Effects of parasitic inductance of current sensing resistor

§0. Abstract

Current measurement by a current sensing resistor is done using the relationship that the voltage difference across the resistor is proportional to the amount of current passing through it. In the high-frequency range, however, this relationship does not hold because of the effects of parasitic inductance. In order to measure the current in the high-frequency range accurately, it is effective to use methods to reduce the influence of parasitic inductance such as CR filters.
Also, in the high-frequency range, the waveform of current passing through the resistor can get distorted under the influence of skin effect, which defies correction by the CR filter. This fact requires your attention.

§1. Equivalent Circuit of Current Sensing Resistor

Fig. 1 shows a simplest equivalent circuit of the resistor. This equivalent circuit can be used in circuit calculations for most applications.

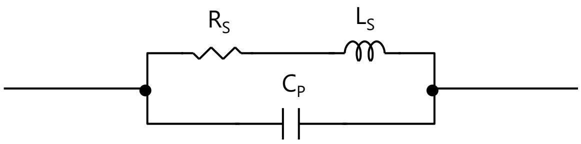

Fig. 1 Equivalent circuit of resistor

R_S is a resistance component, L_S is a parasitic inductance relative to the lengths of lead, resistor, etc., and C_P is a parasitic capacitance that resides between electrodes. It is desired that L_S and C_P are as little as practicable, and attempts are being made to reduce them by downsizing or other improved structure of the resistor. In the high-frequency range, however, it is necessary to heed their possible influence on the impedance characteristics.
Also, it must also be heeded that the degrees of influence vary with the value of R_S. Fig. 2 shows the frequency characteristics of impedance when L_S and C_P are constant at 10nH and 1pF, respectively, and R_S is changed from 0.1Ω to 1kΩ to 100kΩ.

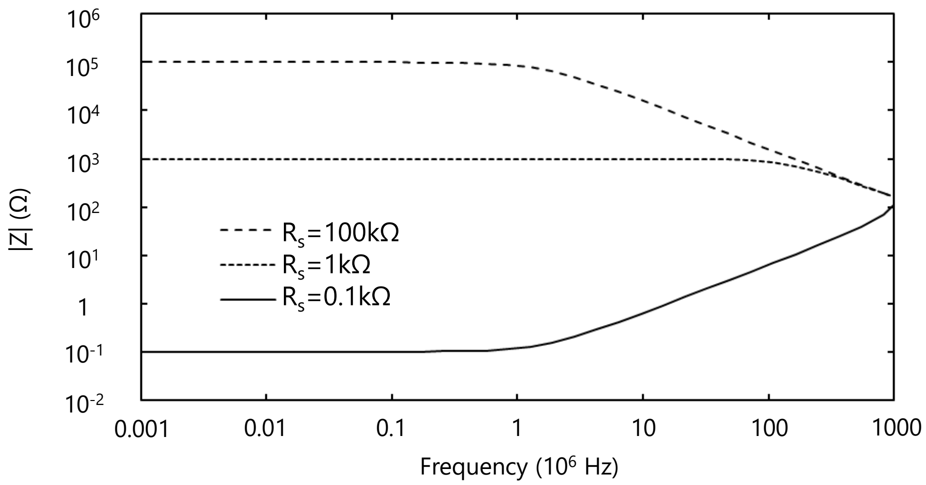

Fig. 2 Effects of R_S on frequency characteristics of impedance |Z|

The resistors whose R_S is 100kΩ and 0.1Ω, respectively, show completely opposite capacitance and inductance characteristics from each other in the frequency band of 1MHz or above. Also, with the resistor whose R_S is 1kΩ, it is evident that the characteristics of resistance are retained up to frequencies higher than the others.
This is due to impedance ratio between R_S and L_S and C_P. The lower the R_S is, the lower the frequencies will be at which the effects of L_S on impedance is evident. Also, the effects of C_P, which are extremely small in comparison with those of L_S, can be ignored for current sensing resistors of low resistance values showing greater effects of L_S (Fig. 3) .

