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A Single Stage Transformerless Inverter Topology With MPPT for PV Systems

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Abstract—The commonly observed trend in photovoltaic (PV) inverter technology is the usage oftransformerless topologies in order to acquire higher efficiencies combining with very low ground leakage current. Usually converter topologies such as buck, boost, buck-boost, sepic, flyback, push pull etc. are used in a Grid Connected Photo-voltaic System (GCPVS). Loss factors such as irradiance, temperature, shading effects etc. have zero loss in a two stage system, but additional converter used will lead to an extra loss which makes the single stage system more efficient when compared to a two stage systems. In this paper a new inverter topology for single stage PV system is proposed. The proposed inverter is synthesized from an inverting and non-inverting Cuk inverter where the diodes are replaced with controllable switches. Here the number of switches are reduced thereby minimizing the switching losses. Sliding Mode Controlled (SMC) maximum power point tracking method is used here. The sliding mode controller is given the estimated maximum power point as a reference which enables it to track that point and force the PV system to operate in this point. The proposed inverter topology for an 80W system was designed and simulation was done in MATLAB-Simulinkand the simulation results are included.

IndexTerms—Inverting and Non-inverting Cuk converter, transformer-less inverter, reduced number of switches,SMC- MPPT, PV-grid system.

I. INTRODUCTION

Of the renewable energy sources available solar photovoltaic systems became the most promising one due to the ease of availability, cost effectiveness, capacity,accessibility and efficiency compared with other renewable energy sources. The electricity generated by PV systems can be either stored using batteries or directly can be connected feeding power to the grid. The PV systems are connected to the grid by means of converters. The converter used has to extract maximum power from PV panels and should inject a sinusoidal current atparticular amplitude and frequency to the grid.Generally power transfer to the grid is completed in two stages [1], Fig.1. Typically, the first stage comprises of a boost or buck-boost type dc–dc converter topology including MPPT algorithm for boosting the voltage supplied by the PV array. The second stage has a dc/ac inverter which is meant for converting the boosted dc voltage to ac.Such two-stageconfigurations are time tested and work well, but have drawbacks such as higher part count, lower efficiency, lower reliability, higher cost, larger sizeand additional losses in each converter. So the best option is to have only a singlepower electronic stagebetween the PV array and the grid to achieve all the functions—namely the electrical MPPT, boosting and inversion leading to a compact system.Because of simplicity and low cost, single stage systems become popular.Module integration becomes easier as the number of power stages are reduced. These commercially used inverters in the single stage topologies usually include a transformer to ensure galvanic isolation for safety reasons.

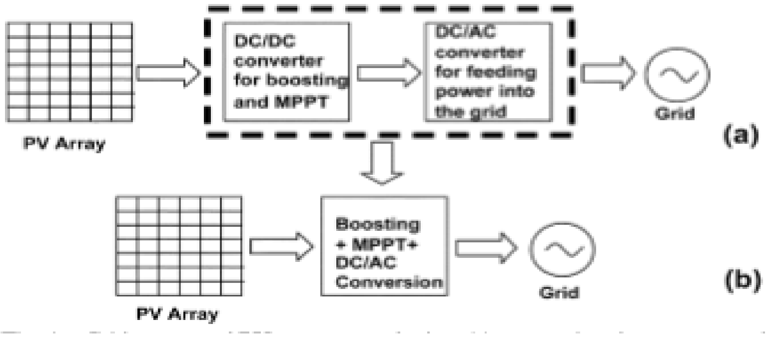


Fig. 1. Different grid connected configurations (a) Two stage (b) Single stage

However, the bulky and expensive transformer increases the volume, weight and costs of the system. It's possible for a transformerless inverter [2] to achieve higher efficiency, smaller size & weight and lower price.

In this paper, a single stage transformerlesssystem, which does not require complex circuitry and modulation techniques, is introduced. It is simple than existing ones and also it is capable of transferring maximum available power from PV cells to the grid or load as provided. The inverter proposed here is synthesized from the inverting and non-inverting dc to dc CUK converter configurations. The inverter topology has the advantage of voltage boosting along with dc-ac conversion which thereby eliminates the need of a transformer. Apart from the commonly used maximum power point tracking methods such as Perturb and Observe (P&O) algorithm, Incremental conductance algorithms, Fractional Open Circuit Voltage method etc. a more advantageous algorithm has been implemented here namely- Sliding Mode Controlled(SMC) MPPT [3] [4]. Due to the inherent buck-boost capability of the CUK converter topology, the output voltage can be higher or lower than the input voltage of the PV array depending on the modulation index when Sinusoidal Pulse width Modulation (SPWM) technique is used.

