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Transformer-less Grid Connected PV Inverter for Single Phase System

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Abstract

There is a strong trend in the photovoltaic inverter technology to use transformer-less topologies in order to acquire higher efficiencies combining with very low ground leakage current. The DC/AC inverters are used in grid-connected PV energy production systems as the power processing interface between the PV energy source and the electric grid. The energy injected into the electric grid by the PV installation depends on the amount of power extracted from the PV power source and the efficient processing of this power by the DC/AC inverter. This paper presents a new methodology for optimal design of transformer-less photovoltaic (PV) inverters targeting a cost-effective deployment of grid-connected PV systems. The proposed configuration cannot only boost the usually low photovoltaic (PV) array voltage, but can also convert the solar dc power into high quality ac power for feeding into the grid. Simulation results confirm the performance of proposed system.
Keywords: Photovoltaic, Transformer-less, Grid connected, Voltage boost, Inverter**.**

Introduction

The importance of renewable energy sources is recognized by both the general public and the power industries. Some researchers believe the concern for environmental damage is now an even greater priority than the need to preserve the finite natural resources for future generations. Photovoltaic (PV) inverters become more and more widespread within both private and commercial circles [1].

These grid/load-connected inverters convert the available direct current supplied by the PV panels and feed it into the utility grid/load. There are two main topology groups used in the case of grid/load-connected PV systems, namely, with and without galvanic isolation. Galvanic isolation can be on the dc side in the form of a high-frequency dc–dc transformer or on the grid/load side in the form of a big bulky ac transformer. Both of these solutions offer the safety and advantage of galvanic isolation, but the efficiency of the whole system is decreased due to power Losses in these extra components [2].

An improvement in inverter efficiency and a reduction in cost have been achieved by omitting the 50 Hz power transformer (transformer less) and by optimizing the Inverter current control strategies. The inverter described in this paper is specifically for grid/Load-connected PV Systems, it can be used for other traditional applications such as in uninterruptible Power supplies (UPS), motor controls and voltage regulation systems. The main aim of this paper was to develop a new design procedure for a single-phase, transformer less PV inverter system suitable for grid/Load connection, which would lead to higher inverter efficiencies, improved output power quality and reduced cost.

Techniques to remove DC offset current will be investigated to ensure that the DC current injected into the grid/Load system is maintained within the legal limits irrespective of its source. To improve the quality of inverter output current, a suitable efficient and cost effective ripple current filter design will also be developed. The specific objectives of the paper are summarized

- High efficiency
- Constant High Frequency Common Mode Voltage
- Very Small Leakage Current
- Low Total Harmonic Distortion

Inverter or power inverter is a device that converts the DC sources to AC sources. Inverters are used in a wide range of applications, from small switched power supplies for a computer to large

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electric utility applications to transport bulk power [8]. This makes them very suitable for when you need to use AC power tools or appliances Control of the switches for the sinusoidal PWM output requires a reference signal (modulating or control signal) which is a sinusoidal wave and a carrier signal which a triangular wave that control the switching frequency.

The benefit of choosing the PWM over analog control is increased noise immunity which the PWM is sometimes used for communication. Switching from an analog signal to PWM can increase the length of a communications channel dramatically. At the receiving end, a suitable RC (resistor-capacitor) or LC (inductor capacitor) network can remove the modulating high frequency square wave and return the signal to analog form. So, the filter requirement can be reduced and the overall inverter size can be reduced [10].

Photovoltaic Generation System

To analyze the power quality behaviors resulted from operation of a PV plant in distributed generation system, a review of the PV generation system and some aspects that involved in their operation as the part of the system must be done, they are: the PV module, PV inverter and the module-inverter configuration, the PV plant-grid interaction and the atmospheric condition [2]. The main components of a PV generation plant are the PV modules and the PV inverters. The PV module is used as energy conversion equipment, converting the light energy to electrical form of the dc voltage and current. The conversion involves interaction process of the light, thermal and electrical parameters in a photovoltaic material. The PV inverter is then used to convert the dc to ac power to be used by consumer or to be connected to the grid. Some functions such as matching the array's dc voltage output with the inverter circuit voltage operation, matching the inverters' output voltage with the grid voltage and grid synchronizing are integrated in this compact equipment. A general structure of the grid connected PV systems is shown in Fig.1.

