A Simple Synchronization Logic Aided Interleaved Fly-Back MIC for Grid Interactive Photovoltaic Power System

Somashree Pathy[1] ,C. Subramani[2] ,Sridhar R[2], SubhransuSekhar Dash[3]

[1]Research Scholar,Department of Electrical and Electronics Engineering,SRMUniversity,Chennai,India

[2]Asst. Professor,Department of Electrical and Electronics Engineering,SRMUniversity,Chennai,India

[3]Professor, Department of Electrical and Electronics Engineering,SRMUniversity,Chennai,India

(p.soma92@gmail.com,csmsrm@gmail.com,sridharmanly@gmail.com,munu_dash_2k@yahoo.com)

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Abstract:. This paper suggest a module integrated converter (MIC) of interleaved fly-back topology which interfaces photovoltaic (PV) with grid power using a simple grid synchronization scheme. The MIC possess inherent advantages like high voltage gain and compact in size. The grid synchronization scheme is ensured by zero crossing detectors and phase locked loop (PLL) circuits. Since PV power is intermittent in nature, MPPT technique is mandatory. A simple Fractional Open Circuit Voltage (FOCV) Maximum Power Point Tracking(MPPT) is deployed. A 100W PV system is considered for the MATLAB based simulation study and hardware experimentation. The simulation and hardware results obtained reveals that the suggested technique is viable for grid synchronization and can be realized as a module integrated inverter.

Keywords: Grid integration, Photovoltaic Cell, Zero Crossing Detector, Interleaved converter, Maximum Power Point Tracking, FOCV

1. Introduction

The depletion of conventional sources forces the whole world to incline towards power generation through RES) [1]. Photovoltaic known for its peculiar advantages like portable and scalable, dragged much attention among all renewable. [2]-[3]. The power output of PV source is non continous in nature due to the varying irradiation and therefore a power tracking mechanism called Maximum Power Point tracker (MPPT) is an essential unit in the PV System [5],[6]. There are numerous research articles archived pertaining to power tracking algorithms [7]. MPPT techniques are known for its fast convergence, simple execution, and reliability[8]-[10]. A sensor less current controlled Maximum Power Point Tracker(MPPT) for flyback inverters has been proposed by Nobuyuki Kasa, etal. for photovoltaic systems[11]. But this sensor less current controlled MPPT is designed for fixed switching frequency operating in discontinuous conduction mode and is applicable for small PV systems.A wide review has been done on various MPPT schemes by the authors in[12].In[13] efficient MPPT controllers are proposed for different solar insolation levels. Here the authors have proposed a Fuzzy logic based MPPT controller and a Zeta buck-boost converter which acts like a MPPT controller with having advantage of less ripple content in the output. From the literature most reliable and simple MPPT algorithm is obsereved to be the Perturb and Observe (P&O) algorithm which is also widely and mostly used in PV system applications. However the demerits of the algorithm must be taken care for the optimum result and smooth operation[14]. Many researchers have shown interest for developing a high efficiency low cost power conversion system for making the use of PV resource more convenient and reliable.

In general the PV source is a low voltage high current source and therefore the gris interaction of PV will be conducive when many PV panels are connected in series to constitute a higher voltage level. Therefore single PV panel getting interacted with gris needs obviously a reliable boost converter or a step up transformer. But again the transformer size may not be compatible with MIC [15-18]. Flyback topologies of dc-dc converters posses switching devices along with transformer, can sustain very high frequency without saturating the transformer. The major drawback of the flyback aided circuit is the power rating of the circuit will be limited and thereby current handling capacity is also less [19]. Therefore interleaving topology got attraction in research forum which facilitated a higher current carrying capacity [20].

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Typical structures of PV-MIC consist of several power conversion stages given in[21].For the grid integration of PV micro-inverter DDS(Direct Digital Synthesis)technique can be used for Phase Locked Loop(PLL) for grid synchronization of the PV sytem[22]. For high voltage output PV systems a transformerless three phase inverter is implemented in[23-25].This work represents a single stage conversion system where the output is directly fed to the grid. But the PV system having low voltage output has not been considered here..For the use of the renewable energies to the optimum point in all stage and mostly for the grid integration purpose we need the power electronics elements which are the sole heart of the entire DG system [26-27]. AzamBagheri et.al proposed a grid synchronization detecting technique for both single phase and three phase systems by using the combination of modified Kalman filter and generalized averaging method which is considered to be an open loop system[28]. From the detailed literature survey, it is inferred that there prevails a complexity in realizing the MIC as the transformer design and grid interaction remains a difficult part to deal with. This paper suggest a interleaved flyback MIC with FOCV MPPT and a simple synchronization logic involving two ZCDs and PLL. The paper is organized in such a manner that section 2 descibes the system description where PV modeling, flyback sircuit operation and transformer designs are dealt. Section 3 discusses the results of simulation and hardware. The conclusive remarks are given in section 4.

