Design and Simulation of Boost Derived Hybrid Converter for Nano Grid Applications

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***Abstract*—This work presents the proficiency in writing C code using Code::Blocks. Code::Blocks is a free C, C++ and Fortran IDE built to meet the most demanding needs of its users. It runs on Linux, Mac, Windows (uses wxWidgets). It is designed to be very extensible and fully configurable. Code::Blocks is used to program hybrid converter topology which can supply simultaneous dc and ac loads from a single dc sources like battery, photovoltaic cells, fuel cells etc. This topology is realized by replacing the controlled switched of single-switch boost converter with a voltage-source-inverter bridge network. The resulting hybrid converter requires lesser number of switches to provide dc and ac output with an increased reliability, resulting from its inherent shoot-through in the inverter bridge. Such multi output converter with better power processing density and reliability can be well suited for system with simultaneous dc and ac loads. This converter is called Boost derived hybrid converter (BDHC). As it is obtained from the conventional boost topology. The study state behaviour of this BDHC will is presented. And also a suitable pulse width modulation (PWM) controlled strategy will be adapted based upon unipolar sine PWM. Simulation of BDHC is carried out. The BDHC converter is able to supply dc and ac loads from a 12V dc input.The programming results are ploted using Gnuplot. Gnuplot is a free, command- driven, interactive, function and data plotting program.**

Keywords*— *Code::Blocks; Gnuplot; BHDC; nanogrid

I. Introduction

Nano grid architectures are being increasingly incorporated in modern smart residential electrical power systems. These systems involve different load types—dc as well as ac—efficiently interfaced with different kinds of energy sources(conventional or nonconventional) using power electronic converters. Fig. 1 shows the schematic of a system, where a single dc source (V_{dcin}) (e.g., solar panel, battery, fuel cell, etc.) supplies both dc (V_{dcout}) and ac (V_{acout}) loads. The architecture of Fig. 1(a) uses separate power converters for each conversion type (dc–dc and dc–ac) while Fig. 1(b) utilizes a single power converter stage to perform both the conversions. The latter converter, referred to as a hybrid converter, it has higher power processing density and improved reliability (resulting from the inherent shoot-through protection capability). These qualities make them suitable for use in compact systems with both dc and ac loads. For Example, an application of a hybrid converter can be to power an ac fan and a LED lamp both at the same time from a solitary dc input in a single stage.

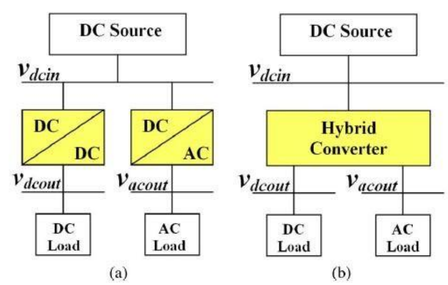

Fig. (1) Representative schematic of a nanogrid architecture with a single dc input and simultaneous dc and ac outputs. (a) Dedicated power converter-based architecture. (b) Hybrid converter-based architecture.

II. The Boost Converter

The boost converter is switching converter that operates by periodically opening and closing an electronic switch. It is called a boost converter because the output voltage is larger than the input voltage. The analysis of converter assumes the following:

1. Steady-state conditions exist.
2. The switching period is T, and the switch is closed for time DT and open for $(1\_D)T$.
3. The inductor current is continuous (always positive).
4. The capacitor is very large, and the output voltage is held constant at voltage Vo.
5. The components are ideal.

The analysis proceeds by examining the inductor voltage and current for the switch closed and again for the switch open.

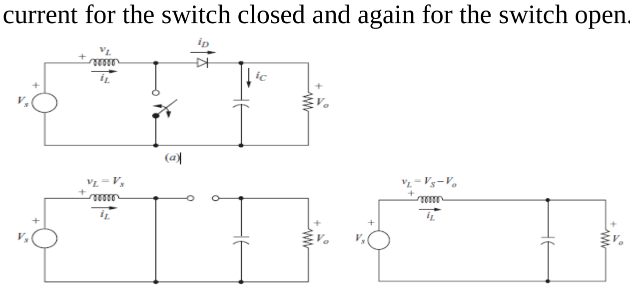

Fig. 2 (a) Circuit: (b) Equivalent circuit for the switch closed (c) Equivalent circuit for the switch open

