A Study on Common-Mode Noise Generation in Switching Circuit due to Unbalanced Characteristic

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Abstract—General switching converter such as the simple high-side switching circuit inherently has unbalanced characteristics of impedance of transmission path, voltage at dc source and load terminals with respect to the frame ground. These unbalanced characteristic effects are the cause of unbalanced voltages at both dc source and load terminals. These unbalanced voltages will produce common-mode noise flowing through frame ground to the LISN during the active switch turn-off and on. This paper presents the analytical and experimental consideration of common-mode noise generation due to the unbalanced effect. The mechanism of common-mode noise generation due to unbalanced effect can be explained by equivalent circuit in both turn-off and turn-on time of the active switch. For common-mode noise reduction, the method for balancing the switching converter is also presented. Common-mode noise generated due to the effect of circuit imbalance is clarified by the experimental results. The balanced switching converter can greatly reduce the common-mode noise is also confirmed by the experimental results.

Index Terms—unbalanced switching converter, conductive common-mode noise generation, balanced switching converter, unbalanced transmission path.

I. INTRODUCTION

It is well know that differential-mode noise is caused by switching operation of the circuit. However, common-mode noise, a dominant component of conductive electromagnetic interference (EMI) is more complicated and not completely clear. Therefore, conductive EMI is a major concern for power electronics engineers. Analysis common-mode noise generation mechanism in a switching circuit is necessary.

Ninomiya [1-2] presented a high frequency model for common-mode noise switching converter, where he used a voltage source to represent the switching action. Unfortunately, his model is not considered the circuit imbalance.

Qian [3-4] presented that the common-mode noise is generated from the common-mode current of all nodes in the switching circuit (Boost converter). The work for balancing all these currents would be quite cumbersome.

Recently, Ninomiya [5-6] tries to balance the switching converter (Boost converter) for reducing the common-mode noise, its mean that common mode noise can be regarded as the results of circuit imbalance.

This paper presents the analytical and experimental consideration of the common-mode noise generation in a switching circuit by the viewpoint of circuit imbalance. Because the circuit imbalance is the main cause of common-mode noise generation. In case the active switch is series connection with the dc source, a simple high-side switching circuit is used for analysis in this paper. The circuit imbalance is mainly caused by the switching action and parasitic elements occurrence in the circuit. Considering the influences of parasitic capacitance on the circuit imbalance and noise voltage, the parasitic capacitances occurrence at load terminal and dc source terminal are the cause of unbalanced load terminals voltage and unbalanced dc source terminals voltage, respectively. According to the switching converter is assembled on the chassis, the transmission path (sending line and return line) imbalance is caused by the switching action and the parasitic capacitance (heat sink) of the active switch is attached to the chassis, this mean that heat sink is shunt connection from only the sending line to the frame ground which make the impedance of sending line difference from return line.

The transmission path imbalance is the most important one characteristic caused by the impedance of active switch changing with the PWM frequency, and resulting in the sending line impedance fluctuating between high-low or low-high values. Meanwhile, the impedance of the returning line is constant. Consequently, the line impedance between the sending line and the returning line seen from them to the frame ground are unbalanced. The common-mode noise is generated during the active switch turn-on and turn-off.

The mechanism of the common-mode noise generation due to unbalanced effect can be explained by equivalent circuit during the switching device (Q1) turn-off and on. For common-mode noise reduction can be done by balancing the circuit. The method to balance the circuit can be also explained by the equivalent circuit during the switching device (Q2 and Q3) turn-off and on.

Common-mode noise generated due to the effect of circuit imbalance is clarified by the experimental results, and the effectiveness of conductive common-mode noise
reduction is also confirmed by the experimental results.

II. UNBALANCED SWITCHING CIRCUIT

The simple switching circuit is generally used the high-side switch of power MOSFET with resistive load as shown in Fig.1, the possibility of three unbalanced characteristics exists in this circuit: (a) transmission line imbalance, (b) dc source terminals imbalance and (c) load terminals imbalance.

![Circuit Diagram](Image)

**Fig.1.** Shows the conventional unbalanced switching circuit.

The transmission path imbalance is the most important imbalance characteristic caused by the impedance of active switch changing with the PWM frequency, and resulting in the sending line impedance fluctuating between high and low values. Meanwhile the impedance of the returning line is constant. Consequently, the line impedance between the sending line and the returning line seen from then to the frame ground are unbalanced.

The dc source terminal imbalance and load terminal imbalance are the shunt imbalance. The dc source terminal imbalance is caused by the parasitic capacitance $C_{23}$ between dc source terminal B and frame ground. The load terminal imbalance is caused by the parasitic capacitance $C_{13}$ between load terminal 1 and frame ground.

III. COMMON-MODE NOISE GENERATION DUE TO UNBALANCED EFFECT

The common-mode noise voltage is generated during both the active switch turn-off and turn-on (existing the transmission path unbalanced) which produces the charging and discharging current flowing through the frame ground. The common-mode noise generation mechanism can be considered by equivalent circuit of the unbalanced converter when the active switch turn off and on.

