DESIGN AND ANALYSIS OF A HYBRID POWER CONVERTER

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Abstract

Hybrid converters have aroused significant attention in performing the multiple operations in a single converter. Further, it gives the economic operation and improves system performance. In this study, a new structure of hybrid power converter is proposed. It is formed by the simple switching structure and it can operate different modes of operation in DC-DC conversions, such as boost, buck and buck-boost mode. Similarly, in DC-AC conversion it gives better Total Harmonic Distortion (THD). The proposed hybrid converter is simulated in MATLAB/SIMULINK environment. Low power prototype circuit is developed and experimental results are validated with simulation results.

Keywords: DC-AC converters, DC-DC converters and hybrid converters.
1. Introduction

Hybrid converters (HYCs), has the following advantages over conventional solutions [1-4] that employ multiple single converters such as 1) lower cost characteristic because of sharing the reactive components and controlled switches. 2) Compact in size 3) High power density. Therefore, HYCs are good choice for nanogrid, electric vehicle (EVs) and photovoltaic applications, which is economic and therefore has good development prospects [5-7].

The HYCs are two types, such as isolated HYCs and non-isolated HYCs DC-DC converters. In isolated HYCs, converters are good candidates for the applications where galvanic isolation is required. However, the major problem is that too many active power switches are used, conversion efficiency gets lowered due to leakage losses, induces high voltage stress in the controlled switches. Similarly, the use of the transformer makes it massive [8-10].

Khan and Chowdhury [11] mentioned that multi-inductor voltage multiplier cell-based boost hybrid converter is proposed for high gain applications. However, it may not be performing the buck-boost operation. Axelrod et al. [12] suggested the switched inductor to the switched capacitor-based hybrid converter. It can improve the performance of the converter when the active switch ON period the inductors are charged in series and capacitors are discharged in parallel. Similarly, inactive switch OFF period, inductors are discharged in parallel and capacitors are charged in series.

Nevertheless, more device count, which leads, to increase the cost and the size of the converter. Bagewadi and Dambhare [13] and Harfman-Todorovic et al. [14] presented the new hybrid converter topology for nanogrid applications and fuel application. Dogga et al. [15], Siddhartha and Hote [16], Tomy and Thomas [17] and Sarath and Kanakasabapathy [18] introduced the conventional DC-DC converter based hybrid converters. These are effectively eliminating the shoot problems and, which is for suitable for nanogrid applications. Kim et al. [19] reported that the phase-shifted full-bridge (PSFB) based hybrid converter is suggested for electric vehicle chargers application. Although in this configuration, overcome the drawbacks of the conventional PSFB converter such as output filter, conduction losses and narrow zero voltage switching range. Kim et al. [20] introduced the hybrid dual full-bridge DC-DC converter for radiofrequency application.

Moreover, it overcomes the drawbacks of a conventional PSFB converter such as the size of the output filter and circulating currents. Zhang et al. [21] presented the hybrid step-down power factor correction (PFC) converter. It is combining the features of boost PFC and buck PFC converter. In addition, improves the peak current control scheme, which results achieve a high power factor. Vecchia et al. [22] proposed that switched capacitor-based hybrid DC-DC converter and it is derived from different types of converters, such as boost, buck, and buck-boost. It has the capability of achieving a high voltage gain with increased switched capacitor cell. However, a number of capacitors cause extra cost and big size.

In this paper, a hybrid converter is introduced, which consist of the DC-DC converter and H-bridge network. It can perform the DC-DC conversion and DC-AC conversion. In inverter operation, it gives better THD%. This paper is structured as follows. In Section 2, the proposed topology and different modes of operations are
discussed and parameter design is presented in Section 3. Section 4 gives the simulation and experimental results in different configurations followed by a conclusion in Section 5.

2. Operating Principle and Different Configurations of Proposed Converter

Hybrid converters are a relatively new class of power converters. These are single-stage converters and can be configured as a DC-DC converter with H-bridge network for hybrid power conversion applications. The schematic diagram of the proposed is shown in Fig. 1. Different configurations of the proposed converter are described in detail, corresponding equivalent circuits are shown and the voltage across the capacitor and current flows through the inductor are presented.

![Fig. 1. Proposed converter configuration.]

2.1. DC-DC converter

2.1.1. Buck mode

Mode 1

In this operating mode, the switching action happens between the switches $S_1$, $S_4$, $S_5$, $S_7$, and the remaining switches are turned OFF. In this mode, source port $V_{DC}$ supplies the energy to the load and inductor is energized. The corresponding equivalent circuit is shown in Fig. 2(a).

