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AN IMPROVED GRID CONNECTED INTERLEAVED FLYBACK INVERTER

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Abstract—This paper proposes a special type of grid-connected inverter system for photo voltaic applications. Here the inverter system is an interleaved high power flyback inverter, ie to implement an improved grid-connected interleaved flyback inverter based on photovoltaic. The existing micro inverter topology based on flyback converter. Therefore the main objective of this paper is to design a new flyback inverter system at high power with good performance. The flyback inverter system designed for 2 KW and it is achieved by interleaving of three flyback cell. The converter is operated in discontinuous current mode (DCM) for easy and stable generation of ac current at grid interface. The system simulation confirms the performance and design of the proposed system using MATLAB Simulink.

Index Terms— Central type PV inverter, Decoupling capacitor, Discontinuous current mode (DCM), Flyback inverter, Interleaving, Photovoltaic, P&O algorithm

1 INTRODUCTION

The sun is probably the most important source of renewable energy available today. The depletion of fossil fuels, renewable sources, generated from natural resources, has caught the eyes in recent years from both the industries and governments all over the world due to their environmental friendliness. Throughout the world, the primary aim in photovoltaic has so far been to generate as much power as possible, irrespective of demand. With growing market shares and feed-in volume, however, a paradigm shift is now beginning to emerge. The direct marketing of solar power is gaining precedence and increasingly requires generators to feed in power on demand. The low cost is greatly important for commercialization especially in small electric power systems including the residential applications. Therefore, the primary objective of the Project is to contribute to the research and development in the photovoltaic (PV) inverter technology by trying the flyback topology at high power.

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In PV ac module systems, a flyback inverter is an attractive solution as the single-phase grid connected inverter because of the advantages of fewer components, simplicity, and isolation between the PV modules and the grid line. Also, by using the interleaved technique in the flyback inverter, the conduction loss of each switch can be reduced due to the decreased current of each phase. Interleaved flyback inverters (ILFIs) for PV ac modules are generally designed for the maximum output power of a PV module. The efficiency of the inverter is the highest when the PV module generates the maximum power. The flyback converter is recognized as the lowest cost converter among the isolated topologies since it uses the least number of components. This advantage comes from the ability of the flyback topology combining the energy storage inductor with the transformer. In other type of isolated topologies, the energy storage inductor and the transformer are separate elements. While the inductor is responsible for energy storage, the transformer on the other hand is responsible for energy transfer over a galvanic isolation. The combination of these two components in a flyback topology eliminates the bulky and costly energy storage inductor and therefore leads to a reduction in cost and size of the converter. However, we have to make it clear here that the cost depends on the implementation as much as the selected topology, so not every implementation of the flyback topology leads to a low-cost converter. For this reason, as we try to achieve the high-power implementation of the flyback converter with good performance.

