# OptiMOS™ and CoolMOS™

# The Optimal Solutions Suitable for DC/DC Converter Used in HVDC System

Application Note

## About this document

This application note analyze two cascaded solutions: Buck followed by LLC and Boost followed by LLC. Both suitable for wide input range DC/DC converters used in ICT HVDC systems. The optimal solution in terms of power loss, occupation of PCB and MOSFETs costs is being presented.

### Scope and purpose

Guide the users select proper solution and power MOSFETs in DC/DC converter of ICT HVDC system.

### Intended audience

Experienced power supply designers who want to optimize their solution and power MOSFETs selection.

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# 1 Introduction

A need for improved and more efficiency power distribution for mission critical application is a result of continuous increases in global power consumption and a shift in power profile of modern loads[1]. About 1.3% of world electricity energy is taken over by equipment in data center and the number is about 2% in United States. The higher efficiency power distribution in data center is meaningful for reducing the consumption of resources and reducing $CO_2$ emission; at the same time the higher efficiency power distribution in data center means IT companies or telecom carriers can reduce CAPEX and OPEX, which in return is beneficial to IT consumers.

Most traditional data centers use alternative current (AC) power system as shown in the Figure 1: three-phase AC voltage main power is handled by UPS (uninterruptible power supply) firstly, a better voltage waveform and backup power provided by battery group are obtained. The output single phase or three-phase AC voltage is distributed by PDU (power distribution unit) to each cabinet or rack, where servers or other IT equipment is installed. The power supplies in a server rectify AC input voltage to 12 $V_{DC}$ and then convert it to a much lower voltage such as 1 $V_{DC}$, which is ultimately consumed by CPUs or other ICs.

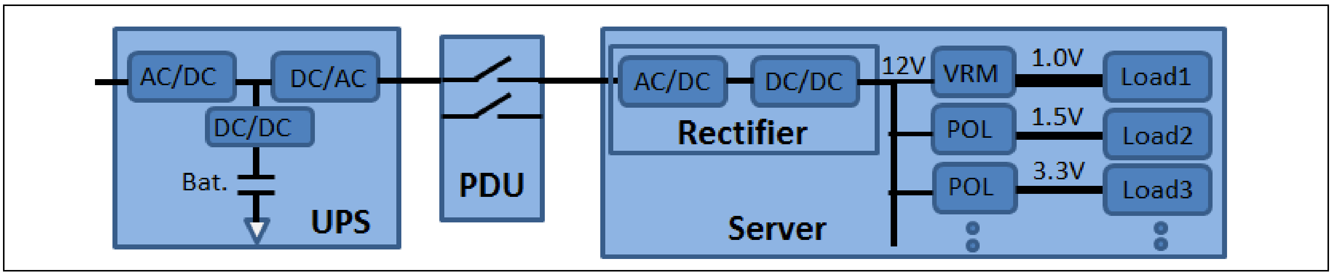


**Figure 1 AC power supply system in data centers**

It is easy to be found that there are two redundant parts in the AC power distribution system, one is the inverter (DC/AC) in UPS and the other is the rectifier (AC/DC) in sever, the redundant parts decrease the power system efficiency and reliability, also increase the cost of equipment. There are other shortcomings in AC power system such as the difficulty in UPS paralleling, large area occupation.

HVDC system is promoted at the end of last century to cope with these problems, the term "higher voltage DC (HVDC)" is used to identify voltage in an information and communication technology equipment(ICTE) space that are higher than 200 $V_{DC}$ and lower than 600 $V_{DC}$[2]. Figure 2 illustrates the architecture of HVDC system. Compared with Figure 2, UPS is replaced by HVDC rectifier whose output voltage is a higher DC value compared to 48 $V_{DC}$, the DC voltage is then distributed by PDU to power supplies in severs, and the followed conversions units are same with those of traditional power system.

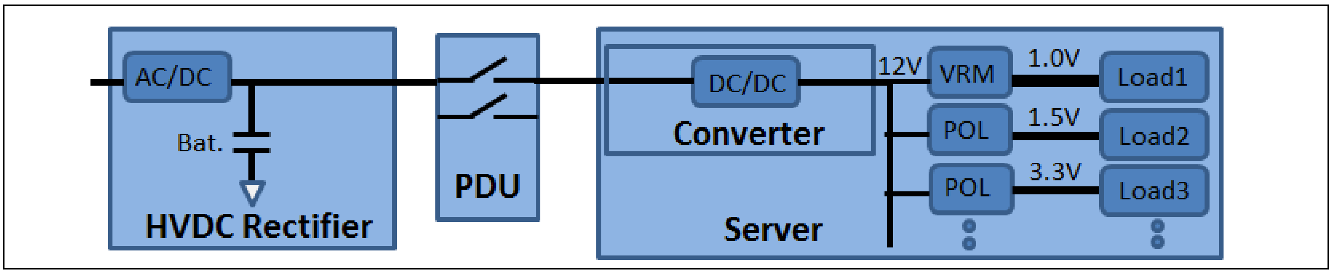


**Figure 2 HVDC power supply system in data centers**

The HVDC system is much simpler and is composed of less power conversion parts compared to UPS showed in Figure 1, therefore higher efficiency, higher reliability and lower cost can be obtained.

Figure 3 shows the advantages of HVDC system compared with traditional power distribution system in data center provided by HP[3].

| | | |
|---|---|---|
| **CapEx Reductions** | •Elimination of Inverters in UPS and PFC correction in PS<br>• Reduced copper in distribution | Up to **15%** Savings |
| **OpEx Reductions** | • Conversion efficiency gains of 5-10%<br>• Lower operational and maintenance cost, 33%<br>• Reduced distribution losses of 2%<br>• Reduced heat dissipated on the data center floor<br>• Increased reliability, 200% plus increase | Up to **35%** Savings |
| **Space Reductions** | • Reduced power conversion volume at compute node by 50%<br>• Reduced data center footprint, 25-33% savings | Up to **25%** Savings |
| **Power Quality Improvements** | • Eliminates phase balance issues from single phase equipment<br>• Harmonics controlled at the DC conversion<br>• Ease of interconnect to alternative energy sources<br>• Ease of connection to back up sources | |

**Figure 3 Advantage of HVDC power system over traditional power system**

The output voltage of HVDC rectifier is specified differently in different countries, Figure 4 shows some of world-wide DC deployments [4]. 380 $V_{DC}$ HVDC system is widely adopted in many counties and groups, in China, however, an additional much lower voltage classs, 240 $V_{DC}$ is implemented in many data centers. As as result, associated standards, which specify the requirements for HVDC rectifier, PDU, protections, components and so on, have been published in some countries and international group such as China and Europe Union and ITU (International Telecommunication Union).

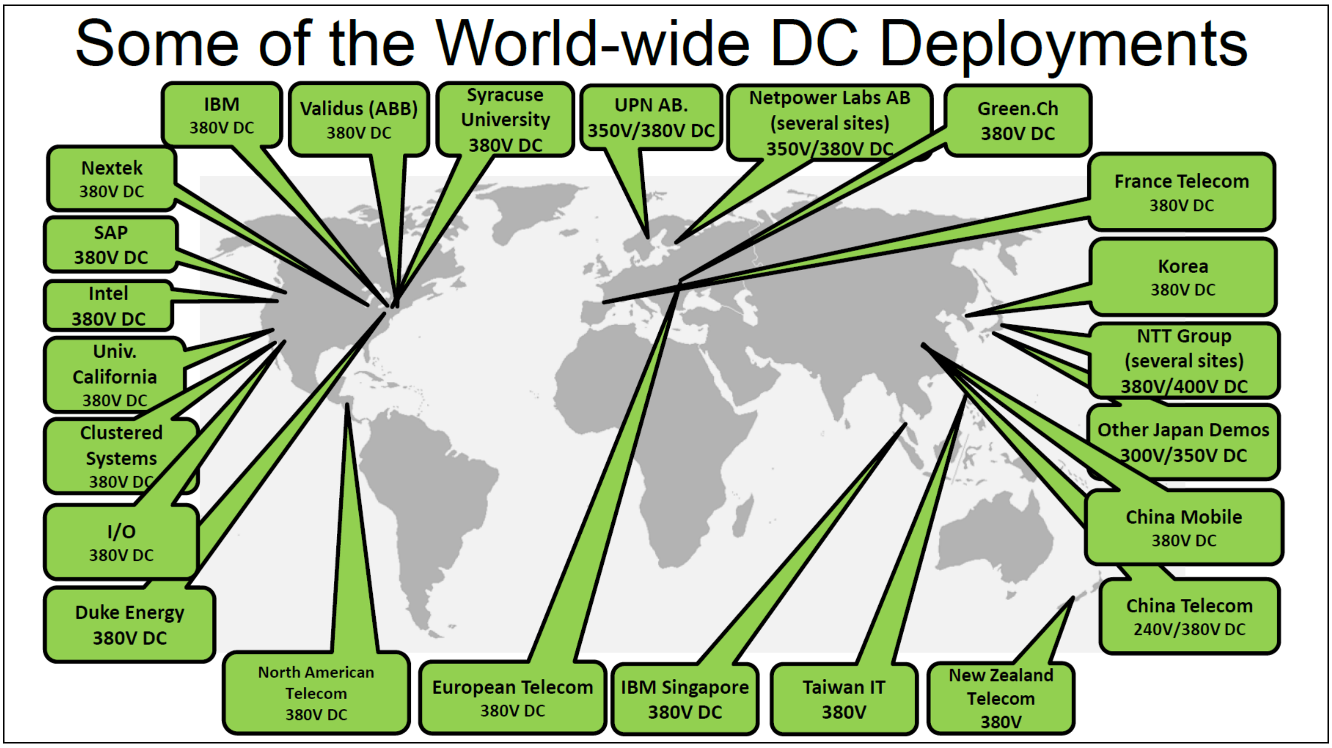


**Figure 4 World-wide HVDC deployment**

In the following, in section 2, the basic information of DC/DC converter of HVDC power system is introduced and the configuration and working conditions of proposed DC/DC converter solutions that are discussed further in the following sections are presented. The detailed calculations of Buck, Boost and LLC converters are shown in section 3. Section 4 compares the inductors and transformers of Buck, Boost and LLC converters in copper loss and magnetic loss. The conclusions of comparisons of different DC/DC converter solutions are shown in section 5, which is intended as an aid for power electonics engineers to choose suitable solutions when designing DC/DC converter of HVDC power system.

