shown in Fig. 4.

Fig. 5 shows the output voltage levels (4-level) in phase with the AC grid voltage when Fig. 6 shows the capacitors voltages.

The proposed control (Predictive -SMS) allows to minimize the output current ripple and to detect islanding with low quality factor Q_f =2.5 at the resonance frequency f_0=50Hz. These parameters are given by:

$$\begin{cases} Q_f = R_l\sqrt{\frac{C_l}{L_l}} \\ f_0 = \frac{1}{2\pi\sqrt{C_l \cdot L_l}} \end{cases} \qquad (5)$$

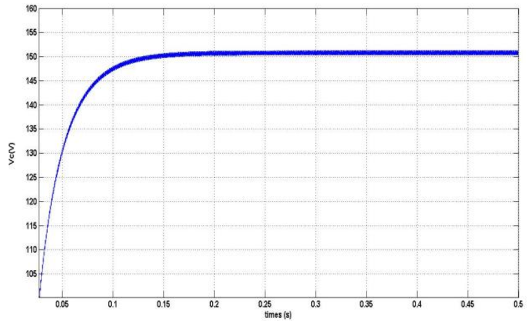

Fig. 4 DC link voltage

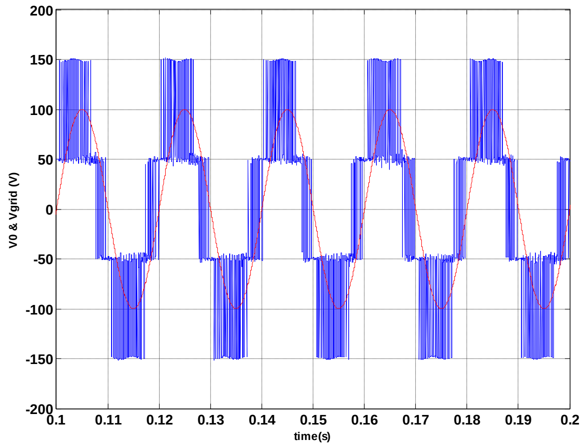

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Fig. 5 Flying capacitors inverter output voltage with grid voltage

Fig. 7 shows the output current and the voltage at the P_{CC} in case of grid disconnection at t = 0.2s.
Although the grid disconnection occurs at t=0.2s, the effectiveness of detecting islanding decreases when quality factor reaches higher values as shown in Fig. 8 with Q_f=4.5. Thus, the inverter fails to detect islanding.

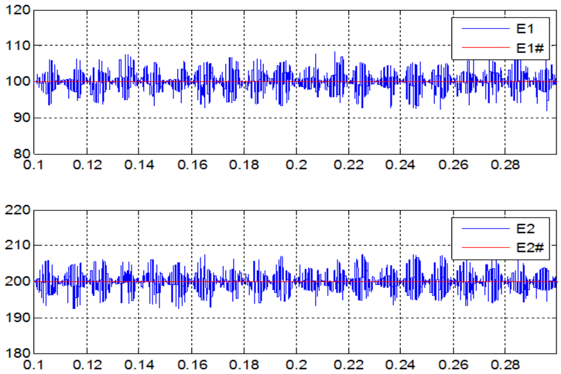

Fig. 6 Capacitors voltages (V) versus time (s)

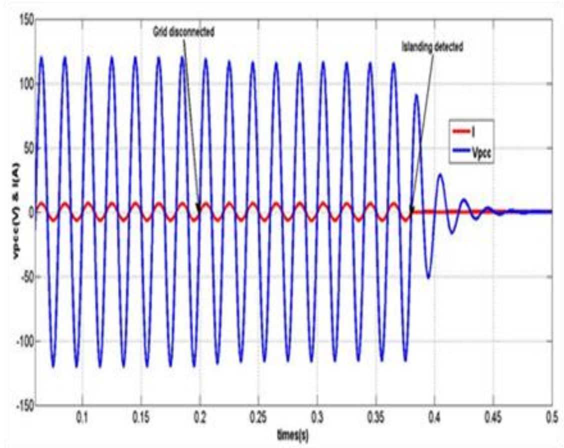

Fig. 7 Voltage at the P_{CC} with the inverter output current (P_{load} = 1kW, Q_f =2.5, f_0=50Hz)

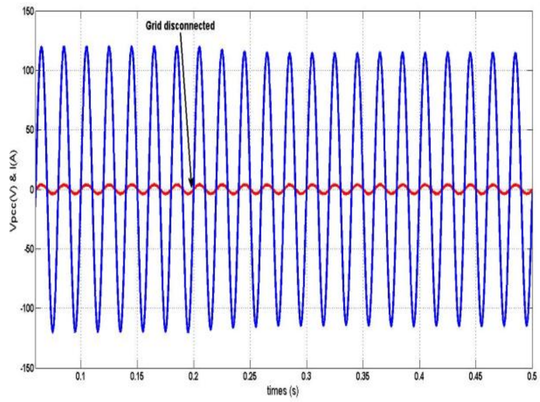

Fig. 8 Voltage at the P_{CC} with the inverter output current (P_{load} = 0.5kW, Q_f=4.5, f_0=50Hz)

IV. Experimental Results

The experiment study of the proposed control was conducted with an equipment (Fig. 9) composed of a three cell converter (C_1=C_2=100µF) associated to a resistor (R=32Ω) through an inductor (L=50mH). The proposed control algorithm is implemented in C language and computations are performed by a dSpace dS1104 controller board. The sampling period is fixed to 70µs. For each period, an interruption starts and the proposed control determines the switching states to apply. The numeric outputs of the dS1104 are used to control the converter drivers by optical fibres. Data recording and reference value tuning are performed within the Control Desk environment.