![Equivalent Circuit](Image)

**Fig.2.** Shows the equivalent circuit for considering common-mode noise generation due to unbalanced the dc source terminals voltage when MOSFET (Q1) turn-off.

$$Z_{S2} = \frac{1 + R_L C_{13} S}{S(C_{13} + C_{23} + C_{23} C_{13} R_L S)}$$

$$Z_{AB} = \frac{SC_{HI} Z_{S2}}{(1 + SC_{HI} Z_{S2})}$$

$$I_{dm} = \frac{V_S}{Z_{AB}} = \frac{V_S SC_{HI}}{1 + SC_{HI} Z_{S2}}$$

$$V_{A3} = I_{dm} Z_{CHI} = \frac{V_S}{1 + SC_{HI} Z_{S2}}$$

$$V_{B3} = -V_{B3} = I_{dm} Z_{S2} = V_S \frac{SC_{HI} Z_{S2}}{(1 + SC_{HI} Z_{S2})}$$

$$|V_{A3}| > |V_{B3}|$$

Equation (3) shows the unbalanced dc source terminal voltages condition resulting to produce the common-mode noise voltage as,

$$V_{CMF} = V_{A3} + V_{B3}$$

where $V_{CMF}$ is the common-mode noise voltage with respect to the frame ground. The $V_{CMF}$ can be measured by digital oscilloscope as shown in Fig.3.

$$V_{AB} = (V_{A3} - V_{B3})$$

where $V_{AB}$ is the differential-mode voltage across the dc source terminal.

![Common-Mode Noise](Image)

**Fig.3.** Shows the common-mode voltage ($V_{CMF}$) generation due to unbalanced dc source terminals voltage when MOSFET (Q1) turn-off.

In case the switching action is off, the impedance of sending line is immediately changed to high value ($\Delta Z_{LI}$)
which provides unbalanced transmission path and due to unbalanced dc source will supply the charging current to parasitic capacitance (heat sink \(C_{1H}\)) passing through the frame ground to load and back to dc source. The charging current passed through the unbalanced elements and back to the source will provide unbalanced terminal voltages (\(V_{A3}>V_{B3}\)) at the dc source with respect to the frame ground. This unbalanced voltage will generate common-mode noise voltage (\(V_{CMF}\)) across the frame ground as shown in Fig.3.

### B. Equivalent circuit of unbalanced switching converter when the switch turn-on

![Fig.4. Shows the equivalent circuit for considering common-mode noise generation due to unbalanced load terminals voltage when MOSFET (Q1) turn-on.](image)

\[
\begin{align*}
i_{dm1} &= i_{dm1} + i_{dm2} \\
Z_{12} &= \frac{R_{t}(C_{13} + C_{23})}{C_{13} + C_{23} + R_{t}C_{11}C_{21}S} \\
I_{dm} &= \frac{V_{s}}{Z_{C13} + Z_{RTN} + Z_{12}} \\
I_{dm2} &= \frac{I_{dn2}}{Z_{C13}} = I_{dm2} \frac{1}{SC_{13}}(I_{dm2} + I_{cmn}) \\
V_{13} &= Z_{C13}(I_{dm2} + I_{cm}) \frac{1}{SC_{13}}(I_{dm2} + I_{cmn}) \\
V_{12} &= -V_{23} \frac{I_{dm2}Z_{C23} = 1}{SC_{23}} \\
|V_{13}| &= |V_{23}| \\
\end{align*}
\]

where \(Z_{C13} = Z_{C23}\)

Equation (8) shows the unbalanced load terminals voltage condition which produces the common-mode noise voltage shown as follows;

\[
V_{CMO} = (V_{13} + V_{23}) \tag{9}
\]

where \(V_{CMO}\) is the common-mode noise voltage with respect to the frame ground. The \(V_{CMO}\) can be measured by digital oscilloscope as shown in Fig.5.

\[
V_{12} = (V_{13} - V_{23}) \quad \tag{10}
\]

where \(V_{12}\) is the differential-mode voltage across the load terminals.

From Fig.4 considering is case of the active switch turn-on, the impedance of sending line is changed immediately to low value (\(\Delta Z_{HL}\)) and providing the low impedance path for discharging current of parasitic capacitor (heat sink \(C_{1H}\)) and the discharging current from the unbalanced dc source flowing though the unbalanced elements of the circuit. These currents will provide unbalanced terminal voltages (\(V_{13}>V_{23}\)) at the load terminals with respect to the frame ground. This unbalanced voltage will generate common-mode noise voltage (\(V_{CMO}\)) across the frame ground as shown in Fig.5.

