Reduction of Lower Order Harmonics in a Grid-connected Single-phase PV Inverter Using Adaptive Harmonic Compensation Technique

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***Abstract*— This paper proposes a novel inverter current control method to mitigate lower order harmonics in a single-phase grid-connected photovoltaic (PV) inverter. The circuit under consideration is composed of a PV array, a boost section, a single-phase inverter with an inductive filter and a step-up transformer interfacing the grid or the load. The lower order harmonics, which may be caused by non-ideal factors such as distorted magnetizing current in transformer due to core saturation, dead time of inverter, on-state voltage drops in switching etc., need to be eliminated in order for the PV inverter to meet IEEE standards. An inverter current control technique, wherein a modification to the conventional PR controller (proportional-resonant controller) is done is put forward. This novel controller, named as proportional-resonant-integral (PRI) controller, eliminates the dc component in the control system, which introduces even harmonics in the grid current. An adaptive harmonic compensation technique, which makes use of an LMS adaptive filter to eliminate a particular harmonic component in the output current, is proposed for the lower order harmonic compensation. The complete design has been validated with simulation results and the THD of the output voltage/ current waveforms has been found to be in conformance with the IEEE standards.**

Keywords—odd and even harmonics, MPPT algorithm, boost converter, PRI controller, THD

I. Introduction

In recent years, distributed generation (DG) systems have started making use of renewable energy sources owing to the depletion of conventional energy sources. Distributed generation allows collection of energy from many sources and may give lower environmental impacts and improved security of supply. In this paper, a system utilizing solar energy as the source and a photo-voltaic inverter to supply the power generated to the grid is elucidated. The topology of the solar inverter system[1] consists of the following three power circuit stages:

1) a boost converter stage to perform maximum power point tracking (MPPT)
2) a low-voltage 2-bridge VSI inverter
3) an inductive filter and an RL load

The objective of the paper is to mitigate the lower order harmonics in this system. The system will not have any lower order harmonics in the ideal case. However, harmonics are generated due to the following aspects: distorted magnetizing current drawn by the transformer due to the nonlinearity in the *B–H* curve of the transformer core, the dead time introduced between switching of devices, on-state voltage drops on the switches, distortion in the grid voltage etc.

Harmonics have a negative impact on distribution networks and influence the behaviour of system components and loads: For example, conductors suffer from losses and skin effects, eddy current losses can have detrimental effects on transformers, with consequent equipment overheating, capacitors may be affected by resonance phenomena with potential breakdown, and machines can suffer from vibration phenomena.

These harmonics need to be mitigated so that the PV inverter meets standards such as IEEE 519-1992 and IEEE 1547-2003. This paper focuses on the design of an inverter current control to achieve a good attenuation of the lower order harmonics.

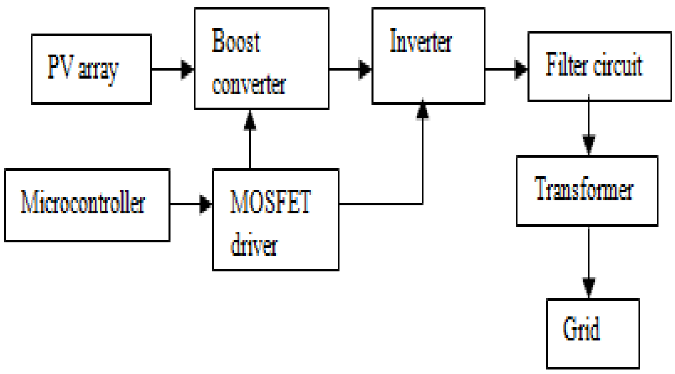


Fig.1: Schematic diagram of the circuit

Fig.1 shows the circuit block diagram of a single phase grid connected PV inverter. The DC output from the solar array is boosted using MPPT scheme. The goal of MPPT technique is to automatically find the voltage V_{MPP} or current I_{MPP} at which a PV array should operate to obtain the maximum power output P_{MPP} under a given temperature and irradiance. The boost converter stage employs duty ratio control during MPPT.

