Hybrid Multi Output Converter for Microgrid Applications

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Abstract

The paper proposes a single stage hybrid multi-output converter with two independent DC sources (e.g. DC battery, PV cell, Fuel cell etc.) having same voltage and three isolated outputs (two DC, one AC). The proposed converter topology does away with extra switches / conversion units which would otherwise be present in case of conventional converter systems supplying both ac and dc loads. This would reduce the cost of energy conversion and overall efficiency of system increases. The AC output obtained is of high frequency which is suitable for loads like fluorescent lighting and induction cooking. Such a conversion system can be of great utility in microgrids and various industrial applications. The simulation as well as hardware realization of this proposed topology is presented.

Keywords: Hybrid multi output converter, Pulse Width Modulation (PWM), Design Parameters for Converter, Small Signal Analysis of Buck Converter, High Frequency AC loads

I. INTRODUCTION

The world’s electricity demand has been growing rapidly for the past few years. Availability of reliable power supply is a major goal of all nations. For meeting this goal, renewed focus is being given to Distributed Generation (DG). The advancements in power electronics and renewable energy, free trade of power, and environmental problems associated with conventional generation have led to increased impetus towards having stand-alone power systems which supply the local loads. The energy sources of
such a network may be green sources like solar energy, wind energy, fuel cell etc. Such a network of distributed energy sources and loads, coupled using power electronic converters, forms a microgrid, as shown in Fig. 1. A microgrid can be integrated with the conventional grid using Point of Common Coupling (PCC). The microgrids can be classified into:

- Dc microgrid
- Ac microgrid
- Hybrid microgrid

DC microgrid provides higher system efficiency than ac microgrid due to absence of losses due to no-load equipment and skin effect. Frequency stability and reactive power issues are not present in dc distribution systems [1-3]. However, various loads are present in a microgrid. Thus, there is power conversion at various stages to meet the requirements of different loads, as shown in Fig. 2.

Fig. 1. A typical dc microgrid
Fig. 2. Multi stage conversions in a dc microgrid

There may be a battery supplying power to an inverter which then supplies ac as well as dc loads. Thus, there is decrease in efficiency due to multiple conversion stages. A separate dc to dc converter may be used to supply loads like small dc fans, dc motors etc. Multistage conversion for most of the domestic and industrial ac/dc loads running on dc power supply adds to the cost of the entire system (since more power electronic converters are needed) and reduces the overall efficiency. A single stage energy conversion would reduce cost of the system and increase its efficiency.

Hybrid output converters are the converters which can supply simultaneous ac and dc loads from a single dc input. They require lesser number of switches, have increased reliability, greater power processing density. They are very useful for microgrid applications having both ac and dc loads [4-8].

Power electronic converters provide energy conservation at reduced operating cost and increased safety in residential and industrial applications, which include space heating, air conditioning, water heating, cooking, lighting, clothes washing and drying etc. Some of the most important applications of high frequency ac supply are fluorescent lighting and induction cooking. Energy efficiency of fluorescent lamps can be increased by almost 20-30% when they are operated at high frequency compared to their line frequency counterparts [9]. Induction based cooking systems utilize fraction of electrical energy compared to the thermal cooking based system. They employ high frequency ac supply for inducing circulating current in the cooking pan placed on top of the induction coil.

The proposed converter is a single stage hybrid multi output converter, with dc energy storage systems which can be charged through the distributed energy sources present in the microgrid, or using conventional grid during off peak hours.

This paper consists of seven sections. Section I is the introduction. In section II, proposed Hybrid multi output converter topology has been discussed. In section III, modes of operation have been discussed. Section IV discusses design and simulation of the converter. In section V, small signal analysis of the converter is presented. Section VI discusses experimental setup and experimental results. Finally section VII concludes the paper.
II. PROPOSED HYBRID MULTI OUTPUT CONVERTER

