Innoscience
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POWER THE FUTURE

# AN003

## Application Note

# EMC Design Guide for Power Supplies with InnoGaN

# List of content

# 1 Overview

EMC(Electromagnetic Compatibility) issues are categorized into EMI(Electromagnetic Interference) and EMS(Electromagnetic Susceptibility) issues as shown in Figure 1.

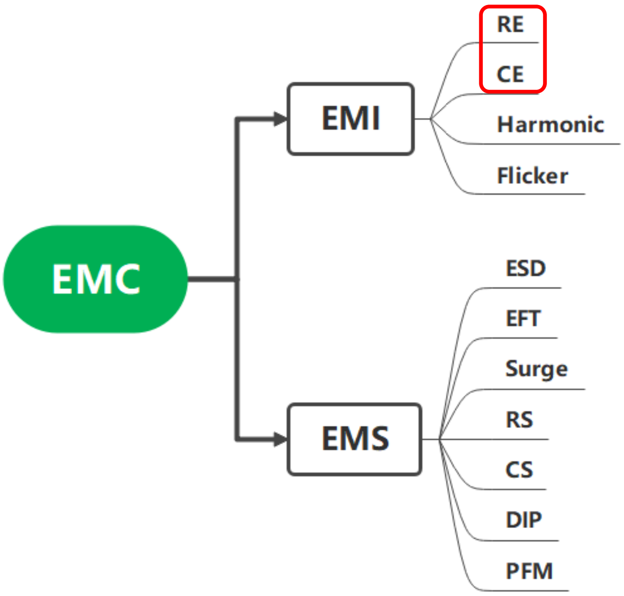



Figure 1 EMC issues

Among these, RE (Radiated Emission) and CE (Conducted Emission) are most commonly concerned due to the greater difficulties caused by higher uncertainty, variability and time-consumption.

This application note presents the basic RE and CE design principles for power supplies with InnoGaN by sharing some practical design and debugging examples. Note that the CE and RE test results mentioned below are based on the 65W ultra-small fast-charger reference design with InnoGaN products.

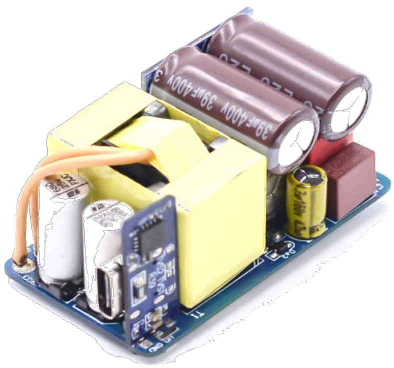


Figure 2 65W ultra small fast-charger with InnoGaN

# 2 Conducted Emission(CE)

CE (Conductive Emission) noise refers to the noise propagated through the traces, which could be categories into differential mode (DM) noise and common mode (CM) noise.

## 2.1 Differential mode noise

Noise source: A small portion of switching frequency ripple current after passing through the BUS capacitor as a filter ,transmitted through the circuit to the input side and LISN.

Paths: DM noise propagates along the L and N lines with the same amplitude and in the opposite direction.

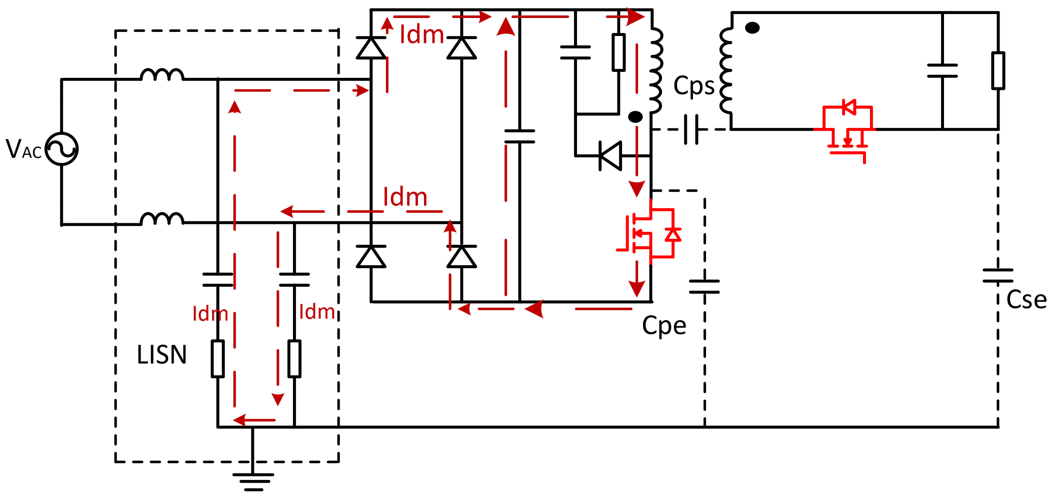



Figure 3 Diagram of DM noise propagation in QR flyback circuit

Influenced frequency range : ≤5MHz.

The curves in Figure 4 shows the original noise and DM noise. The DM noise curve is measured without DM filter while CM noise is eliminated by CM filter. The CM noise attenuates gradually as the frequency increases, and the amplitude could meet the 6dB margin at 5MHz.

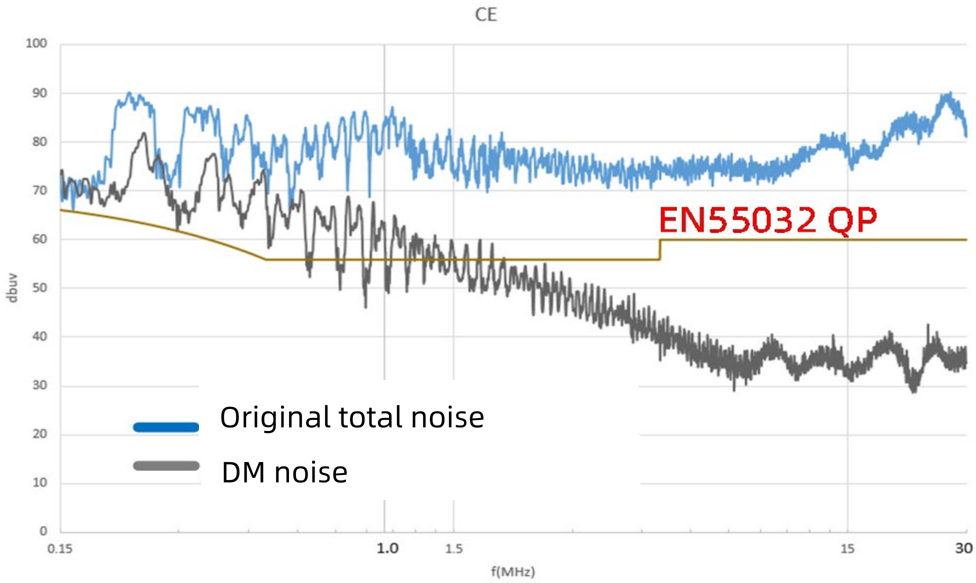
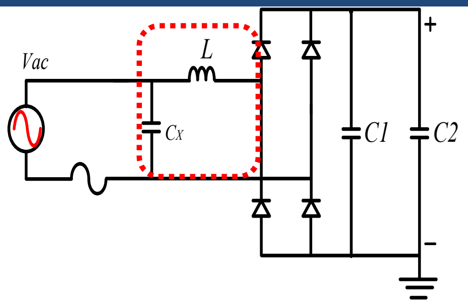
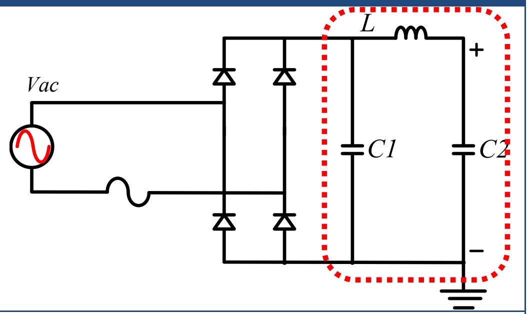



Figure 4 Curves of DM noise

## 2.2 Filtering methods for DM noise

Table 1 Comparison of two kinds of filters

| | LC Filter | π-type Filter |
|---|---|---|
| Circuit |   |   |
| Surge current withstand capacitor | C1、C2 | C1 |
| Surge withstand capacity of BUS capacitors | High | Low |
| Filter capacitor for Switching frequency current ripple | C1、C2 | C2 |
| Temperature rise of BUS capacitor | Low | High |
| Requirements of filter | 1. Ring cores are needed (slightly higher cost and larger volume in board space)<br>2. Cx ≥ 220nf | 1. H-shaped cores (low cost and small volume); (Note 1)<br>2. Cx ≤ 100nf, sometimes omitted |
| Cost of filtering | Medium | Low |

Note 1: For LC filter, DM inductors are on AC lines and suffer from high voltage and current fluctuations. The alternating magnetic field generated by current fluctuations will have a significant impact on the surrounding components if an H-shaped core with an open magnetic circuit is employed. However, the DM inductors are placed between two BUS capacitors in π-type filters, resulting in smaller voltage and current fluctuations and little impact on surrounding components.

Figure 5 shows the curves of DM noise with different filtering parameters (CM noise are eliminated).

