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# Comparative Steady State Analysis of Boost and Cascaded Boost Converter with Inductive ESR Losses & Capacitor Current Behaviour

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**ABSTRACT**

In this paper, an overall comparison between the Boost Converter (BC) & Cascaded Converter/ Cascaded Boost Converter (CBC) has been depicted in terms of ideal condition, as well as with the consideration of Equivalent Series Resistance (ESR) of inductor(s). The loss comparison in the two converters due to the ESR is also included in this paper. It can be seen that in CBC, voltage gain is more but the power loss due to ESR is also more compared to BC. The parameters of the converters are derived with a consideration of per unit ripple quantity of inductor current and capacitor voltage. A boundary condition between the continuous conduction mode (CCM) & discontinuous conduction mode (DCM) of the inductor current is also shown. The behaviour of the capacitor current for the converters is discussed during ON and OFF condition of the switch(es) during DCM. At the end, the simulation results of both the converters are given for a 20V/100V, 100 W output. The analysis and simulation results are presented in this paper for the verification of the feasibility.



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## 1. INTRODUCTION

DC - DC conversion is becoming very important in various portable applications now a days. Many portable devices use power at different levels of voltage. The modern technology is making the renewable energy sources (RES) to become an alternative of the combustion engines for power generation as the cost and the environmental issues are concerned. [1]-[6] But the main hindrance behind RES is less voltage generation per cell. [7] So to fulfill the requirement of high voltage applications, a number of cells to be connected is series or parallel combination. It further reduces the energy generation due to shadow effect on the PV cells. [8]-[11] So a voltage step up process can be used with a fuel cell (FC) or Photovoltaic (PV) cell to boost the output voltage and thus the efficiency can also be increased. [12], [13] As the dc-dc converter injects less current ripple into the source, the efficiency as well as the life span can be increased with that for the PV or FC array. [14], [15]

The voltage build up can be possible by BC and CBC. [16], [17] BC cannot give the significant build up of output voltage for the same duty ratio as compared to CBC as the output voltage of the later one is a quadratic function of duty cycle. Again for BC as high voltage generation requires a large duty cycle, so it further increases the reverse recovery effect of the diodes. [18], [19] Reference [1] has discussed about the closed loop operation.

The works on different dc – dc converters have been published in different Journals and presented in various conferences, but a complete steady state analysis is no where present with reference to various losses.

This paper is not focusing on any kind of modification or changes required for the improvement of the converter operation, but this only shows a comparative view with a proper steady state analysis.

The comparative study of the two converters is focused in this paper along with the consideration of ESR of the inductor(s) in section 3 and power losses due to the ESR effect is discussed in section 4. In section 5, converter parameters are designed with a discussion about the stresses on the switch(es). Section 6 depicts about the boundary condition between continuous conduction mode (CCM) & discontinuous conduction mode (DCM) of inductor current. Behavior of the capacitor current and the simulation performances are shown in section 7 & 8 respectively.

## 2. OPERATION OF THE CONVERTERS

### 2.1. Cascaded Boost Converter

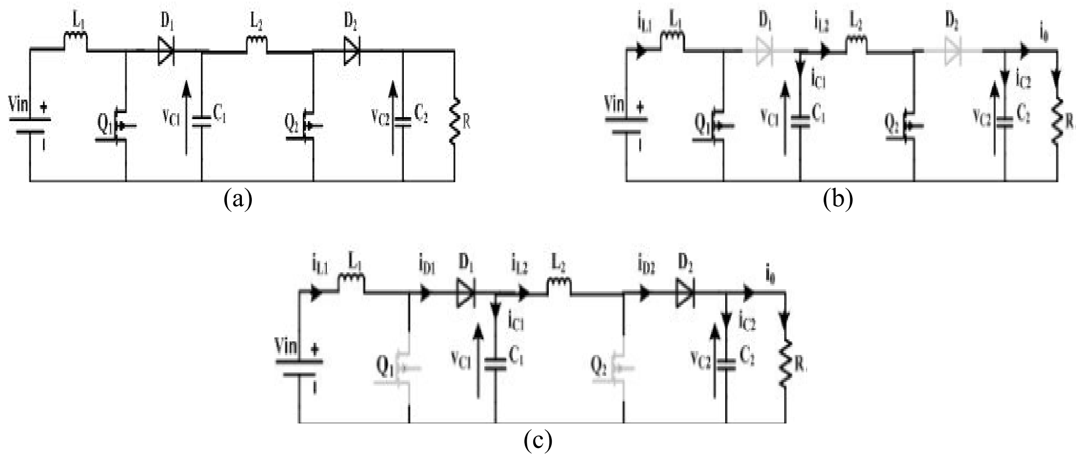


Figure 1(a), (b), (c). Cascaded Boost Converter, Switches are in ON state, Switches are in OFF state

The CBC is shown in Figure 1(a) where $v_{in}$ is the input voltage, $Q_1$, $Q_2$ – are two active switches, $D_1$, D2 are the passive switches and $L_1$, $L_2$ & $C_1$, $C_2$ are the corresponding values of Inductance and Capacitor of the converter. The output voltage is represented by $v_0 = v_{C2}$. The duty ratio is termed as k here.

The steady state parameters of the converter can be found out by considering the ON and OFF conduction mode of the switches, $Q_1$ & $Q_2$.

