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Sheet coil and ultra-thinner VA unit used in EV-WPT

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ABSTRACT: With the spread of EVs, there are increasing expectations for wireless power transfer (WPT) systems that can be easily recharged. The authors have developed a sheet coil for this system that is thinner and lightweight compared to conventional coil using Litz wire. Using this coil, we have demonstrated that power transmission is possible at 11.1 kW, which is the standard for power specified in SAE J-2954[(1)(2)]. In addition, by reducing the distance of ferrite plate and aluminum shield, the entire coil unit can be made thinner, further succeeding in developing a VA coil unit with high performance by suppressing the coil loss due to the reducing distance between both.

KEY WORDS: electric vehicle, power electronics, wireless power transfer

1. INTRODUCTION

Today, motorization of EV has been promoted globally, and there is an increasing interest in wireless charging technology that can be easily recharged. SAE J-2954[(1)] and other standardization organizations are also examining a magnetic field resonance method in the 85 kHz band. To suppress the temperature rise in the case of transmitting a high power, it is necessary to use a thick electric wire containing a large amount of copper. In the situation of dramatically growing number of electric vehicles and to use the wireless power charging system conveniently, we should consider the earth resources such as copper.

We reported on a multi-layer coil that weighs 1/4 of the conventional one. Then we succeeded in reducing the amount of copper used to 1/3 of the coil by improving the line pattern and layer structure. This sheet coil has been demonstrated to be possible to transmit 11.1 kW of power, which is the SAE standard [(2)]. Also, we have made it possible to reduce the overall thickness of the coil unit by reducing the distance of ferrite plate and aluminum shield. In this paper, we describe the features of VA coil units that enable thinner coils and the difference in performance between sheet coil and Litz wire coil.

2. RESULT AND DISCUSSION

2.1. Construction of coil unit

Figure 1 shows the configuration of a conventional Litz wire VA coil unit and our VA sheet coil unit. In the Litz wire coil, the Litz wire held in a litz tray consist of resin. The thickness of the ferrite plate is at least 3 mm, and a space of about 5 mm is left between the ferrite plate and the aluminum shield to prevent coil performance loss. The total thickness of the coil unit is more than 20 mm.

On the other hand, the sheet coil we have developed previously (2nd generation, Gen.2) consists of a sheet coil at least 2 mm thick, an isolation layer, a ferrite plate at least 2 mm thick, an aluminum block for heat radiation, and an aluminum shield, as shown in Figure 1(b). Since the coil unit is in a case, the bottom of the case is located under the sheet coil. Therefore, the minimum total thickness was 20 mm.

By modifying the coil pattern and design, we have succeeded in developing a thinner sheet coil (3rd generation, Gen.3), as shown in Fig. 1(c). By eliminating the heat sink block and closing the ferrite plate and aluminum shield, the total thickness of the unit can be reduced to a minimum of 10 mm. There is concern that the approach of the ferrite plate and aluminum shield may reduce the performance of the coil, which will be discussed in the next section.

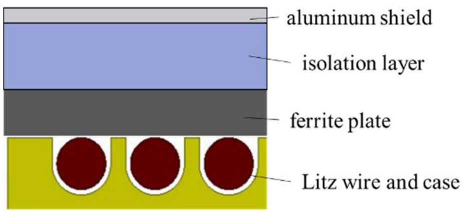

Fig.1 (a) Litz wire coil unit

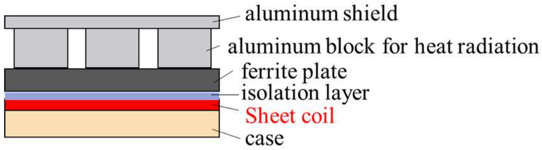

Fig.1 (b) 2nd generation (Gen.2) coil unit

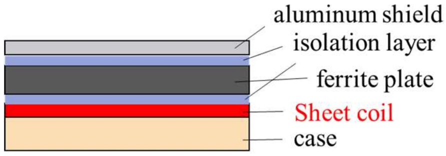

Fig.1 (c) 3rd generation (Gen.3) coil unit

Fig.1 Construction of Litz wire coil unit and sheet coil unit

2.2. Comparison of Litz wire coil and sheet coil with ferrite and aluminum shield distance dependence

2.2.1. Simulation result

(1) Sheet coil (Gen.2) vs. sheet coil (Gen.3)

The electrical characteristics (inductance, resistance, and Q-value) and losses of the coil unit was evaluated when the distance between the ferrite plate and aluminum shield was changed in the Gen.2 sheet coil and Gen.3 sheet coil. The values for the sheet coil were calculated using electromagnetic field simulation software (Femtet, Murata Software). The results are shown in Table 1.

