Tech Web Hand Book

Switching Power Supply
Basic of EMC
and Noise Countermeasures

Powered by ROHM SEMICONDUCTOR

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Introduction

In the world of electronics, noise is a serious problem, and countermeasures against it are a common issue regardless of the field. The accuracy and resolution of electronic devices are limited by their signal-to-noise ratio. Also, if the noise emission is too high, it may adversely affect other equipment, and in some cases, this may lead to serious accidents. For this reason, noise is regulated by laws worldwide, and in addition to national and regional standards such as the Electrical Appliance and Material Safety Law in Japan, FCC in the US, and EN in the EU, there are international standards such as CISPR, IEC, and ISO. Products that do not conform to these safety standards cannot be sold, nor can they be imported or exported.

In recent years, it has become necessary to deal with noise from the perspective of EMC - electromagnetic compatibility. In this book, the basics of EMC and noise countermeasures are discussed, and the subject of noise countermeasures is switching power supplies, which is one of the themes of Tech Web.

1. Basics of EMC

As the basics of EMC, we will start with EMC-related terms, which, like EMC, are often abbreviated in English and have similar alphabets. EMC concepts and terms are well defined as international standards, so a correct understanding of the meaning of each term is necessary.

1.1 What is EMC?

EMC stands for Electromagnetic Compatibility. This term conveys the meaning "Without causing electromagnetic interference to other devices, the ability to maintain the inherent performance even subjected to electromagnetic interference from other devices". Because of the need to sustain both of the capabilities, the term "electromagnetic compatibility" is used.

"Without causing electromagnetic interference to other devices" means that without this proviso devices could give an electromagnetic interference to other devices. EMI stands for Electromagnetic Interference. Since generating electromagnetic waves can be linked to interference, the term EMI is often used in pair with the expression "Emission". In terms of switching power supplies, the action of switching generates switching noise.

Conversely, the term related to "subject to electromagnetic interference from other devices" is EMS (Electromagnetic Susceptibility). Used in pair with EMS is "Immunity". What is needed in a device is the immunity that do not cause errors, such as a malfunction, when subjected to an EMI.

Among the types of EMI are conducted emission and radiated emission. Conductive emission is propagated through wires and PCB wiring. Radiated emission is a type of noise that is emitted (radiated) through the air. With respect to these emissions, in EMS there are immunity required of the devices. The relationship between EMC, EMI and EMS is given below. Table 1 also summarizes the meaning of each term.

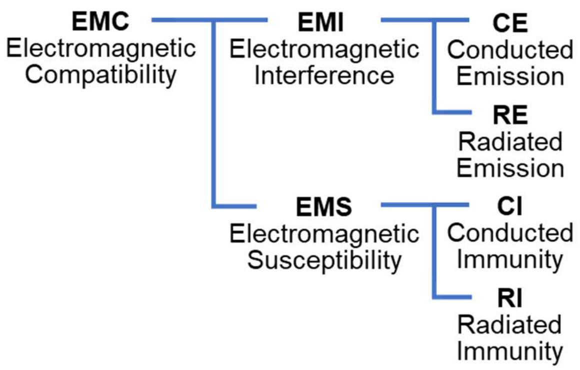

Figure 1. EMC terminology and relationships

Term	Meaning	Notes
EMC: Electromagnetic Compatibility	Without creating EMI, the ability to maintain the device's inherent performance even if subjected to EMI from another device.	Because of a need to ensure both EMI and EMS, the term "electromagnetic compatibility" is used.
EMI: Electromagnetic Interference	Interference to other by radiation/emission of electromagnetic waves.	From the standpoint of EMC, the requirement is not to produce/minimize EMI.
EMS: Electromagnetic Susceptibility	Immunity with respect to EMI.	From the perspective of EMC, it's required to be resistant to EMI without causing damage
Conducted Emission	Noise that is propagated via wires and PCB wiring.	
Radiated Emission	Noise that is emitted (radiated) through the air.	

Table 1. EMC terms and their meanings

1.2 What is Spectrum?

What is a spectrum? According to the Concise Electronics Dictionary Edition of the Encyclopedia Britannica, a spectrum is "the result of analyzing an electromagnetic wave into its sine wave components and arranging the components in order of wavelength", and by extension means "analyzing something with a complex makeup into simple components, and arranging the components in order of the magnitude of a characterizing quantity...". The spectra we will be considering here are the spectra of electrical signals. More specifically, we will be explaining spectra using data obtained using a spectrum analyzer that plots frequency along the horizontal axis, and power or voltage along the vertical axis.

We begin with the schematic diagram in Figure 2. Here the topic is "EMC of a switching power supply", and so it is assumed that an electrical signal is a switching signal. The pulse waveform, which is an image of a switching signal, shows tw (pulse width) and ts (rise/fall time).

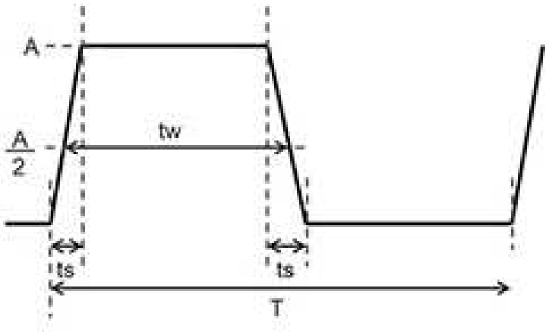

Figure 2. Schematic diagram of switching signal pulse waveform

The upper graph in Figure 3 represents the spectrum of theoretical pulse waveforms obtained from a Fourier transform. This is a familiar spectrum in which, as the frequency rises, the amplitude attenuates, and the slope of the attenuation changes with tw and ts. And the graph below shows the change in the spectrum when the pulse ts is made slower (increased).

It is natural that when the slope changes to -40 dB/dec the frequency at $1/\pi$ts is lower, but as a result, the subsequent amplitude is reduced. Put simply, when ts is slowed, the spectrum amplitude is attenuated.

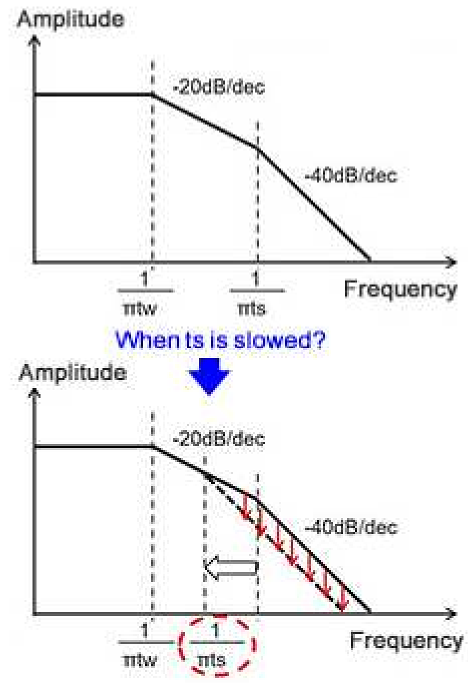

Figure 3. Spectrum of theoretical pulse waveform by Fourier transform (upper) and its change with slowing down ts (lower)

1.3 Waveform changes and spectrum changes

From here, we shall use actual spectrum analyzer data to show changes in a spectrum with changes in the frequency and other parameters. What should be noted here is the manner in which the spectrum tends to change with changes in the signal waveform. This knowledge will be necessary when analyzing EMC and devising countermeasures using spectra related to the switching of an actual switching power supply circuit.

The graph shown in Figure 4 presents the initial conditions, to be used as a basis for comparison. As indicated in the upper waveform graph, these conditions are an amplitude of 10 V, a frequency of 400 kHz, a duty cycle of 50%, and a tr/tf (rise time/fall time) of 10 ns.

The center graph shows nth harmonics and amplitudes (V). The amplitude is greatest for the first harmonic which is the fundamental wave, that is, the 400 kHz component, and the spectrum appears at the frequencies of the odd-numbered harmonics. The fact that only odd-order harmonics are generated is a characteristic of a spectrum with a duty cycle of 50% (=1:1). The magnitude of each component is 1/order of the fundamental component, e.g., the 3rd order harmonic component is 1/3, and the nth order harmonic component is 1/n.

The lower graph is a logarithmic graph with the amplitude in dBμV. Here dBμV is the decibel value of the voltage ratio with a 1 μV voltage as reference (1μV＝0dBμV).

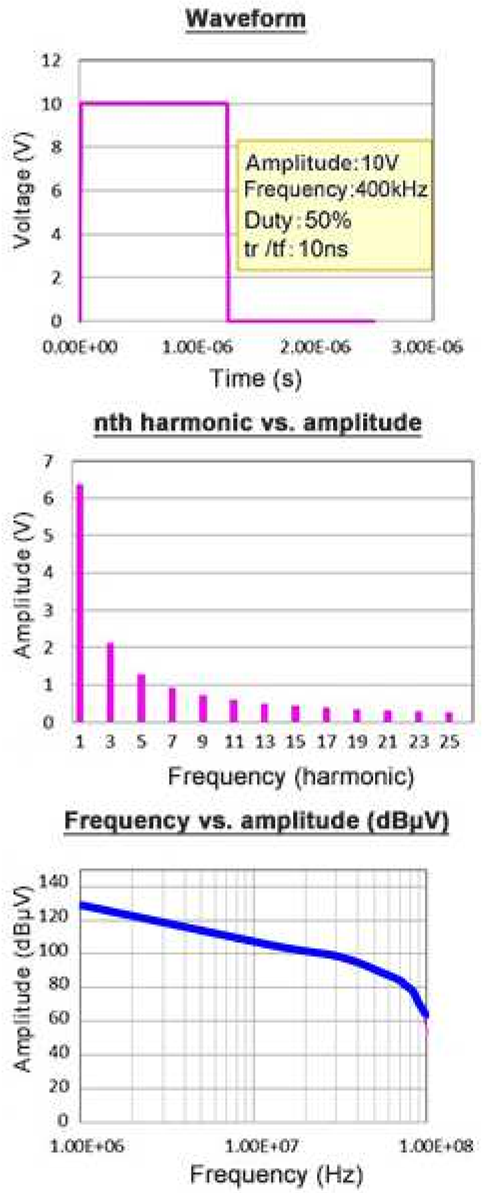

Figure 4. Data under initial conditions as a basis for comparison

This waveform shows the data for each of the following changes: ① Higher frequency, ② Slower rise/fall, ③ Change duty cycle, and ④ Slower rise only.

<u>① Spectrum with the frequency increased to 2MHz (Figure 5).</u>

It is clear from the frequency vs. amplitude (dBμV) graph that as the fundamental frequency increases, the entire spectrum shifts to the right (higher frequency).

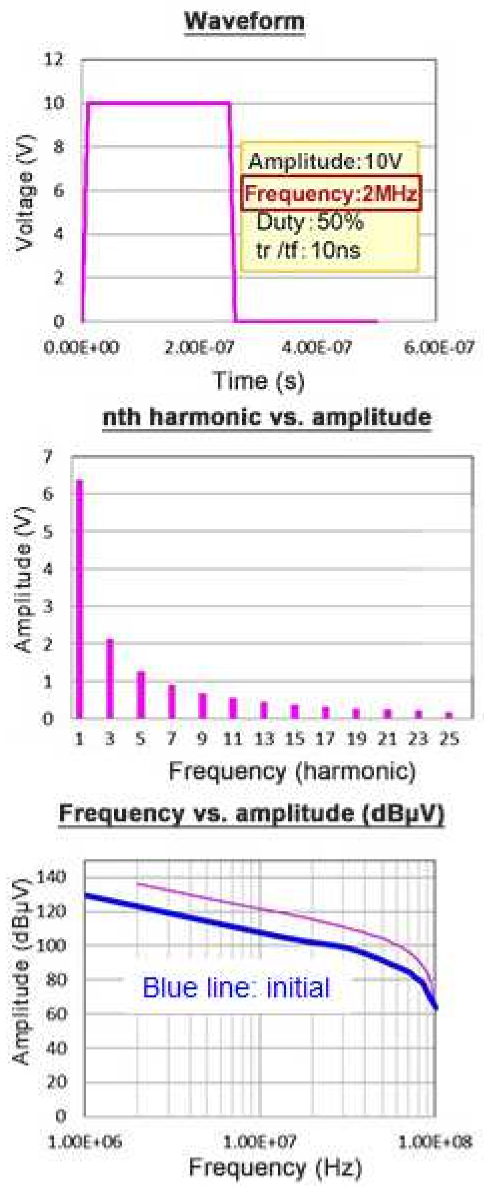

Figure 5. ① Spectrum with the frequency changed to 2 MHz

② Spectrum both tr and tf are slowed (increased) to 100 ns (Figure 6).

As explained in the schematic diagram, this is due to the lower frequency at which -40 dB/dec enters the attenuation, which attenuates the spectrum amplitude of higher harmonics.

