AN1695/D

Handling EMI in Switch Mode Power Supply Design

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APPLICATION NOTE

Introduction

When designing switch mode power supplies (SMPS), undesirable noise and Electromagnetic Interference (EMI) are always present. Their effects are even more severe as the switching frequency increases, especially in applications requiring the use of small size transformer and capacitors.

This application note describes the nature and sources of EMI noise, and the design techniques used to reduce their shortcomings. All the examples of the circuitry used are referred to flyback topology however, they are also applicable to any other common SMPS topology.

Noise Sources

The most effective way to handle EMI is to minimize its source, then use filters to filter away the remaining noise. Therefore understanding the noise sources will greatly help to reduce the effects of EMI.

Noise Generated in the Primary Side of the Switching Regulator

In a linear regulator, output voltage regulation is achieved by dissipating the voltage drop in the form of heat. The switching regulator achieves output regulation by switching on and off the output transistor and varying the on time.

However, switching the transistor on and off causes the generation of high frequency noise.

Primary Voltage and Current Waveforms

The Drain–to–Source voltage of the transistor, VDS, has a high dv/dt characteristics. At the same time, the leakage inductance results in voltage spikes and ringing, consequently generating noise due to the high dv/dt as shown in Figure 1 and 2.

Typically, the collector or drain of the transistor is connected to the tab of the package. (TO–220, TO247 and etc.) The package's tab becomes an antenna radiating noise. Its effects become even more severe when a heatsink is added on to it. In some high voltage regulator ICís like the MC3337X Series, a relatively quiet source is connected to the TO–220 tab to helps reduce the related common mode noise.

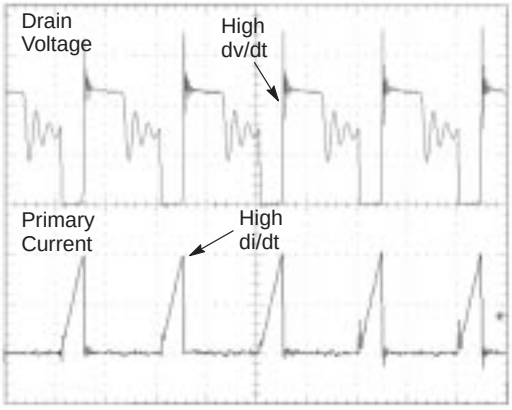


Figure 1. (Discontinuous Mode) of Flyback SMPS

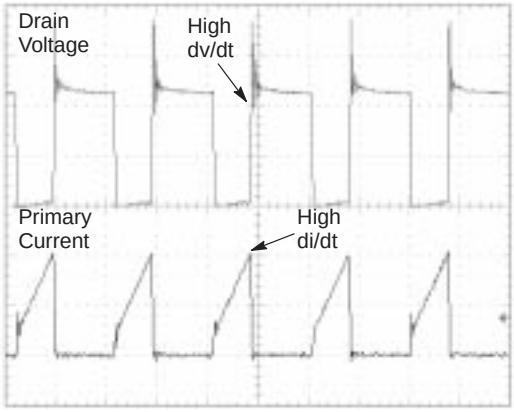


Figure 2. (Continuous Mode) of Flyback SMPS

To minimize the high frequency noise generated by the switching of the output transistor, the high dv/dt path must be made as short as possible. Shortening the high dv/dt path reduces the size of the antenna that radiates the noise. If necessary a snubber can also be added to slow down the dv/dt.

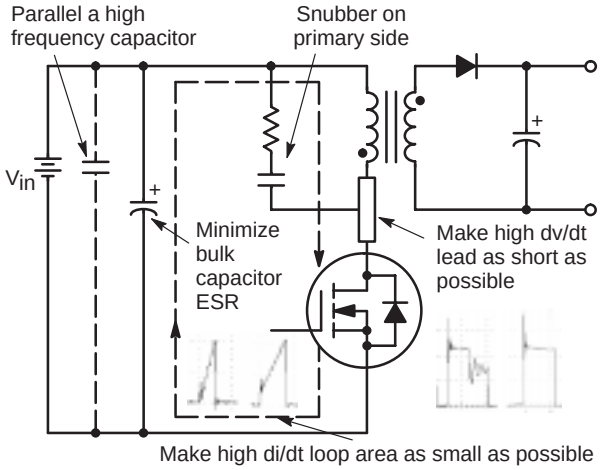


Figure 3. High dv/dt Point and di/dt Loop on Primary Side

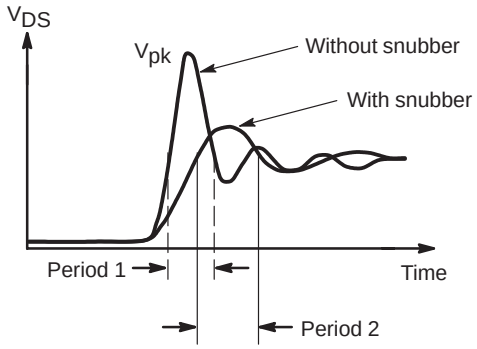


Figure 4. Effect of Snubber

A snubber is used to control both the spike's transition rate and shape, and also the peak voltage.

