An Interleaved Boost converter Based Stand-alone PV-Battery System for Rural Lighting Applications.

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Abstract: This paper describes about utilizing the interleaved boost topology for incorporating two power sources and maintaining voltage regulation at the output terminal. Primary input source is chosen to be PV panel and secondary input source to be a battery. The converter have partial isolation between input and output ports, since the converter uses high frequency transformer the size of the can be reduced. The system topology is derived from a conventional boost converter. Interleaved boost converter improves efficiency and reduces current ripples which makes the topology best suitable for renewable enrgy applications, additional advantage is that the battery source can be replaced with another renewable or non-renewable energy source such as wind or fuel cell with proper controller making the converter to operate in hybrid mode. The DC to DC converter utilizes pulse width modulation (PWM) and phase shift control for energy management and power transfer from input ports to output port respectively, An H-Bridge inverter utilizing unipolar pulse width modulation control scheme is connected at the output terminal of the DC-DC converter. The goal is to drive a load of 100 W and maintain 230 V at the output. Moreover the theoretical values are verified by Matlab Simulink software.

***Index Terms* - Interleaved Boost, three port converter, Pulse width modulation and duty ratio, renewable energy source, controller, unipolar control scheme, H-bridge inverter, output voltage regulation.**

I. Introduction

Technology to utilize the forces of nature for doing work to supply human needs is as old as the first sailing ship. But attention swung away from renewable sources as the industrial revolution progressed on the basis of the concentrated energy locked up in fossil fuels. This was compounded by the increasing use of reticulated electricity based on fossil fuels and the importance of portable high-density energy sources for transport – the era of oil. Renewable energy sources like solar, wind etc. are in the focus of academics and industries because day by day the non-renewable energy sources are reducing [1]. Since clean and safe renewable energy sources are available engineers have been working on various types of power converters mostly step up converters. Since the renewable energy sources are intermittent in nature to balance the deficient power energy storage units has to be employed. Multiport port converters have gained very much attention recently since the shift from conventional power sources to renewable power sources have made drastic changes in engineering as well as commercial field. Basic functionality of the multiport converter is to deliver required power when primary energy source fails to deliver the load demand, based on this various multi input topologies have been investigated. Multiple energy sources hybridization can improve various system performance aspects such as cost, isolation, and system dynamics. Hence, hybrid energy conversions may be employed in situations with lower average power demand and higher load dynamics. As a result, combining renewable energy resources and controlling their power flow are complex issues.

According to the system requirements various converter topologies are proposed in [2]. Since multiport converter uses more than one input power source galvanic isolation is required. This will help extending the input voltage range and power delivery. Converters with galvanic isolation has basically two categories – multiple converter conversion and multiple port conversion. In multiple converter conversions, converters are connected in series or in parallel to cascade sources and loads whereas in multiple port conversion, devices and circuits in various ports such as rectifiers, transformers and output filters are shared. Therefore such converters have been receiving more attention in recent years [3]. Since isolation is essential it is better to go with magnetic coupling methods such as transformer windings or individual transformers. Multiport converters are harvested from pulsating switching cells that includes half bridge, full bridge and their combinations.

The overall disadvantage of the three port converter is that the higher number of switches and individual converters for incorporating other power sources, also the complex control method which includes the pwm and phase shift control. Taking these points into account a number of three port bidirectional dc to dc converters with complete isolation between the ports are proposed in [4], as mentioned earlier larger number switches increase the cost and size of the overall system. Since the size of the converter is increasing with increase in input and output ports partially isolated converters are proposed in [5]. While partial isolation is provided not all the ports are isolated only input and output ports are isolated, there is no isolation between input ports which again brigs difficulty is designing the converter. While adding more power sources it is mandatory to be considered of transformer based isolation but when number of transformer increases the system becomes more bulky. It is important to design proper system when connecting two different types of power sources such as voltage fed and current fed, Ex,. Solar, wind generator etc. For this reason, partially isolated multiple input converters, i.e. only some input/output ports are isolated, have been attracting, because of their simple structure and easy control. Dual input dc to dc converter with BHB and FB switching cell was presented in [6]. Here, two independent transformers are used to integrate current fed and voltage fed sources, this comes in the category of bulky systems.