Fig. 3 Equivalent circuit of low-resistance current sensing resistor

§2. Effects of L_S on Current Sensing

The current sensing resistor is connected in series in a current path and detects the current value and current waveform from the voltage drop and the resistance value of the resistor.
A problem encountered here is the influence of L_S in the high-frequency zone.
In the equivalent circuit of Fig. 3, the impedances at 100Hz and 1MHz, respectively, when R_S=10mΩ and L_S=10nH are as follows:

$$Z\ (\text{m}\Omega)\ @100\text{Hz} = 10 + j0.0063$$
$$Z\ (\text{m}\Omega)\ @1\text{MHz} = 10 + j63$$

The effects of L_S on impedance at 100Hz can be ignored because they are less than 1/1000 of those of R_S. On the other hand, the effects at 1MHz are more than six times those of R_S, which makes accurate calculation of current value and current waveform impossible using the voltage drop and resistance value only.

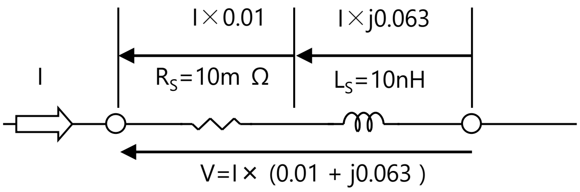

Fig. 4 Voltage drop at 1MHz of 10mΩ resistor

The calculation in Fig. 4 is done for the effects of L_S on the current of sine waveform.
As a practical example, we will consider the effects on current with the waveform changing linearly (Fig. 5).

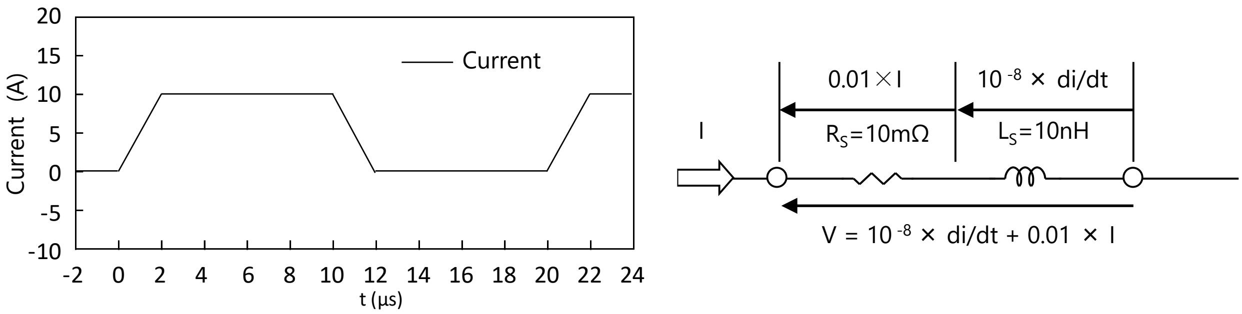

Fig. 5 Linearly changing current waveform and voltage drop

The voltage across the resistor is expressed by the following equation (1):

$$V = L_S \times di/dt + R_S \times I \qquad (1)$$

L_S × di/dt in the first term is the induced electromotive force relative to the change rate of current as shown in Fig. 7, and R_S · I in the second term is the voltage drop caused by R_S and current as shown in Fig. 6.