The ON state of the switches is shown in Figure 1(b). In this condition inductor current $i_{L1}$ is flowing through the switch $Q_1$ and $i_{L2}$ through $Q_2$. So switch current $i_{Q1} = i_{L1}$ and $i_{Q2} = i_{L2}$ . The diodes, $D_1$ & $D_2$ are reverse biased as shown by light color. The capacitor $C_1$ discharges through the inductor $L_2$ - $Q_2$, as well as $C_2$ discharges through the load resistance R. The load current is shown as $i_0$.

During the OFF mode of the switches, no current is flowing through the switch $Q_1$ and $Q_2$ as shown in Figure 1(c). The diodes $D_1$, $D_2$ becomes forward biased now. Current passing through the diodes are $i_{L1}$ & $i_{L2}$ respectively. The output voltage across the load is same as the capacitor voltage, $v_{C2}$.

To find the steady state parameters $I_{L1}$, $I_{L2}$ and $V_{C1}$, $V_{C2}$ the following method has been followed:

During ON & OFF time of the switches,

Average voltage drop across inductor $L_1$,

$$V_{L1}^{ON} = kV_{in}, \quad V_{L1}^{OFF} = (1-k)(V_{in} - V_{C1})$$

Average voltage drop across inductor $L_2$,

$$V_{L2}^{ON} = kV_{C1}, \quad V_{L2}^{OFF} = (1-k)(V_{C1} - V_{C2})$$

Average current passing through capacitor $C_1$,

$$I_{C1}^{ON} = -\,kI_{L2}, \quad I_{C1}^{OFF} = (1-k)(I_{L1} - I_{L2})$$

Average current through the capacitor $C_2$,

$$I_{C2}^{ON} = -\,kI_0, \quad I_{C2}^{OFF} = (1-k)(I_{L2} - I_0)$$

The average voltage drop across any inductor is zero, i.e., $V_L^{ON} + V_L^{OFF} = 0$.

Solution of this above expression gives as,

$$V_{C1} = \frac{V_{in}}{(1-k)} \quad (1)$$

$$V_{C2} = \frac{V_{in}}{(1-k)^2} \quad (2)$$

Average current passing through any capacitor is zero, i.e., $I_C^{ON} + I_C^{OFF} = 0$.
From the solution of the above expression,

$$I_{L1} = \frac{V_{in}}{(1-k)^4 R} \quad (3)$$

$$I_{L2} = \frac{V_{in}}{(1-k)^3 R} \quad (4)$$

Output voltage of the cascaded converter,

$$V_0 = V_{C2} = \frac{V_{in}}{(1-k)^2}$$

### 2.2. Boost Converter

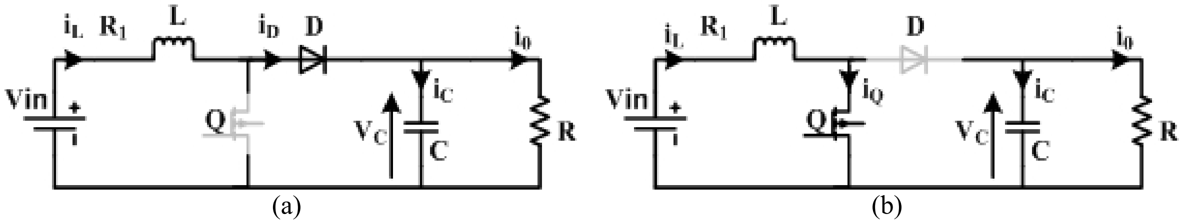


Figure 2(a). Boost converter in ON mode Figure 2(b). Boost converter in OFF mode

The Boost converter is shown in Figure 2(a), (b) where $V_{in}$ is the input voltage, Q – an active switch, D is the passive switch and L & C are the corresponding values of Inductance and Capacitor of the converter. The output voltage is represented by $v_0 = v_c$. The duty ratio is termed as d here.

The On state of the boost converter is shown in Figure 2(a) and OFF state in Figure 2(b). The boost converter is also operating in the same way as the Cascaded boost converter. The inductor current is flowing through the switch Q during ON time and through the diode during OFF time of the switch.

The output voltage equals the capacitor voltage as shown in the Figure 2(a) and 2(b). Steady state parameters of the converter can be found out by following the method stated above.

$$V_C = \frac{V_{in}}{(1-d)} \quad (5)$$

$$I_L = \frac{V_{in}}{(1-d)^2 R} \quad (6)$$

Output voltage of the boost converter,

$$V_0 = V_C = \frac{V_{in}}{(1-d)}$$

The relation between the duty ratios of the two converters with a same voltage gain can be given as-

$$d = 1 - (1-k)^2 \quad (7)$$

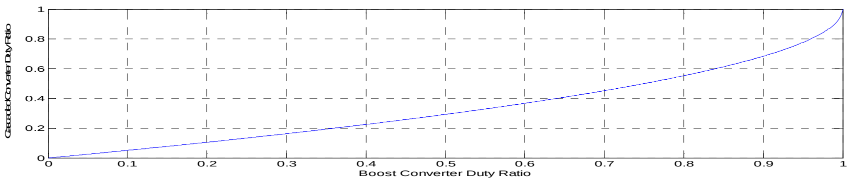


Figure. 3 Comparison between BC and CBC duty ratio at the same voltage gain

It is seen from the curve of Figure 3 that for the same voltage gain, less duty ratio is required in CBC compared to BC. So a cascaded boost converter can provide more voltage build up compared to boost converter with a less duty ratio.