The proposed hybrid multi output converter is shown in Fig. 3, having two dc sources, each dc source having a potential difference of $V_{dc}/2$. The dc sources are three terminal dc sources. The proposed converter circuit topology consists of three parts; one half bridge inverter with one ac output and two buck converters with one dc output each. This configuration is arranged in such a way so as to minimize the number of switches. This configuration uses four switches ($S_1, S_2, S_3, S_4$) and two dc sources, rather than six switches and three dc sources needed for independent converters (one switch and one dc source for each buck converter and four switches and one dc source for full bridge inverter). The first part consists of buck converter having switch $S_3$, diode $D_1$, capacitor $C_1$ and inductor $L_1$. The dc load 1 is connected across this buck converter. The second part consists of buck converter having switch $S_2$, diode $D_2$, capacitor $C_2$ and inductor $L_2$. The dc load 2 is connected across this buck converter. The third part is half bridge inverter having switches $S_1$ and $S_4$. An ac load is connected across this inverter. The gate pulses for switches $S_1, S_2, S_3$ and $S_4$ are shown in Fig. 4. A dead-band of 10 microseconds is provided between switching of $S_1$ and $S_4$ to avoid short circuit of battery which may damage the switches as well as battery. This converter operates in two modes.

![Fig. 3. Circuit topology](image)

![Fig. 4. Gate Signals](image)
III. MODES OF OPERATION

**Mode 1:** Switch $S_3$ and $S_4$ are turned on. Dc voltage is obtained across the first dc-dc buck converter and also negative half cycle of ac voltage is obtained across the ac load. The inductor $L_2$ supplies current to the dc load 2 and diode $D_2$ is forward biased. The switching diagram for mode 1 operation is shown in Fig.5, and output voltage is shown in Fig.7.

![Mode 1 Schematic Diagram](image1)

**Mode 2:** Switch $S_1$ and $S_2$ are turned on. Dc voltage is obtained across the second dc-dc buck converter and also positive half cycle of ac voltage is obtained across the ac load. The inductor $L_1$ supplies current to the dc load 1 and diode $D_1$ is forward biased. The switching diagram for mode 2 operation is shown in Fig.6, and output voltage is shown in Fig.7.

![Mode 2 Schematic Diagram](image2)


**IV. DESIGN AND SIMULATION**

When the switches $S_3$ and $S_4$ are ON, the power source is connected to the upper buck converter. Diode $D_1$ is reverse biased. The current flows through switch $S_3$, inductor $L_1$, and dc load 1. The current through inductor $L_1$ increases as long as switch $S_3$ is ON. In the lower buck converter, switch $S_2$ is OFF. The inductor $L_2$ supplies current to the dc load 2 and the diode $D_2$ is forward biased. The current through inductor $L_2$ keeps decreasing during this time. The ripples in the inductor currents $\Delta i_{L1}$ and $\Delta i_{L2}$ during time interval $T_1$ (turn-on time of switch $S_3$) are given by [10]

\[
\Delta i_{L1} = \frac{(v_{DC/2}-v_o)}{L_1} T_1
\]

\[
\Delta i_{L2} = \frac{(-v_o)}{L_2} T_1
\]

When the switches $S_1$ and $S_2$ are ON, the power source is connected to the lower buck converter. Diode $D_2$ is reverse biased. The current flows through switch $S_2$, inductor $L_2$, and dc load 2. The current through inductor $L_2$ increases as long as switch $S_2$ is ON. In the upper buck converter, switch $S_3$ is OFF. The inductor $L_1$ supplies current to the dc load 1 and the diode $D_1$ is forward biased. The current through inductor $L_1$ keeps decreasing during this time. The ripples in the inductor currents $\Delta i_{L1}$ and $\Delta i_{L2}$ during time interval $T_2$ (turn-on time of switch $S_2$) are given by [10]

\[
\Delta i_{L1} = \frac{(-v_o)}{L_1} T_2
\]

\[
\Delta i_{L2} = \frac{(v_{DC/2}-v_o)}{L_2} T_2
\]

The ripples in the output voltage as well as current should be low for better performance [10-12]. For desired performance parameters, the value of inductor used can be derived as [10],

\[
L = \frac{V_{dc/2}D(1-D)}{f_s\Delta i}
\]

Where $D$ is the duty ratio of the switch, $V_{dc/2}$ is the battery potential difference, $f_s$ is the switching frequency of the switch, $\Delta i$ is the maximum current ripple allowed in the inductor, $\Delta v_o$ is the maximum allowed ripple in output voltage.