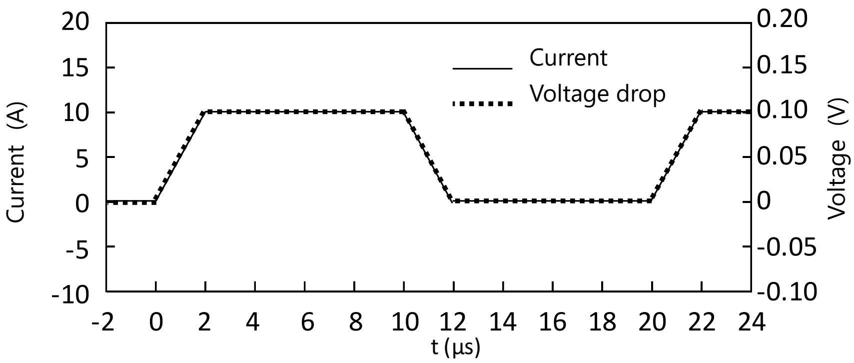

Fig. 6 Voltage drop caused by R_s and current

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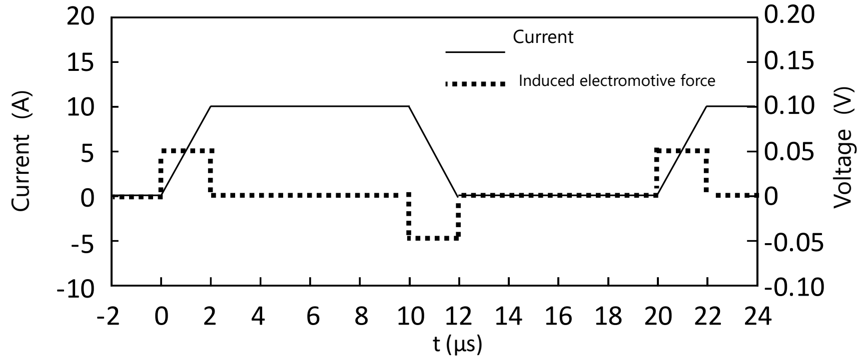

Fig. 7 Induced electromotive force caused by $L_s \times di/dt$

The voltage waveform across the resistor shown Fig. 8 is combined Fig. 6 and Fig. 7.

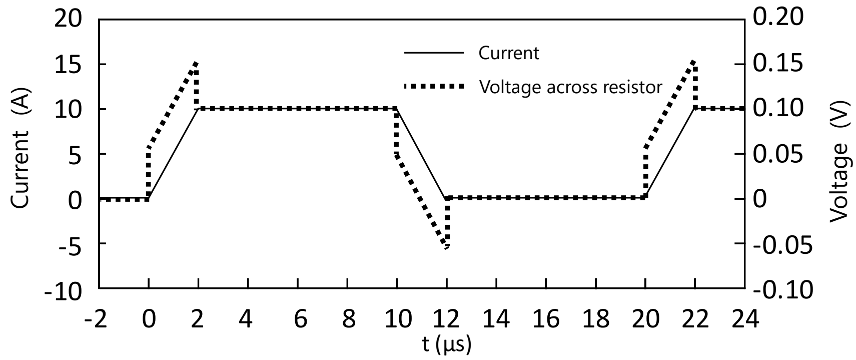

Fig. 8 Voltage waveform across resistor

The induced electromotive force caused by L_S is proportional to the change rate of current. Therefore, even when a resistor of small L_S is selected, caution must be exercised because an extremely large error can crop up when the current change is steep.
The reason for caution is as explained below by citing an example of an output current sensing circuit of a DC-DC converter.
Circuit parameters as shown in Fig. 9 are assumed, and the current that flows through a current sensing resistor is calculated. Then we can obtain a current waveform as shown in Fig. 10.