The rate of Q value decrease in Gen.3 coil is 91%, which is much smaller than that of Gen.2 coil, indicating that the Gen.3 coil was able to suppress performance degradation. In the Gen.2 coil, coil loss also increased when the ferrite plate and aluminum shield were closer together, but in the Gen.3 coil, coil loss was unchanged with only an increase in the loss of the aluminum shield. This indicates that optimization of the coil has made it possible to create a coil unit that has minimal effect on performance even when the coil is thinner.

Table 1. Electrical characteristics of coil units at different distances between ferrite plate and aluminum shield (Gen.2 vs. Gen.3)

		Gen.2 sheet coil		Gen.3 sheet coil	
		Distance 10mm	Distance 1mm	Distance 10mm	Distance 1mm
Loss [W] @ 50 Arms	coil	174.3	185.2	115.6	115.4
	Al shield	11.7	37.0	9.1	20.2
	Total	186.0	222.2	124.7	135.7
	Q	93	73	219	198
	Z [Ω]	0.233	0.278	0.100	0.109
	L [μH]	40.3	38.2	41.0	40.4
	Rate of Q-value decrease		78%		91%

(2) Litz wire coil vs. sheet coil (Gen.3)

Next, the electrical characteristics of the coil unit was evaluated when the distance between the ferrite plate and aluminum shield was changed in the Gen.3 sheet coil and Litz wire coil. The values for the sheet coil were calculated using simulation software, and the values for the Litz wire coil were measured. The results are shown in Table 2.

For the Litz wire coil, moving the distance from 10 mm to 1 mm increased the resistance, resulting in a significant decrease in Q value. On the other hand, in the case of the sheet coil, although the resistance increased slightly and the Q value also went down, the reduction ratio was very low at 91% compared to the Litz wire coil. Therefore, even when the VA coil unit is made thinner, the performance degradation can be suppressed.

Table.2 Electrical characteristics of coil units at different distances between ferrite plate and aluminum shield (Litz wire vs. Gen.3 sheet coil)

	Sheet coil Distance 10mm	Sheet coil Distance 1mm	Litz wire coil Distance 10mm	Litz wire coil Distance 1mm
Q	219	198	480	318
Z [Ω]	0.100	0.109	0.051	0.075
L [μH]	41.0	40.4	45.8	44.6
Rate of Q-value decrease		91%		66%

2.2.2. Measured results

The performance of Gen3 sheet coil and Litz wire coil at different gaps between the ferrite and aluminum shield was measured to investigate the difference of performance.

(1) Resistance value

The frequency dependence of coil resistance is shown in Fig 2. The results are compared in five cases: coil only, coil and ferrite together, and coil, ferrite, and aluminum shield together, varying the distance between the ferrite and aluminum shield to 0.25mm, 1mm, and 10mm. In Litz wire coil, the resistance increases as the distance between the ferrite and aluminum shield is increased, while in the sheet coil, the increase in resistance is small. Therefore, we can see that the same trend is obtained as in the simulation in the Table 2.