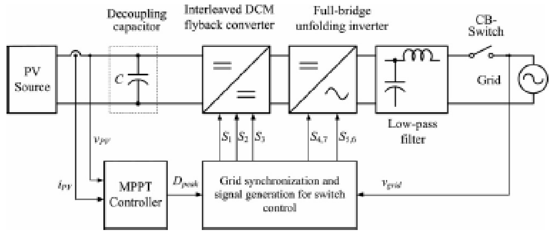

Fig.1. Block diagram of the proposed system

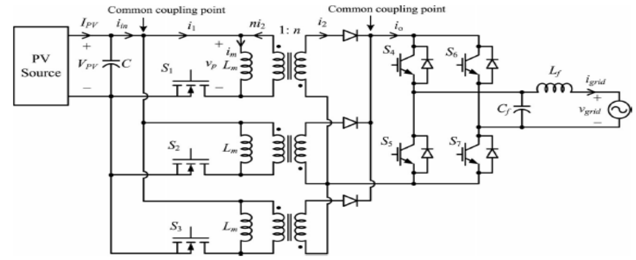

Fig.2. Circuit diagram of proposed topology

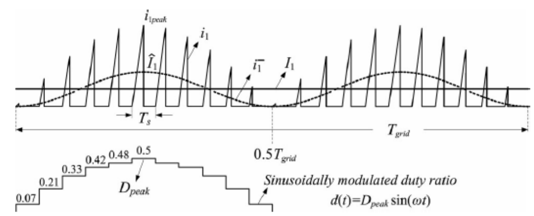

Fig.3.Flyback converter input current over a one grid period

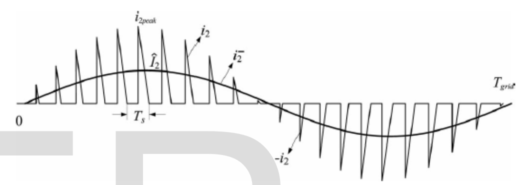

Fig.4. Flyback converter output current after full-bridge inverter

Practical implementation of a transformer with relatively large energy storage capability is always a challenge. The air gap is where the energy is stored, so a high-power flyback converter design needs a relatively large air gap. As a result of this, the magnetizing inductance is going to be quite small. The aforementioned challenge is actually achieving such a small magnetizing inductance with low leakage inductance. A flyback converter built with a transformer that has large leakage flux and poor coupling will have poor energy transfer efficiency. Mainly for this reason, the flyback converters are generally not designed for high power. As a result, the flyback topology finds a limited role in PV applications only at very low power as micro inverter. In this technology, every PV panel comes with a dedicated energy conversion unit; a micro inverter attached to the output terminals. For this reason, the technology is also named as ac PV module application. In this practice, many such ac PV modules are connected in parallel to get the desired power output. The maximum harvesting of solar energy in this method is the best since there is a dedicated maximum power point tracker (MPPT) for each PV panel. However, the overall cost of this application is higher compared to the central-type inverter systems. The interleaving of these high-power flyback stages (cells) facilitates developing a central-type PV inverter. The added benefit of interleaving is that the frequency of the ripple components (undesired harmonics) at the waveforms are increased in proportion to the number of interleaved cells. This feature facilitates easy filtering of the ripple components or using smaller sized filtering elements. The ability to reduce the size of passive elements is beneficial for reducing the cost and obtaining a compact converter.

The choice of operation mode for the converter is discontinuous current mode (DCM). It provides very fast dynamic response and a guaranteed stability for all operating conditions under consideration. The diodes exhibits reverse recovery problems in CCM operation which cause noise, electromagnetic interference problems, and additional losses.

So, DCM operation eliminates all these complications. In DCM it is easy to control. No need for a feedback loop for the control of the grid current. Only an open-loop control is enough to synthesize a sinusoidal current with good total harmonic distortion (THD). This makes the implementation of the control system less complex for DSP and allows faster execution time.

2 PROPOSED TOPOLOGY

To meet the requirements i.e. low cost and higher efficiency, the entire system was designed to use a PV module. The maximum power developed by the panel is fed to H-bridge inverter through a interleaved flyback converter. Fig. 1 shows the block diagram of the proposed system. This topology is derived from conventional flyback micro-Inverter by interleaving three flyback cells. Block diagram consist of mainly five blocks. In which PV source is applied to the flyback converter through a decoupling capacitor. Then the output of the flyback converter fed to the full bridge unfolding inverter. There is a low pass filter block after the inverter to reduce harmonics in the output current. The control block is used to perform two important control jobs. For the first job, it should regulate proper DC input PV current and PV voltage. For the second job, it should provide control to convert DC current into AC current at the grid interface for power injection. The purpose of interleaving of winding reduces the amount of leakage flux and improve coefficient of coupling, so the transformer can transfer more power from one side to another side.

3 PRINCIPLES OF OPERATION AND CONVERTER ANALYSIS

Fig. 2 shows the circuit diagram of the proposed topology. The current I_{PV} from the PV source is applied to the three cell flyback converter through decoupling capacitor C; it is used to reduce harmonics in the input PV current. There are three metal–oxide–semiconductor field-effect transistor (MOSFET) used in primary side as a flyback switch for switching purpose. When the flyback switches (S_1, S_2, S_3) are turned ON, a current flows from the PV source into the magnetizing inductance of the flyback transformers, and energy is stored in the form of magnetic field. When switches are ON, current do not flows to the output due to secondary diodes. When the flyback switches are turned OFF, the energy stored in the magnetizing inductances is transferred into the grid in the form of current. So, the flyback inverter acts like a voltage-controlled current source.