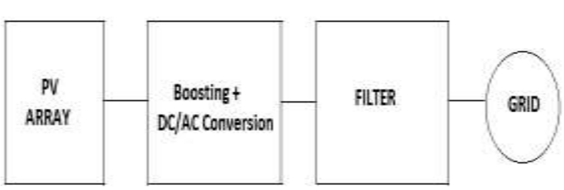

Figure-1: Representation of a single-phase grid connected PV system

Photovoltaic

Photovoltaic (PV) is a method of generating electrical power by converting solar radiation into direct current electricity using semiconductors that exhibit the photovoltaic effect. The basic PV cell model is presented in Figure below

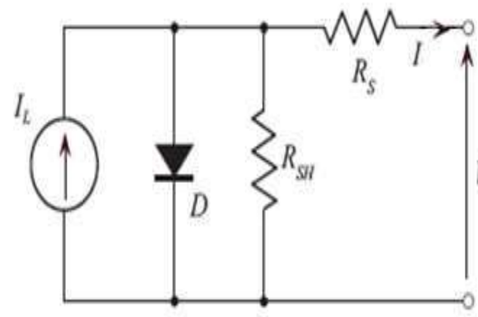

Figure-2: Basic PV cell model

Then from Fig1.the equations could be obtained,

$$I_{SC}=I_D + I \quad (1)$$

$$I= I_S\,(e^{\frac{V}{n.V_T}} - 1) \quad (2)$$

From eq.2,

$$I_D= I_{SC} - I_S\,(e^{\frac{V}{n.V_T}} - 1) \quad (3)$$

Where *Isc* is the photo current; *Is* is diode reverse saturation current; *n* is diode ideality factor normally between 1 and 5; $V_T = k.\frac{T}{q}$ is temperature voltage, which is 25.7 mV at 25^0C; *k* is Boltzmann constant, which is 1.38×10^{-23} *J/K; T* is temperature in *K and q* is electron charge which is 1.6×10^{-19}coulomb.

It can be observed that the PV module's short circuit current highly depends on the radiation. High radiation leads to large short circuit current. And the temperature impacts more on the open circuit voltage. High temperature leads to small open circuit voltage. Because of its *I-V* and *P-V* characteristics, maximum power point tracking *(MPPT*) is required to extract the maximum energy that the PV module can produce [1]

Single Stage Inverter

A single stage inverter is defined as an inverter with one stage of high frequency power processing, that means it has only one high switching frequency stage. Single stage inverter is shown in Fig.3.

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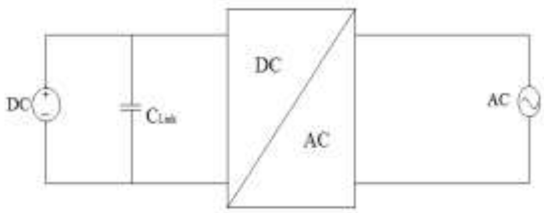

Figure-3: Single Stage Inverter

Other than high efficiency, the most advantage of this inverter is it has no leakage current, which is important for PV application. The drawback of this inverter is that the input voltage of it should be higher than the peak of the grid voltage, which limits the input voltage range for a PV inverter. For these single stage PV inverters, either a transformer is used for boosting the input voltage or the input voltage requires being higher than the peak of the grid voltage, which is not good for PV application because the PV panel's *I-V* characteristics changes all the time.