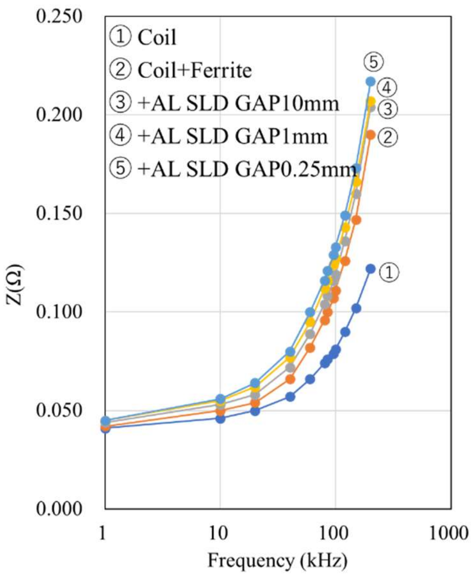

Fig.2 (a)Sheet coil

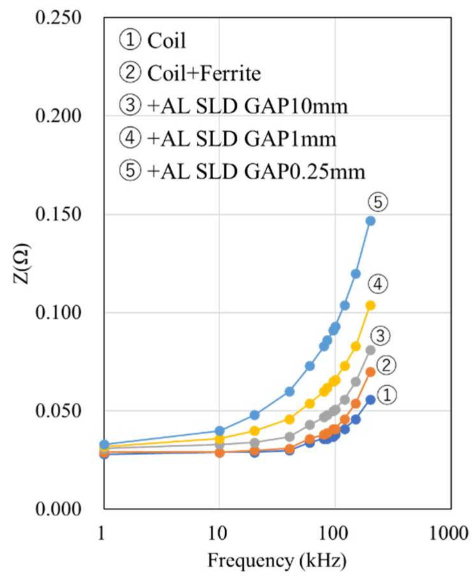

Fig.2 (b)Litz wire coil

Fig.2 coil resistance Z vs. Frequency

(2) Q-value

The ratio of the Q-values of the Litz wire coil and the sheet coil (Q of Litz wire coil) / (Q of sheet coil) versus frequency is shown in Fig 3. From the figure, the closer the distance gaps of the ferrite and the aluminum shield, the smaller the ratio of Q-value. This is due to the difference in the rate of Q value decrease as the gaps becomes smaller, and this is probably because Litz wire has a large rate of decrease, but sheet coil has a small rate of decrease. For this reason, the same trend as in the Table 1 was obtained for the Q-value.

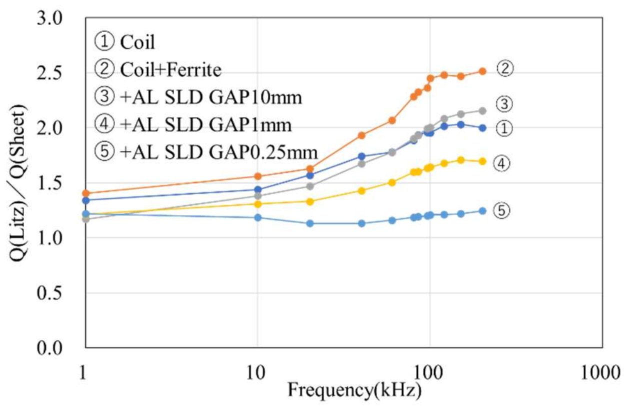

Fig.3 Ratio of the Q-values of the Litz wire coil and the sheet coil vs. frequency

2.3. Verification of VA current and losses for Litz wire coil and sheet coil

2.3.1 Coupling coefficient

The coupling coefficient in power transmission were measured using a SAE J-2954[1] conforming Litz wire GA coil and our Gen.3 sheet VA coil as shown in Fig 4. In the VA coil, the gap between the ferrite and aluminum shield was 1 mm. The Z-class was set to Z2.

A graph of coupling coefficients as a function of VA coil ground height is shown in Fig 5. The following equation was used to calculate the coupling coefficient k. Note that the inductance when the coil on one side is shorted is L_{short}, and when it is open is L_{open}.

$$k = \sqrt{1 - \frac{L_{short}}{L_{open}}} \quad \cdots (1)$$

The coupling shown are for the center and offset VA coil positions, and for the coupling in the SAE publication [1]. This shows that the coupling coefficients for both center and offset are equal or better than the SAE coil with Litz wire.

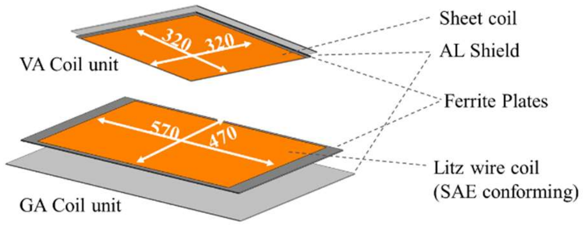

Fig.4 Power transmission test configuration

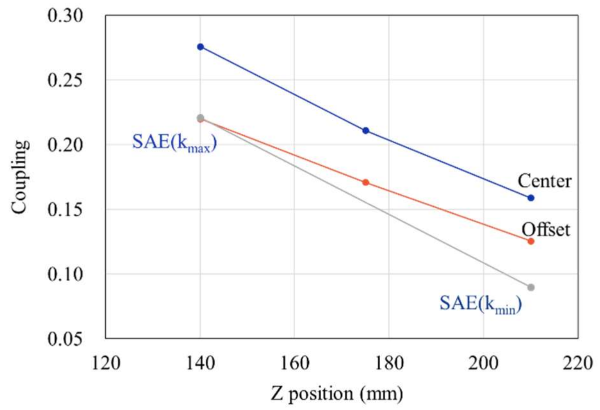

Fig.5 Coupling coefficient vs. Z position

2.3.2. Expected transmission power and losses

Next, the maximum power on the VA coil side was calculated using the following equations (2) and (3) based on the coupling coefficients in Fig 4.