The H-bridge inverter is used for unfolding the sinusoidal modulated dc current packs into ac at the right moment of the grid voltage. The switches of the inverter are operated at the grid frequency, So the switching losses are insignificant. However, for easy control also the availability in the laboratory for fast prototyping, we prefer using insulated-gate bipolar transistor (IGBT) switches for this design. But, the final prototype will not use IGBTs. The low-pass filter after the IGBT inverter is responsible for supplying a current to the grid with low THD by removing the high frequency harmonics of the pulsed current waveforms. The converter is operated in DCM for easy and stable generation of ac currents at the grid interface. The DCM operation of converter under open-loop control produces triangular current pulses at every switching period. If sinusoidal pulse width modulation (PWM) method is used for control, the inverter will regulate these current pulses into a sinusoidal current in phase with the grid voltage. Fig.3 and Fig.4 shows the conceptual input and output current. There are three component ie, instantaneous flyback converter input current (i_1), instantaneous average of i_1 over one switching period and dc component (I_1) for input current and instantaneous flyback converter output current (i_2), instantaneous average ($\bar{i_2}$) for output current. In order to reduce output current distortion and for the good performance of the converter a decoupling capacitor placed before the converter input and sized in such a way that both low and high frequency ac components are bypassed sufficiently and only dc component is allowed to supply by PV source.

The circuit can be analyze using circuit schematic shown in Fig.2 and only consider the first flyback cell; this is done for the designing purpose. Fig.5 shows the control signal for the flyback switch, flyback transformer primary voltage (v_P), and magnetizing current component (i_m).Analysis done for particular switching period when both grid voltage and duty ratio (D_{peak}) are at their peak values.

3.1 Analysis when flyback switch is Turned ON

When flyback switch S_1 is turned ON in Fig. 2, the PV voltage V_{PV} is applied to the primary winding and current flows in the primary circuit. The current starts from zero initial value and increases linearly with positive slope. The magnetizing current shown in Fig.5 can be defined as

$$i_1 = i_m = \frac{V_{PV}}{L_m} t \qquad (1)$$

Where L_m is the flyback transformer magnetizing inductance. At the end of the switch on time, primary current reaches its peak value as follows:

$$i_{1peak} = i_{mpeak} = \frac{V_{PV} D_{peak}}{L_m f_s} \qquad (2)$$

Where f_s is the switching frequency, this particular maximum is the peak value of the largest of the sinusoidally modulated triangular current pulses within a half-grid period shown in Fig.3. The area of this triangle also gives the peak value of the twice the line frequency component of the flyback input current, which is given as follows:

$$\hat{I}_1 = \frac{V_{PV} D^2{}_{peak}}{2L_m f_s} \qquad (3)$$

The half of $\hat{I}_1$ gives the average dc current I_1, that is drawn from the PV source.

$$I_1 = \frac{I_{PV}}{\eta_{cell}} = \frac{V_{PV} D^2{}_{peak}}{4L_m f_s} \qquad (4)$$

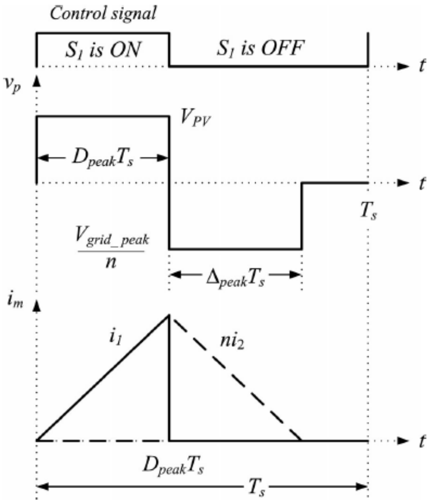

Fig.5.Control signal for flyback switch, flyback transformer primary voltage (v_P), magnetizing current (i_m)