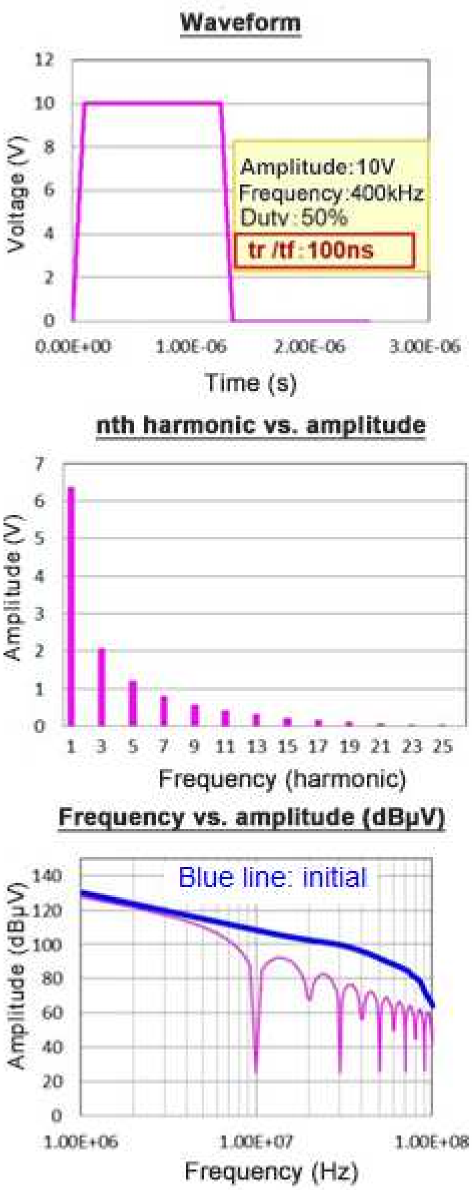

Figure 6. ② Spectrum with both tr and tf slowed to 100ns

③ Spectrum in which the duty cycle is reduced from 50% to 20% (Figure 7).

The duty cycle is no longer 1:1, and so even-numbered harmonics appear, but in essence there is no change in the peak. By narrowing the pulse width tw, the amplitude of the fundamental wave spectrum is attenuated.

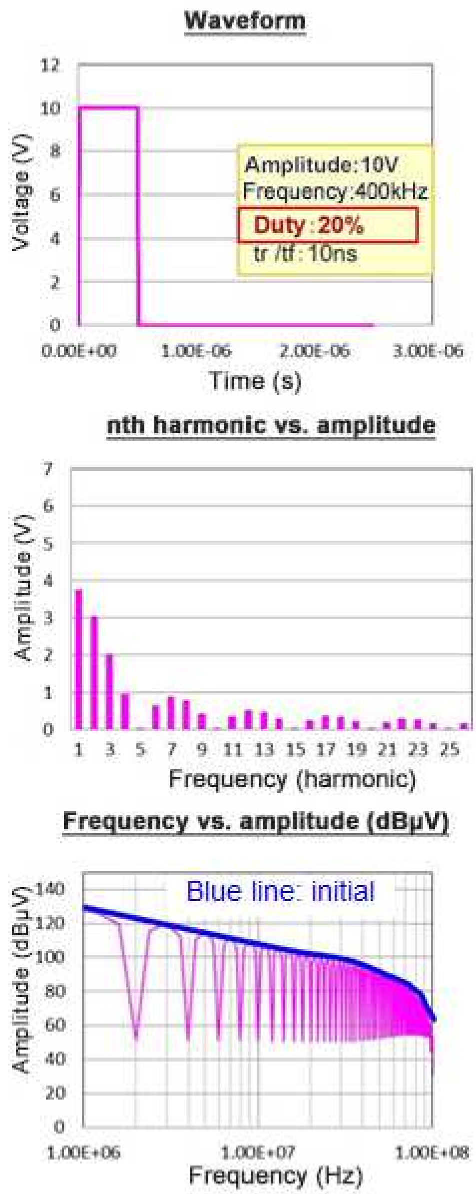

Figure 7. ③ Spectrum when the duty cycle is set from 50% to 20%

④ Spectrum when only tr is slowed (Figure 8).

The higher harmonic components related to tr are attenuated due to the slower tr.

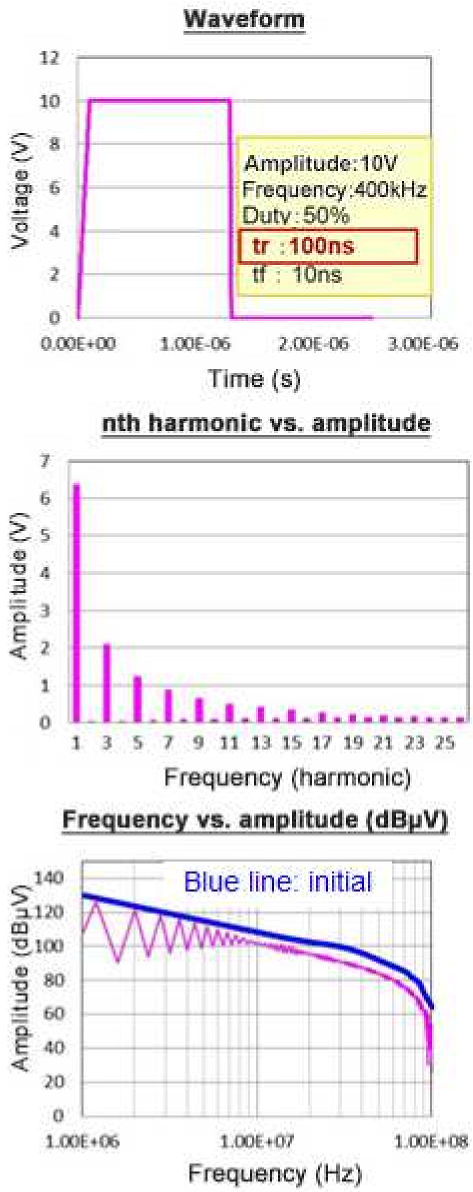

Figure 8. ④ Spectrum with only tr slowed down

Write down each result.

① Higher frequency ⇒ Overall spectrum shifts to the right.

② Slower rise/fall ⇒ The frequency entering the -40dB/dec attenuation is lowered and the higher harmonic spectrum amplitude is attenuated.

③ Change duty cycle ⇒ Even-order harmonics are generated, but the spectrum peak is not affected. The spectrum of the fundamental wave is attenuated.

④ Slower rise only ⇒ Higher harmonics related to the rising edge component are attenuated.

In summary, the lower the fundamental frequency and the slower the rise/fall, the more the harmonic spectrum will be attenuated, from an EMC perspective, the lower the spectrum amplitude, the better.

1.4 Differential (Normal) Mode Noise and Common Mode Noise

We have explained that electromagnetic interference EMI can be broadly divided into two categories: conducted noise and radiated noise. Conducted noise is classified into two types according to the way it is conducted: differential mode noise and common mode noise. Differential mode noise is also called normal mode noise. There are cases where they are used differently depending on the conditions, but here they are assumed to be the same. The figure used for explanation is an example where the printed circuit board (PCB) is in an enclosure and is powered from outside.

Figure 9 shows the conduction path of differential mode noise. The noise source enters in series with the power supply lines, and the noise current flows in the same direction as the power supply current, and is generated between the power supply lines. It is called differential mode because the direction of going and returning are reversed.

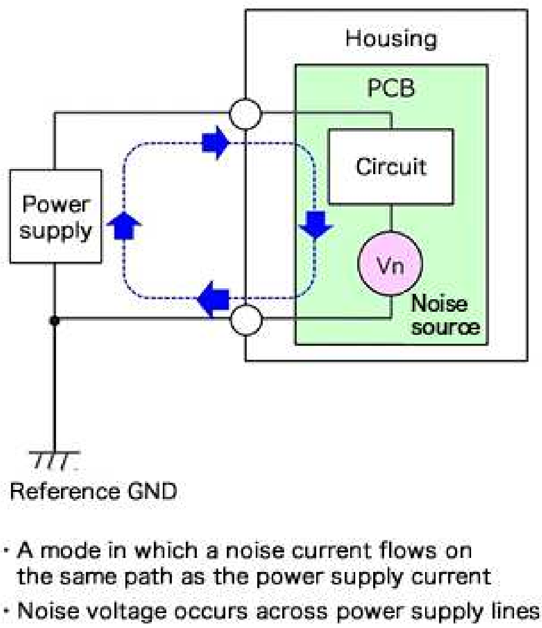

Figure 9. Differential (normal) mode noise

Figure 10 shows the conduction path of common mode noise. Common mode noise is noise in which a noise current that has leaked via a stray capacitance or the like passes through ground and returns to the power supply line. It is called "common mode" noise because the direction of the noise currents on the positive (+) and the negative (-) sides of the power supply have the same direction. A noise voltage does not appear across the power supply lines.

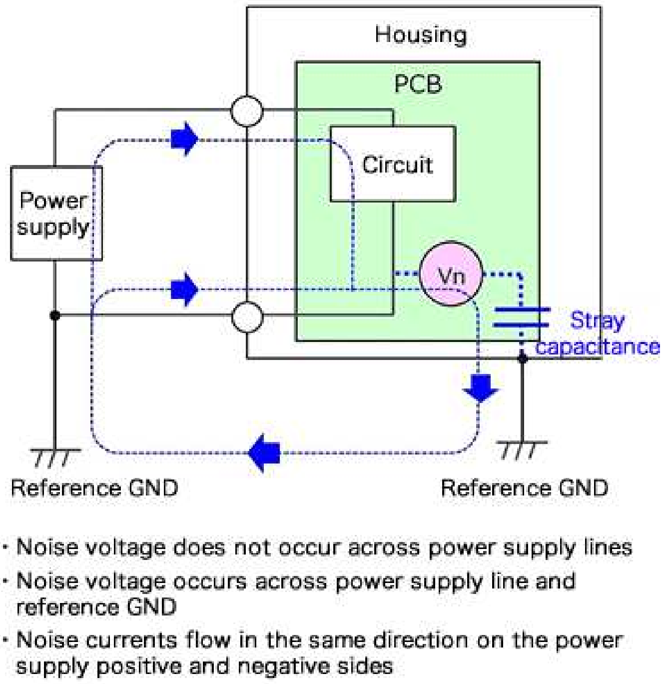

Figure 10. Common mode noise

As explained above, these types of noise are conducted emissions. However, noise currents are flowing in power supply lines, and so noise is radiated.

The electric field intensity Ed of radiation due to differential mode noise can be expressed using the equation in Figure 11. Id is the noise current in differential mode, r is the distance to the observation point, and f is the noise frequency. Differential mode noise creates a noise current loop, and so the loop area S becomes an important factor. As indicated in the diagram and equation, if the other elements are constant, then for a larger loop area, the electric field intensity is higher.

And the electric field intensity Ec of radiation due to common mode noise can be expressed by the equation in Figure 12. As the diagram and equation indicate, the cable length L is an important factor.

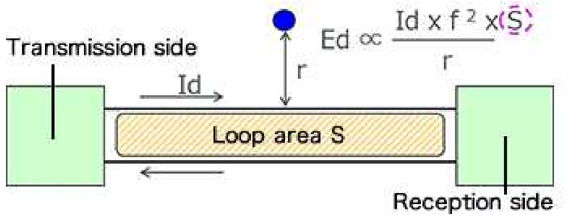

Figure 11. Radiation and electric field strength due to differential mode noise

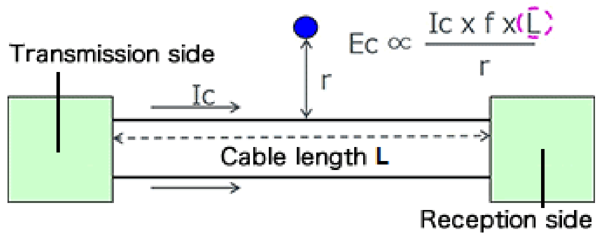

Figure 12. Radiation and electric field strength due to common mode noise

Here, in order to confirm the characteristics of radiation due to the different types of noise, we will insert actual numerical values to calculate[*1] the electric field intensities 'Figure 13). The conditions in each case are exactly the same. Observed electric field intensities are indicated by blue dots. *1. Equations excerpted from: Detailed Explanation--Electromagnetic Compatibility Engineering, Author: Henry W. Ott, Publisher: John Wiley & Sons

Of importance in these calculation results is the fact that, for the same noise current values, the radiation due to common mode noise is far greater (in this example, roughly 100 times greater). In any case, if any of these types of conducted emission and radiated emission that constitute EMI exceed the allowed ranges, noise countermeasures become necessary. In particular, when considering measures to address radiated emission, measures to deal with common mode noise are particularly important.