$$P = \omega M I_{VA} I_{GA} \quad \cdots (2)$$

$$M = k\sqrt{L_{VA} L_{GA}} \quad \cdots (3)$$

The inductances of the VA and GA coils were measured, and the frequency was set at 85 kHz. The GA current is constant at 65 A. Also, the VA coil losses using the measured resistance of the VA coil and its percentage of the VA max power were calculated. The results are shown in Table 3.

The table shows that when the same current is applied to the Litz wire coil and the sheet coil, the sheet coil has lower loss. For example, at a VA power of around 8.5 kW, the Litz wire coil has a loss of 4.1% and the sheet coil has a loss of 3.4%, showing that the sheet coil has lower loss. The VA current is also smaller for the sheet coil, at 50A versus 75A of the Litz wire. Thus, the sheet coil can transmit power at a smaller current than the Litz wire coil and can reduce the loss.

Also, Fig 6 shows loss of VA coil vs. power, calculated in the same way as in the table for the coupling coefficients in the three cases in which the ferrite-to-aluminum shield gap of the Litz wire coil is 1 mm, 10 mm, and the gap of the sheet coil is 1 mm. This indicates that the loss of the sheet coil with a gap of 1 mm is lower than that of the Litz wire coil with a gap of 1 mm, and approaches that of 10 mm. Therefore, the loss can be reduced even when the coil unit is made thinner.

Table.3 Calculation result of max power of VA coil

Table.3 (a) Sheet coil

Coupling	VA Coil Current (A rms)	VA Power Max (kW)	VA Loss (W)	VA Loss (%)
0.126	40	6.9	185.6	2.7%
0.126	45	7.8	234.9	3.0%
0.126	50	8.6	290.0	3.4%
0.126	55	9.5	350.9	3.7%
0.126	60	10.3	417.6	4.0%
0.126	65	11.2	490.1	4.4%
0.126	70	12.1	568.4	4.7%
0.126	75	12.9	652.5	5.1%
0.126	80	13.8	742.4	5.4%

Table.3 (b) Litz wire coil

Coupling	VA Coil Current (A rms)	VA Power Max (kW)	VA Loss (W)	VA Loss (%)
0.09	40	4.6	99.2	2.2%
0.09	45	5.1	125.6	2.5%
0.09	50	5.7	155.0	2.7%
0.09	55	6.3	187.6	3.0%
0.09	60	6.8	223.2	3.3%
0.09	65	7.4	262.0	3.5%
0.09	70	8.0	303.8	3.8%
0.09	75	8.5	348.8	4.1%
0.09	80	9.1	396.8	4.4%

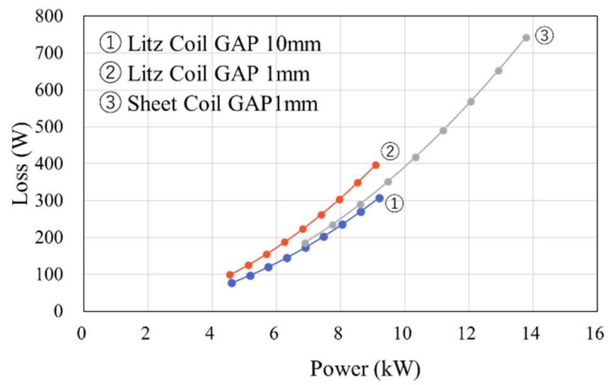

Fig.6 Coil loss vs. VA power

4. CONCLUSION

In this paper, the features of thinner and higher performance sheet coil for EV-WPT were introduced. It was shown that by improving the coil part, the increase in coil loss can be suppressed even when the distance between the ferrite plate and aluminum shield is reduced, and that a thinner VA coil unit can be produced. Measurements were performed by changing the gap between the ferrite and aluminum shield, and the results showed the same trend as in the simulation. Furthermore, the high coupling coefficient indicated that transmission is possible with a smaller amount of current than with conventional Litz wire coil.

Although the sheet coil in this report is for EV-WPT applications, it is expected that the coil technology can be applied to various applications such as automatic guided vehicles (AGV) and IH heaters.

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