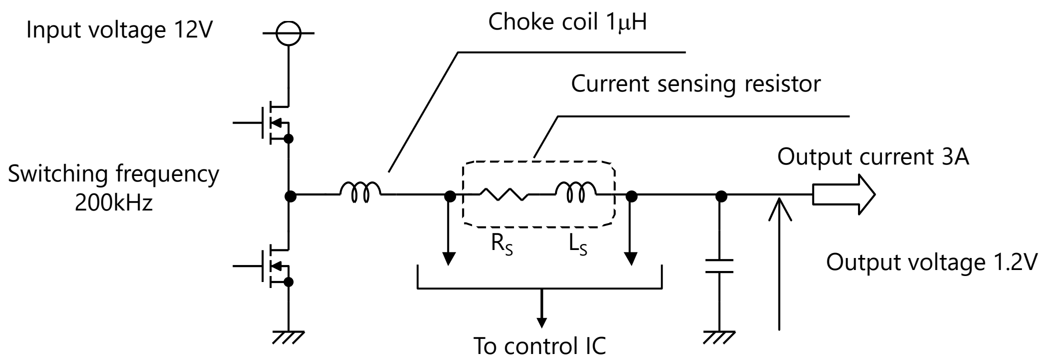

Fig. 9 DC-DC converter output circuit

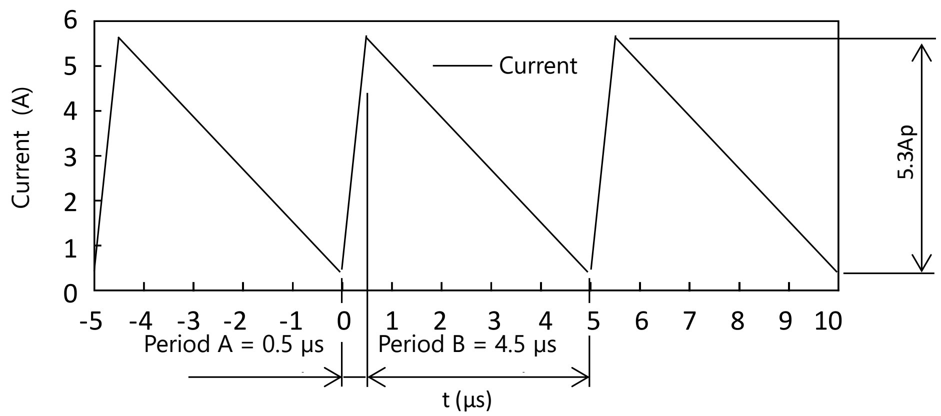

Fig. 10 Current waveform

Let us call the period when the current increases linearly the Period A and the period when the current decreases the Period B.
The voltage waveforms across the current sensing resistor when R_S=10mΩ and L_S=10nH are as shown in Fig. 11.

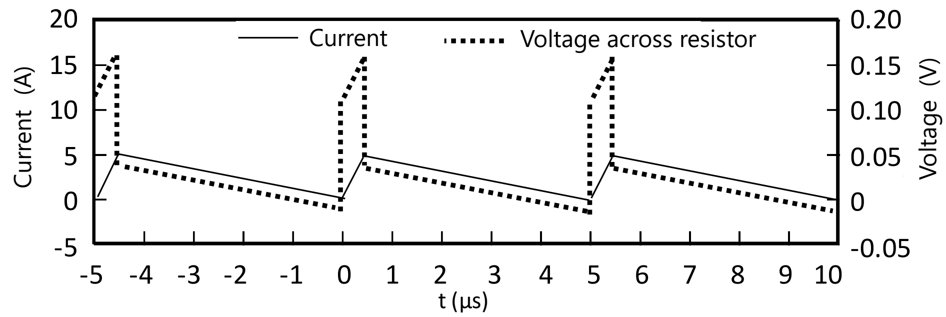

Fig. 11 Voltage waveforms across current sensing resistor

We can see a large error occurring between the maximum value 5A of the current waveform and the maximum current value calculated from the voltage waveform, which is three times as large. Let us find the cause of this error by calculations.
First, let us obtain the change rates of current di/dt of the periods A and B.

$$\text{Period A } di/dt = 5.3 / 0.5\times10^{-6} = 1.06\times10^{7} \text{ (A/s)}$$
$$\text{Period B } di/dt = -5.3 / 4.5\times10^{-6} = -1.18\times10^{6} \text{ (A/s)}$$

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The induced electromotive forces which are derived from L_S and di/dt are as follows:

Induced electromotive force L_S in the period A = 0.106 (V)
Induced electromotive force L_S in the period B = -0.0118 (V)

In contrast to this, the amplitude of voltage drop of R_S is as follows:

Amplitude of voltage drop R_S = resistance value × current amplitude = $10 \times 10^{-3} \times 5.3 = 0.053$ (V_{P-P}) (2)

The value of the voltage drop amplitude R_S to which the induced electromotive force L_S is added is about three times larger.
Even for a current sensing resistor having the same L_S, the rate of error due to the induced electromotive force becomes smaller for higher resistance values. Fig. 12 shows an example when the R_S is changed to 50mΩ.

