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Mitigation of Harmonics in a Grid Connected Photovoltaic Inverter

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Abstract: ***Photovoltaic energy generation is one of the potential sources of renewable green energy because it is dirt free, unlimited source and requires less maintenance. Implementation of solar PV has been increasingly preferred for both commercial and residential purposes. The power quality issues are very common during the developing and integrating stages of solar PV. Inverters are considered as the main medium which enables the integration of solar PV into the grid. Due to the widespread use of inverters, harmonics are introduced into the system. These harmonics result in the degradation of power quality at the output. This research work is concerned with power quality when grid-connected systems are used. This paper proposes a new passive filter topology for a unipolar pulse width modulated single-phase inverter interfaced with the PV source and the grid. As a source for the system, a 25W photovoltaic panel is chosen. The panel is integrated with the proposed inverter and filter design. A hardware prototype was developed and suitable results were obtained and verified.***

Keywords: Photovoltaic energy, Shunt-less filters, PWM, THD.

I.INTRODUCTION

Renewable energy sources are a viable solution for the existing power crisis across the globe due to the depletion of the conventional energy sources and the rising cost associated with it. At present, grid connected Photovoltaic systems are consuming major part of the distributed power generation. The electrical grid is accountable for delivering regulated power at a high-quality standard to the load, even in the presence of high penetration of intermittent PV generation. This requires the grid to have load following functions such as voltage and frequency regulation, reactive power and harmonic currents. On the other hand, in grid-connected inverters, the harmonics produced by the inverter lead to a new measure of research problems and solutions to it. The harmonic profile of the grid-connected inverter output current can also be affected by the variations in the grid voltage background harmonics. To overcome the problems encountered due to harmonics, controlling limits for Total Harmonic Distortion (THD) is fixed in the international standards such as IEEE 519 1992. To offer better quality power to the grid, suitable harmonic mitigation techniques are required for the grid-connected inverter.

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In this paper, we extend to make use of PV source and power conversion devices and attenuate the levels of harmonics injected by incorporating a shunt-less filter in case of a grid integrated system. Different filters, and modulation strategies for the inverter were analyzed and the best suited ones were used for hardware implementation, the results of which are also discussed below.

II. FILTERS

To control the Total Harmonic Distortion in the system, conventional, as well as hybrid power filters, are being used in these days. The passive filters considered in this paper, for comparison is simple LC filter, single tuned and double tuned filters. Apart from these, a special type of filters called shunt-less filters are also compared.

(A) Shunt-less filters

In the case of transformer-less grid-tied PV inverters, the main factor that affects the safety of PV system is the existence of leakage current. This current is because of PV terminal stray capacitors. The existing leakage current suppression methods are effective when photovoltaic (PV) stray capacitors are small. However, when the PV stray capacitors are large, the grid Common mode (CM) noise is the major contributor to the leakage current. Thus a novel filter called shunt-less filter is introduced to suppress the ground leakage current when the PV stray capacitors are large and these filters are based on a single DC-link capacitor for improved reliability [1].

Three different configurations of this type are discussed- LCL, LLCL and LCL-LC.

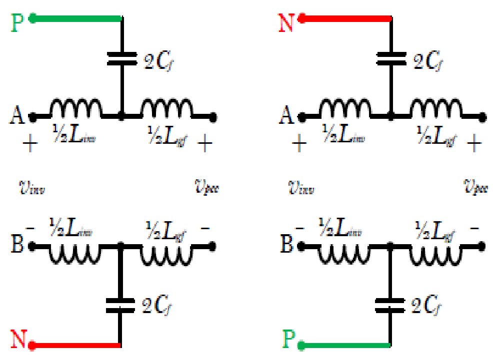

Fig. 1. Shunt-less LCL filter

(B) Design and analysis of filters

The formulae for designing the passive filters are found in [3]. The design considerations of shunt-less filters are similar to that of the conventional LCL, LLCL and LCL-LC [2] filters and the formulae can be referred from [2].

However the main difference lies in the way the filter is connected to the inverter as shown in the Fig 1. The design values used in simulations are shown in the table 1.