Where n_{cell} is the number of the interleaved cells and I_{PV} is the current delivered by the PV source. So, the relationship between the flyback converter parameters and the PV source output power can be written as follows:

$$P_{PV} = V_{PV} I_{PV} = \frac{n_{cell} V^2{}_{PV} D^2{}_{peak}}{4 L_m f_s} \quad (5)$$

At the design stage, the desired value of the magnetizing inductance of the flyback transformer (L_m) is computed using (5) based on the selected switching frequency, the optimum number of the interleaved cells, and the optimum D_{peak} value. The D_{peak} value is generated by the MPPT controller for maximum harvesting of the solar energy under different irradiation levels and applied to the flyback switches.

3.2 Analysis when flyback switch is Turned OFF

When flyback switch S_1 is turned OFF, the flyback transformer primary voltage becomes negative of the grid voltage. The magnetizing current for this case can be written as follows:

$$n_{i_2} = i_m = \frac{\hat{V}_{grid}}{n L_m} t \quad (6)$$

Where n is the flyback transformer turn ratio. At the end of the switch off time, the magnetizing current decreases from its maximum value to zero linearly. The change in the current is given as follows:

$$n i_{2peak} = i_{mpeak} = \frac{\hat{V}_{grid} \Delta_{peak}}{n L_m f_s} \quad (7)$$

Where Δ_{peak} is the ratio of time that takes for the magnetizing current to reset as shown in Fig.5. It can be computed by equating the Volt–second area across the primary voltage (v_p) as follows:

$$\Delta_{peak} = \frac{n V_{PV} D_{peak}}{\hat{V}_{grid}} \quad (8)$$

Using Δ_{peak} we can calculate the peak value of the instantaneous average of the flyback output current.

$$\hat{I}_2 = \frac{\hat{I}_{grid}}{n_{cell}} = \frac{V^2{}_{PV} D^2{}_{peak}}{2 L_m f_s \hat{V}_{grid}} \quad (9)$$

Note that (9) also gives the maximum value of the grid current per interleaved cell. Comparing (5) and (9) verifies the fact that average power from the PV panels equal to the active power transferred to the grid assuming an ideal converter.

$$P_{PV} = V_{PV} I_{PV} = \frac{n_{cell} V^2{}_{PV} D^2{}_{peak}}{4 L_m f_s} = \frac{\hat{V}_{grid} \hat{I}_{grid}}{2} = P_{grid} \quad (10)$$

Assuming Δ_{peak} = 1− D_{peak} and using (8), the turn ratio of the flyback transformers can be computed as follows:

$$n = \frac{\hat{V}_{grid}(1 - D_{peak})}{V_{PV} D_{peak}} \quad (11)$$

The air gap length of the flyback transformer can be found using the following:

$$l_g = \frac{N^2 \mu_0 A_{core}}{L_m} \quad (12)$$

Where N is the number of turns of the primary winding, μ_0 is the permeability of air, and A_{core} is the cross-sectional area of the core material. The maximum voltage stress across the flyback switch when it is in off-state can be calculated using the following:

$$V_{SW\,max} = V_{PVmax} + \frac{\hat{V}_{grid-max}}{n} + \Delta V \quad (13)$$

Where V_{PVmax} is the maximum PV voltage, $\tilde{V}_{gridmax}$ is the peak value of the maximum grid voltage and ΔV is the transient voltage that may occur due to the leakage inductance of the transformer and the parasitic inductances in the circuit during the turn-off of the switch. Secondary diode faces the maximum voltage stress when flyback switch is ON, and it can be determined as follows:

$$V_{Diode\_max} = nV_{PVmax} + \tilde{V}_{grid\_max} \quad (14)$$

The decoupling capacitor works as buffer and provides the power balancing between the PV source and the grid. So, the major sizing criterion of the decoupling capacitor is the effectiveness in diverting the double line frequency component away from the PV source by creating a low impedance path and so maintaining a low ripple at the PV terminals. The following gives the peak-to-peak voltage ripple across the decoupling capacitor.