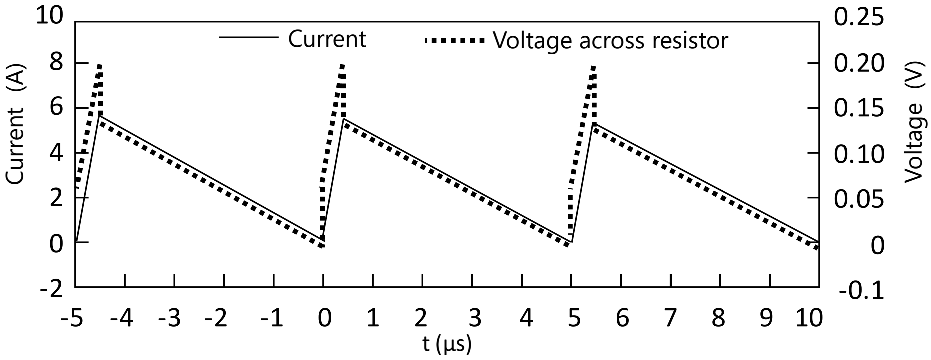

Fig. 12 Voltage across current sensing resistor when R_S =50mΩ

From the viewpoint of detecting the current accurately, it is desirable that a higher resistance value be selected. However, the loss increases in proportion to the resistance value. Therefore, the resistance value must be selected by estimating the temperature rise by simulation or the like in consideration of the size of the resistor to be mounted, the extent of heat dissipation pattern, and the amounts of heat generation by components located nearby.
Notes in the selection of a current sensing resistor are thus summarized as follows:

(a) Select a current sensing resistor having low parasitic inductance.
(b) Select one with as high a resistance value as possible within a range that permits temperature rise.

Note: (b) is important in view of ensuring higher S/N also.

§3. To Reduce Effects of Parasitic Inductance

It is possible to reduce the effects of parasitic inductance L_S by canceling signals by generating induced electromotive force of opposite phase from that of resistor in the voltage detection pattern. The voltage detection pattern should be located immediately below the resistor and set in parallel with the current path and make the parallel part as long as possible (Fig. 13(a), (b) and Fig.14(a), (b)).