Sinusoidal PWM with modulation index of 0.8 and carrier frequency of 5kHz is used in all the simulations. The input voltage is 24V DC source, output power is 24W and a simple R load of 24Ω is considered.The THD values of the output voltage and current waveforms are tabulated. From the table, it is proved that shunt-less LCL and shunt-less LLCL filters exhibit better THD reduction. However, since an additional inductor L_f is needed in case of LLCL filter, which again increases the size and cost of the filter, **shunt-less LCL filters** prove to be the best among the filters considered.

Table 1. Design values of different filters

	L	L_1	C_1	L_2	C_2	L_f	C_f	L_r	C_r
LC filter	7 mH		600 uF						
Single tuned	7 mH	2 mH	600 uF						
Double tuned	7 mH	1 mH	1000 uF	1 mH	3000 uF				
Shunt-less LCL		20 mH		20 mH			600 uF		
Shunt-less LLCL		20 mH		20 mH		2 uH	600 uF		
Shunt-less LCL-$L_r C_r$		20 mH		1 mH			600 uF	2 mH	500 uF

Table 2. Comparison results of different filter

	THD_v	**THD_i**
Without filter	76.93%	76.40%
LC filter	3.75%	3.1%
Single tuned	2.95%	2.66%
Double tuned	1.3%	1.69%
Shunt-less LCL	0.61%	0.46%
Shunt-less LLCL	0.61%	0.46%
Shunt-less LCL-$L_r C_r$	0.68 %	0.51%