$$\Delta V_{PV} = \Delta V_C = X_C \Delta I_C \quad (15)$$

Consequently, using (15), the minimum value of the decoupling capacitor based on the desired peak-to-peak voltage ripple specification can be computed as follows:

$$C \geq \frac{2I_{PV}}{(2\pi 100)\Delta V_{PV}} \quad (16)$$

4 CONVERTER DESIGN

The converter is designed mainly for small electric power system including residential applications. Here the power rating is selected as 2 KW and switching frequency selected as 40 KHz in order to achieve high efficiency. The choice of switching device should have fast current fall time (t_f) to reduce the turn-off losses, So we use MOSFET as the flyback switch. The MOSFETs with low voltage ratings have much lower on-state resistance ($R_{DS(on)}$) and more efficient as far as the conduction losses are concerned, we prefer low voltage design. Table I gives the specifications to be used for the design of the proposed inverter system. The maximum converter input voltage 108.5 V for the selected PV module arrangement. The next important design step is to determine the ideal number of the interleaved cells (n_{cell}). This number selected based on following strategies

a) Interleaving reduces the passive filtering efforts to the practical minimum.
b) To determine the ideal power rating for the single flyback cell. The three cell rated at 700 W are connected in parallel in order to reach 2 KW.

TABLE I
DESIGN SPECIFICATIONS

Design parameters	Specifications
PV model and maximum power	BP365, 65 W
Open circuit voltage and short circuit current per panel	21.7 V, 3.99 A
PV panel group arrangement	5 panels in a string and 6 strings in parallel
Voltage and current at the maximum power point per panel and per the selected panel group arrangement	17.6 V, 3.6932 A 88 V, 22.16 A
Total maximum dc power from the panel group	1950 W
MPPT energy harvesting efficiency	>98%
Grid characteristics	Single-phase, 220 V, 50 Hz 143–264 V RMS 45.5–54.5 Hz
Switching frequency	40 kHz
Number of interleaved cells	3

Based on the selected switching frequency and the cell number, the ripple frequency at the current waveform at the common coupling points (see Fig. 2) becomes 120 kHz. This frequency is high enough for easy filtering of the switching frequency harmonics with relatively small passive elements. Using cell number we can find peak duty ratio as Dpeak = $1/n_{cell}$.

4.1 Flyback Transformer Design

The success of the proposed inverter system is very much related to the success in the design and the practical realization of the flyback transformers. As aforementioned, the flyback transformers have to store large amount of energy

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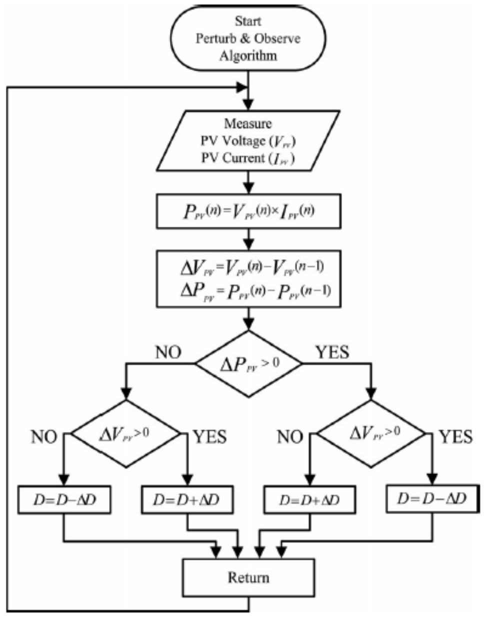

Fig.6 Flow chart of P& O algorithm

and then transfer it to the output through magnetic coupling at every switching cycle. Therefore, during the design process, the strategies that first create the most effective energy storage mechanism and second the most optimum and efficient energy transfer path must be employed. Firstly, the magnetizing inductance of the flyback transformer L_m is determined under nominal conditions. Using 88 V for V_{PV}, 40 kHz for f_s, 1950 W for P_{PV}, 3 for n_{cell}, and 0.3333 for D_{peak} in (5), L_m is calculated as 8.27 μH. Rounding this result to 8 μH and reworking (5), the practical value of D_{peak} is calculated as 0.3278. Then, the turn's ratio of the transformer is determined for the minimum the grid voltage. Using 202 V for V_{grid} (minimum peak grid voltage), 88Vfor V_{PV}, and 0.3278 for D_{peak} in (11), the turns ratio (n) is determined as 4.7. But, it is selected as 4.5 for practical implementation.

