Non-isolated high gain DC-DC converter for smart grid- A review

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Abstract. Smart grids are becoming the most interesting and promising alternative for an electric grid system. Power conditioning units and control over the distribution of power is the essential feature for the smart grid system. In this paper, we reviewed several non-isolated high gain topologies derived from boost converter for providing required voltage to the grid tie inverter from renewable energy sources. Steady state analysis of all the topologies is analyzed to compare the performance of the topologies. Simulation is carried out in nL5 simulator and the results are compared and validated with the theoretical results. This paper is a guide to the researchers to choose the best topology for the smart grid application.

Keywords. Non-isolated DC-DC converter, high gain, Boost converter, Voltage gain, Voltage stress, Energy volume

1. INTRODUCTION

In conventional grid infrastructure due to several problems, leads to increase in the failure due to the continuous usage of the system. Challenges like power system stability, security, reliability, losses occur due to long transmission and distribution system, where the customers are located at a very far distance, traditional electric grid not able to respond quickly to the sudden changes in the peak demand, increase in the load, it does not have the storage capacity which can be used as a backup for the system. Due to the lack of storage system the generated power cannot be utilized for the further, if excess power is produced. How much ever power generated has to be utilized at the same time or else the power generated is wasted because of this issue. If there is a sudden increase in demand the system might collapse and it won’t be able to supply power to the utility. For this reason, always it has to generate more power that the current demand to meet out the sudden increase in the load demand. Figure 1 presents the sources and consumers in the smart grid.

![Figure 1. Smart grid](image-url)
To overcome all these problems an interactive modern grid system introduced to interface all renewable and non-renewable energy resources to the grid network called as Smart grid. Smart grid is an intelligent network which can manage almost all the issues faced by the traditional power grid network. Smart grid network increases the reliability, efficiency, social benefits, accommodate both renewable and non-renewable energy sources in a better way, adapts to the further increase in power demand with increase in cost. Advancement in the digital communication field helps this system to exchange data efficiently and this also improves the responsiveness of the grid network. Smart grid a great revolution in electrical grid systems with its computer intelligence and advancement in the field of communications and it is able to build a nation with energy efficient, secured system from generation, transmission till it reaches the consumer places like home, industries, and factories. They are converted to smart places. DC-DC converter plays a major role in smart grid system [1] [2].

The paper is organized as follows: High gain topologies are chosen and the steady state analysis is carried out in the section 2. Advantage of the converters is compared theoretically to study the gain and energy volume of the inductor in the converters and the results are presented in the section 3. Section 4 presents the simulation results to validate the theoretical results. Finally, the paper is concluded in the section 5.

2. HIGH GAIN TOPOLOGIES WITH BOOST CONVERTER

Figure 2 furnishes the various high gain topologies based on boost converter. To make a review on the high gain topologies, few techniques are considered and compared to study the features of the converter.

2.1 Cascaded boost converter

This converter is obtained by cascading two boost converters. The gain of the converter is improved by the addition of one more converter in series with the traditional boost converter [3][4]. Total power of the converter is processed twice which increases the losses of the converter. As a result of this, the efficiency of the converter is reduced. Figure 3 offers the cascaded boost converter.

2.1.1. Steady state analysis of cascaded boost converter. Voltage across the inductors and current through the capacitor during ON and OFF mode is given as

\[ V_{L1} = V_g; V_{L2} = V_{C1} \ldots \text{ ON mode} \] (1)
\begin{equation}
V_{L1} = V_{g} - V_{C1}; \quad V_{L2} = V_{C1} - V_{0} \quad \text{OFF mode} \quad (2)
\end{equation}

\begin{equation}
I_{C1} = -I_{L2}; \quad I_{C2} = -I_{0} \quad \text{ON mode} \quad (3)
\end{equation}

\begin{equation}
I_{C1} = I_{L1} - I_{L2}; \quad I_{C2} = I_{L2} - I_{0} \quad \text{OFF mode} \quad (4)
\end{equation}

Applying volt-sec balance principle and amp-sec balance to the equation (1)-(4), the following equation are obtained

\begin{equation}
V_{0} = \frac{V_{g}}{[1 - D]^{2}} \quad (5)
\end{equation}

\begin{equation}
I_{L1} = \frac{I_{0}}{[1 - D]^{2}}; \quad I_{L2} = \frac{I_{0}}{1 - D} \quad (6)
\end{equation}

Equation (5) and (6) give the output voltage and inductor current of the cascaded boost converter.