A wide gain unidirectional two port resonant converter was derived in [7] by combining a BHB (Bidirectional H-bridge) with an LLC resonant tank. This converter can be extended to a TPC by replacing low voltage dc bus with voltage source. However the control scheme that employs decoupled control would become complex due to the presence of LLC circuitry. In [8] a perspective of deriving three port converter is described. Magnetization inductance is utilized as the power interfacing element between ports of an isolation transformer, the converter provides complete isolation but it has a drawback of limitation of converters output power capability. Another three port converter topology is derived from improved flyback forward converter, the proposed converter utilizes phase shift and duty cycle control scheme like other multi input converters. This converter make use of the leakage Inductance of coupled inductors in order to transfer power to output port. In this method, the power delivering capability is limited by flyback operation. By integrating a boost converter into a phase shift full bridge buck converter two types of TPC are formed. Such TPC has non isolated input port which connects with renewable energy sources and these input ports are isolated from load. Some TPC are proposed in [9] and [10], to have perfect power sharing between input sources and deliver the load power both duty cycle and phase shift control is to be incorporated. These converter topologies have output dc inductors output diodes will under hard switching condition this will affect the converter efficiency and will reduce power transfer to output port. In [12] a full bridge three port converter is designed out of a interleaved boost full bridge and a bridgeless rectifier was proposed this topology also uses phase shift and pulse width modulation control technique. The phase shift operation is limited to 180 degree which the primary switching legs can reduce the current ripple and current stress in input ports. Phase shift between primary and secondary switches is utilized for output regulation. Therefore, two extra switches are needed in the secondary which increases circuit complexity. Operation of body diodes of secondary MOSFETs under hard switching condition generate reverse recovery losses. Rectifier diodes achieve zero current switching ZCS due to the presence of ac inductor current.

The goal of this work is to design a three port convert from a conventional boost converter and to make the topology usable for rural lighting application by purely relying on renewable energy sources, in this study the primary input source is chosen as PV module and the secondary input source as battery. Even though transformer size have effect in size of the converter the designed transformer is of high frequency, as a result number of windings are reduced. The design values are verified with simulation results.

II. Methodology

As it is decided to rely completely on renewable energy sources the chosen PV panel is of 120 W, 34 V with two series connected modules and the battery is of 12 Volt 7ah. In order to reduce the size of the converter partial isolation is provided between input and output ports with the transformer. The construction of the three port converter is listed in steps below.

1. Design of boost converter.
2. Interleaving the designed boost converter with 180 degree phase shift.
3. Providing additional switches for secondary input source.
4. Design of high frequency transformer and connecting it to the interleaved legs for output port.
5. Connecting bridge rectifier to the transformer secondary windings with leakage inductance.
6. Testing the converter for 400 V DC output.
7. Design for unipolar pwm operated inverter LC filter.
8. Testing the whole system for 100 W, 230 V, AC load.

III. Block Diagram

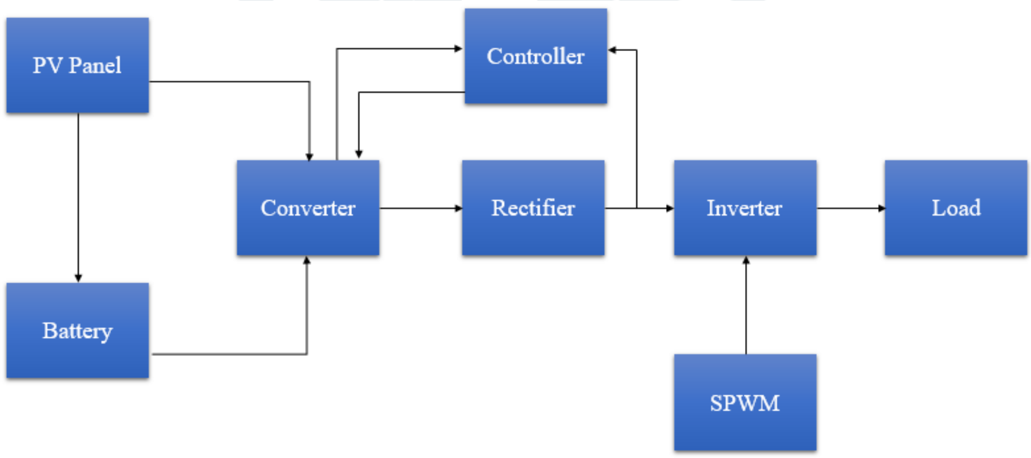

Fig.1: Block diagram of the complete system

The two inputs which are the PV panel and battery are interconnected through a voltage sharing capacitor to the converter, output port is isolated from the two inputs through the high frequency transformer. Based on the renewable energy available the converter is designed to operate under different modes which is described in the coming sections. Since the PV panel is the primary source of power to maintain constant MPP voltage across the voltage sharing capacitor a feedback loop is given to the controller with reference voltage of MPP voltage of PV panel. Based on the error value generated by the PI controller the pulse width of the switching pulses are varied, The converter provides 34 V pulsating high frequency dc voltage to the transformer primary windings the secondary windings provides 800 V dc to the rectifier. To maintain voltage regulation at the output port of the rectifier another control loop is provided with PI controller with reference voltage of 400 and the rectifier output is given to the inverter which is working by the unipolar switching scheme. In order to control the power among the two inputs and the load and thereby balance the power between the different energy sources, two control loops are active at any time. The output port regulation loop is employed to regulate the load voltage by the phase-shift angle ∅. If the renewable input power is smaller than the required power at the output port, the storage unit will compensate the power difference automatically. On the other hand, if the input power is bigger than the power required at the load terminal, the energy surplus is used to charge the energy storage element by inverting the power flow direction at this port. The SOC of the energy storage element is always being monitored, and when it is above or below its recommended values.