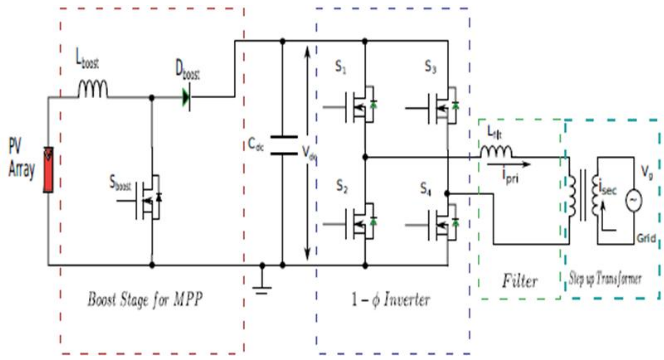


Fig. 2 Power Circuit Topology of single-phase PV System

Fig.2 shows the power circuit topology of a single-phase PV inverter connected to a grid. The controller employed here is a PRI (proportional-resonant-integral) controller. This is a modification to the conventional PR (proportional-resonant) controller wherein any dc offset in a control loop will propagate through the system and results in drawing of even harmonics from the grid. Thus, an integral block is used along with the PR controller to ensure that there is no dc in the output current of the inverter. This would automatically eliminate the even harmonics. The complete scheme is verified experimentally and the results show a good correspondence with the analysis.

The organization of this paper is as follows: Section II discusses the sources of lower order harmonics in the system. Section III explains the MPPT algorithm used, Section IV about the design of fundamental current control using a PRI controller. In Section V, design of the system using MATLAB and the simulation results are elucidated. In Section VI, the hardware details are provided. Conclusions are given in Section VII.

II. LOWER ORDER HARMONICS

A. *Harmonics*

Harmonics are electric voltages and currents that appear on the electric power system as a result of non-linear electric loads. When a non-linear load is connected to the system, it draws a current that is not sinusoidal. These result in distortions, termed as harmonics. Harmonic frequencies in the power grid are a frequent cause of power quality problems. Some of the major effects of power system harmonics are:

- increases the current in the system.
- causes poor power factor
- transformer and distribution equipment overheating
- sensitive equipment failure

B. *Lower order harmonics*

Harmonics are steady-state distortions to current and voltage waves and repeat every 50 hertz or 60 hertz cycle. They occur as integral multiples of the fundamental frequency. As the frequency increases, the magnitude decreases gradually, thus making the lower order harmonics the most predominant and harmful.

For instance, the third harmonic causes a sharp increase in the zero sequence current, and therefore increases the current in the neutral conductor. This effect can require special consideration in the design of an electric system to serve non-linear loads.

The origin of odd and even harmonics is discussed below:

1) Odd Harmonics: The following are the primary causes for the lower order odd harmonics:

- Distorted magnetizing current drawn by the transformer due to the nonlinear characteristics of the *B–H* curve of the core
- Inverter dead time[2] (proportional to the dead time, switching frequency, and the dc bus voltage)
- Semiconductor device voltage drops
- Distortion in the grid voltage
- Voltage ripple in the dc bus

2) Even Harmonics: The system is susceptible to the presence of dc offset in the inverter terminal voltage. The dc offset is caused by one or more of the following factors:

- Varying power reference given by a fast MPPT block
- Offsets in the A/D converter and the sensors.

C.Evaluation of harmonics:

Harmonics can be quantified using the Fourier series. It provides a mathematical analysis of distortions to a current or voltage waveform. Based on Fourier series, harmonics can describe any periodic wave as summation of simple sinusoidal waves which are integer multiples of the fundamental frequency.