### 2.2 Dual boost converter

Dual boost converter is designed to obtain the output voltage as $V_{C1} + V_{C2} - V_{g}$ and the input current of the converter is $I_{L1} + I_{L2} - I_{0}$. Fig 4 presents the dual boost converter. It has floating load connection [5]. The converter is best suited for high power application by incorporating interleaving technique.

![Dual boost converter](image)

**Figure 4. Dual boost converter**

#### 2.2.1. Steady state analysis of Dual boost converter

\begin{equation}
V_{L1} = V_{g}; \quad V_{L2} = V_{g} \quad \text{ON mode} \quad (7)
\end{equation}

\begin{equation}
V_{L1} = V_{C1} - V_{g} \quad \text{ON mode}; \quad V_{L2} = V_{C2} - V_{g} \quad \text{OFF mode} \quad (8)
\end{equation}

\begin{equation}
I_{C1} = -I_{0}; \quad I_{C2} = -I_{0} \quad \text{ON mode} \quad (9)
\end{equation}

\begin{equation}
I_{C1} = I_{L1} - I_{0}; \quad I_{C2} = I_{L2} - I_{0} \quad \text{OFF mode} \quad (10)
\end{equation}

Applying volt-sec balance principle and amp-sec balance to the equation (7)-(10), the following equation are obtained

\begin{equation}
V_{0} = \frac{[1 - D]V_{g}}{[1 + D]} \quad (11)
\end{equation}

\begin{equation}
I_{L1} = \frac{I_{0}}{[1 - D]} \quad (12)
\end{equation}

Equation (11) and (12) give the output voltage and inductor current of the dual boost converter.

### 2.3 Interleaved boost converter with voltage multiplier cell

Interleaved boost converter attracted many researchers due its low input ripple current. It consists of boost cell connected in parallel. Soft switching is achieved by integrating additional active switches. The important feature of this converter is higher power output with low ripple. Figure 5 gives the
interleaved boost converter with voltage multiplier cell [6]. Voltage multiplier is added to increase the gain of the converter.

![Interleaved boost converter with voltage multiplier cell](image)

Figure 5. Interleaved boost converter with voltage multiplier cell

2.4 Boost converter with high gain cell

This converter is achieved by adding an high gain cell to the boost converter. The gain of the converter is similar to the dual boost converter. It achieves this gain with single switch and same number of components of the dual boost converter. Fig 6 offers the circuit diagram of boost converter with high gain cell.

![Boost converter with high gain cell](image)

Figure 6. Boost converter with high gain cell

3. COMPARISON OF THE TOPOLOGIES

The advantage of the topologies are compared by theoretically deriving the formula for switch voltage stress and determining the energy volume of the inductors. Table 1 gives the comparison of all the topologies. Table 1 presents the Inductor design equation and energy volume of the topologies.

| Parameter                      | Cascaded boost converter | Dual boost converter | Interleaved boost converter with VM cell | Boost converter with HG cell |
|--------------------------------|--------------------------|----------------------|----------------------------------------|-----------------------------|
| Voltage gain                   | $\frac{1}{[1 - D_1][1 - D_2]}$ | $1 + D$               | $2$                                    | $1 + D$                     |
| No of switches                 | 2                        | 2                    | 2                                      | 1                           |
| No of diodes                   | 2                        | 2                    | 2                                      | 2                           |
| No of passive components       | 4                        | 4                    | 5                                      | 5                           |
| Voltage stress across switch   | $V_{S1} = \frac{V_g}{1 - D_1}$ | $V_{S1} = \frac{V_g}{1 - D}$ | $V_{S1} = \frac{V_g}{1 - D}$ | $V_S = \frac{V_g}{1 - D}$ |
|                               |                          | $V_{S2} = \frac{V_g}{1 - D}$ | $V_{S2} = \frac{V_g}{1 - D}$ |                             |
|                               |                          | $V_{S2} = \frac{V_g}{1 - D}$ | $V_{S2} = \frac{V_g}{1 - D}$ |                             |
|                               |                          | $V_{S2} = \frac{V_g}{1 - D}$ | $V_{S2} = \frac{V_g}{1 - D}$ |                             |
Figure 7. Duty cycle Vs voltage gain