IV. CIRCUIT DESCRIPTION AND OPERATING PRINCIPLES

The three port circuitry is shown Fig.2 consist of two input inductors L_1 , L_2 and sum of leakage auxiliary inductance of transformer L_{ac}. Four power MOSFET $M_1 – M_4$ and a high frequency transformer with turns ratio 1:n and an H-bridge rectifier at the secondary side of the transformer. The switches $M_{1 – }M_4$ are driven with complementary gate signals. V_1 and V_2 are the input voltages to the three port converter, iL_1 and iL_2 represents the input inductor currents D_1 - D_4 are the rectifier diodes.Voltage between the midpoints of the bidirectional interleaved boost switching legs is represented as vL_{ac}. Duty cycle and phase shift angle are adopted as control variables simultaneously in order to decouple V_1 and V_2 and to regulate the output voltage accurately.

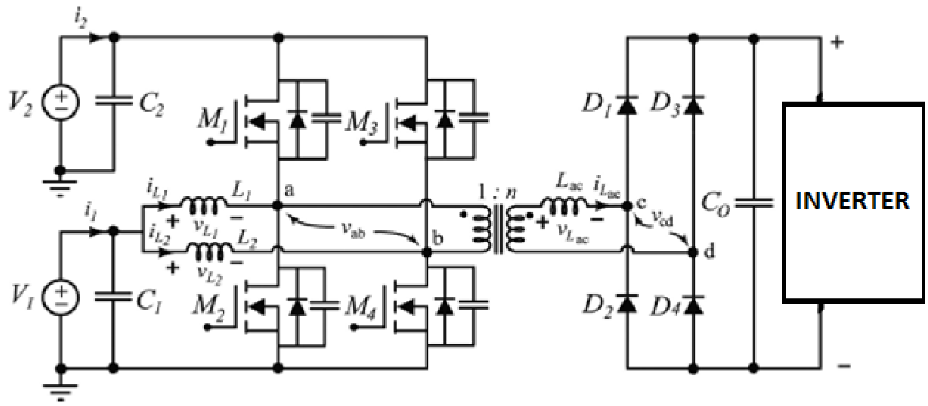

Fig..2: Three port converter

Due to the operation symmetry the variation of the phase shift angle $\varphi\ is: 0 < \varphi < \pi$. Depending on the duty cycle and its relationship with phase shift angle there are three operational cases existing, based on the current shape of the inductor, which can be classified as completely demagnetized, partially magnetized and completely magnetized. Duty cycle adjust the power among the two independent sources, and phase shift angle is employed to regulate the power flow to output port by operating phase shift with duty cycle control and also according to the availability of the renewable energy source and the load demanded, the proposed converter can operate in various modes: DI mode where load demand is higher than source power, energy storage element delivers the extra energy to the load. DO mode where input power is higher than load demand, energy storage element store excess energy and in SISO mode where power transfer occurs between two inputs or from one of the inputs to the output port.

The inverter connected at the rectifier output side utilizes unipolar sine pulse width modulation technique, it have two reference signals with 180 degree phase shift. The carrier signal is a triangular wave and required pulses are obtained for the inverter switches. The load connected to the inverter is of 100 W, 230 V rated, in unipolar switching scheme not all the switches are turned on at the same time this will reduce switching losses. The e inverter output voltage switches between either between zero and $+V_{dc}$ during positive half cycle or between zero and $–V_{dc}$ during negative half cycle of the fundamental frequency thus this scheme is called unipolar modulation. The unipolar switched inverter offers reduced switching losses and generates less EMI. On efficiency grounds, it appears that the unipolar switched inverter has an advantage. Fig. 3 shows the equivalent circuit at their respective time intervals and their waveforms.

During the first interval from $[0\text{-}t_1]$ as shown in Fig.3 (a) switches M_2 and M_3 are turned on simultaneously there for inductors L_1 starts charging L_2 starts discharging, the voltage at the terminal Va will be zero and the voltage at V_b is V_2. The voltage across mid points a and b which is $V_{ab} = V_a – V_b$ is $–V_2$, as a result the AC inductor L_{ac} charges negatively. The drop across L_{ac} will be as and satisfies,

$$Vcd - nV2(drop\ acress\ Lac) = iLac \times XLac \qquad ()$$

$$V = \frac{Ldi}{dt} = L\frac{i_{Lac}}{\emptyset T} \qquad (1)$$

$$V_{cd} - nV_2 = Lac\frac{di}{dt} \qquad (2)$$

$$Vo - nV_2 = L_{ac}\frac{iL_{acpk}}{\emptyset T} \tag{3}$$

$$\therefore iL_{acpk} = \frac{-nV2 + Vo}{Lac} \cdot \emptyset T \tag{4}$$

Where the phase-shift angle normalized to the period is defined as,

$$\emptyset = \frac{\varphi}{2\pi} \tag{5}$$

During the second interval from [t_1-t_2] in Fig.3 (b) at t_1 switch M_4 is triggered on while switch M_2 is still in conducting. Inductor L_1 was in charging condition already now when M_4 is triggered inductor L_2 starts charging. Voltage at the points V_a and V_b are zero there for voltage at the midpoints of the bridge will zero, but the inductors will be still discharging through the diodes and the inductor L_{ac} will be discharged to zero with a slope determined by the output voltage V_o. Defining β as the interval [t_1-t_2] normalized as the period in (9) the Lac inductor discharge interval can be calculated.