# 2 DC/DC Converter

As illustrated in the Figure 2, DC/DC converter in a server is connected to the output of HVDC rectifier through PDU, the input voltage of the converter is equivalent to the output voltage of HVDC rectifier excluding the voltage drops caused by PDU and conduction lines. Normal value of output voltage of HVDC rectifier is showed in Figure 4 in world-wide range, which ranges from 240 $V_{DC}$ to 400 $V_{DC}$. In China, two kinds of HVDC voltage class, 240 $V_{DC}$ and 336 $V_{DC}$, are piloted in some data centers in recent years. Actually 336 $V_{DC}$ HVDC system in China is termed as 380 $V_{DC}$ system in Europe or America, though there are some differences in detailed specifications. The output voltages and numbers of VRLA (Valve Regulated Lead Acid) battery of 240 $V_{DC}$ and 336 $V_{DC}$ HVDC rectifier are listed in the Table 1 and Table 2 according to Chinese standard and company specification [5][6].

**Table 1 Main specifications of 240 $V_{DC}$ HVDC rectifier**

| HVDC voltage class | Normal rectifier output voltage | Range of rectifier output voltage | Input range of DC/DC converter | Numbers of 2 $V_{DC}$ VRLA battery |
|---|---|---|---|---|
| 240 $V_{DC}$ | 268 $V_{DC}$ | 204 $V_{DC}$ ~ 288 $V_{DC}$ | 192 $V_{DC}$ ~ 288 $V_{DC}$ | 120 |

**Table 2 Main specifications of 336V HVDC rectifier**

| HVDC voltage class | Normal rectifier output voltage | Input range of DC/DC converter | Numbers of 2 $V_{DC}$ VRLA battery |
|---|---|---|---|
| 336 $V_{DC}$ | 378 $V_{DC}$ | 300 $V_{DC}$ ~ 400 $V_{DC}$ | 168 |

Table 1 and Table 2 list the numbers of VRLA, which is very important because it plays a decisive role in the output voltage variety range of HVDC rectifier. The input voltage range of DC/DC converter is about 100 V for the two HVDC systems as showed in Table 1 and Table 2, and more challenging for many energy conversion companies is that they have to develop the HVDC DC/DC converter that can be compatible to both HVDC systems for cost down and short time to market. In this application the input voltage will be from 190 $V_{DC}$ to 400 $V_{DC}$. It is very hard to obtain a high conversion efficiency using single topology for such a wide input range during the load range with acceptable cost. Therefore cascaded topology is promoted, on the one hand to increase the efficiency during the whole input and load range, on the other hand to simplify the control strategy. In this application note two cascaded topology solutions- Buck and Boost followed by LLC- are analyzed in a 1200 W(12 V/100 A) server DC/DC converter that suitable for Chinese 240 V $V_{DC}$ and 336 $V_{DC}$ HVDC system.

Buck and Boost are selected for its simplification in architecture and control strategy and well researched. Certainly other topologies such as Buckboost can also be implemented in cascaded topology for its possibility to realize ZVS, flexible output voltage and other merits, but the cost of the cascaded topology will be higher than Buck or Boost so it isn't feasible to be applied. LLC is welcome for its excellent performance in high efficiency during the load range and low cost compared with other resonant converters such as ZVS full-bridge PWM converter. The configuration of the cascaded topology can be Buck/Boost followed by LLC or LLC followed by Buck/Boost, the former, as shown in Figure 5and Figure 6, is arbitrarily chosen in this paper because the analysis method and procedure are same for both configurations. One converter (for example Buck) of cascaded configuration should be closed-loop control to get a high-precision output voltage over the input and output range, the other converter (for example LLC) can be closed-loop, semi-closed-loop or open-loop control, thus the whole control strategy of cascaded topology converter is simpler than that of single topology converter.

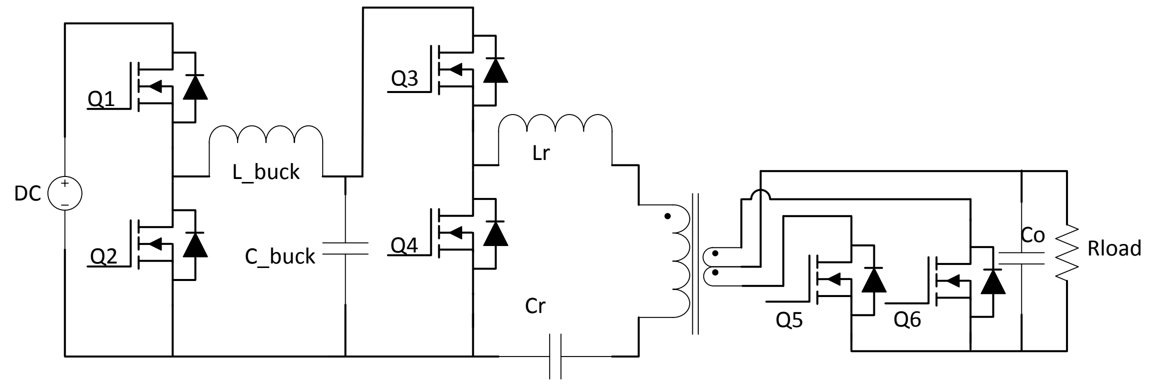


**Figure 5 The cascaded topology of Buck+LLC**

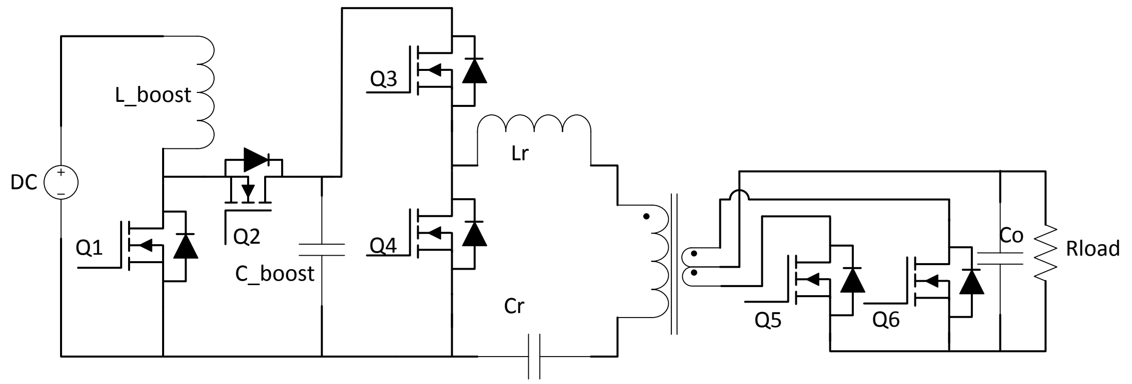


**Figure 6 The cascaded topology of Boost+LLC**

The comparison of different cascaded topologies is implemented in a converter that output is 12 V/1200 W, the analysis is based on the same loss for each MOSFET of the converter, TO-220 package MOSFETs are chosen from Infineon Technologies for Buck, Boost and primary-side of LLC converter switches and SuperSO8 package MOSFETs are selected from Infineon Technologies for secondary-side of LLC converter switches for its low power loss and high thermal dissipation capability. While half-bridge LLC converter is selected and is controlled to make sure that the resonant converters always work at resonant frequency $f_{res}$, the two resonant frequencies are set to be equivalent to each other for the two solutions.

In order to make it easier to comparison, the inductors of Buck and Boost converter perform at continuous mode and the max. ripple currents through Buck inductor and Boost inductor are assigned to 25% of its average value.

Some other presettable working conditions of cascaded topologies are:

(1) Working frequency of Buck/Boost:

$$f_{W\_PWM} = 80K \tag{1}$$

(2) Resonant frequency of LLC:

$$f_{res\_LLC} = 130K \tag{2}$$

The two working frequencies are chosen arbitrarily differently in case of resonating at high frequencies between front and end converters in a cascaded solution and causing system instability and severe EMI noise.

(3) The calculation and comparisons between two solutions will be made at five input voltage points according to Table 1 and Table 2, those are: 190 $V_{DC}$ (min. input voltage), 268 $V_{DC}$ (normal input voltage for 240 V HVDC system), 300 $V_{DC}$ (max input voltage for 240 $V_{DC}$ HVDC system and min input voltage for 336 V HVDC system), 378 $V_{DC}$ (normal input voltage for 336 $V_{DC}$ HVDC system), 400 $V_{DC}$ (max. input voltage).

(4) The comparison between two solutions will be made at three kinds of output load: 20% load (light load); 50% load (medium load) and 100% load (full load).

In the following parts, the performance of Buck converter, Boost converter and two LLC converters following Buck and Boost respectively are analyzed according to these conditions.

# 3 Solutions analysis

## 3.1 Buck converter

The illustration of Buck converter is shown in Figure 7, Q1 and Q2 are high-side and low-side MOSFETs respectively and L_buck is the Buck inductor.

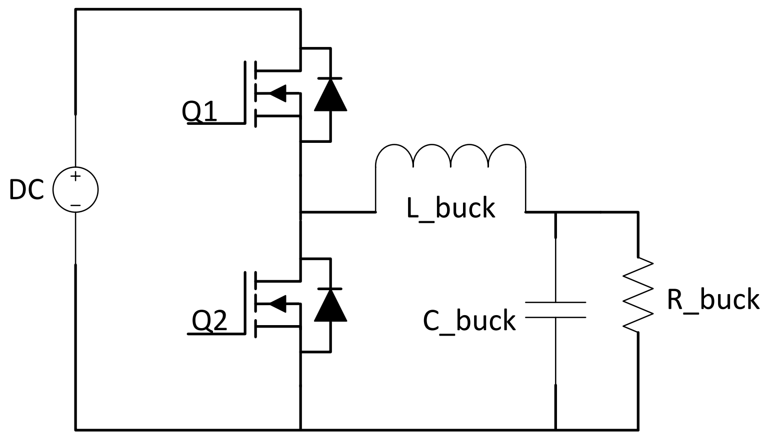


**Figure 7 Topology of Buck converter**

The output voltage of buck converter is arbitrarily assigned to 150 $V_{DC}$ ,

$$V_{out\_buck} = 150\ V \tag{3}$$

It is supposed that efficiency of LLC is 98%,

$$\eta_{LLC} = 0.98 \tag{4}$$

Then the output current (also the average current through the inductor) of Buck converter at full load is:

$$I_{out-buck} = \frac{P_{out}}{\eta_{LLC} * V_{out-buck}} = \frac{100}{0.98*150} = 8.2A \tag{5}$$

The inductor of Buck converter is calculated as:

$$L_{buck} \geq \frac{V_{out-buck} * T_{off-buck}}{\Delta I_{L-buck}} = \frac{V_{out-buck} * (1-D)}{\Delta I_{L-buck} * f_{W\_PWM}} \tag{6}$$

Where D is the duty cycle ratio and for Buck converter:

$$D = \frac{V_{out-buck}}{V_{in}} \tag{7}$$

As the range of input voltage of Buck converter ($V_{in-buck}$) is from 190 $V_{DC}$ to 400 $V_{DC}$, the duty cycle of the Buck converter is from 0.375 to 0.79 according to equation (3) and (7).

