A Grid Connected Photovoltaic Micro-inverter System with a Plug-in Repetitive Current Controller

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***Abstract*—This project works deals with a grid connected photovoltaic (PV) micro-inverter system (MIS) with its controlling technique. Micro-inverter system is a module integrated dc-dc converter which is cascaded by a full bridge inverter. In this proposed system, a dc-dc converter (a transformer isolated boost-half bridge converter) is used to interface the low voltage PV module with the load. The full bridge inverter coupled with a LCL filter used to inject synchronized sinusoidal current to the grid. The controller used in this paper is the plug-in repetitive current controller. A quasi sinusoidal pulse width modulated (PWM) inverter along with this controller helps to generate a rectified synchronized sinusoidal current o the grid and also eliminates the periodic errors. The system stability and dynamic stiffness can be achieved by adopting a high speed fast tracking P & O maximum power point (mpp) algorithmic technique. As a result high power factor and very low total harmonic distortion values are assured. The proposed model has been built by using MATLAB/Simulink model and the performance of the system is analyzed.**

Keywords—Grid – connected photovoltaic (PV), Micro-inverter system (MIS), Boost-half bridge converter (BHB), Plug-in Repetitive current controller (RCC), Perturb and Observe (P&O), Maximum power point (MPP), Total harmonic Distortions (THD's), Synchronized sinusoidal current.

I. INTRODUCTION

The micro-inverter is also known as module integrated converter/inverter. Now a days the concept of micro-inverter is gaining popularity as it offers many advantages such as no fuel costs, free from pollution and requires less maintenances. The only disadvantage faced is the high initial cost. A low voltage is supplied by a PV module to the micro-inverter system (MIS) often requires a high voltage step up ratio to generate desired output voltage. An individual PV module with a dc-dc converter cascaded by an inverter is the most emerging topology in the field of grid-connected photovoltaic (PV) power system and therefore micro-inverter system is becoming the future trend [1].

Along with the decline in production of fossil fuel due to the industrial revolution, there has been a growing interest in exploring renewable energy. Among variety of renewable energy resources PV have become the biggest contributors because of no supply limitations [2]. As the PV sources are intermittent, non linear and produce power that varies with environmental conditions maximum power point tracking (MPPT)must be introduced. For best operation of the system PV module must be operated at its maximum power. Most commonly used MPPT techniques is Perturb and Observe (P&O). Even though this method have many disadvantages like large perturb value result in oscillations and smaller value results in slower response [3]. In this paper, variable step size P & O method is implemented to track maximum power due to its simplicity, ease of implementation and good performances.

In this thesis work, there are two decoupled power processing stages. A Boost-half bridge converter works as the front end dc-dc conversion stage and a full bridge PWM inverter with an output LCL filter serve as the next dc-ac conversion stage. A MIS is the combination of these two stages. A high frequency transformer is implemented within dc-dc conversion stage, as leakage inductance in it serves as energy storage and transfer element. For unidirectional power conversion can be derived from replacing the secondary of the half bridge by a diode voltage doubler circuit. The simple circuit topology with minimal use of semiconductor devices gives ease of control. It provides promising features such as low cost, high efficiency and high reliability [4].

A plug-in repetitive current controller, which is proposed in this paper, provides an effective solution for elimination of periodic harmonic error. Non linear loads produces periodic error, major sources of Total harmonic distortion (THD). The proposed controller composed of a proportional part and a repetitive control (RC) part. In order to achieve high performance control, along with RC part an IIR filter is accommodated so that to obtain very high system open loop gain at a large number of frequencies. Hence harmonic rejection capability is enhanced. So called the name Plug-in repetitive current controller [5]. The system performance can be evaluated by output current and voltage THD's along with power factor and dynamic response. Below features make the proposed controller much more robust and widely accepted:

1. Achieve high power factor.
2. Current harmonic distortion upto 13^{th} order are minimized.
3. Provides outstanding current regulation.
4. Fast dynamic response is achieved.

Hence this technique arises as a simple solution for tracking or rejection of periodic signals [6],[7].

