

## Two Switches Balanced Buck Converter for Common-Mode Noise Reduction

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**Abstract:** The EMI noise source in a switching mode power supply is dominated by a common mode noise. If we can understand the common mode noise occurring mechanism, it is resulted to find out the method to suppress the EMI noise source in the switching mode power supply. The common mode noise is occurring mostly due to circuit is unbalanced which is caused by the capacitive coupling to frame ground, which passes through a heatsink of the switching devices.

This research paper presents a new effective balancing method of buck converter circuit by mean of grounding the parasitic and compensation capacitors in correct proportion which is called that the common mode impedance balance (CMIB). The CMIB can be achieved by source, transmission line and termination balanced, such balancing, the common mode current will be cancelled out in the frame ground. The greatly reduced common mode noise can be confirmed by the experimental results.

**Keywords:** EMI, EMC, Conducted noise, SMPSs, Balanced Buck converter

### 1. Introduction

The conventional buck converters have been usually using unbalanced circuit topology between sending and returning power line. Consequently these cause the differential and common mode noise [6]. This paper proposes a two switches balanced buck converter circuit, the noise reduction can be achieved by source, transmission line and termination balanced. This method can be called common mode impedance balancing or CMIB, which is an alternative effective way to suppress the conducted noise. If the CMIB can be equalized the impedance, the common mode noise will be cancelled out in the frame ground [2],[4].

The heat sinks are usually used with the mosfet and diode, so the parasitic capacitance is formed between the drain of the mosfet or the cathode of the diode and the frame ground through its heat sink [1],[5]. Consequently these cause the large common mode noise currents. The reduction can be achieved by adding the compensation capacitor to build the sub circuit of mosfet-heatsink or diode-heatsink. If the sub circuit can be provided correct proportion to equalize the impedance, which is called that the common mode noise cancellation mechanism, the common mode currents will be cancelled out in the heat sink.

The common mode voltage source causes the common mode currents, when it operates to parasitic capacitances or capacitive paths. The noise source cancellation concept can be achieved by adding one more mosfet switch to the returning power line to generate the common mode voltage source canceller but its phase is out of phase to an original common mode voltage source. And this method can be called common mode source balancing or CMSB.

If the converter can force both of the mosfet switches to share the voltage properly, under all operating conditions, then the switch voltage rating can be reduced with respect to the voltage rating required if only one switch were used [3]. The greatly reduced common mode noise can be confirmed by the experimental results.

### 2. Noise in Conventional Buck converter

The conventional buck converter topology will have inherent unbalanced circuit between sending power line and return power line with only one switching device and one inductor on the sending power line as shown in Fig.1a.

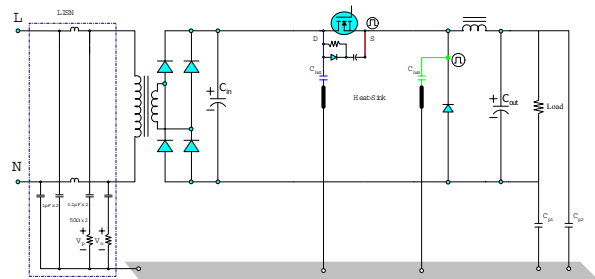


Fig. 1a Conventional buck converter

From fig.1b the common mode current in sending power line are

$$i_{CS1} = C_{hs1} \, dv_1/dt \tag{1}$$

$$i_{CS2} = C_{hs2} \, dv_2/dt \tag{2}$$

$$i_{CS3} = C_{p2} \, dv_3/dt \tag{3}$$

Where,  $C_{hs1}$  is the parasitic capacitance between drain of the switching device and heatsink.

$dv_1/dt$  is the rate of change of the switching voltage when the switching device is on or off condition.

$C_{hs2}$  is the parasitic capacitance between cathode of the diode and heatsink.

$dv_2/dt$  is the rate of change of the switching voltage when the switching device is on or off condition.

$C_{p2}$  is the parasitic capacitance between termination of sending power line and frame ground.

$dv_3/dt$  is the rate of change of the load voltage when the switching device is on or off condition.

And the common mode current in return power line is

$$i_{CR} = C_{p1} \, dv_4/dt \tag{4}$$

$C_{p1}$  is the parasitic capacitance between terminations of returns power line and frame ground.