2. System Description

The block diagram depicting the whole system is shown in Figure1. A PV panel of 100 W is connected with a interleaved Flyback converter which actually functions as a stepu up DC DC conversion. The output of dc dc converter is inturn connected with a two leg inverter circuit having four switches which facilates AC output. The duty cycle for the flyback converter is generated through a simple FOCV MPPT algorithm. The grid synchronization is reliable only when the inverter output is compatible wirh grid with respect to voltage, frequency and phase angle. This prime condition is achieved through zcd circuits and PLL logic.

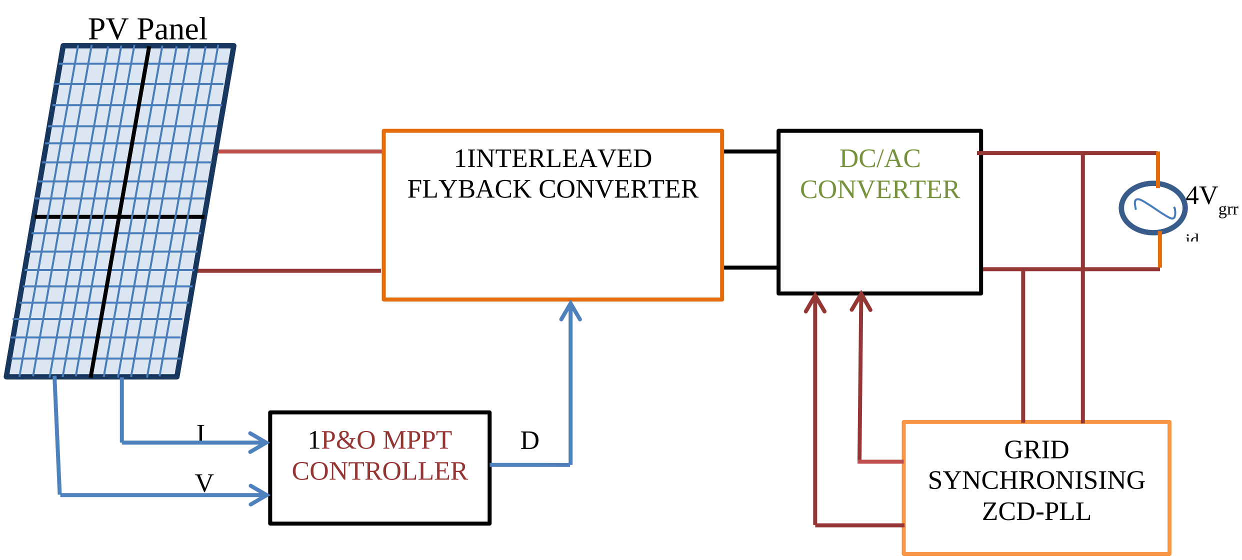

Figure1. System Block Diagram

2.1. Modelling of PV System

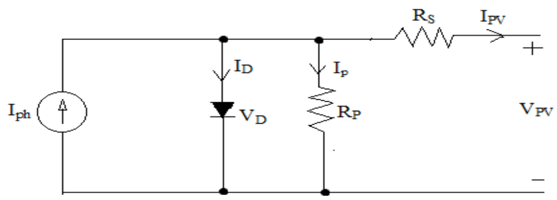

Figure 2. Single diode model of PV Cell

In this work a single diode model PV system is considered as it is the simplest form of the PV system and quiet easy to implement.For a single diode model the equivalent circuit is realized as a diode in parallel with the current source. Two resistances are considered that is one series resistance R_s and one shunt resistance R_{sh}[29]. The characteristic equations of the PV Module are given in equations [1]-[5].