Conventionally a LC filter is used to interface grid connected systems. To obtain high dynamic performances and sufficient attenuation, a high switching frequency must be used. In order to achieve improved harmonic distortion with lower switching frequency an LCL filter is used. It requires a complex current controller to maintain the system stability. This paper presents a micro-inverter system having a boost-half bridge converter with P & O MPPT technique with an inverter clubbed with a LCL filter and a plug-in repetitive controller to form a promising system.

II. PROPOSED SYSTEM

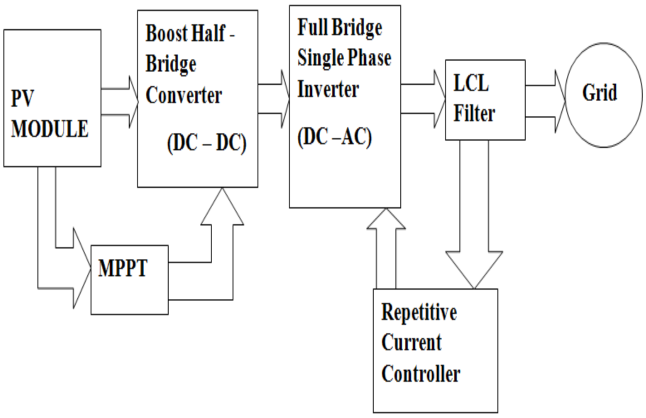

Fig 1 The proposed system

The overall configuration of the proposed system is shown in fig 1. From the fig. we can understand that the system consist of a PV module, whose power is fed to the converter then to the inverter and finally fed to grid. To make the PV module work efficiently a MPPT algorithm is implemented so that maximum power can be drawn from a single PV module. The low dc output voltage from the PV is fed to a dc-dc converter. In the proposed system, we use a boost-half bridge converter, where the voltage is boosted up. The boosted output voltage from the converter is fed to a single phase full bridge inverter and the output is filtered by LCL filter. To obtain synchronized sinusoidal current a plug-in repetitive current controller is used. The controlled inverter helps in converting dc voltage to ac voltage whose magnitude and frequency obtained are same as that of the grid voltage and frequency.

A. Circuit Description

Fig 2 depicts the circuit diagram of the proposed micro-inverter system. In this paper, hard switching is employed and transformer leakage inductance is regarded small enough to be neglected. The boost-half bridge converter is a combination of a boost converter and a half bridge dc-dc converter. The working of the proposed converter is same as that of a conventional boost converter with extra features of galvanic isolation and high step up ratio. Due to use of minimal semiconductor devices, this topology exhibits a low total cost and good reliability.

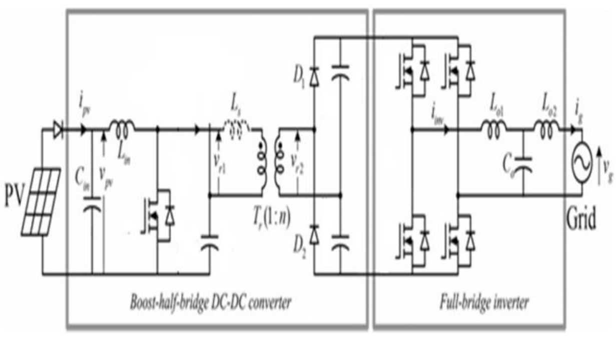

Fig 2 The circuit diagram

B. Modelling of a 250W PV module

A PV module generally consists of a diode a parallel resistor expressing a leakage current and a series resistor for internal resistance to current flow.

Table 1 Specification of a PV panel

Maximum Power Pmax	250W
Voltage at Pmax	36V
Current at Pmax	5A
Open circuit voltage Voc	35V
Short circuit current Isc	8.66A
Shunt resistance Rsh	1000Ω
Series resistance Rs	0.0012Ω
Number of cells in series Ns	60
Number of cells in parallel Np	1

With the equations of these parameters and specifications given on Table 1 a 250W PV module. Fig 3 shows the simulink model of a 250W PV module.