The harmonic voltage amplitude for a *h*th harmonic can be expressed as

$$V_h = \frac{4}{h\pi}\frac{2V_{dc}t_d}{T_s}$$

where t_d is the dead time,
T_s is the device switching frequency, and
V_{dc} is the dc bus voltage

III. MPPT ALGORITHM

Maximum power point tracking (MPPT) is a technique that grid connected inverters, solar battery chargers and similar devices use to get the maximum possible power from one or more photovoltaic devices, typically solar panels. Solar cells have a complex relationship between solar irradiation, temperature and total resistance that produces a non-linear output efficiency which can be analyzed based on the I-V curve. It is the purpose of the MPPT system to sample the output of the cells and apply the proper resistance (load) to obtain maximum power for any given environmental conditions. MPPT devices are typically integrated into an electric power converter system that provides voltage or current conversion, filtering, and regulation for driving various loads.

Tracking the maximum power point (MPP) of a photovoltaic (PV) array is a crucial part of a PV system. Many MPP tracking (MPPT) algorithms have been developed and implemented. In this paper, the Perturb and Observe (P&O) algorithm is made use of. That is, in this system, a PV array is connected to a power converter. Thus, perturbing the duty ratio of power converter perturbs the PV array current and consequently perturbs the PV array voltage.

The graphical representation of the algorithm is shown in Fig 3. It is clear from the graph that incrementing the voltage increases the power when operating on the left of the MPP (maximum power point) and decreases the power when on the right of the MPP. Therefore, if there is an increase in power, the subsequent perturbation should be maintained to reach the MPP and if there is a decrease in power, the perturbation must be reversed.

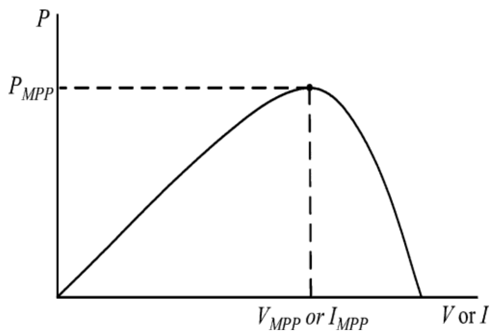


Fig. 3: P&O algorithm graphical representation

The process is repeated periodically until the MPP is reached. The system then oscillates about the MPP. The oscillation can be minimized by reducing the perturbation step size.The block of MPPT used in the MATLAB simulink is shown in Fig.4

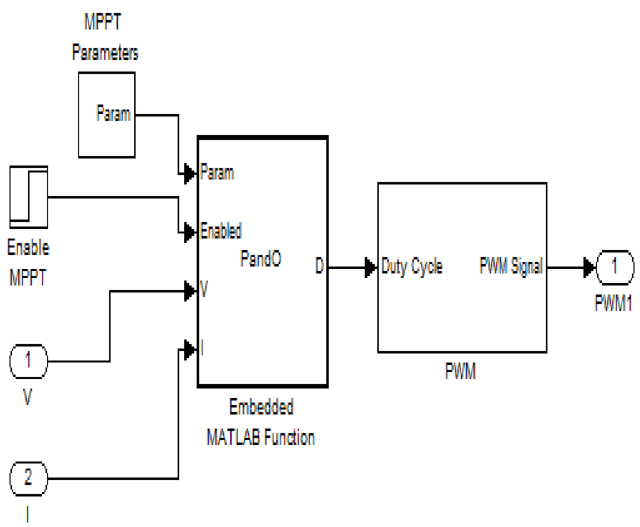


Fig. 4: MPPT block in MATLAB

IV. Design of PRI Controller

This controller uses three blocks- a proportional controller, a resonant controller and an integral controller.

A proportional control system is a type of linear feedback control system. In the proportional control algorithm, the controller output is proportional to the error signal, which is the difference between the set point and the process variable. In other words, the output of a proportional controller is the multiplication product of the error signal and the proportional gain.

The addition of a resonant block results in a PR controller. For low order harmonic compensation, PR controllers are good alternatives to PI(proportional-integral) controller, especially in grid-connected distributed generation systems. PR filters can be used for generating the harmonic command reference precisely in an active power filter and for implementing selective harmonic compensation.