II. PV MODULE AND MPPT

A. PV Modelling In Simulink

The individual solar cells are connected together to form a module called 'solar module' or 'PV module'.The cells can be connected in series or parallel to increase the power level. A PV module consists of many PV cells wired in parallel to increase current and in series to produce a higher voltage. 36 cell modules are the industry standard for large power production [9]. The equivalent circuit of a solar cell is shown in fig 2.

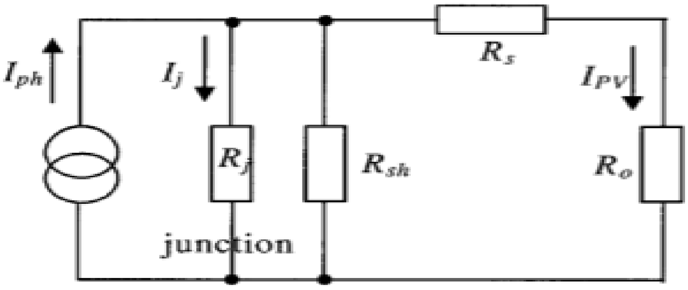


Fig 2: Equivalent circuit of a solar cell

The equivalent circuit is drawn considering PV cell as a current source in antiparallel with a diode, considering the series and parallel resistances as these terms have direct impact on PV cell efficiency. In this paper an 80W PV panel is modelled under standard temperature conditions of 25^0C and was simulated in MATLAB which is shown in figure 3.

Figure 4 shows the output results of the simulated PV model for two different irradiations, 1000W/m^2 and 800W/m^2.

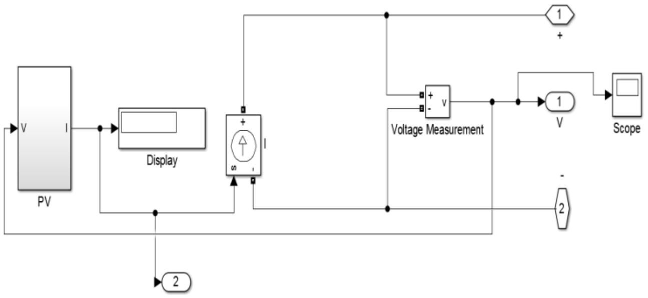
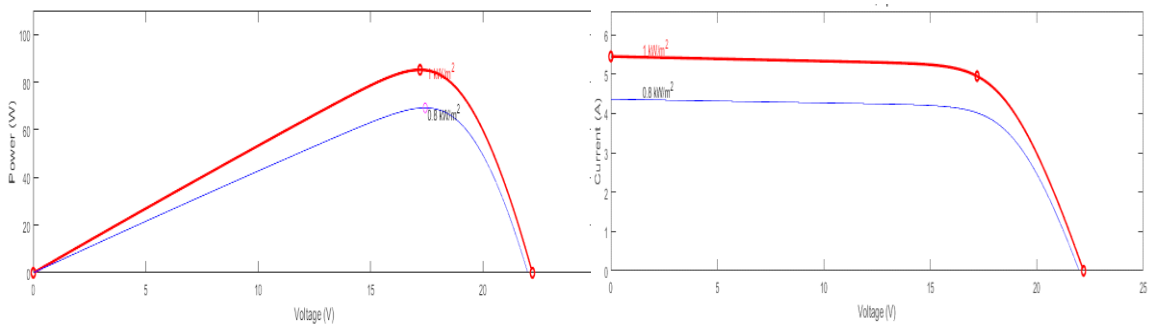


Fig.3. PV panel- SIMULINK model



(a) (b)

Fig.4. PV output results (a) P-V characteristics (b) I-V characteristics

B. SMC Based MPPT

Tracking of the maximum power point (MPP) of a photovoltaic (PV) array is usually an essential part of PV systems. Many methods are used for maximum peak power for PV systems such as Perturb and Observe (P&O) algorithm, Incremental conductance algorithms, Fractional Open Circuit Voltage method etc. All these tracking methods have their own disadvantages like slow response, increased complexity, requirement of more number of sensors etc. In this paper the Sliding Mode Controlled MPPT method is used for extracting maximum power from the PV panel. This is an open circuit voltage based MPPT were it uses the open circuit voltage V_{oc} to find the maximum power point voltage V_{mp} . This control strategy provides accurate estimation of point corresponding to maximum power on PV curve and helps to increase its efficiency.

