Concordia University

Department of Electrical and Computer Engineering

ELEC 6461 - Power Electronics II

PV Based Nano-Grid integrated with battery to Supply Hybrid Residential Loads using single-Stage-Hybrid Converter

Team Member name	ID number
Zain Ali Bhinder	[redacted]

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ABSTRACT

Normally in a Nano-grid architecture, dedicated power converters for both dc and ac loads are used thus increasing the number of passive components and conductions losses. Here, a solar (PV) based Nano grid integrated with battery storage is presented which can be used to supply ac and dc loads simultaneously. The boost derived hybrid converter topology is used in this Nano grid which is realized by replacing the controlled switch of single switch boost converter with a voltage source bridge inverter. It also has an inherent shoot through protection in the inverter stage. It also reduces the number of conversion stages when compared with a conventional solar (PV) based systems to supply the ac/dc loads. A non-isolated buck-boost bidirectional DC-Dc converter is used for charging and discharging of the battery to support the Nano-grid. A suitable Pulse width modulation control strategy based on Uni-Polar sine PWM is implemented. The Converter is simulated in different modes of operation. The simulation is done using PSIM software. Simulation results show the suitability of the converter for the practical application.

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1 INTRODUCTION

1.1 Problem Statement

In this contemporary era, the world is focusing on controlling the environmental pollution. One of the major sources of this pollution is the use of fossil fuel for production of electricity. In the recent years, the demand of electricity has never been higher than before. So, to meet this high demand and to contribute in the reduction of environmental pollution, there is a need of such renewable system that can produce green energy (0 harmful gas emission). Solar energy is one of such kind that has gain significant importance in green energy production. As we know that the output of the photovoltaic panels used for solar power generation is DC. However, our homes are the mixture of AC and DC loads so there is a need of such system that can supply AC power to the AC loads and DC power to the DC loads. Boost derived hybrid converter is a bidirectional converter that provide such functionality in single stage with less losses.

1.2 Literature Review

With substantial advancements in the field of solar power use, the adaptability of standalone Nano grid topologies for smart home electric power systems has been improved. In these Nano grids, Photovoltaic (PV) panels serve as Distributed Generators and Batteries serve as Energy Storage Devices. The energy needs of today's smart homes are hybrid in nature, requiring both AC and DC power. PV-based nano grids are gaining popularity since they are simple to set up and provide a consistent source of electricity. The lighting load, fans, laptops, TV and other home appliances can be powered up by this system. On the other hand, huge PV systems have a greater installation cost and require a large energy storage devices (ESD).

The PV input varies a lot due to the non-steady behavior of solar electricity. In this regard, a DC-DC converter is used to extract the maximum power from a PV panel by using Maximum Power Point Tracking algorithm. To ensure the steady and continuous power supply to the load, ESDs must be integrated in a standalone Nano grid because of the intermittent nature of solar and demand and supply mismatch during day and night time. In the scenario, when PV panels are producing excess energy, then this energy is usually utilized to charge the batteries and in case when there is shortage or no power, then these batteries are discharged to serve the load.

The voltages and power ratings of smart residential systems are often modest since they rely on localized non-conventional greener energy sources (few hundred Watts). Separate converters for DC and AC outputs are required in a traditional topology, which necessitates complicated control algorithms to govern the output. Furthermore, the increase in passive components and number of converters will result in increased losses and reduced efficiency. Thus, A single stage hybrid converter that concurrently provides AC and DC loads is used to reduce complexity and losses. As opposed to dedicated converters for both DC and AC loads which use more passive components thus improving efficiency and cost of the converter. The figure below highlights the difference between dedicated DC and AC converters and single stage hybrid converter.

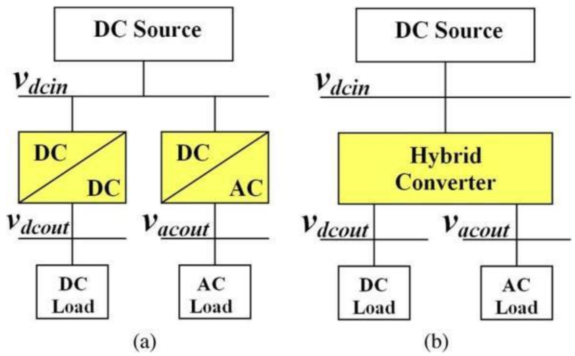


Fig 1. 1: (a) Conventional Design. (b) Boost Derived Hybrid Converter

2 Power Flow Modes

Solar applications require distinct AC/DC and DC/AC converters to support their AC and DC loads. The separate converters increase the circuit elements and increases no of control stages. The proposed BDHC converter caters this issue by having centralized controllers with single stage conversion. BDHC converter has three distinct power modes namely MPPT mode, power reference mode and battery supply mode which will be discussed step by step. Below is the block diagram for the proposed BDH converter.

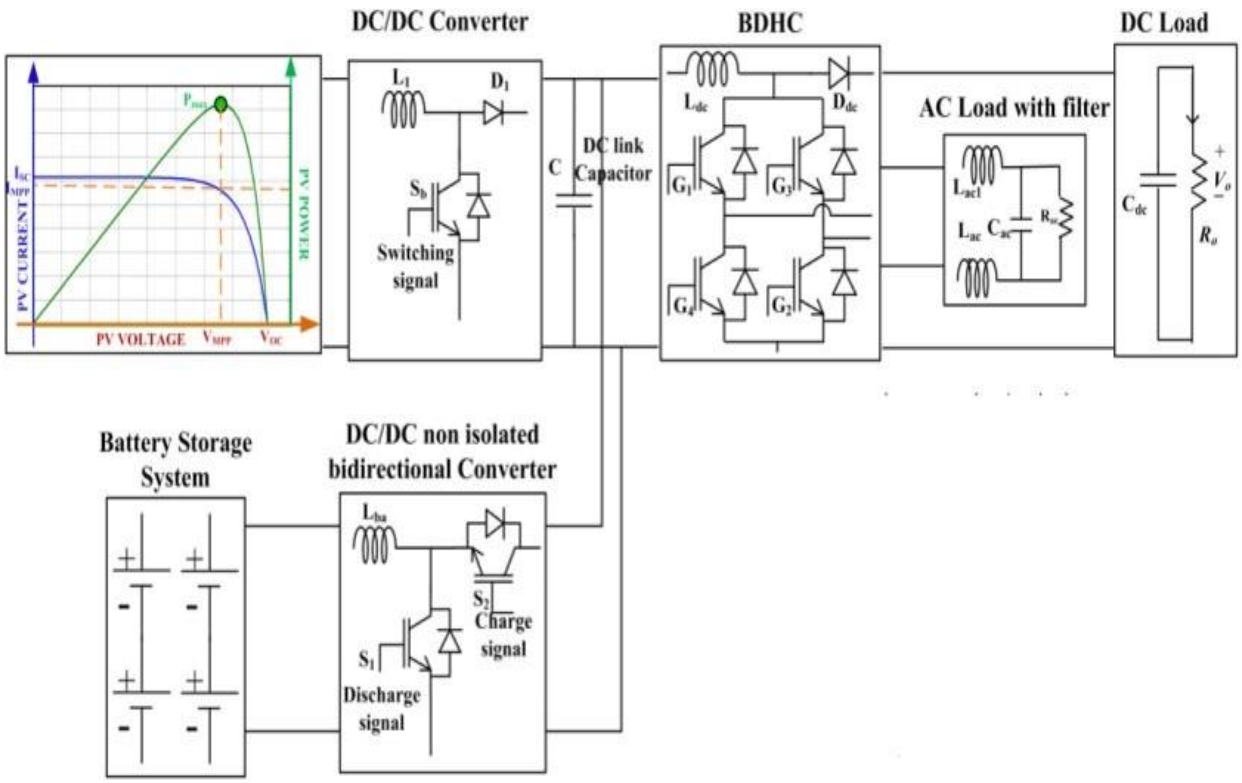


Fig 2. 1: Block diagram representation of Solar Photovoltaic system supplying AC and DC loads using BDHC

2.1 MPPT Mode

During this mode, three converters namely DC/DC converter, BDHC and non-isolated Bidirectional converter will be active to perform different functions. DC/DC converter will be used for implementing MPPT algorithm, BDHC will supply DC and AC load and Bidirectional converter to charge the ESD. In this mode, SPV system exceeds the power limit required by the load. The power from SPV is simultaneously distributed to supply both load as well to charge the battery. This mode uses MPPT algorithm to extract maximum SPV system power and uses BDHC converter to support AC and DC loads. The remaining power will be used to charge the battery through the bidirectional converter operating in the buck mode.