Yet another development has been made in the controller by the inclusion of an integral block. If the main controller used is a PR controller, any dc offset in a control loop will circulate through the system and the inverter terminal voltage will have a nonzero average value. The integral block ensures that there is no dc in the output current and eliminates the even harmonics.

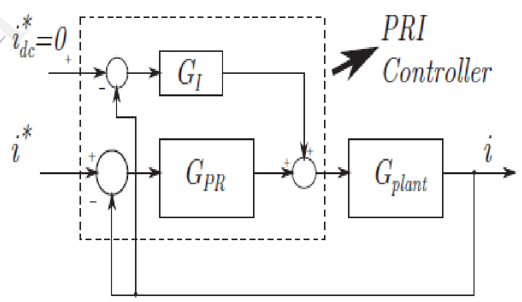


Fig.5: Block diagram of the fundamental current control with the PRI controller.

The transfer function of the PR controller is:

$$G_{PR}(s) = K_p + \frac{K_r s}{s^2 + w_0{}^2}$$

The plant transfer function is formed as

$$G_{plant}(s) = \frac{V_{dc}}{R_s + sL_s}$$

where V_{dc} is the gain of inverter to the voltage reference generated by the controller impedance (R_s + sL_s) is the impedance offered by the controller given in s-domain.

R_s and L_s are the net resistance and inductance referred to the primary side of the transformer, respectively.

L_s includes the filter inductance and the leakage inductance of the transformer.

R_s is the net series resistance due to the filter inductor and the transformer.

First, a PR controller is designed for the system assuming that the integral block is absent, i.e., $K_I = 0$. Design of a PR controller is done by considering a PI controller in place of the PR controller.

$$G_{P1}(s) = K_{P1}\frac{1+sT}{sT}$$

With the PI controller as the compensator block in Fig. 4 and without integral block, the forward transfer function will be

$$G_f(s) = \left(K_{P1}\frac{1+sT}{sT}\right)\frac{V_{dc}}{R_s + sL_s}$$

The closed-loop transfer function for Fig. 4 is given by

$$G_{cl,PRI} = \frac{i(s)}{i^*(s)} = \frac{G_{plant}G_{PR}}{1 + G_{plant}(G_{PR} + G_I)}$$

Without the integral block, the closed-loop transfer function would be

$$G_{cl,PR} = \frac{G_{plant}G_{PR}}{1 + G_{plant}G_{PR}}$$

Now the plant transfer function is,

$$G_{plant} = \frac{M}{1+sT}$$

where $M = V_{dc}/R_s$ and $T = L_s/R_s$

The model of PRI controller used in the simulation is shown in Fig.6.A discrete virtual PLL controller is used in addition to the PRI controller for the sinusoidal waveform.