Noise countermeasures will hereafter be explained, but the basic measures to deal with noise are, in the case of differential mode noise, decreasing the loop area S, for example by using a twisted-wire cable, and for common mode noise, shortening the cable length insofar as possible. However, constraints on the arrangement and type of components always emerge, and so methods such as adding a filter must also be studied.

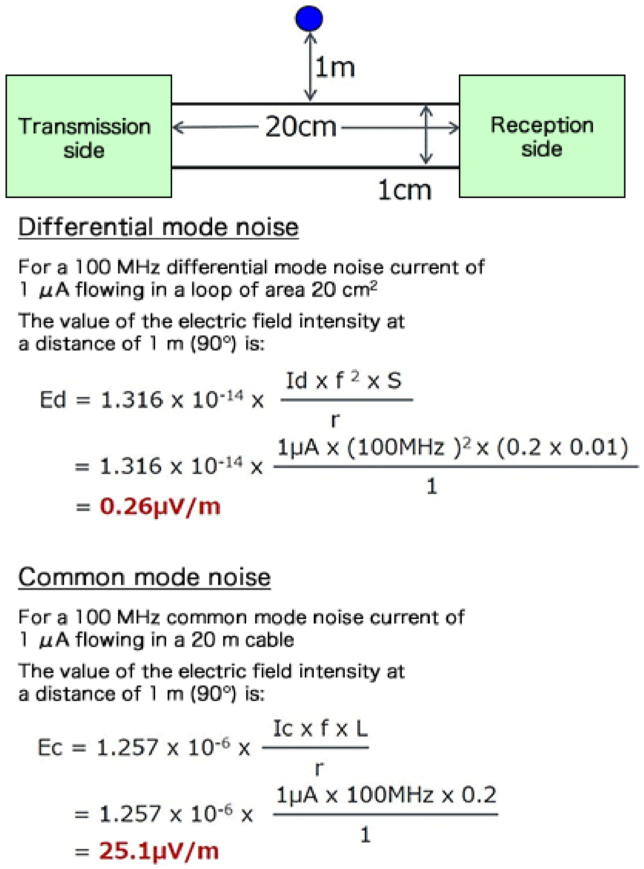

Figure 13. Example of calculating the electric field strength of each noise

<Summary>

- Electromagnetic interference or EMI is broadly divided into "conducted emission" and "radiated emission".
- Conducted emission can be further classified into two types, differential (normal) mode noise, and common mode noise.
- With respect to radiation caused by conducted emission, the important factors are the loop area of the line in the case of differential mode noise, and the line length in the case of common mode noise.
- It should be born in mind that under the same conditions, radiation due to common mode noise is far greater than that due to differential mode noise.

1.5 What is Crosstalk?

Crosstalk is the transmission of signals and noise due to coupling between lines, and is also called interference. The term "crosstalk" itself is evocative of the age of analog telephony, and of "talking across lines". If two wires are separate (including the thin film wiring on a PCB), then electrical signals and noise should not propagate between them, but if two lines are parallel, in particular, the stray (parasitic) capacitance and mutual inductance that exists between the two lines results in noise transmission. Hence crosstalk is regarded as inductive noise.

Coupling between lines can be capacitive (electrostatic) coupling due to the stray (parasitic) capacitance, or can be inductive (electromagnetic) coupling resulting from the mutual inductance. As a result of these, noise is induced. Figures 14 and 15 are illustrations of the two types of coupling and the simplest equivalent circuits in each case.

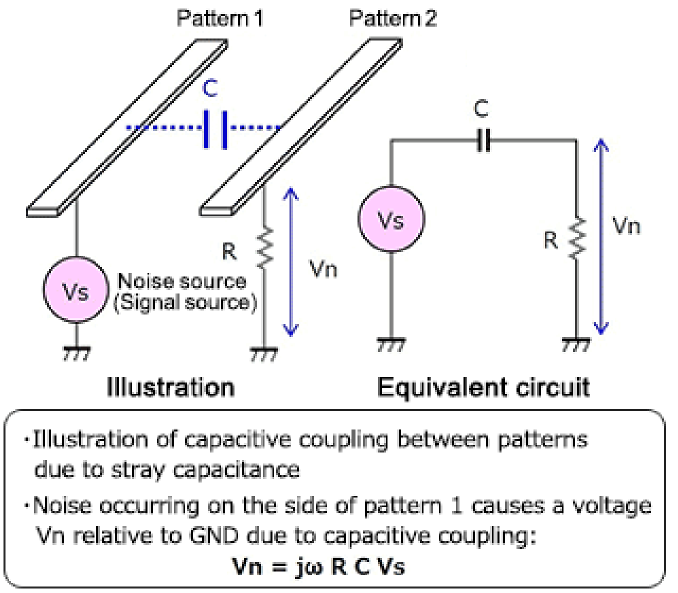

Figure 14. Crosstalk: capacitive coupling

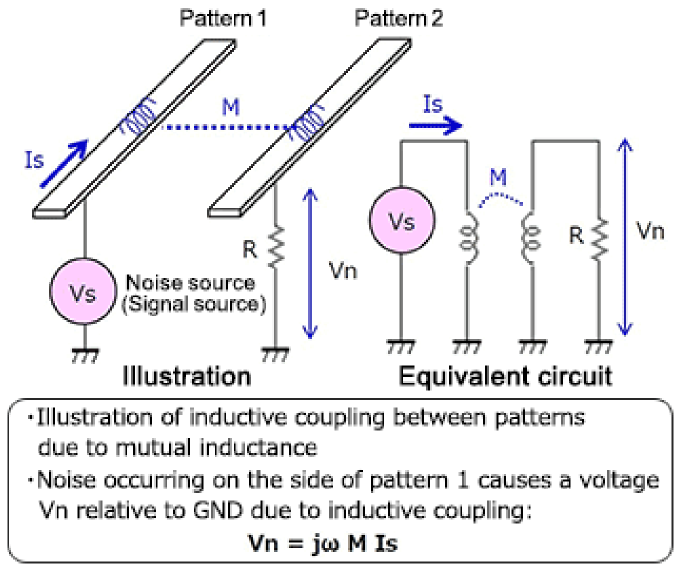

Figure 15. Crosstalk: inductive coupling

In both cases, equations*2 are indicated for the noise voltage Vn that occurs in nearby wiring pattern 2 due to noise in wiring pattern 1, which is a nearby noise source. R is the resistance component, C is capacitance, M is mutual inductance, Vs is the noise source voltage, and Is is the noise source current. *2. Equation for Vn excerpted from: Electromagnetic Compatibility Engineering, Author: Henry W. Ott, Publisher: John Wiley & Sons

<Summary>

- Crosstalk occurs between parallel wires.
- The causes of crosstalk are capacitive (electrostatic) coupling due to stray (parasitic) capacitance, and inductive (electromagnetic) coupling due to mutual inductance.

1.6 Noise Occurring in Switching Power Supplies

To begin with, we use the equivalent circuit for a synchronous step-down DC/DC converter to confirm switching current paths.

We label the high-side switch SW1, and the low-side switch SW2.

When SW1 is ON (and SW2 is OFF), the current path runs from the input capacitor to SW1, and passes through the inductor L before reaching the output capacitor (Figure 16).

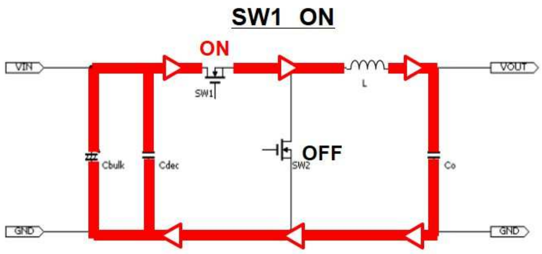

Figure 16. Equivalent circuit of synchronous rectifier step-down DC/DC converter: Current path when SW1 (high-side switch) is ON

When SW2 is ON (SW1 is OFF), the path is from L through the output capacitor to SW2 (Figure. 17).

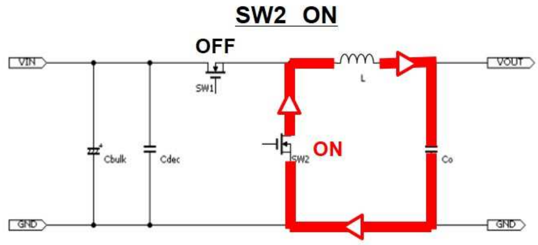

Figure 17. Equivalent circuit of synchronous rectifier step-down DC/DC converter: Current path when SW2 (low-side switch) is ON

In Figure 18, each time the switches are turned ON/OFF, the current in the path indicated by the red line that is the difference between the above two paths changes abruptly.

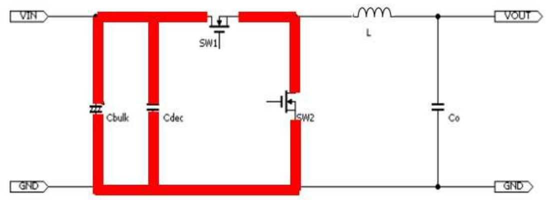

Figure 18. Equivalent circuit of synchronous rectifier step-down DC/DC converter: Difference of current paths between Figure 16 and 17

Because the change in current in this loop is sharp, high-frequency ringing occurs in the loop due to the inductance of the PCB wiring. The voltage generated can be calculated using the following equation.

$$V = L \times \frac{dI}{dt}$$

For example, if a current of 1A changes in 10ns in a wiring with an inductance component of 10nH, a voltage of 1V will be generated.

In Figure 19, we indicate the relationship between ringing and the parasitic components of the external components and the mounting board that constitute a power supply circuit.

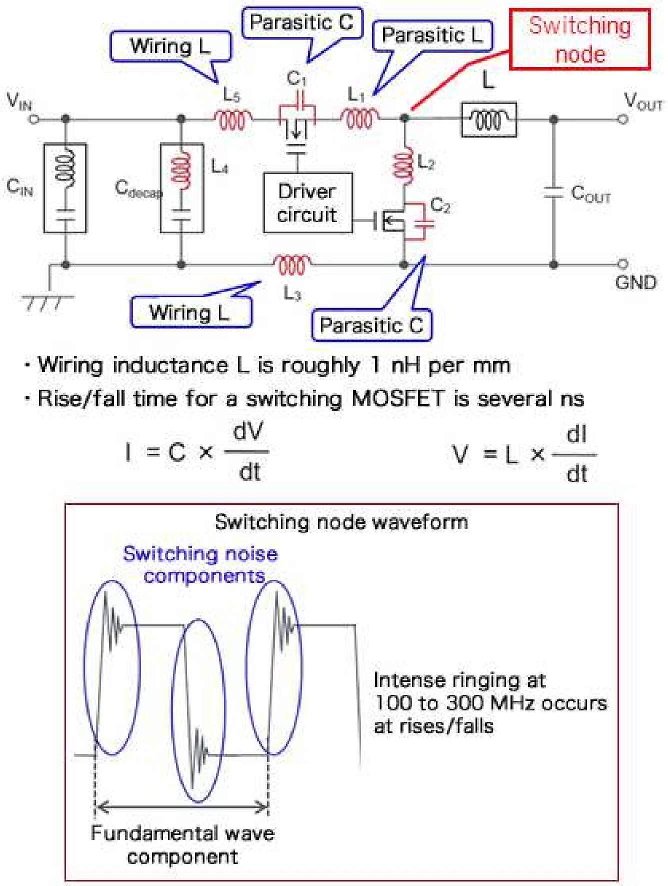

Figure 19. Relationship between parasitic components and ringing of external components and mounted boards that make up the power supply circuit

The parasitic components in the loop with rapidly changing current shown in Figure 18 are shown in red. In any wiring there is a wiring inductance, and in general the inductance is about 1 nH per mm of wiring. Moreover, an equivalent series inductance ELS is present in a capacitor, and a parasitic capacitance exists between the terminals of a MOSFET. These cause ringing of 100MHz to 300MHz at the switch node, as shown in the waveform diagram in the red frame of Figure 19. The generated current and voltage can be calculated by the two equations shown in Figure 19.

This ringing exerts various effects as high-frequency switching noise. In particular, the switching noise component that remains even after optimizing the loop conducts to the power supply side as common mode noise (Figure 20).

Of course, measures to address it can be taken, but parasitic components on the mounting board cannot all be eliminated through power supply ICs, and so innovations are necessary in the PCB wiring layout and through decoupling capacitors.

＜Summary＞

- In a loop in which currents are suddenly turned on and off during switching, high-frequency ringing (switching noise) occurs due to parasitic components.
- This switching noise can be reduced through optimization of the PCB wiring and other measures, but the noise that remains is conducted to an input power supply as common mode noise, and so measures to prevent leakage are necessary.