Analysis for the Switch Closed

When the switch is closed, the diode is reverse biased. Kirchhoff's voltage law around the path containing the source, inductor, and closed switch is,

$$V_L = V_s = L\frac{di_L}{dt}$$

$$\frac{di_L}{dt} = \frac{V_s}{L} \quad (1)$$

The rate of change of current is a constant, so the current increases linearly while the switch is closed. The change in inductor current is computed from

$$\frac{\Delta i_L}{\Delta t} = \frac{\Delta i_L}{DT} = \frac{V_s}{L} \quad (2)$$

Solving for Δi_L for the switch closed,

$$(\Delta i_L)_{c1osed} = \frac{V_s DT}{L} \quad (3)$$

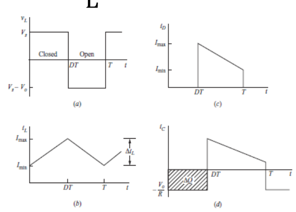

Fig 3 Boost converter waveforms. (*a*) Inductor voltage; (*b*) Inductor current; (*c*) Diode current; (*d*) Capacitor current.

Analysis for the Switch Open

When the switch is opened, the inductor current cannot change instantaneously, so the diode becomes forward-biased to provide a path for inductor current. Assuming that the output voltage *Vo* is a constant, the voltage across the inductor is,

$$V_L = V_s - V_o = L\frac{di_L}{dt}$$

$$\frac{di_L}{dt} = \frac{V_s - V_o}{L} \quad (4)$$

The rate of change of inductor current is a constant, so the current must change linearly while the switch is open. The change in inductor current while the switch is open is given by,

$$\frac{\Delta i_L}{\Delta t} = \frac{\Delta i_L}{(1-D)T} = \frac{V_s - V_o}{L}$$

Solving for Δi_L

$$(\Delta i_L)_{open} \frac{(V_s - V_o)(1-D)T}{L} \quad (5)$$

For steady-state operation, the net change in inductor current must be zero.

$$(\Delta i_L)_{c1osed} + (\Delta i_L)_{open} = 0$$

$$\frac{V_s DT}{L} + \frac{(V_s - V_o)(1-D)T}{L} = 0$$

Solving for V_o,

$$V_s(D - 1 - D) - V_o(1 - D) = 0$$

$$V_o = \frac{V_s}{1-D} \quad (6)$$

The boost converter produces an output voltage that is greater than or equal to the input voltage. However, the output voltage cannot be less than the input. The average current in the inductor is determined by recognizing that the average power supplied by the source must be the same as the average power absorbed by the load resistor. Output power is given by,

$$P_o = \frac{V_o^2}{R} = V_o I_o \quad (7)$$

Input power is $V_s I_s = V_s I_L$. Equating input and output powers and using

$$V_s I_L = \frac{V_o^2}{R} = \frac{V_s^2}{R(1-D)^2}$$

By solving for average inductor current and making various substitutions, I_L can be expressed as,

$$I_L = \frac{V_s}{R(1-D)^2} \quad (8)$$

Maximum and minimum inductor currents are determined by using the average value and the change in current

$$I_{mas} = I_L + \frac{\Delta i_L}{2}$$

$$I_{mas} = \frac{V_s}{R(1-D)^2} + \frac{V_s DT}{2L} \quad (9)$$

$$I_{min} = \frac{V_s}{R(1-D)^2} - \frac{V_s DT}{2L} \quad (10)$$

Equation for voltage was developed with the assumption that the inductor current is continuous, meaning that it is always positive. A condition necessary for continuous inductor current is for I_{min} to be positive. Therefore, the boundary between continuous and discontinuous inductor current is determined from

$$I_{min} = 0 = \frac{V_s}{R(1-D)^2} - \frac{V_s DT}{2L}$$

$$\frac{V_s}{R(1-D)^2} = \frac{V_s DT}{2L}$$

$$(L_f)_{min} = \frac{D(1-D)^2 R}{2L} \quad (11)$$

Output Voltage Ripple: The preceding equations were developed on the assumption that the output voltage was a constant, implying an infinite capacitance. In practice, a finite capacitance will result in some fluctuation in output voltage, or ripple. The peak-to-peak output voltage ripple can be calculated from the capacitor current waveform. The change in capacitor charge can be calculated from