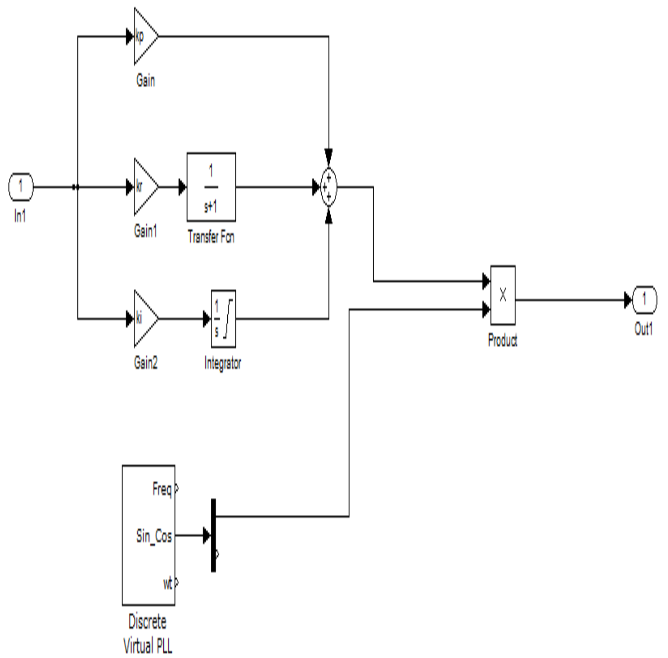


Fig.6: PRI Controller block using MATLAB

V. SIMULATION RESULTS

TABLE I

PV INVERTER PARAMETERS

Parameter	**Meaning**	**Value**
V_{dc}	DC bus voltage	40 V
1:n	Transformer turns ratio	1:15
w_{bw}	Bandwidth of current controller	84.8 X 10^3 rad/s
R_s	Net series resistance referred to primary	0.28 Ω
L_s	Net series inductance referred to primary	1.41 mH
S_1-S_4, S_{boost}	Power MOSFETs	IRF Z44($V_{DS,max}$=60V, $I_{D,max}$=50A)
C_{dc}	DC bus capacitance	6600 µF, 63V
f_{sw}	Device switching frequency	40 kHz
K_p	Proportional term	3
K_r	Resonant term	594
K_I	Integral term	100
K_{adapt}	Gain in harmonic compensation block	25.6
T_a	Time constant	0.03s

The circuit topology was built in laboratory for a max power rating of 150W. The various power circuit and control circuit parameters are listed in Table II. All the design related plots and the simulation result have the parameters as listed in Table II.

Fig.7. shows the grid connected single-phase PV inverter using MATLAB Simulink

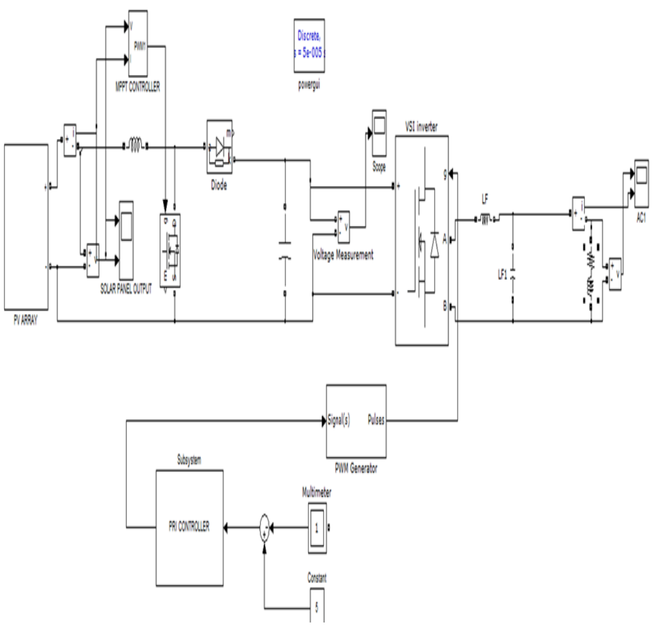


Fig.7. Grid connected single-phase PV Inverter

From the simulation the output voltage waveform from the solar panel is shown in Fig.8.And by implementing the Maximum Power Point Tracking Techinque the output voltage from the inverter is boosted to the maximum voltage and is shown in Fig.9.

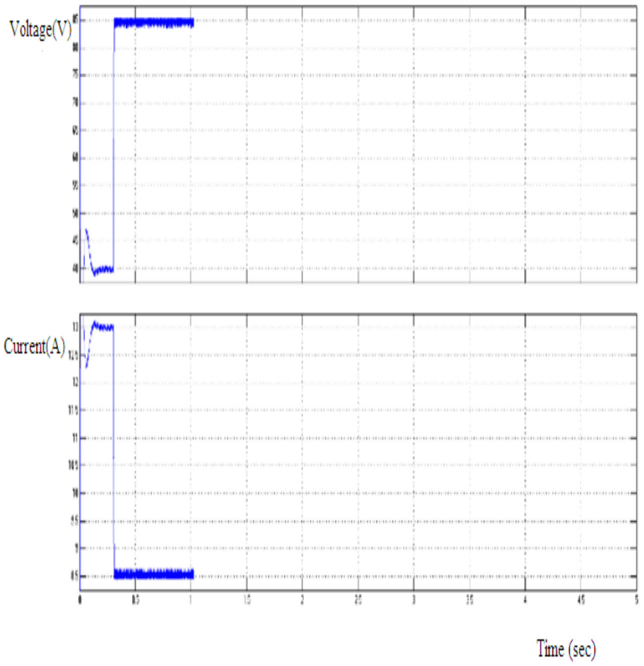


Fig.8. PV voltage with the load .This is the dc output voltage from the solar panel.