## 3. EFFECT OF INDUCTIVE ESR

In section 2, the discussion is related to the ideal converters. But practically in all converters, the inductance is under the influence of a series connected resistor or ESR. Due to the presence of such ESR, the converter performance or the efficiency cannot be practically same as that of the ideal converters. In this section the ESR effect of the two converters is discussed with the loss calculation due to the said ESR effect in the next section.

### 3.1. Cascaded Boost Converter

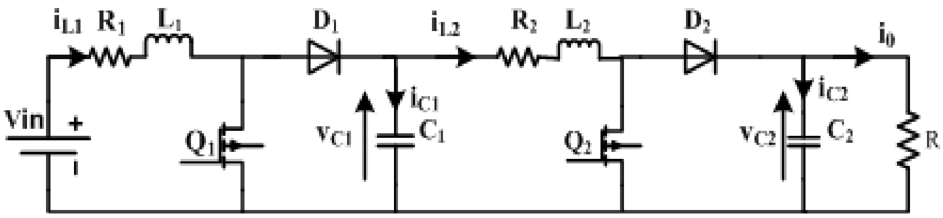


Figure 4. Inductive ESR in cascaded boost converter

To find the steady state parameters of the cascaded Boost converter due to the ESR effect of the inductor, the following method is applied:
During ON & OFF time of the switches,
Average voltage drop across the inductor $L_1$,

$$V_{L1}^{ON} = k(V_{in} - I_{L1}R_1) \tag{8}$$

$$V_{L1}^{OFF} = (1-k)(V_{in} - I_{L1}R_1 - V_{C1}) \tag{9}$$

Average voltage drop across inductor $L_2$,

$$V_{L2}^{ON} = k(V_{C1} - I_{L2}R_2) \tag{10}$$

$$V_{L2}^{OFF} = (1-k)(V_{C1} - V_{C2} - I_{L2}R_2) \tag{11}$$

Average current passing through capacitor $C_1$,

$$I_{C1}^{ON} = kI_{L2} \tag{12}$$

$$I_{C1}^{OFF} = (1-k)(I_{L1} - I_{L2}) \tag{13}$$

Average current through the capacitor $C_2$,

$$I_{C2}^{ON} = kI_0 \quad (14)$$

$$I_{C2}^{OFF} = (1-k)(I_{L2} - I_0) \quad (15)$$

Average voltage drop across any inductor is zero and the average current passing through the capacitor is also zero. So,

$$V_L^{ON} + V_L^{OFF} = 0 \quad (16)$$

$$I_C^{ON} + I_C^{OFF} = 0 \quad (17)$$

Solution of the equations (16) & (17) with reference to equations (8) – (15), the steady state parameters of the cascaded converter due to ESR effect can be obtained as-

$$I_{L1} = \frac{V_{in}}{(1-k)R_1 + (1-k)^4 R + (1-k)^2 R_2} \quad (18)$$

$$I_{L2} = \frac{V_{in}}{R_1 + (1-k)^3 R + (1-k)R_2} \quad (19)$$

$$V_{C1} = \left\{\frac{(1-k)^2 R + R_2}{R_1 + (1-k)^3 R + (1-k)R_2}\right\} V_{in} \quad (20)$$

$$V_{C2} = \left\{\frac{(1-k)^2 R}{R_1 + (1-k)^4 R + (1-k)^2 R_2}\right\} V_{in} \quad (21)$$

### 3.2. Boost Converter

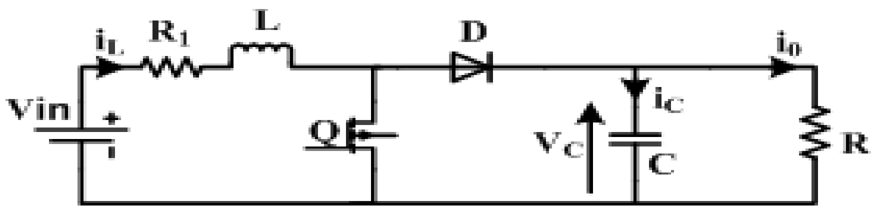


Figure 5. Inductive ESR in Boost converter

The steady state parameters of the Boost converter can be found as,

$$I_L = \frac{V_{in}}{\left\{(1-d) + \frac{R_1}{(1-d)R}\right\}(1-d)R} \quad (22)$$

$$V_C = \frac{V_{in}}{(1-d) + \frac{R_1}{(1-d)R}} \quad (23)$$

Figure 6 shows the comparative analysis of the Cascaded Boost and the Boost converter voltage gain when equal ESR of all the inductor is considered. It is clearly understood from the curve that the attainable voltage gain in Cascaded Boost converter is even more as compared to Boost converter even if with the losses of due to the ESR effect.

Both the converters can work within the Quasi – Linear region only. Beyond that the Non – Linear region appears, where the performance of the converters is disturbed & they cannot be operated. The duty cycle for the operating point of the cascaded converter is less with comparison to boost converter operating point duty cycle.