$$|\Delta Q| = \frac{V_o\, DT}{R} = C\Delta V_o$$

An expression for ripple voltage is then

$$\Delta V_o = \frac{V_o\, DT}{CR}$$

$$\Delta V_o = \frac{V_o D}{CRf}$$

$$\frac{\Delta V_o}{V_o} = \frac{D}{CRf} \qquad (12)$$

where *f* is the switching frequency. Alternatively, expressing capacitance in terms of output voltage ripple yields

$$C = \frac{D}{CRf(\Delta V_o / V_o)} \qquad (13)$$

Derivation of output voltage using volt-second balance:
At switch close condition:
From Fig 2 (b),

$$i_C = -\, i_R$$

$$C\frac{dr_o}{dt} = -\frac{r_o}{R}$$

By solving above equation we get,

$$V_o = V_c e^{(\frac{T}{2} - t)/RC} \qquad (15)$$

At switch open condition:

$$i_C = i_L - i_R$$

$$C\frac{dr_o}{dt} = \frac{1}{L}\int (V_s - V_o)\, dt - \frac{V_o}{R}$$

By solving this we get

$$C\frac{d^2 r_o}{dt^2} + \frac{1}{R}\frac{dr_o}{dt} + \frac{V_o}{L} = 0$$

$$(CD^2 + \frac{D}{R} + \frac{1}{L}) = 0$$

$$b^2 = \frac{1}{R^2}$$

$$4ac = 4 * C * \frac{1}{L} > b^2$$

$$V_o = K_1 e^{\alpha t}\cos(\beta t) + K_2 e^{\alpha t}\sin(\beta t)$$

$$\alpha = \frac{-1}{2RC}$$

$$\beta = \frac{\sqrt{-b^2+4ac}}{2a} = \frac{\sqrt{-(\frac{1}{R})^2 + \frac{C}{L}4}}{2C}$$

$$V_o = V_c + K_1 e^{\alpha t}\cos(\beta t) + K_2 e^{\alpha t}\sin(\beta t)$$

$$K_1 = 0$$

$$V = \begin{cases} V_c + \dfrac{V_s * e^{(\frac{-\alpha T}{2} + \alpha t)} * \sin(\beta t)}{\sin(\beta * \frac{T}{2})} & \text{for } n = 0 \\ V_c + \dfrac{[\frac{V_s}{1-D} - V_c] * e^{(\frac{-\alpha*(n+1)*T}{2} + \alpha t)} * \sin(\beta t)}{\sin(\beta * (2n+1)\frac{T}{2})} & \text{for } n > 0 \end{cases} \qquad (16)$$

n = n^{th} cycle.
T = time period.
V_C = Voltage at switch open instant.

PWM Technique
For switching purpose we prefer MOSFET or the IGBT. For these we must provide pulses to the Gate terminal of either of them. PWM is a technique or a method to control these pulses to provide the required switching. Generally we use a comparator as a PWM IC (i.e. an op-amp). Here, compare two signals, a reference wave and a carrier wave, and get the required pulses. In this case, a dc wave is the reference wave and a triangular wave as a carrier wave. If the magnitude of the triangular wave become more than the referred value the output of the PWM will be a –ve dc value and vice-versa. The output is then fed to the Gate terminal of MOSFET or the IGBT.

Designing of Boost Converter:
Components are assumed to be ideal. Specifications for designing boost converter is shown in the table 1

Table 1: Specifications of Boost Converter

Input Voltage	12V
DC load	50Ω
Output Voltage	24V
Switching frequency	10kHz
Voltage ripple	1.25%

1. Duty ratio (D):

$$V_o = \frac{V_s}{1-D}, \; D = 0.5$$

2. Inductor (L):
Assuming $I_{l min} = 0$

$$(L_f)_{min} = \frac{D(1-D)^2 R}{2f}, \quad (L_f)_{min} = 156uH$$

$$I_{mas} = \frac{V_S}{R(1-D)^2} + \frac{V_s DT}{2L}, \; I_{mas} = 1.96A$$

3. Capacitor (C):

$$C = \frac{D}{Rf(\Delta V_O/V_O)}, \; C = 40uF$$

Numerical techniques:

Numerical analysis involves the study methods of computing numerical data. In many problems this implies producing a sequence of approximation by repeating the procedure again and again. People who employ numerical methods for solving problems have to worry about the following issues: the rate of convergence (how long does it take to terminate), the accuracy (or even validity) of the answer and the completeness of the response (do other solutions, in addition to the one found, exist).