$$I_{PV} = (I_{PV\_STC} + K_i \Delta T)\frac{G}{G_{STC}} \quad (1)$$

$$I_o = I_{rs}[\frac{T_{STC}}{T}]^3 \ \exp[\frac{qE_g}{ak}(\frac{1}{T_{STC}} - \frac{1}{T}) \quad (2)$$

$$I = I_{PV} - I_o\left[\exp\left(\frac{V+R_sI}{aV_t}\right) - 1\right] - \frac{V+R_sI}{R_p} \quad (3)$$

$$I_o = \frac{(I_{PV\_STC} + K_i \Delta T)}{exp\left[(V_{oc\_STC} + K_v \Delta T)/aV_T\right] - 1} \quad (4)$$

$$I_{rs} = I_{sc}/[\exp\left(\frac{qV_{oc}}{N_s knT}\right) - 1] \quad (5)$$

Table 1. Modelling of Single Diodel Model and Flyback converter Parameters

Parameters	Description	Parameters	Description
I_{PV}	Photovoltaic current	K	Boltzmann constant=1.3805*10^{-23}J/K
I_o	Diode Reverse Saturation current	E_g	Band gap energy of semiconductor
V_T	Thermal Voltage	Q	Electron Charge
A	Diode ideality factor	I_{rs}	Reverse saturation current
T	Temperature in Kelvin	I_{o_STC}	Normal saturation current under STC
I_{PV_STC}	Light generated current under Standard Test Condition	R_s	Series Resistance
T_{STC}	Temperature under STC	R_{sh}	Shunt Resistance
ΔT	T-T_{STC} in Kelvin	V_{oc_STC}	Open circuit voltage under STC
G	Surface Irradiance of cell(W/m^2)	V_{in}	Input voltage
G_{STC}	1000(W/m^2)=Irradiance under STC	V_o	Output voltage
K_i	Short circuit current co-efficient=0.0017	L_1,L_2,L_3,L_4	Inductors
K_v	Open circuit voltage co-efficient	ΔI	Current ripple
N1	Primary side turns	N2	Secondary side turns

2.2 PV Panel Specifications

The stipulations of the 100W panel used for simulation are stated in Table 2.

Table 2. Specifications of PV-Panel (100W) - SOL-100P-01

Maximum power(P_{max})	100 W
Open circuit voltage (V_{oc})	21.5V
Short circuit current (I_{sc})	6.28A
Voltage at maximum power(V_{mp})	17.5V
Current at maximum power(I_{mp})	5.71A

2.3 PV Characteristics

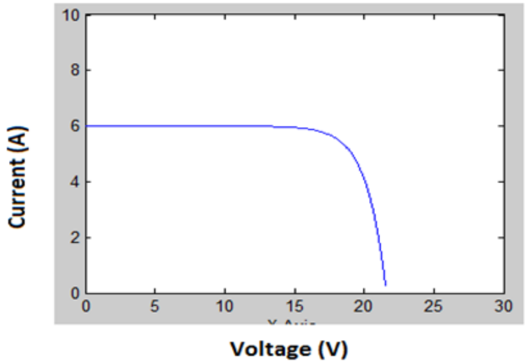

Fig 2(a):I-V characteristics of PV system

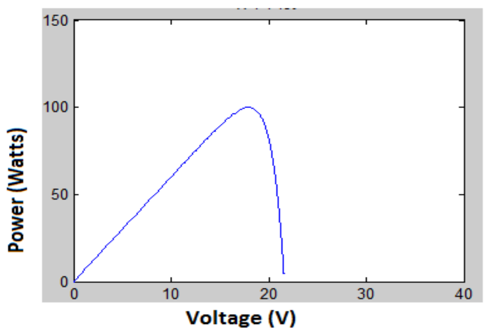

Fig2(b):P-V characteristics of PV system

The above simulation graphs shows the I-V and P-V characteristics. Fig 2(a) and Fig 2(b) represents PV characteristics.In Fig 2(a) the graph has been drawn between the current and voltage of the PV panel. Similarly Fig 2(b) represents the power and voltage graph of the PV panel.

2.4 Fractional Open Circuit Voltage(FOCV) MPPT

Fractional open circuit voltage algorithm is used for extracting the maximum power from the PV at all operating conditions. This MPPT technique utilizes the fact that the PV panel voltage at maximum power point is linearly dependent with the open circuit voltage of the PV panel for different values of solar irradiation and temperature. FOCV algorithm is the simplest and easy to implement MPPT algorithm. This algorithm finds the maximum power point by controlling the open circuit voltage of the PV panel.Here a proportionality constant is considered (shown as K in figure 3) which generally depends on the PV panel material and the fabrication and the value of K generally lies between 0.71 to 0.78[30]. From these values the maximum power point can be calculated.Figure 3 represents the flow chart of the FOCV MPPT algorithm. In the flowchart $V_{pv}(t)$ represents the old value, $V_{pv}(t+1)$ is the new value and ΔV is the change in voltage.