$dv_4/dt$  is the rate of change of the switching voltage when the diode is on or off condition.

The unbalanced circuit of Fig.1b is mean that  $i_{CS}$  is not equal to  $i_{CR}$  and the summation of  $i_{FG}$  in the frame ground will become

$$i_{FG} = i_{CS1} + i_{CS2} + i_{CS3} + i_{CR} \tag{5}$$

The  $i_{FG}$  in equation (5) is the cause of common mode noise.

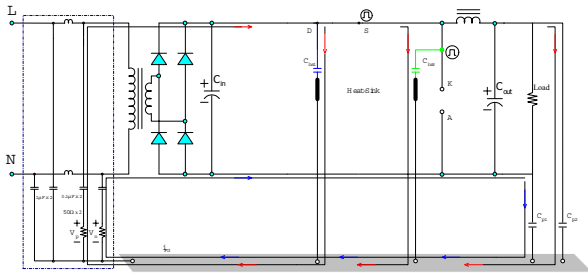


Fig. 1b Common mode current of conventional Buck converter during the period Mosfet is turned on

### 3. Noise source cancellation with two switches

The noise source cancellation concept can be achieved by adding one more mosfet switch to the returning power line to generate the *common mode voltage source canceller* but its phase is out of phase to an original common mode voltage source as shown in fig.2

The drain voltage of lower mosfet switch on returning power line with respect to frame ground  $V_{ts2}$  and the source voltage of upper mosfet switch on sending power line  $V_{ts1}$  change complementarily, that is, by the same amount but in an opposite polarity in the switching time between the both of common mode noise sources. As a result, the common mode voltage [3]  $V_{CM}$  is cancelled by itself.

$$V_{CM} = (V_{ts1} + V_{ts2}) / 2 \quad (6)$$

In the ideal case, this voltage is zero. And this idea can be called *common mode source balancing* or CMSB.

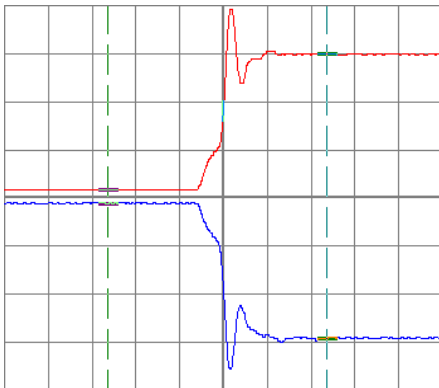


Fig.2. Compare the transmission line voltage at sending  $v_{ts1}$  and returning  $v_{ts2}$  with respect to frame ground, with Over-shoot voltage at frequency 10-12.5MHz combined; (5V/div, 0.2μs/div)

In practical, the voltage sharing problem due to device parameter tolerances, which can cause dynamic and static voltage unbalance. If the RCD snubber circuit can force the switches to share the voltage properly, under all operating conditions including power up and power down, then the switch voltage rating can be reduced with respect to the voltage rating required if only one switch were used.

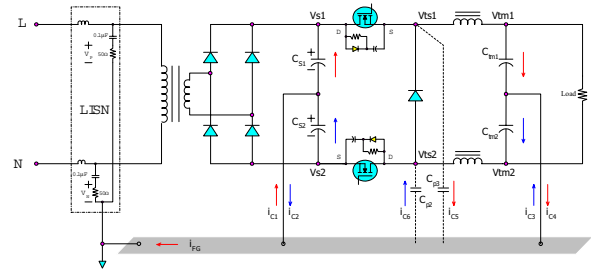


Fig.3 Common mode currents with CMIB technique in two switches balanced Buck converter without heat sink

### 4. Noise cancellation mechanism with CMIB technique

Topology modification in conventional buck converter to two switches balanced buck converter, which is topology modified for balancing can be applied to achieve the concepts of *impedance balancing* and *noise source balancing*.

The impedance balancing concept can be achieved by source, transmission line and termination balanced as shown in Fig.3, the common mode current will be cancelled out in the frame ground. The purpose of these three balancing for common mode current paths is to make, the three pair of common mode currents become opposite in direction and the summation of  $i_{FG}$  in the frame ground will become

$$i_{FG} = i_{c1} - i_{c2} + i_{c3} - i_{c4} + i_{c5} - i_{c6} \quad (7)$$

The common mode current cancellation mechanism by the bridge balancing condition is

$$Z_{cs1} / Z_{cs2} = Z_{tm1} / Z_{tm2} \quad (8)$$

This idea can be called *common mode impedance balancing* or CMIB.