A high di/dt loop creates noise due to radiated magnetic fields. Its effects are especially severe when the loop encircles a large area. In order to reduce the high di/dt loop generated noise, the loop needs to be made as small as possible.

In addition, we must ensure that there is enough decoupling capacitance to filter away the high frequency noise. The equivalent series resistance (ESR) of the input bulk capacitor must be taken into account during capacitor selection since a high ESR will also promote noise. The capacitor's ESR must therefore be minimized as well.

Noise Generated in Secondary Side Diode's Characteristics

Not just the switching of the output transistor generates EMI. The fast rising and falling of the current in the high–speed output diode also produces noise interference.

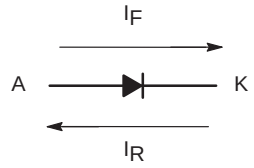


Figure 5. Output Diode Becomes a Source of EMI Due to Reverse Leakage Current

An ideal diode should have no reverse leakage current, IR. In reality however, there is a reverse leakage current flowing from the cathode to the anode of the diode. Under high frequency condition, the effect of the reverse leakage current becomes very critical as shown on Figure 6. The reverse recovery time, trr should be as short as possible to reduce the reverse leakage current.

At the same time, the reverse recovery waveforms of a diode also affect the noise performance. In Figure 6(b), 6(c) and 6(d), hard recovery waveforms show a steep slope between the peak reverse leakage current point, IRM, and the 0Amp horizontal axis intercept.

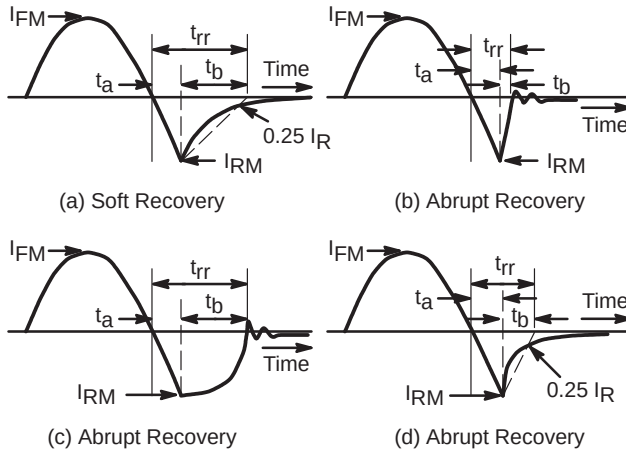
On the other hand, in Figure 6(a) a soft recovery diode waveform shows a smoother slope from the point of IRM to the 0A intercept. Comparing the soft and hard recovery waveforms, the soft recovery diode exhibits significantly less switching noise than the hard recovery diode.

Snubbers can be used to make the reverse recovery waveform soft, however this results in a drop in efficiency. So a diode with small trr and soft reverse recovery is definitely an advantage. The effects of a snubber are shown in Figure 7.

Table 1. Types of Diode and Reverse Recovery Characteristics

Types of Diodes	Reverse Recovery Characteristics	Reverse Recovery Time, t_{rr}
General Purpose	Soft	Very Slow, 1μsec
Fast Recovery	Soft	Slow, 150nsec
Ultrafast Recovery	Very Abrupt	Fast, 25–100nsec
Schottky	Soft	*

* Schottky diode has no reverse recovery time, ringing is due to parasitic carriers



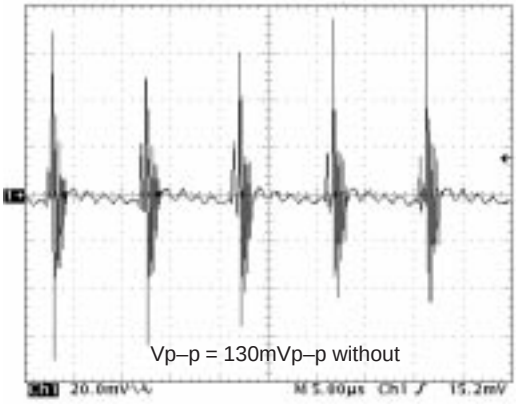


Figure 6. Test Current Waveforms for Various Types of Rectifier Diodes.