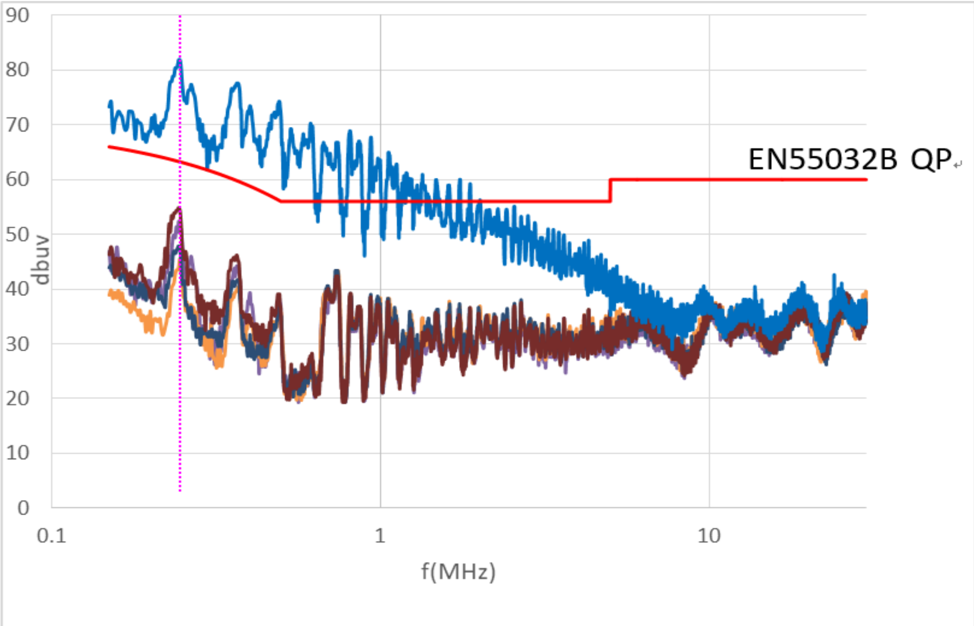
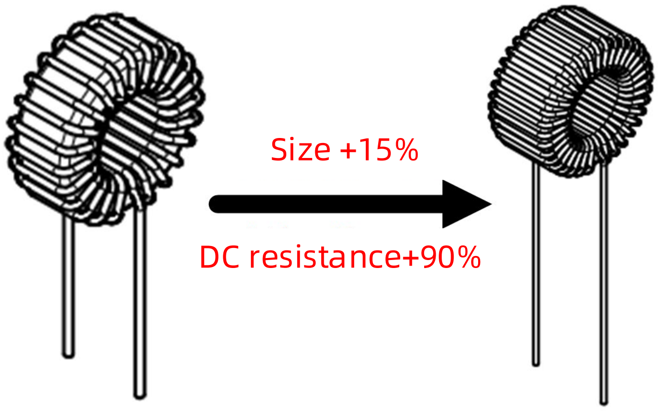



Figure 5 Curve comparison with and without DM filter

Table 2 Peak noise with different filter parameters

| | DM filter parameters (DM inductor + X capacitor) | Decrement of peak noise @ 260kHz |
|---|---|---|
| (blue line) | Without DM filter | / |
| (red line) | 50uH+220nF | 28db |
| (light purple line) | 100uH+220nF | 3db |
| (dark blue line) | 220uH+220nF | 5db |
| (orange line) | 220uH+470nF | 3db |

Compared to the combination of 100uH+224 filtering, the combinations of 220uH+220nF and 220uH+470nF can provide a larger differential mode margin, however with larger footprints and higher power losses.




100uH Toroidal Inductor 220uH Toroidal Inductor

Please note that the above filtering parameters are for theoretical analysis only, and should be determined based on measured results in practical design cases.

## 2.3 Common mode noise

Noise Source: High frequency switching voltage generated at Drain of the GaN deviecs.

Propagation path:

- Flow through Cps and Cse towards secondary side and the Ground (Dominant part).
- Flow through Cpe to the Ground directly.

where Cpe<< Cps, Cpe << Cse.

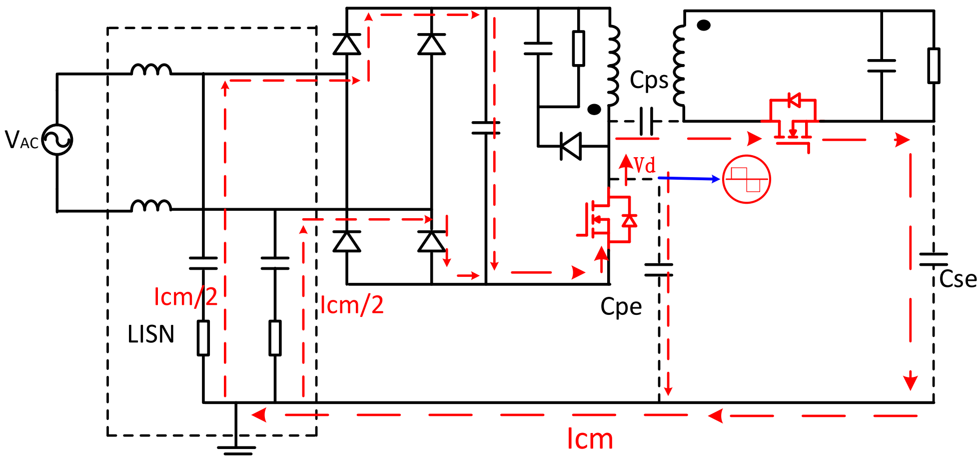



Figure 6 CM Noise propagation path in QR flyback

The flow path of CM noise from Figure 7 has been extracted and simplified to the equivalent circuit shown in Figure 7.

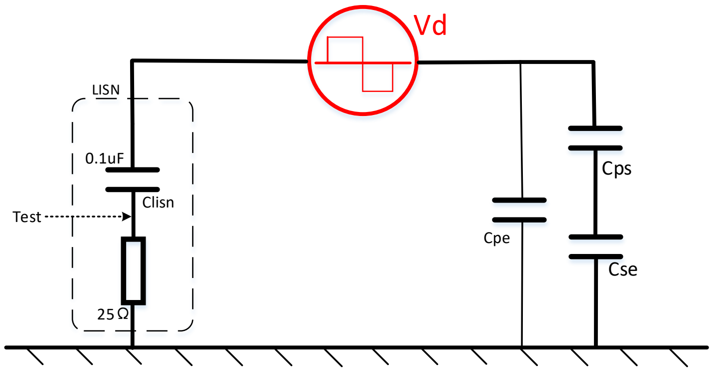



Figure 7 Equivalent circuit of CM noise

The capacitance Cpe is much smaller compared to Cps and Cse, resulting in much less CM noise flowing through Cpe. The analysis below will neglect the CM noise flowing through Cpe for simplification.

Figure 8 shows the waveforms of the original total noise and CM noise (with DM filter).

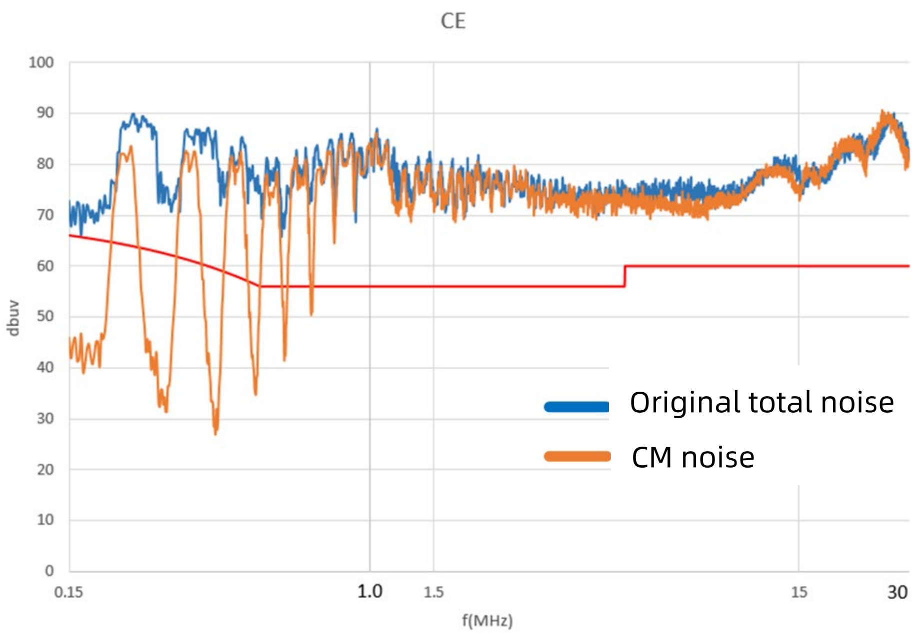



Figure 8 CM noise

The frequency range of CM noise within the CE noise range is 150kHz~30MHz.

## 2.4 CM Noise Filtering Methods

### 2.4.1 Method I: Y-capacitor

The Y-capacitor between the primary and secondary sides of the transformer provides an internal low impedance return path for CM noise.

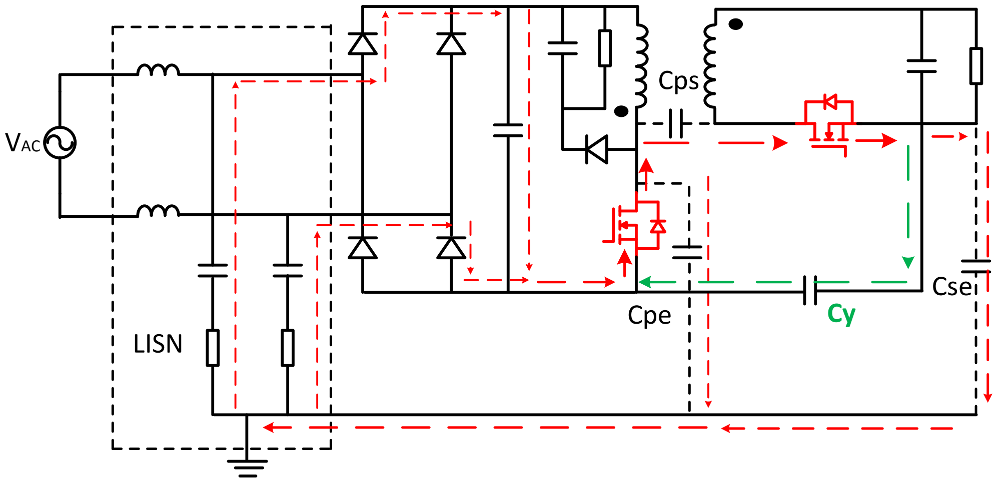



Figure 9 CM Noise propagation path with Y-capacitor in QR flyback

After adding 150pf+150pf Y-capacitors in the 65W fast-charging demo, the peak value of CM noise is reduced by about 25dB.