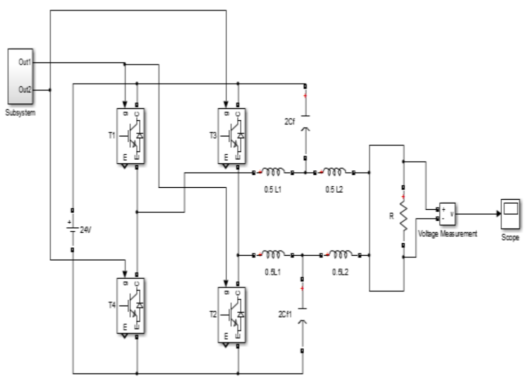

Fig. 2. Simulation of LCL filter

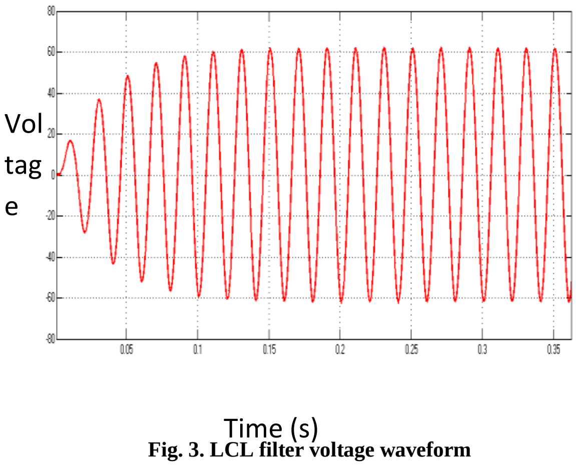

Fig. 3. LCL filter voltage waveform

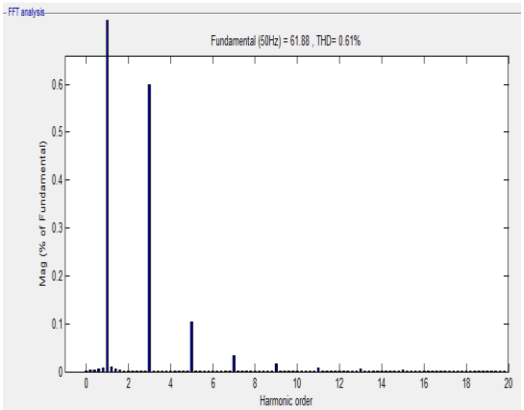

Fig. 4. FFT analysis of the output voltage of inverter connected to LCL filter

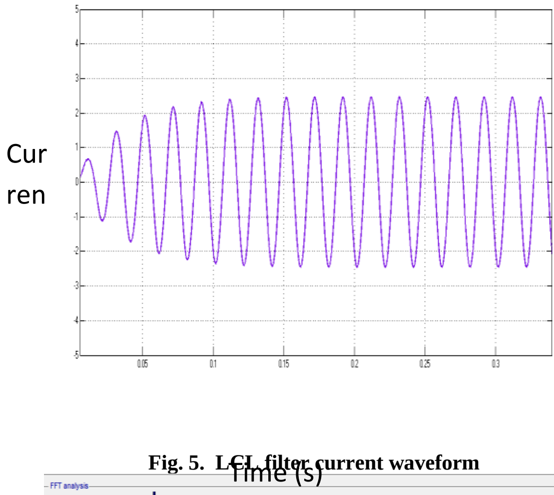

Fig. 5. LCL filter current waveform

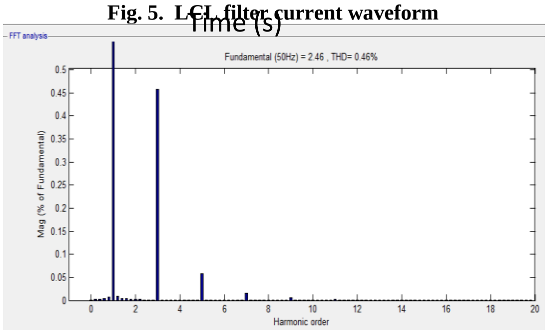

Fig. 6. FFT analysis of the output current of the inverter connected to LCL filter

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III.MODULATION STRATEGIES

For improving the spectral quality of the output of inverter, Pulse-Width Modulation (PWM) technique is used, the advantages of which are: The lower order harmonics in the output voltage gets eliminated, the filtering requirements are minimized as higher order harmonics can be filtered easily and the output voltage can be easily controlled by modifying the width of the pulses. The various pulse width modulation techniques analyzed here are: Sinusoidal PWM or Bipolar PWM, trapezoidal PWM, inverted sinusoidal PWM [5] and unipolar PWM [6]. The shunt-less filter values are as follows: $L_1 = L_2$ = 20mH, C_f = 600uF.

3.1 Comparison of discussed modulation strategies

From table 3, it is evident that the voltage and the current THD values of unipolar PWM is the least compared to other modulation strategies.

Table 3. Comparison results of different PWM techniques with m_a=0.8

PWM techniques	THD_v (%)	THD_i (%)
Unipolar	0.05	0.08
Inverted Sinusoidal	0.24	0.18
Trapezoidal	0.48	0.36
Sinusoidal	0.81	0.48

However, the fundamental voltage of inverted sinusoidal PWM is the highest. Hence, the filter design parameters are calculated in such a way, that the overall output voltage and current THD of all the above-discussed modulation strategies is maintained lesser than 5% as per the IEEE standard. From the filter design parameters, the filter size, and hence its cost are observed to be less in unipolar PWM.

Table 4. Comparison results of different modulation strategies after balancing with the filter design

PWM techniques	THD_v (%)	THD_i (%)	Fundamental voltage (V)	Filter design parameters	
				L (H)	C (F)
Unipolar	4.12	0.07	24.05	80 µ	50 µ
Trapezoidal	4.02	3.07	30.61	10 m	400 µ
Sinusoidal	4.56	3.47	26.42	10 m	400 µ
Inverted Sinusoidal	4.68	3.56	43.74	16 m	300 µ

Thus unipolar PWM strategy is considered the most suitable modulation technique for mitigating the harmonics produced in the system considered.