$$Vo = \frac{L_{ac}di}{dt} = \frac{L_{ac}iL_{acpk}}{\beta T} \tag{6}$$

$$Vo = \frac{L_{ac}}{\beta T}\left[\frac{-nV_2 + Vo}{L_{ac}} \cdot \emptyset T\right] \tag{7}$$

$$\therefore \beta = \frac{nV2 - Vo}{Vo} \cdot \emptyset\,, \qquad \Delta T = t_1 - t_2 = \beta \cdot T \tag{8}$$

When the ac inductor current reaches zero, the bridge rectifier diodes stop conducting, which concludes the second interval. During interval [$t_2 - t_3$] inductors L_1 and L_2 will continue being charged as represented in Fig.3 (c) until switch M_2 is triggered off at $t_{.3}$. Switches M_2 and M_4 are still conducting the voltage at the midpoints of the bridge is zero since V_a and V_b are zero. Since the inductor L_{ac} is completely demagnetized in this interval there in no power flow from input side to output side. The equivalent circuit for interval from [t_3-t_4] are shown in Fig.3 (d), it can be observed that the circuit operation is identical to that of circuit that operating in the interval at [0-t_1]. Switches M_1 and M_4 are turned on simultaneously there for voltage at the point V_a is V_2 and voltage at the point V_b is 0. The bride voltage at the midpoints will be V_{ab} is V_2. As a result the inductors charges opposite of interval [0-t_1] such as inductor L_1 starts discharging from peak value and inductor L_2 is already in charging condition and will charge till t_4.

From the key waveforms shown in Fig.2 it can be seen that the phase shift value Ø should be smaller than duty cycle D and the compliment of (1-D) as expressed by

$$\emptyset < \min[D, (1 - D)) \tag{9}$$

Using equation (1)-(9), the output voltage of the converter can be obtain as,

$$Vo = \frac{nV_2}{k} \cdot \emptyset\left(-\emptyset + \sqrt{\emptyset^2 + 2k}\right) \tag{10}$$

Where the parameter k is a dimensionless magnitude defined by the inductance, the output load, and switching frequency as shown

