Hysteresis Current Control and Sensorless MPPT for Grid-Connected Photovoltaic Systems

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Abstract – **This paper describes a control method for single-phase transformerless grid-connected inverter system for photovoltaic (PV) application. The system consists of a DC-DC Boost Converter and a full-bridge inverter. The DC-DC Boost Converter implements a Sensorless Maximum Power Point Tracker (MPPT) algorithm with regulated DC bus voltage while the full-bridge inverter implements a Hysteresis Current Control as the control method. These control method provides robust current regulation, achieve unity power factor, low THD and optimize the PV energy extraction suitable for grid connected PV systems. Simulation and experimental results are provided to demonstrate the effectiveness of the design.**

I. INTRODUCTION

As the world is concerned with fossil fuel exhaustion and environmental problems caused by conventional power generation, renewable energy sources are becoming the alternative. This includes Photovoltaic and Wind Generation systems. Photovoltaic sources are used today in many applications as they have the advantage of being maintenance and pollution free[1]. PV system that supplies power directly to the utility grid are becoming more popular due to cost reduction from elimination of battery subsystem and high feed in tariff. Furthermore, string inverter topology allows further cost reduction because of more efficient energy extraction than widely used centralized inverter[2].

In order to extract maximum power from the solar module, MPPT is used. It is an electronic system that operates the PV modules in a manner that allows the modules to produce all the power they are capable of. MPPT is a fully electronic system that varies the electrical operating point of the modules so that the modules are able to deliver maximum available power[3]. In the proposed system a DC-DC Boost converter is used to obtain the maximum power from the modules. It uses a simple PID control algorithm to extract maximum power and regulate the DC bus voltage as well.

The regulated DC bus voltage is then applied to the main inverter which implements a single band hysteresis current control technique to produces power to be fed into the grid. A reference current is used in order to produce switching pulses for the power switches. The current produced by the inverter must be synchronized and in phase with grid voltage in order to achieve high efficiency and unity power factor. Simulations and experimental result have operates at verified the feasibility of the proposed PV inverter system.

II. EQUIVALENT CIRCUIT DIAGRAM OF SOLAR CELL

Equivalent circuit of a solar cell is a current source in parallel with a diode as shown in Fig 1. The output of the current source is directly proportional to the light falling on the cell. When light hits the solar cell, the energy of the photons generates free charge carriers. The current source produces the *photoelectric current* (photocurrent) I_{Ph}. Since the current is dependent upon the radiance,

$$I = I_{Ph} - I_D - I_P \tag{1}$$

$$I_P = V_D / R_P = (V + I \times R_S)/(R_P) \tag{2}$$

In the solar cells, a voltage drop occurs as the charge carriers migrate from semiconductor to the electrical contacts. This is described by the series resistance R_S. It is in the range of few mille-ohms. In addition, the so called leakage current arises, which are described by the parallel resistance R_P. Both resistances bring about a flattening of the solar cell characteristic curve. With the series resistance, it is possible to calculate characteristic curves for current or voltage of solar cells at different irradiance and temperature[4].

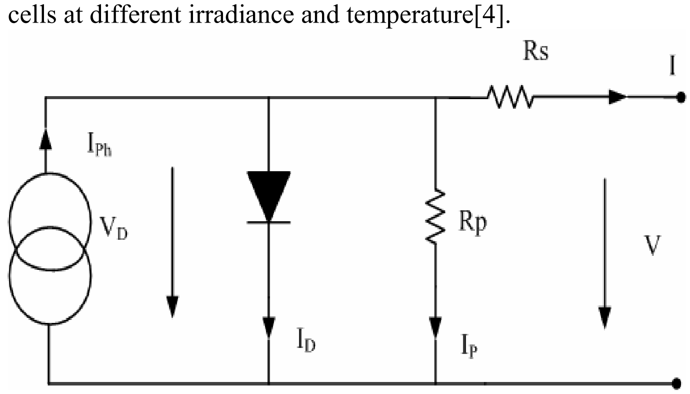

Fig. 1. Equivalent circuit diagram of a solar cell

To complete the equivalent circuit diagram, a general load resistance R was added in order to describe the solar characteristic curve mathematically in sufficient quality. Therefore, it is possible to determine the maximum power point under the changing operation conditions and thereby set the optimum operating point of the PV system. I-V (Current – Voltage) curve of solar cell is given in Fig 2.