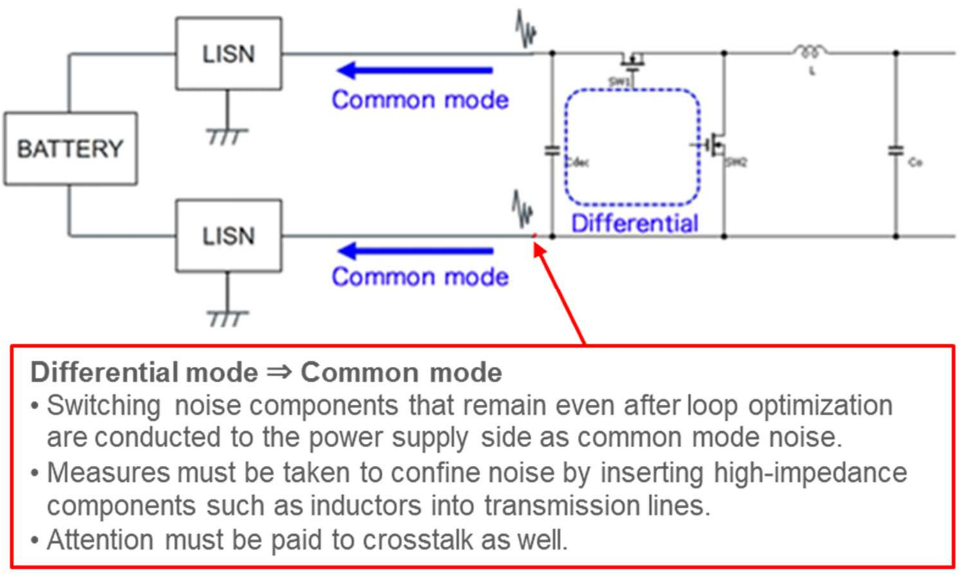

Figure 20. Noise occurring in switching power supplies

2. Noise Countermeasures for Switching Power Supplies

Before going into the explanation of actual noise countermeasures, an overview of countermeasure procedures and the basics of countermeasures will be given.

2.1 Noise Countermeasures and Product Development Phase

First, let us talk about at what stage of the process from product design/development to mass production noise countermeasures should be taken. Figure 21 shows an image of the degree of freedom of noise countermeasures, that is, the number of countermeasure options that can be taken, and the cost of the countermeasures against the time axis of design/development, evaluation, and mass production. The vertical axis should be seen as "high" as you go up.

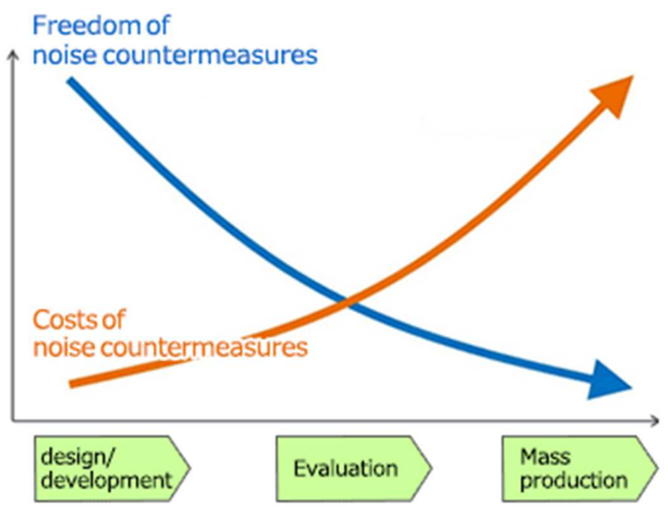

Figure 21. Noise Countermeasures and Product Development Phase

Figure 21 illustrates the fact that as development advances, the techniques and means that can be used to address noise become limited, and that the costs of countermeasures rise inexorably. If a noise problem is discovered only after mass production is begun, there are few options available; all that remains are highly undesirable measures such as modifying boards and the like.

As a basic rule, by conducting through studies and evaluations in the initial stage of product development, any noise problems that are discovered can be addressed with plenty of margin for error. It is also essential that noise types and properties be understood, and that effective countermeasures be employed for the respective types of noise. If measures are taken haphazardly, in many cases no effect may be observed, and the situation may even be worsened.

2.2 Procedures in Noise Countermeasures

As stated above, random countermeasures may merely worsen the problem. A number of procedures must be taken before a measure can be finalized. An example is presented below.

- Step 1: Ascertain the frequency components of the switching waveform

It is necessary to determine the frequency components of various phenomena that occur together with the fundamental wave--the switching frequency, rising and falling edges, overshoot/undershoot, ringing, and the like. This is because the countermeasures and components to be used will differ depending on the frequency of the noise that is to be addressed, and if appropriate methods and components are not selected, an improvement cannot be expected.

- Step 2: Ascertain the sources of the noise and the conduction paths

Determine the paths of conduction of the switching noise that is occurring on the primary side, or on the secondary side. Noise countermeasures must be implemented along the paths of noise conduction. Moreover, measures must be taken for all the conduction paths. If even one conduction path is overlooked, the countermeasure will be incomplete.

- Step 3: Ground reinforcement

The final step in taking noise countermeasures is adding components to deal with the noise, but prior to this, reinforcement of the PCB (printed circuit board) ground should also be studied. A capable ground design is important not only for noise countermeasures, but for boosting performance and improving stability as well. Improved ground design can reduce loop impedance. Moreover, ground reinforcement is also effective for enhancing the effect of filters.

- Step 4: Add filters or other components to address the noise

Finally, components for dealing with noise are studied and are added to the circuit--filters for attenuation, capacitors for noise bypass, chip beads and other resistive components to absorb noise, and so on, according to the type and properties of the noise. The effect of filters and bypass capacitors will differ according to the quality of the circuit ground, as explained in Step 3, and so ground reinforcement should always be performed beforehand.

＜Summary＞

- The further along product development advances, the more the techniques and means available to address noise are limited, and the more expensive the available options become.
- By conducting thorough studies and evaluations early in the product development stage, it is possible to implement noise countermeasures with a considerable margin for error.
- It is extremely important that noise types and properties be understood, and that measures suited to the respective noise types be implemented.
- Noise countermeasures are implemented through the procedures of first ascertaining frequency components, then grasping the sources and conduction paths of the noise, then reinforcing the circuit ground, and finally adding components to deal with the noise.

2.3 Basics of Noise Countermeasures in Switching Power Supplies

Figure 22 summarizes the basic countermeasures against basic noises such as differential noise, common mode noise, and crosstalk.

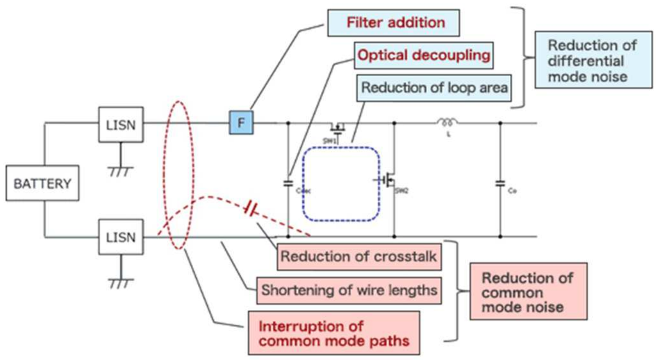

Figure 22. Basic countermeasures for fundamental noise

In order to reduce differential mode noise (shown in blue), in addition to decreasing the area of the loops of large-current paths on the circuit board, optimized decoupling and an input filter are added. It is important that differential mode noise, which is a noise source, be suppressed insofar as possible, and this also results in reduction of common mode noise.

On the other hand, methods to reduce common mode noise (shown in red) include shortening wires to suppress crosstalk, and interrupting common mode paths (increasing the impedance).

The details of filter addition, decoupling, and common mode path blocking (common mode filter), indicated by red letters in the figure, are described below.

＜Summary＞

- In order to reduce differential mode noise, the area of the loops of large-current paths is decreased, and optimal decoupling and an input filter are added.
- It is important that differential mode noise, which is a noise source, be suppressed to the extent possible; this will result in reduced common mode noise as well.
- To reduce common mode noise, wires are shortened to suppress crosstalk, and common mode paths are interrupted (filtered).

2.4 Input Filters for Switching Power Supplies

As input filters for switching power supplies, filters with characteristics suited to dealing with common mode noise and with differential noise respectively are used.

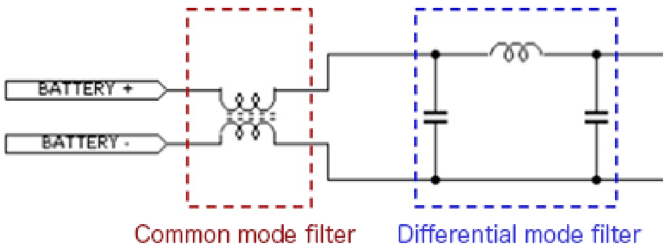

Figure 23. Representative Power Supply Input Filters

●Differential Mode Filters

Differential mode filters employ capacitors, inductors, ferrite beads, and resistors. The example shown is an Notes-type filter using an inductor and capacitors. These components act on noise components as follows.

- Capacitors: Bypass noise currents to ground.
- Inductors: Reflect noise currents.
- Ferrite beads: Inductive component reflects low-frequency noise currents, and resistive component converts higher-frequency noise currents into heat.
- Resistors: Convert noise currents into heat.

●Common Mode Filters

To address common mode noise, a common mode filter (common mode choke) is used. Common mode filters can be broadly divided into filters for power supply lines and filters for signal lines. In general, common mode filters for power supply lines are used in the inputs to switching power supplies. The impedance of paths in which common mode currents flow is raised to shut out the common mode noise.

<Summary>

- Input filters for switching power supplies are provided to address common mode noise and differential mode noise respectively.
- To address differential mode noise, a filter is constructed from components such as capacitors, inductors, beads, and resistors.
- Common mode filters are used to handle common mode noise.

3. Noise Countermeasures Using Capacitors

In the previous chapter, we explained that capacitors, inductors, ferrite beads, and resistors are used in differential mode filters for the input stage of switching power supplies. From here, we discuss measures to address noise using capacitors and inductors, explaining what might be called the fundamentals of noise countermeasures. Here we use a simple four-element model. In order to represent resonances at still higher frequencies, models based on still more elements may be used. The first one is capacitors.

3.1 Frequency Characteristics of Capacitors

When using capacitors to handle noise problems, a good understanding of the capacitor characteristics is essential. Figure 24 shows the relationship between capacitor impedance and frequency, and is a characteristic that is basic to any capacitor.

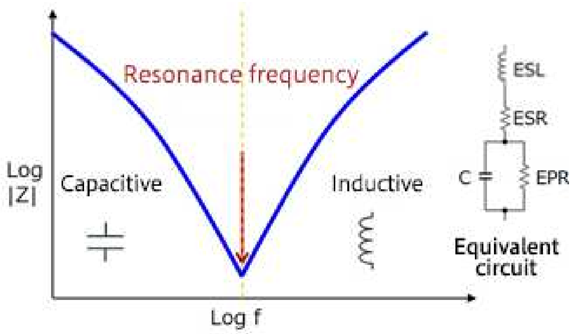

Figure 24. Example of frequency response of a capacitor

In addition to the electrostatic capacitance C of the capacitor, there are also the resistive component ESR (equivalent series resistance), the inductive component ESL (equivalent series inductance), and the EPR (equivalent parallel resistance), which exists in parallel with the electrostatic capacitance. The EPR means that there is an insulating resistance IR between electrodes, or that there is a leakage current between electrodes. It may be that the term IR is generally used.

C and ELS form a series resonance circuit, and the impedance of the capacitor has what is essentially a V-shape frequency characteristic, as shown in the diagram. Up until the resonance frequency, the capacitive characteristic is exhibited, and the impedance falls. The impedance at the resonance frequency depends on the ESR. When the resonance frequency is exceeded, the impedance characteristic changes to inductive, and as the frequency rises, the impedance increases. The inductive impedance characteristic depends on the ESL. The resonance frequency can be calculated using this equation:

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

This equation indicates that the smaller the electrostatic capacitance and the smaller the ESL of a capacitor, the higher is the resonance frequency. When applying this to the elimination of noise, a capacitor with a smaller capacitance and smaller ESL has a lower impedance at a higher frequency, and so is better for removing high-frequency noise.

The order of the explanation here is reversed, but noise countermeasures that employ capacitors make use of the basic capacitor characteristic of "passing AC currents, and passing them more easily at higher frequencies". Capacitors are thus used to shunt unwanted noise (AC components) away from signals or power supply lines to ground, for example.

Figure 25 shows the frequency characteristics of the impedance of capacitors with different electrostatic capacitances. In the capacitive characteristic region, the larger the capacitance, the lower is the impedance. Moreover, the smaller the capacitance, the higher is the resonance frequency, and the lower is the impedance in the inductive characteristic region.

Put simply, capacitors with lower impedance are better at removing noise, but the frequency characteristic of the impedance depends on the capacitor, and so it is important to verify the capacitor characteristics. When selecting capacitors for use in dealing with noise, one should select the device according to the frequency characteristic of the impedance rather than the capacitance.

