Improvement of High-Frequency Characteristics of Small-Size Toroidal Reactors with New Wire Guides

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In this paper, a new reactor with a wire guide for a small-size toroidal core that can be used in the high frequency range is proposed. Theoretically, the reactor size can be reduced in proportion to the switching frequency. However, practically, as the switching frequency is increased, reactors are affected by the parasitic capacitance existing between the windings and between the winding and the core, and the inductance characteristic of the reactors is deteriorated. Therefore, there is a limit to increasing the switching frequency. This paper proposes two types of wire guides, namely a two-layer winding guide and a three-layer winding guide, to reduce the parasitic capacitance. Moreover, the impedance characteristics of the reactors using the proposed wire guides are evaluated. The wire guides are manufactured using a 3D printer and attached to the center hole of the toroidal core. With the proposed guides, the parasitic capacitance decreases by 0.73 times and 0.66 times compared with the conventional reactor. The linear regions of the impedance, which can be regarded as a pure inductance, are enlarged. In addition, the materials of the wire guide are also evaluated. It is shown that the ultraviolet curing resin guide is superior to the thermoplastic resin guide.

Keywords: reactor, parasitic capacitance, high frequency, wire guide

1. Introduction

Recently, power devices such as SiC and GaN have been put into practical use, and low-loss and high-frequency drive has been realized (1). Reactors used in DC-DC converters can theoretically reduce current ripples in proportion to frequency. In other words, the higher the switching frequency is, the smaller the inductance can be used if the current ripple is the same. Especially, since the size and weight of converter systems are dominated by those of reactors, the size and weight reductions of reactors can greatly contribute to those reductions of converter systems. Furthermore, by increasing the switching frequency and reducing the current ripples, the vibrations of the reactors and the motor system can be reduced, so the acoustic noises can be reduced. In addition, the response of the current control can be improved by shortening the control cycle of the converter. However, practically, as the switching frequency is increased, the reactors are affected by the parasitic capacitances existing between the windings and between the winding and the core, and the inductance characteristic of the reactor is deteriorated (2). As a result, there is a limit to increasing the switching frequency (3). This problem has been pointed out about not only reactors but also EMI filters and high frequency transformers, and their modeling, impedance evaluation and winding method in the high frequency region have been reported (4)–(9). The authors had reported the wire guide for a relatively large-size core (10). The wire guide to reduce the parasitic capacitances for a relatively large-size core had been reported.

This paper proposes new reactors to which the technique shown in the Ref. (10) presented by the authors are applied, and they can be used under high frequency conditions with wire guides for a small-size toroidal core. The wire guides are manufactured by using a 3D printer and are attached to the center hole of the toroidal core. In the case of a small-size core, the winding arrangement and the realization of the wire guide are restricted. The wire guides enable to reduce the parasitic capacitances between the windings and between the winding and the core. In this paper, the impedance characteristics of the reactors using the proposed wire guides are evaluated. Then, the reduction effect of the parasitic capacitances and the expanding effect of the frequency range which can be regarded as a pure inductance are evaluated. Moreover, the impedance characteristics are evaluated when the shape and the material of the guide are changed.

2. Problem of a Reactor used Under High Frequency Conditions

Figure 1 shows a main circuit of a bidirectional DC-DC converter system.
converter \((E_1 < E_2)\). The system of Fig. 1 consists of two switching devices \((S_1, S_2)\) and a reactor. The red line is the current path of the boost converter, and the voltage \(E_1\) is boosted to \(E_2\) via the switching devices. The blue line is the current path of the buck converter, and the voltage \(E_2\) is stepped down to \(E_1\) via the switching devices. This circuit is used in electric vehicles with rechargeable batteries and is operated as the boost converter and the buck converter in the power running and the regenerative modes, respectively.

Figure 2 shows the simulation results of the current \(i_t\) flowing in the inductance \(L\) when the switching frequency is changed in the power running mode. In \(i_t/s\), the ripple currents are superimposed on the DC current. If the ripple currents are large, adverse effects such as vibration and noise of the reactor may occur. The magnitude of the ripple can be calculated by

\[
I_{\text{ripple}} = \frac{E_1}{L} \times T_{s2},
\]

where \(T_{s2}\) is the conduction time of \(S_2\). From (1), the ripple current can be reduced by (i) increasing the inductance \(L\) or (ii) increasing the switching frequency \((\text{decreasing } T_{s2})\). The method (ii) is generally used since the weight and volume of the reactor becomes large in method (i). According to Fig. 2, under the ideal condition, the higher the switching frequency is, the smaller the ripple current becomes.