The designing of SMC includes two main steps. The first step is designing a Switching function called Sliding Surface and the second step is a Control law. To design the sliding mode controller we have to select the desired surface. We want to obtain the maximum power that can be extracted from the PV module at the given temperature and irradiance conditions. From (6) we can relate that maximum power to an optimal voltage. Since we know required output voltage in order to extract the maximum power from the PV system, we choose a surface that will force the system to reach that voltage in a definite time and stay there for infinite time. Considering the above said facts, we chose the following sliding surface:

$$\sigma = V - V_{op}$$

Here 'V' is the output voltage of PV module and 'V_{op}' is the optimal voltage.This sliding surface will assure us to force all the trajectories of the system to reach the optimal voltage and to keep it in the optimal voltage for all future time. Since the optimal voltage is dynamic as it changes when changes occur in the temperature and irradiance this sliding surface is also changing with respect to the temperature and irradiance giving us a dynamic sliding surface. The sliding mode will be controlling the duty cycle of a switching device. So the switching device will have two operation state:

$$\begin{cases} \text{ON, if } (V - V_{op}) > 0 \\ \text{OFF, if } (V - V_{op}) < 0 \end{cases}$$

The sliding mode control algorithm will operate considering the above condition. The duty cycle is controlled only when the output voltage of PV panel exceeds the optimal voltage and if not the system tries to increase the corresponding voltage

III. ANALYSIS OF INVERTER TOPOLOGY

A. Circuit Diagram

The inverter topology shown in Fig. 5, is a combination of inverting and non-inverting CUK converter, with six switches, where the converter is responsible for producing inverted and non-inverted output voltage and current. The presence of L, reduces the input current ripple and hence high value of electrolytic capacitor need not be used across the PV array terminals.It consists of two inductors (L1 and L2) and an intermediate capacitor (C1) for energy storage similar to a Cuk converter.

In the proposed model, the number of swiches are reduced to five as shown in figure 4 thereby reducing the swiching losses.

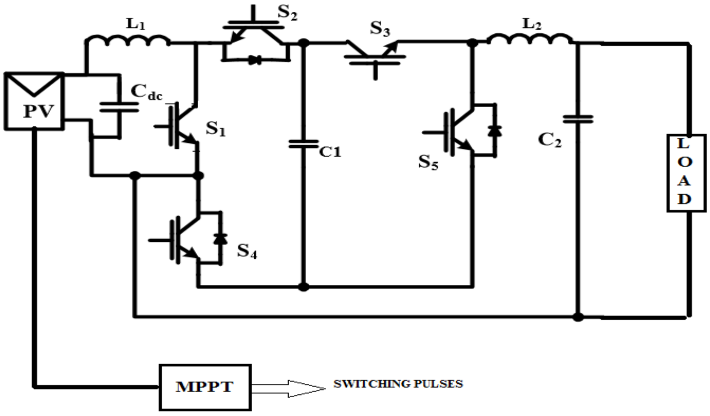
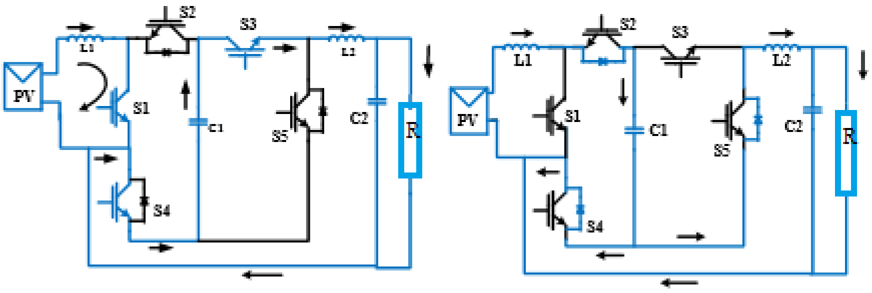