The current flows through an inductor current ($i_L$) and voltage across capacitor ($v_C$) equations as follows:

$$i_L(t) = \frac{V_{DC}}{R} + e^{-\alpha t} \left[ c_1 \cos \omega_d t + c_2 \sin \omega_d t \right]$$ (1)

$$v_C(t) = V_{DC} - \frac{L}{2C} e^{-\alpha t} \left[ \cos \omega_d t \left( \frac{\alpha c_1}{R} + \omega_d c_2 \right) + \sin \omega_d t \left( -\alpha c_2 + \frac{\omega_d c_1}{R} \right) \right]$$ (2)

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Mode 2

In this mode, the input supply is off and inductor $L$ is delivered its stored energy to the load resistance $R$ through the active switches $S_5$, $S_7$, and $S_9$. Inductor current ($i_L$) and voltage across the capacitor ($v_C$) equations in this state as follows.

$$i_L(t) = e^{-\alpha t} \left[ c_3 \cos \omega_d t + c_4 \sin \omega_d t \right]$$  \hspace{1cm} (3)

$$v_C(t) = -Le^{-\alpha t} \left[ (-\alpha c_3 + \omega_d c_4) \cos \omega_d t + \right.$$  
$$\left. (\omega_d c_3 - \alpha c_4) \sin \omega_d t \right]$$  \hspace{1cm} (4)

where

$$\alpha = \frac{1}{2RC}$$  \hspace{1cm} (5)

$$\omega_d = \frac{1}{2} \sqrt{\frac{1}{R^2C^2} - \frac{4}{LC}}$$  \hspace{1cm} (6)

The values of $c_1$, $c_2$, $c_3$ and $c_4$ are obtained from the initial conditions.
The output voltage \( V_0 \) expression of the proposed converter in buck mode.

\[
V_0 = dV_{DC} \tag{7}
\]

where ‘\( d \)’ is the duty cycle of the switch.

2.1.2. Boost operation

Mode 1

In this state, active switches \( S_1, S_2 \) are turned ON and the equivalent circuit in this mode is shown in Fig. 3(a). In this mode, the voltage source charges the inductor and capacitor is delivering its stored energy to the load resistance \( R \).

Current flows through an inductor \( (i_L) \) and the voltage across the capacitor \( (v_C) \) as follows:

\[
i_L(t) = \frac{V_{DC}}{L} t + i_{L(0)} \tag{8}
\]

\[
v_C(t) = v_{C(0)} e^{-\frac{1}{RCt}} \tag{9}
\]

Mode 2

The equivalent circuit in this state is shown in Fig. 3(b). During this mode, energy stored inductor is discharged and delivers its stored energy to the capacitor \( C \) and load \( R \) through the switches \( S_1, S_4, S_5, S_7 \), respectively.

![Equivalent circuits in boost mode.](image)
Current flows through an inductor and voltage across the capacitor as follows:

\[ i_L(t) = \frac{V_{DC}}{R} + e^{-at} \left[ c_1 \cos \omega_d t + c_2 \sin \omega_d t \right] \]  
\[ v_c(t) = V_{DC} - \frac{L}{2C} e^{-at} \left[ \cos \omega_d t \left( \frac{\alpha c_1}{R} + \alpha \omega_d c_2 \right) + \sin \omega_d t \left( -\alpha c_1 + \frac{\alpha \omega_d c_1}{R} \right) \right] \]  

The values of \( c_1 \) and \( c_2 \) obtained from the initial conditions. Output voltage expression of the proposed converter in boost mode.

\[ V_0 = \frac{V_{DC}}{(1 - d)} \]  
where 'd' is duty cycle of the switch.

### 2.1.3. Buck-boost mode

**Mode 1**

In this mode, controlled switches \( S_1, S_2 \) are turned ON and magnetizing inductor \( L \) is energized by the input supply \( V_{DC} \) is illustrated in Fig. 4(a). Similarly, the capacitor is releasing its stored energy to the load resistance \( R \).

The current flows through an inductor current \((i_L)\) and voltage across capacitor \((v_c)\) equations are as follows:

\[ i_L(t) = \frac{V_{DC}}{L} t + i_{L(0)} \]  
\[ v_c(t) = v_{c(0)} e^{\frac{-1}{RC}t} \]

**Mode 2**

In this state, energy stored in inductor \( L \) is released to the load resistance \( R \) through the switches \( S_5, S_7 \) and \( S_9 \). The corresponding equivalent circuit is depicted in Fig. 4(b). The voltage across the capacitor and current flows through an inductor equation can be expressed as follows:

\[ i_L(t) = e^{-at} \left[ c_1 \cos \omega_d t + c_2 \sin \omega_d t \right] \]  
\[ v_c(t) = -Le^{-at} \left[ (-\alpha c_1 + \alpha \omega_d c_2) \cos \omega_d t + (\omega_d c_1 - \alpha c_2) \sin \omega_d t \right] \]  

The values of \( c_1 \) and \( c_2 \) obtained from the initial conditions.