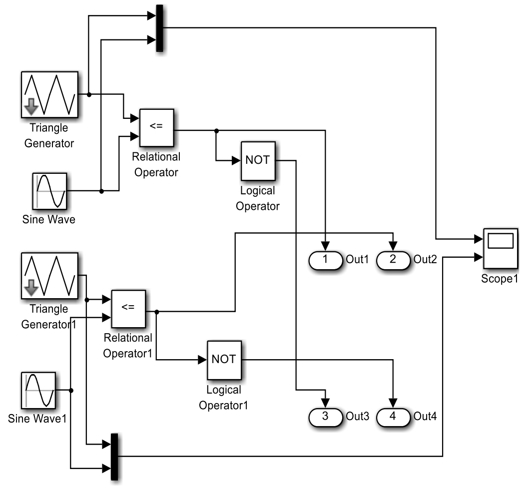


Fig. 7. Simulink model of unipolar PWM

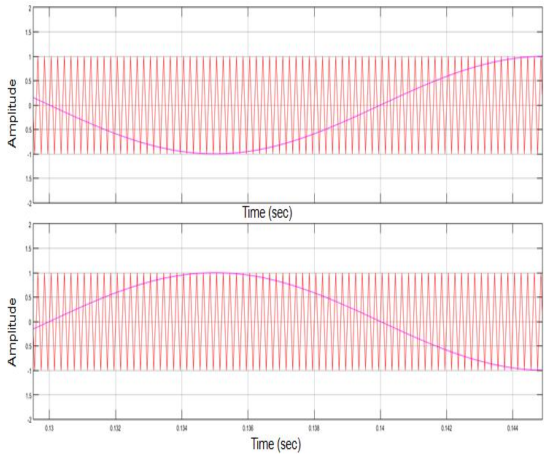
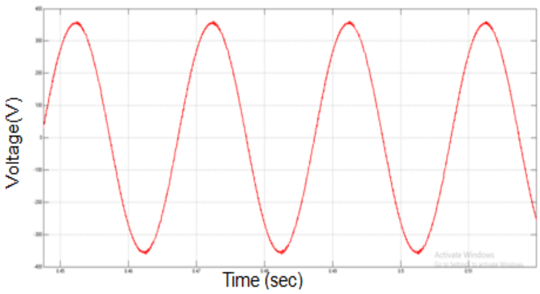
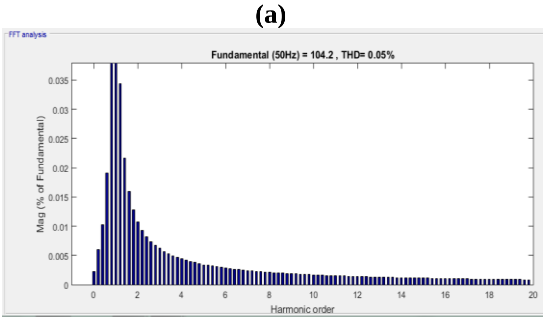


Fig. 8. Unipolar PWM – reference and carrier waves



(a)



(b)

Fig. 9. (a) Output voltage waveform and (b) THD analysis

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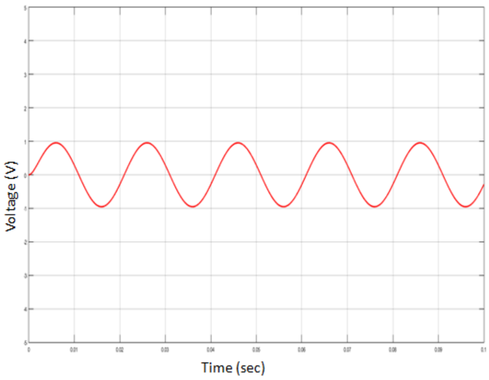
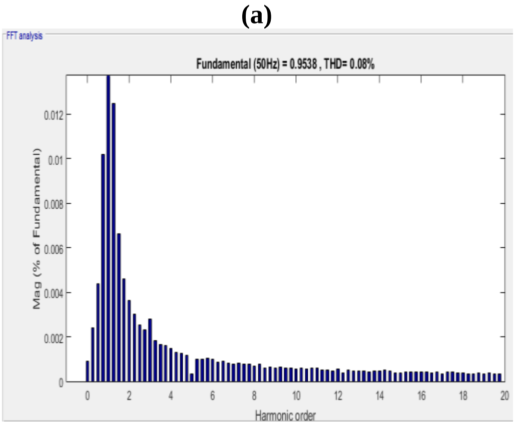


(a)



(b)

Fig. 10. (a) Output current waveform and (b) THD analysis

3.2. Performance parameters for the proposed pwm strategy

Based on the comparison of THD, Unipolar PWM which has minimum harmonic content is suitable for the proposed grid-connected PV inverter and this topology is further analyzed for computing the performance parameters such as Weighted THD, Harmonic Spread Factor and Distortion Factor. [5]

A. Weighted THD:

The weighted total harmonic distortion gives the measure of the harmonic pollution for components in each order as its weight factor. The expression for WTHD is

$$WTHD=\frac{\sqrt{\sum_{n=2}^{\infty}\left(\frac{Vn}{n}\right)^2}}{V1} \qquad (1)$$

Where V_1 = Fundamental voltage, V_n = total Harmonics voltage & n = number of harmonics

B. Harmonic Spread Factor:

The quality indicator, harmonic spread factor (HSF) is used for evaluating the harmonic spread effect of unipolar PWM technique. The expression for HSF is

$$HSF=\sqrt{\frac{\sum_{n=2}^{N}(Hn-Ho)^2}{N}} \qquad (2)$$

Where H_n= Value of nth harmonic & H_o=Average value of all N harmonics.