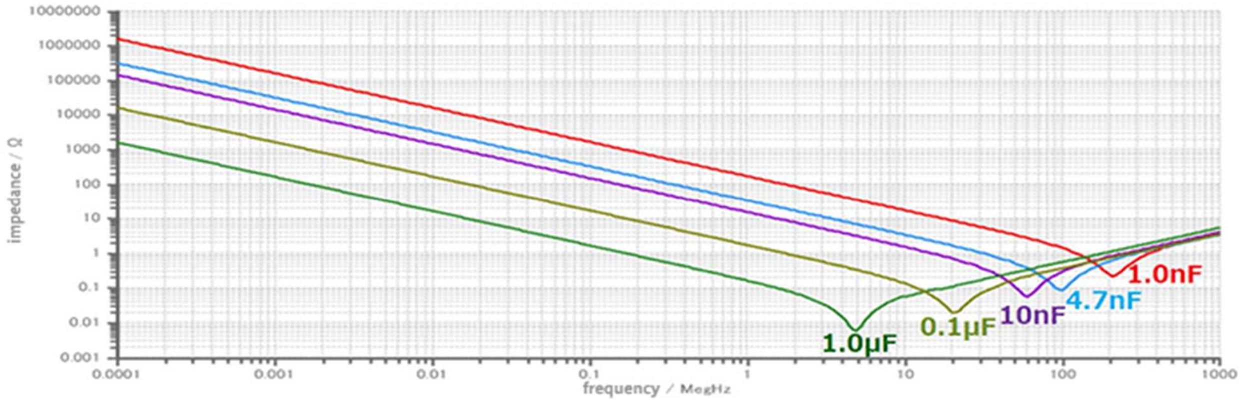

Figure 25. Comparison of frequency characteristics of capacitors with different

An important point when selecting a capacitor as a noise countermeasure is to consider it not as a capacitance, but as a series resonance circuit of LC, and to look at the frequency characteristics.

<Summary>

- Capacitors for use in dealing with noise should be selected based on the frequency characteristic of the impedance rather than the capacitance.
- When the capacitance and the ESL are smaller, the resonance frequency is higher, and the impedance in the high-frequency region is lower.
- The larger the capacitance, the lower is the impedance in the capacitive region.
- The smaller the ESR, the lower is the impedance at the resonance frequency.
- The smaller the ESL, the lower is the impedance in the inductive region.

3.2 Measures to Address Noise Using Capacitors

There are various types of noise, having a wide variety of characteristics. Hence there are also various noise countermeasures, that is, methods for reducing noise. Here we are essentially considering noise relating to switching power supplies, and so the reader should assume high-frequency noise with comparatively low voltage levels, present in DC voltages. Moreover, in addition to capacitors, Zener diodes, suppressors for noise, surge or ESD and the like are also used to deal with noise. There are various components to deal with noise according to the noise properties; when DC/DC converters are assumed, due to the circuits and voltage levels involved, in many cases LCR circuits are used.

Figures 26 and 27 are an example in which the noise in the output voltage of a DC/DC converter is suppressed through addition of capacitors.

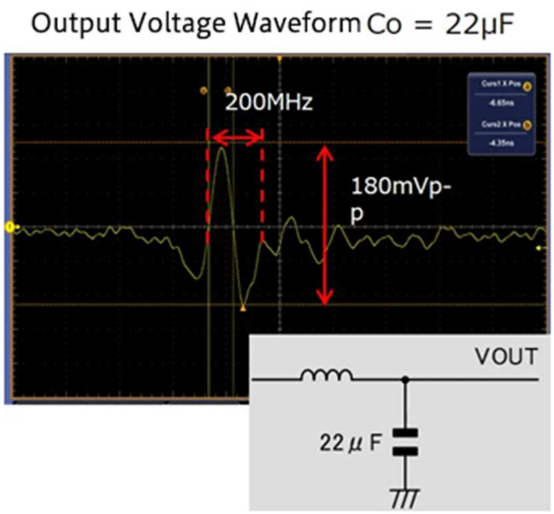

Figure 26. Output LC filter with C of 22 μF

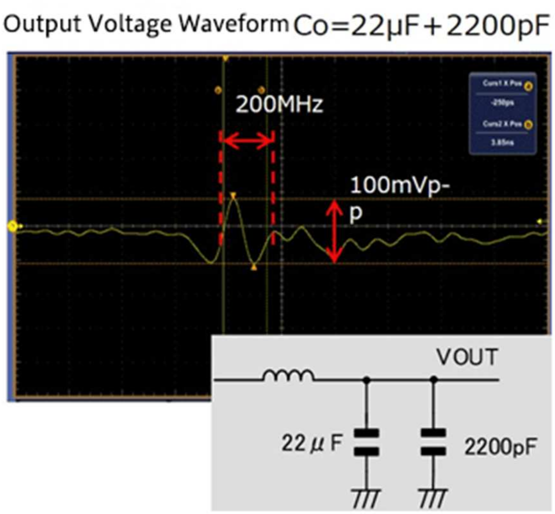

Figure 27. Adding 2200 pF to the output LC filter

The waveform in Figure 26 is for a case in which the capacitor of the output LC filter is 22 μF; there is noise (ringing, reflection) at about 200 MHz with an amplitude of 180 mVp-p. In order to reduce this noise, a 2200 pF capacitor was added; the result is the waveform in Figure 27. By adding the 2200 pF capacitor, the noise was attenuated to about 100 mV.

What the reader should be asking here is, "why 2200 pF?" The frequency characteristic of the impedance of the added capacitor is shown in Figure 28.

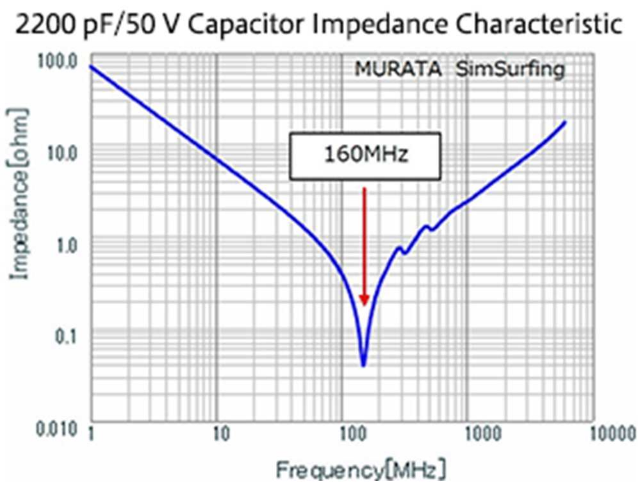

Figure 28. Impedance characteristics of the added 2200 pF capacitor

As the graph in Figure 28 shows, the impedance is lowest near 160 MHz; the reason for selecting this 2200 pF capacitor was to utilize this impedance characteristic in order to attenuate the noise amplitude at about 200 MHz.

In this approach, by adding the capacitor so as to lower the impedance at the frequency of the noise being targeted, the noise amplitude is reduced. When thus adding a capacitor to reduce noise, it is necessary to ascertain the frequency of the noise (ringing, reflection), and then select a capacitor having a corresponding impedance frequency characteristic.

＜Summary＞

- Noise amplitudes can be reduced by lowering the impedance at the frequency of the targeted noise.
- A capacitor to be used to address noise is selected for its impedance frequency characteristic rather than for its capacitance value.

3.3 Effective Use of Decoupling Capacitors: Point 1

There are two main points and a few precautions to be taken in order to use decoupling capacitors effectively.

The first point is that there are ways to decouple with multiple capacitors instead of just one. When using multiple capacitors, the effect is different when using capacitors with the same capacitance and when using a combination of capacitors with different capacitance values.

- When using multiple capacitors with the same capacitance value

The graph in Figure 29 indicates the frequency characteristics for cases in which a single 22 μF capacitor is used (blue), in which another such capacitor is added (red), and in which still another is added, to use three capacitors (purple).

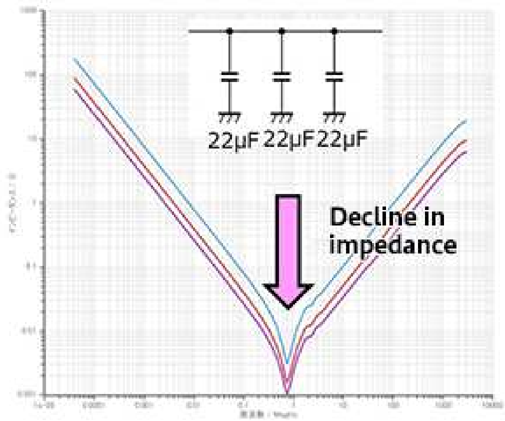

Figure 29. Using multiple capacitors with the same capacitance

As the graph indicates, when capacitors with the same capacitance value are added, the impedance is shifted downward, that is to say, the impedance is lowered, over the entire frequency range.

This can be understood when one considers the capacitive characteristic up to the resonance point when capacitors with the same value are connected in parallel, the fact that the resonance-point impedance depends on the ESR (equivalent series resistance), and the inductive characteristic due to the ESL (equivalent series inductance) beyond the resonance point.

Capacitances connected in parallel are additive, and so when three such capacitors are connected the capacitance is 66 μF, and the impedance in the capacitive region decreases.

The ESRs of three capacitors are connected in parallel, and so the impedance at the resonance point is $\frac{1}{ESR_1}+\frac{1}{ESR_2}+\frac{1}{ESR_3}$, and if the ESR values of all the capacitors are assumed to be the same, then the ESR is reduced to 1/3 and the impedance is also reduced.

The ESLs of the capacitors in the inductive region beyond the resonance point are also in parallel, so that $\frac{1}{ESR_1}+\frac{1}{ESR_2}+\frac{1}{ESR_3}$ results, and if the ESL values of the three capacitors are all the same, the ESL is reduced to 1/3 and the impedance is also reduced.

In this way, by using multiple capacitors with the same value, the impedance can be lowered over the entire frequency range, and so noise can be further attenuated.

- When using multiple capacitors with different capacitance values

Figure 30 is the frequency characteristic for a case in which capacitors with values of 22 µF, 0.1 µF, and 0.01 µF are added in parallel.

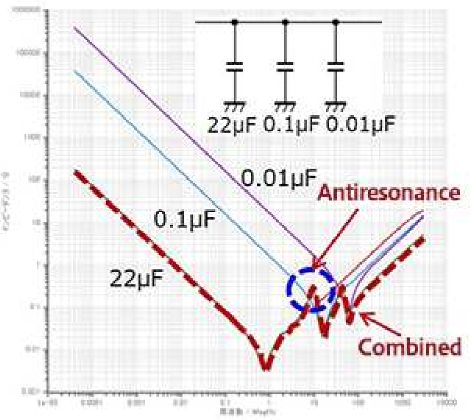

Figure 30. When using multiple capacitors with different capacitance values

By adding a capacitor with a small capacitance, the impedance at high frequencies can be lowered. The frequency characteristics of 0.1 µF and 0.01 µF capacitors are combined with the characteristic of a lone 22 µF capacitor, resulting in the characteristic shown (broken red line).

What requires attention here is the fact that an antiresonance may occur depending on the frequency, so that impedance is increased rather than decreased, and the EMI is worsened.

An antiresonance occurs at the point at which the capacitive characteristic and the inductive characteristic intersect.

In general, the value of a capacitance to be added is selected according to the frequency of the noise to be reduced.

The frequency characteristic diagrams shown here are ideal examples, and parasitic components due to pattern wiring in the circuit board and the like have not been considered. When taking actual measures to counter noise, the effects of parasitic components must be included.

3.4 Effective Use of Decoupling Capacitors: Point 2

The second point in the effective use of decoupling capacitors is the approach of lowering the capacitor ESL, or equivalent series inductance. However, the ESL of a capacitor cannot itself be changed, and so lowering the ESL in effect means using a capacitor with the same electrostatic capacitance, but with a lower ESL. By lowering the ESL, the high-frequency characteristics are improved, and high-frequency noise can be more effectively decreased.

- Using a capacitor that has the same value but is smaller in size

Some multilayer ceramic capacitors (MLCCs) are made available as products having the same capacitance value, but in different-size packages. The ESL depends on the structure of the terminal portions. Smaller-size capacitors necessarily have smaller terminals, and so normally the ESL is smaller.