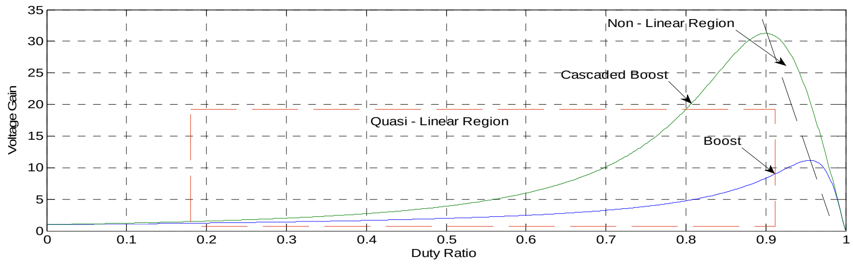


Figure 6. Shows the Voltage gain ratio with ESR (0.1 Ω) for the two converters

## 4. LOSSES DUE TO INDUCTIVE ESR

Theoretically DC-DC converters can provide a infinite voltage gain. But practically it is never possible as there are some inherent parasitic elements present such that ESR. In this section the losses due to ESR effect of the inductor is considered. The losses have more impact when the device is used for any low power application. [20]-[21] So the loss calculation is discussed as under:

The value of the inductor, $L \propto \frac{N^2 A}{l}$ (24)

where, N = no. of turns in the inductor,
A = cross sectional area of the inductor
*L* = length of the inductor
Again the length, $l \propto N$
So equation (24) can be written as,

$$L \propto NA \quad (25)$$

Since the current passing through the conductor, $I_L \propto x^{3/2}$
Cross sectional area,

$$A \propto x^2 \propto I_L^{4/3} \quad (26)$$

where, *x* is the diameter of the conductor.
The equation (25) now can be re-arranged as,

$$L \propto N I_L^{4/3} \quad (27)$$

The ESR value, $R \propto \frac{l}{A} \propto N/I_L^{4/3}$ (28)

So the ESR per unit Inductor is,

$$\frac{R}{L} \propto 1/I_L^{4/3} \quad (29)$$

For Boost converter, ESR of the inductor L,

$$R_{esr} \propto L/I_L^{8/3} \quad (30)$$

For Cascaded Boost converter,
ESR of the inductor $L_1$,

$$R_{esr1} \propto L_1/I_{L1}^{8/3} \quad (31)$$

ESR of the inductor $L_2$,

$$R_{esr2} \propto L_2/I_{L2}^{8/3} \tag{32}$$

Since, in the cascaded converter, $I_{L2} = (1-k)I_{L1}$, equation (32) can be written as,

$$R_{esr2} \propto L_2/\{I_{L1}(1-k)\}^{8/3} \tag{33}$$

Since the input power for the Boost as well as Cascaded converter is same. So for the same input voltage, $I_L = I_{L1}$.

Thus the relation between the ESR values of $L_1$ inductor in cascaded to the ESR value of Boost converter inductor L can be given as,

$$R_{esr1} = \frac{L_1}{L} R_{esr} \tag{34}$$

In the same way,

$$R_{esr2} = \frac{L_2}{L(1-k)^{8/3}} R_{esr} \tag{35}$$

Power losses in the Boost converter,

$$P_B = I_L^2 R_{esr} \tag{36}$$

Power loss in the inductors of cascaded Boost converter,

$$P_{L1} = I_{L1}^2 R_{esr1}$$

$$P_{L2} = I_{L2}^2 R_{esr2}$$

Total loss in the cascaded boost converter due to inductive ESR,

$$P_C = P_{L1} + P_{L2} = I_{L1}^2\{R_{esr1} + (1-k)^2 R_{esr2}\} \tag{37}$$

So the power loss ratio of the cascaded boost converter to the boost converter can be derived as,

$$\frac{P_C}{P_B} = \frac{k}{\{1-(1-k)^2\}}\left\{1 + \frac{1}{(1-k)^{5/3}}\right\} \tag{38}$$

Figure 7 shows the power loss ratio curve in Cascaded to Boost converter with a change in the duty ratio of the cascaded boost converter. It is seen that with an increment of the duty ratio, the voltage gain of the cascaded converter increases. But the power loss due to the inductive ESR effect also increases compared to the conventional Boost converter.

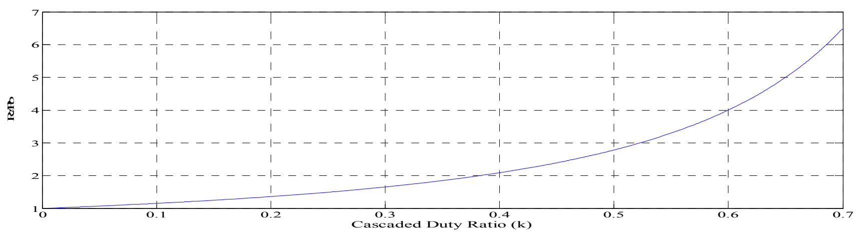


Figure 7. Shows power loss ratio curve due to inductive ESR

The on state loss of the Cascaded converter is less compared to the Boost converter for the same voltage gain. Whereas the off state loss is more in Boost converter compared to Cascaded Boost converter.