4.2 Control System design

The control system is designed to perform two important control jobs simultaneously without using a feedback loop. While it is harvesting the maximum power available in the solar cells, it must pump that power into the utility grid with high power quality. For the first job, it should regulate a proper dc current I_{PV} and voltage V_{PV} at the PV interface for maximum energy harvesting. For the second job, it must provide control to convert the dc current, which comes from the panels and continuously regulated for the MPPT purpose,

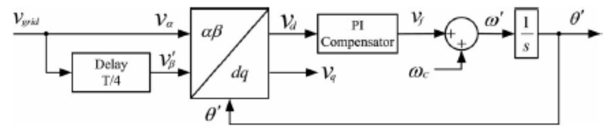

Fig.7. PLL structure based on T/4 transport delay technique

in to ac current at the grid interface for power injection. In addition, this ac current should be synchronized with the grid frequency, should have low harmonic distortion, and a power factor close to unity. Because of its implementation simplicity, the perturb and observe (P&O) method is selected as the MPPT algorithm.

Perturb & observe algorithm: In this approach, the module voltage is periodically given a perturbation and the corresponding output power is compared with that at the previous perturbing cycle. In this algorithm a slight perturbation is introduce to the system. This perturbation causes the power of the solar module various. If the power increases due to the perturbation then the perturbation is continued in the same direction. After the peak power is reached the power at the MPP is zero and next instant decreases and hence after that the perturbation reverses. The fig.6 below shows the flowchart of the P & O algorithm.

Besides the magnitude regulation for maximum power transfer, the controller should achieve synchronization of the current with grid voltage and a wave shape that is sinusoidal. For this purpose, the output of the MPPT block is multiplied by the PLL output and the switching signals for the MOSFETs are generated for sinusoidal duty ratio modulation. The PLL output is a sinusoidal waveform with unity gain and synchronized to the grid voltage. The structure of the PLL implemented in this controller is based on the $T/4$ transport delay technique shown in Fig. 7, where T is the fundamental period of the grid signal .If this control process is implemented successfully, the instantaneous average of the secondary currents is going to be sinusoidal and in phase with the grid voltage. Another control signal (Control 2) that is also synchronized with the PLL output is used to control the H-bridge IGBT inverter for unfolding purpose.

5 SIMULATION SET UP & DISCUSSIONS

Simulations are done to verify the design, also to determine some of the hardware requirements. For example, current ratings of the capacitors, inductors, cables, and so on can be easily determined from the simulation results. The proposed system is verified with MATLAB/SIMULINK