Numerical methods provide approximation to the problems in question. No matter how accurate they are they do not, in most cases, provide the exact answer. In some instances working out the exact answer by a different approach may not be possible or may be too time consuming and it is in these cases where numerical methods are most often used.

Numerical technique implemented:

The simulation each subsystem is done by solving the set of first order, simultaneous constant coefficient differential equation using Backward Euler's numerical method. The above mentioned numerical method is implemented using 'C' language and Code Blocks on Windows platform. GNU plot is used to draw the graphs of data generated from the program.

Backward Euler's numerical method:

Consider the ordinary differential equation

$$\frac{dx}{dt} = f(t, x_n)$$

Here, initial value $x(t_O) = x_O$, the function f and the initial data t_O and x_O are known ; the function x depends on the variable 't' and is unknown. A numerical method produces a sequence $x_O, x_1, x_2, ...$ such that x_k approximates $x_{(t_O+kh)}$, where 'h' is called the step size.

The backward Euler method computes the approximations using

$$\frac{x_n - x_{n-1}}{h} = f(x_n, t)$$

Where,

- x_n is the present value.
- X_{n-1} is the previous value.
- h is the step size.
- $f(x_n,t)$ is the function for the parameter we are calculating.

Simpson's one third rule:

Simpson's Rule Formula is used to calculate the integral value of any function. It calculates the value of the area under any curve over a given interval by dividing the area into equal parts. It follows the method similar to integration by parts. In order to integrate any function f(x) in the interval (a,b), follow the steps given below:

1. Select a value for n, which is the number of parts the interval is divided into. Let the value of n be an even number.
2. Calculate the width, h = (b-a)/n..
3. Calculate the values of x_0 to x_n as $x_0 = a$, $x_1 = x_0 + h, ...x_{n-1} = x_{n-2} + h$, $x_n = b$.
4. Consider y = f(x). Now find the values of $y(y_0$ to $y_n)$ for the corresponding $x(x_0$ to $x_n)$ values.
5. Substitute all the above found values in the Simpson's Rule Formula to calculate the integral value.

Simpson's One Third Rule Formula is,

$$\int_a^b f(x)dx = \frac{h}{3}[(y_0 + y_n) + 4(y_1 + y_3 ... + y_{n-1}) + 2(y_2 + y_4 + \cdots y_{n-}$$

Program Results:

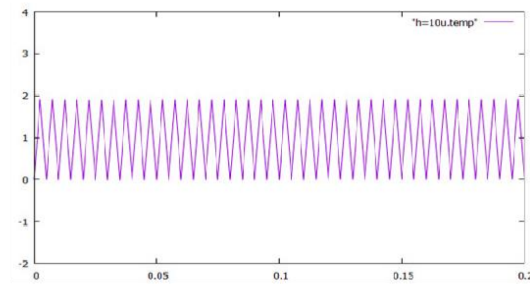

Fig 4 a) Inductor current

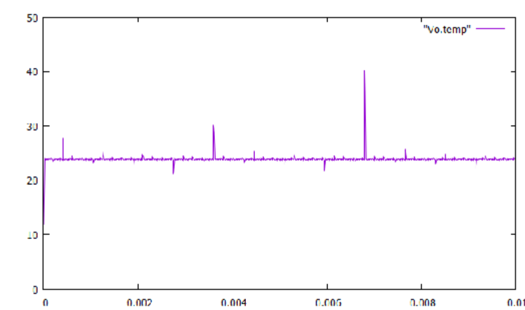

Fig 4 b) Boosted output voltage.