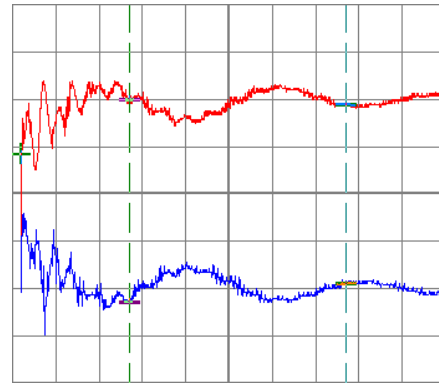


Fig.4. Compare the supply voltage at positive terminal  $v_{s1}$  and negative terminal  $v_{s2}$  with frequency of 25-28 MHz range on 2.5MHz; (100ns/div, 200mV)

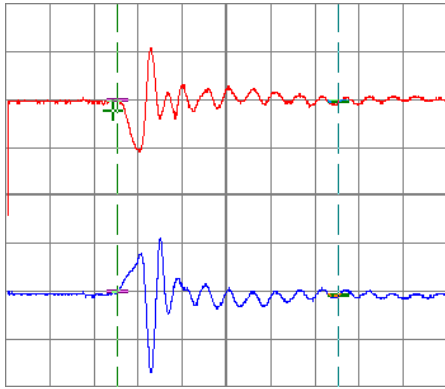
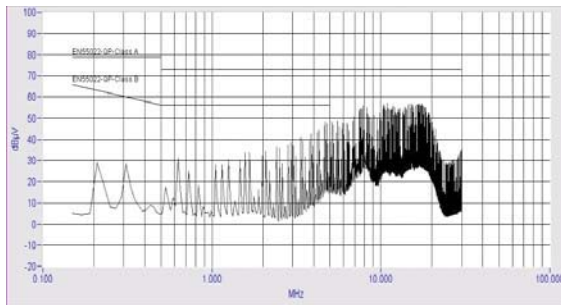
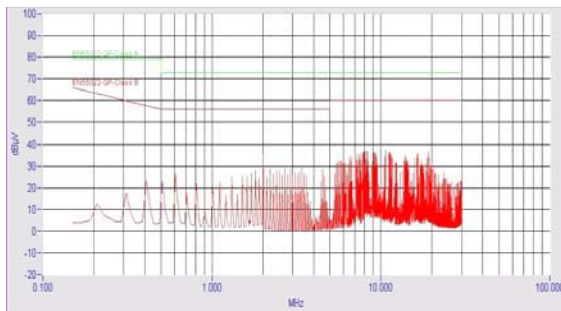


Fig.5. Compare the termination voltage at positive terminal  $v_{tm1}$  and negative terminal  $v_{tm2}$ : (100ns/div, 200mV)

In order to verify this idea a Buck converter prototype was constructed using the same layout and the components except the inductor. The inductor in proposed buck converter was replaced by split inductor, which was built with the same ferrite core and number of winding turns used in conventional buck. In order to confirm the effect of this modification, the layout of printed circuit board and other components remain unchanged, this eliminated influence from other factors.