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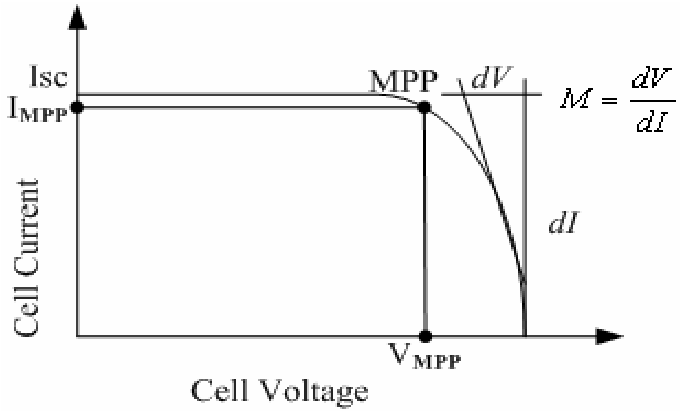

Fig. 2. I-V curve of a solar cell

$$M = dV / dI = \tan\alpha \approx \Delta V / \Delta I \quad (3)$$

Where, M is gradient of I-V curve.

Circuit diagram in Fig. 1 can be transform into effective solar cell model for easier calculation and obtaining information on suitable module parameters as shown in Fig. 3.

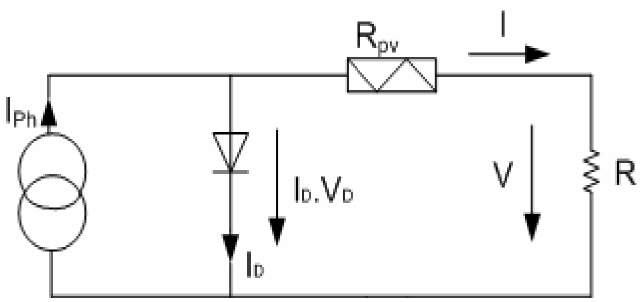

Fig. 3. Effective solar cell model

$$I = I_{Ph} - I_O(e^{V + IR_{PV}/V_T} - 1) \quad (4)$$

$$V = V_T \ln[(I_{Ph} - I + I_O)/I_O] - IR_{PV} \quad (5)$$

The advantage of effective solar cell is that both R_s and R_P are combined into a virtual photovoltaic resistance R_{PV}. The four required cell parameters (R_{PV}, V_T, I_0 and I_{Ph}) can be calculated as follows from the gradient M and from the cell parameters of open-circuit voltage V_{oc}, short-circuit current I_{sc}, MPP voltage V_{MPP} and MPP current I_{MPP}.

$$R_{PV} = -M\frac{I_{SC}}{I_{MPP}} + \frac{V_{MPP}}{I_{MPP}}\left(1 - \frac{I_{SC}}{I_{MPP}}\right) \quad (6)$$

$$V_T = -(M + R_{PV})I_{SC} \quad (7)$$

$$I_O = I_{SC}e^{-(V_{OC}/V_T)} \quad (8)$$

$$I_{Ph} = I_{SC} \quad (9)$$

The gradient M is a function of the following parameters:

$$M = f(V_{OC}, I_{SC}, V_{MPP}, I_{MPP}) \quad (10)$$

III. CONFIGURATION OF PV SYSTEM

Recently, interconnecting a PV inverter system with the utility line has been widely adapted to process renewable energy and improve power factor [5]. The general configuration of the PV system is shown in Fig. 4. It consist a DC-DC Boost Converter which functions as MPPT and a typical PWM inverter with Hysteresis Current Control using a full-bridge configuration. The switching frequency is much higher than the power line frequency and an order greater than the sampling frequency in a typical DSP implementation. Since there is no load connected in between the inverter and the utility grid, the utility grid itself acts as a load. The power produced by the system is transferred directly to the grid. The MPPT tracks for the maximum power and regulates the DC voltage to a constant value higher than the grid voltage in order to transfer power to the grid. In this case,

$$V_{DC} > \sqrt{2} \times V_{grid} \quad (11)$$

The reference voltage is sensed directly from the grid and is converted to current waveform which is then used as the reference current in the Hysteresis Current Control method. In this way the current produced by the system is in phase with the grid voltage. Therefore, neither additional circuitry nor method needed for power factor correction. This new method also enables us to achieve unity power factor.