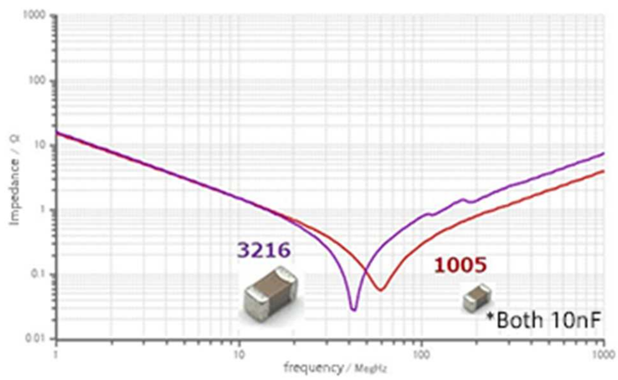

Figure 31. Frequency characteristics of capacitors with the same capacitance but different sizes

The graph in Figure 31 is an example of the frequency characteristics of capacitors having the same value but different sizes. As indicated in the graph, the resonance frequency is higher for devices of size 1005, and the impedance is lower even at frequencies in the inductive region beyond this. As explained in "3.1 Frequency Characteristics of Capacitors", this is because, from the equation for the capacitor resonance frequency shown below, for a given capacitance value, a lower ESL means a higher resonance frequency. Moreover, as previously explained, the impedance characteristic in the inductive region also depends on the ESL.

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

● Using a capacitor with a lowered ESL

Among multilayer ceramic capacitors, there are types the ESL of which is lowered through innovations in the shape and structure.

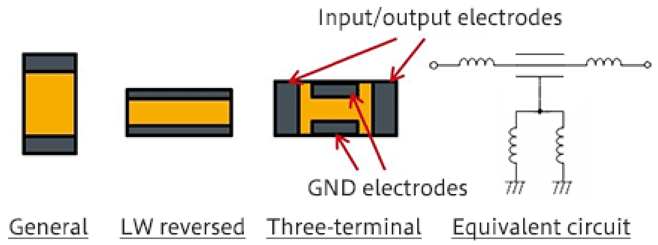

Figure 32. A standard capacitor and a capacitor with reduced ESL

As shown in Figure 32, capacitors generally have electrodes on the short-edge sides; in contrast, LW reversed type capacitors have the electrodes on the long-edge sides. The name derives from the fact that the length (L) and the width (W) edges are reversed. By increasing the electrode width, the ESL is lowered.

A three-terminal capacitor is a capacitor obtained by modifying structure of a general (two-terminal) capacitor to improve the frequency characteristic. In a three-terminal capacitor, the other end of one of the terminals (electrodes) of a two-terminal capacitor is passed to the outside as a feed-through terminal, and the other terminal is used as a ground terminal. In the diagram above, the input/output electrodes correspond to a penetrating terminal both ends of which are drawn out, and the left and right electrodes are of course conducting. A dielectric is present between the input/output electrodes (feed-through terminals) and the ground electrode, so that the device functions as a capacitor.

The input/output terminals are connected in series with a power supply and a signal line (one of the input/output terminals is connected to the input side, and the other is connected to the output side), and the GND electrode is connected to ground. As a result, the ESL of the input/output terminals is not included on the ground side, and so the ground impedance is extremely low. Moreover, series insertion into the noise path means that the ESL of the input/output terminals contributes to reduce noise (increase the insertion loss). The ground electrodes are placed in pairs on the long side to keep the ESL small, and since they are connected in parallel, the ESL is halved.

Using such a structure, a three-terminal capacitor can be designed with the ESR held low in addition to the extremely small ESL, the frequency characteristic can be improved dramatically compared with a two-terminal capacitor having the same capacitance value.

3.5 Effective Use of Decoupling Capacitors: Matters to be Noted

To use decoupling capacitors effectively, there are a few things to keep in mind.

① Ceramic capacitors with a high Q factor

Capacitors have a characteristic value called a Q factor, or simply Q. Figure 33 shows the relationship between Q and the frequency-impedance characteristic.

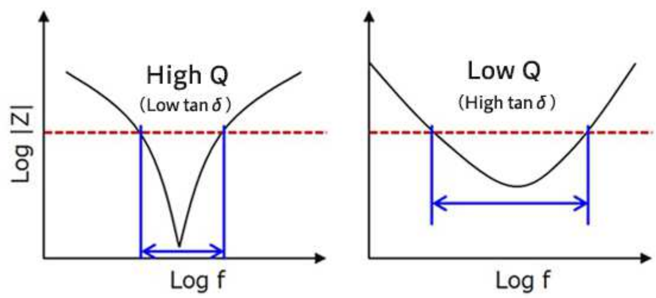

Figure 33. Relationship between Q and frequency-impedance characteristics of a capacitor

When Q is high, the impedance becomes extremely low in a specific narrow band. When Q is low, the impedance does not fall in this extreme manner, but the impedance can be lowered over a broad band. This characteristic is useful for conformance to a specific EMC standard. For example, when using a capacitor that has large variation in the electrostatic capacitance, if the Q factor is high, there is the possibility that the capacitor cannot eliminate noise at the targeted frequency. In such cases, there is the option of using a low-Q capacitor to suppress the effect of such variation.

② PCB patterns such as thermal relief

Thermal relief and other PCB patterns, which are used with the goal of improving heat dissipation characteristics at mounting, increase the inductance component of the pattern. The increase in the inductance component causes the resonance frequency to be shifted to the low-frequency side, and so in some cases the desired noise elimination effect is not obtained.

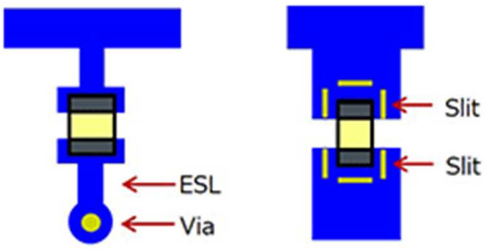

Figure 34. Increase in ESL due to PCB patterns such as thermal relief

③ Virtual capacitor mounting when studying countermeasures

After prototyping, measures to counter high-frequency noise are necessary, and the addition of small-value capacitors may be studied. At this time, if capacitors are mounted on a large-value capacitor as shown in the example on the left of Figure 35, an excess inductance component is added in the vertical direction, and so the effect of adding the capacitors is not adequately exhibited. In the center example, although not conflicting with the reasoning that "small-value capacitors are brought as close as possible to a noise source", in actuality the impedance differs from that of the PCB layout for modification. The best method is to study the possibility of placing the capacitors as close as possible to where the modification is actually to be made (example on the right).

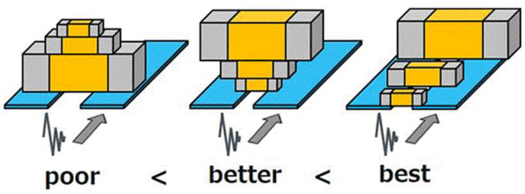

Figure 35. Virtual capacitor mounting when studying countermeasures

It is also possible that a noise countermeasure may be sufficient at the time of noise tests, but ultimately be inadequate when mounted on the modified PCB. Hence actual mounting must be taken into consideration from the start.

④ Capacitance change rate of capacitors

If the capacitance change rate of a capacitor used to deal with noise is high, there may be large fluctuations in the resonance frequency, so that fluctuations and variation may occur in the band to be attenuated, and it may be difficult to achieve the intended noise suppression. Noise countermeasures that require large attenuation in a narrow band require special attention. Table 2 indicates actual capacitance values for different capacitance change rates and the resulting resonance frequency. The table indicates that, depending on conditions of use, there are many cases in which changes in capacitance cannot be tolerated.

Capacitance change rate (%)	Capacitance (pF)	Resonance frequency (MHz)
+20	1,200	145
+10	1,100	152
±5	1,050	155
±0	1,000	159
-5	950	163
-10	900	168
-20	800	178

Table 2. Capacitance change rate, capacitance and resonant frequency (calculated assuming L = 1 nH)

⑤ Temperature characteristics of capacitors

It is well known that the characteristics of capacitors fluctuate with temperature. At present, there aren't standardized EMC tests with temperature characteristics, but there are capacitors that, depending on the application, must be used at high or at low temperatures, or that are used under conditions and in environments in which large temperature changes occur.

In such cases, there is a high probability of the occurrence of problems such as those described in ④ above, on the capacitance change rate, and so care must be taken to use capacitors with better temperature characteristics, such as those with CH or C0G characteristics, for noise countermeasures, insofar as possible.

3.6 Effective Use of Decoupling Capacitors: Summary

This is a summary of Effective Use of Decoupling Capacitors.

● Point 1: Use of Multiple Decoupling Capacitors

In decoupling using multiple capacitors, the effects are different when using several capacitors having the same electrostatic capacitance and when using capacitors with different capacitances in combination.

■ When using multiple capacitors with the same capacitance value

The impedance is lowered over all frequency ranges; effective for reducing noise overall.

■ When using multiple capacitors with different capacitance values

The impedance can be lowered at higher frequencies; effective for reducing high-frequency noise. However, antiresonance may occur depending on the frequency, and conversely, the impedance may rise and noise may grow worse, so care must be taken.

● Point 2: Reducing the Capacitor ESL

If capacitances are the same, the lower the ESL, the higher the resonance frequency rises. Thus, reducing the ESL can improve the high-frequency characteristic, and high-frequency noise can be reduced more effectively.

■ Using a capacitor that has the same value but is smaller in size

The ESL depends on the structure of the terminal portions; basically, smaller-size capacitors have smaller terminals, and so the ESL is normally smaller. When noise must be reduced at higher frequencies, selecting smaller-size capacitors is one option. However, attention must be paid to the DC bias characteristic.

■ Using a capacitor with a lowered ESL

Among multilayer ceramic capacitors, there are types the ESL of which is lowered through innovations in the shape and structure, such as LW reversed type capacitors and three-terminal capacitors.

● Effective Use of Decoupling Capacitors: Matters to be Noted

■ Ceramic capacitors with a high Q factor

When Q is high, the impedance becomes extremely low in a specific narrow band. When Q is low, the impedance does not fall in this extreme manner, but the impedance can be lowered over a broad band.

■ Thermal relief and other PCB patterns

Thermal relief and other PCB patterns at mounting, which are used with the goal of improving heat dissipation characteristics, increase the inductance component of the pattern. The increase in the inductance component causes the resonance frequency to be shifted to the low-frequency side, and so in some cases the desired noise elimination effect is not obtained.

■ Virtual capacitor mounting when studying countermeasures

When adding a small-value capacitor to deal with high-frequency noise, placement of the capacitor as close as possible to the place where actual correction is needed should be studied, based on the theory that low-capacitance capacitors should be located as close to the noise source as possible. If placement is different during studies and after correction, impedance may differ, and the characteristics expected from evaluations may not be attained.

■ Capacitance change rate of capacitors

If the capacitance change rate of a capacitor used to deal with noise is high, there may be large fluctuations in the resonance frequency, so that fluctuations and variation may occur in the band to be attenuated, and it may be difficult to achieve the intended noise suppression. Noise countermeasures that require large attenuation in a narrow band require special attention.

■ Temperature characteristics of capacitors

The characteristic of a capacitor changes with temperature, and so when it is obvious from the application that a capacitor will be exposed to high or low temperatures or to extreme temperature changes, a device with a good temperature characteristic should be used.

4. Noise Countermeasures Using Inductors

This section describes noise countermeasures using inductors, which are the second most important noise countermeasure component after capacitors, and ferrite beads, which are related components.

If the capacitor alone is not sufficient to eliminate the noise, consider using inductors and ferrite beads.

4.1 Frequency Characteristics of Inductors

First, we will briefly review the frequency characteristics of inductors as well as capacitors.

An inductor (coil) has the following basic characteristics, which is said to be an inductive reactance.

① An inductor passes a DC with essentially no change.

② An inductor has an impedance to AC.

③ The higher the frequency, the harder it is for an alternating current to flow.

Figure 36 is a schematic graph indicating the frequency-impedance characteristic of an inductor.

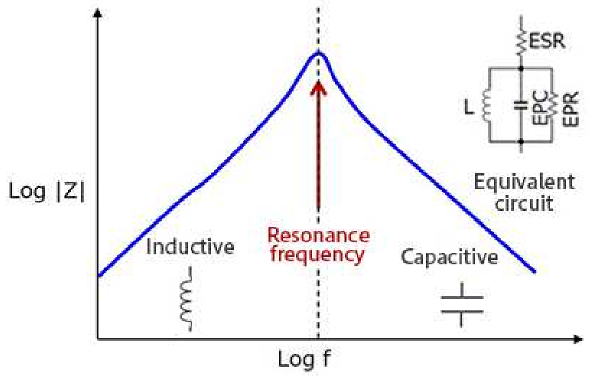

Figure 36. Frequency characteristics of an inductor

In an ideal inductor, the impedance rises linearly with rising frequency, but in actuality, as indicated by the equivalent circuit, a parasitic capacitance EPC is present in parallel with the inductor, and so a self-resonance phenomenon occurs.

Hence up to the resonance frequency, the inductive characteristic inherent in the inductor (in which the impedance increases as the frequency rises) is exhibited, but beyond the resonance frequency, the influence of the parasitic capacitance becomes dominant, and a capacitive characteristic (in which the impedance decreases as the frequency rises) is exhibited. In other words, in the frequency region above the resonance frequency, the device no longer functions as an inductor.