Figure 3 shows a conventional reactor with a toroidal-core and its equivalent circuit under the high switching frequency condition. Figure 3(a) is the schematic of a reactor in which a copper wire coil is wound around a toroidal core. Since the toroidal core has no gap, the leakage flux is small. However, when the coil windings are increased, the wires become densely gathered together at the center hole of the toroidal core. In this case, the parasitic capacitances between the copper wires and between the copper wire and the core may affect the impedance characteristic of the reactor.

Figure 3(b) is the equivalent circuit of the reactor at high switching frequency \(f_o\). It is assumed that the coil windings \((t_1, t_2, t_3)\) whose diameters are \(r\) are wound at the interval \(d\) and the distances between the coil windings and the core are \(h\). In this case, the parasitic capacitances \(C_d\) and \(C_h\) per unit length, which exists between the windings and between the winding and the core, respectively, can be expressed as follows \((5)\):

\[
C_d = \frac{\pi \varepsilon_0}{\ln \left( \frac{d}{2r} + \sqrt{\left( \frac{d}{2r} \right)^2 - 1} \right)}
\]

\[
C_h = 2\pi \varepsilon_0 \ln \left( \frac{h}{r} + \sqrt{\left( \frac{h}{r} \right)^2 - 1} \right)
\]

From (2) and (3), if \(d\) and \(h\) can be increased, \(C_d\) and \(C_h\) can be reduced, and the impedance characteristic of the reactor can be improved under the high switching frequency condition.

### 3. The Proposal of New Wire Guide for a Toroidal Core

In the proposed high-frequency reactor, the distances between the windings and between the coil winding and the core are increased by using a resin wire guide. Figure 4 shows the dimensions of the toroidal core (dust core: HK-14D (TOHO ZINC CO., LTD.)) used for the evaluation. In the proposed high-frequency reactor, the wire guide is attached to the center hole of the toroidal core. This wire guide enables to reduce the parasitic capacitances by increasing the distance between the windings and between the winding and the core. The wire guide is made by 3D printer. In this paper, two types of wire guide are proposed. One is two-layer winding type and the other is three-layer winding type (hereinafter called “proposed wire guide I and II”, respectively).

Figure 5 shows the proposed wire guide I. Figure 5(a) is the photograph of the wire guides. The transparent one and the white one are made from the ultraviolet curing resin and the thermoplastic resin, respectively. Figure 5(b) shows their dimensions. The thickness of the guide is 1 mm. Figures 6 and 7 show the photographs and winding order of the proposed
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(a) photograph of wire guides

(b) dimensions of the wire guide

Fig. 5. Proposed wire guide I

Fig. 6. Photographs of the reactor with proposed wire guide I

Fig. 7. Winding order of the reactor with the proposed wire guide I

The rated current of the reactor is assumed to be several A. Because of the high frequency condition, thin wires connected in parallel or litz wires may be used in consideration of the skin effect. In this paper, each winding of the all prototypes is 56 turns by using single wire.

As shown in the enlarged view of Fig. 6, the length of the guide in the axial direction is slightly longer than that of the core. And, as shown in Fig. 7, the windings are alternately wound around the inner frame of the wire guide and the clearance between the core and the wire guide. The wire guide keeps the distances between the wires and between the wires and the core as far as possible. In this case, although there is concern about the increase of the leakage magnetic flux, it may become small since the toroidal core has no gap. In the proposed reactor, the part of the wire guide protruding from the core in its axial direction prevents overlapping of the windings and extends the distance between the windings and the core. As a result, the proposed wire guide has the effect of reducing the parasitic capacitances $C_d$ and $C_h$ in Fig. 3.

Figure 8 shows the proposed wire guide II. Figure 8(a) is the photograph of the wire guides and Fig. 8(b) shows their dimensions. The thickness of the guide is 0.5 mm, so that the windings are not crowded at the inner frame of the wire guide. Because the guide is extremely thin, the guide must be made from the ultraviolet curing resin which can be manufactured with high accuracy. Figures 9 and 10 show the photographs and winding order of the proposed high-frequency reactor with the proposed wire guide II, respectively.