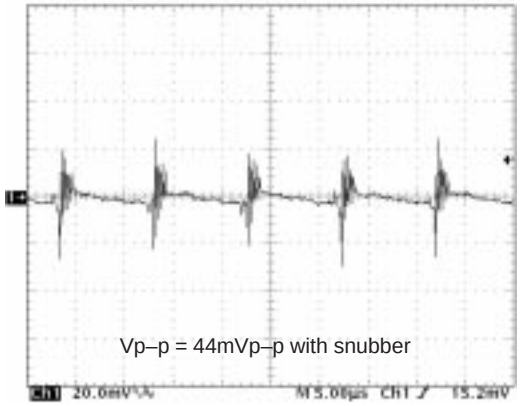


Figure 7. Effect of Snubber on Output Noise

Secondary Voltage and Current Waveforms

Similarly to the drain–to–source voltage waveform of the output transistor, the voltage across the output diode also displays high dv/dt characteristics as shown in Figure 8 and 9. Consequently, this lead needs to be made as short as possible.

Likewise, a high di/dt loop in the secondary also creates noise due to radiated magnetic fields. So, the high di/dt loop area needs to be made as small as possible.

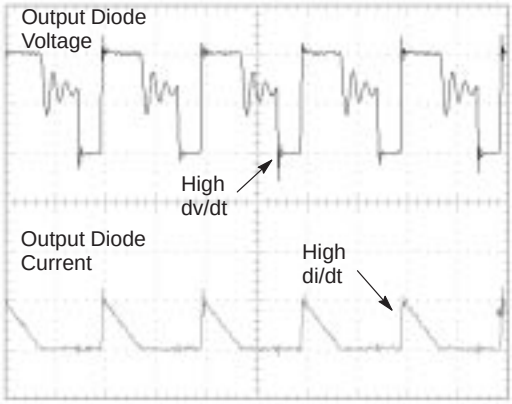


Figure 8. Typical Secondary Waveforms (Discontinuous Mode) of Flyback SMPS

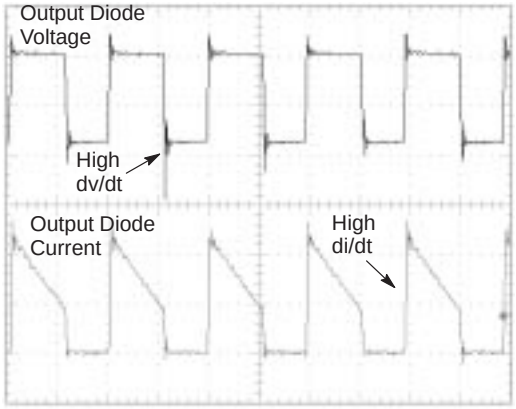


Figure 9. Typical Secondary Waveforms (Continuous Mode) of Flyback SMPS

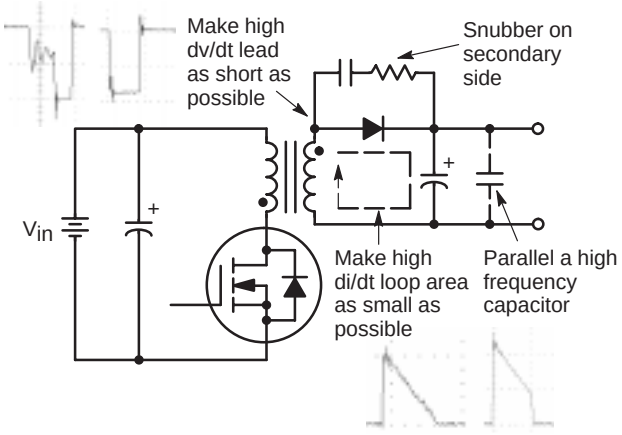


Figure 10. High dv/dt Point and di/dt Loop on Secondary Side

Step by Step Design of Snubber

1. Measure the ringing frequency, fo (1/period1 in Figure 4), without any snubber, with a low capacitance probe to avoid distorting the waveform when connecting the probe. If the probe capacitance is too high, the scope can be set on high sensitivity, also do not connect it to any component, just place the probe close to the device. The high frequency ringing noise can simply be observed due to radiated noise.
2. Record the peak voltage and ringing frequency, f_o (1/period1 in Figure 4) of the spike on the waveform.
3. Connect a very small capacitor, C in parallel with the element terminals to be snubbed. Adjust the value of the capacitor so that the ringing frequency is half of the original unsnubbed ringing frequency (1/period2 in Figure 4). At this point, the value of the sum of the parasitic capacitance (C_o) will be one–third of the paralleled capacitor value.
4. Calculate the estimated optimum value of the snubber's damping resistor by