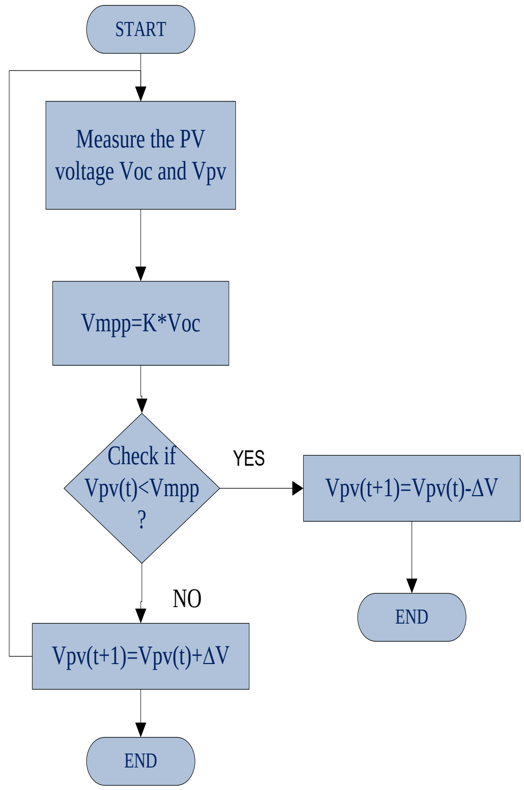

Fig. 3. Flowchart of FOCV MPPT

2.5 Flyback Converter Design Parameters

Table 3. Design Specifications

Input voltage(V_{in})	14V-22V
Output Voltage(V_o)	346V-350V
Switching Frequency(f_{sw})	51.8KHz
Input Current (I_{in})	3.57A
Output Current(I_o)	0.142
Co-efficient of coupling of Flyback coupled inductor(K_f)	0.9
Leakage inductance co-efficint(K_l)	0.8
Magnetic flux density(B_m)	0.2T
Voltage across mutual inductance(V_{fm})	15.75V
Primary current(I_{pripk}) and I_{prirms}	16.262A and 6.227A
Primary inductance(L_p)	9.1μH
Secondary inductance(L_s)	6.09mH
Secondary current(I_{secpk}) and I_{secrms}	0.62A and 0.24A
Primary turns(N_p)	9

Secondary turns(N_s)	198
Output filter capacitor min and max value(C_{outmin}&C_{outmax})	0.35µF-3.80µF
Required Airgap(L_g)	0.90933mm
Input power(P_{in})	62.60Watts
Output Power(P_{out})	50.08Watts
Efficiency(η)	80%
Energy delivered plus the energy lost due to leakage inductance(W_{fb})	1.208mJ or 0.001208KJ

Equation (6) to (14) represents the flyback converter design equations.

Voltage across mutual inductance(V_{fm})

$$V_{fm} = K_f * V_{in(min)} \tag{6}$$

No of Secondary turns(N_s)

$$N_s = K * N_p \tag{7}$$

Where K=Transformation ratio

No of primary turns

$$N_p = (L_p * I_{pripk})/(B_m * A) \tag{8}$$

Energy delivered plus the energy lost due to leakage inductance(W_{fb})

$$W_{fb} = {(W_c * P_o)}\Big/{f_{sw}} \tag{9}$$

Where W_c= Energy in the coupled inductor

Primary inductance

$$L_p = {(2W_{fb})}\Big/{I_{pripk}^2} \tag{10}$$

Primary current peak value(I_{pripk})

$$I_{pripk} = {(2W_{fb}) * f_{sw}}\Big/{V_{in(min)} * D_{max}} \tag{11}$$

$$I_{secpk} = \frac{2I_0}{1-D_{max}-D_{dt}} \tag{12}$$

Where $D_{max}$is the maximum duty cycle

Output filter capacitor min and max value(C_{outmin})

$$C_{outmin} = {I_{outmax} * T_{on}}\Big/{\Delta V_o} \tag{13}$$

Required Airgap(L_g)

$$L_g = {\mu_0 * I_{pripk} * N_p}\Big/{B_m} \tag{14}$$

Where μ_0 is the permeability of free space.