So the minimum inductance of Buck converter inductor is

$$L_{buck-min} = \frac{V_{out-buck} * (1-D_{\min})}{\Delta I_{L-buck} * f_{W\_PWM}} = \frac{V_{out-buck} * (1-0.375)}{0.25 * I_{out-buck} * 80K} \approx 574\ \mathrm{uH} \tag{8}$$

The inductance of the Buck inductor is assigned to 720uH, that is

$$L_{buck} = 720\ uH \tag{9}$$

Concerning the material and manufacture errors of inductor (generally ±20%), then the current ripple through the inductor and the minimum and maximum current through the inductor can be obtained according to:

$$\Delta I_{L\_buck} = \frac{V_{out-buck}*(1-D)}{L_{buck}*Fw_{pwm}} \quad (10)$$

$$I_{L\_min} = I_{L-avg} - 0.5 * \Delta I_{L\_buck} \quad (11)$$

$$I_{L\_max} = I_{L-avg} + 0.5 * \Delta I_{L\_buck} \quad (12)$$

The results from equation (9)~(12) are listed in Table 3.

**Table 3 Ripple, min. and max. current through Buck inductor**

| | $V_{in\_1}$=190 $V_{DC}$ | $V_{in2}$=268 $V_{DC}$ | $V_{in\_3}$=300 $V_{DC}$ | $V_{in\_4}$=378 $V_{DC}$ | $V_{in\_5}$=400 $V_{DC}$ |
|---|---|---|---|---|---|
| $\Delta I_{L\_buck}$ [A] | 0.548 | 1.147 | 1.302 | 1.571 | 1.628 |
| $I_{L\_buckmin}$@20%load [A] | 1.359 | 1.059 | 0.982 | 0.847 | 0.819 |
| $I_{L\_buckmax}$@20%load [A] | 1.907 | 2.206 | 2.284 | 2.418 | 2.446 |
| $I_{L\_buckmin}$@50%load [A] | 3.808 | 3.508 | 3.431 | 3.296 | 3.268 |
| $I_{L\_buckmax}$@50%load [A] | 4.356 | 4.655 | 4.733 | 4.867 | 4.895 |
| $I_{L\_buckmin}$@100%load [A] | 7.889 | 7.59 | 7.512 | 7.378 | 7.349 |
| $I_{L\_buckmax}$@100%load [A] | 8.437 | 8.737 | 8.814 | 8.949 | 8.977 |

It is feasible to suppose that max. power loss of high-side MOSFET of buck converter is about 6W concerning the package of MOSFETs and cooling condition for ICT servers. The power losses of high-side MOSFET of Buck converter include switching loss, conduction loss and Coss loss.
The switching loss can be calculated as [7]:

$$P_{sw} = V_{in} * I_{out} * f_w * (\frac{tri+tfu}{2}) \quad (13)$$

Where tri and tfu are the current rise time and voltage fall time during turn on and turn off respectively.
Conduction loss is calculated as:

$$P_{cn} = I_{rms\_hs}{}^2 * R_{DS(on)} \quad (14)$$

Where $R_{DS(on)}$ is the conduction resistor of MOSFET at some junction temperature such as 120°C, $I_{rms\_hs}$ is the rms current through the high-side MOSFETs of Buck converter and is calculated as:

$$I_{rms-hs}{}^2 = \frac{1}{3} * D * (I_{min}{}^2 + I_{max}{}^2 + I_{min} * I_{max}) \quad (15)$$

As the current through the inductor is illustrated by Figure 8.

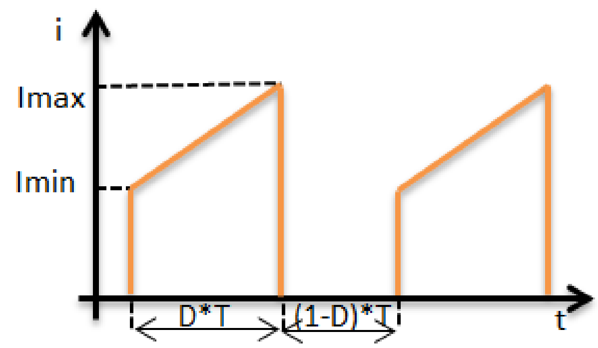


**Figure 8 Waveform illustration of high-side MOSFET of Buck converter**

Coss loss can be calculated as:

$$P_{C_{oss}} = E_{oss} * f_{W\_PWM} \quad (16)$$

However, when we calculate the $R_{DS(on)}$ suitable for the application $C_{oss}$ loss is omitted for it is related to the specific MOSFET.

It is supposed that:

$$tri = tfu = 10 * 10^{-9} \tag{17}$$

Then, we can get the different $R_{DS(on)}$ of high-side MOSFET at different input voltage that can meet the loss requirement according to:

$$R_{DS(on)} = \frac{P_{total} - P_{sw}}{I_{rms-hs}{}^2} \tag{18}$$

From equation (13) to (18), the $R_{DS(on)}$ can be obtained, as shown in the following table

**Table 4 $R_{DS(on)}$ of high-side MOSFET of Buck converter suitable for the application**

| | $V_{in\_1}$=190 $V_{DC}$ | $V_{in\_2}$=268 $V_{DC}$ | $V_{in\_3}$=300 $V_{DC}$ | $V_{in\_4}$=378 $V_{DC}$ | $V_{in\_5}$=400 $V_{DC}$ |
|---|---|---|---|---|---|
| $R_{DS(on)}$ [Ω] | 0.09 | 0.114 | 0.121 | 0.133 | 0.135 |

From Table 4, it is known that the $R_{DS(on)}$ of the high-side MOSFET suitable for the application should be smaller than 0.09Ω

The maximum total power loss of low-side MOSFET of Buck converter is also supposed to be 6 W, the power loss of low-side MOSFET includes conduction loss caused by MOSFET and by body diode, which can be calculated

$$P_{cn\_mos\_ls} = I_{rms\_ls}{}^2 * R_{DS(on)} \tag{19}$$

$$P_{cn\_bd\_ls} = Fw * V_{sd-body} * Iout * T_{dt} \tag{20}$$

Where $I_{rms\_ls}$ is the rms current through the low-side MOSFETs of Buck converter, and:

$$I_{rms\_ls}{}^2 = \frac{1}{3} * (1 - D) * (I_{min}{}^2 + I_{max}{}^2 + I_{min} * I_{max}) \tag{21}$$

$V_{sd-body}$ is the forward voltage drop of body diode of low-side MOSFET, $T_{dt}$ is the dead time between the high-side and low-side driving signal.

It is supposed that:

$$V_{sd-body} = 1V \tag{22}$$

$$T_{dt} = 200 * 10^{-9} S \tag{23}$$

Then we can get the different $R_{DS(on)}$ of low-side MOSFET at different input voltage that can meet the loss requirement according to equation (19)~(23)

The results are shown in the following table:

**Table 5 $R_{DS(on)}$ of low-side MOSFET of Buck converter suitable for the application**

| | $V_{in\_1}$=190 $V_{DC}$ | $V_{in\_2}$=268 $V_{DC}$ | $V_{in\_3}$=300 $V_{DC}$ | $V_{in\_4}$=378 $V_{DC}$ | $V_{in\_5}$=400 $V_{DC}$ |
|---|---|---|---|---|---|
| $R_{DS(on)}$ [Ω] | 0.418 | 0.2 | 0.176 | 0.146 | 0.14 |

From Table 5 we can know that the $R_{DS(on)}$ of low-side MOSFET of Buck converter suitable for the application should be smaller than 0.14Ω.

The max. voltage MOSFETs have to endure for Buck converter is the max. input voltage, which is 400 $V_{DC}$ for the application. Considering 80% or more voltage derating and voltage spike produced by parasitic parameters, the voltage class of 600V or 650V CoolMOS™ is suitable for the application. Therefore, two paralleled IPP60R099P6 and two paralleled IPP65R150CFD are chosen for high-side and low-side MOSFETs respectively concerning $R_{DS(on)}$ for high-side and low-side MOSFETs and excellent body diode requirement for low side MOSFETs.

For IPP60R099P6 used as high side switch of Buck converter, $R_{DS(on)}$ is 0.165Ω at 120°C junction temperature and $E_{oss}$ (Energy of $C_{oss}$) is about 4 uJ[8]; for IPP65R150CFD used as low side switch of Buck converter, $R_{DS(on)}$ is 0.29Ω at 120°C junction temperature, and forward voltage drop of body diode is about 0.8V[9]. The power loss of each MOSFET can be calculated at 120°Cjunction temperature of MOSFET at different input voltage and output load after the MOSFETs are selected, the results are shown from Table 6 to Table 8.

**Table 6 Each MOSFET loss of Buck converter at 20% load at different input voltage**

| | $V_{in\_1}$=190 $V_{DC}$ | $V_{in\_2}$=268 $V_{DC}$ | $V_{in\_3}$=300 $V_{DC}$ | $V_{in\_4}$=378 $V_{DC}$ | $V_{in\_5}$=400 $V_{DC}$ |
|---|---|---|---|---|---|
| High-side MOS[W] | 0.532 | 0.559 | 0.574 | 0.614 | 0.626 |
| Low-side MOS[W] | 0.062 | 0.109 | 0.123 | 0.146 | 0.152 |

**Table 7 Each MOSFET loss of Buck converter at 50% load at different input voltage**

| | $V_{in\_1}$=190 $V_{DC}$ | $V_{in\_2}$=268 $V_{DC}$ | $V_{in\_3}$=300 $V_{DC}$ | $V_{in\_4}$=378 $V_{DC}$ | $V_{in\_5}$=400 $V_{DC}$ |
|---|---|---|---|---|---|
| High-side MOS[W] | 1.174 | 1.145 | 1.156 | 1.213 | 1.234 |
| Low-side MOS[W] | 0.307 | 0.588 | 0.661 | 0.79 | 0.817 |

**Table 8 Each MOSFET loss of Buck converter at 100% load at different input voltage**

| | $V_{in\_1}$=190 $V_{DC}$ | $V_{in\_2}$=268 $V_{DC}$ | $V_{in\_3}$=300 $V_{DC}$ | $V_{in\_4}$=378 $V_{DC}$ | $V_{in-5}$=400 $V_{DC}$ |
|---|---|---|---|---|---|
| High-side MOS[W] | 3.111 | 2.736 | 2.677 | 2.648 | 2.66 |
| Low-side MOS[W] | 1.122 | 2.235 | 2.525 | 3.028 | 3.134 |

## 3.2 Boost converter

The illustration of Boost converter is shown in Figure 9, Q1 is the main switch MOSFET and Q2 is the diode MOSFET, L_boost is the Boost inductor.