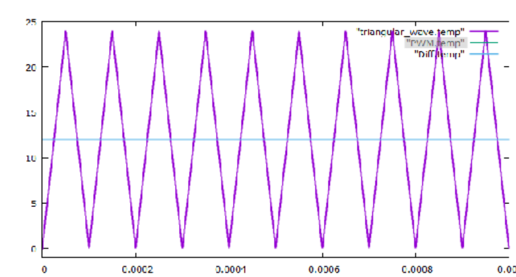

Fig 4 c) Reference and Carrier wave form

Reference wave is a dc wave at 12V and carrier wave is a triangular wave of 24V peak.

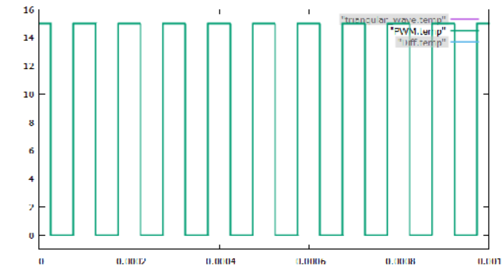

Fig 4 d) Output of PWM Technique

III. Inverter

Inverters are circuits that convert dc to ac. More precisely, inverters transfer power from a dc source to an ac load.. In other applications, the objective is to create an ac voltage when only a dc voltage source is available. Inverters are used in applications such as adjustable-speed ac motor drives, uninterruptible power supplies (UPS), and running ac appliances from an automobile battery.

Operation of Inverter:

Simultaneous opening and closing switches of switches (S_1 - S_4) and (S_3 - S_2) is not possible in this case of inverter otherwise short circuit may happen in the circuit may happen in the circuit and the real switches do not turn on instantaneously. Therefore switching transition times must be accommodated in the control of switches. Overlap of switches on times will result in a short circuit. Sometimes it is called as shoot through interval. Figure. 5(a) shows the circuit diagram of the inverter.

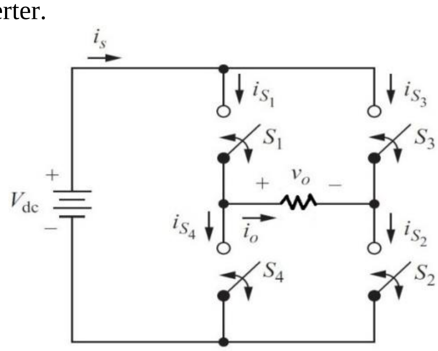

Fig 5(a): Basic circuit diagram of the inverter

1. When S_1 and S_2 are closed:

When the switches S_1 and S_2 are closed the switches connect the load to the $+V_{dc}$ shown in fig 5(b)

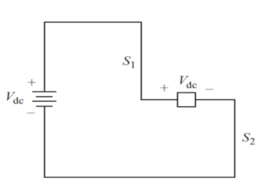

Fig 5(b): S_1 and S_2 are closed

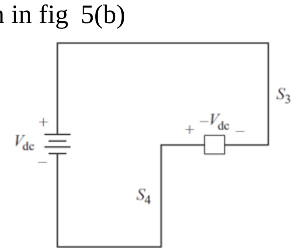

Fig .5(c): S_3 and S_4 are closed

When S_3 and S_4 are closed:

When the switches S_3 and S_4 are closed the switches connect the load to the $-V_{dc}$ shown in Fig.5(c)

The periodic switching of the load voltage between $+V_{dc}$ and $-V_{dc}$ produces a square wave voltage across the load.
Applying KVL to the circuit shown in Fig.5 (b), i.e. when the switches S_1 and S_2 are closed.

$$V_O = +V_{dc},\ \mathrm{R}i_L = V_O$$

Applying KVL to the circuit shown in Fig. 5(c), i.e. when the switches S_3 and S_4 are closed

$$V_O = -V_{dc},\ \mathrm{R}i_L = -V_O$$

Designing of Inverter:

Components are assumed to be ideal. Specifications for designing Inverter is shown in the table 3.1

Table 2: Specifications of Inverter

Input Voltage	12V
DC load	50Ω
Output Frequency	50Hz

Program results:

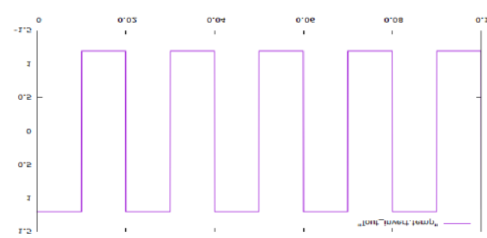

Fig.6 (a). Inverter Current

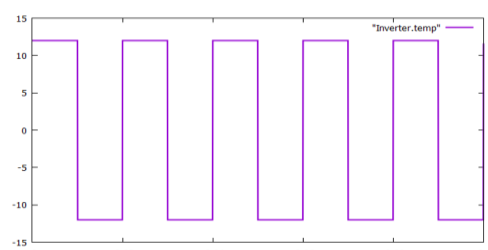

Fig.6 (b) Inverter output voltage

IV. Boost Derived Hybrid Converter

In boost derived hybrid converter with experimental validation is presented and discussed. The control switch Sa of a conventional boost converter [shown in Fig. 7 (a)] has been replaced by the bidirectional single-phase bridge network switches (Q1–Q4) to obtain the BDHC topology [shown in Fig. 7(b)]. This proposed converter provides simultaneous ac output (V_{acout}) in addition to the dc output (V_{dcout}) provided by the boost converter. For the BDHC, the hybrid (dc as well as ac) outputs have to be controlled using the same set of four controlled switches Q1–Q4. Thus, the challenges involved in the operation of BDHC are the following: 1) defining the duty cycle (D_{st}) for boost operation and the modulation index (Ma) for inverter operation; 2) determination of voltage and currents through different circuit components. The schematic of the BDHC with the reference current directions has been shown in Fig. The continuous conduction mode of operation has been assumed (the boost inductor current (i_L) never goes to zero).

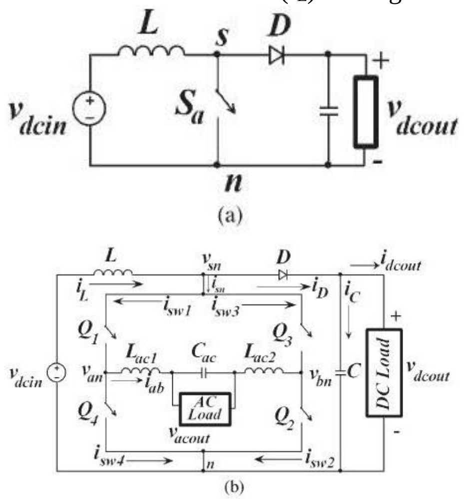

Fig.7 (a) Conventional boost converter. (b) Proposed BDHC obtained by replacing Sa with a single-phase bridge network.

Operating principle:

Each of the four bidirectional switches (Q1–Q4) of BDHC comprises the combination of a switch Si and an antiparallel diode Di (i = 1 to 4). The boost operation of the proposed converter can be realized by turning on both switches of any particular leg (either S1–S4 or S3–S2) simultaneously. However, for the proposed modification, this operation is equivalent to the switching "ON" of the switch "Sa" of the conventional boost converter as in Fig.8.

The ac output of the BDHC is controlled using a modified version of unipolar sine-PWM switching scheme. In the BDHC, the switch node voltage (V_{sn}) acts as the input to the inverter, it switches between the voltage levels—V_{dcout} and zero. The switching scheme should ensure that the interval for power transfer with the source occurs only when V_{sn} is positive, i.e., when V_{sn} is clamped to the dc output voltage V_{dcout}. The BDHC has three distinct switching intervals as described in the following.

1) Interval I—Shoot-through interval:

The equivalent circuit schematic of the BDHC during the shoot-through interval is shown in Fig 8(b). The shoot-through interval occurs when both the switches (either Q1–Q4 or Q3–Q2) of any particular leg are turned on at the same time. The duration of the shoot-through interval decides the boost converter duty cycle (D_{st}). The diode "D" is reverse biased during this period. The inverter output current circulates within the bridge network switches.

Diode current = 0, Inverter output voltage = 0

2) Interval II—Power interval:

The power interval, shown in Fig.8 (b) occurs when the inverter current enters or leaves the bridge network at the switch node "*s*". The diode "D" conducts during this period, and the voltage at the switch node (V_{sn}) is equal to the V_{dcout} (neglecting the diode voltage drop). In this interval, either Q1–Q2 or Q3–Q4 is turned on.