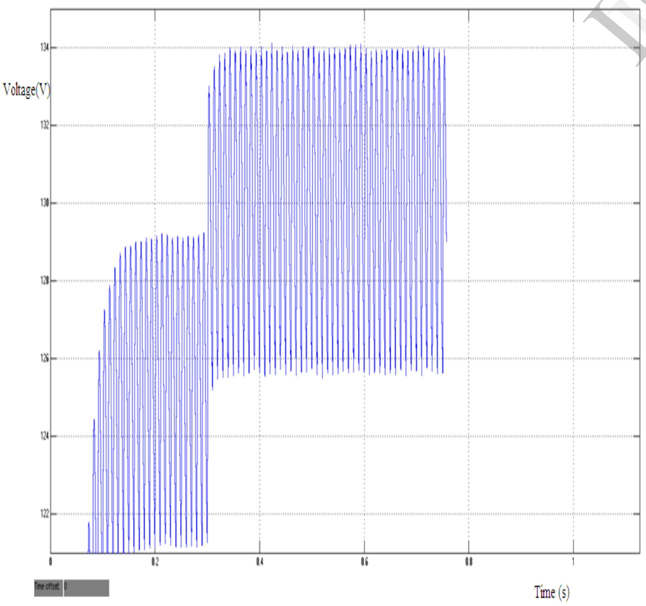


Fig 9. Boosted output DC voltage waveform.

This boosted (i.e.,) Maximum power is passed to the filter to remove the harmonic content. Harmonic of high frequency will be eliminated using the filter. The ac voltage from the transformer is shown in Fig.10.The r.m.s voltage of the output voltage is 230V .is connected to the grid.This voltage is free from lower order harmonics.