C. Distortion factor:

Distortion factor (DF) is used to measure the intensity of the non-linear distortion of the unipolar PWM technique. The mathematical expression for DF is

$$DF=\frac{1}{V1}\left[\sum_{n=2,3,..}^{\infty}\left(\frac{Vn}{n^2}\right)^2\right]^{\frac{1}{2}} \qquad (3)$$

Where V=Fundamental voltage, V_n=Total harmonics voltage & N= Number of harmonics.

The performance parameters for unipolar PWM inverter for various modulation indices are shown in table 5.

Table 5. Performance parameters of unipolar PWM inverter

M_a	THD (Vo) %	THD_i (Io) %	WTHD (%)	DF (%)	HSF (%)
0.4	7.78%	0.19%	0.0356	0.0121	0.4054
0.5	6.83%	0.16%	0.0358	0.0119	0.5072
0.6	5.82%	0.14%	0.0227	0.00769	0.6089
0.7	4.88%	0.12%	0.0335	0.0177	0.7108
0.8	4.01%	0.1%	0.0155	0.00476	0.8123
0.9	3.26%	0.09%	0.0165	0.00420	0.9133
1	2.68%	0.08%	0.0282	9.01E-05	1.0139

The performance parameters for each modulation indices are charted in the below graphs

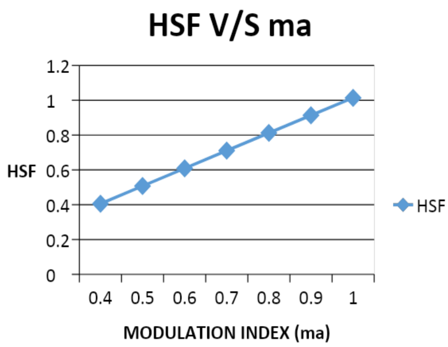


Fig. 11.HSF versus ma graph

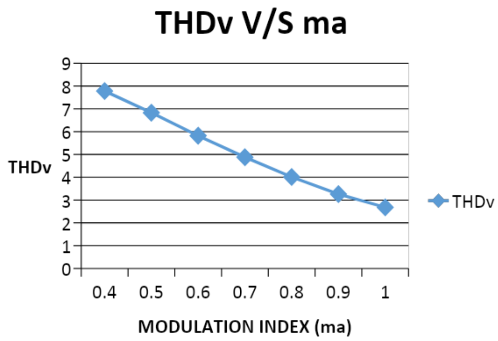


Fig.12. THD_v versus m_a graph

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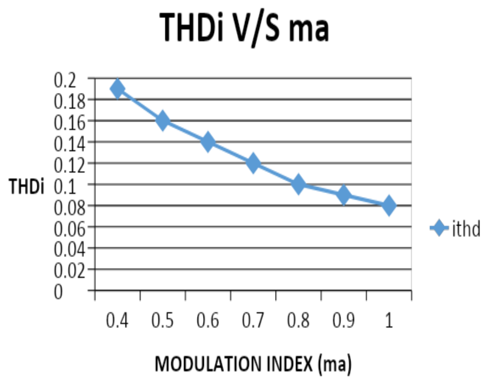