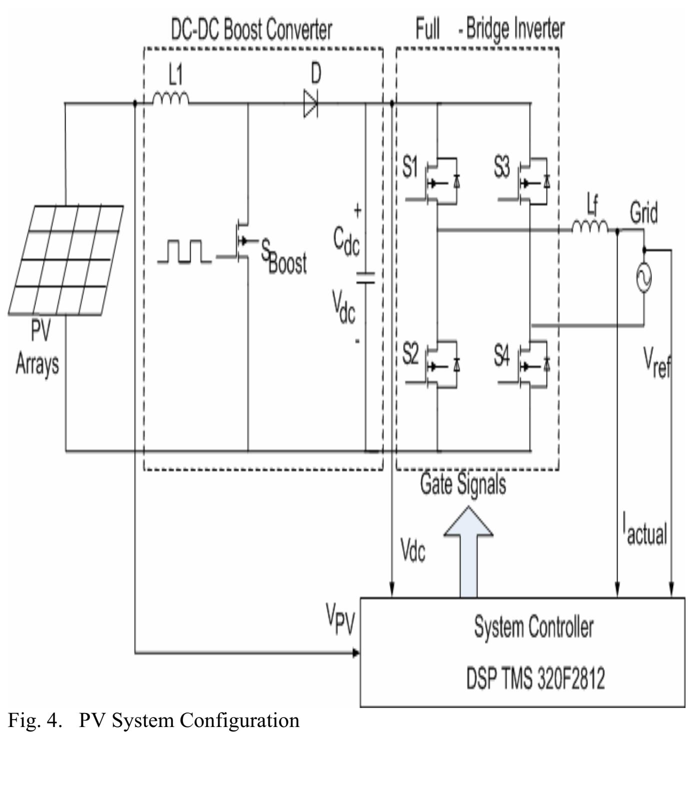

Fig. 4. PV System Configuration

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IV. MAXIMUM POWER POINT TRACKER

Mechanical and Electronic systems has been commonly used to extract maximum power from the PV array. Mechanical systems usually optimize the solar incidence angle while the electronic approach a maximum power transfer at the PV array terminals is pursued by means of Maximum Power Point Tracking (MPPT) methods. Mechanical and electronic systems for power maximization are compatible and complementary requiring a measurement of the array operating conditions and a posterior adjustment if the external conditions change[6].

In this paper, electronic method is used which implements a DC-DC Boost converter to track maximum power and to regulate the voltage as well. The conventional method of MPPT is obtaining the power from the PV arrays by multiplying the voltage and current of PV arrays and comparing it with previous measured power while sensorless MPPT only sense the output of the converter [7]. In this case the bus voltage of the DC-DC Boost converter is sensed and regulated to a constant value. The current extracted from the PV arrays is determined by the reference current signal used in the Hysteresis Current Controller as shown in Fig 7. It will be adjusted in order to extract maximum current from the PV arrays and since the output voltage is fixed, the maximum power is directly proportional to the current extracted from the PV arrays. The switching frequency has been set to 20kHz. A digital FIR Filter is used for better filtering of the signals and it is implemented in the DSP itself.

Since the maximum power extracted from the PV arrays is a function of V_{oc}, I_{sc}, V_{mpp}, and I_{mpp}, the tracker and the inverter should be designed accordingly by taking into consideration of these parameters. This will ensure maximum utilization of the PV arrays. The tracker implements a proportional-integral-derivative (PID) control method which can easily implemented on DSP's. TMS320F2812 were chosen since it is robust and reliable for power electronic application. Figure 5 shows the proposed closed loop system with a PID control method.