2.6 *Interleaved Converter*

In this work an interleaved flyback DC_DC converter is used to boost the output voltage of the PV panel.The flyback converter has the advantage of having an isolating input and output side.Theflyback converter is similar as that of a buck-boost converter. In flyback the inductor is split to form the flyback transformer. Here the boosting capacity is very high as it operates at a very high frequency.This converter is less expensive and also less bulky so more convenient for use. Interleaving two converters together increases the converter reliability and also the boosting capacity as it consists of two inductors and capacitors.And also it reduces the ripple current. In this paper an interleaved flyback converter is used for increasing the voltage level of the PV panel and the boosted voltage is fed to the inverters of the converter.In figure 4 the circuit diagram of the proposed flyback converter is given and the operation of the two modes of the converter is given in figure in figure 5 and 6. For the modes of operation the simple buck-boost converter equations are provided for understanding and the flyback converter output voltage equation depending on its turns ratio is given in equation 29.

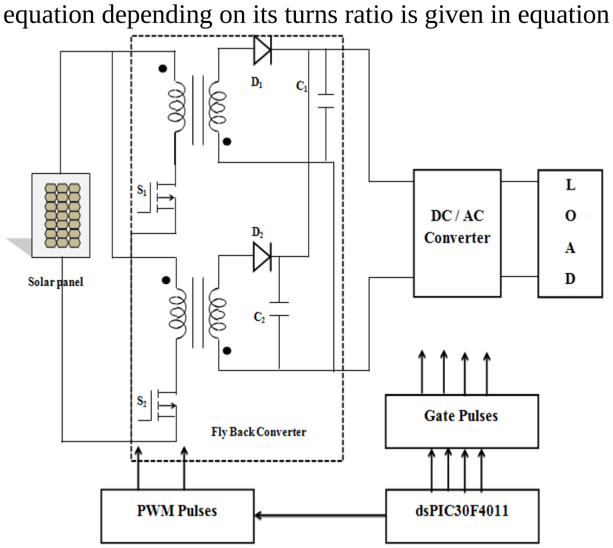

Figure 4.PV with Interleaved Converter

Mode 1:

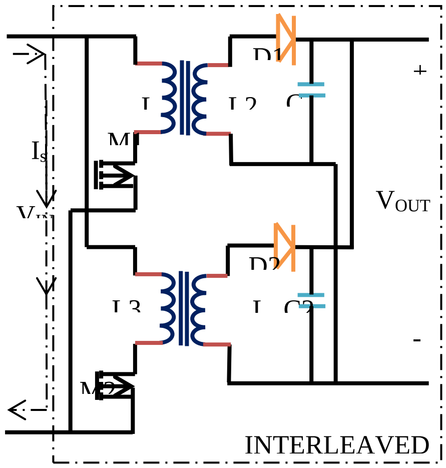

Figure 5. Operation during Mode-1

In Figure 5 mode 1 operation of interleaved flyback converter is shown. In this mode the two switches M1 and M2 are turned on hence the primary side coil L1 and L3 gets energized. Here as the two diodes D1 and D2 are reverse biased hence no current flows in the secondary side i.e. L2 and L4 of the transformer. But the secondary coils get energized due to mutual inductance and energy is stored in it. L1 and L2 values are considered to be equal and taken as L. The mode 1 operation equations are considered as buck-boost operating conditions and the equations are given in (15) to (18). The primary and secondary voltage during mode 1 operation is given in equation (19) and (20).The voltage equation of the converter during mode 1 is

$$V = 2L\frac{di_s}{dt} \qquad (15)$$

The equation (15) can be further written as

$$V = 2L\frac{\Delta I}{t_{on}} \qquad (16)$$

From equation (16)

$$T_{on} = 2L\frac{\Delta I}{V} \qquad (17)$$

Current ripple (ΔI) is

$$\Delta I = \frac{V * T_{on}}{2L} \qquad (18)$$

$$V_{primary} = V_{in} \qquad (19)$$

$$V_{secondary} = V_{in} \times \frac{N_2}{N_1} \qquad (20)$$

Mode 2:

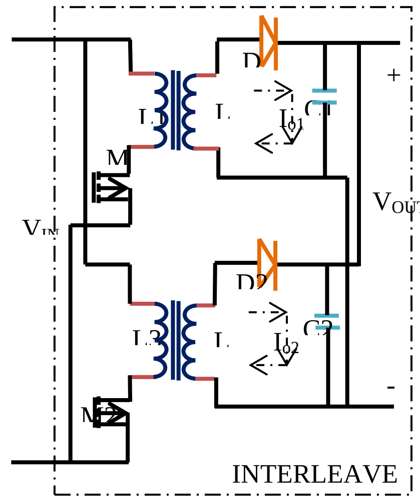

Figure 6. Operation during Mode-2

Figure 6 shows the mode 2 operation of the interleaved flyback converter. Here the two MOSFETS M1 and M2 are turned off hence no current flows in the primary side coils i.e. L1 and L3.The polarities of the secondary side coils changes and hence they start to deliver the stored energy and a current flows in the secondary side as diodes D1 and D2 are in forward bias.In this mode the two diodes D1 and D2 are forward biased. The inductors L2 and L4 are equal to L. The output voltage equation V_0 is given by