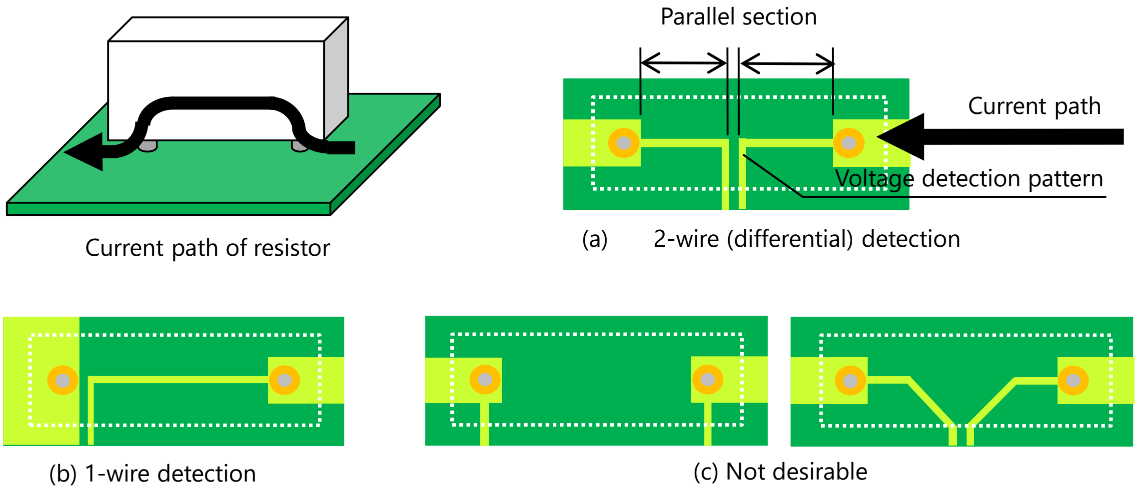

Fig. 13 Example of voltage detection pattern of leaded resistors

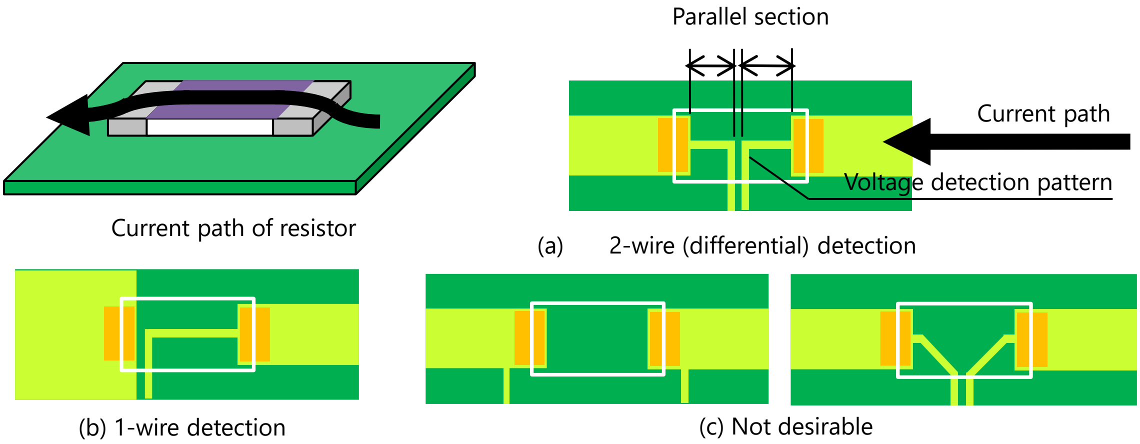

Fig. 14 Example of voltage detection pattern of surface mount resistors

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When reduction of the effects of parasitic inductance by use of a voltage detection pattern is not enough, a filter may be added to the input of the detection amplifier. Design the filter circuit and select parameters as shown in Fig. 15.

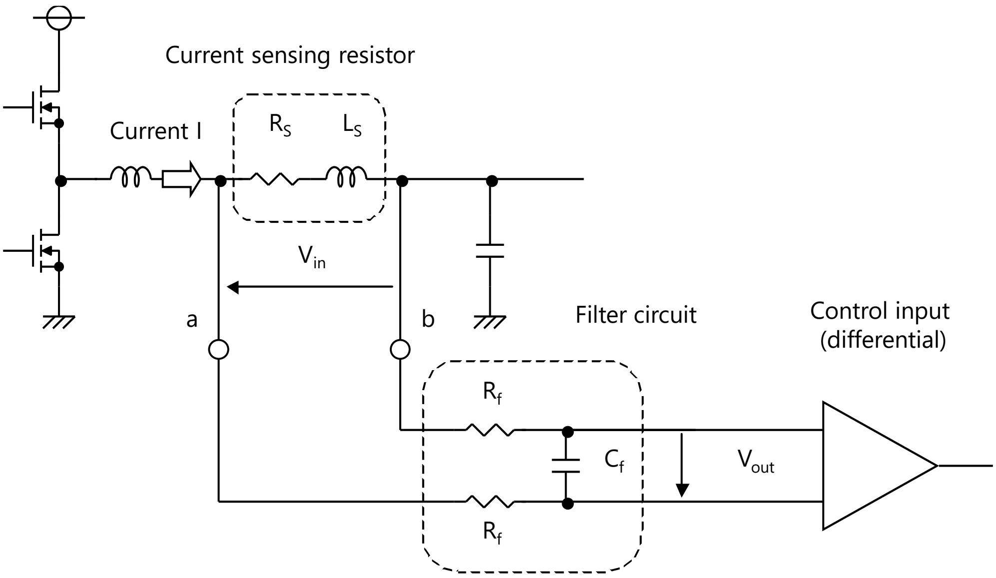

Fig. 15 Filter circuit (differential detection)

Here, if the impedance $|Z_r|$ when the current sensing resistor is viewed from points a and b is sufficiently lower than the impedance $|Z_f|$ when the filter side is viewed, the following equation can be written:

$$V_{in}(t) \fallingdotseq R_S \times I(t) + L_S \times di(t)/dt \qquad (3)$$

(Time functions $V_{in}(t)$, I(t), di(t)/dt are employed to distinguish from those after Laplace transform.)

By applying Laplace transform to both sides,

$$V_{in} \fallingdotseq R_S \times I + S \times L_S \times I \qquad (4)$$

(S is Laplace operator. V and I, which are correctly V(S) and I(S) will be abbreviated below.)

$$V_{out} \fallingdotseq V_{in} / (1 + S \times C_f \times 2 \times R_f) \qquad (5)$$
$$= I \times R_S \times (1 + S \times L_S / R_S) / (1 + S \times C_f \times 2 \times R_f)$$

Hence,

$$V_{out} = I \times R_S \times (1 + S \times L_S / R_S) / (1 + S \times C_f \times 2 \times R_f) \qquad (6)$$