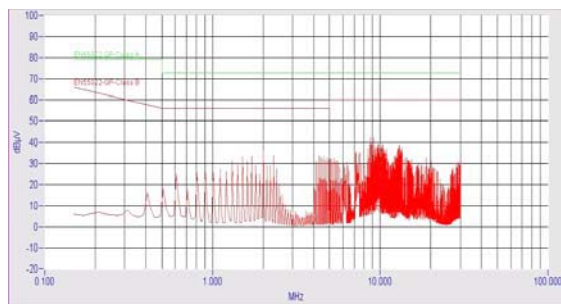


(a) Total noise spectrum

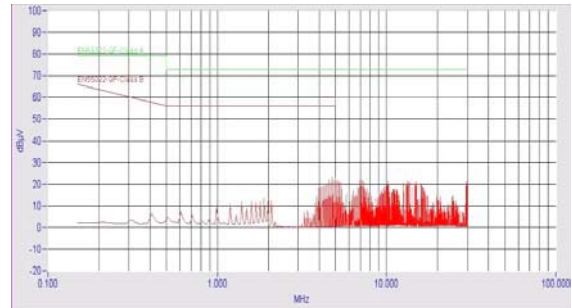


(b) Common mode noise spectrum

Fig.6. Spectrums of conventional Buck converter



(a) Total noise spectrum



(b) Common mode noise spectrum

Fig.7. Spectrums of two switches balanced Buck converter

The spectrum of common mode noise current flow out from buck converter is measured with high frequency current probe. And the spectrum of total noise current is measured with LISN. Experiment result of conventional buck converter is shown in fig. 6. Comparing with proposed buck converter as shown in fig.7, we can see that there are nearly 15 dB drops from 2 to 30MHz. The method of "CMSB and CMIB" proposed in this paper make great contribution to reduce the common mode noise.

## 5. Cancellation mechanism for effect from heat sink

The heat sinks are usually used with the mosfet and diode, so the parasitic capacitance  $C_{hs}$  is formed between the drain of the mosfet or the cathode of the diode and the frame ground through its heat sink. These parasitic capacitances, in general, are especially high and play a major role in production of common mode noise component. In proposed buck converter, there are three parasitic capacitances are formed from heat sink of two mosfets  $C_{hs1}$ ,  $C_{hs2}$  and free wheeling diode  $C_{hs3}$  as shown in fig.8. The cathode and drain voltage changes very rapidly in the switching time, as shown the waveforms in fig.2. So the large current pulses flow through the parasitic capacitances  $C_{hs1}$ ,  $C_{hs2}$  and  $C_{hs3}$ . Consequently these cause the large common mode noise currents.

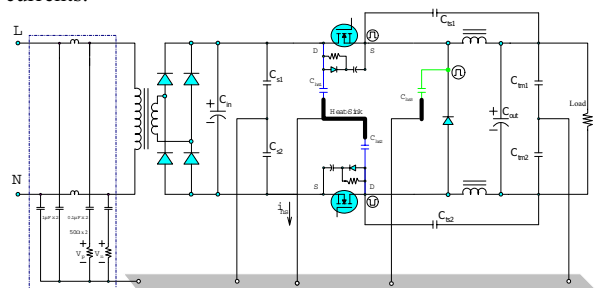


Fig.8. Parasitic capacitance  $C_{hs}$  is formed between drain and cathode through its heat sink to frame ground.

### 5.1 Mechanism on heat sink of Mosfets

In proposed buck converter can be reduced the effect from heat sink that mounted by mosfets. The reduction can be achieved by add the compensation capacitor to build the sub circuit of mosfet-heatsink, as shown in fig.9. There are two loops of common mode current, upper loop is  $i_{C3}$  and lower loop is  $i_{C4}$ . As shown the waveform of currents in fig.12. Both of the currents are opposite in direction. If the sub

circuit can be correctly proportioned to equalize the impedance, which is called that the *common mode impedance balancing* and *common mode source balancing*, the common mode currents  $i_{C3}$  and  $i_{C4}$  will be cancelled out in the heat sink.

$$Z_{hs1}/Z_{com2} = Z_{com1}/Z_{hs2} \quad (9)$$

In equation (9) is the Bridge balancing condition of the common mode current cancellation mechanism.

In order to verify this concept, the auxiliary impedance  $L_{aux}$  was removed during measurement. There are two testing conditions, first the converter operating during without  $C_{com}$  condition, as shown the setup circuit for testing in fig.8. Second the converter operating under common mode current cancellation mechanism on heatsink, as shown the setup circuit for testing in fig.9. The measurement results of heat

sink current  $i_{hs}$  waveforms, are shown in figure 14, where it can be seen that there are reduction in amplitude of 200 mA.