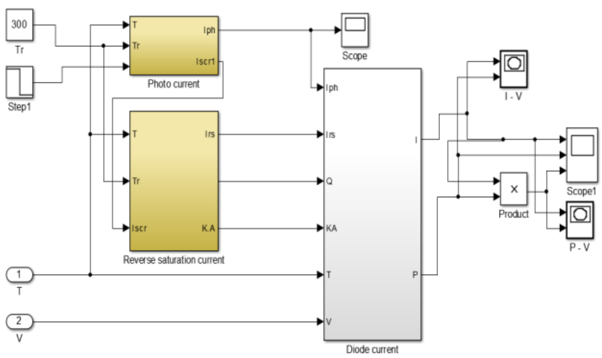

Fig 3 The simulink model of a 250W PV module

C. Boost-half bridge converter with its control

The proposed converter act as power conditioning circuit between the PV module and the load. The boost-half bridge converter operates identically as a conventional boost converter having extra features of galvanic isolation and high step up ratio. Table 2 shows the design parameters and with the help of equations (1), (2) and (3). A boost-half bridge converter has been developed.

Design Consideration

The input inductance is given by:

$$L = \frac{V_I . D}{\Delta I_L . f} \tag{1}$$

Switching frequency is 20 kHz
Current ripple is assumed to be 45% of the nominal input current.

The input capacitance is given by:

$$C = \frac{I_0 . D}{V_1 . f} \tag{2}$$

The output voltage of the boost-half bridge converter is given by :

$$V_2 = \frac{N2}{N1} V1 \tag{3}$$

Table 2 The Specification of Boost- half bridge converter

Nominal Power	250W
Input Voltage	30V-50V
Output Voltage	180V-213V
Transformer turns ratio	1:6
Switching Frequency	21.06kHz
Input Inductor	200µH
Input Capacitor	462µF

The primary objective of MPPT algorithm is to continuously tune the system for drawing maximum power under varying conditions. The P & O MPPT algorithm is the simplest algorithm which operates at standard test condition at constant voltage equals to MPP voltage. The algorithm rapidly tracks and provides switching pulses to the boost-half bridge converter. Direct control duty cycle is implemented. The algorithm is represented in flow chart as shown in fig.4.

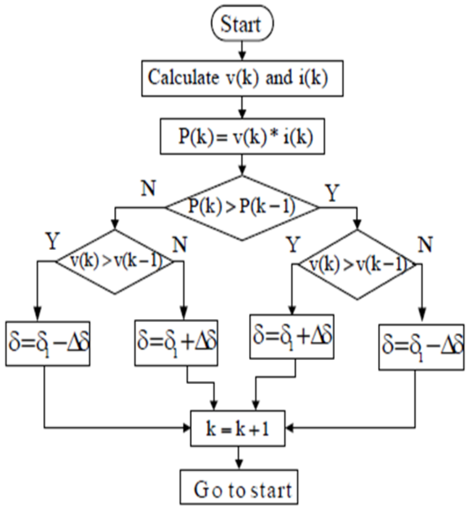

Fig 4 The flow chart of P & O MPP Algorithm

The simulink model f PV module incorporated with P & O MPP algorithmic technique to generate switching pulse is shown in Fig 5.

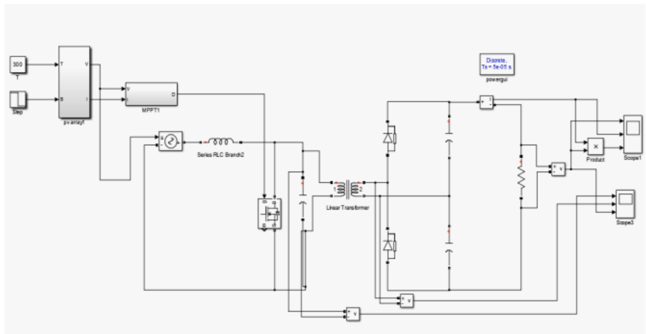

Fig 5 The control Circuit of the BHB Converter

D. Overall Control Implementation of the MIS system

Fig 6, depicts the controlling technique of the proposed system. The instantaneous PV power P_{PV} is calculated by frequently perturbing PV voltage V_{PV} and PV current I_{PV}. At the inverter side, the instantaneous angle θg is extracted with the help of Phase Locked Loop (PLL) by calculating the grid voltage Vg. A low pass filter incorporated between the inverter and grid eliminates the high frequency noise by pre-filtering the inverter output current. The filtered output is fed to the actual controller of the system that is, Plug-in repetitive current controller, where the dc link voltage are also regulated.