$$R = \frac{1}{6.28 \times f_o \times C_o},\ C_o = \frac{C}{3}$$

5. Place this damping resistor in series with the added capacitor. Its value may have to be adjusted one way or the other to obtain the desired peak voltage and damping.
6. The power rating of the resistor can be sized according to the power dissipation $P = CV^2F_{SW}$, with F_{SW} being the switching frequency of the SMPS.
7. Keep the leads of the snubber as short as possible.

Transformer Construction

Transformers play a key role in SMPS' noise performance. Therefore proper selection, construction, and use of the transformer are essential to improve SMPS noise performance.

Using a center–gapped transformer can help reduce EMI noise. This is because there exists a fringing field as shown in Figure 11. Fringing field causes magnetic flux leakage, which leads to common mode emission. For center–gapped core, the winding can act as a shield to the fringing field.

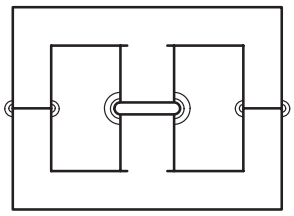


Figure 11. A Center–Gapped E–core

The winding end, which is connected to the drain of the MOSFET, should be buried in the innermost transformer winding as shown in Figure 12. The outer windings will act as a shield to the noisy half of the primary winding connected to the MOSFET Drain.

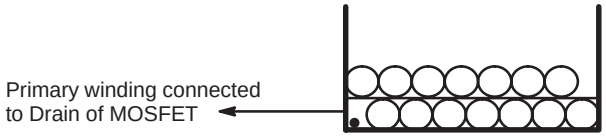


Figure 12. Wind the Primary Winding in the Innermost Layer of Transformer

To improve the shielding, a few strands of wires can be paralleled for auxiliary winding which turns number is typically small in order to cover more of the bobbin.

Figure 13 illustrates the equivalent circuit of a transformer. It can be observed that there are many parasitic capacitors.

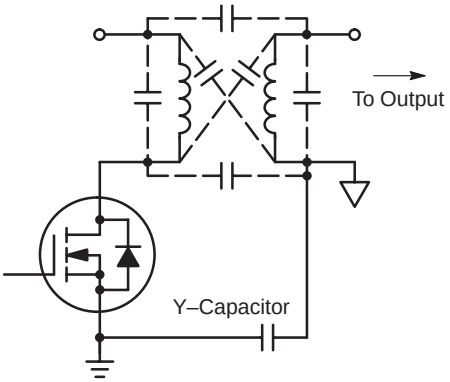


Figure 13. Parasitic Capacitors of Transformer.

Primary and secondary are isolated from direct current. However for high frequency noise, parasitic capacitors cause capacitive coupling of the common mode noise between the primary and secondary. Typically a Y–capacitor is used to provide a return path for the noise to go back to the primary. The value of the Y–capacitor is restricted by safety regulation.

Adding a shield between the primary and secondary can help to reduce the parasitic capacitance. This technique is implemented by winding an additional layer of wire covering the whole bobbin's width. One end of the winding is left floating and the other end is connected to the primary ground, as shown in Figure 14. The resistance and inductance of the lead connected to ground must be as small as possible.

Figure 15 and 16 show two examples of transformer shield placement.