The output voltage ripple is equal to the capacitor voltage ripple. The value of capacitor can be derived as [10],

\[
C = \frac{\Delta i}{8f_s\Delta v_o}
\]

The values of inductor and capacitor for buck converter are calculated for load current 1A, $\Delta v_o=5\%$, $\Delta i=10\%$, $V_{dc/2}=12V$, switching frequency=1000 Hz, duty ratio of switch=0.5. Therefore, $\Delta i=0.1A$ and $\Delta v_o=0.3V$. The parameter values obtained from (5) and (6) are $L=30mH$ and $C=42\mu F$. 

Following parameters (Table I) have been used for simulation

**Table I. Parameters used for simulation**

<table>
<thead>
<tr>
<th>Parameters/Components</th>
<th>Attributes</th>
</tr>
</thead>
<tbody>
<tr>
<td>Input Voltage ($V_{DC}/2$)</td>
<td>12 V</td>
</tr>
<tr>
<td>Switching Frequency ($f_s$)</td>
<td>1 kHz</td>
</tr>
<tr>
<td>Inductor (L1 and L2)</td>
<td>30 mH</td>
</tr>
<tr>
<td>Capacitor (C1 and C2)</td>
<td>42 µF</td>
</tr>
<tr>
<td>dc Load 1</td>
<td>6 Ω</td>
</tr>
<tr>
<td>dc Load 2</td>
<td>6 Ω</td>
</tr>
<tr>
<td>ac Load</td>
<td>12 Ω</td>
</tr>
</tbody>
</table>

MATLAB/SIMULINK has been used for simulation work. Open loop operation has been developed which can be extended to closed loop operation, in case of tightly regulated output supply using weighted voltage mode control strategy.

The simulation results are shown in Fig. 7. From Fig. 7, we can observe that when switch $S_3$ and $S_4$ are ON, the voltage across dc load 1 is increasing, voltage across dc load 2 is decreasing and negative half cycle of ac voltage is obtained. When switch $S_1$ and $S_2$ are ON, the voltage across dc load 2 is increasing, voltage across dc load 1 is decreasing and positive half cycle of ac voltage is obtained.

Fig. 8 shows the output voltage and current of buck converter 1. From this figure, we can observe that the ripples in current and voltage are within the desired range. The voltage ripple is less than 0.3 V, and current ripple is less than 0.1 A.

![Fig. 7. Simulation output with design values](image-url)
V. SMALL SIGNAL ANALYSIS OF PROPOSED CONVERTER

State space averaging is used to describe a circuit that changes over a switching cycle. Two sets of state equations: one set for the switch closed and other set for switch open are averaged over the switching period [10,13,15]. Steady state and small signal analyses are separated by the assumption that the variables are perturbed around the steady state operating point. In the proposed topology, there are two buck converters. The small signal analyses is shown for one of these identical buck converters. The state variables are inductor current and voltage across capacitor.

For switch closed, the state space representation is

\[
\begin{align*}
\dot{x} &= A_1 x + B_1 V_S \\
v_o &= C_1^T x
\end{align*}
\]

(7) (8)

Where, from [13],

\[
A_1 = \begin{bmatrix}
-r_c & -1 \\ 
L & L \\ 
1 & -1 \\
C & RC
\end{bmatrix}
\]

\[
B_1 = \begin{bmatrix}
1 \\ L \\
0
\end{bmatrix}
\]

\[
C_1^T = [r_c \\ 1]
\]

Where \(r_c\) is the equivalent series resistance (ESR) of the capacitor, \(L\) is the inductance in the buck converter circuit, \(C\) is the capacitance of the buck converter circuit, \(V_s\) is the supply voltage, \(v_o\) is the output voltage, and \(d\) is the duty ratio of the switch. For switch open,

\[
\dot{x} = A_2 x + B_2 V_S
\]

(9)
Here, $A_1=A_2$, $B_2=0$, $C_1^T=C_2^T$.