$$k = \frac{2L_{ac}}{R_L T} \tag{11}$$

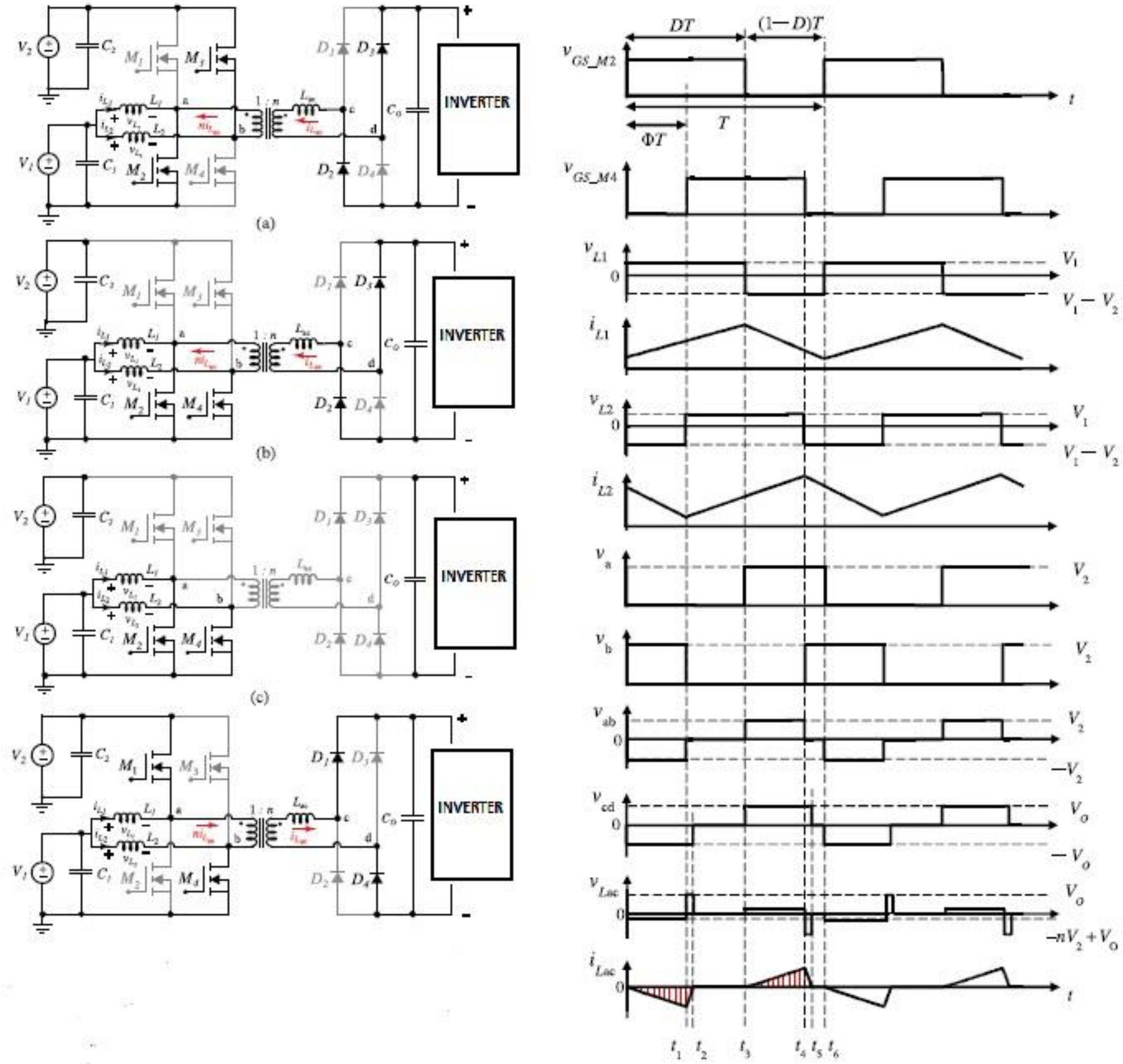

Fig.3: equivalent circuits and corresponding waveforms.

The relation between V_1 and V_2 is obtained from the below stated equations,

$$V_1(D) = (V_1 - V_2)(1 - D)\,T \tag{12}$$

$$= -V_1(1 - D)\,T + V_2(1 - D)\,T \tag{13}$$

$$V_1(DT + T - DT) = V_2(1 - D)\,T \tag{14}$$

$$V_1.T = V_2(1 - D)T \tag{15}$$

$$\therefore V_2 = \frac{V_1}{1 - D} \tag{16}$$

It is noteworthy that in this operation mode the energy transferred to the output port does not directly depend on the duty cycle. Therefore, in the completely demagnetized operating mode the power flow fromV_1 and V_2 to the output port will be entirely controlled by $\emptyset$. If the inductor current iL_{ac} does not decrease to zero before M_2 is triggered, the ac current is partially magnetized In the same way, if the iL_{ac} does not reach zero before M_2 is turned off, the ac current becomes fully magnetized. Out of these three operating modes it can be inferred that partial and fully magnetized, allow to transfer higher power to the output than the completely demagnetized counterpart. However, during the time intervals in which the inductor current does not reach zero, [0-t_1] in the partially magnetized mode and [0–t_1] and [t_3– t_4] in the fully magnetized mode, the same current flowing through the ac inductor is flowing in the primary side and, therefore, sent back to the source V_2. Therefore, when the input voltage and the inductor current are not in phase reactive power is generated, which results in higher current stress in the converter primary side and, therefore, higher losses than in the completely demagnetized operating mode. Partially and fully magnetized operations allow for higher power transfer for the same inductor value than the completely demagnetized mode. This is due to the increased charge per switching cycle delivered to the output capacitor, compared to the completely demagnetized inductor current. However, as discussed before, these operating modes move the current stress from the converter secondary to the primary side due to the generated reactive power, which acts in detriment of the efficiency in step up applications. Moreover, when the converter leaves the completely demagnetized mode, the converter output voltage is no longer controlled solely by the phase-shift angle. This characteristic increases the difficulty in the implementation of the dual power flow converter control strategy. Considering all the aforementioned characteristics, completely demagnetized ac inductor current is the preferred operation mode.

The basic inverter circuits performs the task of converting DC input power to AC output power. Inverter can be widely classified based on many parameters but considering one of them based on the arrangement of the power electronic switches are Half Bridge Inverter and Full bridge inverter. A Full bridge inverter has two legs consisting of two semiconductor switches in each of them with the load connected at the center points of the two legs. Four semiconductor switches S1, S2, S3, S4 are arranged with the load connected at the midpoints of the two legs hence forming the letter H, so is the name H-Bridge inverter. Feedback diodes are provided for all the switches. DC source Vs is supplied to H-Bridge. The switches s1, S2, S3, S4 can be switched in three different sequences. When S1 and S4 are turned on +Vs is obtained at the output, When S2nand S3 are turned on –Vs is obtained at the output, When S1 and S2 or S3 and S4 are turned on together zero voltage is obtained at the output. In SPWM (Sinusoidal Pulse Width Modulation) two signals are compared. The Modulating reference signal is sinusoidal and the carrier wave is triangular. Gating pulses are produce by comparing the two signals and the width of each pulse is varied is proportion to the amplitude of the sine wave . The frequency of the reference signal determines the inverter output frequency and the reference peak amplitude controls the modulation index and the RMS value of the output voltage.