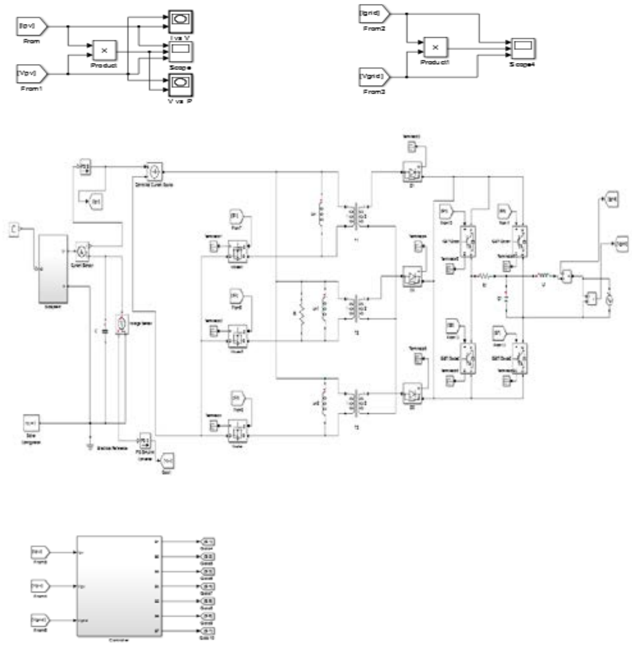

Fig.8. Simulation set up of proposed inverter system

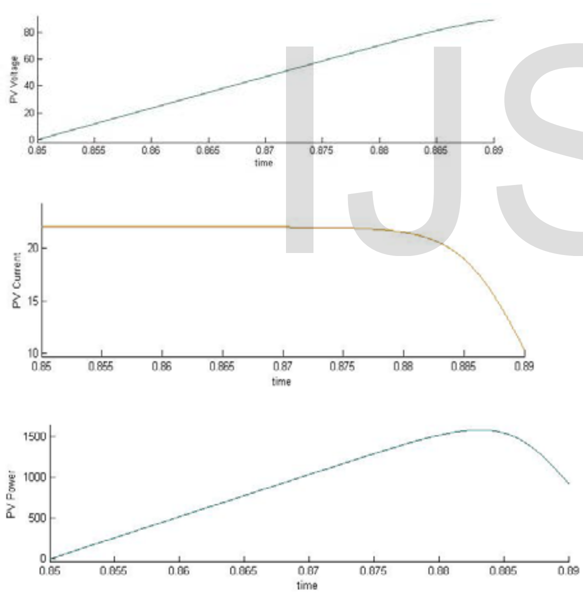

Fig.9. Simulated Photo voltaic Power, Voltage and Current.

version 2013. Fig.8. shows the simulation setup of proposed system. The top trace in Fig. 9 shows the Simulated Photo voltaic Power, Voltage and Current. The output PV Voltage is 88V and PV Current is around 22A. In addition, Fig. 10 shows the simulated waveforms of the grid Power, voltage and current. The waveforms demonstrate the success of the controller and the DCM mode flyback topology in achieving the high quality energy transfer into the grid. Moreover, it is verified via simulations that if the value of the decoupling capacitor is increased, the THD reduces almost proportionally. Therefore, if the THD value somehow exceeds the 5% requirement during the experiment, the decoupling capacitor is going to be resized accordingly; otherwise, it is going to be maintained at the selected value.

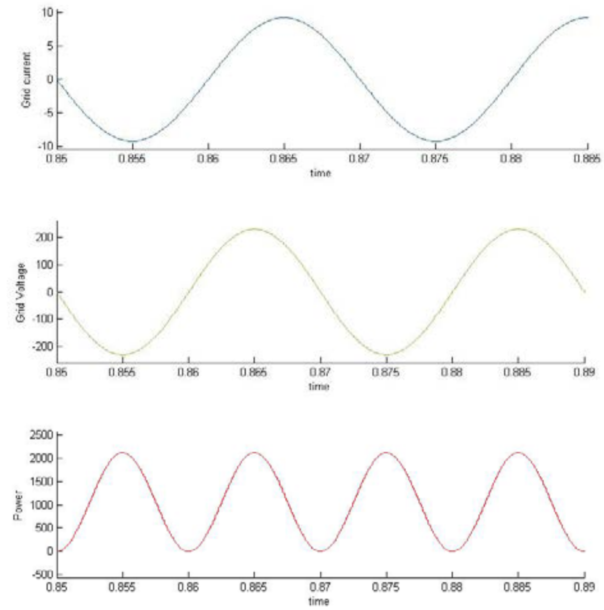

Fig.10. Simulated waveforms of the grid Power, voltage and current.

5 CONCLUSION

In this proposed system, a converter inverter system for small electric power system rated at 2 KW is implemented based on the interleaved flyback topology. The interleaving of three flyback cell each rated at 700 W used to achieve 2 KW power level also it was easy to filter harmonics in the output current because of interleaving provide high switching frequency. The flyback topology is selected because of its simple structure and easy power flow control with high power quality outputs at the grid interface. The output of the flyback converter system is given to the inverter system and it given to the grid as current. Here PLL and MPPT controller is provided to operate the switch. The proposed system may have some cost advantage due to topological benefit.

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