Output voltage expression of the proposed converter in buck-boost operation as follows:

\[ V_0 = \frac{V_{DC}d}{(1 - d)} \]

where 'd' is the duty cycle of the switch.
2.2. Inverter operation

The proposed topology is operated in inverter configuration, the corresponding mode of operation and equivalent circuits are shown in Fig. 5. It is obtained from the conventional DC-DC converter and H-bridge network. In this structure, suggested the approach gives better THD%.

Mode 1

In this mode, switch S1, S5, S7 and S4 are turned ON and the inductor is energized by the source port. The corresponding equivalent circuit is shown as follows.

Mode 2

In this state, supply voltage remains OFF energy stored inductor is de-energized through the switches S1, S1 and switch S9. The corresponding equivalent circuit is shown below. Mode 1 and Mode 2 are generating a positive level of the output voltage.
Mode 3
In this mode, switches $S_1$, $S_6$, $S_8$, and $S_4$ are turned ON and the inductor is energized by the input voltage. The corresponding equivalent circuit is shown below.

Mode 4
In this state, energy stored inductor is de-energized through the switches $S_6$, $S_8$ and switch $S_9$. The corresponding equivalent circuit is shown below. Modes 3 and 4 are generating the negative level of the output voltage.
Fig. 5. Operating modes of proposed converter in inverter configuration.

Output voltage

\[
V_{\text{rms}} = \sqrt{\frac{1}{T} \int_{0}^{T} V_{\text{DC}}^{2} dt}
\]  

\[
V_{\text{rms}}^{2} = \frac{V_{\text{DC}}^{2}}{T} \left[ \frac{d_{1}T + \frac{L}{2R} + \frac{2L}{R} e^{-\frac{L}{2R}}} {2L \frac{L}{2R} e^{-\frac{(d_{1}+d_{3})R}{L}}} \right]
\]

3. Parameters Design

The circuit design considerations mainly depend on magnetic components, capacitors, duty ratio, type of switches and switching frequency. Even though inductors and transformers are both magnetic components, there is a very important difference in their functioning and design aspect [23].

**Step 1.** Calculation of maximum and minimum power.

\[
P_{0\text{max}} = V_{0}I_{0\text{max}}
\]

\[
P_{0\text{min}} = V_{0}I_{0\text{min}}
\]

**Step 2.** Calculation of maximum and minimum of the load resistance.

\[
R_{L\text{max}} = \frac{V_{0}}{I_{0\text{min}}}
\]

\[
R_{L\text{min}} = \frac{V_{0}}{I_{0\text{max}}}
\]

**Step 3.** The voltage conversion ratio of the converter.

\[
M_{V\text{DC min}} = \frac{V_{0}}{V_{\text{DC max}}}
\]
\[ M_{V \text{DCmax}} = \frac{V_o}{V_{\text{DCmin}}} \]  \hspace{1cm} (22)

**Step 4.** Calculation of the duty cycle.

\[ D_{\text{min}} = \frac{M_{V \text{DCmax}}}{\eta} \]

\[ D_{\text{max}} = \frac{M_{V \text{DCmin}}}{\eta} \]  \hspace{1cm} (23)

where ‘\( \eta \)’ is efficiency.

**Step 5.** Calculation of minimum inductance.

\[ L_{\text{min}} = \frac{R_{L_{\text{max}}} (1 - D_{\text{min}})}{2f_s} \]  \hspace{1cm} (24)

\( f_s \) = switching frequency

**Step 6.** Selection an inductance \( L \), which is greater \( L_{\text{min}} \) and \( \Delta i_{L_{\text{max}}} \) are computed as:

\[ \Delta i_{L_{\text{max}}} = \frac{V_o (1 - D_{\text{max}})}{f_s L} \]  \hspace{1cm} (25)

**Step 7.** Calculation of filter capacitance.

\[ C_{\text{min}} = \frac{D_{\text{max}}}{2f_s r_c} \]  \hspace{1cm} (26)

where

\[ r_{C_{\text{max}}} = \frac{V_f}{\Delta i_{L_{\text{max}}}} \]  \hspace{1cm} (27)