V. SIMULATION RESULTS

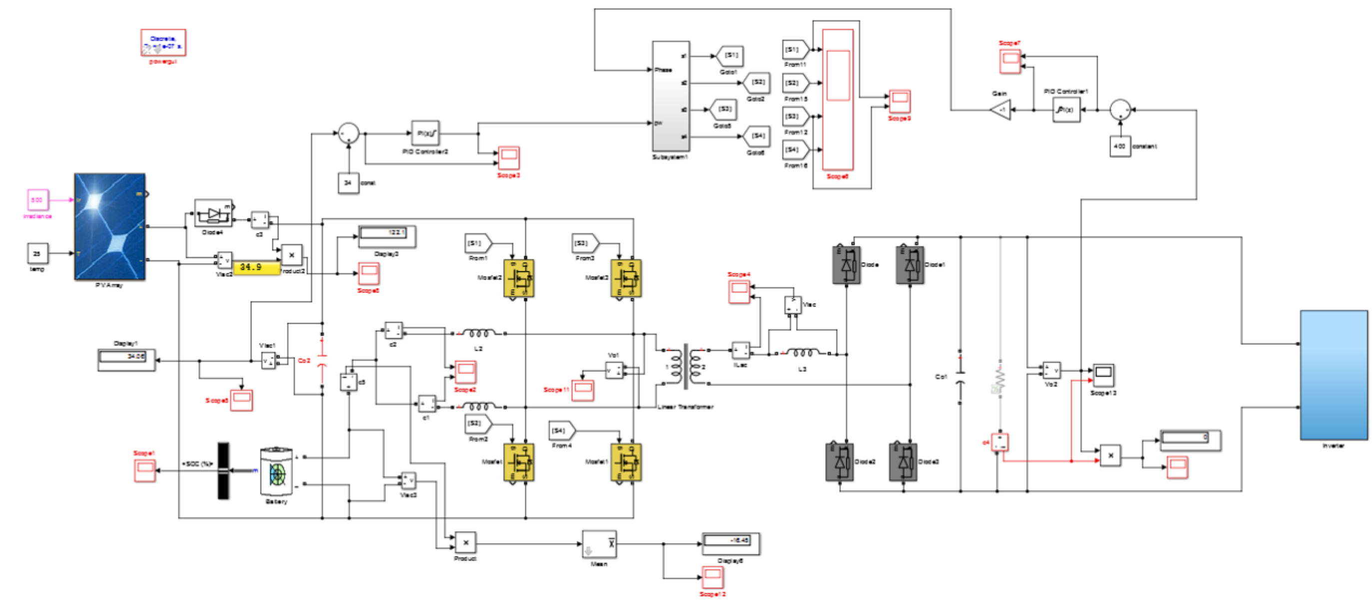

Fig.4: Converter coupled with single phase inverter.

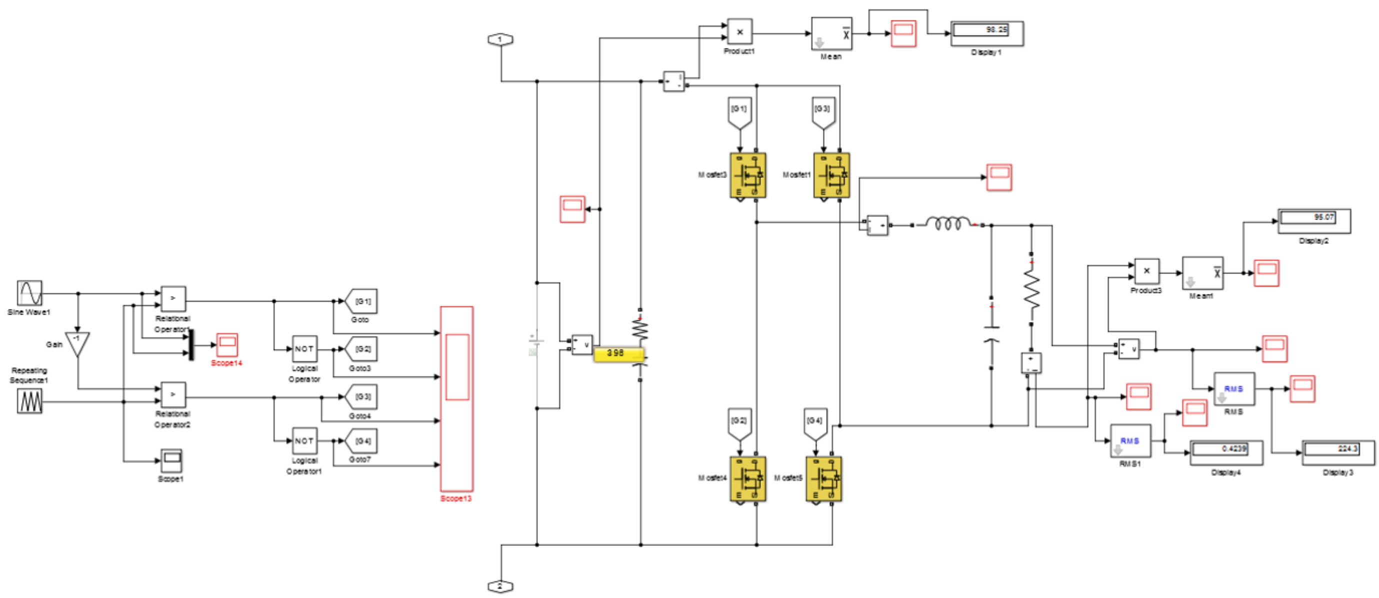

Fig.5: Single phase inverter with unipolar PWM switching scheme.