(15)

$$V_o = 2L\frac{di_o}{dt} \qquad (21)$$

$$V_o = 2L\frac{\Delta I}{t_{off}} \qquad (22)$$

From equation (20)

$$T_{off} = 2L\frac{\Delta I}{V_o} \qquad (23)$$

(17)

$$\Delta I = \frac{V_o * T_{off}}{2L} \qquad (24)$$

Comparing (18) and (22) we get

$$\frac{V * T_{on}}{2L} = \frac{V_o * T_{off}}{2L}$$

Substituting $T_{on} = kT$ and $T_{off} = (1-k)T$ we get

$$VkT = V_o(1-k)T \qquad (25)$$

From (24) we get

$$V_o = \frac{Vk}{(1-k)} \qquad (26)$$

Interleaved converter primary and secondary voltage equations are given in equation (27) and (28).

$$V_{primary} = V_o \times \frac{N_1}{N_2} \qquad (27)$$

$$V_{secondary} = V_o \qquad (28)$$

The output voltage of the flyback converter is given in equation (29).

$$V_o = \frac{nVk}{1-k} \qquad (29)$$

Where n=Turns ratio of the transformer

2.7 Zero Crossing Detector

Grid synchronization is a challenging task particularly when the utility signal is polluted with instabilities and harmonics of distorted frequencies.To control and meet the power quality standards a Phase detecting technique can be used which provides a reference phase signal in synchronization with the grid voltage. ZCD is taken as an applied form of a voltage comparator.It is an op-amp based circuit .It changes the output from+$V_{Sat}$to –V_{Sat} when thethe input voltage crosses the zero reference voltage.In some applications the input signal may be of a low frequency, (i.e. input may be a slowly changing waveform). In such a case output voltage may not switch quickly from one saturation state to another. Because of the noise at the input terminals of op-amp, there may be fluctuation in output voltage between two saturation states (+Vsat and –Vsat). Figure 7 depicts the synchronization operation. Thus, zero crossing may be detected for noise voltages as well as input signal. The flowchart depicting the operation of the ZCD's for synchronization operation is shown in Figure 8.

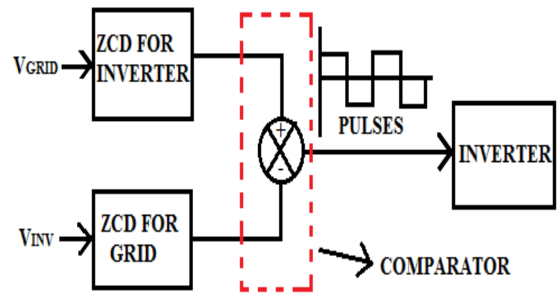

Figure 7. Generation of Pulses for Inverter from ZCD

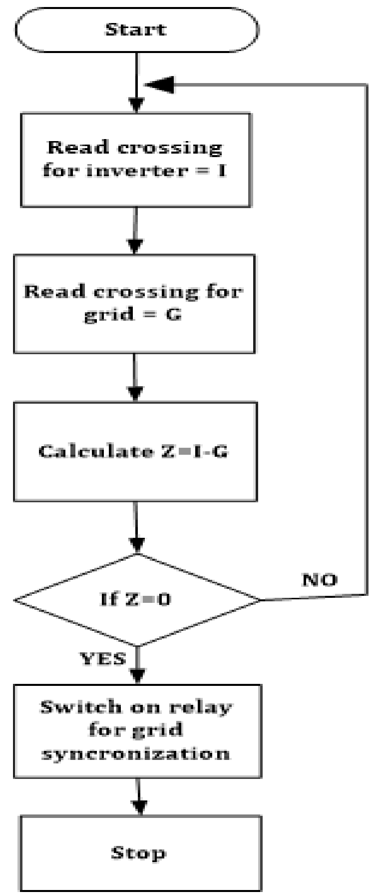

Figure 8. Flowchart depicting ZCD Operation

2.8 Phase Locked Loop(PLL)

PLL is a negative feedback based synchronization technique which locks the phase and frequency of the output to a reference signal. Here the entire loop is controlled depending upon the phase angle. A phase locked loop generally consists of three main parts such as phase detector, Amplifier and low pass filter and Voltage control oscillator. The block diagram of a PLL is given in figure 8(a).