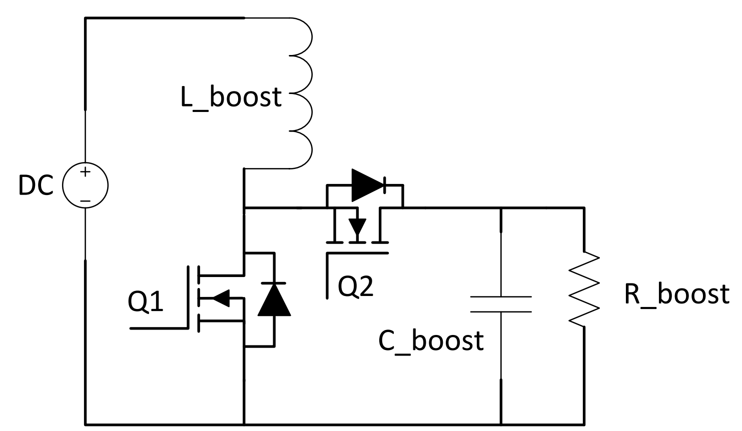


**Figure 9 Topology of Boost converter**

The output voltage of Boost converter is arbitrarily assigned to 460 $V_{DC}$, it is supposed that efficiency of Boost converter and its followed LLC converter are both 98%, then average input current of the Boost converter is:

$$I_{in\_boost} = \frac{P_{out}}{\eta_{LLC} * \eta_{boost} * V_{in}} \tag{24}$$

The ripple current through the Boost inductor is

$$\Delta I_{L\_boost} = \frac{V_{out-boost} * D * (1-D)}{L_{boost} * Fw_{pwm}} \tag{25}$$

Where D is the duty cycle ratio and for Boost converter

$$D = 1 - \frac{V_{in}}{V_{out\_boost}} \tag{26}$$

So the maximum ripple current through the inductor appears when D is equal to 0.5 according to equation (25), then the input voltage when D=0.5 is

$$V_{in\_D0.5} = V_{out\_boost} * (1 - 0.5) = 230V \tag{27}$$

And the average input current when D=0.5 is obtained according to equation (24) and (27)

$$I_{in\_D0.5} = \frac{P_{out}}{\eta_{LLC} * \eta_{boost} * V_{in\_D0.5}} = \frac{1000}{0.98 * .098 * 230} = 5.433 \tag{28}$$

The inductance of Boost inductor is calculated as:

$$L_{boost} = \frac{V_{out-boost} * D * (1-D)}{\Delta I_{L\_boost} * f_{W\_PWM}} \tag{29}$$

Therefore the minimum inductance of the boost inductor is obtained when D is equal to 0.5:

$$L_{boost} = \frac{460 * 0.5 * 0.5}{0.25 * 5.433 * 80 * 10^3} = 1.06 * 10^{-4} \tag{30}$$

Concerning the material and manufacture errors of inductor (generally ±20%) the inductance of Boost inductor is set to 1.33 mH, that is

$$L_{boost} = 1.33\ mH \tag{31}$$

Then the current ripple through the inductor and the minimum and maximum current through the inductor can be obtained according to equation (25) and equation (11) and equation (12)

**Table 9 Ripple, min. and max. current through Boost inductor at different input voltage**

| | $V_{in\_1}$=190 $V_{DC}$ | $V_{in\_2}$=268 $V_{DC}$ | $V_{in\_3}$=300 $V_{DC}$ | $V_{in\_4}$=378 $V_{DC}$ | $V_{in\_5}$=400 $V_{DC}$ |
|---|---|---|---|---|---|
| $\Delta I_{L\_boost}$[A] | 1.048 | 1.051 | 0.981 | 0.633 | 0.49 |
| $I_{L\_boost,min}$@20%load[A] | 0.791 | 0.407 | 0.343 | 0.344 | 0.38 |
| $I_{L\_boost,max}$@20%load[A] | 1.839 | 1.458 | 1.323 | 0.978 | 0.87 |
| $I_{L\_boost,min}$@50%load[A] | 2.764 | 1.805 | 1.592 | 1.336 | 1.317 |
| $I_{L\_boost,max}$@50%load[A] | 3.812 | 2.857 | 2.573 | 1.969 | 1.807 |
| $I_{L\_boost,min}$@100%load[A] | 6.052 | 4.137 | 3.675 | 2.989 | 2.897 |
| $I_{L\_boost,max}$@100%load[A] | 7.1 | 5.188 | 4.655 | 3.622 | 3.369 |

Similar to high-side MOSFET of buck converter, the power loss of main switch MOSFET(Q1 in Figure 9) of Boost converter include switching loss, conduction loss and Coss loss, and calculation of these power loss are same to those of high-side MOSFET of Buck converter(equation (13)~(16)). Also it is feasible to suppose that max. power loss of main switch MOSFET of Boost converter is about 6W, then we can get the $R_{DS(on)}$ of the MOSFET suitable for the application, as shown in the Table 10.

**Table 10 $R_{DS(on)}$ of main switch MOSFET of Boost converter suitable for the application**

| | Vin1=190 $V_{DC}$ | Vin2=268 $V_{DC}$ | Vin3=300 $V_{DC}$ | Vin4=378 $V_{DC}$ | Vin5=400 $V_{DC}$ |
|---|---|---|---|---|---|
| $R_{DS(on)}$ [Ω] | 0.141 | 0.469 | 0.735 | 2.445 | 3.8 |

From Table 10 we know that the $R_{DS(on)}$ of the main switch MOSFET suitable for the application should be smaller than 0.141 Ω.

For boost diode MOSFET (Q2 in Figure 9), the power loss include conduction loss of MOSFET and its body diode, the calculation of the two loss is also same with that of low-side MOSFET of Buck converter (equation (19)~(21)), the assumptions of equation (22) and (23) of low-side MOSFET are applicable to the calculation of boost diode MOSFET, then we can get the $R_{DS(on)}$ of the boost diode MOSFET suitable for the application, as shown in the Table 11.

**Table 11 $R_{DS(on)}$ of diode MOSFET of Boost converter suitable for the application**

| | $V_{in\_1}$=190 $V_{DC}$ | $V_{in\_2}$=268 $V_{DC}$ | $V_{in\_3}$=300 $V_{DC}$ | $V_{in\_4}$=378 $V_{DC}$ | $V_{in\_5}$=400 $V_{DC}$ |
|---|---|---|---|---|---|
| $R_{DS(on)}$ [Ω] | 0.329 | 0.465 | 0.521 | 2.445 | 3.8 |

The max. voltage MOSFETs have to endure for Boost converter is the max. output voltage, which is 460 $V_{DC}$ for the application. Considering 80% or more voltage derating and voltage spike produced by parasitic parameters, the voltage class of 600V or 650V CoolMOS™ is suitable for the application. As a result, two paralleled IPP60R125P6 and two paralleled IPP65R310CFD are chosen for main switch and diode MOSFETs respectively concerning $R_{DS(on)}$ for main switch and diode MOSFETs and excellent body diode requirement for diode MOSFET.

The power loss of each MOSFET then can be calculated. For main switch MOSFET $R_{DS(on)}$ of IPP60R125P6 at 120°C junction temperature is 0.22Ω and Eoss at 460V is about 8.3uC[10]. For diode MOSFET, $R_{DS(on)}$ of IPP65R310CFD at 120°C junction temperature is 0.58Ω and forward voltage drop of the body diode is 0.8V, $E_{oss}$ at 460 $V_{DC}$ is about 4 uC[11]. Then the power loss of each MOSFET is obtained at different input voltage and output load.

**Table 12 Each MOSFET loss of Boost converter at 20% load at different input voltage**

| | $V_{in\_1}$=190 $V_{DC}$ | $V_{in\_2}$=268 $V_{DC}$ | $V_{in\_3}$=300 $V_{DC}$ | $V_{in\_4}$=378 $V_{DC}$ | $V_{in\_5}$=400 $V_{DC}$ |
|---|---|---|---|---|---|
| Main switch MOS[W] | 0.965 | 0.786 | 0.779 | 0.769 | 0.767 |
| Diode MOS[W] | 0.446 | 0.413 | 0.404 | 0.385 | 0.38 |

**Table 13 Each MOSFET loss of Boost converter at 50% load at different input voltage**

| | $V_{in\_1}$=190 $V_{DC}$ | $V_{in\_2}$=268 $V_{DC}$ | $V_{in\_3}$=300 $V_{DC}$ | $V_{in\_4}$=378 $V_{DC}$ | $V_{in\_5}$=400 $V_{DC}$ |
|---|---|---|---|---|---|
| Main switch MOS[W] | 1.621 | 1.041 | 0.998 | 0.941 | 0.932 |
| Diode MOS[W] | 1.015 | 0.817 | 0.764 | 0.671 | 0.65 |

**Table 14 Each MOSFET loss of Boost converter at 100% load at different input voltage**

| | $V_{in\_1}$=190 $V_{DC}$ | $V_{in\_2}$=268 $V_{DC}$ | $V_{in\_3}$=300 $V_{DC}$ | $V_{in\_4}$=378 $V_{DC}$ | $V_{in\_5}$=400 $V_{DC}$ |
|---|---|---|---|---|---|
| Main switch MOS[W] | 3.273 | 1.665 | 1.497 | 1.271 | 1.234 |
| Diode MOS[W] | 3 | 2.224 | 2.021 | 1.668 | 1.593 |

## 3.3 LLC converter

The topology of half-bridge LLC converter with synchronous rectification following Buck/Boost converter is illustrated in Figure 10.