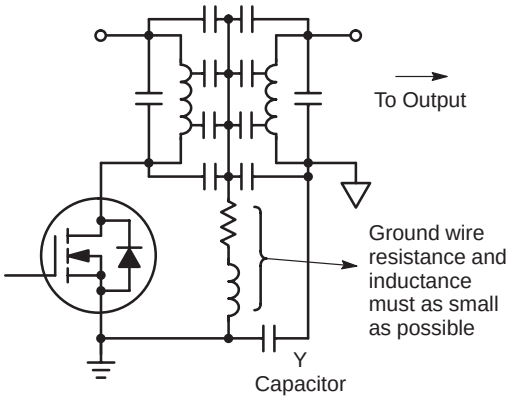


Figure 14. Transformer and Shield

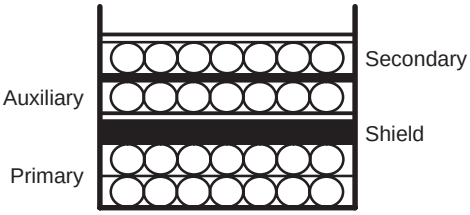


Figure 15. Transformer Shield Placement on Bobbin for Isolated Wire

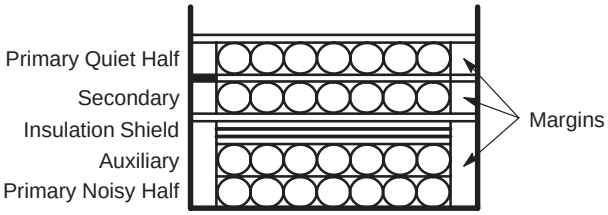


Figure 16. Transformer Shield Placement for Margin Wound Transformer.

Splitting the primary winding into 2 halves as shown in Figure 16 can minimize the primary winding capacitance and leakage inductance. Also inserting a layer of tape between the primary layers will help to reduce the winding capacitance further.

Using a split bobbin as shown in Figure 17 can make capacitive coupling between primary and secondary very small, however, this will result in high leakage inductance due to poor coupling.

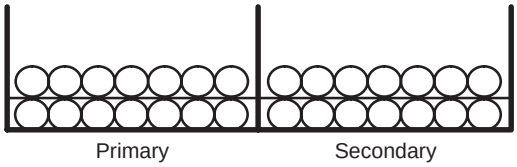


Figure 17. Split Bobbin Reduces Capacitive Coupling but Increases Leakage Inductance

Improving the coupling between primary and secondary and reducing the leakage inductance of the transformer can reduce the noise generated by high voltage spikes. This can be achieved by using interleaved winding where secondary winding is sandwiched between primary windings as shown in Figure 18. This method though is not recommended for primary regulated SMPS.

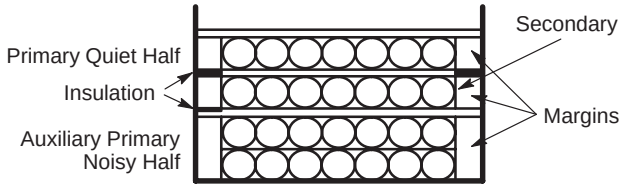


Figure 18. Interleaved Winding (Not Recommended for Primary Regulated SMPS)

Use of transformer flux band can further reduce the EMI generated by the transformer's stray magnetic field. A transformer with a flux band is shown in Figure 19.

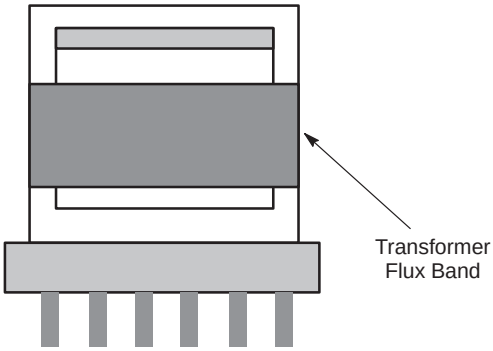


Figure 19. Transformer Flux Band

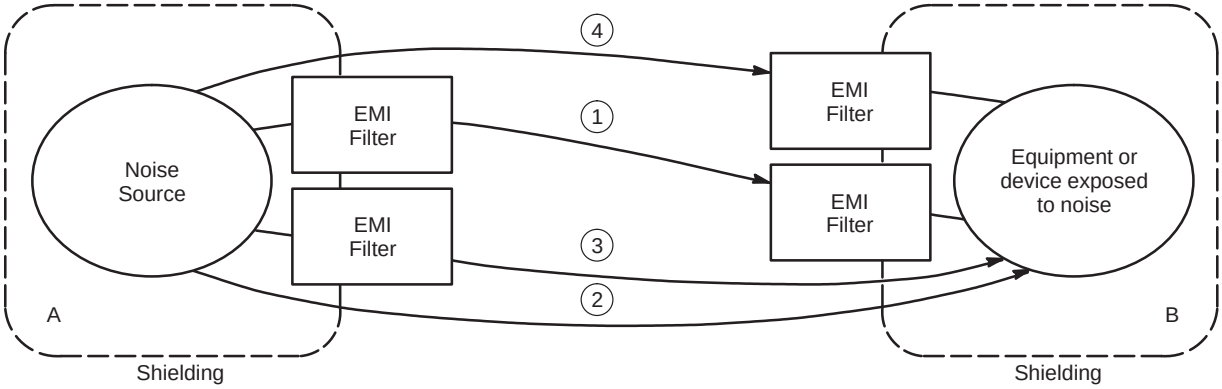
Noise Suppression

We have gone through techniques to avoid pitfalls in generating EMI noise. The remaining noise that cannot be avoided generating needs to be filtered by using filters. On the primary side, an EMI filter is typically used. It consists of inductors and capacitors. On the secondary side, a LC filter is generally used at the output. Since most SMPS have a high working current, great care must be taken to ensure that none of the inductors will saturate.