## 5. PARAMETER DESIGN

The designing of the parameters of the cascaded boost converter is considered here in terms of per unit ripple in the inductor current ($\Delta I_L/I_L$) and per unit ripple in the capacitor voltage ($\Delta V_C/V_C$).
During ON time of the switches, voltage drop across the inductor $L_1$,

$$L_1 \frac{di_{L1}}{dt} = V_{in} \tag{39}$$

Considering the ripple current in the inductor as $\Delta I_{L1}$, equation (39) gives the solution as,

$$L_1 = \frac{kT_{sV_{in}}}{\Delta I_{L1}} \tag{40}$$

The inductor value can be found in terms of per unit ripple from equation (40) as,

$$L_1 = \frac{kT_s V_{in}}{per\ unit\ ripple\ x\ I_{L1}} \tag{41}$$

Equation (3) can be placed in equation (41) and thus,

$$L_1 = \frac{k(1-k)^4 RT_s}{per\ unit\ ripple} \tag{42}$$

where, $T_s$ is the switching period = $1/f_s$
Second inductor $L_2$ value can also be found out in the same way as,

$$L_2 = \frac{k(1-k)^3 RT_s}{per\ unit\ ripple} \tag{43}$$

Current passing through the capacitor $C_1$ during the ON time of the switches,

$$\begin{aligned} iC1 &= C_1 \frac{dv_{C1}}{dt} = i_{L2} \\ C_1 \frac{\Delta v_{C1}}{k\ T_s} &= \frac{V_{in}}{(1-k)^3 R} \end{aligned} \tag{44}$$

The capacitor values can be found out by considering a per unit ripple in the capacitor voltage in the same way as,

$$C_1 = \frac{kT_s}{(1-k)^2 R\ x\ per\ unit\ ripple} \tag{45}$$

$$C_2 = \frac{kT_s}{R\ \ x\ per\ unit\ ripple} \tag{46}$$

A cascaded boost converter as shown in Figure 1(a) where the nominal values considered as: input voltage $V_{in}$ = 20 V, output voltage $V_0$ = 100 V, the nominal duty ratio $k$ = 0.55. Considering a 2% ripple in the inductor current and the capacitor voltage as well with switching frequency $f_s$ = 20 kHz. To make a 100 W converter, the parameters can be found out by the equations (42), (43), (45) & (46) is shown in Table 2.

During Boost Converter designing the value of the inductor and the capacitor can also be found out by the same way as shown above.

$$L = \frac{d(1-d)^2 RT_s}{per\ unit\ ripple} \tag{47}$$

$$C = \frac{dT_s}{R\ \ x\ per\ unit\ ripple} \tag{48}$$

When the switches are ON, the current passing through them is the current stress on the switches. Whereas during OFF condition of the switches the voltage stress can be obtained. The current stress will be the maximum peak current passing through the respective switch. But since the voltage ripple is considered as very small, so the voltage stress will be as same as the average value of the voltage applied to the switch.

In cascaded boost converter, the current stress on the switches is as follows:

$i_{Q1peak} = i_{L1peak}$; $i_{Q2peak} = i_{L2peak}$
$i_{D1peak} = i_{L1peak}$; $i_{D2peak} = i_{L2peak}$

In Figure 8 the inductor current with the maximum and the minimum value of the ripple is shown. The peak value of the inductor can be found out as:

$$I_{Lmax} = IL + \Delta I_L/2 \quad (49)$$

Taking the reference of equation (40), the current stress equation of the inductor can be written as,

$$ILmax = I_L + \frac{duty\ ratio}{2Lf_s} V_{in} \quad (50)$$

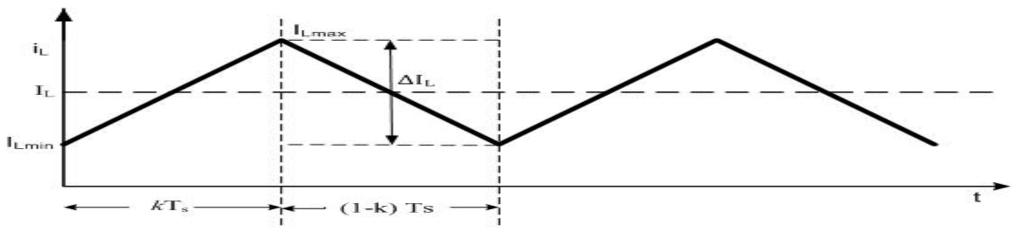


Figure 8. Shows inductor current ripple with minimum and maximum peak

So the current stress on the switch $Q_1$ & $D_1$,

$$i_{Q1peak} = i_{D1peak} = I_{L1} + \frac{k}{2L_1 f_s} V_{in} \quad (51)$$

Current stress on the switch $Q_2$ and $D_2$,

$$i_{Q2peak} = i_{D2peak} = I_{L2} + \frac{k}{2L_2 f_s} V_{in} \quad (52)$$

In case of the Boost converter, the current stress on the switch and the diode will be as,