Topologies for Grid Connected Photovoltaic Systems

The basic elements of PV system are the modules that are usually series connected. A series of PV module is usually called a PV string. If the voltage of the PV string is always higher than the peak voltage of the grid the PV converters does not require a step up stage. In this case higher efficiency can be obtained because a single stage full bridge converter can be used. Otherwise, a DC-DC converter or a transformer must be added for voltage amplification reducing efficiency [3]. A PV system is combination of PV fields and the related power converters.

The peak current that can be delivered by one string is determined by the PV module characteristics. To achieve higher power level several strings can be connected in parallel as shown in fig 4a. In this way, a single converter can be used reducing the cost and the losses of the static energy conversion [11]. In this topology, usually referred to as central converter, the lack of individual MPPT for each string does not permit to harvest the maximum electric power from PV modules, especially when shading or different orientation of modules occurs [3]. This major shortcoming results in avoiding this simple topology in newer photovoltaic system designs.

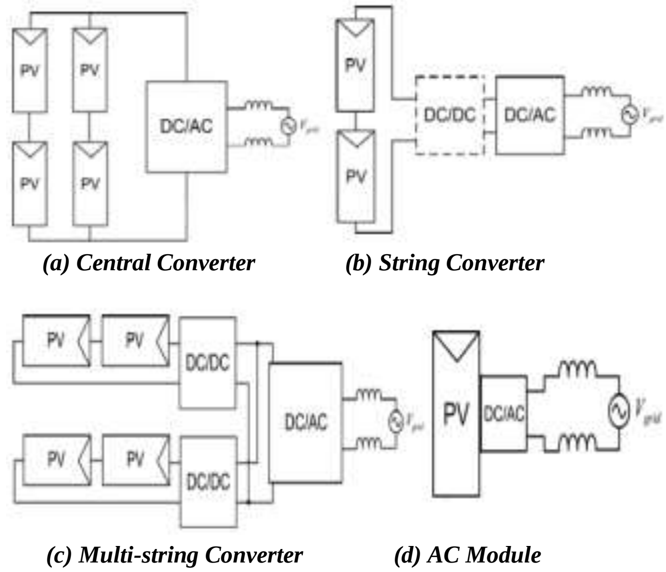

Figure-4: Configuration of the power converters for a grid connected PV system, (a) Central Converter, (b) String Converter, (c) Multi-string Converter and (d) AC Module

Other options are possible as sketched in fig.4.The string converter topology is shown in fig.4(b). This configuration does not employ the parallel connections of the strings. Each string has its own MPPT and is completely independent from each other. Therefore it is easy to build PV systems with different orientation, shading conditions and number of PV modules for each string. A disadvantage of string-converters in comparison to central converters is the higher price per KW [3]. String converters are often built only as single phase converters due to the low power level. A very common classic topology is the full bridge with a line frequency transformer on the AC side for galvanic isolation and for voltage step-up. This multi-string converter (fig.4(c)) manages two or three strings, and provides independent MPPT by different DC-DC converters [9]. In this case a two stage configuration is mandatory.

In these topologies the modules of one string have to be well matched and should be installed in the same orientation to achieve a high energy harvest. The photovoltaic energy harvesting can be maximized by using an individual MPPT for each PV module, that is called AC module (fig.4(d)). The AC module is connected directly to the grid and no DC wirings are needed between PV modules.

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Proposed Topology

The schematic diagram of the proposed $1-\varphi$ PV inverter is shown in Fig.3. Unlike some other topologies, which use two PV strings, the circuit of Fig.3 employs only one PV string as the energy source. The circuit uses five switches (S1 through S5). It uses only one buck–boost inductor *L*. Inductor *Lf* and capacitor *Cf*