The structure of Fig. 8 is designed so that the pillars between the sections support the inner layer do not interfere with wiring. Although the number of sections is different in the guides I and II, it is clear from the photographs of Figs. 6 and 9 that the windings are evenly wound regardless of the pillars between the sections.
winding orders of Fig. 10 show only a part of the whole. The enameled copper wire with a diameter of 0.6 mm is used for the coil winding and the number of turns is 56, which are the same condition in Fig. 6. By winding in the order shown in Fig. 10, the ratios of the number of windings at the outer part, the middle part, and the center part can be 3: 2: 1. The wire guide keeps the distances between the wires and between the wires and the core as far as possible, which is the same as Fig. 7. The wire guide of Fig. 8 can use the inner space of the center hole of the toroidal core than that of Fig. 5. The length of the outer frame of the guide in the axial direction is slightly longer than that of the core, and that of the inner frame is slightly longer than that of the outer frame as shown in Fig. 8(b) and Fig. 9. The differences in the length prevent overlapping of the windings. As a result, the proposed wire guide has the effect of reducing the parasitic capacitances $C_d$ and $C_b$ in Fig. 3.

### 4. Evaluations of the Impedance Characteristics

#### 4.1 The Effect of the Proposed Wire Guides

In this section, the impedance characteristics of the proposed reactors shown in Figs. 6 and 9 are evaluated. In addition, the conventional reactor and the concentrated winding reactor in which the coil winding is densely wound around a part of the core are also evaluated for comparison. Figure 11 shows the photographs of a conventional reactor and a concentrated winding reactor, respectively. The toroidal core (HK-14D) shown in Fig. 4 is used for all reactors, and the copper wire diameter and the turns of the coil winding are fixed to be 0.6 mm and 56, respectively. The material of the guides for the proposed wire guide I and II are the ultraviolet curing resin. For the measurement, the impedance analyzer (E4990A, KEYSIGHT Technology) is used.

Figure 12 shows the impedance characteristics of each reactor. The resonance frequencies of the conventional reactor, the concentrated winding reactor, the reactors with the proposed wire guide I and II are 3.39 MHz, 1.60 MHz, 4.14 MHz and 4.14 MHz, respectively. Both resonance frequencies of the proposed reactors can be increased by 750 kHz than that of the conventional reactor. The resonance frequency of the concentrated winding reactor is 1.87 MHz lower than that of the conventional reactor, and the characteristics at high frequencies are remarkably deteriorated.

Table 1 shows the resonance frequencies $f_r$, inductances $L$ and parasitic capacitances $C$ of each reactor. Each reactor can be regarded as an $LC$ parallel circuit. However, the influence of resistance appears near each resonance point. Appendix shows detailed impedance evaluation. Here, $L$ are derived assuming that the reactor can be approximated to be only the inductance $L$ at 100 kHz. $C$ is obtained by substituting $f_r$ and $L$ into

$$C = \frac{1}{(2\pi f_r)^2 L}$$

The parasitic capacitance of the concentrated winding reactor is about 4.1 times larger than that of the conventional reactor. This is because the parasitic capacitances $C_d$ between windings in Fig. 3 are increased by densely winding. That is, even when making a conventional reactor, it is important that the coil winding is wound evenly in order to reduce the parasitic capacitance. The parasitic capacitances of the reactors with the proposed wire guide I and II can be reduced by about 0.73 and 0.66 times, respectively, as compared with that of the conventional reactor. This is because the proposed wire guides reduce the parasitic capacitances $C_d$ and $C_b$ in Fig. 3.

The reactors can be regarded as ideal coils at low frequency where their impedances increase linearly with the frequency as shown in Fig. 12. In this evaluation, the frequency range where the error between $L$ and actual inductance in Fig. 12 is within ±20% is defined as the linear region. The upper limit frequencies of the linear regions for the conventional reactor, the concentrated winding reactor, the reactors with the proposed wire guide I and II are 1.56 MHz, 661 kHz, 1.93 MHz, and 1.99 MHz, respectively. Therefore, the frequencies which can be regarded as a pure inductance in the reactors with the proposed wire guide I and II can be increased to 371 kHz and 436 kHz, respectively, than that in the conventional reactor.