Here

$$L_S / R_S = C_f \times 2 \times R_f \qquad (7)$$

Then the following relationship holds for any frequency components:

$$V_{out} = I \times R_S \qquad (8)$$

Accordingly, as long as R_S and L_S of the current sensing resistor are known, C_f and R_f can be selected such that $|Z_r| << |Z_f|$.
For example, if R_S=0.01Ω and L_S=10nH, then $L_S / R_S = 10^{-6}$. Here, if R_f = 100Ω, C_f, which satisfies $L_S / R_S = C_f \cdot 2 \cdot R_f$, can be calculated as follows

$$C_f = 10^{-6} / 200 = 5\times10^{-9}\,(F) = 0.005\,(\mu F) \qquad (9)$$

Under this condition, at frequency 10MHz, the impedance Z_r when the current sensing resistor is viewed from the broken line ab and the impedance Z_f when the filter side is viewed can be compared as follows:

$$Z_r \fallingdotseq 0.01 + j0.63\ (\Omega)$$
$$Z_f \fallingdotseq 200 - j3.18\ (\Omega)$$

We can see that the condition of $|Z_r| << |Z_f|$ is satisfied. In actual applications, however, too large $|Z_f|$ is not desirable from the viewpoint of noise reduction, and adjustments must be made as appropriate while checking the waveform.
When the control input is 1-wire detection, a filter is introduced as shown in Fig. 16, and C_f and R_f are selected to satisfy the following formula, according to the same concept:

$$L_S / R_S = C_f \times R_f \text{ and } |Z_r| << |Z_f|$$

At this time, the GND of the current sensing resistor and the GND of the filter must be located as close to each other as practicable.

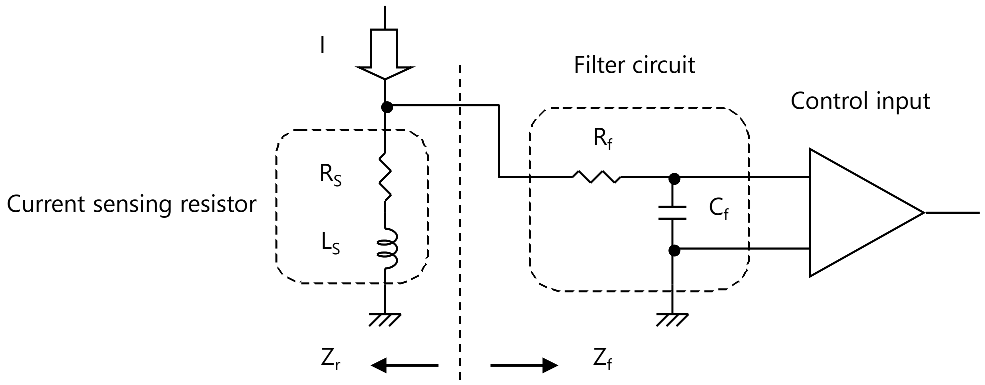

Fig. 16 Filter circuit (one-wire detection)

As already mentioned, the apparent L_S in a mounted state is subject to the influence of voltage detection pattern. In many cases, the data of L_S provided by resistor manufacturers are slightly different from the values in actual mounted applications. Ultimately, therefore, it is necessary to make fine adjustments of filter constants so as to obtain correct current waveform on actual equipment.

§4. Products of Low Parasitic Inductance

Generally speaking, surface-mounted resistors show lower parasitic inductance L_S than leaded resistors.
Among KOA's surface-mounted resistors, TLR is a representative product featuring low L_S. L_S is 1nH or below. By use of special wiring of voltage detection pattern, the apparent L_S can be held 0.1nH or below. This is particularly optimal for applications for detecting currents changing at high speed.
Leaded resistors are often used for high-power applications. The L_S is one order higher than that of surface-mounted resistors. The value is 10nH to 20nH even for BPR and such products using flat metal resistors. You must consider addition of a filter for applications of detecting fast-changing currents.

§5. Influence of Skin Effect

The skin effect is a phenomenon of AC current concentrating more on the surface as it flows through a conductor. This is more conspicuous for higher frequencies and raises the resistance of the conductor.