Fig. 13. THD_i versus m_a graph

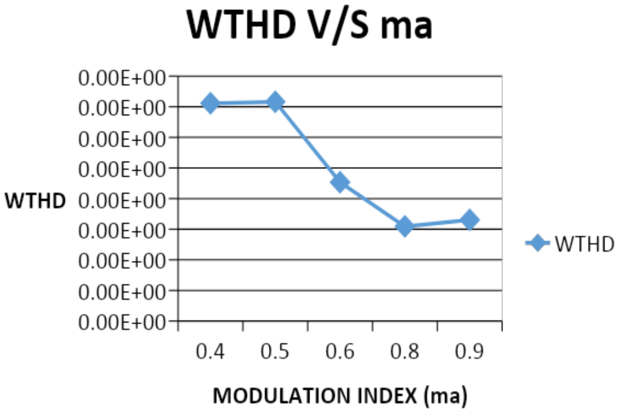

Fig. 14. WTHD versus ma graph

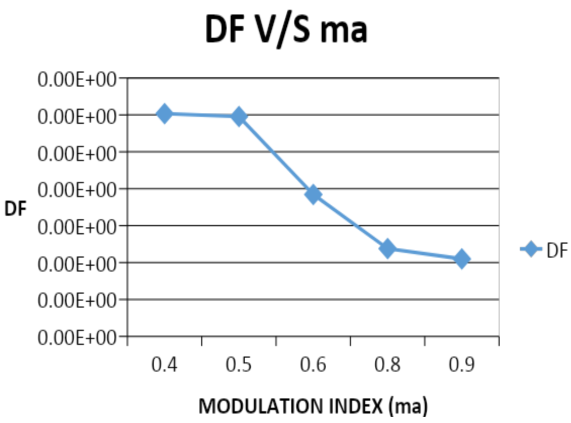

Fig. 15. DF versus ma graph

For unipolar PWM, the amplitude modulation index (m_a) 0.8 is selected based on the comparison of THD, WTHD, HSF and DF values for various m_a from the Figures 11,12,13,14 and 15.

IV. INTEGRATION OF PV ARRAY WITH PROPOSED TOPOLOGY

Fig. 16 shows the simulation model of the system consisting of a single phase unipolar PWM inverter and a shunt-less LCL filter connected with the panel. Figure 6.7 shows the output of the proposed system integrated with a solar panel.

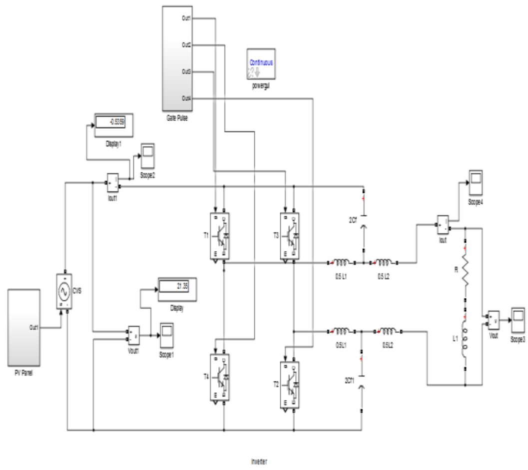

Fig. 16. Proposed system integrated with solar panel

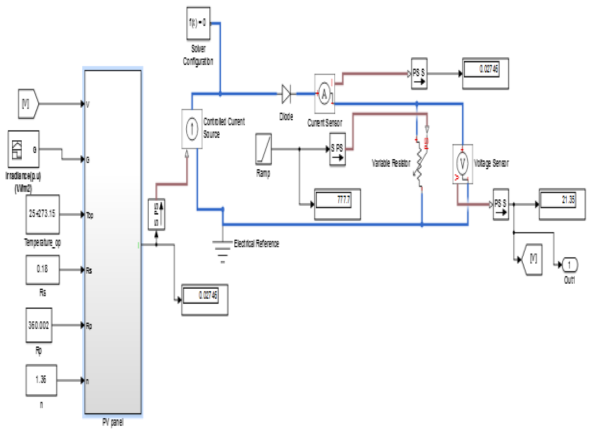

Fig. 17. Internal blocks of PV panel

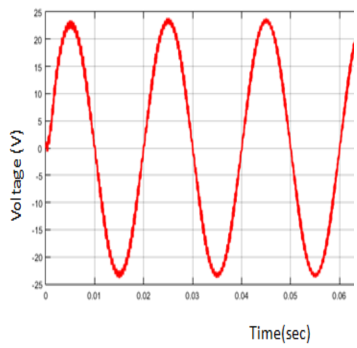

Fig. 18. Output voltage waveform of the PV integrated system

The voltage THD value for the proposed system is found to be 4.54 %

V. HARDWARE

The components used for hardware implementation are shown in the table. The entire setup is shown in the fig. The single-phase inverter is powered by a 25W panel, the specifications of which are shown in the table.

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Gate pulse generation, adopting unipolar PWM strategy, was done using the software Xilinx 14.5 and MATLAB 2013a, the Simulink diagram of which is shown in the figure.