Principle of Noise Suppression

Now knowing the sources of noise and how noise is being transmitted, they can be suppressed effectively.

The principle of noise suppression is to use an EMI filter for conducted noise, and shielding for radiated noise.



		How to Suppress Noise	
		Side A	Side B
1	Conduction	EMI Filter	EMI Filter
2	Radiation	Shielding	Shielding
3	Conduction Radiation	EMI Filter	Shielding
4	Radiation Conduction	Shielding	EMI Filter

Figure 20. Principle of Noise Suppression

Common and Differential Mode Noise

Common mode noise is transmitted on all the lines in the same direction. For SMPS, noise is transmitted on both lines in the same direction as shown in Figure 21.

To eliminate common mode noise, EMI suppression filters are installed on every line promoting noise. Noise is suppressed by installing an inductor on both the signal and neutral lines, between the signal source and the load as shown in Figure 22(a), and by connecting capacitors from the signal and neutral lines to the reference ground, see Figure 22(b).

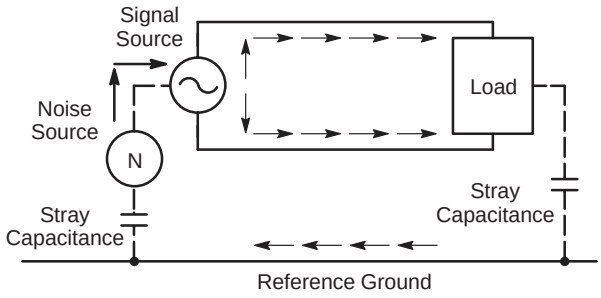
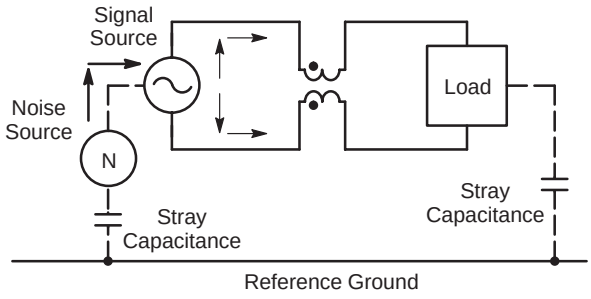
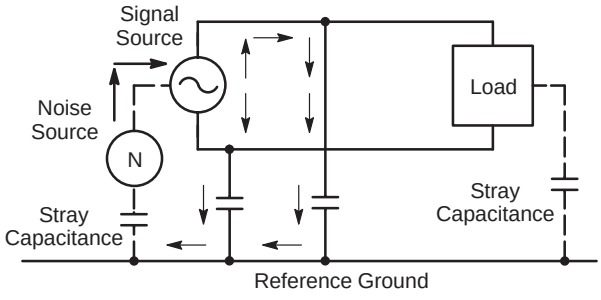


Figure 21. Common Mode Noise



(a)



(b)

Figure 22. Common Mode Noise Suppression Methods

Differential mode noise exists on the signal (Vcc) line and neutral line and propagates in opposite direction, as shown in Figure 23. This type of noise is suppressed by installing a filter on the hot (Vcc) side on the power supply line as depicted in Figure 24.