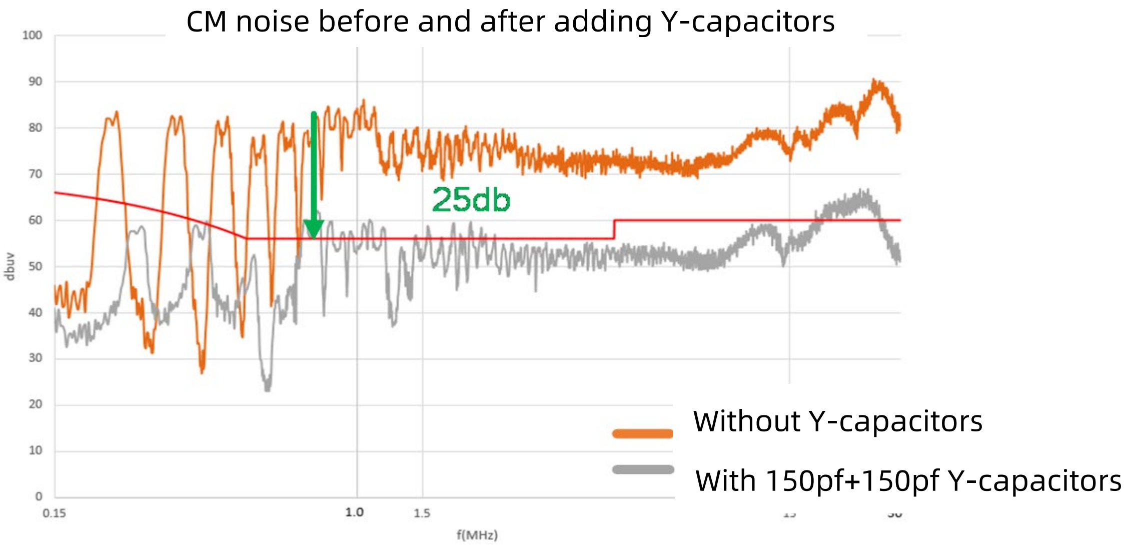



Figure 10 CM noise omparison with and without Y-capacitors

$$\text{Zcy} = \frac{1}{2 * \pi * f * Cy}$$

From the equation above of Y-capacitance impedance, it can be conclude that with larger Cy, the impedance Zcy becomes smaller and more CM noise is generated by internal current circulation. Thus, the CM noise detected by LISN is also smaller. However the leakage current is tend to be larger. In this case, a Y-capacitor combination of 150pf+150pf is selected to meet the leakage current requirement of 25uA.

### 2.4.2 Method II: Shield winding of the transformer

Adding shield windings in the transformers is a common method to eliminating CM noise in flyback-type topologies (including CCM, QR, ACF, aZVS, AHB). The shield winding in the transformer forms a reversed noise, which is in the opposite phase with the original noise voltage and thus reduces the original CM noise.

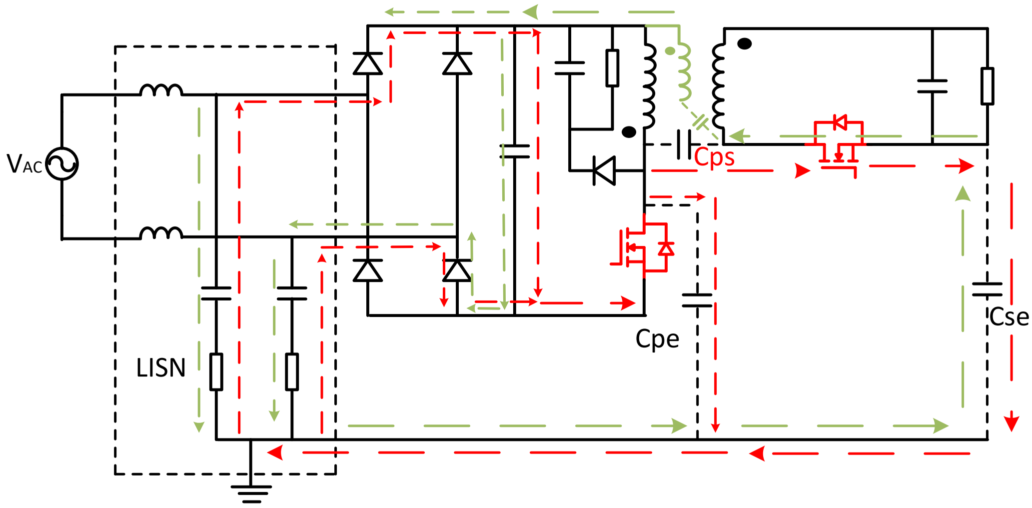



Figure 11 CM Noise propagation path with shied winding in QR flyback

Figure 12 shows is a cross-section view of the transformer with shield windings. The key voltage waveforms at each node are also noted in Figure 12.

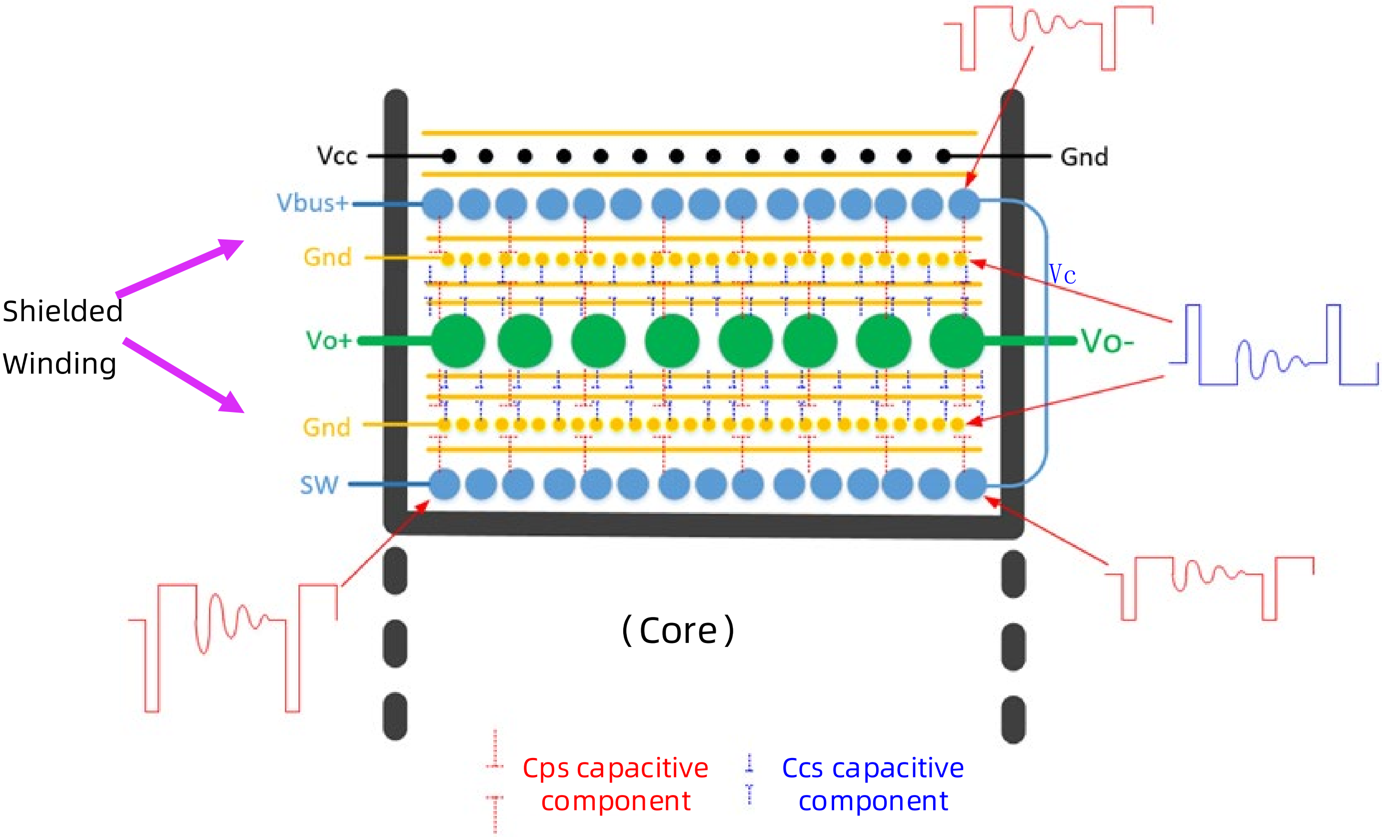



Figure 12 Cross-section view of the transformer with shield windings and voltage waveforms at each node

Ccs is the parasitic capacitance between the shield winding and the secondary winding. Vc is the voltage at the end of the shielding winding.

The voltage of the primary winding is Vp. The number of turns of the primary winding is Np The parasitic capacitance between the primary side and the secondary side is Cps. The number of strands is Tp. The CM noise current transmitted from the primary side to the secondary side is Ips. Then, the following relations can be obtained as:

$$Cps \propto Tp$$

$$Ips \propto Vp * Cps \propto Np * Tp$$

The number of turns Np, number of strands Tp, voltage Vp, and parasitic capacitance Cps of the primary winding are all certain values in a certain design. So the value of Ips is determined.

The voltage of the shield winding is Vc. The parasitic capacitance between the shield winding and the secondary winding is Ccs. The number of turns of the shield winding is Nc. The number of strands is T. The CM compensation current transmitted from the shielding winding to the secondary winding is Ics. Then, the relation can be obtained as:

$$Vc \propto Nc$$

$$Ccs \propto T$$

$$Ics \propto Vc * Ccs \propto Nc * T$$

While $Ics \approx Ips$, the CM noise transmitted from the primary side to the secondary side is approximately canceled by the shield winding. The CM voltage detected by LISN is very small and expressed as:

$$Ips \approx Ics \propto Nc * T$$

Therefore, a reasonable selection of the number of turns and strands of the shield winding can achieve the elimination of CM noise.

Figure 13 shows the measured CM noise with and without the shield winding of the transformer. The peak value of the noise is reduced by 20dB.