The resonance frequency of an inductor can be found from the following equation.

$$\mathrm{f} = 1/(2\pi\sqrt{(L \times EPC)})$$

The equation is the same as the equation for the resonance frequency of a capacitor, the only difference being whether a term as the subject is capacitance or an inductance. As is clear from the equation, as the inductance L decreases, the resonance frequency rises.

Parasitic components of an inductor include, in addition to the electrostatic parasitic capacitance EPC, the resistance component of the inductor windings ESR (equivalent series resistance), and an EPR (equivalent parallel resistance) in parallel with the electrostatic capacitance. The resistance components limit the impedance at the resonance point.

<Summary>

- An inductor exhibits an inductive characteristic (the impedance increases as the frequency rises) up to a resonance frequency.
- Beyond the resonance frequency, the inductor exhibits a capacitive characteristic (the impedance decreases as the frequency rises).
- At frequencies higher than the resonance frequency, the inductor does not function as an inductor.
- When the inductance L is small, the resonance frequency of the inductor is high.
- The impedance of an inductor at the resonance point is limited by parasitic resistance components.

4.2 Dealing with Noise Using Inductors

Inductors used for noise countermeasure are mainly of the wire-wound type, and basically constitute a π-type filter. π-type filters work as low-pass filters with an inductor and a capacitor in the low-frequency range.

However, at high frequencies, the inductor behaves as a capacitance and the capacitor behaves as an inductor, acting as a high-pass filter and thus not providing noise rejection (Figures 37, 38, and 39).

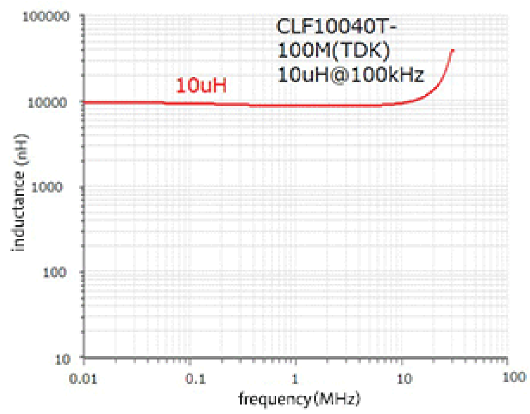

Figure 37. Inductance and frequency characteristics of an inductor

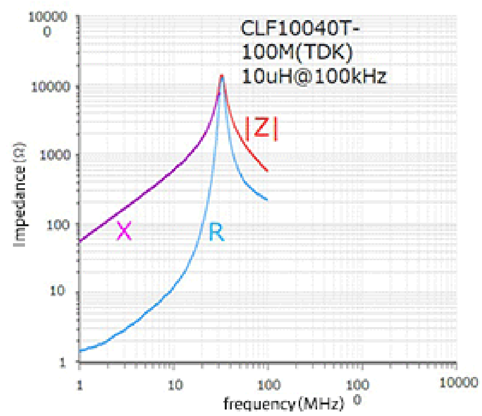

Figure 38. Impedance and frequency characteristics of an inductor

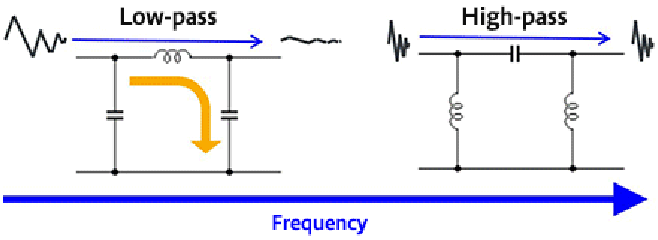

Figure 39. A π-type filter becomes a high-pass filter at high frequencies and does not provide noise reduction.

4.3 Dealing with Noise Using Ferrite Beads

First, we will review the basic characteristics of ferrite beads by comparing them to inductors. Although ferrite beads are classified as inductors, their frequency-impedance characteristics are different from those of common inductors (Figures 40 and 41).

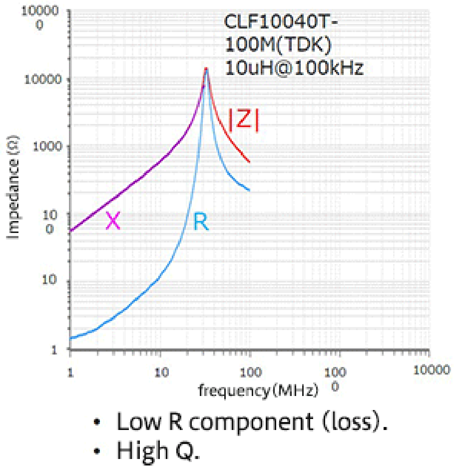

Figure 40: Impedance characteristics of an inductor

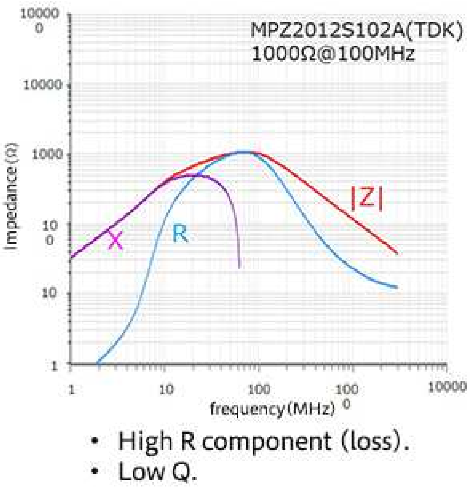

Figure 41: Impedance characteristics of ferrite beads

Compared with general inductors, ferrite beads have a high resistance component R and a low Q value. These characteristics can be utilized in noise elimination.

The direct current characteristics are also different (Figures 42 and 43).

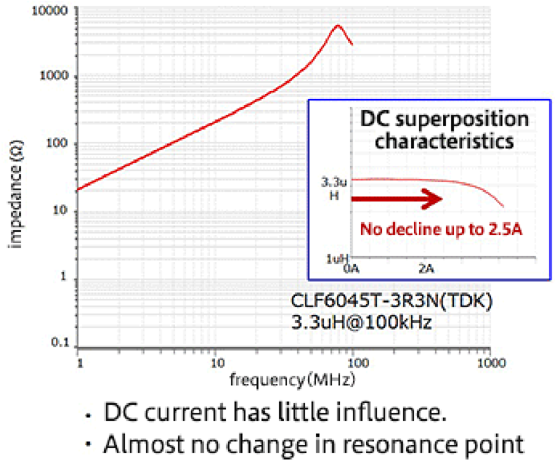

Figure 42. Impedance and DC superposition characteristics of inductors

Inductors generally can tolerate comparatively large DC superposition currents, and within this range the DC current does not have much of an effect on the impedance, with almost no change in the resonance point. In contrast, ferrite beads easily reach saturation due to a DC current, and saturation causes the inductance to fall and the resonance point to shift to higher frequencies. Consequently, the filter characteristics change, and so due caution is necessary.

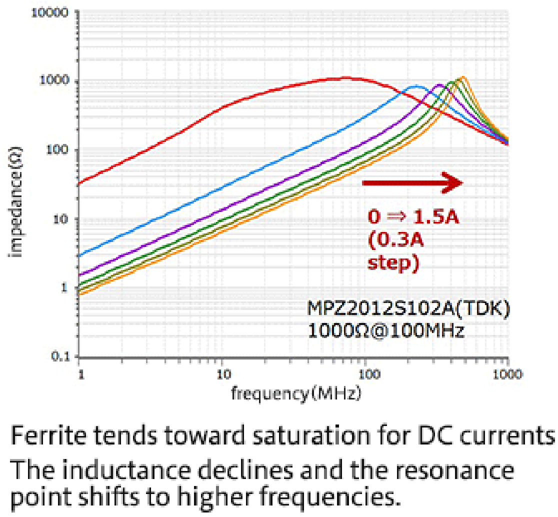

Figure 43. Impedance and DC superposition characteristics of ferrite beads

Based on these characteristics of ferrite beads, we will explain the noise countermeasures using ferrite beads. While inductors eliminate noise by forming a filter, ferrite beads eliminate noise by converting it into heat. This is the main difference, but ferrite beads also function as a low-pass filter in the low frequency range. However, in this region, as mentioned earlier, they tend to saturate against DC current, inductance decreases, and the resonance point moves to a higher frequency range, making it difficult to remove noise in the targeted band (Figure 44).

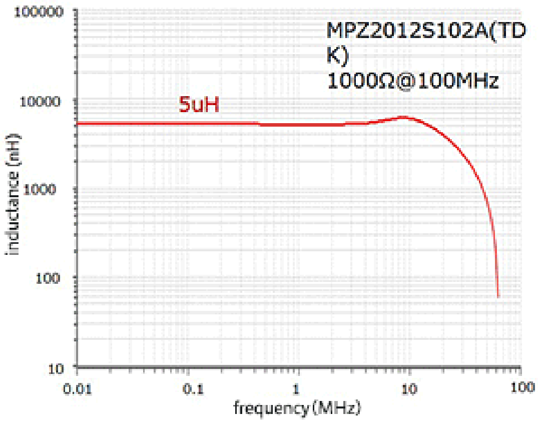

Figure 44. Inductance and frequency characteristics of ferrite beads

Referring to the graph in Figure 45, there is a point at which the reactance declines and crosses the resistance component. If the band exceeds this point, called the cross point, the ferrite bead functions as a resistor, and serves to convert noise into heat. This is a major difference from filters that use winding-type inductors. In still higher-frequency regions, the ferrite bead functions as a high-pass filter, similarly to a winding-type inductor (Figure 46).

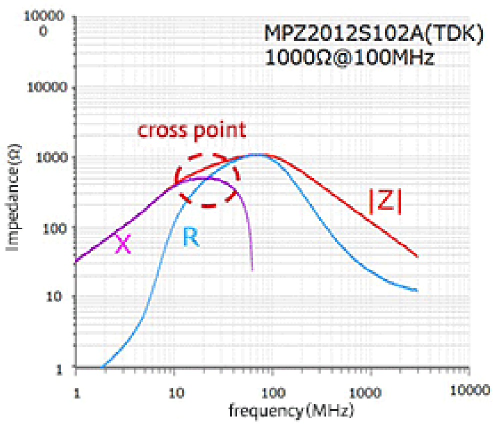

Figure 45. Frequency response and cross point of ferrite beads

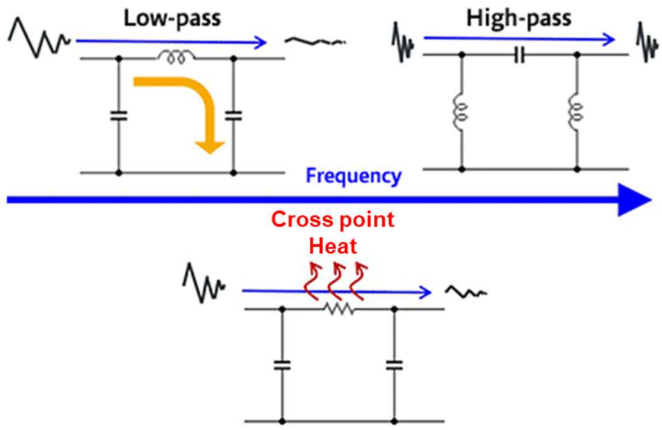

Figure 46. Noise reduction behavior of ferrite beads

Because filters that use ferrite beads convert noise into heat in addition to shunting noise away, they can be expected to provide excellent noise elimination performance. However, attention must be paid to their DC bias current characteristics.

4.4 Dealing with Noise Using Common Mode Filters

A common mode filter is not strictly an inductor, but it is a magnetic component and is important for noise countermeasures.

In a common mode filter, there are two windings on a single core, in a structure that is equivalent to two inductors merged together (Figure 47). When current flows in the windings, magnetic flux is generated in the core, and action in response to a sudden current change makes it difficult for current to flow (choke function). This is the same as the self-induction action of an inductor.

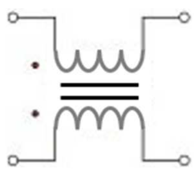

Figure 47. Schematic diagram showing the structure of a common mode filter

A common mode filter basically acts to pass a differential mode current without passing a common mode current. Here, the fact that two conducting wires are wrapped around one core in the same direction is important.

A differential mode current travels in both directions in the two wires, so that magnetic flux is generated in the core in opposite directions, thereby cancelling out. As a result, there is no action impeding the flow of current, which passes through the filter (Figure 48).

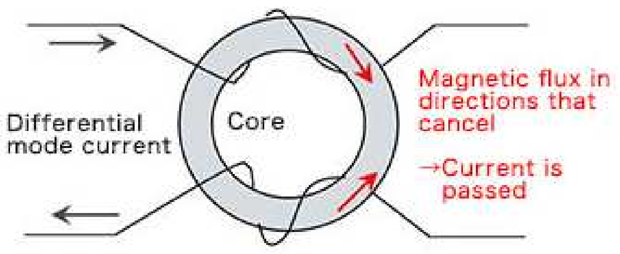

Figure 48. Differential mode current for common mode filter

On the other hand, a common mode current flows in the same direction, so that magnetic flux is intensified, and consequently current does not flow readily. In other words, a common mode current, which is common mode noise, is not easily passed, and is filtered out (Figure 49).