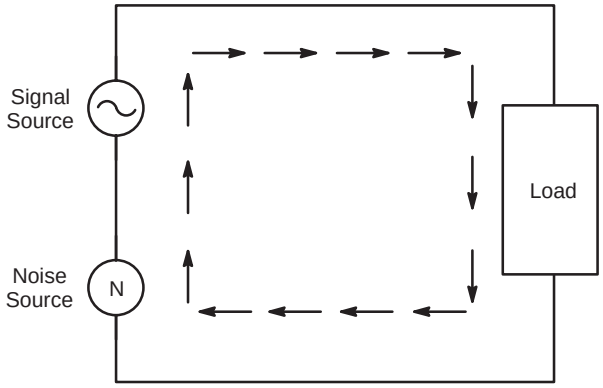


Figure 23. Differential Mode Noise

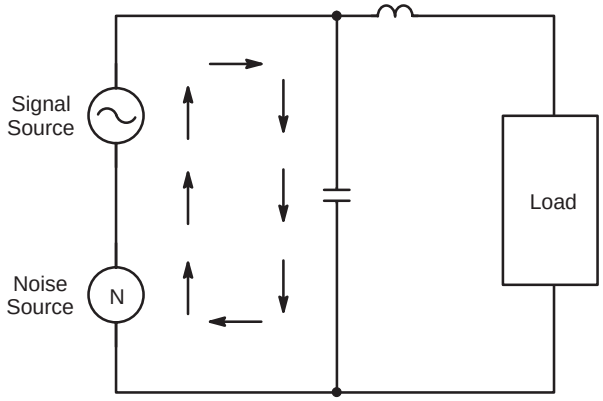


Figure 24. Differential Mode Noise Suppression Method

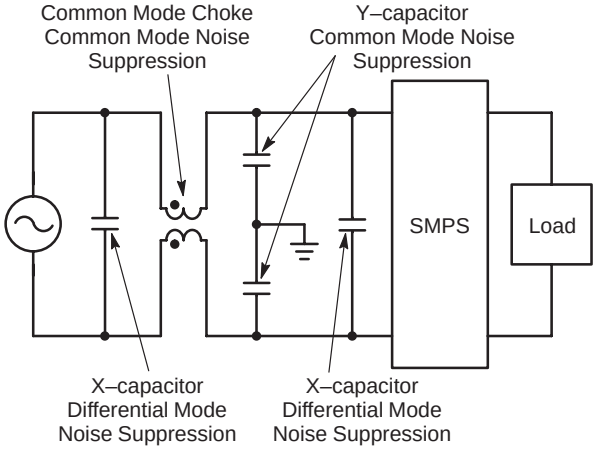


Figure 25. Example of Noise Suppression on AC Power Supply Line

Figure 25 figure shows an example of noise suppression on an SMPS.

Common mode noise is suppressed by using a common mode choke coil, and a capacitor (Y–capacitor) connected between each line and the earth ground. The Y–capacitor returns the noise to the noise source.

Also, an X–capacitor is connected across the supply lines to suppress differential mode noise.

EMI Filter Components Common Mode Choke

Common mode chokes are used to suppress common mode noise.

Since magnetic flux flows inside the ferrite core, common mode chokes behave as an inductor to common mode current. Accordingly, using a common mode choke provides larger impedance against common mode current and is more effective for common mode noise suppression than using several normal inductors.

X–Capacitor

X–capacitors are suitable to use in situations where failure of the capacitors would not lead to the danger of an electrical shock. They are typically connected across the AC lines for differential mode suppression.

According to EN 132400, X–capacitors are divided into 3 sub classes, depending on the peak impulse voltage to which they are exposed during operation. This kind of impulse can be caused by lightning in overhead cable, switching surges in neighboring equipment or in the device in which the capacitor is being used to suppress interference.

Typically, X2–capacitors are use for MC3337X based SMPS, X3–capacitors are seldom used. X1–capacitor can be used but come at a higher cost.

Sub–Class	Peak Pulse Voltage, V_P in Operation	Application
X1	2.5KV < V_P ≤ 4.0KV	For high peak voltages
X2	V_P ≤ 2.5KV	General purpose
X3	V_P ≤ 1.2KV	General purpose

Y–Capacitor

Y–capacitors are intended for use where the failure of the capacitor could result in a dangerous electrical shock. They have a higher electrical and mechanical reliability intended to eliminate the possibility of short circuits in the capacitor. The value of Y–capacitor is limited by safety regulations.

Y–capacitors are usually connected from the AC lines or bridge rectifier output to the secondary, chassis, shield, or earth ground.