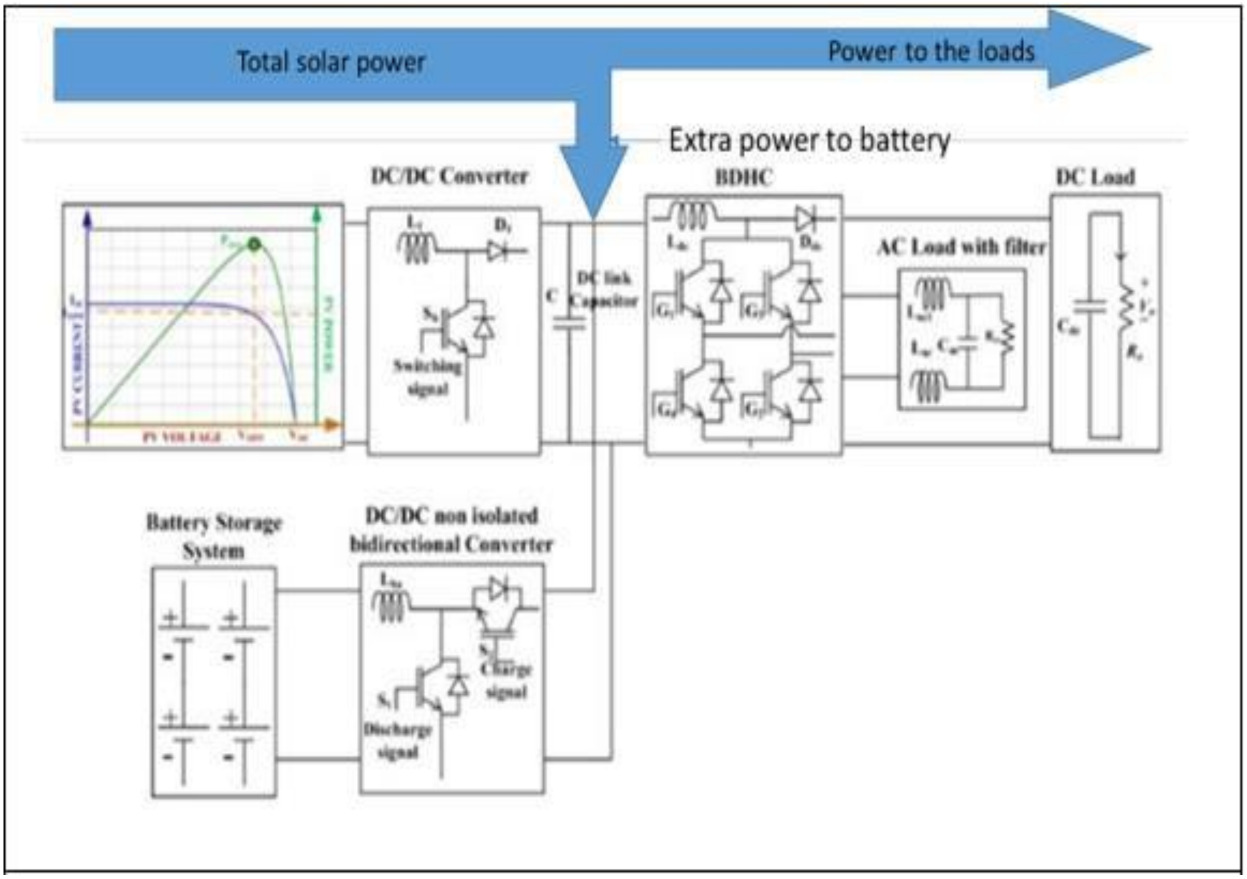


Fig 2. 2: Power flow representation in MPPT mode.

2.2 Power Reference Mode

After obtaining sufficient power in the MPPT mode such that the battery is fully charged up to its upper limit of the SOC, the Bidirectional will stop its operation and moves in to idle state. Now all the power from SPV system will be served to supply the load. If the demand of load is less than the maximum generating capacity of SPV system. Then there will be need to operate at maximum power point (MPP). Thus, MPPT converter will operate at particular power reference and named as power reference mode which solely depends on the power requirement of AC and DC loads. This can be calculated through the addition of total power requirement.

$$P_{pv\,ref}=P_{ac}+P_{dc}$$

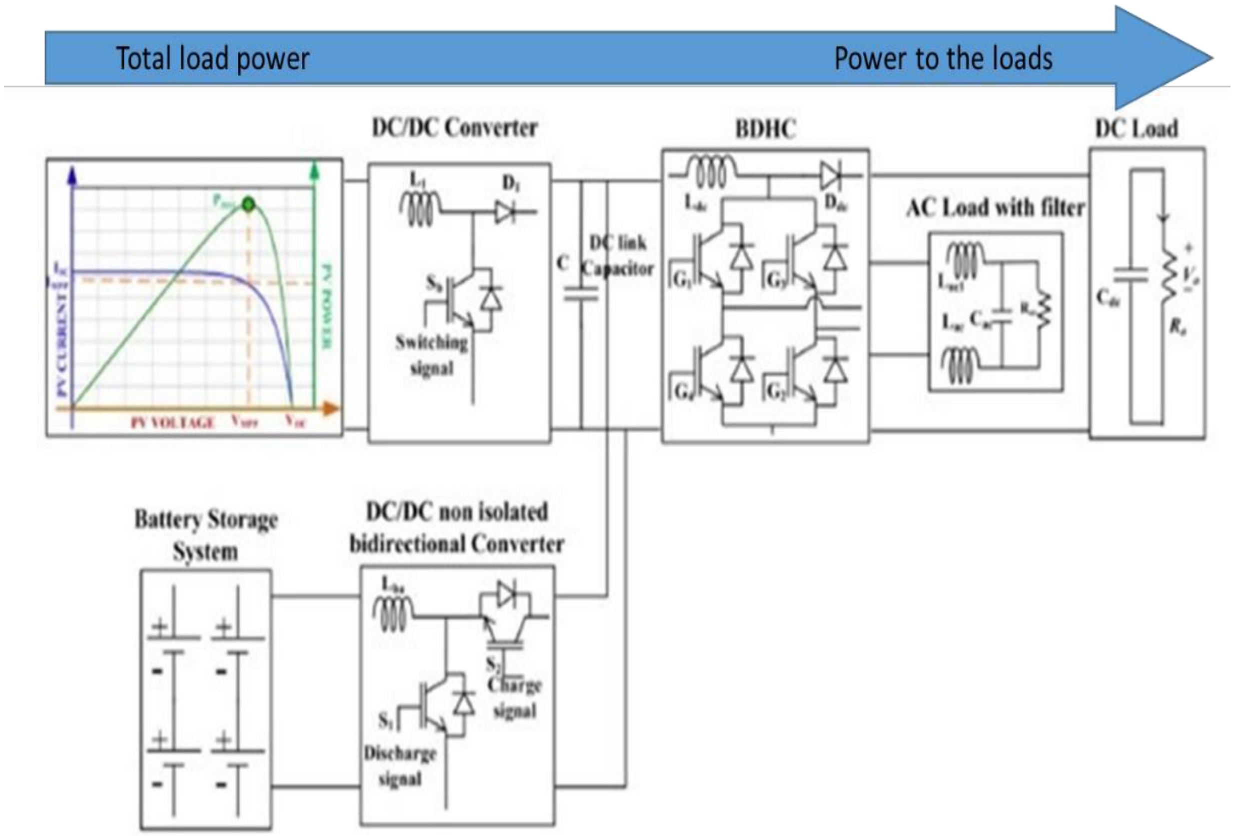


Fig 2. 3: Power Flow representation in Power Reference Mode

2.3 Battery Supply Mode

This mode is subdivided in to battery supply mode 1 or battery supply mode 2. These modes are dependent on the unavailability or insufficiency of power supplied from the SPV system to supply the loads.