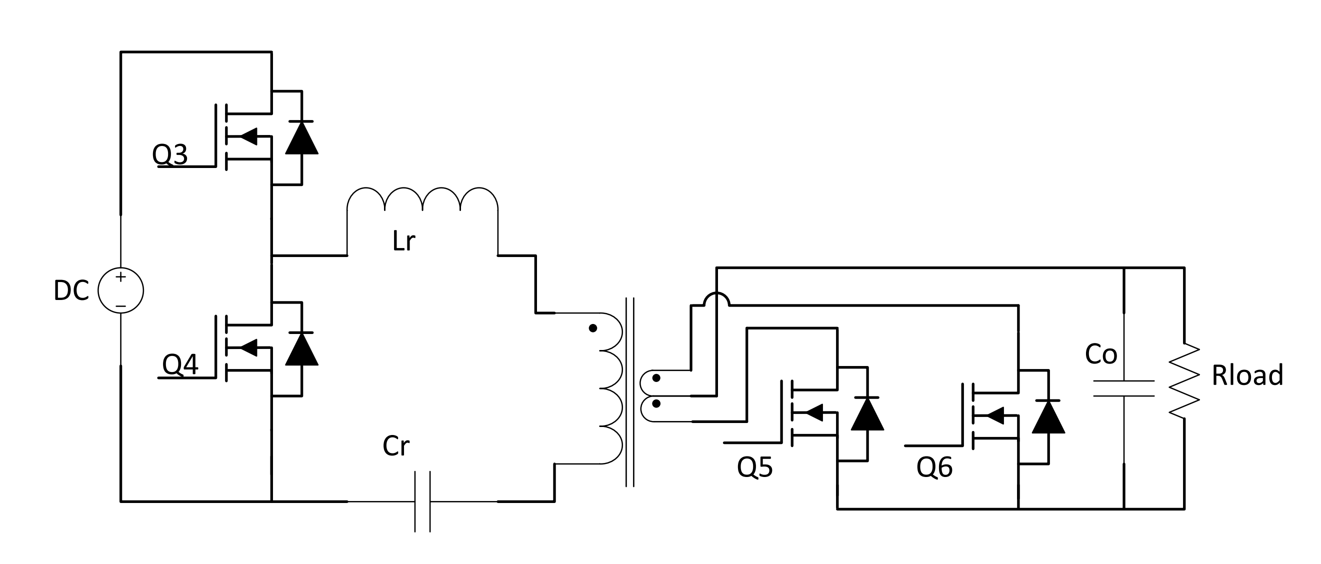


**Figure 10 Topology of half-bridge LLC converter**

As mentioned in the second part, the main specifications of LLC converter include:

(1) Output voltage is 12 $V_{DC}$ and output full load is 100 A

$$V_{out\_LLC} = 12\,V, I_{out\_LLC} = 100A \tag{32}$$

(2) Resonant frequency (also working frequency) is 130 kHz, time of turn off is 20nS.

$$f_{res} = 130K, T_{off\_LLC} = 20 * 10^{-9}S \tag{33}$$

The LLC will always work at resonant frequency to get a high efficiency.

For LLC converter following Buck converter, input voltage is 150 $V_{DC}$, so the expected turn ratio of primary side to secondary side of transformer is

$$N_{buckLLC\_exp} = \frac{V_{in\_buckLLC}}{2*V_{outLLC}} = \frac{150}{2*12} = 6.25 \tag{34}$$

The final turn ratio of transformer of LLC following Buck is determined as 6, that is

$$N_{buckLLC\_Tx} = 6 \tag{35}$$

For LLC converter following Boost converter, input voltage is 460Vdc, then the expected turn ratio is

$$N_{boosLLC\_exp} = \frac{V_{in\_boostLLC}}{2*V_{out\_LLC}} = \frac{460}{2*12} = 19.167 \tag{36}$$

The final turn ratio of transformer of LLC following Boost is determined as 19, that is

$$N_{boostLLC\_Tx} = 19 \tag{37}$$

It is supposed that magnetic cores of the two LLC transformers are same, which means the effective magnetic area and air gap are same. Another critical presupposed condition is that winding number of secondary side transformer is 1(total winding number is 2 for center-taped winding) for the two transformers, which is realized in many server power supplies to reduce the secondary-side winding conduction loss, so the ratio of primary winding inductance of two transformers is

$$L_{m\_buck2boost\_Tx} = \left(\frac{N_{buckLLC\_TX}}{N_{boostLLC\_Tx}}\right)^2 = \left(\frac{6}{19}\right)^2 = 0.1 \tag{38}$$

If the inductance of primary side transformer of LLC following Buck converter is assigned to 80µH, that is

$$L_{m\_buckLLC\_Tx} = 80uH \tag{39}$$

Then according to equation (38) the winding inductance of primary side transformer of LLC following Boost converter is

$$Lm_{boostllc\_Tx} = \frac{L_{m\_buckLLC\_Tx}}{L_{m\_buck2boost\_Tx}} = \frac{80}{0.1} = 800uH \tag{40}$$

So the peak values of magnetizing currents of two transformers are

$$Ip_{Lm\_buck} = \frac{V_{in\_buckLLC}}{4f_{res}L_{m\_buckLLC\_Tx}} = \frac{150}{4*130*10^3*80*10^{-6}} = 3.606 \quad (41)$$

$$Ip_{Lm\_boost} = \frac{V_{in\_boostllc}}{4f_{res}Lm_{boostLLC\_Tx}} = \frac{460}{4*130*10^3*800*10^{-6}} = 1.103 \quad (42)$$

As it is known that the rms current of primary side of LLC converter can be calculated as

$$I_{rms\_ps\_llc} = \frac{1}{4\sqrt{2}}\frac{V_{out}}{N*R_{load}}\sqrt{N^4 * \frac{R_{load}{}^2}{Lm^2*f_{res}{}^2} + 4\pi^2} \quad (43)$$

Where N is the turn ratio of primary-side winding to secondary-side winding and $L_m$ is the inductance of primary-side winding, $R_{load}$ is the resistor of output load and can be calculated as

$$R_{load} = \frac{V_{out\_LLC}}{I_{out\_LLC}} \quad (44)$$

The rms current of primary-side LLC following Buck converter at different load can be obtained according to equation (43) and (44), as shown in the Table 15.

**Table 15 Primary-side rms current of LLC converter following Buck converter at different load**

| | 20% load | 50% load | 100% load |
|---|---|---|---|
| rms current[A] | 3.899 | 9.337 | 18.552 |

For LLC following Boost converter, the rms current of primary-side transformer at different load is

**Table 16 Primary-side rms current of LLC converter following Boost converter at different load**

| | 20% load | 50% load | 100% load |
|---|---|---|---|
| rms current[A] | 1.231 | 2.948 | 5.859 |

The power loss of MOSFET used in LLC converter includes conduction loss and turn off loss, the conduction loss is calculated as:

$$P_{con\_llc} = I_{rms\_mos}{}^2 * R_{DS(on)} \quad (45)$$

Where $I_{rms-mos}$ is the rms current through MOSFET, for LLC converter

$$I_{rms-mos} = \frac{1}{\sqrt{2}} I_{rms\_ps\_llc} \quad (46)$$

When LLC converter performs at its resonant frequency, turn off loss can be calculated as:

$$P_{toff\_llc} = \frac{1}{2} Vin * Ip_{Lm} * T_{off\_llc} * Fr \quad (47)$$

Where $V_{in}$ is the input voltage of LLC(output voltage of Buck or Boost converter), $Ip_{Lm}$ is the peak current of magnetic inductance of transformer as calculated in equation (41) or (42), $T_{off\_llc}$ is the turn off time during which $V_{DS}$ (voltage between Drain and Source pin of MOSFET) of MOSFET increase from zero to $V_{in}$.

We suppose that the power loss of high-side or low-side MOSFETs of LLC is 5W, the $R_{DS(on)}$ of high-side or low-side MOSFETs can be calculated

$$R_{DS(on)} = \frac{P_{totalloss} - P_{toff\_llc}}{I_{rms}{}^2} \quad (48)$$

The max. $R_{DS(on)}$ of the MOSFETs used in the two LLC converters then can be obtained according to equation (33), (45)~(48):

$$R_{DS(on)\_\max\_buckLLC} = 0.025 \quad (49)$$

$$R_{DS(on)\_\max\_boostLLC} = 0.253 \quad 50)$$

Where $R_{DS(on)\_max\_buckLLC}$ and $R_{DS(on)\_max\_boostLLC}$ are the max. MOSFET $R_{DS(on)}$ of the LLC converter following Buck and Boost respectively.

The max. voltage MOSFETs have to endure for LLC converter following Buck converter is 150 $V_{DC}$ in the application. Considering 80% or more voltage derating and voltage spike produced by parasitic parameters, the voltage class of 250 V OptiMOS™ is suitable for the application. However, the max. voltage MOSFETs have to endure for LLC converter following Boost converter is 460 $V_{DC}$ in the application. Considering 80% or more voltage derating and voltage spike produced by parasitic parameters, the voltage class of 600 V or 650 V CoolMOS™ is suitable for the application. Therefore two paralleled IPP220N25NFD and two paralleled IPP65R190CFD are chose for LLCs following Buck converter and Boost converter respectively concerning power loss and excellent body diode requirement. $R_{DS(on)}$ is 0.0388Ω and 0.58Ωat 120°C for IPP220N25NFDand IPP65R190CFD respectively[12][13], then the power loss of each MOSFET using IPP220N25NFD and IPP65R190CFD for LLCs following Buck and Boost converter can be obtained according to equation (45)~(47), as shown in the following table.

**Table 17 Power loss of each MOSFET in the two LLC converters**

| | 20% load | 50% load | 100% load |
|---|---|---|---|
| Power loss of each MOSFET of primary side of LLC following Buck[W] | 0.777 | 1.126 | 2.372 |
| Power loss of each MOSFET of primary side of LLC following Boost[W] | 0.728 | 1.051 | 2.204 |

For secondary-side MOSFETs of the two LLC converters, the rms currents through any branch of synchronous rectifier (Q5 or Q6 in fig.10) of the two LLC converters are same and can be calculated

$$I_{rms_{ss}} = \frac{1}{4} * \frac{V_{out} * \pi}{R_{load}} * \sqrt{\frac{N^4 * R_{load}^2}{L_m^2 * f_{res}^2} * \frac{5\pi^2 - 48}{12\pi^4} + 1} \qquad (52)$$

Because LLC converters work at resonant frequency, the power loss of secondary-side MOSFETs is mainly composed of conduction loss and is expressed as:

$$P_{cl\_ss} = {I_{rms\_ss}}^2 * R_{DS(on)} \qquad (52)$$

It is reasonable to choose SuperSO8 package of Infineon Technologies as the secondary-side MOSFET for its very low $R_{DS(on)}$ and excellent heat dissipating capability. It is supposed that max. power loss for any branch of synchronous rectification(Q5 or Q6 in Figure 10) is about 4W. The $R_{DS(on)}$ of the MOSFET than can meet the power loss requirement can be obtained according to equation (51) and (52)

$$R_{DS(on)} = \frac{P_{cl\_ss}}{I_{rms\_ss^2}} = \frac{4}{\left(\frac{1}{4} * \frac{12 * \pi}{\frac{12}{100}} * \sqrt{\frac{6^4 * \left(\frac{12}{100}\right)^2}{(80 * 10^{-6})^2 * (130 * 10^3)^2} * \frac{5\pi^2 - 48}{12\pi^4} + 1}\right)^2} = 0.65 * 10^{-3} \qquad (53)$$

The max. voltage MOSFETs have to endure for secondary side of LLC converter is 24 $V_{DC}$ in the application. Considering 80% or more voltage derating and voltage spike produced by parasitic parameters, the voltage class of 40 V OptiMOS™ is suitable for the application.