#### 4.2 The Effect of the Winding Arrangement

In this section, the influence of the winding arrangement in the

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†††† The resistance at 100 kHz is about 5 Ω and the impedance can be regarded as a pure inductance. $L$s in Table 1 are measured values.
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The center hole of the toroidal core is evaluated on the reactor with three-layer winding type wire guide. Figure 13 shows the dimensions of the guide for a comparative evaluation. The thickness of the wire guide in Fig. 13 is thicker than that in Fig. 8. The reactor for the comparative experiment can be more use of the inner space. However, the diameter of the inner frame of the guide of Fig. 13 is smaller than that of Fig. 8. Figures 14 and 15 show photographs and winding order of the reactor with the guide of Fig. 13. The winding orders of Fig. 15 show only as a part of the whole. In the innermost layer, the stray capacitance increases because the wires are close to each other. The winding order of the reactor with proposed wire guide II is designed so that the wires are not close to each other at the innermost layer. Therefore, the winding order shown in Fig. 15 is different from that in Fig. 10. The toroidal core (HK-14D) is used for the reactor and the copper wire diameter and the turns of the coil winding are 0.6 mm and 56, respectively, which are the same as those of the reactor with the proposed wire guide II in Fig. 9. The distance between the windings can be sufficiently obtained between the inner frame and the outer frame. However, the windings are dense in the inner frame, since the thickness of the wire guide is large and the diameter of the inner frame is small.

Figure 16 shows the impedance characteristics of the conventional reactor, the reactor with the proposed wire guide II and the reactor for the comparative experiment. Here, the ultraviolet curing resin is used as the material of each guide. The resonance frequencies of the conventional reactor, the reactor with the proposed wire guide II and the reactor for the comparative experiment are 3.39 MHz, 4.14 MHz and 2.94 MHz, respectively. The resonance frequency of the reactor for the comparative experiment is 1.2 MHz lower than that of the reactor with the reactor with the proposed wire guide II, and is lower than that of the conventional reactor.

Table 2 shows the resonance frequencies $f_r$, inductances $L$ and parasitic capacitances $C$ of each reactor. Here, $L$ and $C$ are also derived in the same way as Table 1. The parasitic capacitance of the reactor for the comparative experiment is about twice as large as that of the reactor with the proposed wire guide II. Furthermore, according to Fig. 16, the upper limit frequencies of the linear regions for the conventional reactor, the reactor with the proposed wire guide II and the reactor for the comparative experiment are 1.56 MHz, 1.99 MHz, and 1.40 MHz, respectively. The upper limit frequency of the reactor for the comparative experiment is 595 kHz lower than that of the reactor with the proposed wire guide II. Despite using the guides for three-layer winding type, there is a significant difference in frequency characteristics. This is because, in the reactor for the comparative experiment, the parasitic capacitances are arisen at the windings in the inside of the inner frame where the windings are dense as shown in Fig. 17. Especially, in the innermost layer, not only the stray capacitance between the wires in the layer is increased since the wires are close to each other, but also...
the whole stray capacitance between the start and end winding is large because the parasitic capacitance is existed between Turn 4 and Turn 8 in Figs. 15 and 17. As a result, the combined capacitance of the reactor for the comparative experiment becomes greater than that of the reactor with the proposed wire guide II. On the other hand, in the reactor with the proposed wire guide II, the wire guide is extremely thin and the diameter of the inner frame is large, so that the windings are evenly separated from each other in the inside of the inner frame. Therefore, the consideration of the diameter of the innermost frame and the winding arrangement, so that the distance between the windings is increased, is important to design the wire guide for the high-frequency reactor.

4.3 The Effect of the Material of Proposed Wire Guides

In this section, the effect of the material of the wire guide is evaluated on the impedance characteristics of the reactors. As the material of the guide, ultraviolet curing resin and thermoplastic resin (ABS resin) are used. Generally, the tensile strength and the bending strength of the ultraviolet curing resin are larger than those of the thermoplastic resin, that is, the hardness of the ultraviolet curing resin is higher than that of the thermoplastic resin. The relative permittivity of ultraviolet curing resin is about the same as or slightly higher than that of the thermoplastic resin.

Figure 18 shows a photograph of the reactor with a thermoplastic resin guide for the proposed wire guide I which is shown in Fig. 5. The toroidal core (HK-14D) is used for this reactor, and the copper wire diameter and the turns of the coil winding are 0.6 mm and 56, respectively, which is the same as the reactor with the proposed wire guide I in Fig. 6. The dimension of the wire guide and the winding order are also the same as Figs. 5 and 7, respectively.

Figure 19 shows the impedance characteristics of the reactors with the ultraviolet curing resin guide and thermoplastic resin guide. The resonance frequencies are 4.14 MHz and 3.84 MHz, respectively. The resonance frequency of the reactor with the ultraviolet curing resin guide is 300 kHz higher than that of the reactor with thermoplastic resin guide. This is probably because thermoplastic resin is so soft that the wire guide is slightly deformed when the windings are wound, and the distance between the windings becomes narrower as shown in Fig. 18.