To achieve fast and dynamic responses grid current and dc link voltage have to be regulated. A current reference feed forwarded added to the system whose magnitude is given by the equation:

$$|I_{inv}|_{ff} = \frac{2P_{PV}}{|V_g|} \tag{4}$$

Where Vg is grid voltage, which is calculated by:

$$|V_g| = \int_0^{\pi} V_g \, d\theta_g \qquad (5)$$

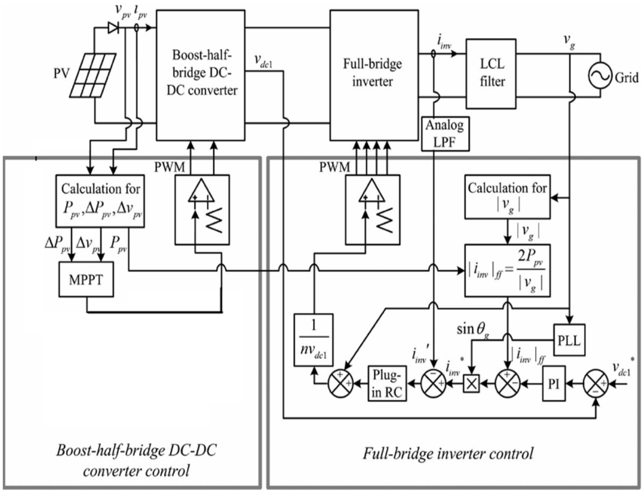

Fig 6 The block diagram of the control circuit of overall system

The simulink model of the overall control system is described in this paper depicted in Fig 7.

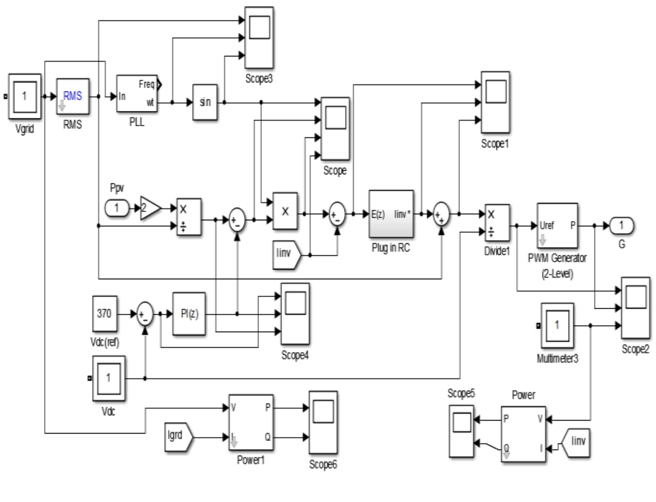

Fig 7 The simulink model of overall control system

E. *PLUG-IN REPETITIVE CURRENT CONTROLLER*

In a grid connected inverter system, LCL filter act as an attractive solution to reduces current harmonics around switching frequency, improves system dynamic response and also reduces the total size and cost of the system.. The main drawback of the LCL filter is it exhibits a sharp LC resonant peak which affects the potential stability of the current controller and hence the system.

To attenuate the resonant peak below 0 dB either by using active damping or passive damping techniques. Otherwise by selecting the location of the current sensor properly, that is by introducing a damping technique at the inverter side instead of grid side we can stabilize the system. This solution makes the current controller simple and effective.