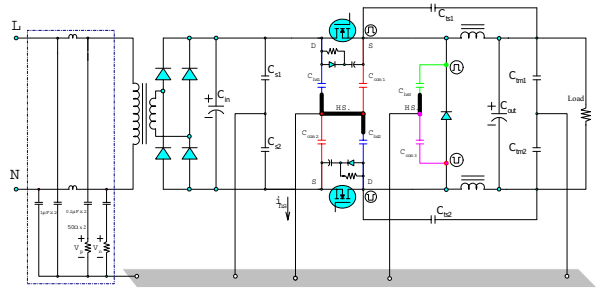


Fig. 9 Topology for common-mode current cancellation

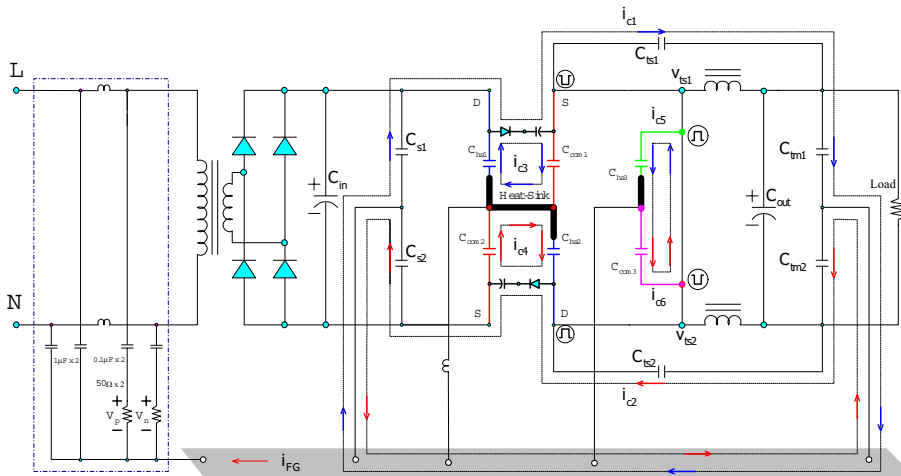


Fig.10. Common-mode current cancellation mechanism during Mosfet is turned off condition.

More efficiency of the common mode current cancellation mechanism in the heat sink of mosfet by independence the sub circuits of mosfet-heatsink from converter, which can be achieved by inserting auxiliary impedance  $L_{aux}$  to a wire of heatsink ground, in order to force the common mode current directions only in the loop of sub circuits. As shown the circuits in fig.11, and 10.

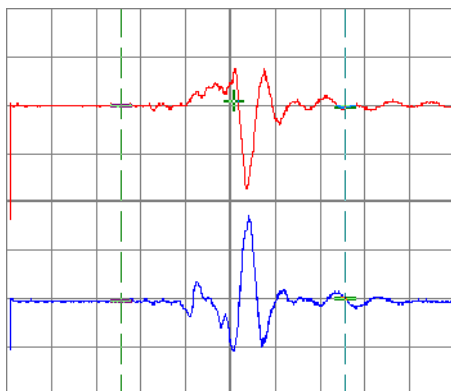


Fig.12. Compare the waveforms of CM current  $i_{C3}$  and  $i_{C4}$ ; (100ns/div, 200mV)

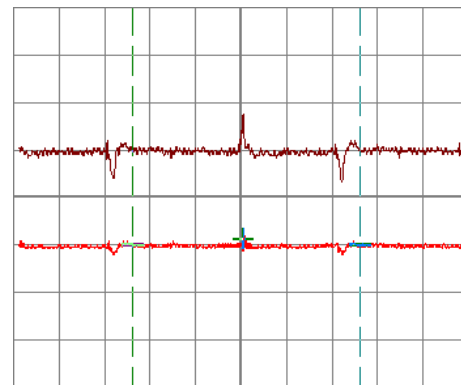


Fig.14. Compare the waveforms of heat sink current  $i_{hs}$  (without  $C_{com}$ : upper, with  $C_{com}$ : lower); (2μs/div, 500mV)

## 5.2 Mechanism on heat sink of Diode

In proposed buck converter can be reduced the effect from heat sink that mounted by free wheeling diode. The reduction can be achieved by add the compensation capacitor  $C_{hs3}$  to build the sub circuit of diode-heatsink, as shown in fig.10. There are two common mode current  $i_{C5}$  and  $i_{C6}$ . The waveforms of currents are shown in fig. 13. Both of currents are opposite in direction on frame ground. If the sub circuit can correctly proportion to equalize the impedance, which is called that the *common mode impedance balancing* (CMIB),

the common mode currents  $i_{C5}$  and  $i_{C6}$  will be cancelled out in the frame ground when diode is in the turned off condition.

$$Z_{cs1}/Z_{cs2} = Z_{hs3}/Z_{com3} \quad (10)$$

Equation (10) is the Bridge balancing condition of the common mode current cancellation mechanism.