The two paralleled BSC010N04LSI are used in any branch of synchronous rectification, $R_{DS(on)}$ of the BSC010N04LS at 120°C junction temperature is about 1.35 mΩ [14], then the power loss of each MOSFETs of secondary side of LLC converter is calculated according to equation (51) and (52), the results at different load condition are shown in the Table 18.

**Table 18 Power loss of each MOSFETs of secondary side of LLC converter**

| | 20% load | 50% load | 100% load |
|---|---|---|---|
| Power loss of each MOSFET [W] | 0.084 | 0.521 | 2.082 |

# 4 Inductors and transformer

## 4.1 Inductors

From calculation results in the previous parts, inductor of Buck converter is 720 µH and inductor of Boost converter is 1.33 mH, it is supposed that we choose the two magnetic cores with same dimension and material such as ferrite for the two inductors, and the airgap of the two cores are supposed to be same to each other so the ratio of winding number of Buck inductor to Boost inductor is

$$N_{buck2boost\_L} = \sqrt{\frac{L_{buck}}{L_{boost}}} = \sqrt{\frac{720u}{1.33m}} = 0.736 \quad (54)$$

As the current through the Buck or Boost inductor is of saw-tooth waveform so the rms current is calculated

$$I_{rms\_L} = \sqrt{\frac{{I_{min}}^2 + I_{min} * I_{max} + {I_{max}}^2}{3}} \quad (55)$$

For different input voltage, the rms current through the Buck inductor is nearly same so we can get the rms current at different load according to Table 3 and equation (55), results are shown in the following table

**Table 19 Rms current through the Buck inductor**

| | 20% load | 50% load | 100% load |
|---|---|---|---|
| rms current through the Buck inductor [A] | 1.7 | 4.1 | 8.2 |

Different from Buck inductor, however, the rms current through the Boost inductor is related not only to output load but also to input voltage, so the rms current through the Boost inductor is obtained in Table 9 and equation (55), results are shown in the Table 20.

**Table 20 Rms current through the Boost inductor**

| | $V_{in\_1}$=190 $V_{DC}$ | $V_{in\_2}$=268 $V_{DC}$ | $V_{in\_3}$=300 $V_{DC}$ | $V_{in\_4}$=378 $V_{DC}$ | $V_{in\_5}$=400 $V_{DC}$ |
|---|---|---|---|---|---|
| 20% load | 1.4 A | 1.0 A | 0.9 A | 0.7 A | 0.7 A |
| 50% load | 3.3 A | 2.4 A | 2.1 A | 1.7 A | 1.6 A |
| 100% load | 6.6 A | 4. 7 A | 4.2 A | 3.3 A | 3.1 A |

It is supposed that the maximum current density of the windings of two inductors is same, therefore the ratio of cross-section area of windings of Buck inductor to Boost inductor is

$$A_{buck2boost\_L} = \frac{I_{rms\_buck\_max}}{I_{rms\_boost\_max}} = \frac{8.2}{6.6} = 1.242 \quad (56)$$

Then the ratio of DC winding resistance of buck inductor to that of boost inductor is

$$R_{buck2boost} = \frac{N_{buck2boost\_L}}{A_{buck2boost\_L}} = \frac{0.736}{1.242} = 0.592 \quad (57)$$

The ratio of DC copper loss of Buck inductor to that of Boost inductor is calculated as

$$P_{cl\_buck2boost} = \frac{{I_{rms\_buck}}^2}{{I_{rms\_boost}}^2} * R_{buck2boost} \quad (58)$$

The results of equation (58) at different input voltage and load are shown in the Table 21.

**Table 21 The ratio of DC copper loss of Buck inductor to that of Boost inductor**

| | $V_{in\_1}$=190 $V_{DC}$ | $V_{in\_2}$=268 $V_{DC}$ | $V_{in\_3}$=300 $V_{DC}$ | $V_{in\_4}$=378 $V_{DC}$ | $V_{in\_5}$=400 $V_{DC}$ |
|---|---|---|---|---|---|
| 20% load | 0.873 A | 1.711 A | 2.113 A | 3.493 A | 3.493 A |
| 50% load | 0.914 A | 1.728 A | 2.257 A | 3.445 A | 3.889 A |
| 100% load | 0.914 A | 1.803 A | 2.257 A | 3.657 A | 4.144 A |

The current change (ΔI) through Buck and Boost inductor, as calculated in the Table 3 and Table 9, are shown again in the Table 22.

**Table 22 Current change (ΔI) through Buck and Boost inductor**

| | $V_{in\_1}$=190 $V_{DC}$ | $V_{in\_2}$=268 $V_{DC}$ | $V_{in\_3}$=300 $V_{DC}$ | $V_{in\_4}$=378 $V_{DC}$ | $V_{in\_5}$=400 $V_{DC}$ |
|---|---|---|---|---|---|
| $\Delta I_{L\text{-}buck}$[A] | 0.548 A | 1.147 A | 1.302 A | 1.571 A | 1.628 A |
| $\Delta I_{L\text{-}boost}$[A] | 1.048 A | 1.051 A | 0.981 A | 0.633 A | 0.49 A |

The inductance of inductor is expressed as

$$L = \frac{d\Psi}{di} = \frac{N*\Delta B*A_e}{\Delta I} \tag{59}$$

We choose the same magnetic cores for the two inductors so effective core area ($A_e$) is same, then the ratio of magnetic density change of the Buck inductors to Boost inductor is

$$\Delta B_{buck2boost} = \frac{L_{buck}}{L_{boost}} * \frac{\Delta I_{buck}}{\Delta I_{boost}} * \frac{1}{N_{buck2boost}} \tag{60}$$

The results of equation (60) at different input voltage is obtained through equation(9), equation(31), equation(60) and Table22, as shown in the following table

**Table 23 The ratio of magnetic density change for the Buck and Boost inductor**

| | $V_{in\_1}$=190 $V_{DC}$ | $V_{in\_2}$=268 $V_{DC}$ | $V_{in\_3}$=300 $V_{DC}$ | $V_{in\_4}$=378 $V_{DC}$ | $V_{in\_5}$=400 $V_{DC}$ |
|---|---|---|---|---|---|
| $\Delta B_{buck2boost}$ | 0.385 | 0.803 | 0.977 | 1.826 | 2.445 |

According to magnetic core loss of Steinmetz equation, the magnetic loss is expressed as

$$P_{ml} = V * K * \Delta B^{\alpha} * {f_W}^{\beta} \tag{61}$$

Where V is the volume of the magnetic core, K,α,β are constant coefficients, ΔB is the magnetic density change and fw is the working frequency, as we have selected same magnetic cores for the two inductors V, K, fw, α and β are same for the two inductors, then the ratio of magnetic loss of the Buck inductor to Boost inductor can be obtained:

$$P_{ml-buck2boost} = {\Delta B_{buck2boost}}^{\alpha} \tag{62}$$

## 4.2 LLC transformers

We have supposed that the winding numbers of secondary-side transformers are same such as 1(each brach of synchronous rectification) for the two LLC transformers that following Buck and Boost converter respectively and the working frequencies are same for the two LLC converters. As a result the voltage-second products of the two transformers are same, so the magnetic density change ΔB is equivalent to each other. The two transformers use identic magnetic core (equivalent in volume and Steinmetz coefficients), therefore the magnetic losses are same for the two transformers.

If it is supposed that the maximum current density of the windings (include primary side and secondary side) of the two transformers are same, the ratio of cross-section area of primary-side windings of two transformers is

$$A_{buck2boost\_ps\_Tx} = \frac{I_{rms\_buckllc\_ps\_max}}{I_{rms\_boostllc\_ps\_max}} \tag{63}$$

As it is known that the rms primary-side current of LLC converter is expressed by equation (43), and at most times the equation can be simplified as

$$I_{rms\_ps\_LLC} = \frac{\pi}{2\sqrt{2}} * \frac{V_{out}}{N*R_{load}} \tag{64}$$

Thus according to equation (64), the ratio of rms current through primary-side windings of the two transformers is

$$\frac{I_{rms\_ps\_buckllc}}{I_{rms\_ps\_boostllc}} = \frac{N_{boostllc\_Tx}}{N_{buckllc\_Tx}} \tag{65}$$

Then the DC resistance ratio of primary-side windings of two transformers is obtained according to equation (63) and (65)

$$R_{DC\_buck2boost\_ps\_Tx} = \frac{N_{buckllc\_Tx}}{N_{boostllc\_Tx}} * \frac{1}{A_{buck2boost_{ps_{Tx}}}} = \frac{{I_{rms\_boostllc\_ps}}^2}{{I_{rms\_buckllc\_ps}}^2} \tag{66}$$

Therefore the ratio of primary-side winding copper loss of the two transformers is

$$P_{cl\_buck2boost\_Tx} = (\frac{I_{rms\_buckllc\_ps}}{I_{rms\_boostllc\_ps}})^2 * R_{DC\_buck2boost\_ps\_Tx} = \left(\frac{I_{rms_{buckllc_{ps}}}}{I_{rms_{boostllc_{ps}}}}\right)^2 * \frac{{I_{rms_{boostllc_{ps}}}}^2}{{I_{rms_{buckllc_{ps}}}}^2} = 1 \tag{67}$$

We can know from equation (67) the copper loss of primary-side windings of the two transformers are same. As about copper loss of secondary-side windings, the winding numbers the current density of the windings and the currents through the windings are same and therefore the copper losses are same.