Fig.5. Proposed configuration

B. Modes of Operation

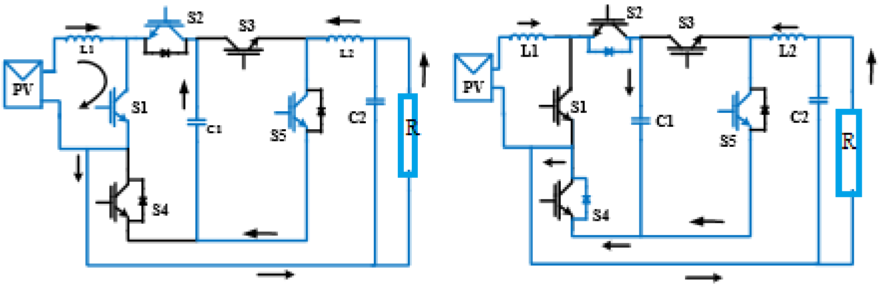
The working of the proposed inverter can be explained in four modes. Among the 4 modes of operations, Mode 1 and 2 are operated in the positive half cycle and Mode 3, 4 during the negative half cycle.



(a) Mode 1 (b) Mode 2

Fig.6. Mode1 and Mode 2 of operation

In Mode 1, Figure 6(a),when S1 is ON, energy is stored in L1 and energy stored in C1 is delivered to L2 and to the load. S1 is operated using sinusoidal pulse width modulation (SPWM) technique with a switching frequency of 10kHz. In Mode 2,Figure 6(b),when S1 is OFF, energy stored in L1 and the energy from the input source is delivered to the intermediate capacitor C1 and the output inductor L2 delivers energy to the load.



(c) Mode 3 (d) Mode 4

Fig.7. Mode 3 and Mode 4 of operation

When S1 is ON in Mode 3,Figure 7(a), in the negative half cycle, energy is stored in L1 and C1 discharges through the load, thereby charging L2. When S1 is OFF in Mode 4,Figure 7(b),L1 discharges through C1 and L2 discharges through the load.

Here switches S4 and S5 are operated at grid frequency (50Hz) and S1, S2, S3 are operated at high frequency.

The four operating modes are tabulated below:

	S1	S2	S3	S4	S5
MODE 1	1	0	1	1	0
MODE 2	0	0	0	1	0
MODE 3	1	1	0	0	1
MODE 4	0	0	0	0	1

TABLE1- Operating modes

IV. DESIGN OF CIRCUIT ELEMENTS

Design of L1, L2, CI and C2 is discussed in this sub section for an 80W system. These energy storage elements are designed for a switching frequency of 10kHz.

A. Design of Inductor L1

The maximum power obtained from the PV string is given by

$$P_{PV\ max} = V_{PV\ MPP\ max} I_{PV\ MPP\ max} (1)$$

where VPV mpp max and IPVmpp max are the output voltage and current of the PV array, when working at MPP under maximum insolation and uniform conditions.Assuming a lossless inverter, the maximum power injected into the grid is,

$$P_{g\ max} = \frac{V_{gm}}{\sqrt{2}} \frac{I_{gm}\ max}{\sqrt{2}} = P_{PV\ max} = V_{PV\ MPP\ max} I_{PV\ MPP\ max}\ (2)$$

Here, $I_{gm}\ max$ is the amplitude of current injected into the grid under maximum insolation and uniform insolation conditions.

During the ON period,

$$T_{on} = \frac{L_{crit} I_{peak}}{V_{pv\ mpp\ \ max}} (3)$$

During the OFF period,

$$T_{off} = \frac{L_{crit}\, I_{peak}}{V_{gm}} \quad (4)$$

whereI_{peak} is the peak inductor current and L_{crit} is the inductance value for the critical conduction mode.
Now,

$$T_S = T_{on} + T_{off} = L_{crit}\, I_{peak} \left[\frac{1}{V_{gm}} + \frac{1}{V_{pv\ mpp\ \ max}}\right] (5)$$

Using the above equation, the energy stored in the inductor during this period is given as follows:

$$\frac{L_{crit}\, I_{peak}{}^{2}}{2} = \frac{T_S{}^{2}}{2L_{crit}} \left[\frac{1}{V_{gm}} + \frac{1}{V_{pv\ mpp\ \ max}}\right]^{-2} \quad (6)$$

On further equating the above equations the expression for critical value of inductance can be obtained.

$$L_{crit} = \frac{0.25 T_s}{V_{PV\ \ MPP\ \ max} I_{PV\ \ MPP\ \ max}} \left[\frac{1}{V_{gm}} + \frac{1}{V_{pv\, mpp\, max}}\right]^{-2} \quad (7)$$

To ensure discontinuous conduction mode, L1 should be smaller than Lcrit.