When the free wheeling diode is in conducting condition, as shown in fig.10 and the impedances of  $Z_{hs3}$  equal to  $Z_{com3}$ , the common mode currents  $i_{C5}$  and  $i_{C6}$  will be cancelled out within the loop of diode-heat sink.

$$C_{hs3} dV_{ts1} / dt + C_{com3} dV_{ts2} / dt = 0 \quad (11)$$

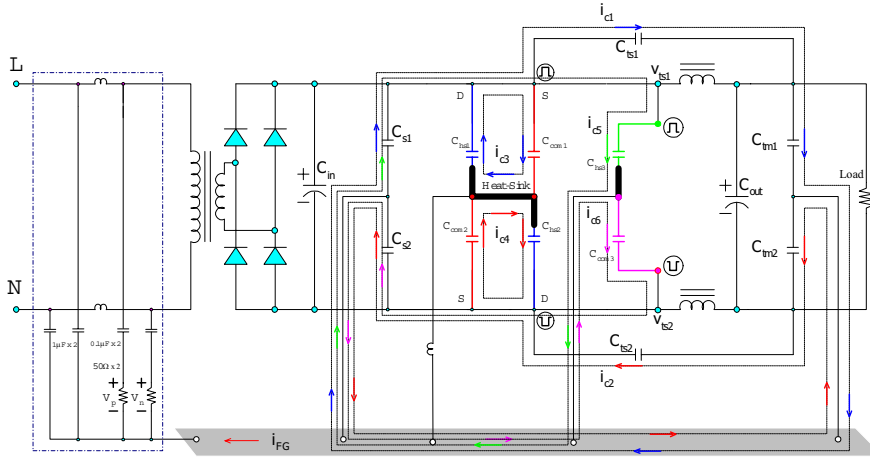


Fig.11. Common-mode current cancellation mechanism during Mosfet is turned on condition.

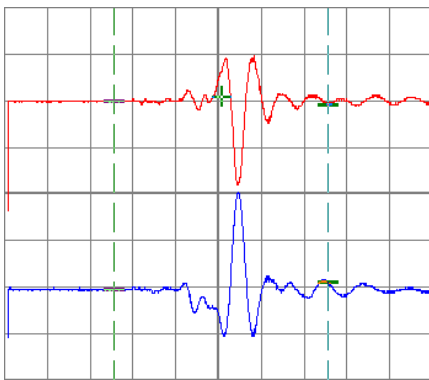
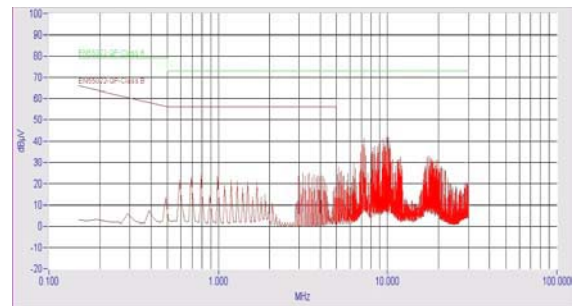
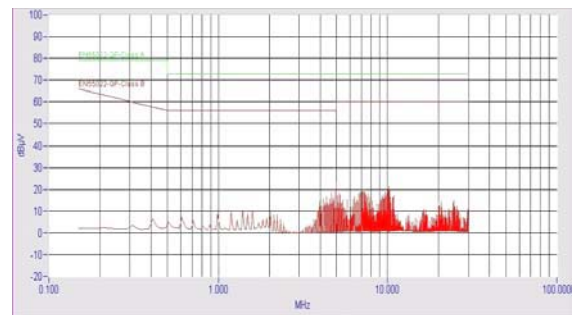


Fig.13. Compare the waveforms of CM current  $i_{C5}$  and  $i_{C6}$ ; (100ns/div, 200mV)

The spectrum of common mode noise current is measured with high frequency current probe by clamping on both of sending and returning power lines. And the conducted noise of the buck converter is to be measured by the noise voltage across the terminator of 50 ohm in LISN. This noise voltage includes not only the common mode but also the differential mode. Figure 15 shows both of the noise spectrum of the two switches balanced Buck with  $C_{com}$ . Comparing fig. 7, it is found that they are very similar except in the high frequency region. The reason for this is considered that the current waveforms of figure 12 and 13 are evidenced. There are two pair of common mode current  $i_{C3}$ ,  $i_{C4}$  and  $i_{C5}$ ,  $i_{C6}$ . Both of the current pair are opposite in direction and cancels out in the frame ground or heatsink. These cancellations cause the noise spectrum to be reduced, because the frequency of these current waveform are around 12-14 MHz, and it can be observed that there are nearly 20 dB average drops around 12 to 30MHz of frequency spectrum range.