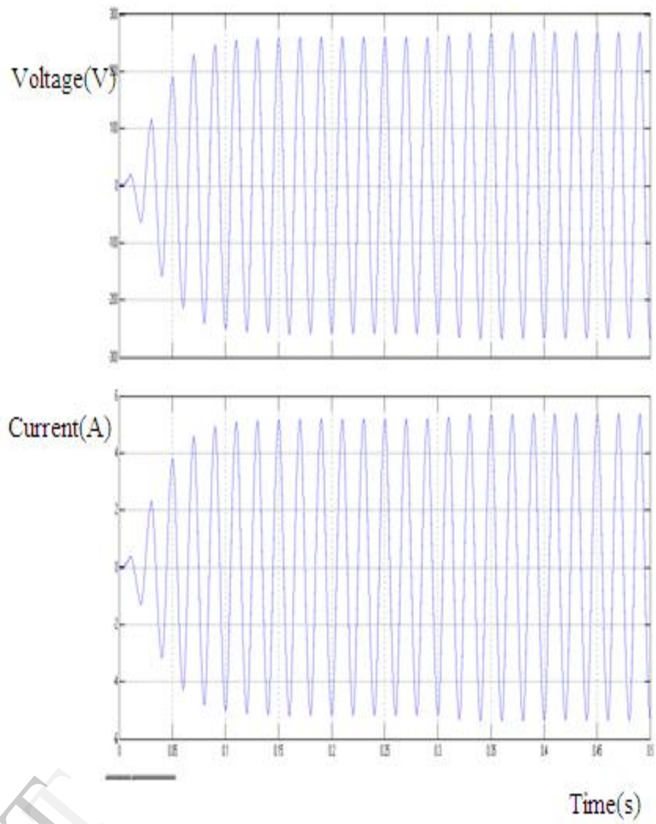
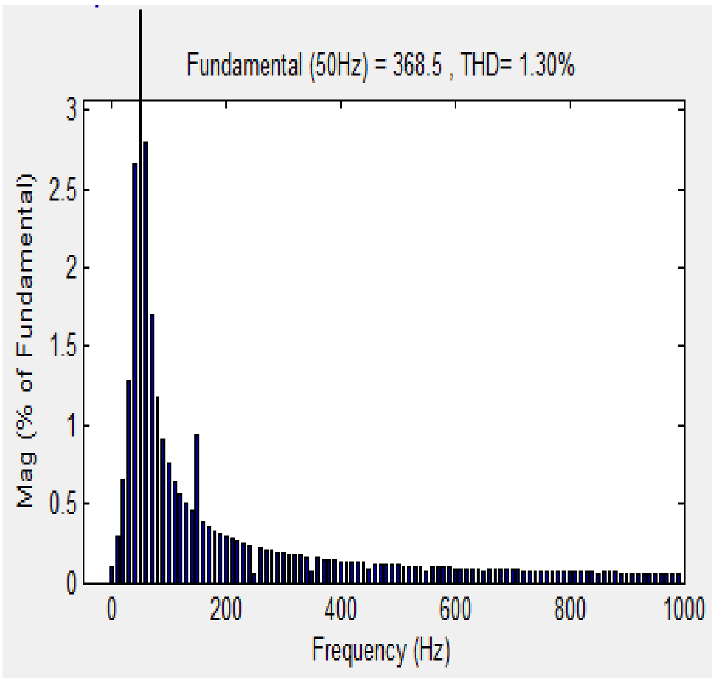
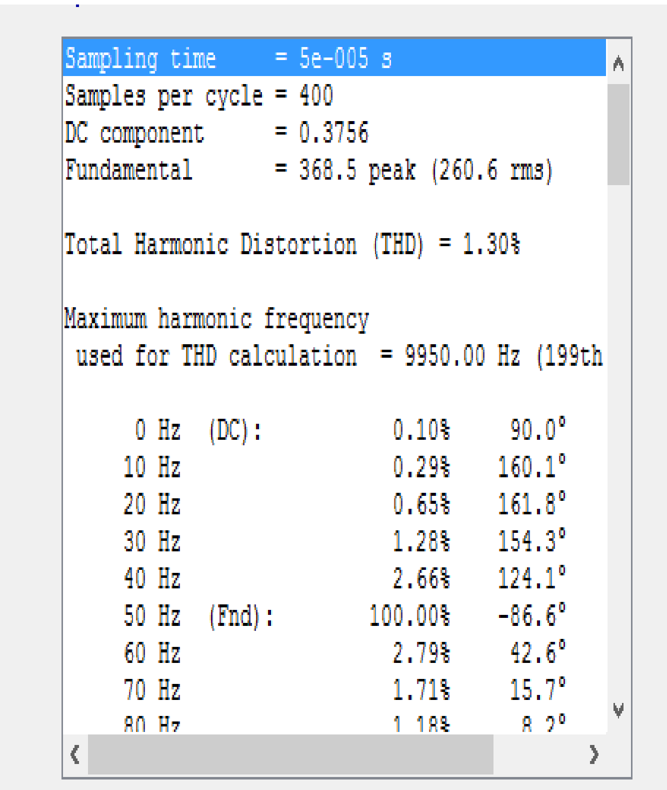


Fig.10. AC output voltage with the load connected to grid.

A. *FFT Analysis with load*

This is the fast fourier transform analysis for the given circuit. Here it is seen that the harmonics value is reduced and the THD is only 1.30%




Sampling time = 5e-005 s
Samples per cycle = 400
DC component = 0.3756
Fundamental = 368.5 peak (260.6 rms)

Total Harmonic Distortion (THD) = 1.30%

Maximum harmonic frequency
used for THD calculation = 9950.00 Hz (199th

0 Hz	(DC):	0.10%	90.0°
10 Hz		0.29%	160.1°
20 Hz		0.65%	161.8°
30 Hz		1.28%	154.3°
40 Hz		2.66%	124.1°
50 Hz	(Fnd):	100.00%	-86.6°
60 Hz		2.79%	42.6°
70 Hz		1.71%	15.7°
80 Hz		1.18%	8.2°

Fig. 11: FFT Analysis of output voltage.