B. Design of Capacitor C2 (filter capacitor)

The value of filter capacitor C2 is obtained by equating the energy released by the inductor L1 and the energy received by the capacitor C2.

$$\frac{L_{crit}\, I_{peak}{}^{2}}{2} = \frac{C_2}{2}\left[(V_{gm} + \Delta V)^2 - (V_{gm} - \Delta V)^2\right] (8)$$

$$C_2 = \frac{T_S{}^{2}}{4L_{crit} V_{gm} \Delta V} \left[\frac{1}{V_{gm}} + \frac{1}{V_{pv\, mpp\, max}}\right]^{-2} \quad (9)$$

The above equation 9 gives the value of C2 in terms of L1, grid voltage, PV string parameters, switching frequency, and acceptable highfrequency ac voltage ripple, superimposed on the sinusoidal capacitor voltage.

C. Design of Inductor L2 (filter inductor)

The value of filter inductor L2 is obtained as follows,

$$L_f = \frac{1}{\omega^2 C_f} = \frac{1}{(2\pi f_c)^2 C_2} (10)$$

Here f_c is the cut off frequency which should be the less than the switching frequency. It is taken to be 2kHz.

D. Design of capacitor C1

$$C_1 = \frac{1}{\omega_r{}^2 (L_1 + L_2)} \qquad (11)$$

CI is designed considering the fact that the resonant frequency of C1, L1, L2 must be much greater than thegrid frequency. It is designed for a cutoff frequency of 5kHz

V. SIMULATION RESULTS

The operation of the proposed inverter topology connected to a resistive load is simulated with PV model as input in MATLAB-Simulink and results are presented in this section.

Simulation is carried out with a solar PV model as input, Figure 8. Sliding Mode Control (SMC) MPPT is incorporated here which compares the open circuit voltage, V_{OC} and the terminal voltage, V_T. The MPPT logic is designed such that the maximum power is transferred only when the terminal voltage exceeds the PV open circuit voltage.

Simulation is done for the following values: Vpv=20V, LI=110µH, CI=47µF, L2=5mH, C2=5µF.

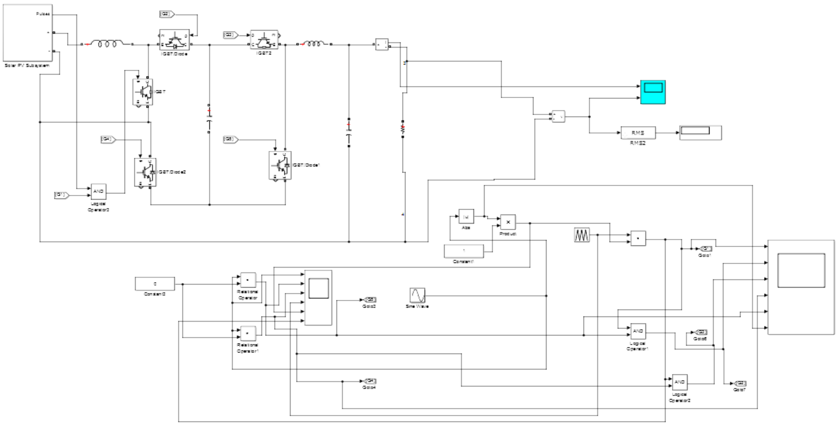


Fig.8. Single stage PV system with MPPT-SIMULINK Model

SPWM technique is used to generate the switching pulses for switches S2, S3, S4, and S5. Switch S1 is triggered using the signal generated by MPPT control. To verify the tracking of maximum power, the irradiation is changed from 1000 W/m2 to 800W/m2.