The \(V_{CMO}\) is much larger than \(V_{CMR}\), these voltages are the cause of common-mode current flowing into the LISN, as shown in Fig.6.

\[
\begin{align*}
I_{CM} &= \text{common-mode current during MOSFET(Q1) turn-on} \\
I_{CM} &= \text{common-mode current during MOSFET(Q) turn-off} \\
\end{align*}
\]

\[
V_{CMO} = 21.6 \text{ V}, \quad V_{CMO} \text{ (avg)} = 9.4 \text{ V}
\]

Fig.6. Shows the waveform of common-mode current generated by unbalanced switching circuit during active switch turn-off and on.
IV. BALANCED SWITCHING CONVERTER

Balanced DC Source Terminal
Balanced Transmission Path
Balanced Load Terminal

* is used to indicate the component added into the converter unbalanced circuit for balancing the three parts of circuit, \(C_{A3}\) and \(C_{B3}\), \(C_{COM1}\) and \(Q_{1}\), \(C_{COM2}\) and \(C_{2}\) that are used to balance the dc source terminal, transmission line and load terminal, respectively.

Fig. 7. Shows the proposed balanced switching converter.

A. Equivalent Circuit of balanced switching converter when the switch (Q1 and Q2) turn-off

\[
\text{Fig. 8. Shows the equivalent circuit of balanced switching converter when MOSFET (Q1 and Q2) turn-off}
\]

\[
V_{A3} = i_{dm} Z_{A3} = i_{dn} \frac{1}{S(C_{A3} + C_{H1})}
\]

(11)

\[
V_{B3} = -V_{B3} = i_{dn} Z_{B3} = i_{dn} \frac{1}{S(C_{B3} + C_{COM1})}
\]

(12)

\[
|V_{A3}| = |V_{B3}|
\]

(13)

\[
V_{CMF} = (V_{A3} + V_{B3}) = 0
\]

(14)

where \(Z_{A3} = Z_{B3}\)

and \(C_{A3} + C_{H1} = (C_{B3} + C_{COM1})\)

Equation (13) shows the balanced dc source terminal voltages condition \((V_{A3} = V_{B3})\), then the common-mode voltage \((V_{CMF})\) existed across the frame ground will be zero.

The \(V_{CMF}\) can be measured by digital oscilloscope as shown in Fig. 9.

The balanced circuit, during switch MOSFET Q1 and Q2 turn-off will generate only the differential-mode current \((i_{dm} = i_{dm1} + i_{dm2})\) as shown in Fig. 8.

B. Equivalent circuit of balanced switching converter when the switch (Q1 and Q2) turn-on

\[
\text{Fig. 10. Shows equivalent circuit of balanced switching converter when MOSFET (Q1 and Q2) turn-on}
\]

\[
V_{13} = Z_{COM2}(i_{cm1} + i_{cm2})
\]

(15)

\[
V_{23} = -V_{23} = Z_{CH2}(i_{cm3} + i_{cm4})
\]

(16)

\[
|V_{13}| = |V_{23}|
\]

(17)

\[
V_{CMO} = (V_{13} + V_{23}) = 0
\]

(18)

where \(Z_{COM2} = Z_{CH2}\)

and \((i_{cm1} + i_{cm2}) = (i_{cm3} + i_{cm4})\)

In balanced switching converter, when the switching devices (Q1 and Q2) are turn-on, \(V_{13}\) and \(V_{23}\) will have the same amplitude and opposite phase. Therefore the common-mode noise \((V_{CMO})\) due to balanced load terminals voltage will be zero. The \(V_{CMO}\) can be measured by digital oscilloscope as shown in Fig. 11.
The balanced circuit, during active switches (Q1 and Q2) turn-on will generate the balanced common-mode currents (icm1=icm3, icm2=icm4) which pass through the load terminals. They are cancelled out in the frame ground. The results of common-mode current can be measured by high-frequency current probe which is clamped on the both ac lines at the output of LISN, as shown in Fig.12.

The balanced switching converter can reduce icm much greater than the reduction of icmo.

V. EXPERIMENTAL RESULTS

Fig.13 and 14 show the frequency spectrum of common-mode current of the unbalanced and balanced switching converter, respectively. Fig.15 shows the frequency spectrum of conductive common-mode noise of the comparison of the conventional unbalanced switching converter with the balanced switching converter. It can be seen that conductive common-mode noise is greatly reduced in the balanced switching converter, especially 30dBµV reduction in low frequency region below 1MHz. and reduction average 10dBµV in frequency range between 1MHz. and 10MHz. It shows that conductive common-mode noise is generated by the effect of imbalance in the frequency range from 150kHz. to 10MHz. as shown in Fig.15.

VI. CONCLUSION

The general switching converters have many factors which cause circuit imbalance. There are three possible unbalanced parts in the circuit: dc source, transmission path, and load terminal imbalance. The common-mode noise generation in the unbalanced switching circuit is caused by the switching action on and off of the active switch which provides charging and discharging currents existed in the parasitic capacitances. These currents will flow through the unbalanced elements in circuit to make unbalanced dc source terminal voltages and unbalanced load terminal voltages during the switching device turn-off and on, respectively. The results of these unbalanced voltages will produce the common-mode (current) noise flowing through frame ground to LISN.

REFERENCES