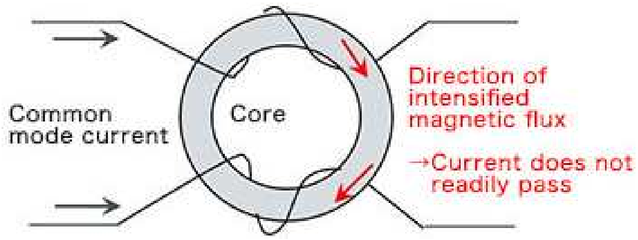

Figure 49. Common mode current for common mode filter

Now here is an example of using it as an input filter for a switching power supply.

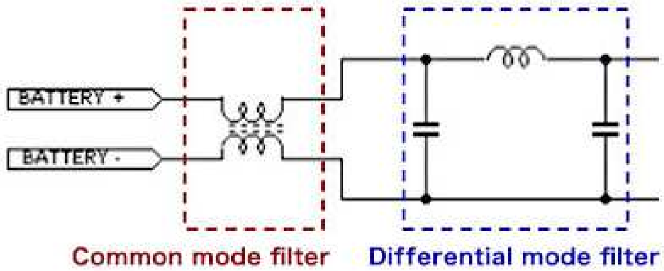

Figure 50. Example of an input filter for a switching power supply

The common mode filter is inserted against the input line of the power supply as shown in Figure 50. Compared with a common mode filter for a signal line, a common mode filter having a split-winding construction such that the differential mode impedance is higher is used as the common mode filter for a power supply line. Such components are commonly prepared as common mode filters for power supply lines, and an effect in attenuating differential mode noise can also be expected. However, because the differential mode impedance at frequencies from hundreds of kHz to several MHz is extremely low, in general π-type filters and other filters for differential mode noise are also used.

4.5 Dealing with Noise Using Inductors: Matters to be Noted

When constructing a filter using inductors or ferrite beads, depending on the component layout and the wiring pattern layout of the board, not only can the filter not provide sufficient noise rejection, but it can also make the situation worse by coupling the noise in the opposite direction. Crosstalk and noise from the ground line are explained as cautions related to the board layout.

● Crosstalk

In “1.5 What is Crosstalk?” it was explained that crosstalk results when stray capacitances and mutual inductances between wiring on a board cause noise to be coupled with other, adjacent board wiring. Below are shown examples of measures for dealing with crosstalk through LC filter pattern layouts and component arrangement.

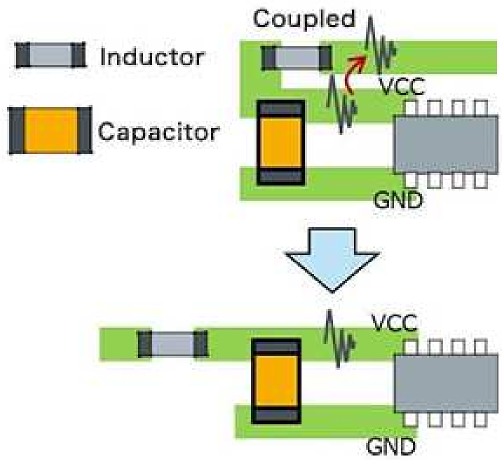

Figure 51. Example of crosstalk caused by PCB layout

In the upper layout of Figure 51, an LC filter is inserted in the VCC line, but because the wiring after the filter is close to unfiltered wiring that includes noise, in this example noise coupling due to crosstalk results in a reduced filtering effect. The example in the lower layout addresses this problem: by using a layout that is not close to a line containing noise, such noise coupling can be kept as small as possible.

● Noise from ground Lines

Figure 52 shows an example of noise from ground lines caused by the way the capacitors placed before and after the inductors that make up the π-type filter are grounded.

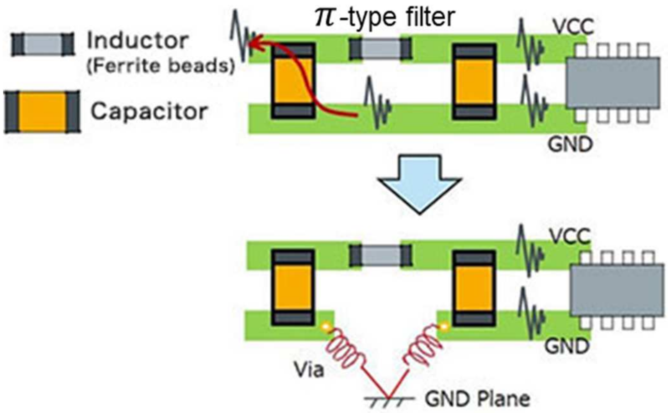

Figure 52. Example of noise from ground caused by PCB layout

In the example shown in Figure 52, noise from the ground can go around through the capacitor and out of the filter, as indicated by the red arrow.

In such a case, a method in which the parasitic inductance of vias is utilized, providing connections to the ground plane through the vias so as not to allow noise to be transmitted directly, may be effective.

PCB layout is very important in switching power supply circuits, and Tech Web's "DC/DC Converter PCB Layout" explains the basics of board layout for your reference.

4.6 Dealing with Noise Using Inductors: Summary

This is a summary of noise countermeasures using inductors, ferrite beads, and common mode filters.

●Dealing with noise using inductors

If a capacitor alone is not sufficient to remove the noise, consider using a filter that uses an inductor.

■Construct a filter with a wire-wound inductor

・A filter using a general inductor can be selected from a wide range of inductance values.

・A π-type filter using an inductor works as a low-pass filter with an inductor and a capacitor in the low frequency range.

・At higher frequencies, the inductor behaves as a capacitance and the capacitor behaves as an inductor, acting as a high-pass filter and thus not providing noise rejection.

●Dealing with noise using ferrite beads

A filter using ferrite beads not only bypasses noise, but also converts it into heat, so high noise rejection performance can be expected.

■Impedance characteristics of ferrite beads

・Ferrite beads are classified as inductors, but their frequency-impedance characteristics differ from those of general inductors.

・Compared with general inductors, ferrite beads have a high resistance component R and a low Q value. These characteristics can be utilized in noise elimination.

・Inductors generally can tolerate comparatively large DC superposition currents, and within this range the DC current does not have much of an effect on the impedance.

・Ferrite beads easily reach saturation due to a direct current, and saturation causes the inductance to decline, so that the resonance point shifts to higher frequencies and the filter characteristics change. Hence appropriate caution is required.

■Ferrite beads convert noise into heat

・Ferrite beads have low Q values, and so are an effective means of dealing with noise over a relatively broad range of frequencies.

・Ferrite beads also basically function as a low-pass filter in the low frequency range. But in this range, ferrite beads are easily saturated due to a DC current, so that the inductance declines and the bead cannot eliminate noise in the targeted band.

・If the reactance declines below the point at which the reactance crosses the resistance component curve, the ferrite bead functions as a resistor, and serves to convert noise into heat.

・Because filters that use ferrite beads convert noise into heat in addition to shunting noise away, they can be expected to provide excellent noise elimination performance.

・Functioning as a resistor to convert noise into heat is a major difference with filters that use a winding-type inductor.

・At still higher frequencies, ferrite beads function as high-pass filters, similarly to winding-type inductors.

●Noise countermeasures using common-mode filters

Common mode filters are essential for removing common mode noise.

■About common mode filter

・Strictly speaking, a common mode filter is not an inductor, but it is a magnetic component that is vital as a noise countermeasure.

- In a common mode filter, there are two windings on a single core, in a structure that is equivalent to two inductors merged together.
- A common mode filter is used to remove common mode noise by utilizing self-induction action to hinder (choke) the flow of a common mode current.
- A common mode filter passes a differential mode current without passing a common mode current.

■ Common mode filter to remove common mode noise

- When a common mode filter is used as an input filter to a switching power supply, a filter with a split-winding structure having a high differential mode impedance is used.
- This type of filter is generally sold as a common mode filter for power supply lines.
- An effect in attenuating differential mode noise can also be expected, but because the differential mode impedance is extremely low at frequencies between several hundred kHz and several MHz or so, use in conjunction with a filter for differential mode noise such as a π-type filter is standard.

● Points to Be Noted

■ Crosstalk

- Depending on the board wiring layout, crosstalk may detract from the efficacy of filters.
- The crosstalk means that noise coupling between close wirings due to stray capacitances and mutual inductances.
- If the wiring after the filter is close to unfiltered wiring that includes noise, noise coupling due to crosstalk results in a reduced filtering effect.
- As one countermeasure, a layout that is kept distant from lines containing noise can hold noise coupling to a minimum.

■ Noise from ground lines

- Depending on the way the capacitors placed before and after the inductors that make up the π-type filter are grounded, noise can get around them.
- As one countermeasure, in order to prevent direct noise propagation, connections to the ground plane can be made through vias to effectively utilize the parasitic inductance of the vias.

5. 5. Other Noise Countermeasures

As noise countermeasures for switching power supplies, we previously explained features and important points relating to methods using capacitors and inductors. In addition to these, however, there are a number of other methods for dealing with noise. Among these, we here explain RC snubber circuits, which are frequently used.

5.1 RC Snubber Circuit

An RC snubber circuit can be added with the objective of reducing spike voltage occurring at a switch node. In the example of Figure 53, when a rectifying diode is turned off (when the high-side switch is on), the RC snubber circuit discharges the electric charge accumulated in the diode junction, the parasitic inductance, the parasitic capacitance, and the inductance in the PCB trace, converting the voltage into heat through a resistance to reduce spikes (Figure 54).

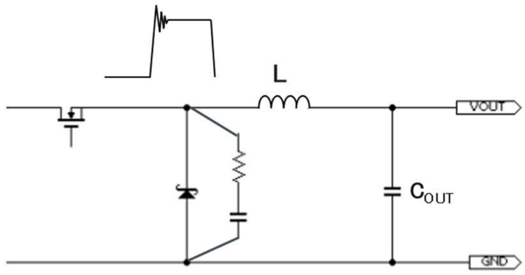

Figure 53. Adding an RC snubber circuit to a switch node.

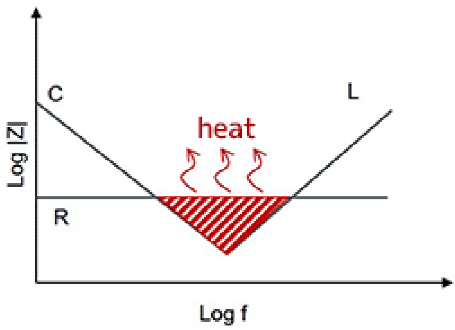

Figure 54. An RC snubber circuit converts noise into heat.

As the RC values, generally R = 2Ω and C = 470 pF are used to start with, and actual measurements are performed to determine optimal values.

As one point to note, if the addition of a snubber circuit causes the switching transition to be more gradual, efficiency will be reduced. Hence it will be necessary to examine the trade-off between the noise level and efficiency.

Moreover, as it is assumed that the resistance will convert noise voltages into heat, attention must be paid to the allowable dissipation of the resistance. Resistance loss can be calculated using the following equation.

$$\mathrm{Loss} = \mathrm{C} \times \mathrm{VIN}^2 \times \mathrm{fsw}$$

Snubber circuits are frequently used on the high side as well as on the low side.

＜Summary＞

・RC snubber circuits reduce voltage spikes, occurring due to parasitic capacitances and parasitic inductances, by using resistors to convert the voltages into heat.

・The addition of a snubber circuit may possibly reduce circuit efficiency, and so the trade-off between noise level and efficiency must be studied.

・A resistance converts noise voltages into heat, and so attention must be paid to the allowable dissipation of the resistance.

6. Conclusion

Starting from "Basics of EMC", and focusing on switching power supply applications, we have discussed basic topics related to "Noise Countermeasures (procedures and summary)", "Dealing with Noise Using Capacitors", "Dealing with Noise Using Inductors (including ferrite beads and common mode filters)", and "Other Noise Countermeasures".

As mentioned at the beginning of this book, noise is not only related to product performance, but is also a very important consideration for compliance with international regulations. As for power supplies, the use of highly efficient switching power supplies is essential due to global energy saving requirements and regulations, and noise in switching power supplies is an issue that must be overcome.

We believe that the most important thing in taking noise countermeasures is to always be aware of noise from the initial stage of development as we progress. In addition to the electrical circuit countermeasures described in this book, there are other noise control methods, such as shielding and spread spectrum, that are mainly aimed at conforming to standards. However, please remember that the basic principle is to have a design that is resistant to noise and does not emit noise.

Revision History

Date	Version	Details
2021.05.30	001	Initial version

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