$$i_{Qpeak} = i_{Dpeak} = I_L + \frac{d}{2Lf_s} V_{in} \quad (53)$$

Table 1. Parameter comparison of Boost & Cascaded Boost Converter

| Parameters | Boost Converter | Cascaded Boost |
|---|---|---|
| Voltage Gain | $\frac{1}{(1-d)}$ | $\frac{1}{(1-k)^2}$ |
| Inductor value(s) | $\frac{d(1-d)^2RT_s}{per\ unit\ ripple}$ | $L_1 = \frac{k(1-k)^4RT_s}{per\ unit\ ripple}$<br>$L_2 = \frac{k(1-k)^3RT_s}{per\ unit\ ripple}$ |
| Capacitor value(s) | $\frac{dT_s}{R\ x\ per\ unit\ ripple}$ | $C_1 = \frac{kT_s}{(1-k)^2R\ x\ per\ unit\ ripple}$<br>$C_2 = \frac{kT_s}{R\ x\ per\ unit\ ripple}$ |
| Voltage stress on switch | $\frac{V_{in}}{(1-d)}$ | $V_{C1} = \frac{V_{in}}{(1-K)}$<br>$V_{C2} = \frac{V_{in}}{(1-k)^2}$ |
| Inductor Current | $I_L = \frac{V_{in}}{(1-d)^2R}$ | $I_{L1} = \frac{V_{in}}{(1-k)^4R}$<br>$I_{L2} = \frac{V_{in}}{(1-k)^3R}$ |
| Current stress on switch | $I_L + \frac{d}{2Lf_s}V_{in}$ | $I_{L1} + \frac{k}{2L_1f_s}V_{in}$<br>$I_{L2} + \frac{k}{2L_2f_s}V_{in}$ |
| Current stress on Diode | $I_L + \frac{d}{2Lf_s}V_{in}$ | $I_{L1} + \frac{k}{2L_1f_s}V_{in}$<br>$I_{L2} + \frac{k}{2L_2f_s}V_{in}$ |

Table 2. Parameter comparison of Boost & Cascaded Boost Converter for 100 W

| Parameters | Boost Converter | Cascaded Boost |
|---|---|---|
| Duty Ratio | 0.80 | 0.55 |
| Inductor value(s) | L = 4 mH | $L_1$ = 2.82 mH<br>$L_2$ = 6.26 mH |
| Capacitor value(s) | C = 40 µF | $C_1$ = 136 µF<br>$C_2$ = 27.5 µF |
| Load Resistance R | 50 Ω | 50 Ω |
| Voltage stress on switch | $V_Q$ = 100 V | $V_{Q1}$ = 50 V<br>$V_{Q2}$ = 100 V |
| Current stress on switch | $i_{Qpeak}$ = 10.1 A | $i_{Q1\ peak}$= 9.85 A<br>$i_{Q2\ peak}$= 4.43 A |
| Current stress on Diode | $i_{Dpeak}$ = 10.1 A | $i_{D1peak}$= 9.85 A<br>$i_{D2peak}$= 4.43 A |

## 6. BOUNDARY BETWEEN CCM & DCM

The boundary between the CCM & DCM can be derived only when the inductor current touches zero. During the OFF state of the switches, the inductor current gradually reduces to a minimum value $I_{Lmin}$ as shown in Figure 8.

The value of the lowest inductor current can be found as,

$$I_{Lmin} = I_L - \Delta I_L/2 \tag{54}$$

Equation (54) can be re-written with reference to equation (50) as,

$$I_{Lmin} = I_L - \frac{duty\ ratio}{2Lf_s}V_{in} \tag{55}$$

For the Boost converter, equation (55) can be written as,

$$I_{Lmin} = I_L\{1 - \frac{d(1-d)^2R}{2Lf_s}\} \quad (56)$$

As the condition for the boundary condition to be satisfied,

$$I_{Lmin} = I_L\left\{1 - \frac{d(1-d)^2R}{2Lf_s}\right\} = 0 \quad (57)$$

The solution of the above equation gives the value of inductor for the boundary condition as,

$$L = \frac{d(1-d)^2R}{2f_s} \quad (58)$$

In the same way the value of the inductors for the boundary condition can be found out for the CBC as,

$$L_1 = \frac{k(1-k)^4R}{2f_s} \quad (59)$$

$$L_2 = \frac{k(1-k)^2R}{2f_s} \quad (60)$$

The boundary condition for the input current to be continuous can also find with the above equations. Whereas the values of the inductor values to satisfy the boundary conditions for the two converters are as for BC, L = 40 μH and for CBC, $L_1$ = 28 μH for the same power output condition specified above in Section 5.

## 7. BEHAVIOR OF THE CAPACITOR CURRENT

The capacitor of the Boost converter as shown in Figure 2(a) has to discharge through the load resistance during ON state of the switch and to be charged during the OFF state of the switch as shown in Figure 2(b). But practically the charging and discharging does not always depend upon the switching period. It may depend upon the value of minimum inductor current and the output current.

When $I_{Lmin} > I_0$ as shown in Figure 8, the capacitor charges during ON time and discharges during the OFF time of the switch. But when $I_{Lmin} < I_0$, the capacitor does not wholly operate in the same way as stated above. During ON time, capacitor discharges through the load; but during OFF time, the capacitor is getting charged until $I_{Lmin} < I_0$. As soon as the inductor current falls below the output current level, capacitor starts to discharge to maintain a constant average load current. So in DCM, capacitor charging-discharging does not depend upon the switching time periods.