According to EN 132400, Y–capacitors are divided into the following sub classes:

Sub–Class	Type of bridge insulation	Rated AC Voltage	Peak values of surge voltage V_P
Y1	Double or reinforced insulation	VR ≤ 250V	8.0KV
Y2	Basic or Supplementary insulation	150V ≤ VR ≤ 250V	5.0KV
Y3	Basic or Supplementary insulation	150V ≤ VR ≤ 250V	No Test
Y4	Basic or Supplementary insulation	VR ≤ 250V	2.5KV

Input EMI Filter Design Example

One needs to determine the level of attenuation needed at the SMPS frequency. This is done with the following formulas

$$\text{Attenuation}(-\text{dB}) = 40 \log \frac{f_C}{f_{SW}} \qquad \text{or}$$

$$f_C = f_{SW} \times 10^{\text{Att}/40}$$

where f_C is the desired corner frequency of the filter and f_{SW} is the switching frequency of the SMPS

For example, if the switching frequency is a 100kHz, and an attenuation of –24dB is desired, the corner frequency will be

$$f_C = 100000 \times 10^{-24/40} = 25.1 \text{ kHz}$$

We assume the line impedance is 50Ω, the same as the LISN Test impedance. A damping factor, ς larger than 0.707 should be used.

Common mode inductance and Y–capacitor values can be computed with the help of the equations below

$$L = \frac{R_L \varsigma}{\pi f_C} = \frac{(50)(0.707)}{\pi(25.1\ \text{k})} = 448.3\ \mu\text{H}$$

$$C_Y = \frac{1}{(2\pi f_C)^2 L} = \frac{1}{[2\pi(25.1\ \text{k})]^2\ 448.3\ \mu} = 89.7\ \text{nF}$$

To meet safety regulation and pass AC leakage current test, there is a limit on the size of the capacitor. Use a 4.7nF Y–capacitor, so the inductance becomes 8.55mH. This will result in a damping factor, ς of 13.5 which is acceptable.

The values of X–capacitors are mainly arbitrary.

Output LC Filter

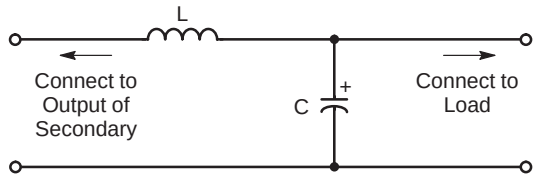


Figure 26. Output Filter

The design equation is as below:

$$f = \frac{1}{2 \times \pi \times \sqrt{L \times C}}$$

where f is the cut off frequency of the low pass filter.

PCB Layout and Components Placement

A careful layout of the PCB and placement of the components is essential in SMPS in dealing with EMI. Figure 27 shows a poorly laid PCB with poor components placement that can possibly generate EMI noise coupling around the filter. In this arrangement, when a voltage surge occurs at the input, the high frequency surge signal will not flow through the EMI filter but will rather directly couple to the output.

If such a PCB layout and components placement cannot be avoided, the input and output should be kept as far as possible from each other. However, such an arrangement is NOT recommended.

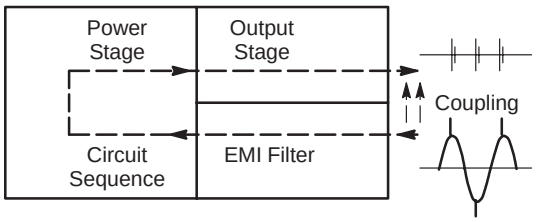


Figure 27. Poor PCB Layout and Component Placement.

Keeping the input EMI filter at a distance from the output helps to prevent coupling around the filter. Figure 28 shows a recommended PCB layout and components placement for SMPS. The input stage is at one end of a rectangular board and the output stage is at the other end.

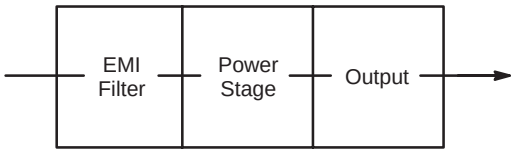


Figure 28. PCB layout and Components Placement that Minimize Noise Coupling

The leads of the capacitors should be made as short as possible. PC traces length connecting capacitors should also be as short as possible.

Shielding

As depicted in Figure 20, radiated noise in SMPS can be suppressed using shielding.

In applications where the SMPS is enclosed by a plastic casing, like in an adapter or a battery charger, EMI noise is suppressed by proper PCB layout, components placement, transformer construction and EMI filter selection. In some cases, conductive paint can be used to add EMI shielding to the case.

Any joint between sections responsible for shielding should have a very low resistance; or else the effectiveness of the shield will be greatly impaired. RF gaskets are used in some cases.

EMI filters should be fitted at the points of entry and exit of wires that enter or exit the shield box.

Combating EMI Noise

An ounce of prevention is worth a pound of cure. Remember that to combat EMI noise, one should first identify the noise sources, then apply the proper techniques described in this application note to minimize their effects. EMI filters can then be used to suppress those that cannot be avoided generating.

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Notes

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