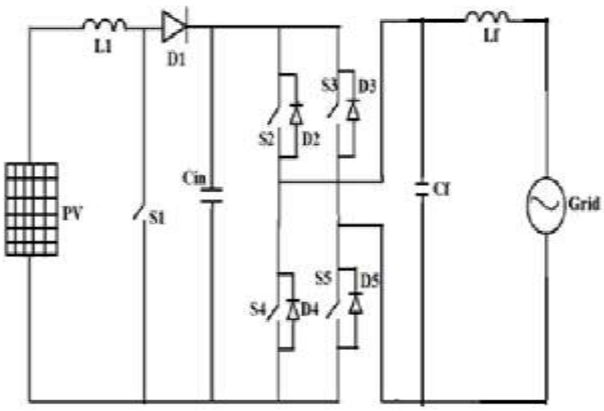

Figure-5: Proposed Circuit Diagram

form the low-pass filter, which allows only the 50-Hz component of the inverter output current to enter into the grid. In the proposed two point grounding, the first part is system grounding which includes filter circuit and transformerless buck boost converter [4].The switches used in the system are power electronic devices. In first stage the switch S1, Inductor L1 and Diode D1 forms a boost converter which boost the voltage from PV panel up desired set DC output voltage. Switch S1 is continuously ON during the positive or negative half cycle, other switches S2-S5 are triggered with pulse width modulation method (PWM generator) .When switch S1 is ON energy is stored in the buck boost inductor L1 by PV source. When switch S1 is off diode D1 gets forward biased , discharging the stored inductor energy into capacitor Cin. Switches S2-S5 forms a inverter which converts this boosted D.C. voltage into sinusoidal a.c. voltage which is fed into grid. During positive half cycle switch S2 &S5 along with diode D2&D5 are always kept ON, while switches S3&S4 with diode D3&D4 remain off. During the negative of A.C. cycle switch S3& S4 along with diode D3&D4 remain ON while switch S2 always remains off. Switch S1 is triggered by pulse generator while switches S2-S5 are triggered with PWM generator.

The amplitude of the "reference" sinusoidal waveform used for the sine-triangle PWM (mentioned before) is controlled to track the maximum power point (MPP). The controller implements the perturb and observe (P&O) method, and identifies whether to increase or decrease the amplitude of the reference waveform to achieve MPP. It then increases/decreases the amplitude of the sinusoidal template, which is derived from the grid voltage. The operation in both the half cycles is based on the buck–boost principle, hence it is possible to operate the proposed configuration even with asymmetric operating principle. During the negative half cycle, the operating modes are similar, i.e. employing the buck–boost principle.. This is a desirable yet unacceptable proposition on account of the asymmetry it introduces between the positive and negative half cycles because the topology does not support distinct buck and boost operations during the negative half cycle.

Salient Features of Proposed topology

Features of Proposed topology are:

- It meets the double grounding requirement.
- Even under partially shaded conditions, there is no probability of injecting dc component into the grid.
- It has a single buck–boost inductor and uses the same operating principle (as that of a buck–boost converter) inboth the halves of the ac cycle. As a result, a symmetrical grid current with low THD and dc component is obtained.
- It uses only one PV string as the input source, which is used in both halves of the ac cycle. Due to this, the ripple in the voltage of the input capacitor C_{in} is less, leading to the extraction of more average output power.
- The proposed topology is more suitable in effective utilization of the PV array.
- It can be used irrespective of the PV voltage being greater or smaller than the grid voltage amplitude. This feature renders it suitable for places where the environmental conditions vary over a wide range or the array is likely to receive nonuniform solar insolation .
- All the features like MPPT control, inversion, and voltage transformation are encompassed into a single stage.
- It uses fewer components, and is therefore, more compact

Design of Components

In the proposed inverter the design of various components are needed for generating a sinusoidal grid current, which is in phase with the grid voltage. The design formulae for different components are

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shown.

Design of Inductor L

The design of the buck–boost inductor should ensure DCM operation of the inverter under all conditions of temperature and peak insolation levels. The inductor should also be able to handle the maximum energy corresponding to the peak power rating of the PV array. The value of the inductance is obtained for the boundary condition (critical conduction mode), i.e., for the operation on the boundary of DCM and CCM.