**Condition for $I_{Lmin} > I_0$ & $I_{Lmin} < I_0$ :**

The OFF state average inductor current in BC is equal to the average output current since the average capacitor current is zero. So the condition can be written with reference to Figure 8 as,

$$I_0 = \frac{{}^1\!/_2\,(1-d)T_s\Delta I_L + I_{Lmin}(1-d)T_s}{T_s} \quad (61)$$

$$\text{So}, I_{Lmin} = I_0\left[\frac{1}{(1-d)} - \frac{\Delta I_L(1-d)R}{2V_{in}}\right] \quad (62)$$

Equation (62) clearly states that,

when, $\left[\frac{1}{(1-d)} - \frac{\Delta I_L(1-d)R}{2V_{in}}\right] > 1;\ \ I_{Lmin} > I_0$ and
$\left[\frac{1}{(1-d)} - \frac{\Delta I_L(1-d)R}{2V_{in}}\right] < 1;\ \ I_{Lmin} < I_0$

The load side capacitor of the CBC is also showing the same behaviour. The relevant waveforms are shown in the Simulation Section.

## 8. SIMULATED PERFORMANCE

Simulation results of the two converters are shown below. The converters were simulated in MATLAB/ Simulink software.

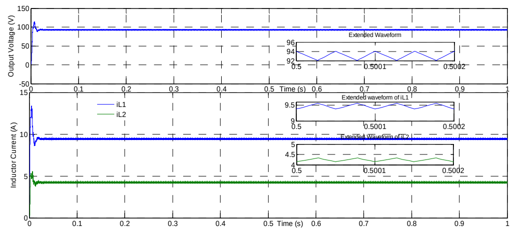


Figure 9. Output voltage waveform (with extended format), $i_{L1}$ & $i_{L2}$ waveform (with extended format) of CBC

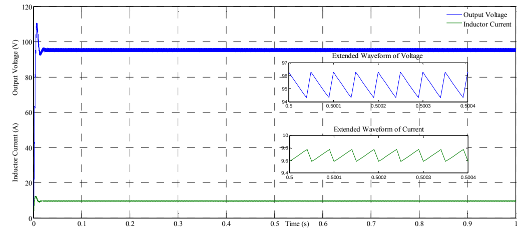


Figure 10. Output voltage & Inductor Current waveforms are shown for BC

The simulation results of CBC are shown in Figure 9. The output voltage of the converter is constant at 94 V. The inductor currents are continuous in nature and the values of $iL1$, $iL2$ are 9.75 A & 4.39 A respectively. The peak value of $iL1$, $iL2$ are respectively 9.85 A & 4.43 A. So the current stress on the switch Q1 as well as diode D1 is 9.85 A. Current stress on Q2 & D2 is 4.43 A. It is clear that the ripple present in the voltage and current is 2% each. The voltage & current is a bit less due to the parasitic losses in the circuit.

Figure 10 shows the output voltage waveform as a constant at 96 V, inductor current at 10 A. the inductor current is continuous in nature. The peak value of $i_L$ is 9.9 A. So the current stress on the switch Q as well as diode D is 9.9 A. It is clear that the ripple present in the voltage and current is 2% each. Here also some losses present due to parasitic effect.

As discussed in section 7, the simulation result of the behaviour of the capacitor current for the BC is shown in figure 11. Here $I_{Lmin}$ > $I_0$, so the capacitor discharges through the load during ON time of the switch Q, whereas during OFF time of the switch, the capacitor gets charged.

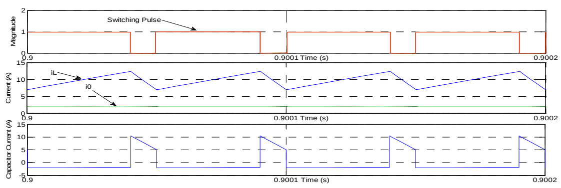


Figure 11. Shows the switching pulse, inductor current with output current waveforms & capacitor current waveform for BC when $I_{Lmin} > I_0$

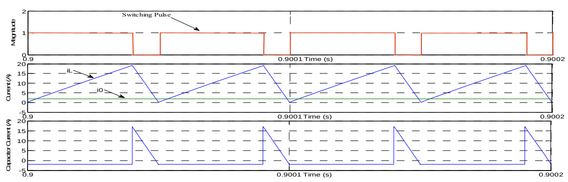


Figure 12. shows the switching pulses, inductor current with output current waveforms & capacitor current waveform for BC when $I_{Lmin} < I_0$

Figure 12 shows the simulated result of the behaviour of capacitor current when $I_{Lmin}$ falls below $I_0$. The capacitor discharges during the ON state of the switch as usual. But during OFF state of the switch, capacitor gets charged only when $I_{Lmin}$ more than $I_0$. At once the capacitor starts to discharge through the load even though the switch in OFF state when $I_{Lmin}$ becomes less than the load current.

The capacitor currents for the CBC also show the same behaviour as the BC capacitor current shown above.

## 9. CONCLUSION

The main idea behind this paper is to get a clear view of the comparative study of the two converters. The CBC can give a high voltage gain compared with the BC for a given duty ratio. As the switching frequency is fixed, for the same load if the duty ratio is less, the voltage and current ripple is also be less. So the CBC is better option compared to BC. At low power applications where ESR losses are considered as a main constraint, the BC is useful. But at high power application where ESR losses are not a constraint, CBC can be used. The charging and discharging of the load side capacitor does not wholly depend upon the switch ON/OFF time. If the minimum inductor current is less than the load current, the capacitor starts to discharge even when the switch is not being turned off to maintain a continuous load current.