Fig. 10 shows the experimental inverter output current compared to the generated reference current. The capacitors voltage references are suitably maintained (Fig. 11). The load voltage levels are given by Fig. 12. It can be noted that four voltage levels can be obtained.

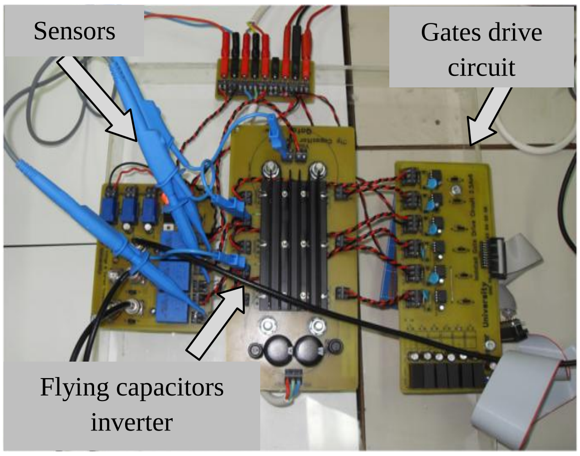

Fig. 9 Experiment set

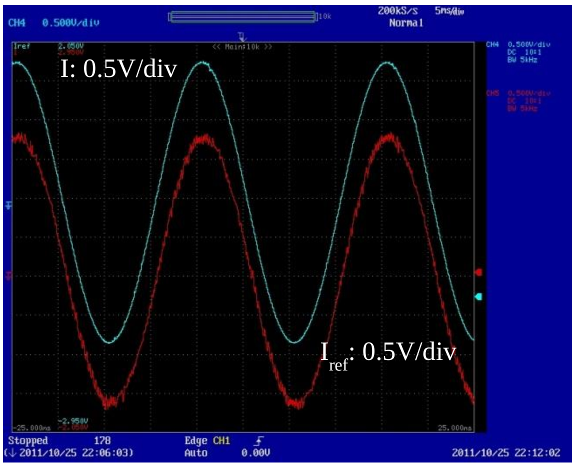

Fig. 10 Experimental output current and reference current (A) versus Time (s) (50Hz)

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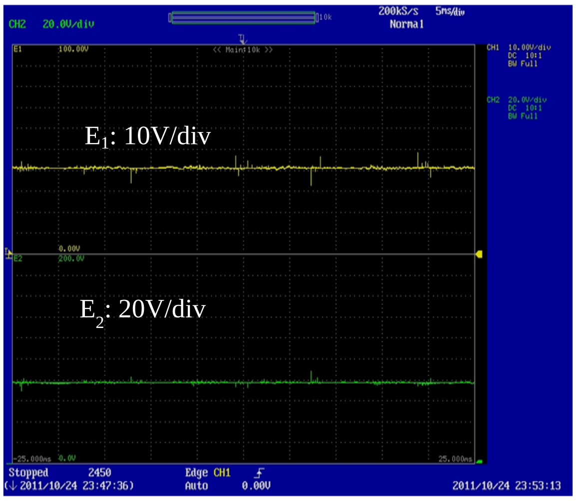

Fig. 11 Experimental capacitors voltages (V) versus Time (s) (50Hz)

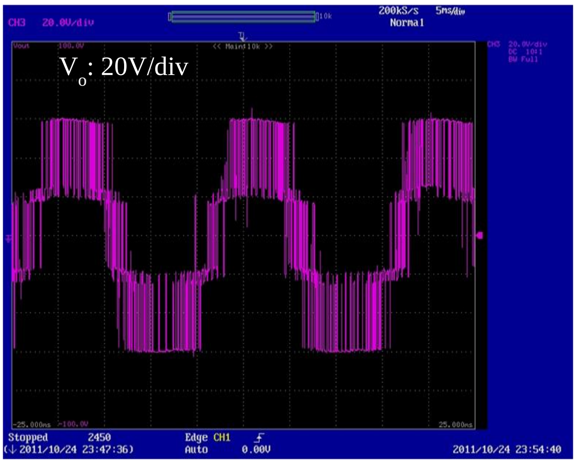

Fig. 12 Experimental inverter output voltage (V) versus Time (s) (50Hz)

V. Conclusion

In this paper, an experimental photovoltaic (PV) power conditioning system with line connection and active islanding detection method is proposed. The conditioner consists of a flying capacitors multi-cell inverter fed by a boost converter. This dc-dc converter is designed to step-up the PV voltage to the stable required dc level. A dSpace microcontroller-based real-time digital predictive control is proposed to control the flying capacitors voltage of the inverter and the output current with unity PF.

The real-time digital predictive controller was designed with high flexibility by using a weighting factor in the control algorithm. The amplitude of the predictive controller's reference current was determined by the proposed MPPT algorithm while the phase was given by the proposed IDM. This technique (SMS) consists on the injection of a phase shift into the reference current to increase disturbance at the P_{CC} when islanding occurs in order to detect this phenomenon.

Theoretical analyses were confirmed by simulation and implementation using a 1kW prototype controlled by dS1104 microcontroller.

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BIOGRAPHIES

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