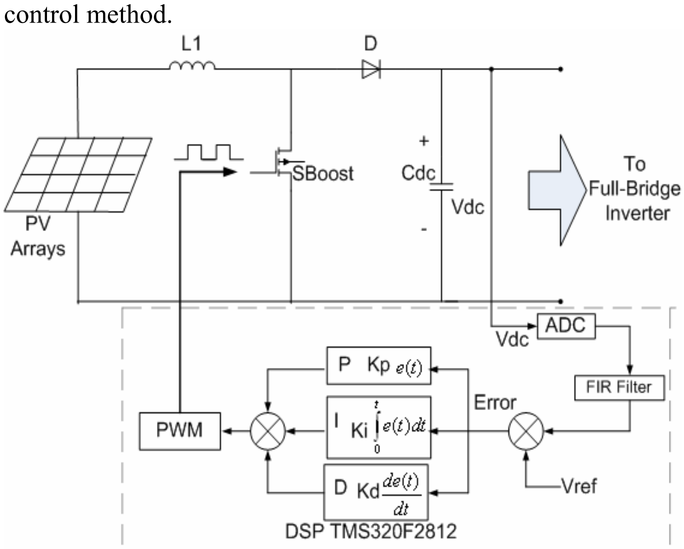

Fig. 5. MPPT with PID Controller

The transfer function of the PID controller looks like the following:

$$K_p + \frac{K_I}{s} + K_D s = \frac{K_D s^2 + K_p s + K_I}{s} \tag{12}$$

K_P = Proportional gain

K_I = Integral gain

K_D = Derivative gain

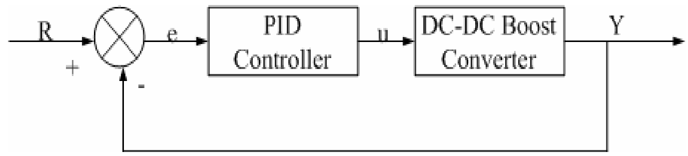

Fig. 6. PID Controller

From Figure 6, variable (e) represents the tracking error, the difference between the desired input value (R) and the actual output (Y). This error signal (e) will be sent to the PID controller, and the controller computes both the derivative and the integral of this error signal. The signal (u) just past the controller is now equal to the proportional gain (Kp) times the magnitude of the error plus the integral gain (Ki) times the integral of the error plus the derivative gain (Kd) times the derivative of the error.

$$u = K_P e + K_I \int edt + K_D \frac{de}{dt} \tag{13}$$

This signal (u) will be sent to the DC-DC Boost Converter, and the new output (Y) will be obtained. This new output (Y) will be sent back to the sensor again to find the new error signal (e). The controller takes this new error signal and computes its derivative and its integral again.

Here, the DC output voltage i.e the V_{ref} has been set to 400V. Power flows from PV system to the grid only occurs if the potential of the inverter output is greater than the potential of the grid. By referring to (11) the output of the DC-DC Boost converter, V_o is regulated using PID control method by varying the duty cycle of the switching pulse to give 400VDC regardless of the input. The input voltage has a condition which it should be more than 160V and must be less than 300V. This the operating range of the PV system. The system is idle if the operating range is outside of this limits.

V. HYSTERESIS CURRENT CONTROL

Hysteresis current control is a method of controlling a voltage source inverter where the measured current is compared to reference current on instantaneous basis. The current error is then compared directly against a predefined band called hysteresis band to produce switching pulses for the voltage source inverter. This method controls the switches in an inverter asynchronously to ramp the current through an inductor up and down so that it tracks a reference current signal. Hysteresis current control is one of the easiest control method to implement.

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The proposed hysteresis current controller is shown in Fig. 7 and 8. The error signal *e(t)* is used to control the PV inverter switches. The error is the difference between the desired current i_{ref} and current being produced by the inverter i_{actual}. The minimum and maximum values of the error signal are *emin* and *emax* respectively. This forms the Upper Hysteresis Band (I_{ref} + *emax*) and Lower Hysteresis Band (I_{ref} - *emin*). When the actual current I_{actual} reaches the Upper Hysteresis Band, switches S2 and S3 will turn on to force the current down. Once the current reaches the Lower Hysteresis Band, Switches S1 and S4 will turn on to force the current up. This will ensure the current is kept between the Lower and Upper Hysteresis Band.