Battery Supply Mode 1:

During this mode, SPV system is unable to supply the sufficient amount of power to the load due to different reasons. The reasons could be the hinderance in sunlight due to cloud or the season when SPV is unable to operate at maximum power. Therefore, the remaining power will be provided by the energy stored in the battery. And to support this action, battery needs to charged and battery SOC should not fall below its lower limit. To regulate the power flow, bi directional converter will be used which regulates the DC link capacitor voltage and discharges it to supply the power shortage during this event.

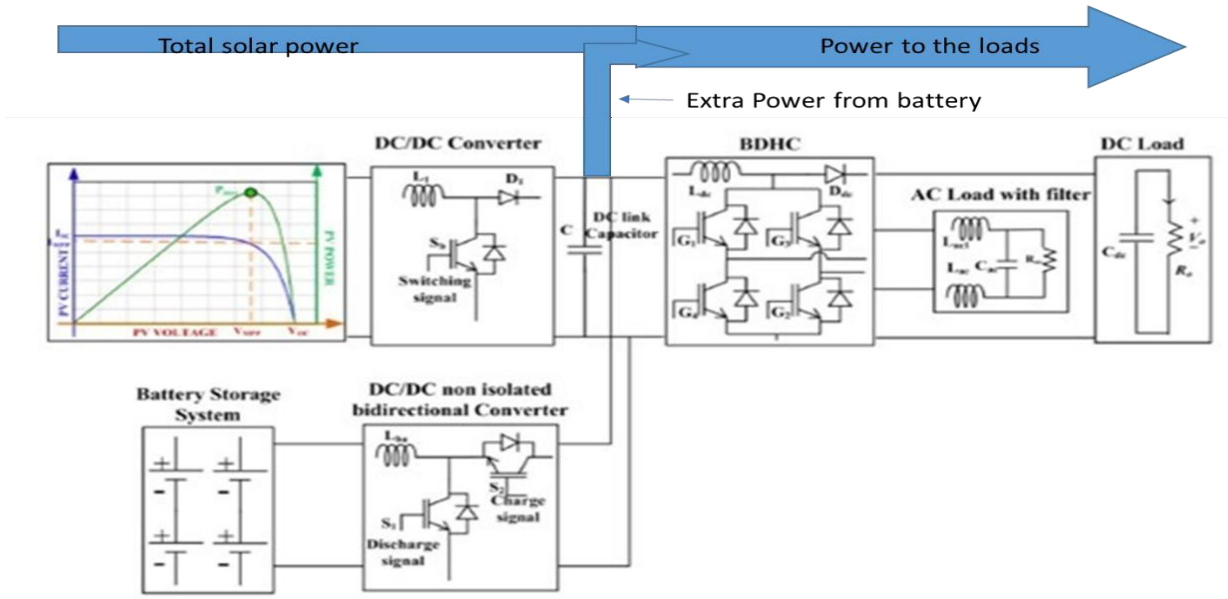


Fig 2. 4: Battery Supply Mode 1

Battery Supply Mode 2:

This mode depicts the night time situation, when there will be zero source of sun energy and the SPV system will be off. Thus, MPPT converter will be idle and does not perform any operation. The power requirement of the load will be fulfilled by the battery during this time.

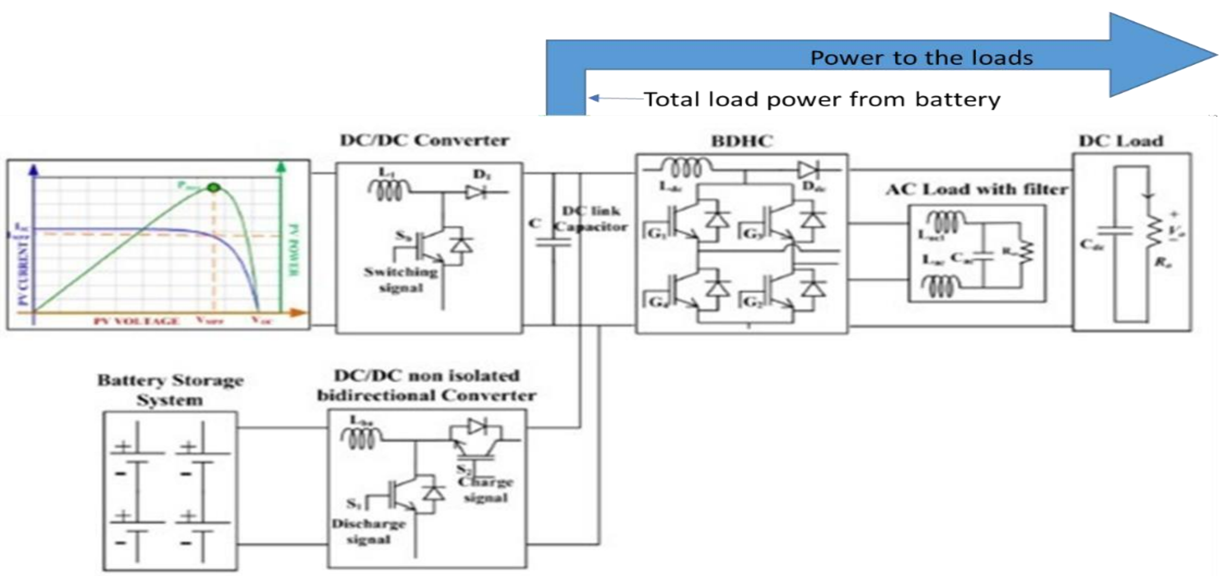
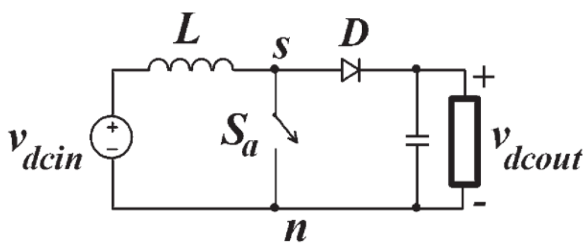


Fig 2. 5: Battery Supply mode 2

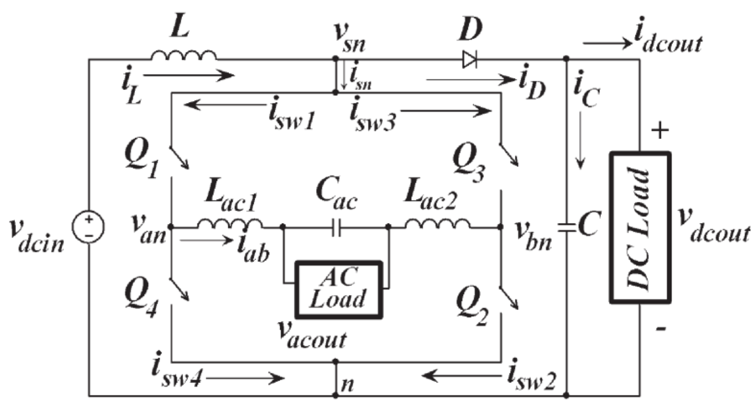
3 Boost Derived Hybrid Converter

3.1 Derivation of BDHC Topology

The boost converter consists of two switches of which S_a is used to control the duty of the converter while the other can be implemented by replacing it with a diode. In case of bi-directional power flow, diode will be replaced with a switch. Hybrid converter topology is implemented by replacing switch S_a with either a single phase or three phase bridge network inverter to supply ac loads. The single bridge inverter consists of switches $(Q_1 - Q_4)$. The converter derived can supply ac and dc loads simultaneously. The modification which has been applied to the circuit is given in the Fig. 3.1.



(a)



(b)

Fig 3.1: (a)Conventional boost Converter. (b) Modification of Boost Converter to Hybrid Converter

The major complications faced for the control of BDHC include the defining of the duty cycle (D_{st}) for boost operation and modulation index $(M_a)$for inverter since both of these operations are controlled by switches $Q_1 - Q_4$. Thus,the control strategy becomes quite complex.