Weighing the state variables over one switching period gives

\[ \dot{x}d = A_1xd + B_1Vs d \] (10)

And,

\[ \dot{x}(1-d) = A_2x(1-d) + B_2Vs (1-d) \] (11)

The steady state output is $V_o=VsD$, where $V_o$, $Vs$ and $D$ are the steady state values of output voltage, supply voltage and duty ratio respectively. The small signal transfer characteristic is developed as

\[ \ddot{x} = A\dot{x} + BVs \dot{d} \] (12)

\[ \tilde{V}_o = C^T \ddot{x} \] (13)

Where $\dot{x}$, $\dot{d}$, $\dot{V}_o$, $\ddot{x}$ represent the small signal values.

The transfer function of output to variations in the duty ratio (when $r_c<<R$) is obtained as [12],

\[ \frac{\tilde{V}_o(s)}{\dot{d}(s)} = \frac{Vs}{LC} \left[ \frac{1+sr_cC}{s^2+s(1/RC+r_C/L)+1/LC} \right] \] (14)

For the design values obtained in Section IV, i.e. $L=30\text{mH}$, $C=42\mu\text{F}$, $R=6\Omega$, $r_c=0.5\Omega$, $Vs=12\text{V}$,

\[ \frac{\tilde{V}_o(s)}{\dot{d}(s)} = \frac{200s + 9523810}{s^2 + 3985s + 793651} \]

For $L=10\text{mH}$, $C=10\mu\text{F}$, $R=50\Omega$, $r_c=0.5\Omega$, $Vs=12\text{V}$,

\[ \frac{\tilde{V}_o(s)}{\dot{d}(s)} = \frac{600s + 120000000}{s^2 + 3985s + 793651} \]

The bode plots for above transfer functions are shown in Fig.9. The Phase margins are 68.2 deg and 14.4 deg, with gain crossover frequencies of $2.18e+03 \text{rad/sec}$ and $1.13e+04 \text{rad/sec}$ for $L=30\text{mH}$, $C=42\mu\text{F}$ and $L=10\text{mH}$, $C=10\mu\text{F}$ respectively.
VI. EXPERIMENTAL SETUP

The experimental setup for realizing the proposed converter is shown in Fig.10. An experimental power electronic bed consisting of six IGBT legs with twelve IGBTs and six power diodes is used. Four IGBTs and two diodes have been used for realizing the proposed converter circuit. Capacitor is not connected across load. The gating signals for the IGBT’s have been generated using TMS320F28335 digital signal controller [14]. However, the output of Digital Signal Controller is not sufficient to drive the IGBT’s. Thus, a TLP 250 based driver circuit has been used to enhance the voltage level of gating pulses and to isolate the controller from the power circuit. Following parameters (Table II) have been used for experimental study.

**Table II.** Parameters used for experimental study

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</tr>
<tr>
<td>dc Load 2</td>
<td>50 Ω</td>
</tr>
<tr>
<td>ac Load</td>
<td>50 Ω</td>
</tr>
</tbody>
</table>

The gate signals generated by the driver circuit are shown in Fig.11. The switches operate in pairs (S<sub>1</sub>-S<sub>2</sub> and S<sub>3</sub>-S<sub>4</sub>) with a duty ratio of 0.5. While giving gating pulses
to the switches, to avoid short circuit, a dead-band of 10 micro-seconds is given between alternating between the two pair of switches. The experimental output of proposed circuit is shown in Fig.12. Two chopper outputs (pink and blue), and one inverter ac output (yellow) are obtained. The frequency of ac output obtained is 1 kHz.
VII. CONCLUSION
In this paper, a single stage hybrid multi output converter is proposed. The desired design values of inductor and capacitor are calculated. The simulation of the above converter is shown using MATLAB/SIMULINK for the calculated design values. The simulated output is in accordance with the design parameters. The small signal analysis of the proposed converter is also shown. For the experimental setup, gating pulses are generated using TMS320F28335 Digital Signal Controller, and the converter experimental results are obtained. This converter can be used for domestic/industrial applications, where both dc and ac loads are present. The ac output is at a high frequency, which is suitable for applications requiring high frequency ac input, like induction heating etc.

REFERENCES
Hybrid Multi Output Converter for Microgrid Applications