In this proposed hysteresis current controller, the reference signal is sensed directly from the grid. First, the grid voltage is sensed and adjusted to a desired value before converting it to current signal to become the reference current signal. This will ensure the current produced by the PV inverter is in phase with grid voltage and also achieve unity power factor. This new topology is better and effective than conventional reference signal generation by the controller and matching it with the grid voltage at later stage. This method also reduces the number of components such as Phase Lock Loop (PLL) circuits and cost significantly.

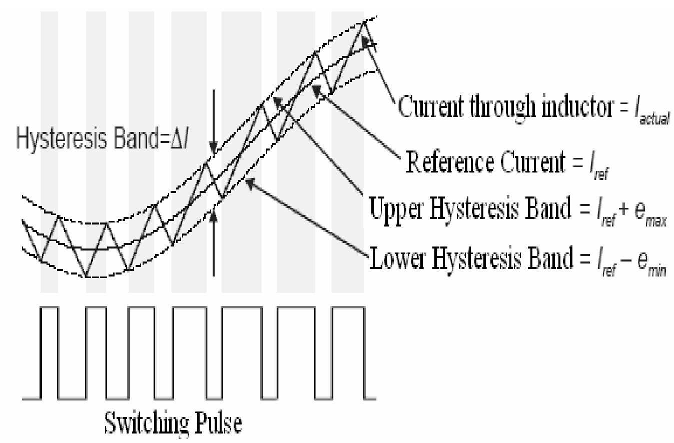

Fig. 7. Hysteresis Current Control

VI. SIMULATION AND EXPERIMENT RESULT

The performance and practicality of the presented transformerless PV Inverter with MPPT and Hysteresis Current Control have been confirmed by simulation and experiment result. It consists of a DC-DC Boost Converter and a full bridge inverter. Simulations were performed using Matlab/Simulink with practical limitation such as dead-band and system delay taken into consideration in order to match the experiment condition. The prototype system was tested at 1.2kW and directly connected to the utility grid. Fig. 9 and Fig. 10 shows the simulation results of utility voltage and current injected to the grid by the PV system. Fig. 11 shows the combination of utility voltage and current injected to the grid in order to prove that the voltage and current are in phase and at unity power factor.