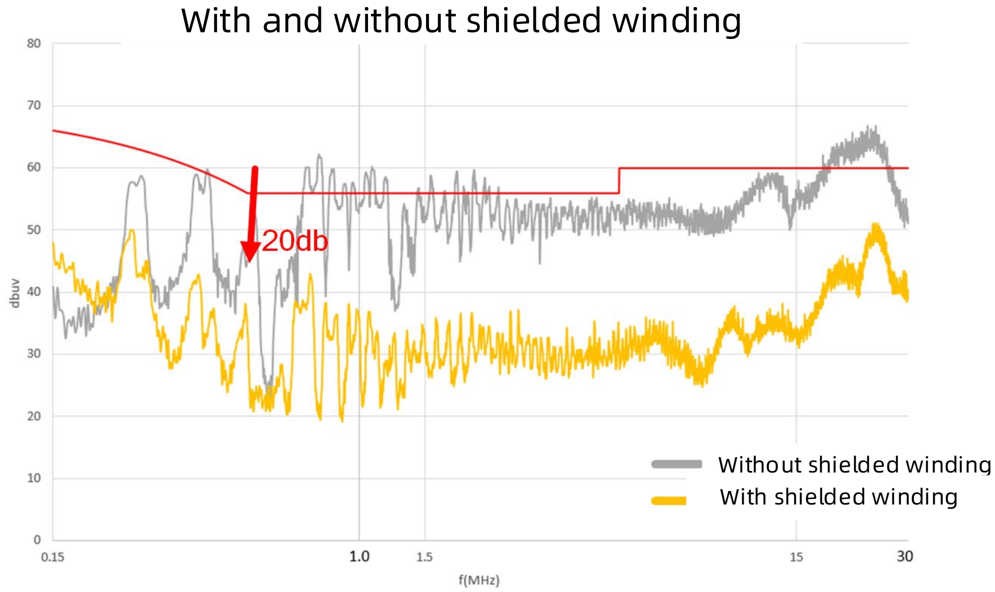



Figure 13 CM noise comparison with and without shield winding of the transformer

### 2.4.3 Method III: Ni-Zn inductor

Ni-Zn are used to deal with the high frequency range in CM noise (≥ 10MHz);

Source: Noise generated by the resonance of parasitic inductance and capacitor in the power supply;

Path: Same as CM noise in the middle and low frequency range;

Suppression method: Use inductors with low inductance and Mn-Zn or Ni-Zn cores;

Figure 14 shows the insertion loss comparison between Mn-Zn inductor with high inductance, Mn-Zn inductor with low inductance, and Ni-Zn inductor.

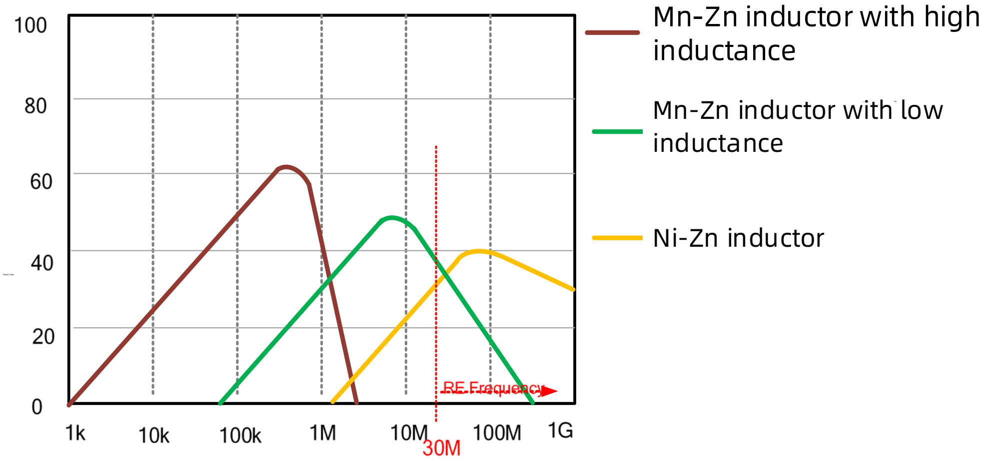



Figure 14 Insertion loss comparison with different inductors

Figure 15 shows the measured CE noise before and after using a Ni-Zn core inductor .With the inductor, the noise at 22MHz increased by 12dB.

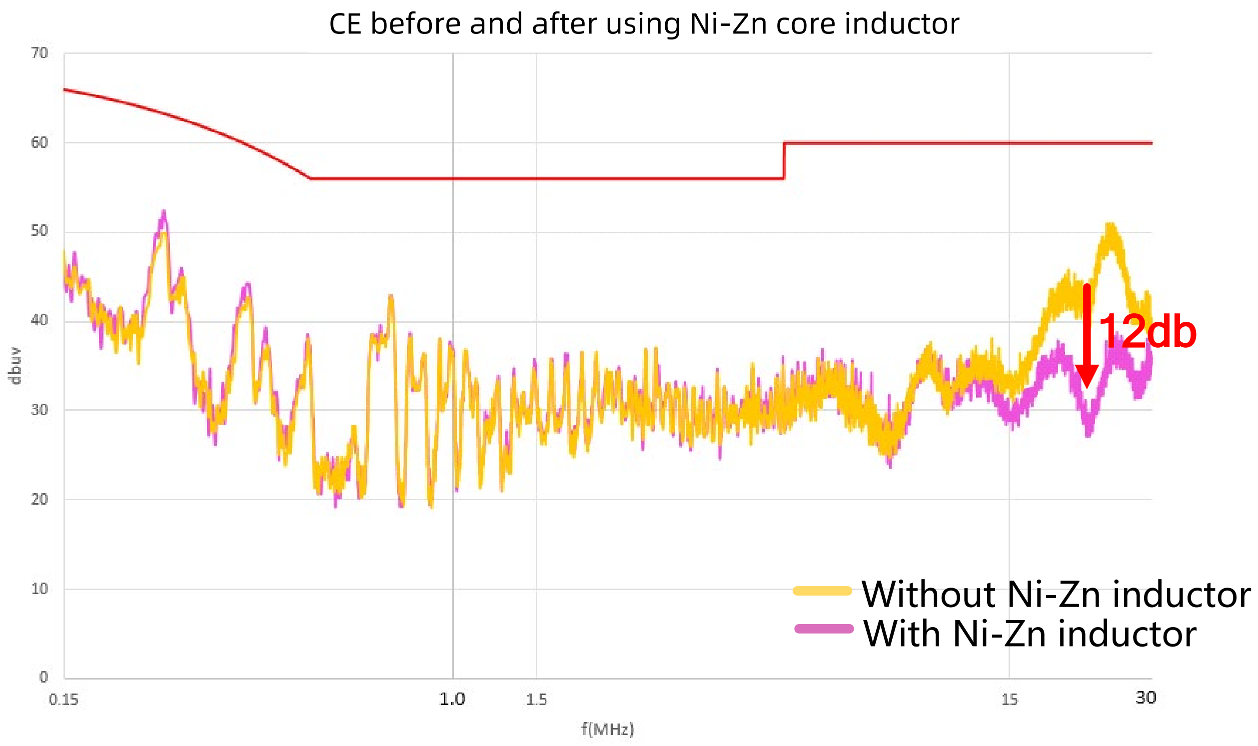



Figure 15 CM noise comparison with and without Ni-Zn core inductor

The summary of CM noise filtering methods are shown in Figure 16.

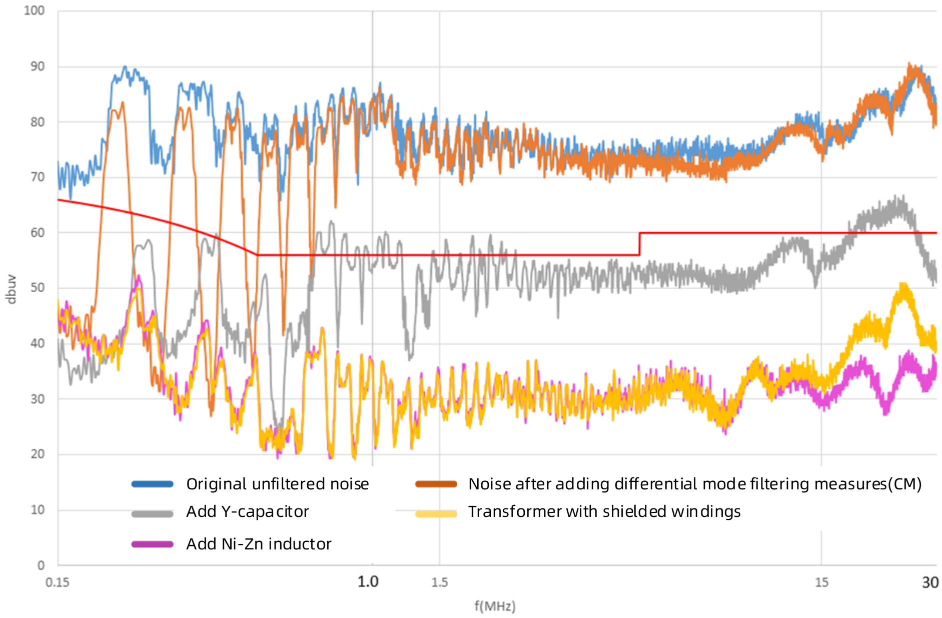



Figure 16 Measured CM noise with different filtering methods

## 2.5 Magnetic field interference

The mechanism of magnetic field interference: The alternating magnetic field generated by the interference source couples to the input filter, and generates noises in the coil of the input filter. Most of the noises cross the filter and directly flow to the L line, N line, and LISN;

The sources of magnetic field interference include (but are not limited to):

a) High current AC wires (see Figure 17 a, b, c) exposed outside the magnetic core;

b) Magnetic core junction (see Figure 17 d);