When Q_1 and Q_2 are ON: Voltage = V_{dcout}

When Q_3 and Q_4 are ON: Voltage = $-V_{dcout}$

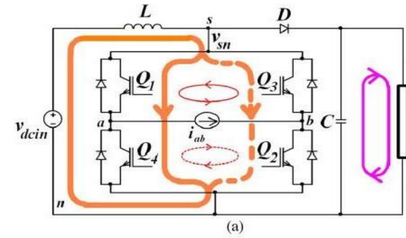

Fig 8(a) Equivalent circuit schematic of the BDHC during shoot through interval

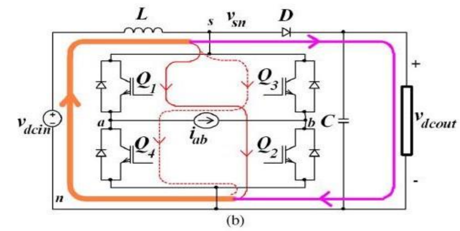

Fig 8 (b) Equivalent circuit schematic of the BDHC during power interval

3) Interval III—Zero interval:

The zero interval occurs when the inverter current circulates among the bridge network switches and is not sourced or sunk. The diode "D" conducts during this interval. Fig.8(c) shows the equivalent circuit for this interval.

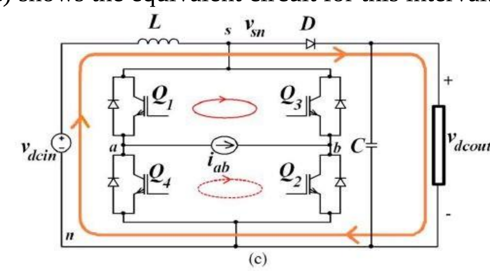

Fig 8 (c) Equivalent circuit schematic of the BDHC during zero interval.

Here,

Diode current = i_L, Inverter output Voltage = 0

Switching technique in BDHC

In BDHC, we should use a suitable technique of switching so that V_{sn} (Switch node voltage) have a frequency of nearly 10kHz and the output AC voltage should have a frequency of 50Hz. Table 3 shows the switching technique of the BDHC assuming frequency of V_{sn} to be 10kHz and frequency output AC voltage to be 50Hz.

Table 3: Switching technique in BDHC

Interval	S_1	S_2	S_3	S_4	
Shoot Through	1	0	0	1	Positive Half Cycle
Power	1	0	1	0	
Zero	0	0	0	0	

Shoot Through	0	1	1	0	Negative Half Cycle
Power	0	1	0	1	
Zero	0	0	0	0	

The switching technique for positive half cycle as shown in table 3 is for a period of T (Time period of V_{sn}). This should be repeated till 0.01sec (Period of positive half cycle). This should be followed by the switching technique for negative half cycle as shown in the table 3 till 0.02sec.

Designing of BDHC

Specifications for designing BDHC is shown in the table 4.

Table 4: Specifications of Boost Converter

Input Voltage	12V
DC load	50Ω
AC load	10Ω
DC Output Voltage	24V
Switching frequency (boost converter)	10kHz
Output frequency	50Hz
Voltage ripple	1.25%

Program results:

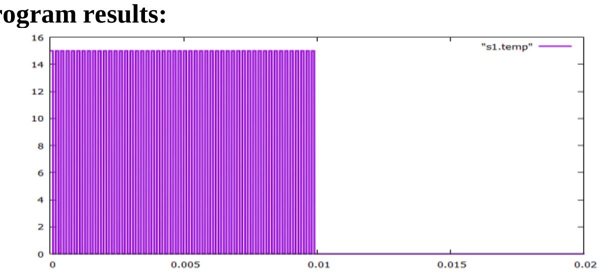

Fig 9 (a) **Switching action S_1**

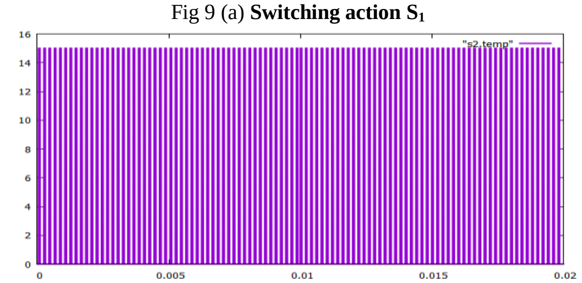

Fig 9 (b) **Switching action S_2**

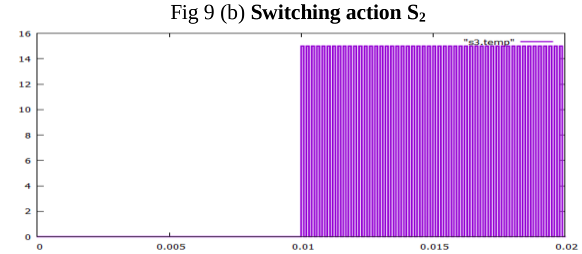

Fig 9 (c) **Switching action S_3**

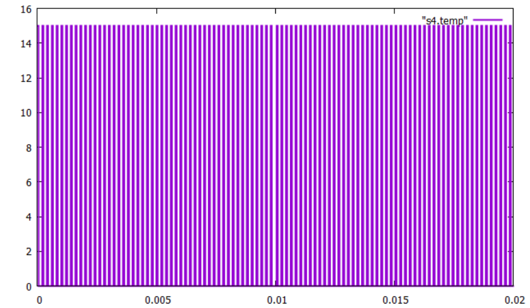

Fig 9 (d) **Switching action S_4**

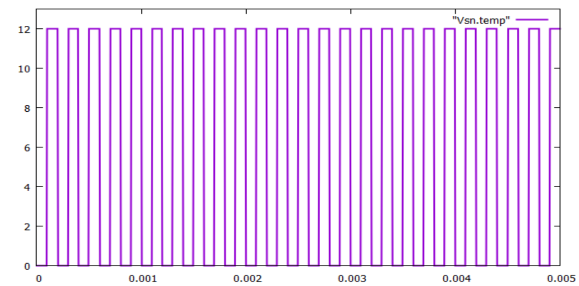

Fig 9 (e) **Switch node voltage:**

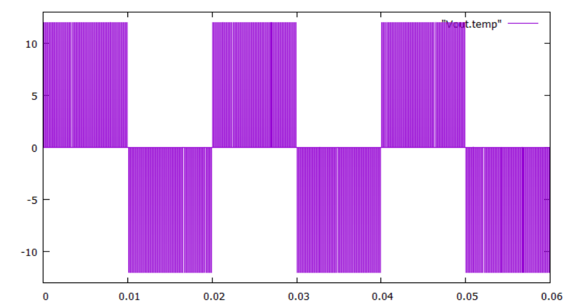

Fig 9 (f) **AC output voltage:**

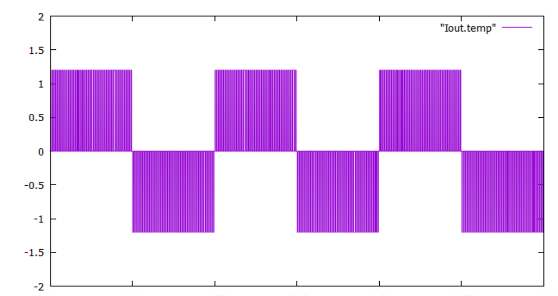

Fig 9 (g) **AC load current:**

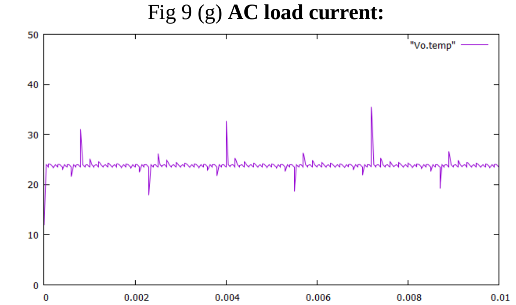

Fig 9 (h) **DC output voltage:**

V. CONCLUSION

This work presents new hybrid converter, Boost Derived Hybrid Converter (BDHC), which can supply simultaneously DC and AC loads from a single dc source. The converter has reliability and inherent shoot through protection. This converter reduces the conversion stages as compared to a DC-DC converter and an Inverter individually. This converter with better power processing density and reliability can be well suited for systems with simultaneous dc and ac loads, e.g., nano-grids in residential applications**.**

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