Table 6. List of components

Components	Specifications	Quantity
PV panel	25W, 23.5V	1
Single phase inverter module		1
Opto coupler		4
Transformer	230V/15V, 500mA	2
Transformer	230V/15V, 1A	1
FPGA	Spartan 3E xe3s500E	1
Inductor	40uH	4
Capacitor	100uF	2

Table 7. PV Panel specifications

Power	25W
Open circuit voltage (V_{OC})	23.50 V
Short circuit current (I_{SC})	1.50 A
Peak power voltage (V_{MP})	19.50 V
Peak power current (I_{MP})	1.30 A

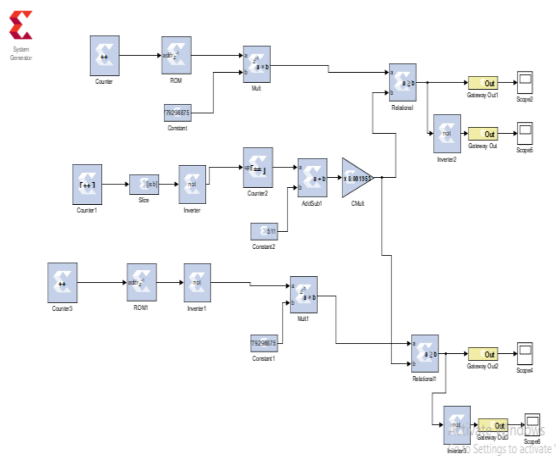

Fig. 19. SIMULINK diagram of pulse generation using FPGA

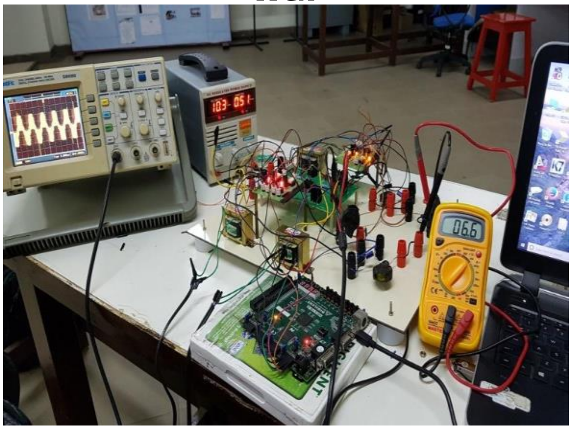

Fig. 20. Entire hardware setup

Fig. 20 shows the overall view of the hardware setup consisting of Regulated Power Supply (RPS), Single phase inverter module, shunt-less filter arrangement, FPGA kit, transformer, opto coupler and Digital Storage Oscilloscope (DSO).With RPS, the output voltage of a two level single-phase inverter connected to a shunt-less filter for a 10V input is shown in Fig. 21. The RMS value of voltage is around 3.75V and the peak value is about 5.4V.

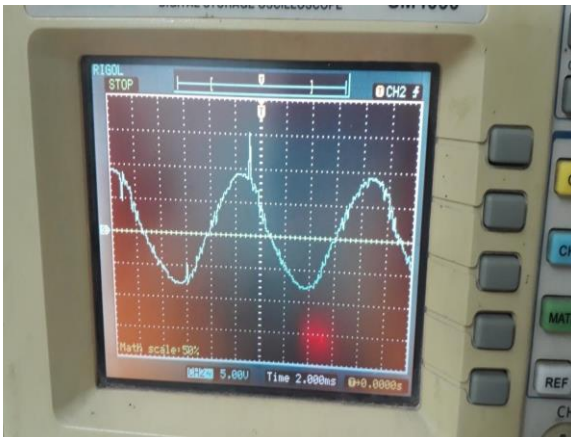

Fig. 21. Output voltage of the inverter with filter

VI. CONCLUSION

The various filter topologies were analyzed and the proposed shunt-less filter was found to be the most efficient filter. Secondly, various modulation strategies for single phase inverter were analyzed and unipolar PWM strategy was found to be the efficient one, and was then integrated with the PV, proposed shunt-less filter and finally to the grid thereby reducing the levels of harmonics. The proposed shunt-less filter was compared with the conventional filter and found out to possess the following features: Suppresses the ground leakage current and reduces the overall noise produced in the system. Hardware prototype of the proposed topology was also developed and the results were validated.

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