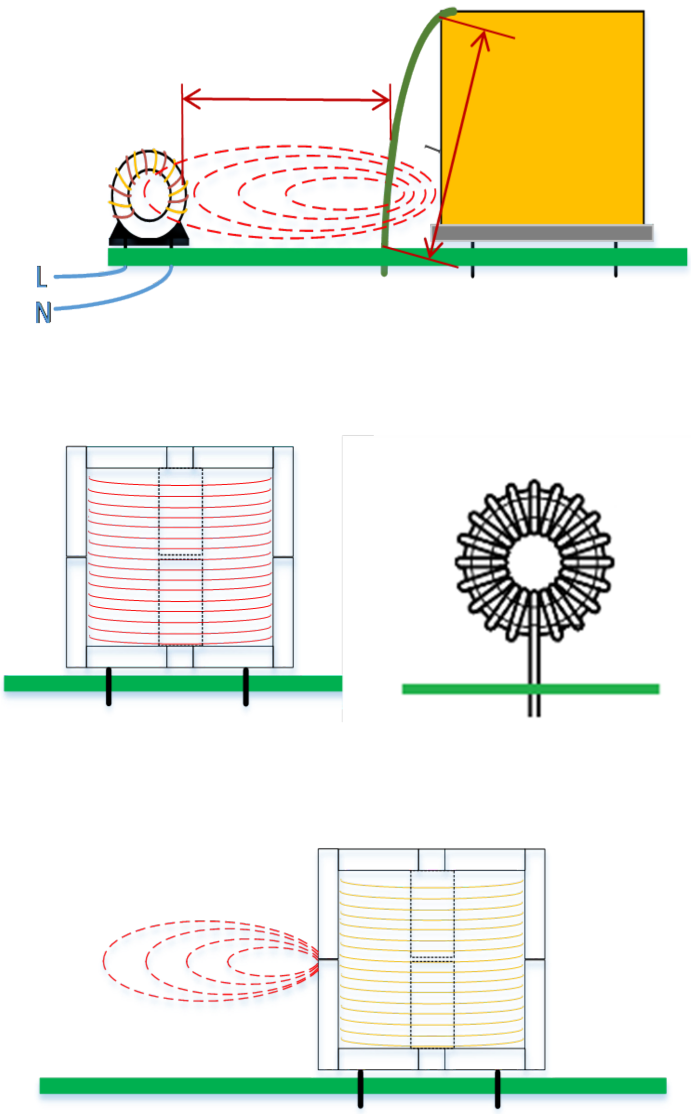



Figure 17 Different noise sources

The characteristics of magnetic field interference include:

a) The density of the magnetic field lines increase when closer to the interference source, thus leads to higher interference.

b) The interfered area becomes larger with longer alternating high current wire exposed outside the magnetic core.

c) When the di/dt slew rate of the alternating current is higher in the circuit, the density of the magnetic field lines becomes higher and generates and stronger magnetic interference.

The solutions for magnetic field interference include (but are not limited to):

a) Reduce the length of high current alternating wires exposed outside the magnetic core;

b) Increase the distance between EMI filter and noise sources;

c) Use the overall surface of the transformer magnetic core for shielding;

d) Optimize the direction of EMI filtering components;

As shown in Figure 18, the transformer coil is facing the filtering components before optimization. The amplitude of AV noise exceeds the standard at 260kHz and 380kHz.

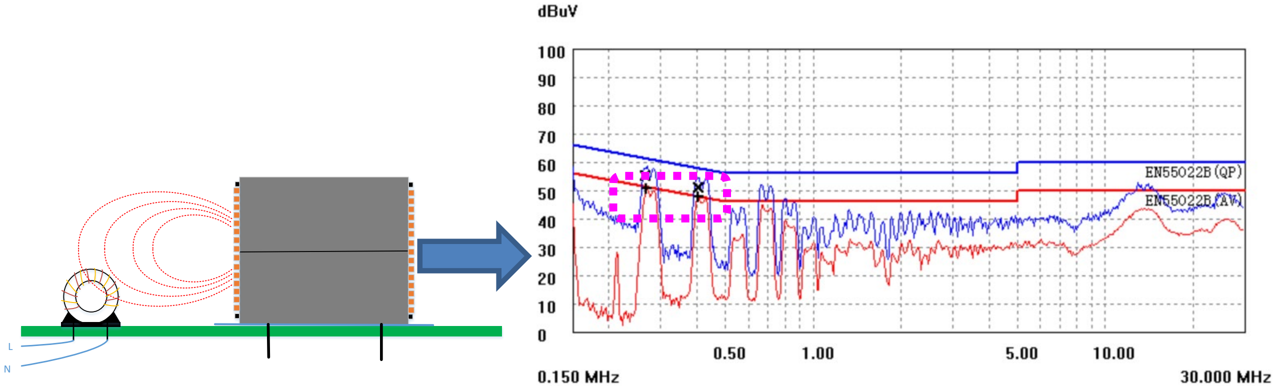



Figure 18 The diagram of transformer and CE test results without optimization

Solution: The bobbin of transformer are optimized with 90° bent pins. The bottom side of the magnetic core is facing the filter inductor. The specifications and winding methods of the transformer remain unchanged. CE/AV noise achieved reduction of 12dB and 10dB at the frequency of 260kHz and 380kHz, respectively.

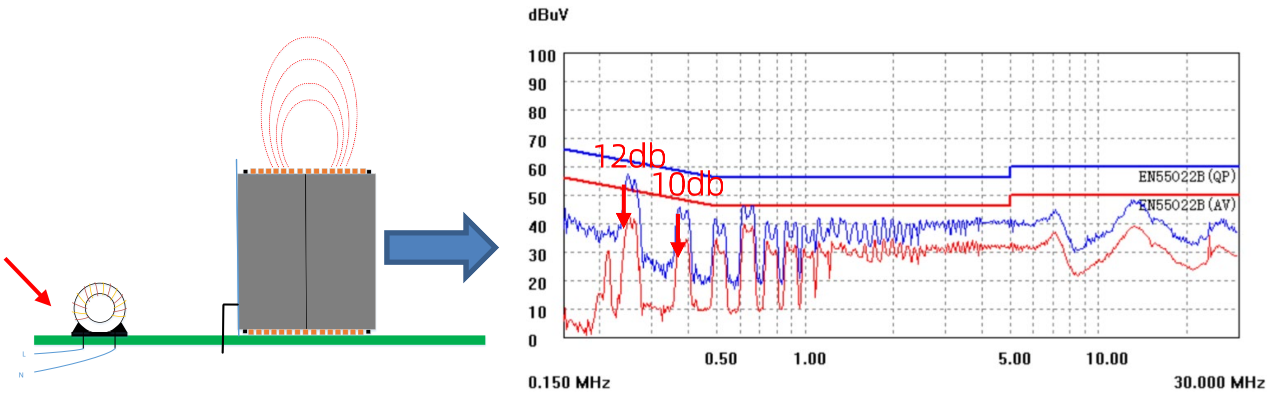



Figure 19 The diagram of transformer and CE test results after optimization

# 3 Radioactive Emission -RE

## 3.1 Fundamentals of RE Noise Testing

RE (Radioactive Emission) refers to the noise propagated through space electromagnetic waves.

When the switching devices in the power supply turn on/off in high speed, the high frequency components contained in the voltage and current waveforms, such as dv/dt and di/dt, are the main sources of RE noises.

Compared to CE testing, RE testing are usually with higher uncertainty. Many factors may have impacts on RE results, such as the length of input and output lines, the placement method of power supply and load, etc..

In RE testing, the following precautions should be taken:

- Place the EUT in the center of the test bench with a distance of approximately 10cm between the power supply and the load;
- The output charging cable naturally droops with a distance of 40cm between the lowest point and the floor. Any excess length needs to be wrapped with tape;
- Make sure there is no other powered on instruments, such as output end lures, etc.. , Shielding methods are necessary if other instruments have to be used.
- Fix the input and output lines/sockets with tape to prevent from unintended movement;
- Make sure there is no overlap between the input and output traces on the board;
- Keep the testing bench clean and without place other prototypes or items with metal.

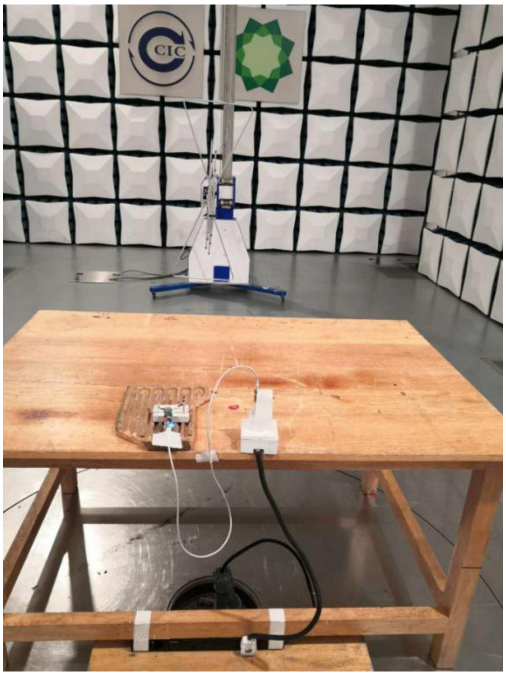
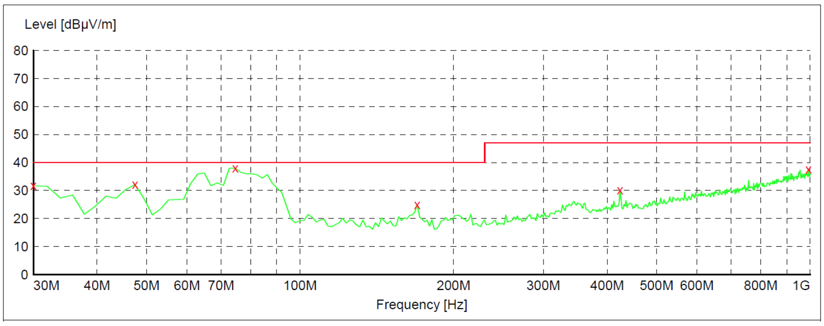
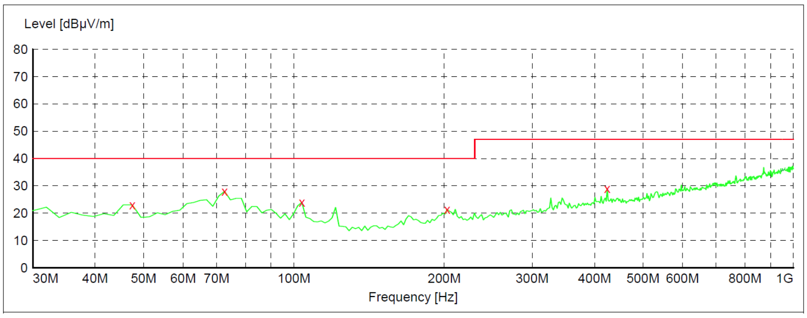



Figure 20 Photo of the test bench

Radiation noise testing can be divided into V-phase testing (Vertical antenna) and H-phase testing (Horizontal antenna). Among them, the noise received by the vertical (V-phase) coupling of the antenna is relatively greater. Therefore, only V-phase test results are shown in the following sections.