3.2 Operating Principle

The boost operation of the converter is accomplished by changing the turn on and turn off time of the either of the legs $(S_1 - S_4 \; or \; S_2 - S_3)$. The control for these switches is done through modified version of unipolar sine-PWM. The BDHC consists following three switching intervals:

3.2.1 Shoot Through interval:

The Shoot through condition occurs when both switches of a particular leg of the inverter are turned on. ($Q_1 - Q_4$ or $Q_2 - Q_3$).Diode D is reverse biased during this interval. The duration during which overshoot occurs decides the duty cycle (D_{st}). The duration of the shoot through period decides duty cycle(D_{st}) of the boost converter. Here the inverter current circulates in the bridge switches. The inverter current circulates between the switches of the bridge and dc current circulates between output capacitor and load.

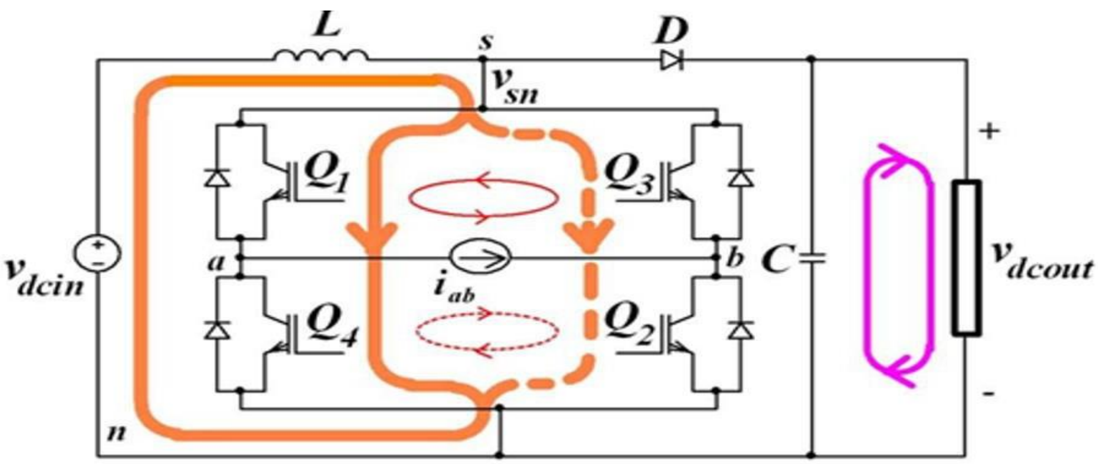


Fig 3. 2: Equivalent Circuit and current directions during shoot-though interval

3.2.2 Power Interval:

In this interval, either of the two legs are turned on. During this interval, current enters or leaves the single-phase bridge through the node **S.** Since the diode is forward biased during this interval so the voltage across the switch node (V_{sn}) is equal to the V_{dcout}.

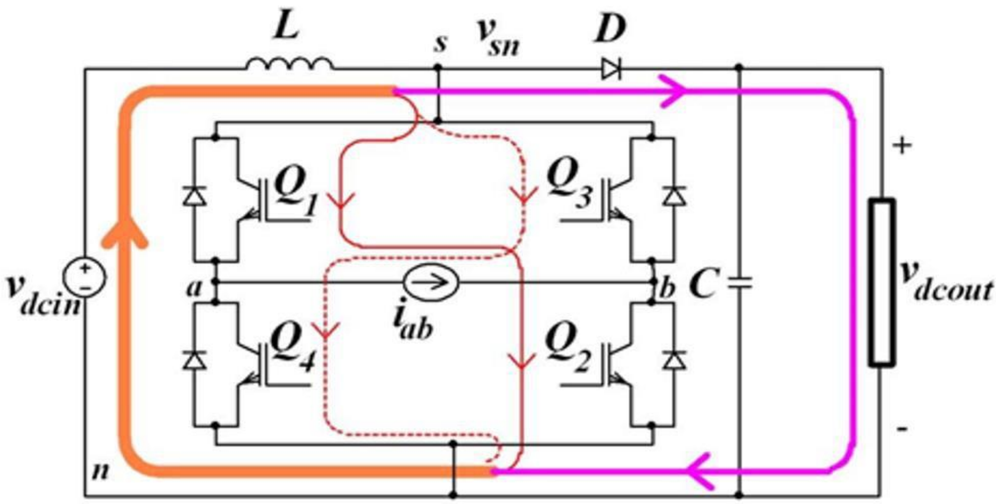


Fig 3. 3: Equivalent Circuit and current directions during the power interval.

3.2.3 Zero Interval:

In this interval, either $Q_1 - Q_3$ or $Q_4 - Q_2$ are turned on, so the current circulates among the inverter switches. Diode is forward biased during this interval and input supplies to the load.

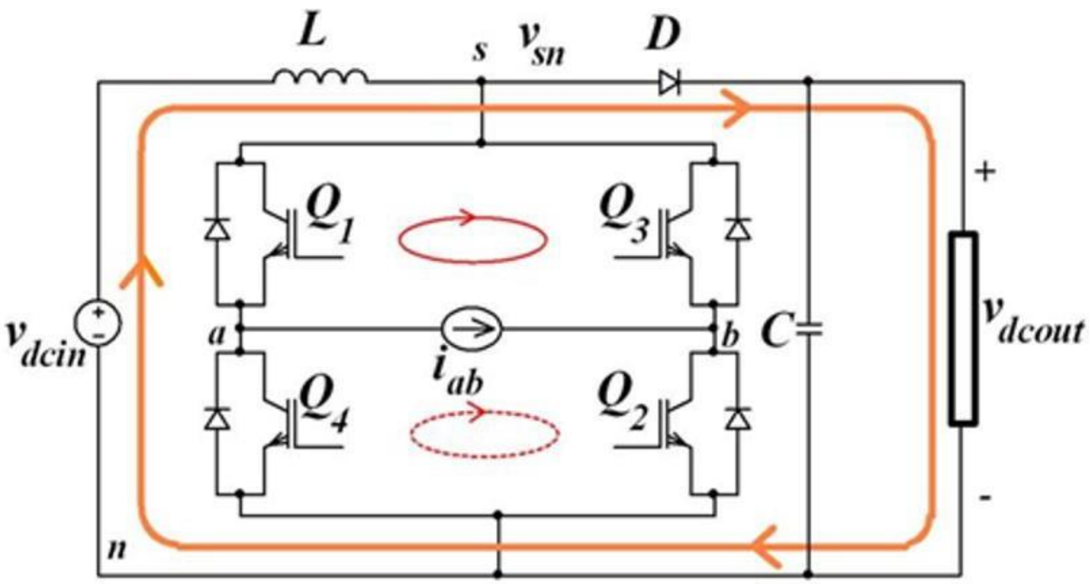


Fig 3. 4: Equivalent circuit and current directions during the Zero interval.

The table given below indicates the current across diode, capacitor, inverter output voltage and switch node voltage during different modes of operation.

Table 1: Currents across diode and capacitor, inverter output and switch node voltages during different intervals of operation.

Interval	Shoot-through	Power	Zero
Diode Current	$i_D = 0$	$i_D = i_L - \lvert i_{ab} \rvert$	$i_D = i_L$
Capacitor Current	$i_C = -i_{dcout}$	$i_C = i_D - i_{dcout}$	$i_C = i_D - i_{dcout}$
Inverter output voltage	$v_{ab} = 0$	$v_{ab} = v_{dcout}$ if Q_1 and Q_2 are 'on' $v_{ab} = -v_{dcout}$ if Q_3 and Q_4 are 'on'	$v_{ab} = 0$
Switch node voltage	$v_{sn} = 0$	$v_{sn} = v_{dcout}$	$v_{sn} = v_{dcout}$

4 Steady State Analysis

For the purpose of steady state analysis, we have considered that output capacitor voltage and input inductor current ripple to be quite small compared with their dc values.