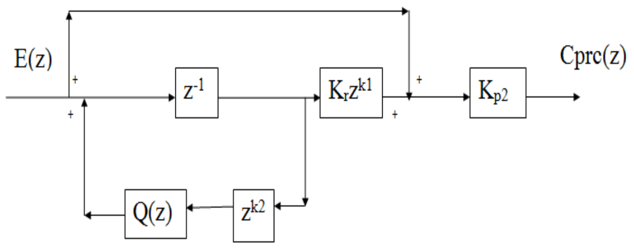

Fig 8 The block diagram of Plug-in repetitive controller

Here in the proposed controller the repetitive controller is plugged in parallel with the proportional controller. From fig 8 E(z) represents the tracking error.

The positive feedback loop inside RC plays very crucial role. In an ideal RC, all repetitive errors are based on the fundamental periods which are completely eliminated by unity gain along with the positive feedback, hence the system attains equilibrium. However, a zero-phase low pass filter is often incorporated rather than unity gain to obtain sufficient stability margin. In this controller there are two phase lead compensators Z^{k1} and Z^{k2} to realize the stability margin by cascading to the linear phase low pass filter and Z^{k1} compensates the phase lag of the inverter at high frequencies. K_1 and K_2 are number of sampling periods. K_r represents the constant gain to determine the weight of the controller in the whole system.

From fig 8, the transfer function of the controller is given by:

$$C_{prc}(Z) = \frac{K_r K_{p2} Z^{-N} Z^{K_1}}{1 - Q(Z) Z^{k2} Z^{-N}} + K_{p2} \qquad (6)$$

Design and Analysis

The proposed controller modifies the transient response and steady state error and produces an output signal which is proportional to the error signal. This output in turn amplifies the error signal to increase the loop gain. During transients, larger the value of K_{p2} results in the smaller tracking error.

$$|H(Z)|_{z=e^{j\omega T_{sw2}}} = \left[\left| Q(Z) Z^{k2} - \frac{K_r K_{p2} Z^{K_1} G_{inv}(Z)}{1 + K_{p2} G_{inv}(Z)} \right| \right], \omega\varepsilon \left[0, \frac{\pi}{T_{sw2}}\right]$$

Where T_{sw2} is the sampling period, w is the sampling frequency.

To meet the stability, $|H(e^{j\omega T_{sw2}})| < 1$

Z^{-N} must be equal to unity.

For obtaining a good stability as well as small steady state error, the general design criteria are summarized below:

1. At high frequencies, sufficient attenuation must be required for Q(Z).
2. Q(Z) must be close to unity as it covers large number of harmonics in the system.
3. When Q(z) is close to unity, $Q(Z)Z^{k2}$ must have zero phase.

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Linear phase IIR filter is used with RC and obtain a flat gain in the pass band which make it appropriate to use here than the conventional finite impulse filter.

$$Q(Z) = Q_e(Z) * Q_s(Z)$$

The magnitude of Q(Z) determines the steady state error and yields an excellent harmonic rejection capability.

III. SIMULATION RESULTS AND ANALYSIS

The tool used for simulation in MATLAB is R2013a/Simulink. The entire block diagram of fig 1, is simulated. The voltage and current from PV module is measured using voltage and current measurement block and is given to the MPPT algorithm to generate duty cycle for the boost-half bridge converter utilizing maximum permissible power from sun. The output of the converter is fed to inverter. The switching pulses for the inverter are produced by the plug–in RC controller along with PI controller for excellent current and voltage regulation.

Table 3 Specifications of the inverter parameters

Input Voltage	180V
Switching Frequency	10.8kHz
Sampling Frequency	10.8kHz
Grid Voltage	230V
Grid Frequency	50Hz
Filter Inductors	8.5mH
Filter Capacitor	3.3µF

From the parameters given in Table 3, a single phase full bridge inverter to which a Repetitive current controller is introduced. Fig 9, shows the simulated model of the whole MIS.

The proposed plug in RC achieves 1.03% voltage THD, 1.17% current THD and a power factor of about 0.99.

All simulation results are shown below. From the 250W PV module had been simulated which will produce a voltage of about 37V. The low voltage from the PV module is fed to the boost-half bridge converter which boosts up the 37V to 180V steady state dc voltage.