It is concluded that the power loss of two transformers are same if we choose same magnetic core, current density for windings and same winding numbers for secondary side.

# 5 Conclusion

We compare the two solutions, Buck followed by LLC and Boost followed by LLC, in three dimensions: occupation of PCB, power loss and the cost of power MOSFETs

## 5.1 Occupations of PCB by MOSFETs and magnetic elements

For the solution of Buck followed by LLC, total eight TO-220 package MOSFETs and four SuperSO8-package MOSFETs are chosen for Buck and its followed LLC converters. The same number and package of MOSFETs are chosen for Boost and its followed LLC converters, so the occupations of PCB by MOSFETs are same for the two solutions. However, for the LLC following Buck converter, the input voltage is only $150V_{DC}$, the MOSFETs used in the LLC belongs to the OptiMOS™ series of Infineon Technologies, in which there is more available SMD package such as SuperSO8, DPAK, therefore for high power density application the solution of Buck followed by LLC will be predominant.

For the magnetic elements, the magnetic cores and current density of windings are same for inductors and transformers, so the dimensions of inductors and transformers for the two solutions are nearly same.

## 5.2 Power loss of MOSFETs and magnetic elements

We can get the power loss of MOSFETs used in Buck, Boost and two LLC converters according to the previous calculation at different loads and input voltages, as shown in the followed tables.

**Table 24 MOSFETs loss of two solutions at 20% load**

| Stage | $V_{in\_1}$=190 $V_{DC}$ | $V_{in\_2}$=268 $V_{DC}$ | $V_{in\_3}$=300 $V_{DC}$ | $V_{in\_4}$=378 $V_{DC}$ | $V_{in\_5}$=400 $V_{DC}$ |
|---|---|---|---|---|---|
| Buck | 1.188 W | 1.336 W | 1.394 W | 1.52 W | 1.556 W |
| Boost | 2.828 W | 2.408 W | 2.372 W | 2.31 W | 2.296 W |
| LLC following Buck | 3.108 W | | | | |
| LLC following Boost | 2.912 W | | | | |

**Table 25 MOSFETs loss of two solutions at 50% load**

| Stage | $V_{in\_1}$=190 $V_{DC}$ | $V_{in\_2}$=268 $V_{DC}$ | $V_{in\_3}$=300 $V_{DC}$ | $V_{in\_4}$=378 $V_{DC}$ | $V_{in\_5}$=400 $V_{DC}$ |
|---|---|---|---|---|---|
| Buck | 2.962 W | 3.466 W | 3.634 W | 4.006 W | 4.102 W |
| Boost | 5.28 W | 3.724 W | 3.534 W | 3.226 W | 3.166 W |
| LLC following Buck | 4.504 W | | | | |
| LLC following Boost | 4.204 W | | | | |

**Table 26 MOSFETs loss of two solutions at 100% load**

| Stage | $V_{in\_1}$=190 $V_{DC}$ | $V_{in\_2}$=268 $V_{DC}$ | $V_{in\_3}$=300 $V_{DC}$ | $V_{in\_4}$=378 $V_{DC}$ | $V_{in\_5}$=400 $V_{DC}$ |
|---|---|---|---|---|---|
| Buck | 8.466 W | 9.942 W | 10.404 W | 11.352 W | 11.588 W |
| Boost | 12.552 W | 7.786 W | 7.046 W | 5.882 W | 5.656 W |
| LLC following Buck | 4.744 W | | | | |
| LLC following Boost | 4.408 W | | | | |

Based on previous data it is easy to get the comparison of MOSFETs loss in the two solutions (Buck followed by LLC and Boost followed by LLC) at different load and input voltage, as shown in the followed figures.

At light load such as 20% load, the solution of Buck plus LLC will have a low MOSFETs loss compared with Boost plus LLC. At medium load such as 50% load, the solution of Buck plus LLC will have a low MOSFETs loss at low input voltage, with the increase of input voltage, however, the solution of Boost plus LLC will have a low MOSFETs loss. Similar to medium load, when the load is heavy such as full load, the solution of Boost plus LLC will have a low MOSFETs loss compared with Buck plus LLC solution.

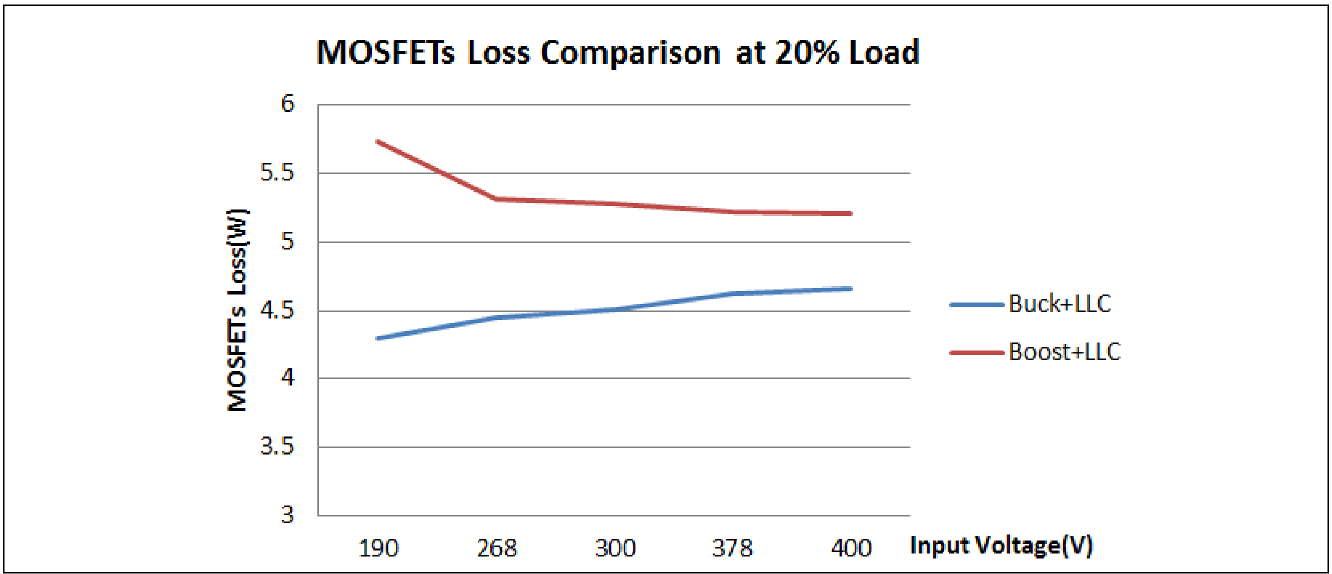


**Figure 11 MOSFETs loss comparison at 20% load**

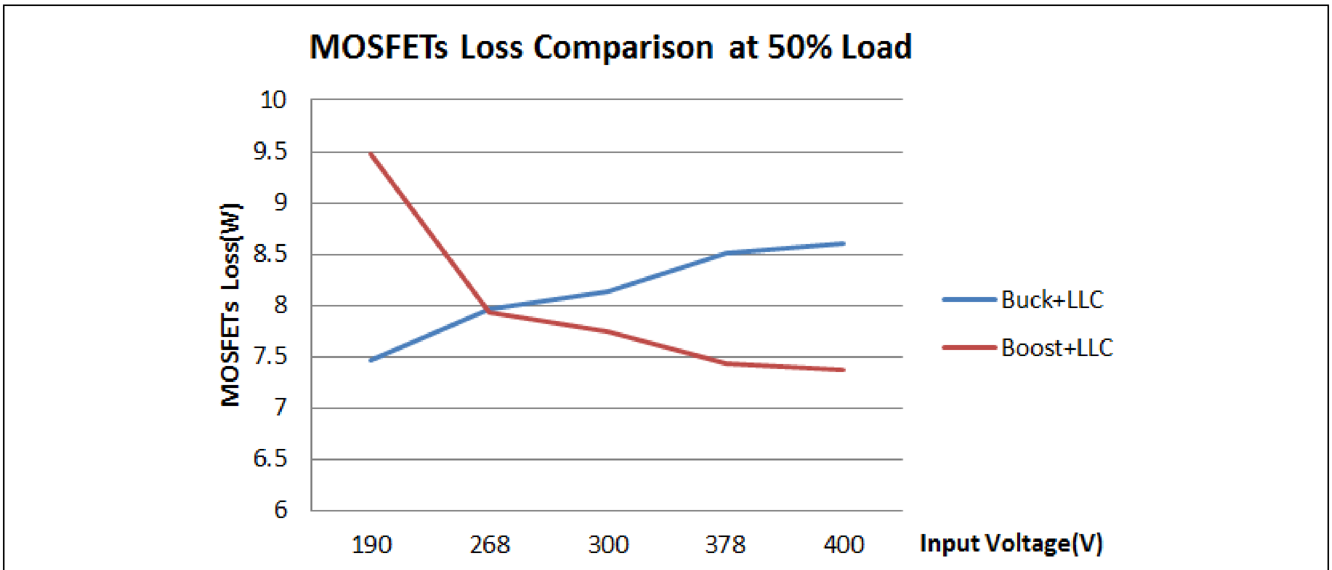


**Figure 12 MOSFETs loss comparison at 50% load**

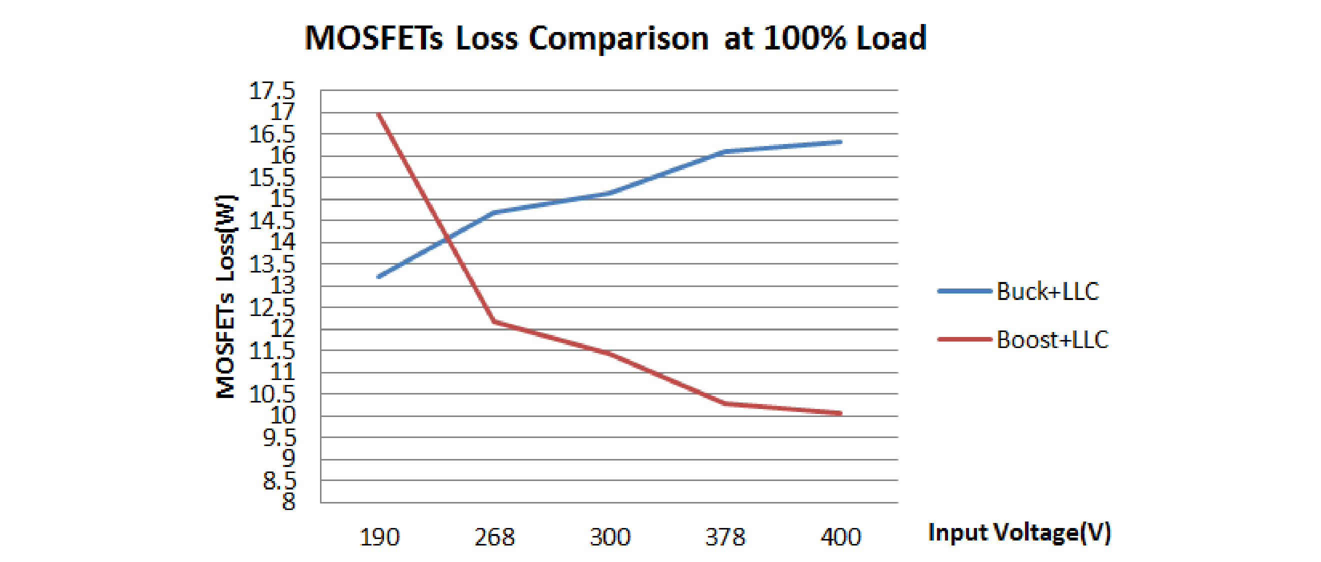


**Figure 13 MOSFETs loss comparison at 100% load**

Next is about the inductor power loss comparison, as we have calculated the DC copper loss ratio of Buck inductor to Boost inductor as shown in Table 21, the data can be transformed to curve to get a more clear comparison.