V-phase




H-phase

Figure 21 RE noises of the V-phase and H-phase of the fast-charger demo

The RE noise emission path of fast-charger power supply includes:

- AC input lines
- Power supply demo itself
- Output lines

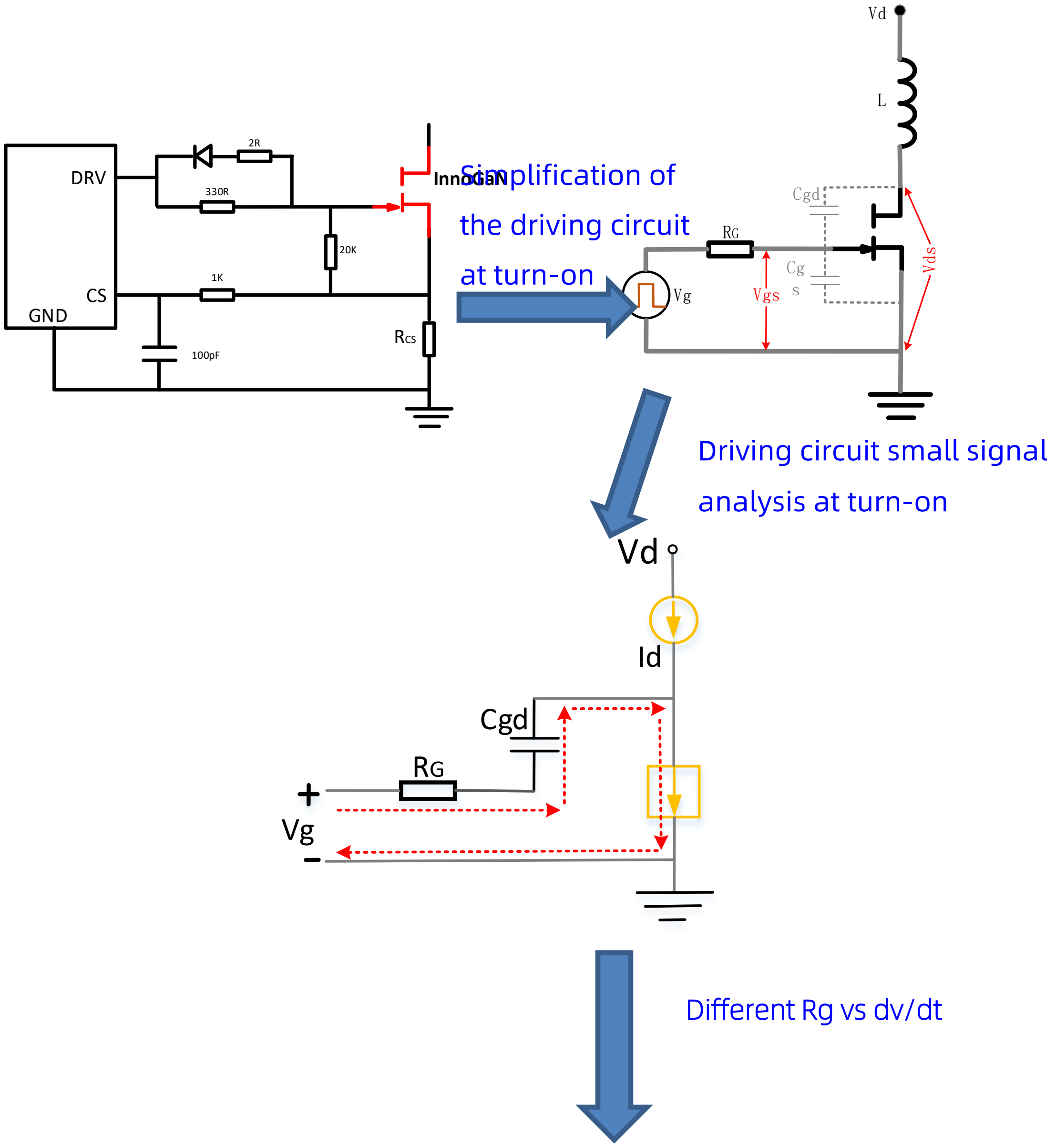
The AC input lines are taken as examples in this section to explain the method of determining the noise emission path. Firstly, add a magnetic buckle on the input line near the power source port. If there is a certain noise reduction in the corresponding frequency (such as a decrease of more than 5dB), it can be considered that the input line is the main emission path of the noise. The greater the noise reduction is, the stronger correlation is. To determine the noise emission of the power supply demo itself, a shielding metal connected the secondary side (or primary side) can be added in the board and observe the changes in RE noise.

## 3.2 RE Noise Eliminating Methods

### 3.2.1 Method I: Eliminate from the noise source

The amplitude of the noise could be reduce with reduced dv/dt and di/dt, which could be achieved slowing the turn-on speed of GaN devices with higher gate driving resistance.

Figure 22 illustrates the relationship between Rg and dv/dt of Vds voltage in QR flyback circuits.



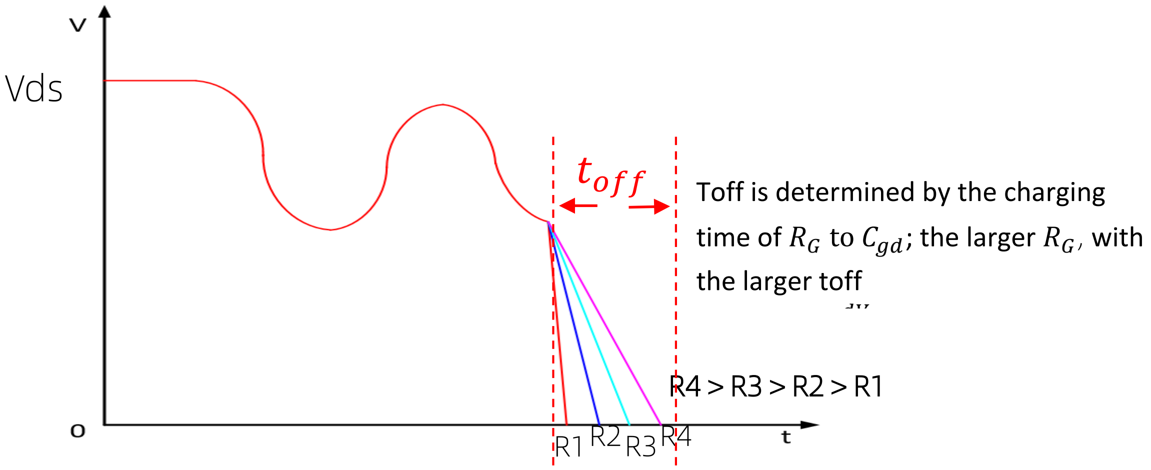
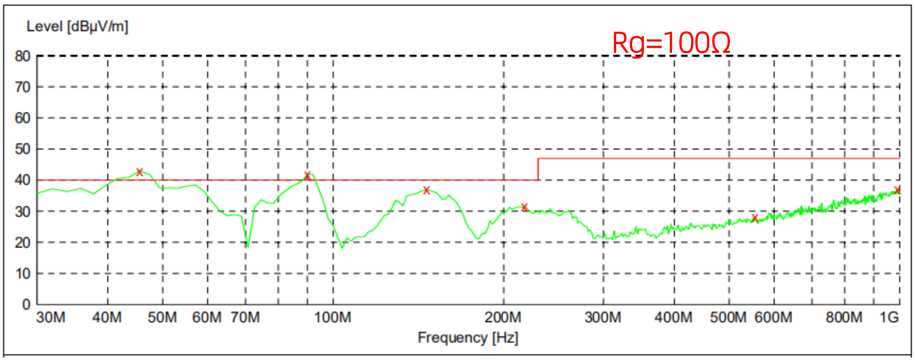
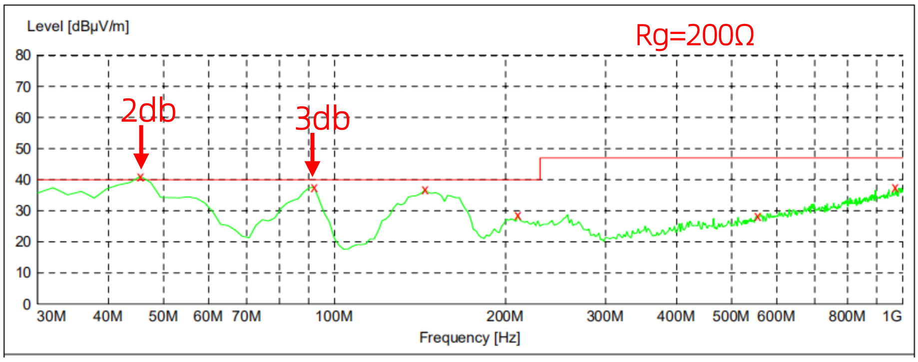
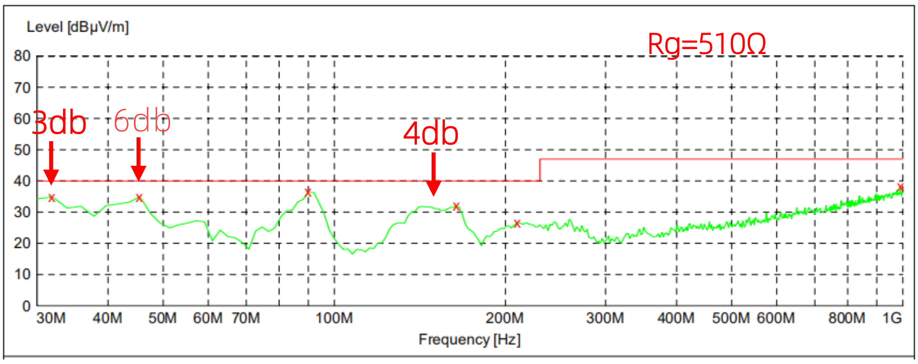



Figure 22 The dv/dt slew rate of Vds voltage with different Rg



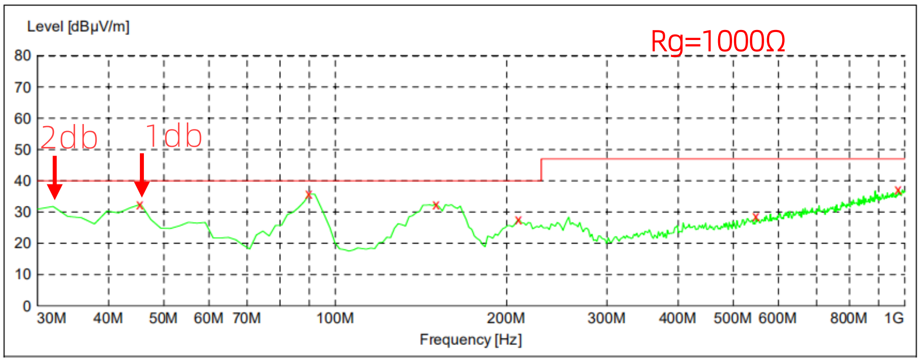



Figure 23 RE noise test results with different Rg (with GaN FET INN650D02)

- Note: There may be an system efficiency reduction when the gate driving resistance is increased with limited improvement of RE noise elimination. Therefore, it is not recommended to excessively increase the gate driving resistance. The effect of increasing the gate driving resistance should be comprehensively evaluated.