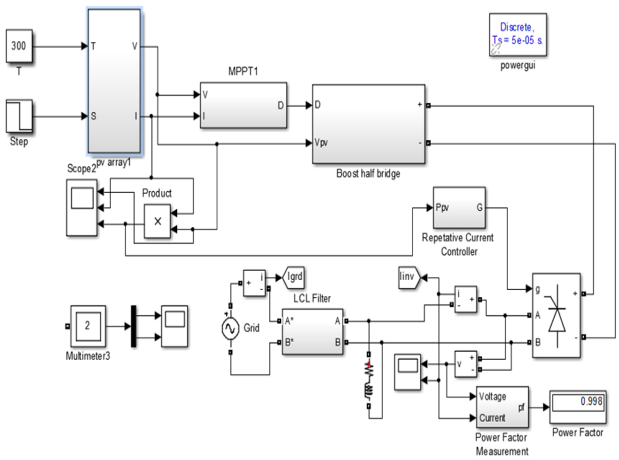

Fig 9 The simulink model of overall system.

Fig 10, shows the simulated result of the converter output at step irradiance from the PV module.

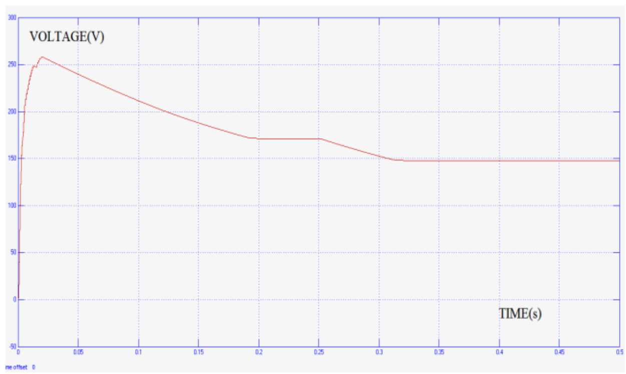

Fig 10 The stimulated results of the converter

The boosted voltage from the converter is fed to the inverter. Inverter is incorporated with the plug-in RC controller and LCL filter.

Fig 11 shows the stimulated result of the steady state voltage obtained from the inverter side. Presence of the controller produces a voltage exactly same as the grid voltage so that synchronization become very much easier.

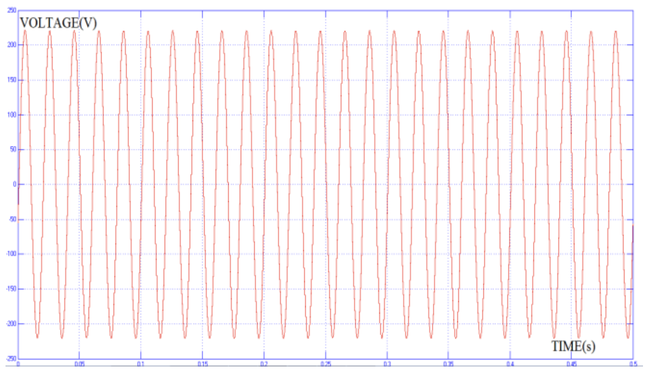

Fig 11 The stimulated result of the inverter side voltage

The plug-in RC enhances the micro-inverter so that it produces the harmonic distortion very low. The THD of the voltage produced by the inverter is found to be 1.03% which is shown in fig 12.