The proposed converter is simulated and the test results with circuit parameters are shown below. Here, dual output mode is simulated where the output power requirement is met by the primary input source. The battery is in full charge condition so it is not being used when load power requirement is met by PV alone. V_{bat}=12 V, V_{pv}=34 V.

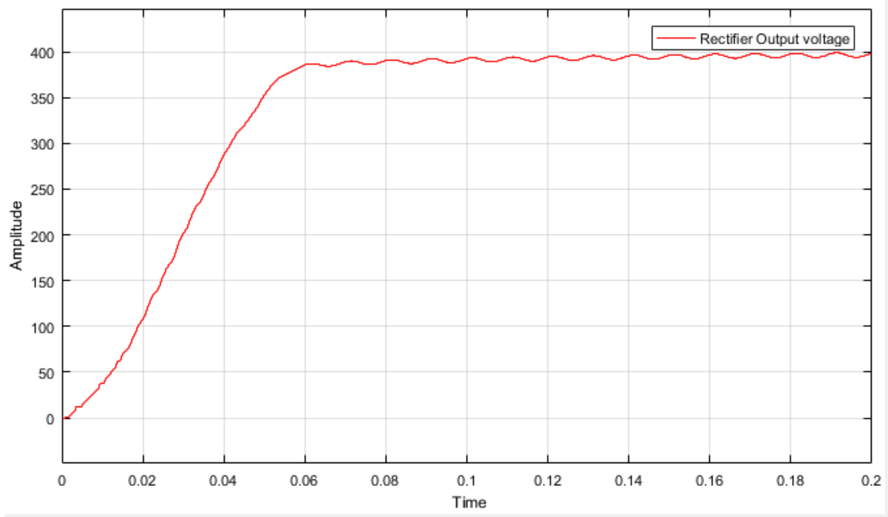

Fig.6: Output voltage of bridge rectifier. V_{rec}= 400 V

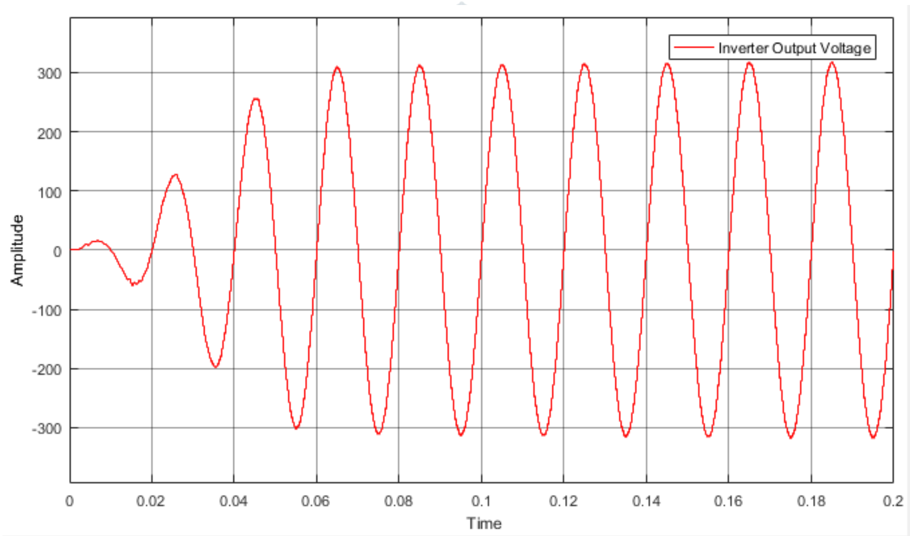

Fig.7: Output voltage of single phase inverter at 230 V RMS.

Test results for different solar irradiations.

Table.1: Test results.

Irradiance (W/m^2)	PV Voltage (V)	PV Power (W)	Battery Power (W)	Output Power (W)
100	34.82	22.44	80	94
200	34.82	48.13	55.25	94.81
300	34.83	72.94	31.46	94.85
400	34.83	97.6	7.434	94.98
500	34.83	122.1	-16.45	95.07
600	34.83	146.4	-39.86	95.1
700	34.83	170.4	-63.46	95.13
800	34.83	194.8	-82.63	95.14
900	34.83	217.4	-109.2	95.14
1000	34.83	240.4	-131.2	95.14