The current injected into the grid is in phase with the grid voltage ($V_g = V_{gm} \sin \omega t$, where V_{gm} is the amplitude, ω is the angular frequency, and t is the time), the maximum power is injected into the grid at the time when the grid voltage is at its peak (i.e., ωt=90◦). Thus, the design for the inductor should be in accordance with the current, voltage, and power values at that instant. The maximum power obtained from the PV string is given by,

$$\mathrm{Ppv} = \mathrm{Vpv} * \mathrm{Ipv} \quad (4)$$

Where,
V_{pv} = output voltage of PV array
I_{pv} = output Current of PV array
assuming a lossless inverter, the maximum power injected into the grid is

$$P_{gm} = \frac{V_{gm}}{\sqrt{2}}\frac{I_{gm}}{\sqrt{2}} = V_{PV} I_{PV} \quad (5)$$

The energy Transferred to the grid during this period is

$$\mathrm{E_{max}} = \mathrm{V_{gm} I_{gm} T_{s.}} \quad (6)$$

During the ON Period

$$\mathrm{T_{ON}} = \frac{\mathrm{L_1 I_{peak}}}{\mathrm{V_{PV}}} \quad (7)$$

During The OFF period

$$\mathrm{T_{OFF}} = \frac{\mathrm{L_1 I_{peak}}}{\mathrm{V_{gm}}} \quad (8)$$

I_{peak} = Peak Inductor Current
L_1 = Inductance Value for for the critical Conduction Mode.
Calculating and putting the values of E_{max} *and* P_{gm} in the above equation we get the value of inductor in critical conduction mode is,

$$\mathrm{L_1} = \frac{0.25\mathrm{T_s}}{\mathrm{V_{PV} I_{PV}}}\left[\frac{1}{\mathrm{V_{PV}}} + \frac{1}{\mathrm{V_{gm}}}\right]^{-2} \quad (9)$$

The value of critical value of inductor is obtained from the PV string parameters, the grid voltage and switching frequency.

Design of Filter Capacitor

The value of filter capacitor is obtained by equating the energy released by the inductor $L1$ and the energy received by the capacitor Cf . If ΔV is the ac voltage ripple on Cf, at ωt = 90◦, the energy balance between Cf and $L1$ is given by

$$\frac{\mathrm{L_1 I_{peak}^2}}{2} = \frac{\mathrm{C_f}}{2}\left[\left(\mathrm{V_{gm}} + \Delta\mathrm{V}\right)^2 - \left(\mathrm{V_{gm}} - \Delta\mathrm{V}\right)^2\right] \quad (10)$$

And

$$\mathrm{C_f} = \frac{\mathrm{I_{peak}^2 L_1}}{4\mathrm{V_{gm}}\Delta\mathrm{V}} \quad (11)$$

From above value of filter capacitor and total switching time,

$$\mathrm{C_f} = \frac{\mathrm{T_s^2}}{4\mathrm{L_1 V_{gm}}\Delta\mathrm{V}}\left[\frac{1}{\mathrm{V_{gm}}} + \frac{1}{\mathrm{V_{PV}}}\right]^{-2} \quad (12)$$

Which gives the value of C_f in term of L_1, grid voltage, PV string parameters, switching frequency and acceptable high frequency AC voltage ripple, superimposed on sinusoidal capacitor voltage.

Design of Filter Inductor

The filter inductor can be obtained as

$$\mathrm{L_f} = \frac{1}{\omega^2 \mathrm{C_f}} = \frac{1}{(2\pi \mathrm{f_c})^2 \mathrm{C_f}} \quad (13)$$

Where
Fc= is the cut-off frequency,
f_s= switching frequency
Cut-off frequency is much less than the switching frequency at which the switch S1 is operated.

Design of Decoupling Capacitor

$$\mathrm{C_{in}} = \frac{\mathrm{P_{pv}}}{4\pi \mathrm{f V_{pv}}\Delta\mathrm{V_{pv}}} \quad (14)$$

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Hence,

$$C_{in} = \frac{I_{pv}}{4\pi f \Delta V_{pv}} \quad (15)$$

Where
f = is the frequency of the grid voltage
ΔV_{pv} = is the amplitude of the ripple voltage across the decoupling capacitor connected across the PV array.