4.1 Gain of the BDHC

Voltage Gain of the DC outputis is regulated by Duty Cycle (Duty Cycle of the Shoot Through condition) represented by D_{ST}.The mathematical expression is similar to that of a boost converter and can be varied by varying the shoot through interval duration during the switching cycle.

$$\frac{V_{dcout}}{V_{dcin}} = \frac{1}{1 - Dst} \tag{2}$$

In this case, DC_{BUS}voltage has been kept constant at 24V which will result in V_{dcin} equal to 24 V as being the input to the Boost Derived Hybrid Converter. The output DC voltage of this converter is kept at 48V. After plugging in the values in the equation (2), the D_{ST} is obtained as following:

$$Dst = \frac{V_{dcout} + V_{dcin}}{V_{dcout}} = \frac{48 - 24}{48} = 0.5 \tag{3}$$

Modulation Index ranging from a minimum of 0 to a maximum of 1 regulates the AC output voltage of the converter and derived equation for Gain is similar to traditional DC-AC inverters. Duration of the power reference mode decides the output power of the ac converter. The gain of the ac output voltage is given by the equation (3)

$$\frac{V_{acout(pk)}}{V_{dcin}} = \frac{M_a}{1 - D_{ST}} \tag{4}$$

AC gain increases with increase in Modulation index for a constant value of D_{ST} but the since the output of DC and Ac are both being controlled by the same switch so it has to obey the condition that sum of D_{ST} and $M_a$should not be greater than 1given by the following equation:

$$M_a + D_{ST} \leq 1 \tag{5}$$

Using Eq. (5), value of $V_{acout(pk)}$is calculated as follow:

$$V_{acout(pk)} = \frac{M_a}{1 - D_{ST}} . V_{dcin} = \frac{0.5}{1 - 0.5} . 24 = 24V$$

4.2 Expression for DC and AC output Power

From Eq. (2), the DC power can be derived as follows:

$$P_{dc} = \frac{V_{dcin}^2}{R_{dc} * (1 - D_{ST})^2} \tag{6}$$

AC power can be derived from Eq. (4) as follows:

$$P_{ac} = \frac{0.5 * V_{dcin}^2 * M_a^2}{R_{ac} * (1 - D_{ST})^2} \tag{7}$$

4.3 Design of Passive components

The average input current of the inductor (L) in the inductor is given by:

$$I_L = \frac{V_{dcout} * I_{dcout} + 0.5 * V_{ab} * i_{ab} * cos\varphi}{V_{dcin}} \quad (8)$$

$$\frac{1}{2} L.\, I_L.\, \Delta i_{L(pk-pk)} + C.\, V_{dcout}.\, \Delta v_{dcout(pk-pk)=} \quad \frac{P_{ab}}{\omega} \quad (9)$$

4.4 Stress Across switches and Diodes

The switching sequence of the switches are Q1,Q4 and its complimentary switches are Q2,Q3. As we know that Vdcout is basically the output voltage of the H-Bridge. Thus, it is obvious that the stress on the switches connected in BDHC will be equal to Vdcout. To realize the voltage stress across diode we have to consider the shoot through condition when the diode is off thus the voltage appear across it at this time will be same as Vdcout.Here $V_{dcout} = 48V$, accommodating the derating factor of 1.6, the stress is approximately 78V.

5 Designing and Calculation of BDHC

5.1 Parameters for MPPT Converter

The table 2 indicates the parameters for a solar panel receiving 500 and 1000 w/m^2 radiation.

Solar parameter	Radiation	
	1000 W/m^2	500 W/m^2
open circuit voltage (V_{OC})	27 V	26 V
short circuit current (I_{SC})	10 A	5 A
MPP voltage (V_{MPP})	21.6 V	21 V
MPP current (I_{MPP})	8 A	4 A
maximum power	210 W	105 W

To calculate further parameters for MPPT Boost converter, panel with 1000 w/m^2 radiation is chosen.

$$V_{MPP}(V_d) = 21V$$

$$I_{MPP} = 8A$$

$$V_{dclink}(Vo) = 24\text{V}$$

$$D = \frac{V_{dcout} - V_{dcin}}{V_{dcout}} = \frac{24 - 21}{24} = 0.13$$

$$f_{sw} = 2KHz$$

$$\Delta I = 0.14(\,for\ 2\ percent\ ripple\ in\ output\ current)$$

$$\Delta V = 0.24(for\ 1\ percent\ ripple\ in\ output\ voltage)$$

$$L = \frac{V_d * D}{\Delta I * f_{sw}} = \frac{21 * 0.13}{0.14 * 2000} = 10mH$$

$$R = \frac{{V_o}^2}{P} = \frac{24 * 24}{200} = 2.88$$

By using the values calculated above we can calculate the value of capacitance using following formula which in our case came out to be approximately equal to 2200uF.

$$C = \frac{V_o * D}{\Delta V * R * f_{sw}}$$

Table 2: MPPT Boost Converter Parameters

$V_{dclink}(Vo)$	24V
$V_{MPP}(V_d)$	21V
D	0.13
$C_{dc-link}$	2200UF
$MPPT\ Boost\ Inductor\ L1$	10mH

Table 3: Parameters for Boost Derived Hybrid Converter

D_{ST}	0.5
M_a	0.5
$V_{in}(V_{dclink})$	24V
V_{dcout}	48V
I_{dcout}	3A
P_{dcout}	150W(approx)
$V_{acout(pk)}$	24V
$I_{acout(pk)}$	2.5A
$AC\ Inductor\ L_{ac1}$	250uF

AC Inductor L_{ac2}	**250uF**
Boost Inductor L	**10mH**
C_o	**1000uF**

Table 4:Parameters for Bi-directional DC-DC Converter in battery supply mode

Battery Rating	**12V, 48Ah**
$V_{in}(V_{ba})$	**12V**
$V_{out}(V_{dclink})$	**24V**
D_{ba}	**0.5**
Inductor L	**50mH**

6 Algorithm for Controlling switching Sequence in BDHC

We have employed an open loop control logic in this report in order to drive the switching sequence of BDHC.In this project, Sinusoidal pulse width modulation is used which produce output voltage at three different levels. The simulated version on PSIM of this control algorithm can be seen from following figure:

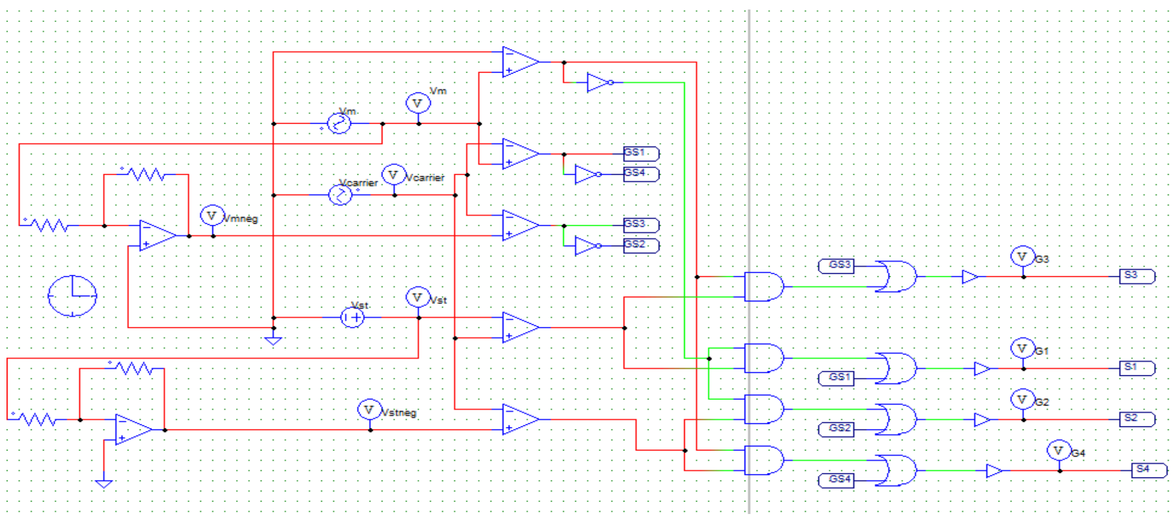


Fig 6.1:Simulation Model of Control Algorithm

The comparison of |+Vst| and carrier wave is done to produce the shoot-through signal which also help in determining the duty ratio. In order to calculate the modulation index 'Ma' for output from AC terminals, the modulation signal and triangular carrier wave is compared. The simulation result generated for gating sequence can be seen from figure # 5.2:

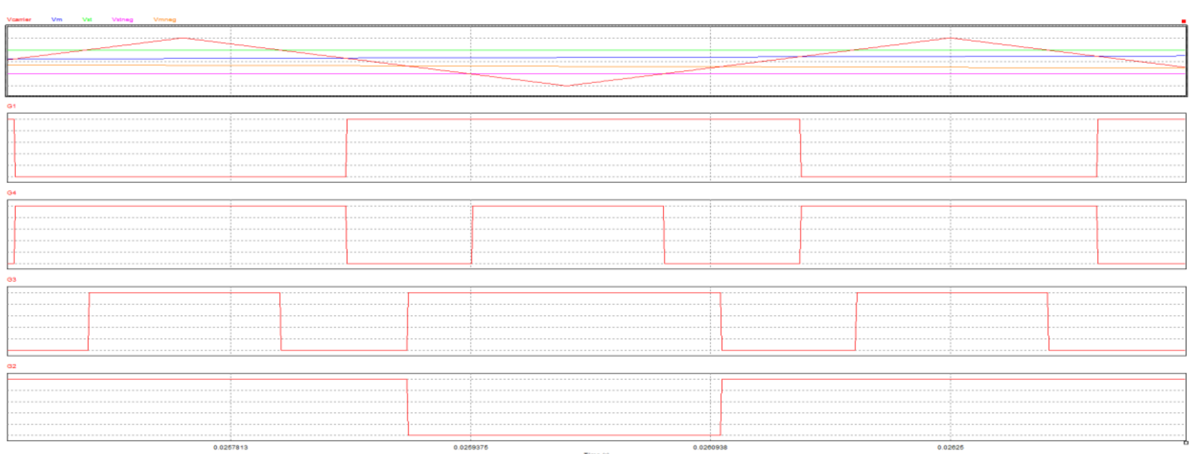


Fig 6.2:Gating Pulse Generation

7 Simulation of BDHC

As discussed in the power modes, the power reference mode will only supply power to the dc and ac loads and the battery converter will remain in the idle state. This mode becomes active when the battery is fully charged. For this mode implementation, the circuit is simulated in the PSIM in which open loop control logic is designed and implemented where rather than using the PV panel as the input voltage, a DC source has been elected. The circuit for the simulation is as follows:

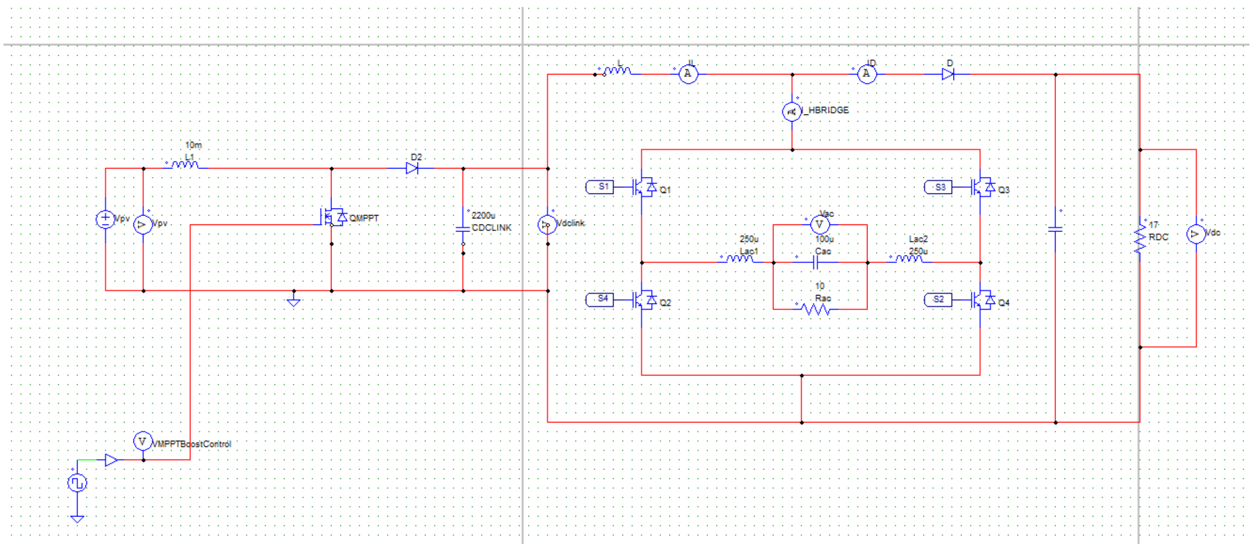


Fig 7.1: Model of BDHC in MPPT Mode of Operation

A sawtooth waveform with the switching frequency of 2000hz is compared with the dc value to get the gating pulse of the switch. The duty is kept to be 0.13 which Ton period= 0.13 and the Toff period = 0.87. Thus, we get the output voltage of 24v at the DC link capacitor. The output voltage is desired to be 48V at DC and 24V with the AC with the converter power rating of 150watt at the DC and 20W at the AC. Knowing the power and voltage values, their resistance can be easily calculated. Thefigures below represent the DC input and output voltage of the converter in which dc voltage is provided to the BDHC which is Vdclink=24v and the Vdc = 48V is the output from the converter.

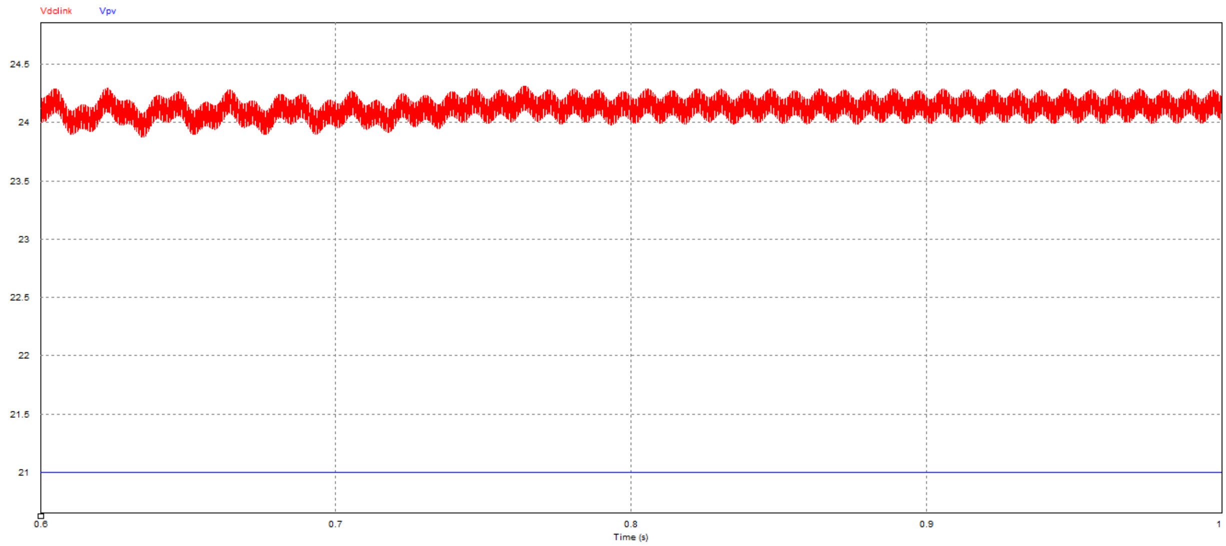


Fig 7.2:V_{dclink} Vs V_{pv} in Power Reference Mode

In order to obtain the AC voltage of the BDHC converter. We have set the dst = 0.5 and ma =0.5 which was calculated previously and the waveform shows that the BDHC converter DC voltage is equal to the AC voltage which can be observed in the figure below where blue waveform depicts the dc input voltage and red waveform shows the Ac voltage at the load.