Figure 8. Total energy volume of the topologies

Figure 7 and 8 present the comparative graph of the topologies with respect to the voltage gain and energy volume of the inductor respectively. From figure 7, we infer that the interleaved boost converter with VM cell has high gain compared to all the converter with duty cycle less than 0.5. However, it has less voltage gain for D > 0.5. Cascaded boost converter has very high gain for large duty cycle. It is also observed that the cascaded boost converter’s switch voltage stress is high compared to other topologies. From figure 8, we observed that the interleaved boost converter with VM cell has less total energy volume which in turn reduces the size and weight of the converter.

Table 2. Inductor design equation and energy volume of the topologies

| Parameter  | Casceded boost converter | Dual boost converter | Interleaved boost converter with VM cell | Boost converter with HG cell |
|------------|--------------------------|----------------------|----------------------------------------|-----------------------------|
| L1         | $\frac{R[1-D]^4D}{2f_s}$ | $R[1-D]^2D$          | $\frac{R[1-D]^2D}{4f_s}$              | $\frac{R[1-D]^2D}{2[1+D]^2f_s}$ |
| L2         | $\frac{R[1-D]D^2}{2f_s}$ | $\frac{2[1+D]Df_s}{4}$ | $\frac{2[1+D]f_s}{4}$               | $\frac{R[1-D]^2}{2[1+D]}$   |
| I_L1       | $\frac{1}{[1-D]}$       | $\frac{1}{[1-D]}$    | $\frac{1}{[1-D]}$                    | $\frac{1}{[1-D]}$            |
| I_L2       | $\frac{1}{[1-D]}$       | $\frac{1}{[1-D]}$    | $\frac{1}{[1-D]}$                    | $\frac{1}{[1-D]}$            |
| Total Energy volume | 0.211 mJ | 0.0723 mJ | 0.0626 mJ | 0.146 mJ |
4. Simulation results and Discussion

Simulation is carried out in the n15 simulator. The simulation data for all the topologies are tabulated in the table 3. Figure 9 and 10 give the simulation results of the cascaded and dual boost converter respectively. We simulated all the topologies to validate the theoretical results. Simulation results of first two topologies are presented as proof of the analysis.

| Parameter | Cascaded boost converter | Dual boost converter | Interleaved boost converter with VM cell | Boost converter with HG cell |
|-----------|--------------------------|----------------------|----------------------------------------|-----------------------------|
| \( V_g = 12 \text{V}, \ V_o = 96 \text{V}, \ P_o = 40 \text{W}, \ f_s = 60 \text{kHz}; \ R = 230 \text{Ω}; \ I_o = 0.417 \text{A} \) |
| \( L_1 \) | 19 \text{uH} | 44 \text{uH} | 45 \text{uH} | 25 \text{uH} |
| \( L_2 \) | 155 \text{uH} | 44 \text{uH} | 45 \text{uH} | 191 \text{uH} |
| \( D \) | 0.646 | 0.77 | 0.75 | 0.77 |

Figure 9. Simulation results of cascaded boost converter (Output voltage switch stress voltage)

Figure 10. Simulation results of dual boost converter (Output voltage switch stress voltage)
5. CONCLUSION
A comprehensive review on boost converter based high gain topologies are carried out and the results are presented. Simulation and theoretical results are compared to validate the analysis. We concluded the results of the study as follows.

- Interleaved boost converter with VM cell is found to be superior compared to all the other topologies.
- The total energy volume of the interleaved boost converter with VM cell is very less compared to other topologies and it is just 30 % of the total energy volume of the cascaded boost converter for the same power and voltage rating.
- The switch voltage stress of the interleaved boost converter with VM cell is very less.
- Interleaved structure adds advantage to the topologies in reducing the ripples of the input current.

Due to the advantages of the interleaved boost converter with VM cell, it can be used for all the application where the source badly requires a less ripple driven converters. So, this converter can be used for smart grid application running with low powered renewable voltage source.

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