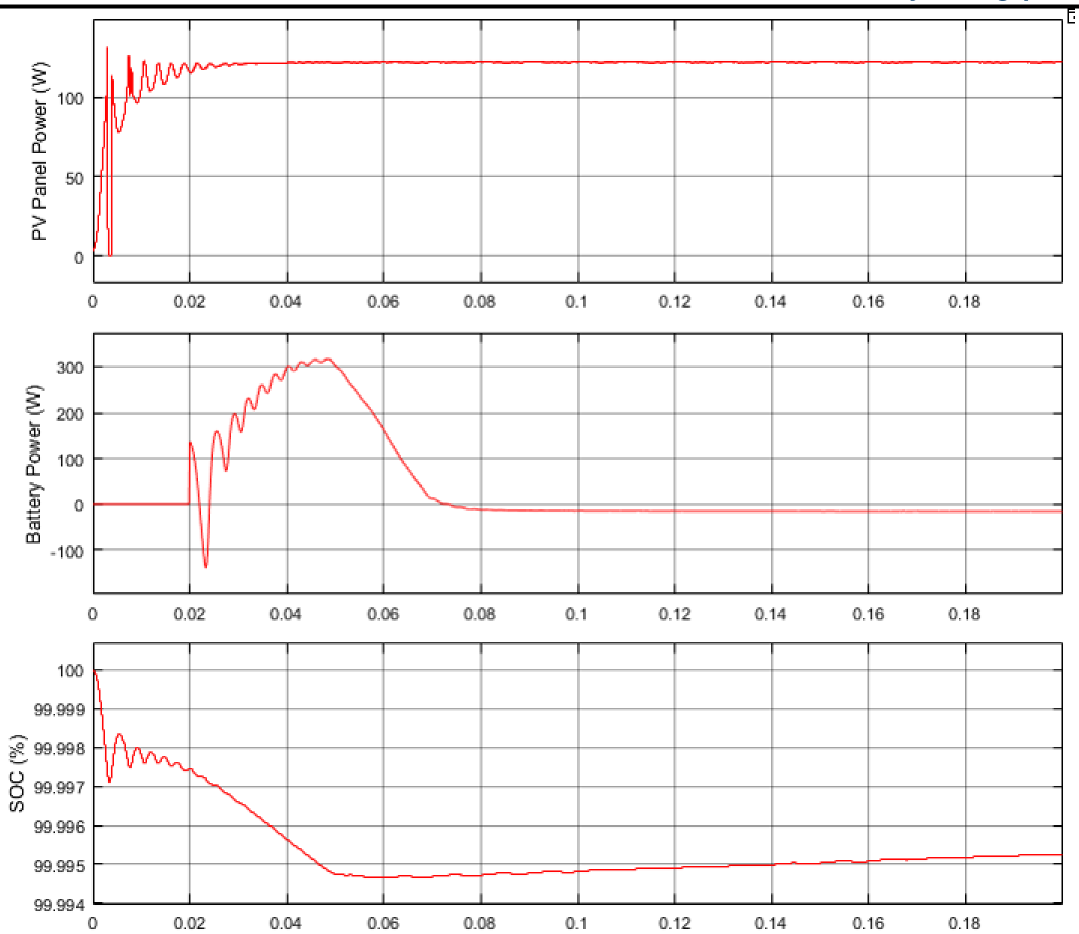

Fig.8: Input sources power when Pv irradiance is maximum and SOC of battery.

Since the proposed converter utilizes two series connected solar panel of 120 volts at 500 W/m^2 irradiance the load power requirement is met by the PV panel alone, below the average irradiance value both the input sources are delivering power to the load. It can be observed from the table that battery does not supply after 500 W/m^2 irradiance. The simulation is done with SOC of battery 100 % so the battery neither charges nor discharges at this point. The simulation is run for 0.2 seconds.

Design values of circuit elements

Table.2: Component specifications.

Component	Design Value
V_{in}	34 V_{PV}, 12 $V_{battery}$
V_{out}	230 V RMS
Transformer	1:n
L_1, L_2, L_{ac}, L_{filter}	110µH, 110µH, 2000µH, 10µH
C_{in}, C_{rec}, C_{inv}, C_{filter}	5000µF, 150µF, 15µF, 3µF
F_S	20KHz

VI. Conclusion

In this paper an interleaved boost converter based on three port converter coupled with a single phase inverter is proposed. The converter is built on conventional boost converter. The step by step working of the converter with their intervals are explained in detail in this paper. The design values are verified with simulation results. In order to control the power flow between the different ports, a duty cycle and phase-shift control scheme is adopted. The duty cycle is used to control the power flow between the two independent sources, whereas the phase-shift angle is employed to regulate the output voltage. The converter is designed for 100 W applications there for this converter is best suitable for lighting in rural applications. This converter eliminates the additional circuitry to charge the battery. The bidirectional nature of the converter can be utilized to charge and use the battery for different purposes. The symmetry of the converter can be edited to accompany non renewable energy sources and renewable sources with slight modification in the input side with isolation between input ports. The advantage of the proposed topology is that it can be dynamically modeled as individual converters, which makes it possible to design a control strategy with totally uncoupled control variables. This fact makes this topology a very interesting solution in renewable energy applications where an energy storage element is required.

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