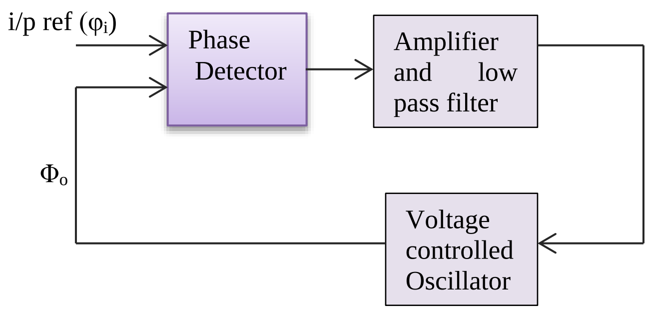

Figure8(a). PLL Block Diagram

3. Results and Discussions

The PV panel is considered for the standard test conditions i.e. the insolation level 1000W/m^2 and temperature 25^{0}C and the PV voltage found to be 17.5V DC which is shown in figure 9.In figure 10 the boosted output voltage of the PV panel by the FOCV integrated interleaved fly-back converter is given.The inverter output volatage after the LC-filter is given in figure 11.

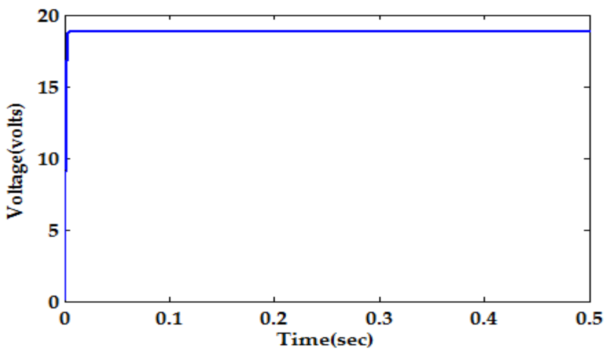

Figure 9. Output Voltage of PV Panel

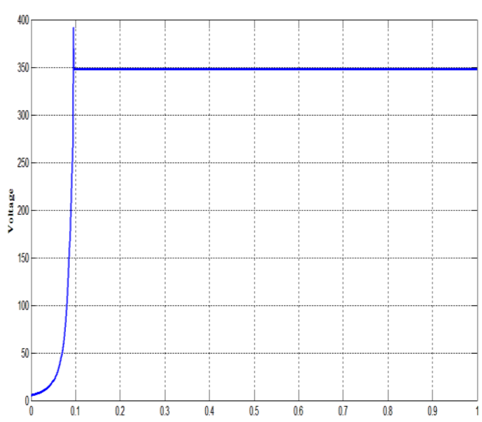

Figure 10. Output Voltage of Fly-back Converter

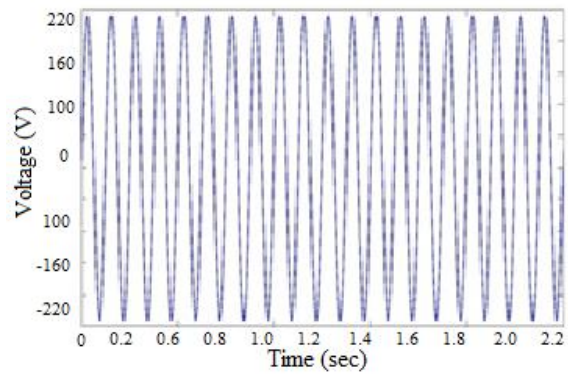

Figure 11. Inverter Output Voltage

4. Hardware Implementation and Results

The Hardware implementation prototype of the proposed work is shown in Figure 12. The results derived from the hardware is shown in Figure 13 and Figure 14. In figure 13 the ZCD output for grid and inverter is shown and in figure 14 the synchronization of inverter with grid is shown. Table 4 shows all the components details and their specifications that are used to build the hardware prototype.