The above Fig.11 shows the FFT analysis for the output voltage waveform in the grid where the load is connected. The Total Harmonic Distortion is found to be 1.30% for 5 cycles and this is within the IEEE standard. Thus the quality of power is improved and the lower order harmonics are reduced.

VI. HARDWARE DETAILS

A. Specifications

Transformer	230/15v step-down transformer
MOSFET switches	IRF840 (400v, 5A)
Inductor	47microH, 10mH, 100microH
Capacitors	1000µF, 2200 µF, 10 µF, 0.01 µF
PN junction diodes	1N4007
Microcontroller	dsPIC33FJ64MC802
Voltage sensors	15v/5v (potential divider type)
Current sensors	ACS714(hall effect sensor)
MOSFET driver& Optocoupler	IRS2110

B. Hardware snapshots

The hardware setup of a single-phase PV inverter connected to RL load is shown in Fig. 12. The MOSFET IRF840 of voltage rating 400V and current rating 5A is taken. Peripheral Integral Controller of 33FJ64 family is used. In the driver circuit, IRS2110 has been used. The value of the resistance is 50 Ohm and inductor 1 mH respectively. The output voltage across the load RL is shown in Fig. 13.

Fig 12. Hardware setup

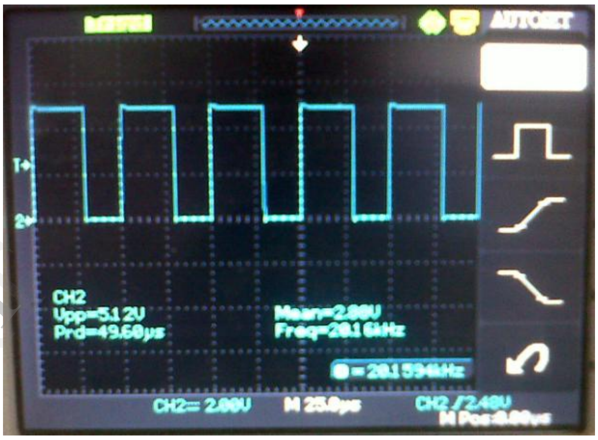


Fig 13. Output Voltage waveform

VII. CONCLUSION

Modification to the inverter current control for a grid connected single-phase photovoltaic inverter has been proposed in this paper, for ensuring high quality of the current injected into the grid. For the power circuit topology considered, the dominant causes for lower order harmonic injection are identified as the distorted transformer magnetizing current and the dead time of the inverter. It is also shown that the presence of dc offset in control loop results in even harmonics in the injected current for this topology due to the dc biasing of the transformer. A novel solution is proposed to attenuate all the dominant lower order harmonics in the system. The estimated current is converted into an equivalent voltage reference using a proportional controller and added to the inverter voltage reference. The design of the gain of a proportional controller to have an adequate harmonic compensation has been explained. To avoid dc biasing of the transformer, a novel PRI controller has been proposed and its design has been presented. The interaction between the PRI controller and the adaptive compensation scheme has been studied.

It is shown that there is minimal interaction between the fundamental current controller and the methods responsible for dc offset compensation and adaptive harmonic compensation. The PRI controller and the adaptive compensation scheme together improve the quality of the current injected into the grid. The complete current control scheme consisting of the adaptive harmonic compensation and the PRI controller has been verified experimentally and the results show good improvement in the grid current THD once the proposed current control is applied.

The transient response of the whole system is studied by considering the startup transient and the overall performance is found to agree with the theoretical analysis. It may be noted here that these methods can be used for other applications that use a line interconnection transformer wherein the lower order harmonics have considerable magnitude and need to be attenuated.

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