### 3.2.1.1 PCB Layout

PCB layout is closely related to EMC performance. Good layouts are the basis for reducing the noise source and simplify EMC debugging process.

The PCB layout precautions in power supplies with GaN FETs are as follows:

- Reducing the power loop area
- Reducing the gate driving loop area

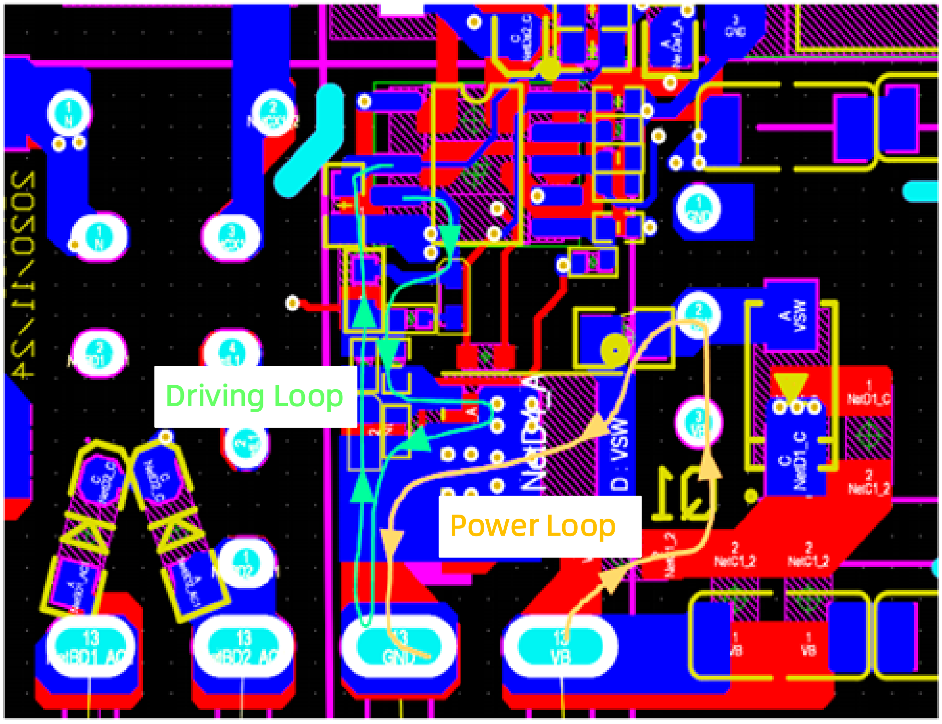



Figure 24 A PCB layout example

Layout design suggestions for power supplies with InnoGaN:

- Place the GaN FETs close to output pin of the control IC to keep the gate driving loop as short as possible.
- The resistors and capacitors of the gate driving circuit should be placed near the GaN FETs.
- Parallel routing method is recommended for multi-layer PCB. The gate driving traces and return traces should be placed on the top layer and the adjacent inner layers to reduce the parasitic inductance.
- The gate driving loop and power loop should not overlap to keep gate driving loop from the interference of the power loop.
- The thermal pad of GaN FETs should be covered with a large area of copper to improve the heat dissipation.

The methods for eliminating noise from the noise source also include:

1. Increase the turn-off gate driving resistance Rgoff.

2.Pparallel capacitors between drain and source of GaN FETs.

3. Add ferrite beads at drain terminals of GaN FETs.

### 3.2.2 Method II: Eliminating from the paths

#### 3.2.2.1 Ni-Zn core inductor

Ni-Zn core inductors (or inductors with Mn-Zn core and low inductances) could be used to increase the high-frequency impedance to prevent the noises flow through the input and output lines, thus reduce the emission of noises through the lines.

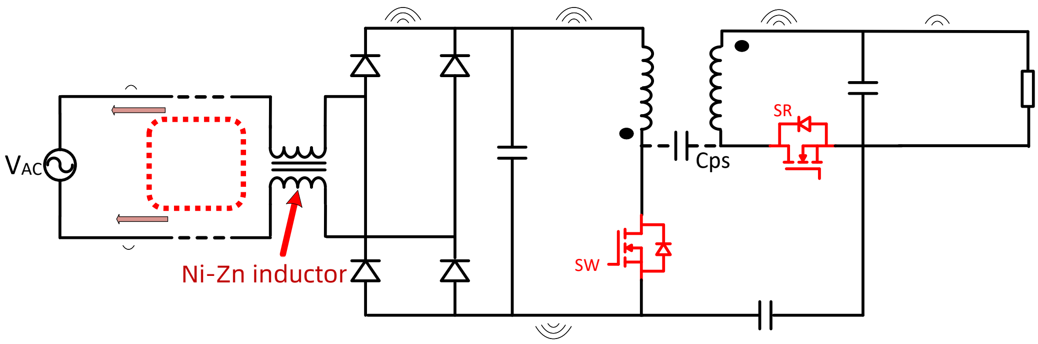



Figure 25 Circuit diagram with Ni-Zn core inductor

Similar as the high-frequency CE noise filtering method mentioned in the previous sections, inductors with low inductance and Mn-Zn core or high inductance and Ni-Zn core could also be used to filter the noises in the RE frequency band. For low frequency RE noise (30~50MHz), both inductors provide good effects. However Ni-Zn core inductors are recommended if high-frequency noise (≥ 100MHz) needs to be taken into consideration.

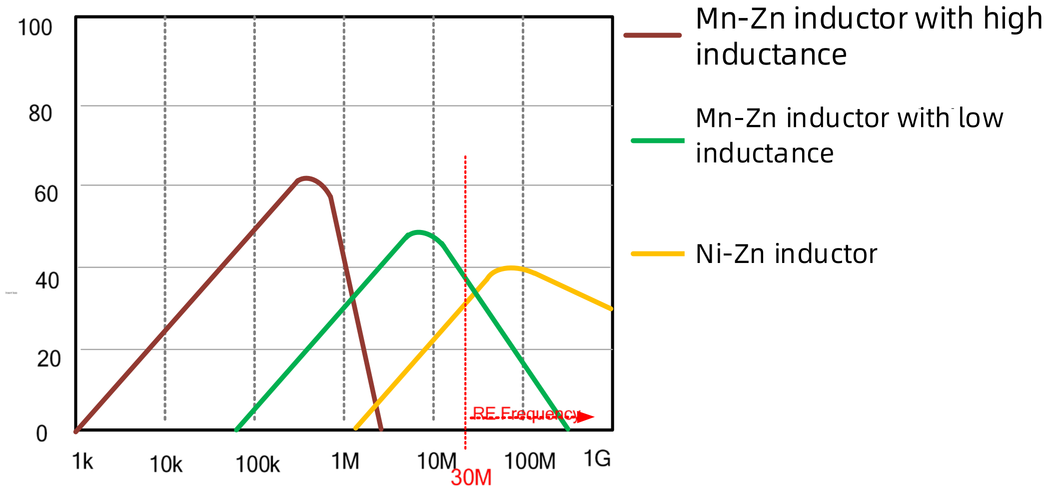



Figure 26 Insert loss with different inductors

Figure 27 shows the difference in RE noise before and after adding Ni-Zn core inductors at the input side.

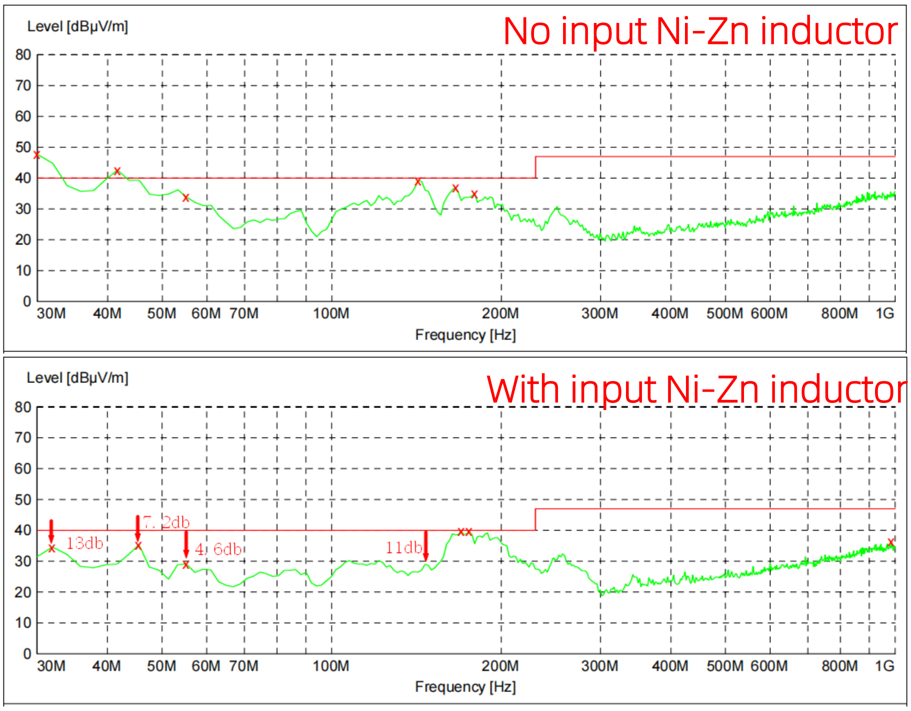



Figure 27 RE test results with and without Ni-Zn core inductor at the input side

### 3.2.2.2 Shielding

The noise emission of the power supply demo itself could be reduced with shielding metal. When using shielding metal, attentions should be paid to as follows:

1. Shielding metal should be connected to static nodes (such as at BUS capacitors, etc.).

2. Choose the appropriate emitting surface for shielding.

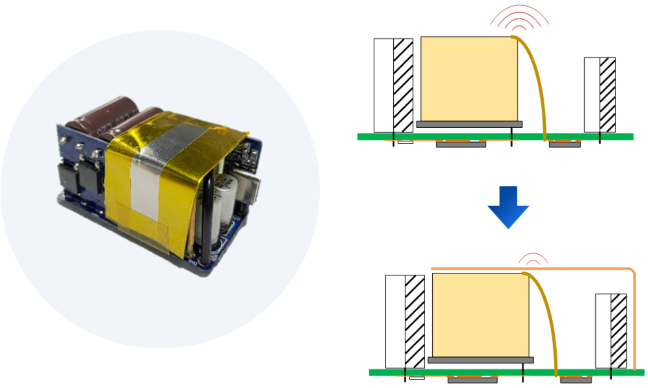
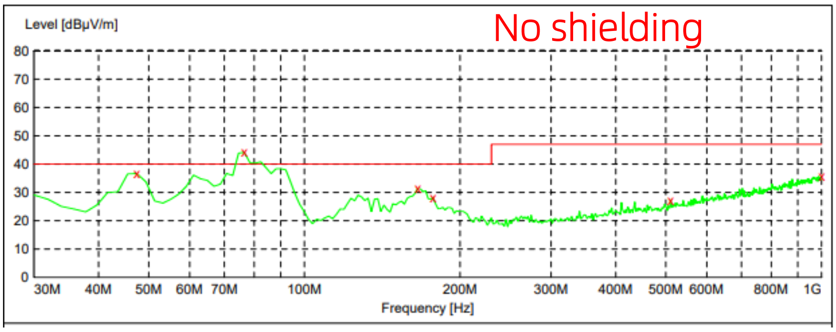
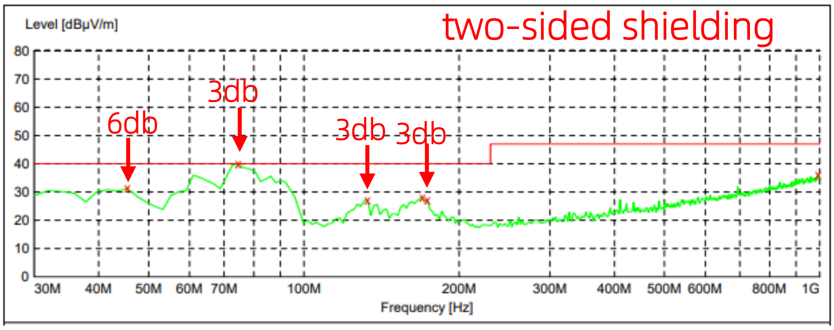
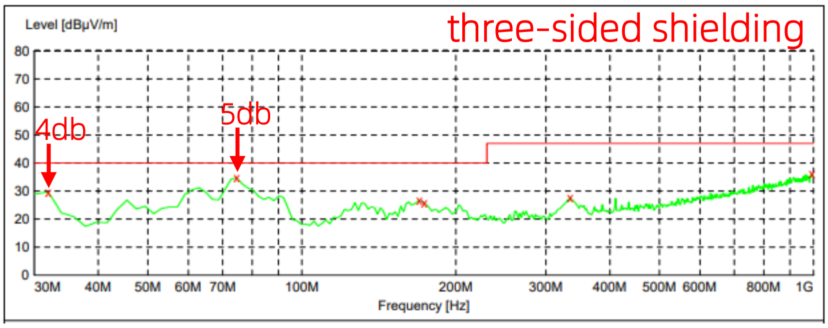


Figure 28 Diagrams of demo with shielding metal



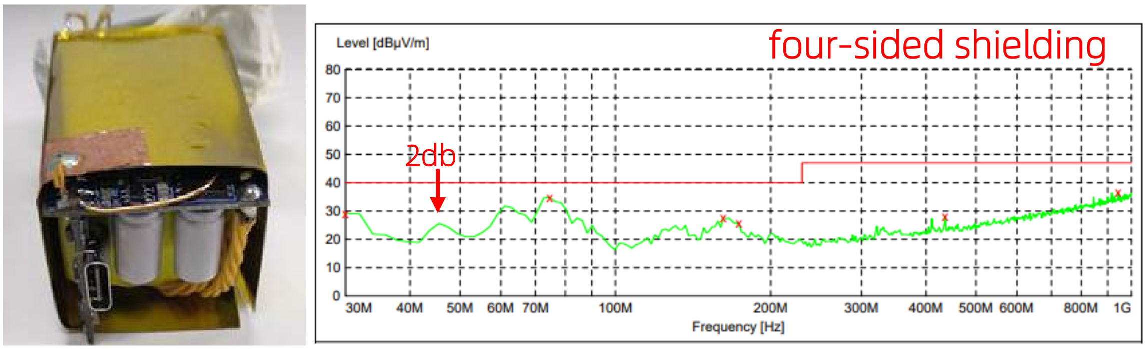



Figure 29 RE noise test results with different shielding designs

#### 3.2.2.3 Y-capacitor

The Y-capacitor provides a low impedance path for high-frequency noises, reducing the noises that flow to the input and output lines.

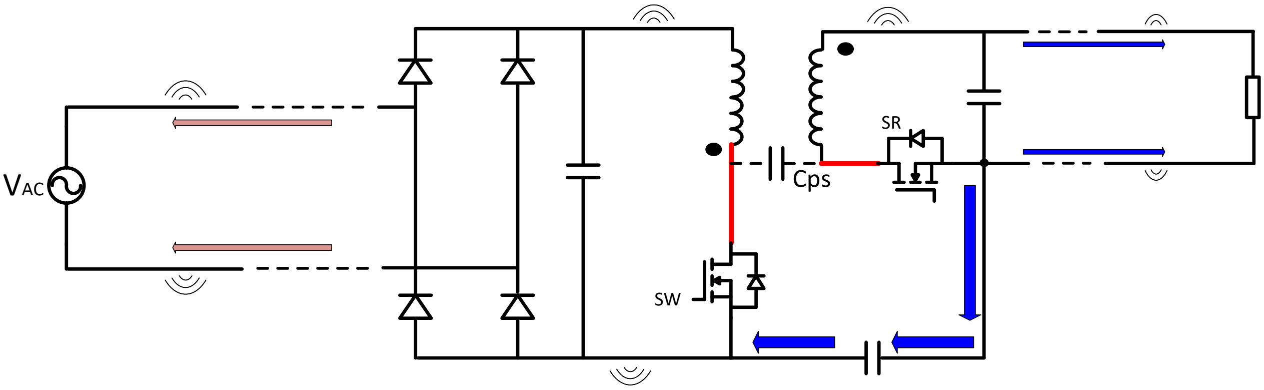



Figure 30 Noise propagation path with Y-capacitors

When using Y capacitors, attention should be paid to as follows:

- The Y-capacitor should not be connected to the switching nodes in both primary and secondary sides(marked as red lines in Figure 30).
- For the primary side, Y-capacitor could be connected to BUS+/-, Vcc/gnd, X capacitors, CBB capacitors (for power supply with PFC).
- For the secondary side, Y-capacitor could be connected rectifying capacitors and output ports.
- Use short and thick wires for Y-capacitor connections to reduce the high-frequency impedance introduced by the wires.

Figure 31 shows the RE noise test results with and without Y-capacitors. An overall improvement of 10dB~22dB is observed in RE noise in the frequency band ≤ 300MHz with Y-capacitors compared to that without Y-capacitors.

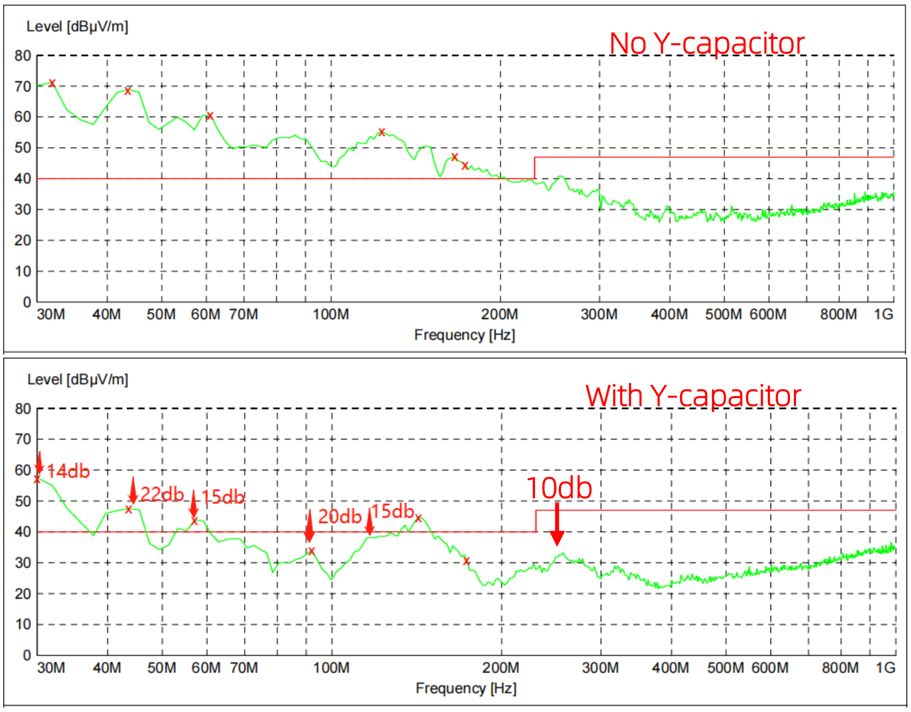



Figure 31 RE noise test results with and without Y-capacitors

# Revision History

| Date | Version | Description | Author |
|---|---|---|---|
| 2024/06/06 | 1.0 | English translation | AE team |
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Note:
There is a dangerous voltage on the demo board, and exposure to high voltage may lead to safety problems such as injury or death.
Proper operating and safety procedures must be adhered to and used only for laboratory evaluation demonstrations and not directly to end-user equipment.

Reminder:
This product contains parts that are susceptible to electrostatic discharge (ESD). When using this product, be sure to follow antistatic procedures.

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