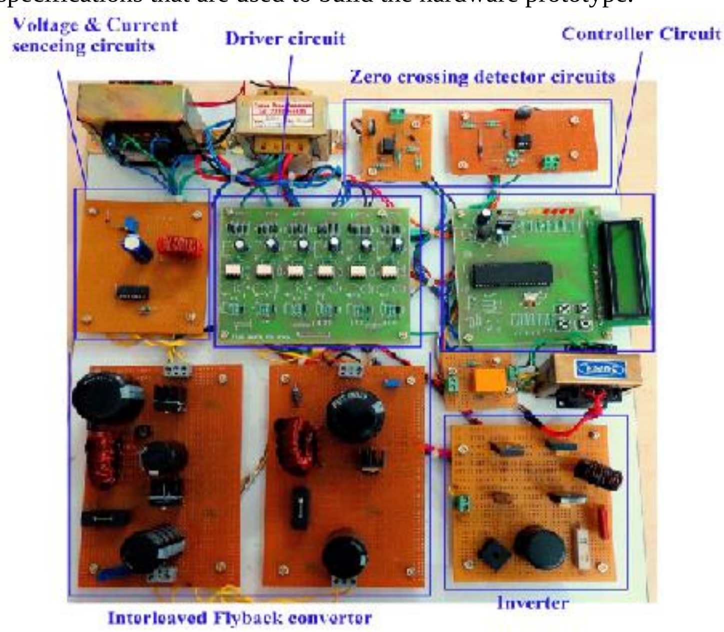

Figure 12. Experimental setup

Table 4. Hardware Components Description

Component	Specification	Functionality
Controller	DSPIC30F 4011-16bit	Generates MPPT pulses for DC-DC converter and PWM signal for inverter

ZCD	LM358P	Detects zero crossing and facilitates grid synchronization
IGBT	IRF P450LC	Switches
MOSFET	IRF 840	
Driver IC	TLP 250	Amplifies the gate voltage signal
MPPT Sensors-Voltage Sensor Current Sensor	LV20-P LA55-P	For sensing voltage and current

The operation of two ZCDs (one for inverter and other for grid) is the most critical aspect of this work. Figure 13 shows that the control relay for grid synchronization can be enabled when both the ZCD outputs are in phase. It can be inferred from Figure 14 that the grid voltage and inverter voltage are overlapping and thereby synchronization is achieved.

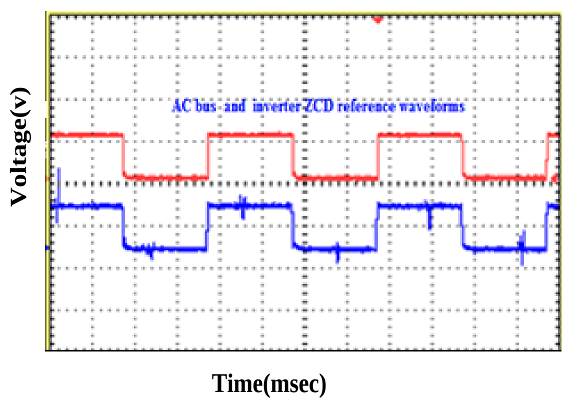

Figure 13. ZCD Outputs for Inverter and Grid (X-axis 1unit=5ms,Y-axis 1unit=5V)

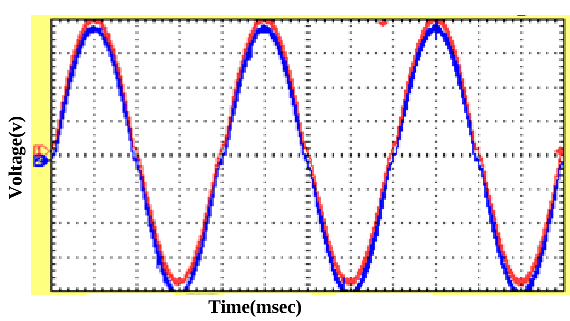

Figure 14. Grid synchronization waveform (In X-axis 1unit=5ms,Y-axis 1cm=60V)

5. Conclusion

In this work a PV fed interleaved flyback with ZCD-PLL grid synchronized MIC is suggested. The interleaved topology enhances the power handling capacity. The power delivery of PV source is enhanced though a FOCV MPPT. The proposed system is realized for a 100 W PV panel..Here two ZCDs have been used i.e one for inverter and the other one for grid. The reliabity of grid synchronization is ensured when PLL is also implemented along with ZCD logic. The fly back transformer is having a high boosting capacity so that it is convenient for small voltage output PV systems and can be synchronized with grid more easily. In future the said work can be extended for Synchronous Reference Frame phase locked loop(SRF-PLL) for achieving efficient and reliable grid synchronization.

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