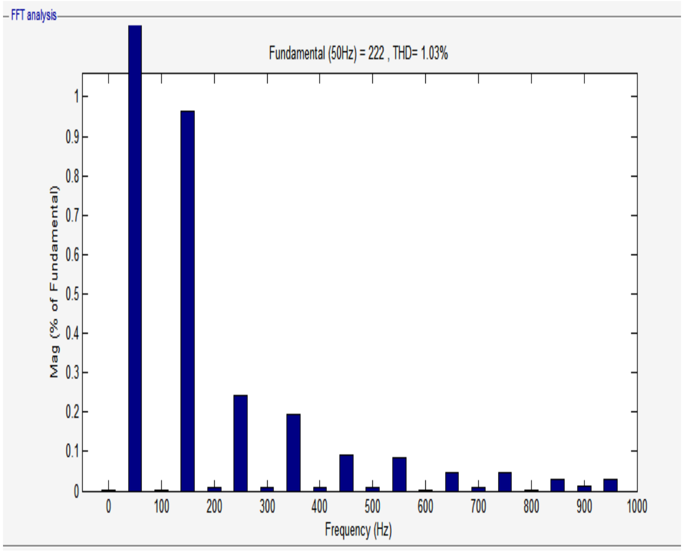

Fig 12 Voltage THD from the inverter side

The controller helps the inverter to inject synchronized current to grid and also regulate the grid current. Fig 13, shows the output current of the system. The plug-in RC monitors the grid voltage and current continuously. The plug-in controller consists of two parts the RC part works in parallel with the PI controller part. The harmonic distortion at several fundamental cycle are eliminated by the RC part and proportional part promptly responds to the abrupt reference changes.

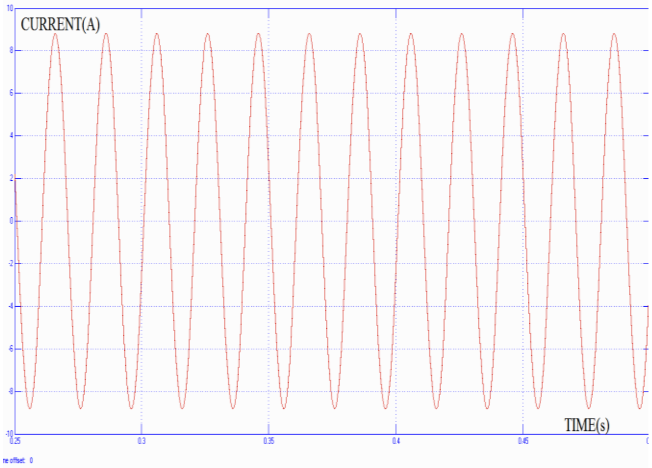

Fig 13 The stimulated result of the output inverter current

Fig 13, shows the output current of the inverter which produces a small harmonic distortion. Hence the voltage and current are regulated by means of plug-in repetitive current controller based on fourth-order linear –IIR filter. Fig 14, shows the low THD produced by the output current.

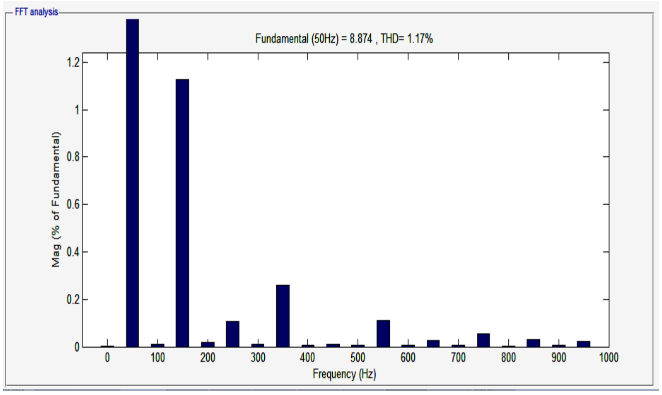

Fig 14 The current THD level from inverter side

IV. CONCLUSION

A grid connected photovoltaic micro-inverter system with its control implementation has been presented in this paper. A 250W PV module has been modelled along with P & O MPPT algorithmic technique to extract maximum power. A plug-in repetitive current controller was studied and introduced to inject synchronised current to the grid, which was regulated stiffly and precisely. Simulation of the proposed system was done by MATLAB/Simulink.

The MIS having simple circuit topology and ease of control is exhibited in this paper. The controller provides high power factor and low THD's. Power factor of about 0.99 and low THD values of about 1.03% and 1.17% of output voltage and current are achieved. All these advantages make the system very promising on in the field of grid-tie photovoltaic applications.

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