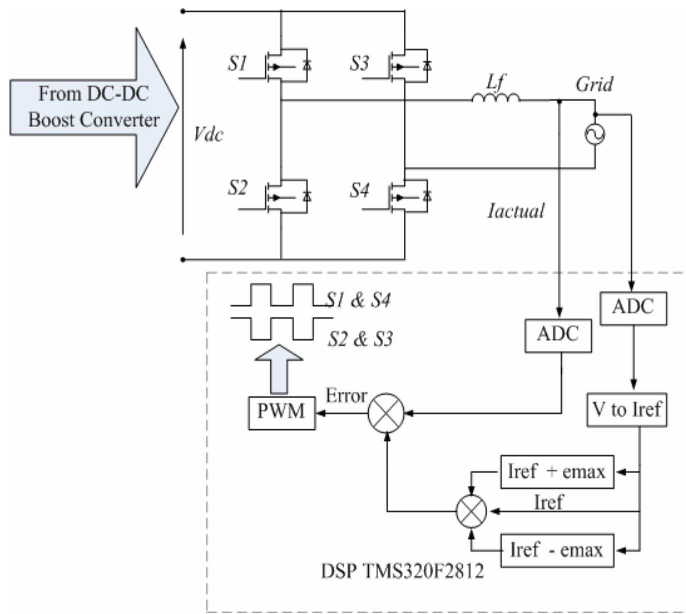

Fig. 8. Hysteresis current control configuration

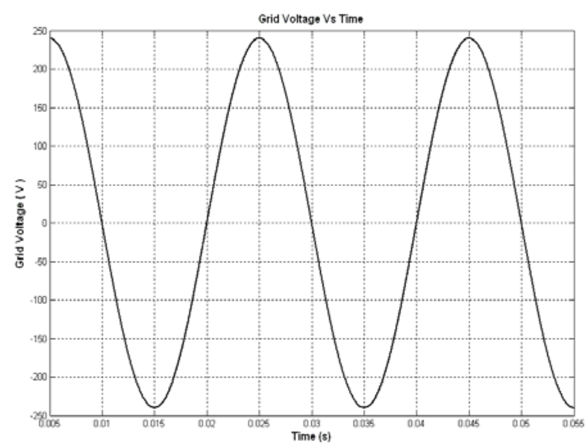

Fig.9. Simulation Result - Utility Grid Voltage

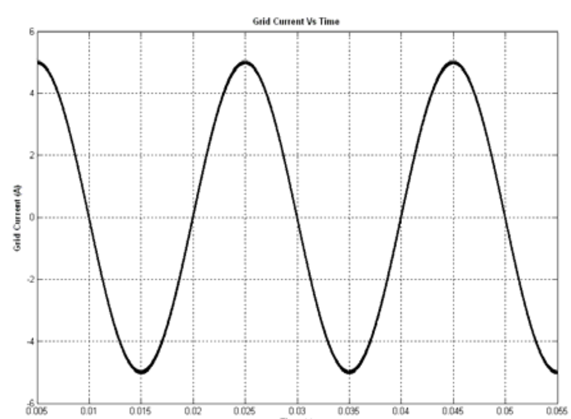

Fig. 10. Simulation Result - Grid Current

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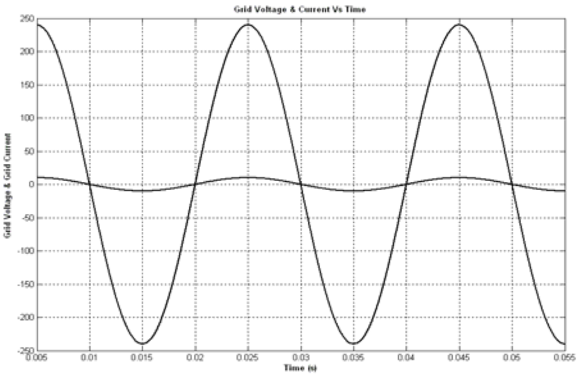

Fig. 11 Simulation Result - Grid Voltage and Grid Current

Fig. 12 is enlarging image of Fig. 10 to show the hysteresis current control algorithm. It consist of Upper Hysteresis Limit, Lower Hysteresis Limit, reference signal, the actual measured current and switching pulses for S1&S4 and S2&S3 respectively resulting from the Hysteresis action. Fig. 13 shows the experimental result of grid voltage and current fed into the grid also known as grid current. Fig. 14 proves that the grid voltage and grid current are in phase and at unity power factor while Fig. 15 shows % of Total Harmonic Distortion (THD) which is 3.42%.