**REFERENCES**


[1] Morales-Saldana, J.A.; Galarza-Quirino, R.; Leyva-Ramos, J.; Carbajal-Gutierrez, E.E.; Ortiz-Lopez, M.G., “Modeling and Control of a Cascaded Boost Converter with a Single Switch”, *IECON 2006 - 32nd Annual Conference on IEEE Industrial Electronics*, Year: 2006, Pp: 591 – 596.

[2] R. Samuel Rajesh Babu M.E., S.Deepa M.E, S. Jothivel M.E, “A Closed Loop Control of Quadratic PID Controller”, *International Journal of Engineering (IJE), TRANSACTIONS B: Applications* Vol. 27, No. 11, (November 2014) 1653-1662.

[3] Smallwood, C., "Distributed generation in autonomous and Non autonomous micro grids”, *IEEE in Rural Electric Power Conference*, (2002), D11-D16.

[4] Luo, F.L., "Switched-capacitorized DC/DC converters", *4th IEEE Conference on Industrial Electronics and Applications, ICIEA, IEEE*, (2009), 1074-1079.

[5] Abutbul, O., Gherlitz, A., Berkovich, Y. and Ioinovici, A., "Step-up switching-mode converter with high voltage gain using a switched-capacitor circuit", *IEEE Transactions on Circuits and Systems I: Fundamental Theory and Applications*, Vol. 50, No. 8, (2003), 1098-1102.

[6] Luo, F.L. and Ye, H., "Positive output multiple-lift push-pull switched-capacitor luo-converters", *IEEE Transactions on Industrial Electronics*, Vol. 51, No. 3, (2004), 594-602.

[7] Geoffrey R. Walker, Paul C. Sernia,” Cascaded DC–DC Converter Connection of Photovoltaic Modules”, *IEEE Transactions on Power Electronics*, vol. 19, No. 4, July 2004, pp- 1130 – 39.

[8] Keshav Patidar, Amod C. Umarikar, “High step-up converters based on quadratic boost converter for micro-inverter”, *Electric Power Systems Research*, 119 (2015) 168–177.

[9] T. Wang, Y. Tang,”A high step-up voltage gain DC–DC converter for micro-inverter”, *8th IEEE Conference on Industrial Electronics and Applications (ICIEA)*, 2013, pp. 1089–1094.

[10] M.A.G. de Brito, L.P. Sampaio, L.G. Junior, C.A. Canesin, “Research on Photovoltaics: Review, Trends and Perspectives", Brazilian Power Electronics Conference (COBEP), 2011, pp531-537.

[11] S.B. Kjaer, J.K. Pedersen, F. Blaabjerg, "A Review of Single-Phase Grid-Connected Inverters for Photovoltaic Modules", *IEEE Transactions on Industry Applications*, vol. 41, no. 5, Year: 2005, Page(s): 1292 – 1306.

[12] Nayak, B.; Dash, S.S.; “Battery Operated Closed Loop Speed Control of DC Separately Excited Motor by Boost-Buck Converter”, *IEEE 5th India International Conference on Power Electronics (IICPE)*, 2012, pp – 1-6.

[13] Rosas-Caro, J.C.; Ramirez, J.M.; Peng, F.Z.; Valderrabano, A., “A DC-DC multilevel boost converter”, *IET, Power Electronics,* Vol: 3 (1), Year: 2010, pp 129-137.

[14] Esram T, Chapman PL, “Comparison of photovoltaic array maximum power point tracking techniques”, *IEEE Trans Energy Convers*, 2007; 22(2) pp: 439-49.

[15] Gerard M, Crouvezier JP, Pera DA., “Ripple current effects on PEMFC aging test by experimental and modeling”, *J Fuel Cell Sci Technol*, 2011; 8.

[16] N. Mohan, T.M. Undeland, W.P. Robbins; “Power Electronics: Converters, Applications and Design”, Third Ed, Reprint 2010, pp- 172-173, *Willey India (P) Ltd.*, ISBN: 978-81-265-1090-0.

[17] Maksimovic, D.; Cuk, Slobodan, “Switching converters with wide DC conversion range”, *IEEE Transactions on Power Electronics*, Vol: 6, Issue: 1, Year: 1991, pp- 151-157.

[18] George Cajazeiras Silveira, Fernando Lessa Tofoli, Luiz Daniel Santos Bezerra, and René Pastor Torrico-Bascopé, “A Nonisolated DC–DC Boost Converter With High Voltage Gain and Balanced Output Voltage”, *IEEE Transactions on Industrial Electronics*, vol. 61, no. 12, 2014, pp – 6739-46.

[19] O. Lopez-Santos, L. Martinez-Salamero, G. Garcia, H. Valderrama-Blavi, and D.O. Mercuri, “Efficiency analysis of a sliding-mode controlled quadratic boost converter”, *IET Power Electron*., vol. 6, no. 2, pp. 364–373, 2013.

[20] Byamakesh Nayak, Saswati Swapna Dash; “Transient Modeling of Z-Source Chopper with and without ESR used for Control of Capacitor Voltage”, *WSEAS Transactions on Circuits and Systems*, Vol 13, 2014, pp – 175-187.

[21] J. Leyva-Ramos, M.G. Ortiz-Lopez, and L.H. Diaz-Saldierna; “The Effect of ESR of the Capacitors on Modeling of a Quadratic Boost Converter”, *11th workshop on Control and Modeling for Power Electronics, COMPEL-* 2008, pp- 1-5.

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