Results and discussion

Table.1. System Parameters

Components	Value
Buck – boost inductor (L_1)	210 μH
Filter capacitor(C_f)	66 μF
Filter inductor(L_f)	20 mH
DC link capacitor(C_{in})	4500 μF
Carrier frequency(f_c)	750 Hz
Switching frequency(f_s)	10 KHz
Grid voltage(V_g)	230 V

A detailed system as shown in Fig.5. has been modelled by MATLAB/SIMULINK. However, in the positive cycle of grid voltage, instead of operating the circuit as a buck–boost converter, the circuit is operated as a buck converter when the PV voltage is greater than the grid voltage and as a boost converter when the grid voltage is greater than the PV voltage. The Simulation diagram for the proposed system is shown below:

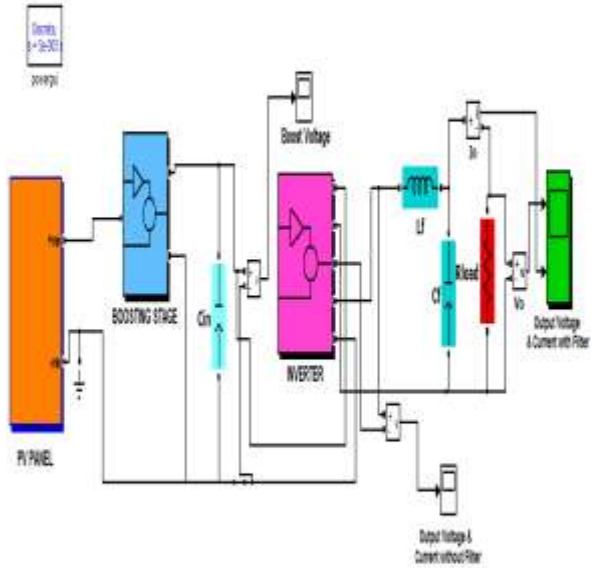
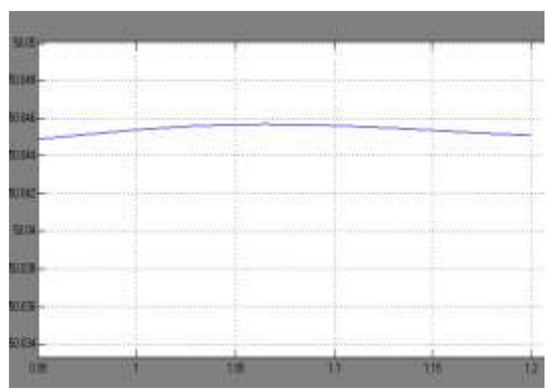


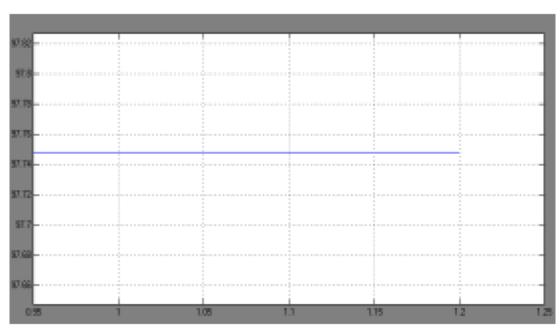
Figure-6: Simulation for Transformer-less grid connected PV inverter

Different results have been observed for various load conditions.