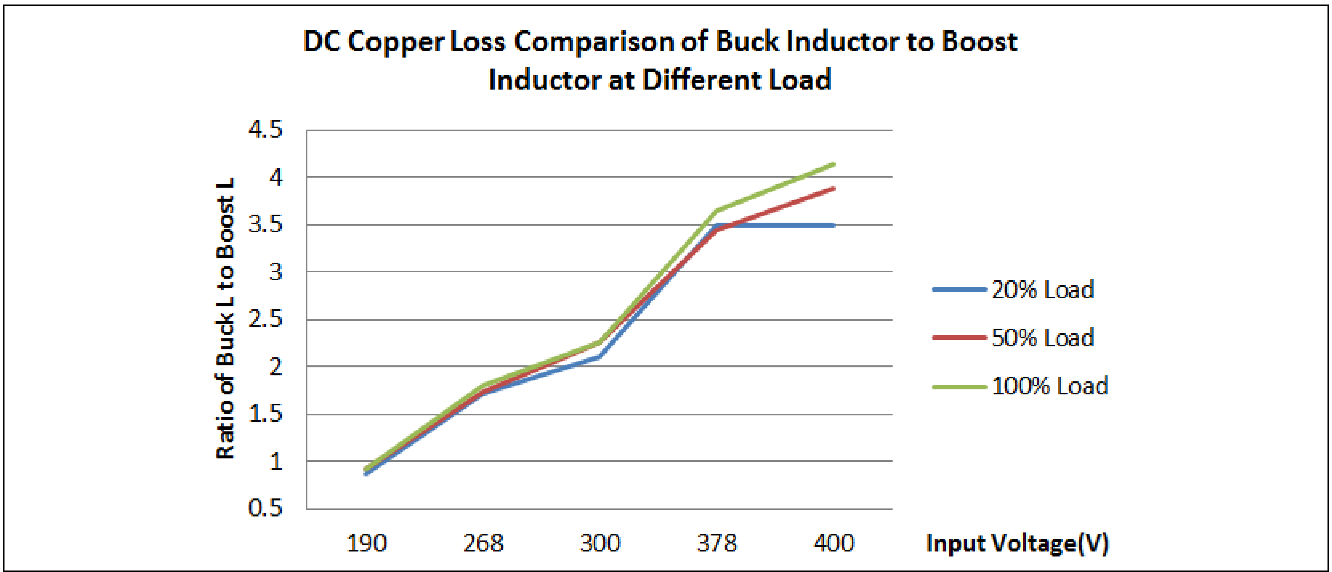


**Figure 14 Ratio of DC copper loss of Buck inductor to Boost inductor at different load and input voltage**

As show in the Figure 14, Buck converter will have a higher DC copper loss compared with Boost converter if the ripple current through the two inductors and current density of windings are same. And the higher input voltage the higher Buck inductor DC copper loss compared with Boost converter.

We have obtained the ratio of magnetic loss of Buck inductor to that of Boost inductor in equation (62), for ferrite material such as 3C95 or PC95 that is widely used in SMPS(Switched Mode Power Supply), the range of $\alpha$ is generally from 2.5 to 3 at about 100 kHz working frequency, so the ratio of magnetic loss of the two inductors as a function of α is shown in the following figure according to equation (62) and Table (23).

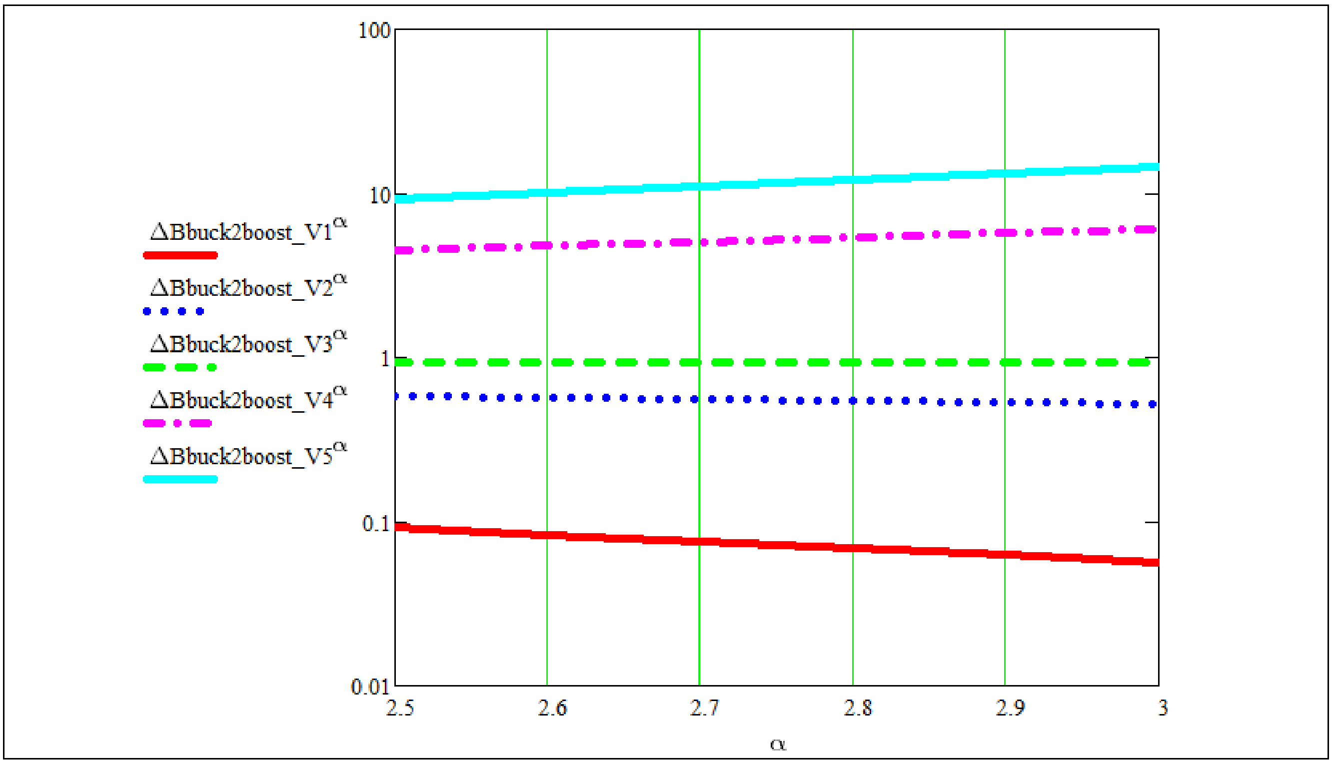


**Figure 15 Ratio of magnetic loss of Buck inductor to Boost inductor**

$\Delta Bbuck2boost\_V1^{\alpha}$ in Figure 15 represents the ratio of magnetic loss of Buck inductor to Boost inductor when input voltage is 190 $V_{DC}$, and V2 to V5 represents input voltage of 268 $V_{DC}$, 300 $V_{DC}$, 378 $V_{DC}$ and 400 $V_{DC}$ respectively. When input voltage is smaller than 300 V (green, blue and red curve in Figure 15), Buck inductor will have a smaller magnetic loss compared to Boost inductor, as input voltage increase, however, Buck inductor will have a larger magnetic loss compared to Boost inductor, the higher input voltage, the higher Buck inductor magnetic loss compared to Boost inductor if the dimension of the magnetic cores and air gap are same for the two inductors.

The two solutions will have same loss of transformers of LLC if magnetic core, winding current density and secondary-side winding number are same.

## 5.3 Cost of MOSFETs

The cost of MOSFETs can be obtained according to the choice of MOSFETs and price listed in Infineon website, as shown in the following table

**Table 27 Cost of MOSFETs for the two solutions**

| | Part Items | Number(PCS) | Price per part(€) | Total cost(€) |
|---|---|---|---|---|
| Buck+LLC | IPP60R099P6 | 2 | 2.76 | 19.96 |
| | IPP65R150CFD | 2 | 1.93 | |
| | IPP220N25NFD | 2 | 3.07 | |
| | BSC010N04LSI | 4 | 1.11 | |
| Boost+LLC | IPP60R125P6 | 2 | 1.91 | 14.08 |
| | IPP65R310CFD | 2 | 1.3 | |

| | Part Items | Number(PCS) | Price per part(€) | Total cost(€) |
|---|---|---|---|---|
| | IPP65R190CFD | 2 | 1.61 | |
| | BSC010N04LSI | 4 | 1.11 | |

As shown in the Table 27, the cost of MOSFETs of Boost+LLC is smaller than that of Buck+LLC, about 30% cost down is realized according to the price listed in Infineon Technologies website.

As a conclusion, the solution of Boost followed by LLC is predominant in the application of HVDC DC/DC converter that suitable for 240 $V_{DC}$ and 336 $V_{DC}$ HVDC system considering medium to high load efficiency and power MOSFETs cost. On the contrary, solution of Buck followed LLC will be good at high power density and high efficiency requirement at light load and low input voltage.

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# Revision History

**Major changes since the last revision**

| Page or Reference | Description of change |
|---|---|
| -- | First Release |
| | |
| | |

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