Table 3 shows the resonance frequencies $f_r$, inductances $L$ and parasitic capacitances $C$ of each reactor. Here, $L$ and $C$ are also derived in the same way as Tables 1 and 2. The parasitic capacitance of the reactor with the ultraviolet curing resin guide can be reduced about 0.87 times than that of the reactor with thermoplastic resin guide. According to Fig. 19, the frequencies of linear regions for the reactors with the ultraviolet curing resin guide and the thermoplastic resin guide are 1.93 MHz and 1.73 MHz, respectively. That is, the ultraviolet curing resin is more suitable material of the wire guide for the high frequency reactor than the thermoplastic resin. Furthermore, the difference of material does not affect the reactor characteristics as much as the shape of the wire guides.

5. Conclusions

This paper has proposed the high-frequency reactors with the wire guides for a small-size toroidal core. These wire guides have enabled to reduce the parasitic capacitances between the windings and between the winding and the core. The wire guides have been manufactured by using a 3D printer. Furthermore, the impedance characteristics have been evaluated for the cases where the shape and the material of the guide are changed. The following results were obtained.

- In the conventional reactors, since the coil windings are densely gathered together at the center hole of the toroidal core, the parasitic capacitances between the copper wires and between the copper wire and the core increases. When the switching frequency is increased, the parasitic capacitances become the factor of deteriorating the impedance characteristics of the reactor.
- Two types of wire guides with two-layer winding type and three-layer winding type (the proposed wire guide I and II) have been proposed to reduce the parasitic capacitances. These wire guides can increase the distances between the windings and between the winding and the core, and reduce the parasitic capacitances.
- The parasitic capacitances of the reactors with the proposed wire guide I and II can be reduced by about 0.73 and 0.66 times, respectively, as compared with that of

\[\text{Table 3. Inductances and capacitances when the material of the guides are different} \]

<table>
<thead>
<tr>
<th>Material</th>
<th>Resonance frequency $f_r$ [MHz]</th>
<th>Inductance $L$ [$\mu$H]</th>
<th>Capacitance $C$ [pF]</th>
</tr>
</thead>
<tbody>
<tr>
<td>thermoplastic resin</td>
<td>3.84</td>
<td>465</td>
<td>3.70</td>
</tr>
<tr>
<td>ultraviolet curing resin</td>
<td>4.14</td>
<td>458</td>
<td>3.23</td>
</tr>
</tbody>
</table>

$^{15}$ The capacitance which is directly connected between Turn 4 and Turn 8 in Fig. 17 is greater than the series combined capacitance between Turn 4 and Turn 8.
the conventional reactor. Furthermore, the upper limit frequencies of the linear regions for the reactors with the proposed wire guide I and II can be increased to 371 kHz and 436 kHz, respectively, than that in the conventional reactor. On the other hand, the parasitic capacitance of the concentrated winding reactor is about 4.1 times larger than that of the conventional reactor.

- The parasitic capacitance of the reactor for the comparative experiment is about twice as large as that of the reactor with the proposed wire guide II. The upper limit frequency of the linear region for the reactor which is for the comparative experiment is 595 kHz lower than that of the reactor with the proposed wire guide II. This is because the parasitic capacitances are arisen at the windings in the inside of the inner frame in the reactor for the comparative experiment. Therefore, the consideration of the diameter of the innermost frame and the winding arrangement, so that the distance between the windings is increased, is important to design the wire guide for the high-frequency reactor.

- The parasitic capacitance of the reactor with the ultraviolet curing resin guide can be reduced about 0.87 times than that of the reactor with thermoplastic resin guide. This is because the ultraviolet curing resin has high strength and hardness, and there are few problems due to deformation.

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### References


app. Fig. 3. Characteristics of $|\omega L|$ and $R$ of the reactor in app. Fig. 1

app. Fig. 4. Detailed equivalent circuit for the characteristics of app. Fig. 1

app. Fig. 5. Impedance characteristic of the circuit in app. Fig. 4

(The resistance at 100 kHz is 5.57 $\Omega$, and the impedance can be regarded as a pure inductance.)

app. Fig. 4 shows the detailed equivalent circuit for the characteristic of app. Fig. 1. Here, $R_s$ is the resistance connected to $L$ in series and $R_p$ is the resistance connected to $C$ in parallel. The values of the circuit are calculated by the same way as the values in Table 1. app. Fig. 5 shows the impedance characteristic of the circuit in app. Fig. 4. It is confirmed that the characteristic of app. Fig. 1 is similar to that of app. Fig. 5 and the inductance can be considered to be extremely dominant in the linear region. Although it can be assumed that $R_s$ increases as the frequency increases due to the skin effect, the impedance of $L$ becomes much larger than $R_s$.

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