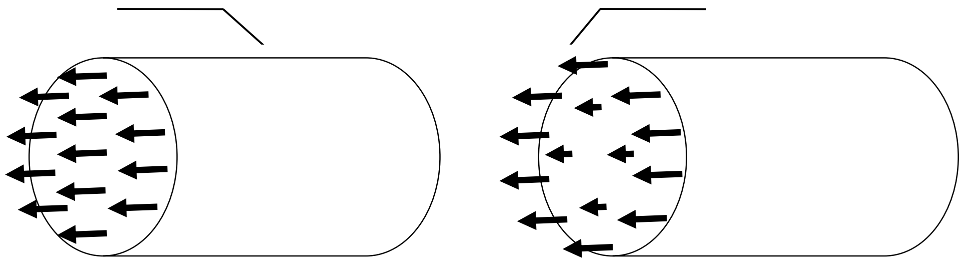

Fig. 17 Skin effect

The current flowing through a conductor, if it is a direct current or of low frequency, flows uniformly through the conductor as shown in Fig.17(a) provided that the resistivity of the conductor is uniform.
As the frequency increases, however, the current flowing through the center of the conductor decreases as shown in Fig. 17 (b).
The depth (skin depth δ) where the current is 1/e of the surface current can be written as the following equation:

$$\delta = (2 \times \rho / \omega / \mu)^{1/2} \quad (\mathrm{m}) \qquad (10)$$

Where ρ is the resistivity (S / m) of the conductor, ω is the angular frequency (rad / s) of the current, and μ is the magnetic permeability (H / m) of the conductor.
The influence of skin effect on sine wave current can be seen in a simple phenomenon of increased resistance. However, the influence from the actual waveform is more complicated.

Fig. 18 shows voltage waveforms of detected output current of a DC-DC converter when a resistor subject to much influence of parasitic inductance and skin effect is used.

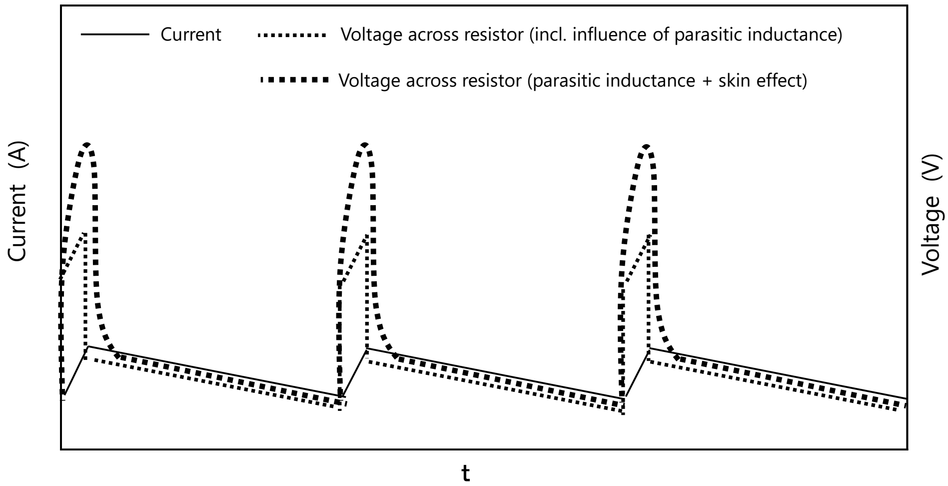

Fig. 18 Current sensing waveform of DC-DC converter output under the influence of skin effect

It can be seen that the waveform shows more complex distortion than when it is affected by parasitic inductance only. Fig. 18 is just an example, and completely different waveforms can appear depending on the difference in high-frequency components contained in the current waveform or characteristics of the resistor.
It is difficult to reduce the skin effect using a filter, and therefore measures must be taken by selecting the product type and the resistance value appropriately.
From equation (10), the influence of the skin effect are smaller with smaller cross section of the resistor and greater resistivity and lower magnetic permeability of materials.
Note that among KOA’s current sensing resistors, SR73 and UR73, employing thick film resistors, feature limited influence of skin effect.
Generally, the higher the resistance value, the lower the skin effect is. For the same resistance value, however, the skin effect can vary with the shape and material of the resistor.
Please attach information such as current waveform, frequency and etc. when further detail is needed.