(a) Total noise spectrum



(b) CM noise spectrum

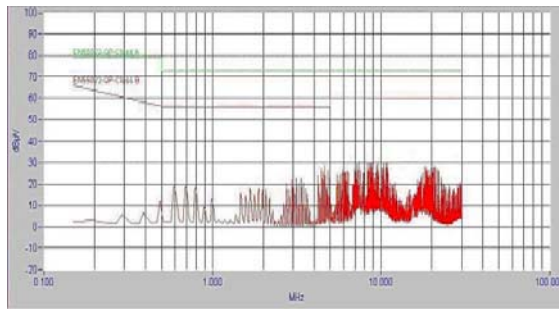
Fig.15. Spectrums of two switches balanced Buck with  $C_{com}$

## 6. Common mode path improvement on transmission lines

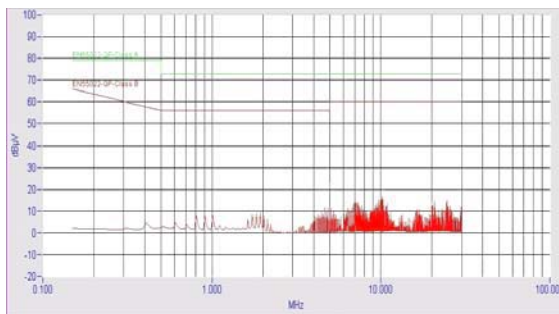
To increase the efficiency of cancellation mechanism, common mode current paths on sending and returning transmission line can be added the capacitive paths across both inductors, where these paths provide for high frequency current or common mode current. The less expensive capacitors may be used, as ESR is no longer an issue. And the capacitance selection of these external capacitors should not effect to normal operating mode where it is essential.



If these transmission line capacitor  $C_t$ s can be selected properly, the efficiency of cancellation mechanism is more improved.



(a) Total noise spectrum



(b) CM noise spectrum

Fig.16. Spectrums of two switches Buck with  $C_{ts}$  &  $C_{com}$

Experiment result of this idea is shown in fig.16. Comparing with figure 15, it can be seen that there are approximately 20 dB average drops around 7 to 10MHz of frequency range. In the case of spectrum results, comparing between conventional buck converter and two switches balanced buck converter that has been proposed, the concept of “CMSB and CMIB” proposed in this paper make great contribution to reduce the common mode noise in a wide range of frequency.

### Conclusion

The heat sinks are usually used with the mosfet and diode, so the parasitic capacitance is formed between the drain of the mosfet or the cathode of the diode and the frame ground through its heat sink. So the large current pulses flow through the parasitic capacitances. Consequently these cause the large common mode noise currents. The reduction can be achieved by adding the compensation capacitor to build the sub circuit of mosfet-heatsink or diode-heatsink. If the sub circuit can achieve correct proportion to equalize the impedance, which is called that the *common mode noise cancellation*

*mechanism*, the common mode currents will be cancelled out in the heat sink.

The impedance balancing concept can be achieved by source, transmission line and termination balanced. The purpose of these three balancing for common mode current paths making, the pair of common mode currents become opposite in direction. And they will be cancelled out in the frame ground. This idea can be called *common mode impedance balancing* or CMIB.

The noise source cancellation concept can be achieved by adding one more mosfet switch to the returning power line to generate the *common mode voltage source canceller* but its phase is out of phase to an original common mode voltage source. They change complementarily, that is, by the same amount but in an opposite polarity in the switching time between both of the common mode noise sources. And this idea can be called *common mode source balancing* or CMSB

If the converter can force the mosfet switches to share the voltage properly, under all operating conditions, then the switch voltage rating can be reduced with respect to the voltage rating required if only one switch were used.

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