System with Resistive Load



(a) PV Voltage



(b) Boost Voltage

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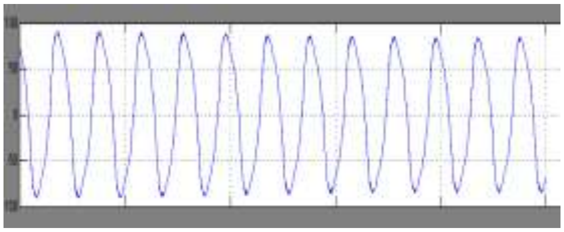
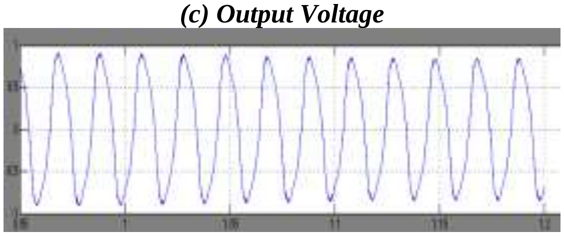


(c) Output Voltage

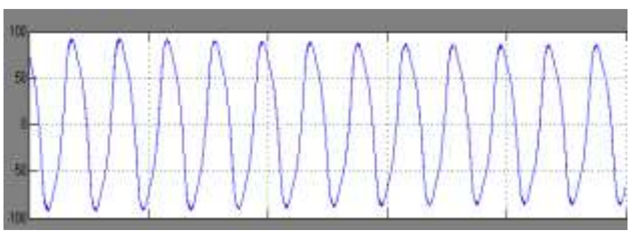


(d) Output Current

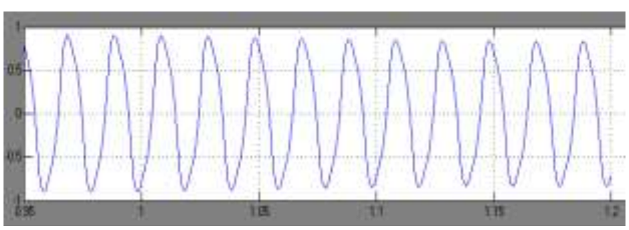
Figure-7: (a),(b),(c),(d) Simulation results for resistive load with 50V input PV voltage

This output show the performance of the inverter. The figures show asymmetrical distortion-free, sinusoidal output current that is in phase with the output voltage. The output voltage is 85V and output current is 0.8A for 50V input PV voltage.

System with RL Load



(a) Output Voltage



(b) Output Current

Figure-8: (a) Output Voltage (b) Output Current for RL Load

The output voltage is 86V and output current is 0.84A for 50v input PV voltage. Here output voltage and output current are in phase with each other.

Inductor Current

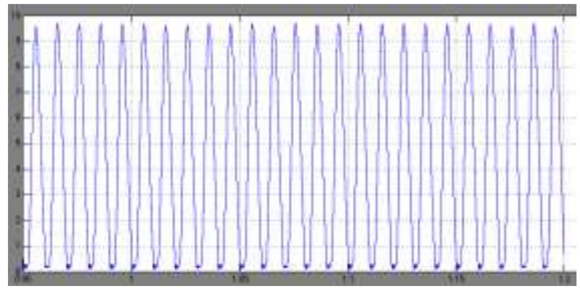


Figure-9: Simulation results showing inductor current waveform in boosting stage

From fig.9. it can be seen that Inductor current is non-negative and can have high peak value depending upon available power.

Conclusion

Transformer-less grid-connected PV inverter, uses only one PV source, a single buck–boost inductor, and a decoupling capacitor that are shared in both the half cycles. This topology is capable of resolving the double grounding problem, have been reviewed. Most of the existing transformer-less topologies achieve double grounding by using a split PV source. A compact PV–grid interface, which operates with a single PV source and has the capability of double grounding has been proposed, and developed. It is observed that the maximum voltage that can develop on the ungrounded conductor is limited to the PV array output voltage, and hence, the topology exhibits a good safety feature. In such a topology, PV maximum power is delivered into the grid with high efficiency, small size, and low cost. However, to fulfil grid requirements, such a topology requires either a step-up transformer, which reduces the system efficiency and increases cost, or a PV array with a high dc voltage. The analysis of the working principles and computer simulations of the operation for this inverter have proved its feasibility for dc-ac conversion in PV applications.

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