4. **Simulation and Experimental Results**

4.1. **Simulation results**

The simulations are performed to evaluate the operation of the proposed converter using MATLAB/Simulink. The test was conducted in different modes such as DC-DC and DC-AC mode. The input voltage is considered 50 V, the duty cycle of 60\%, switching frequency is 10 kHz, the capacitor value is 120 uF and the inductor value is chosen 5 mH. Simulation output voltage and inductor current in a step-down mode are depicted in Fig 6(a), 6(b) respectively. In this mode, from Fig. 6(b) \( I_{\text{Final}} \) value is 2.57 A and \( I_{\text{Initial}} \) value is 2.43 A. In boost and buck-boost operation, output voltage and inductor are shown in Figs. 7(a) and (b) and 8(a) and (b) respectively. In boost operation, from Fig. 7(b), \( I_{\text{Final}} \) value is 3.12 A and \( I_{\text{Initial}} \) value is 2.9 A. Similarly, buck-boost mode, from Fig. 8(b), \( I_{\text{Final}} \) value is 5.01 A and \( I_{\text{Initial}} \) value is 4.798 A. In inverter configuration, the input voltage is set to be 50 V and inductor value 19 mH is considered. The corresponding output voltage, load current, and FFT analysis are illustrated in Figs. 9(a) to (c) respectively.

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Fig. 6. Simulation results in buck operation.

(a) Output voltage.

(b) Inductor current.
Fig. 7. Simulation results in boost operation.

(a) Output voltage.

(b) Inductor current.

Fig. 8. Simulation results in buck-boost mode.

(a) Output voltage.

(b) Inductor current.
Fig. 9. Simulation results in inverter operation.
4.2. Experimental results

In order to verify the effectiveness of the proposed converter, low power prototype circuit is developed in the laboratory. It is tested under the buck, boost, buck-boost and inverter operations. In DC-DC conversion, the test was performed with the input voltage is 50 V, the duty cycle of $D = 60\%$, inductor value is 5 mH, the capacitor is 200 uF and switching frequency 10 kHz is chosen. dSPACE1104 is used as a core controller for generating a controlling signal for active switches IGBT’s (STGW30NC120HD). In the buck mode, the experimental output voltage and current flow the inductor are depicted in Figs. 10(a) and (b) respectively. Similarly, output voltage and inductor current in the boost is illustrated in Figs. 11(a) and (b), these are close to the theoretical and simulation results. In addition, output voltage and inductor current in the buck-boost state are shown in Figs. 12(a) and (b) respectively. Afterwards, the proposed converter was tested in inverter configuration, with an input voltage of 50 V and an inductor value is 19 mH, 20 A. Corresponding output voltage load current and FFT analysis are shown in Figs. 13(a), to (c) respectively. Experimental setup developed in the laboratory is shown in Fig. 14.

(a) Output voltage (Voltage: 50 V/div, time: 500 us/div).

(b) Inductor current (Current: 2 A/div, Time: 100 us/div).

Fig. 10. Experimental results in buck mode.
Fig. 11. Experimental results in boost operation.

(a) Output voltage (Voltage: 100 V/div, Time: 500 us/div).

(b) Inductor current (Current: 2 A/div, time: 100 us/div).

(a) Output voltage (Voltage: 100 V/div, time: 500 us/div).
Fig. 12. Experimental results in buck-boost operation.

(a) Output voltage (Voltage: 20V/div, Time: 10 ms/div).

(b) Inductor current (Current: 5 A/div, time: 100 us/div).

(b) Load current (Current: 5A/div, time: 10 ms/div).
4. Conclusions

A family of the hybrid converter has been proposed in this paper. The proposed hybrid converter is obtained by combining the traditional DC-DC converter and H-bridge network. The topology, operating principle and different modes of operations are explained in detail. In DC-DC conversion, it can be performed the boost, buck and buck-boost modes, similarly in DC-AC conversion suggested approach is given better THD. Finally, the low power prototype circuit has been developed and experimental results are validated with simulation results.

Nomenclatures

\[ i_L \] Inductor current
\[ v_C \] Voltage across capacitor
\[ V_{DC} \] Input voltage

### Abbreviations

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<thead>
<tr>
<th>Abbreviation</th>
<th>Description</th>
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<tbody>
<tr>
<td>EV</td>
<td>Electrical Vehicle</td>
</tr>
<tr>
<td>HYC</td>
<td>Hybrid Converter</td>
</tr>
<tr>
<td>PFC</td>
<td>Power Factor Correction</td>
</tr>
<tr>
<td>THD</td>
<td>Total Harmonic Distortion</td>
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### References