The switching pulses are generated by simple logic circuitry including pulse generators. The generated pulse waveforms are shown below,

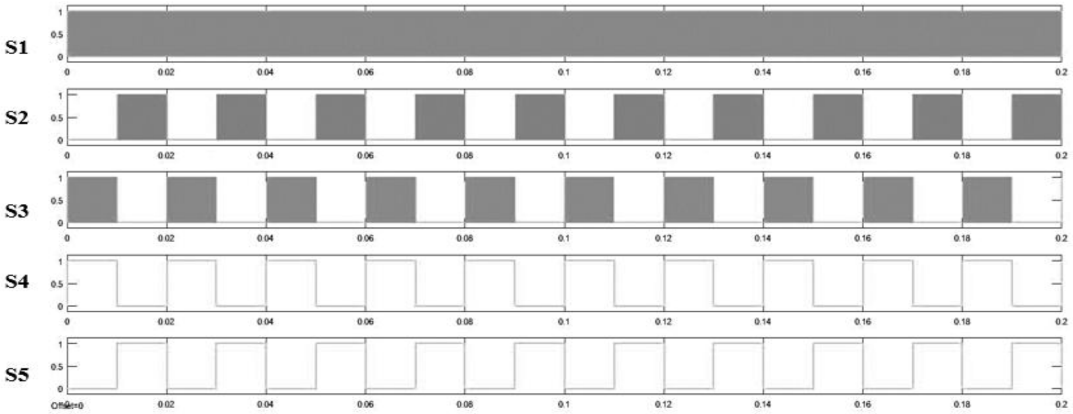
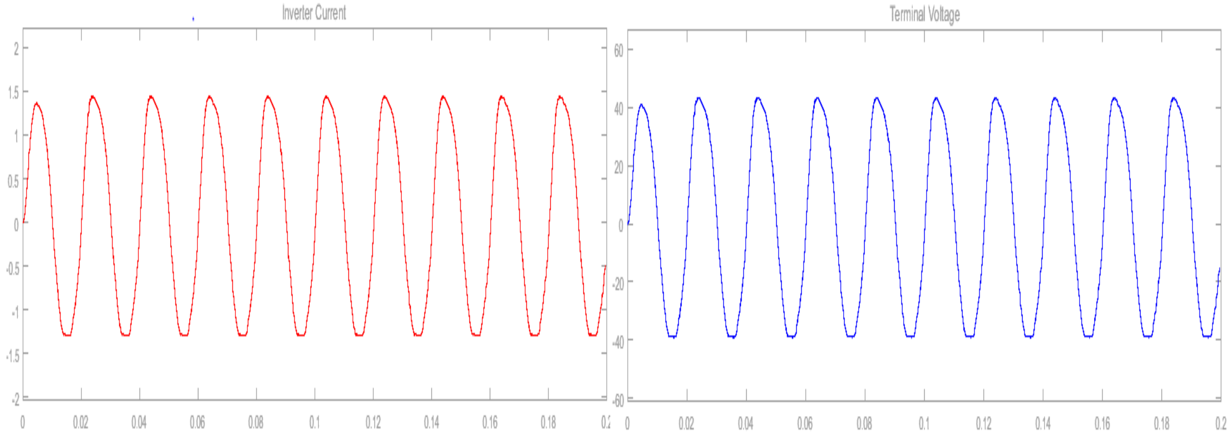


Fig. 9. Switching pulses

The simulation results show that the proposed inverter is capable of producing a boosted sinusoidal 50Hz waveform across the resistive load, Figure 10. The input voltage to the inverter fed by the PV panel is in the range of 20V approximately and the boosted output voltage level is in the range of 30.9V rms approximately.



(a) Output current (b) Output voltage

Fig. 10. Output current and voltage wave forms of simulated inverter with PV panel

VI. CONCLUSION

A single stage inverter topology for PV systems was introduced with reduced number of switches. The inverter is synthesized from an inverting and non-inverting Cuk inverter by replacing the diodes with controllable switches. The advantages of the proposed inverter topology include voltage boosting capability, long operational life, compact in size, and easier extraction of maximum power from PV array. The SMC maximum power point tracking used here is very much advantageous since it requires only a single sensor- for either voltage or current measurement from the PV panel. This improves the system efficiency. Design of the energy storage elements, and the simulation for an 80Watts system was done. A more detailed study was done by performing the simulations of the proposed inverter with PV panel (including MPPT). SPWM technique was used here for switching. The proposed inverter is applicable to Grid tied systems and further study of this idea can be done in future.

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