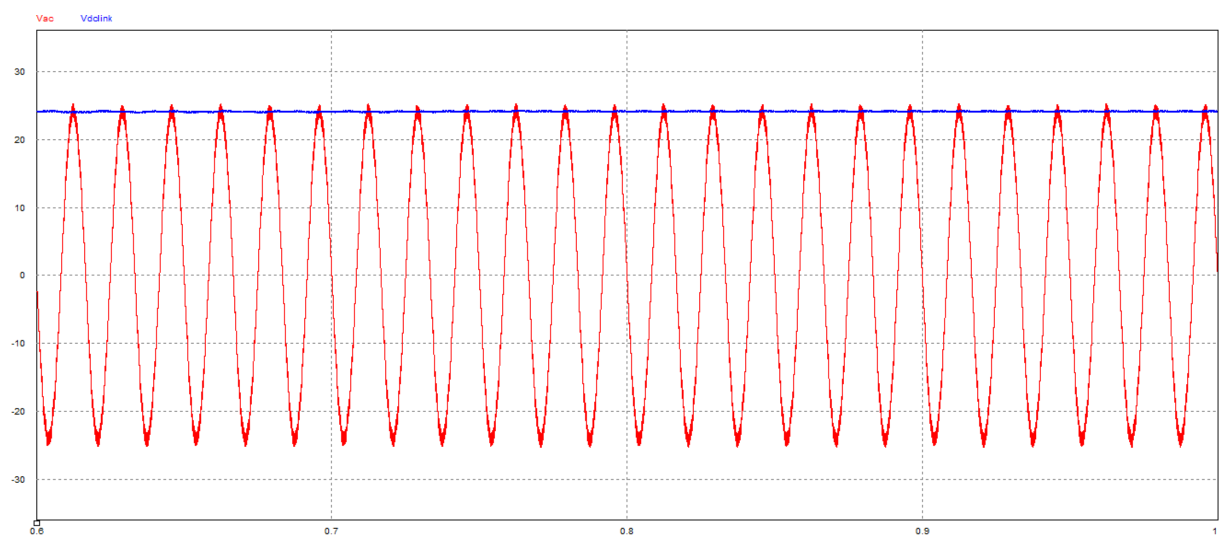


Fig 7.3:V_{dclink} Vs V_{ac} across load

The figure for the output DC and AC voltage and current waveform during power reference mode has been shown below.

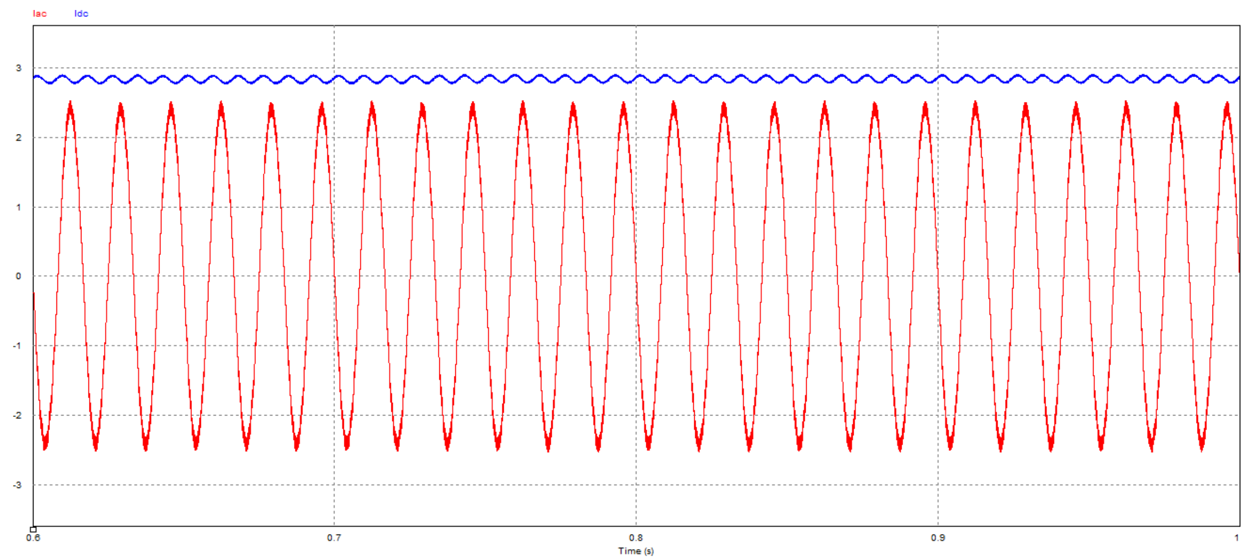


Fig 6.4:DC and AC Currents in Power Reference Mode

7.1 In Battery Supply mode:

This mode represents the time when there is no source of sunlight will be available. So SPV system will not be providing any power and all the power requirement of battery will be fulfilled by battery. Thus, in this mode, the battery will be discharged from its charged state through the help of the bidirectional DC-C converter. Similar to the power reference mode, a dc source of 12V is used for the simulation purpose to represent the battery output voltage. The equivalent circuit can be found in the figure below:

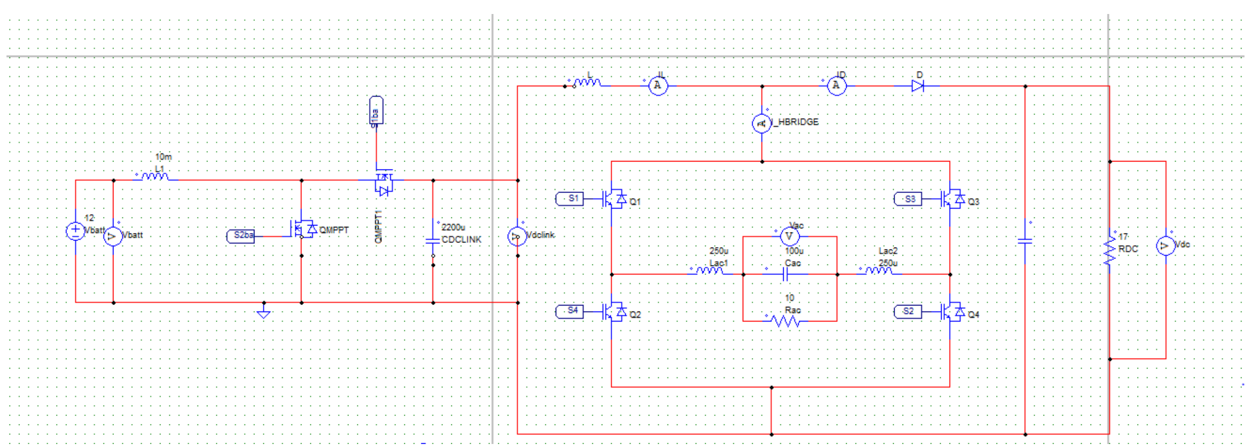


Fig 6.5:Simulation Model of BDHC in Battery Supply Mode

The control logic for Bidirectional DC-DC converter during boost mode is designed where we compared the sawtooth waveform of 2000hz switching frequency with the constant 0.5v constant dc source to get the duty value at 0.5. We will obtain the DC voltage of 24v at the obtain through providing the battery source as the input to the boost circuit. The gating signal provided for the switches to operate the bidirectional converter as boost can observed in the figure below:

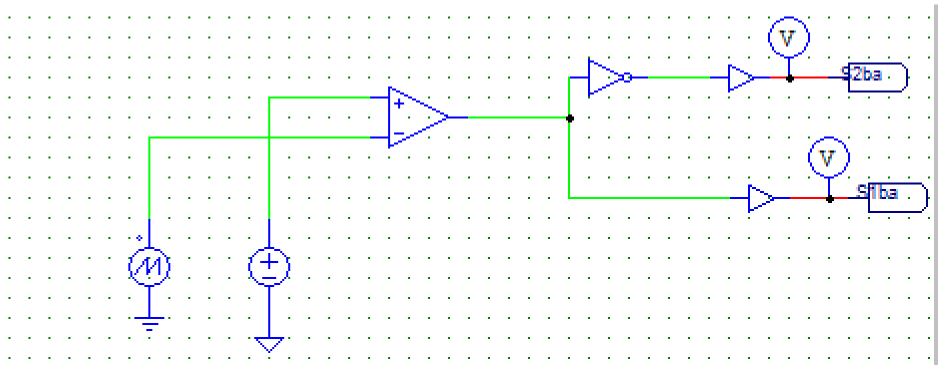


Fig 6.6:Gating signal generation circuit for switch

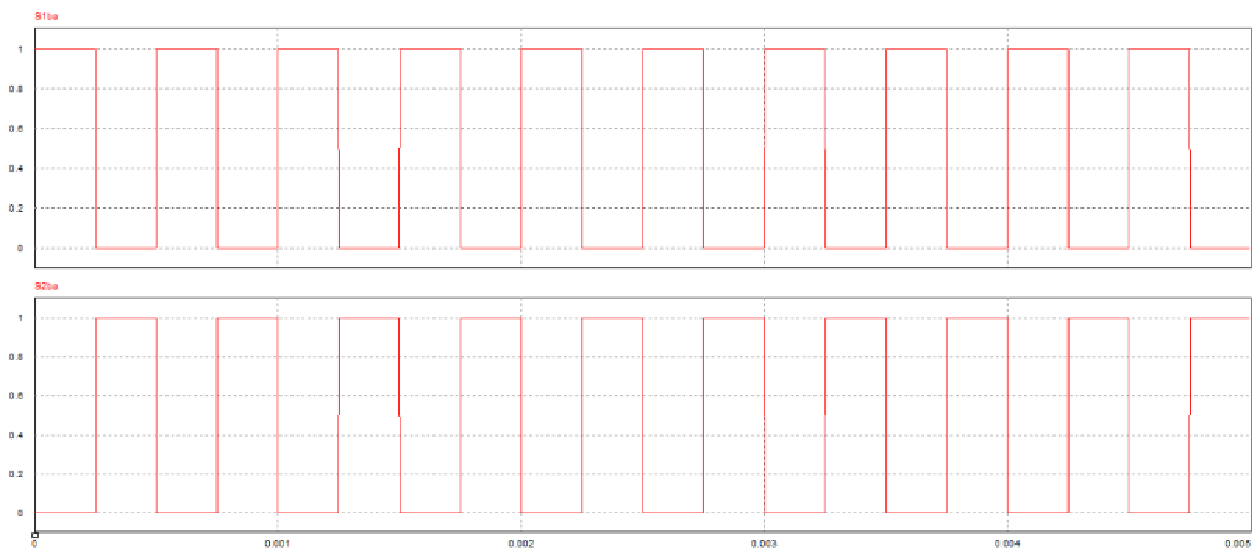


Fig 6.7:Gating signal waveforms of switch

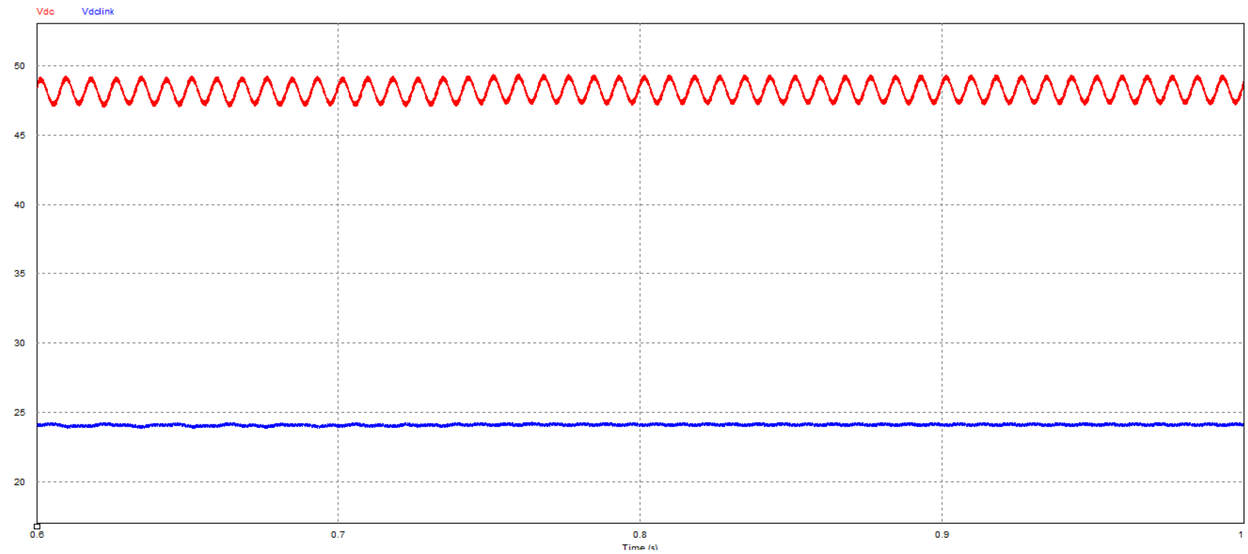


Fig 6.8:Vdc vs Vdclink

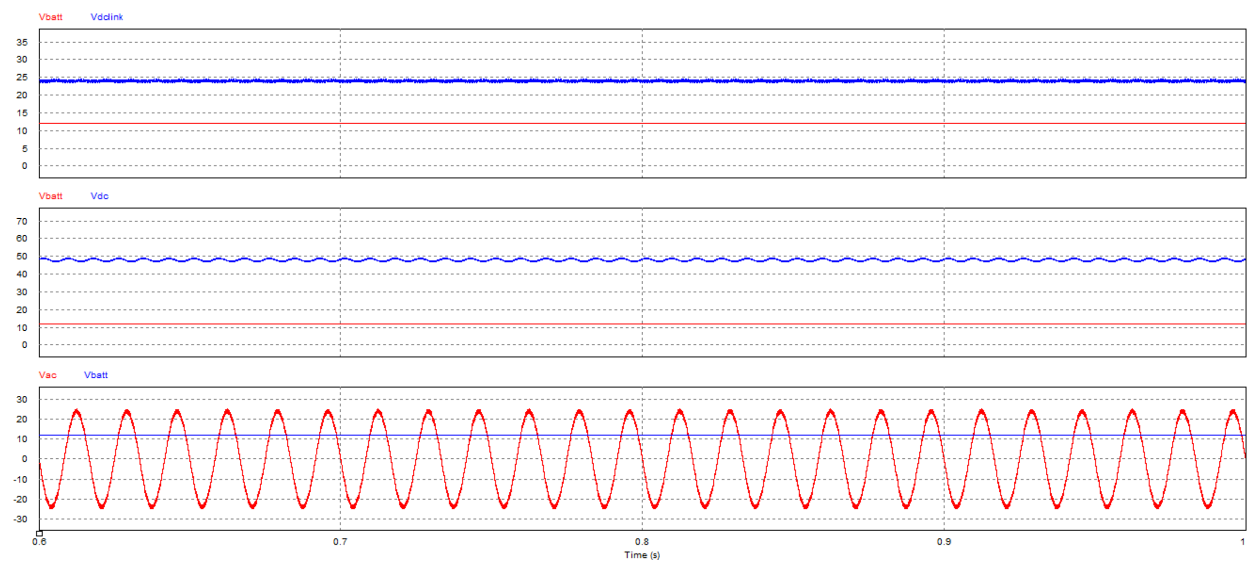


Fig 6.9:(a) Vbatt vs Vdclink (b) Vbatt vs Vdc (c) Vac vs Vbatt

8 Conclusion And Future Scope

During this report, we have performed calculations to obtain the parameters for different mode of operation of this circuit namely Boost MPPT DC-DC converter, BDHC and DC-DC bidirectional converter. In the next step we designed and implemented the unipolar SPW control circuit for BDHC using its control algorithm. Finally, we have used the calculated parameters to simulate the circuits in different power modes to get the input and output voltage and power waveform which comply with the theoretical analysis and fulfills the load requirement during different operation modes.

For the future work, we will aim to also monitor the battery SOC and solar panel input power to perform the simultaneous operation of battery and PV panel and implement the MPPT mode.

REFERENCES

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DOI: 10.1049/iet-esi.2019.0030

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Boost-Derived Hybrid Converter With Simultaneous DC and AC Outputs. Olive Ray, Student Member, IEEE, and Santanu Mishra, Senior Member, IEEE