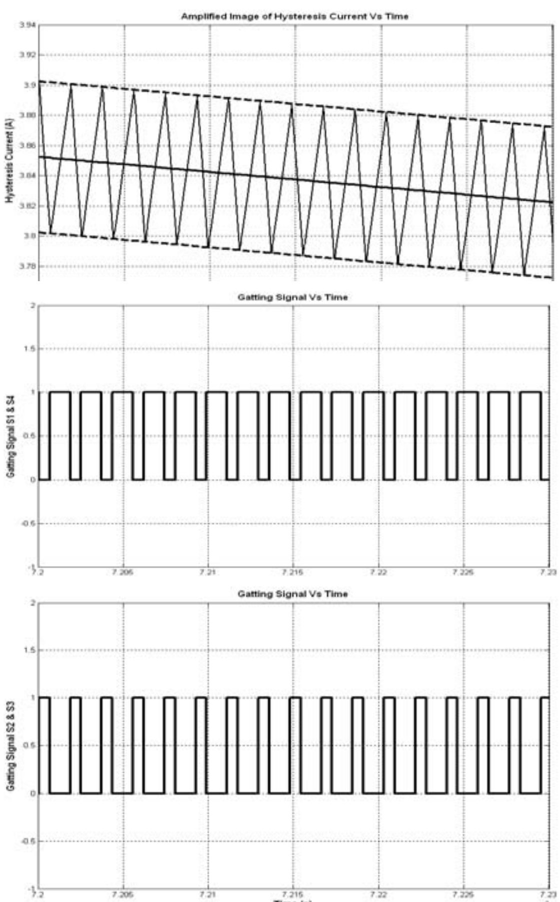

Fig. 12. Simulation Result - Enlarged image of Hysteresis Current Control method

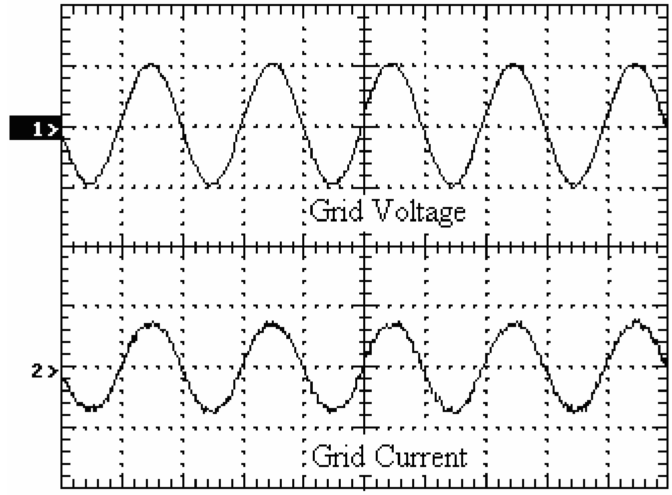

Fig. 13. Experimental Result – Grid Voltage and Grid Current

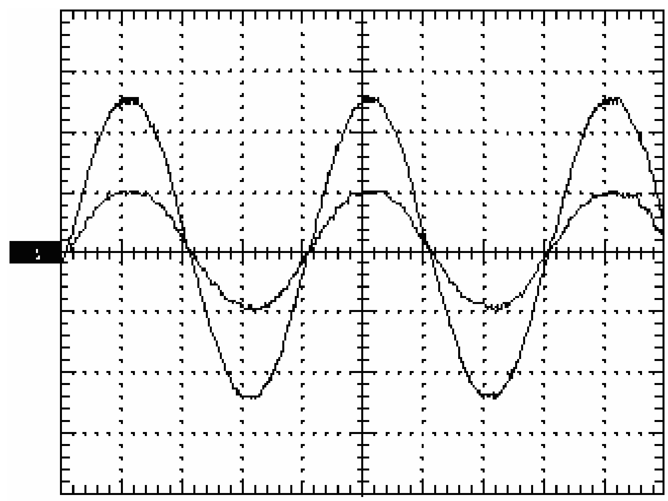

Fig. 14. Experimental Result – Grid Voltage and Grid Current at unity power factor

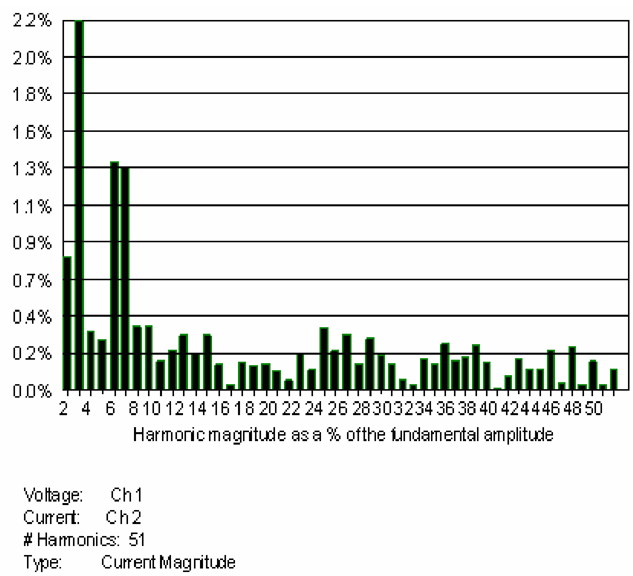

Fig. 15. % of Total Harmonic Distortion (THD)

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VII. CONCLUSION

This paper presents a novel single band hysteresis current control with regulated MPP voltage for PV inverter system. The control strategy for the full bridge inverter retains all the benefits associated with hysteresis current control while the MPPT extracts maximum power from the solar arrays. The cost of this system will also be relatively low as minimum number of sensors and power devices used. It also proves that the proposed PV inverter system has low THD and suitable to be connected the grid. The effectiveness of the control scheme has been verified both by simulation and experimentally.

VIII. ACKNOWLEDGMENT

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