Low Loss Reactor Comprising Dust Core and Copperbelt Coil

Hiroshi HASHIMOTO*1, Kyoji ZAITSU*1, Shumpei HAYASHI*1, Hiroyuki MITANI*2, Dr. Kenichi INOUE*3

*1 Electronics Research Laboratory, Technical Development Group
*2 Research & Development Planning Dept., Technical Development Group
*3 Technology Unit, Kobelco Research Institute, Inc.

To achieve the downsizing and weight reduction of voltage boosters for hybrid and electric cars, a voltage boosting reactive coil made by winding a flat, thin copperbelt of about 0.1 to 0.3 mm in thickness was contemplated. The coil was enclosed in a pot-shaped magnetic core made of pure iron powder. Numerical analysis and a model experiment indicated the possibility of making a reactor with a coil having a high-frequency loss that has been reduced to one-third to one-tenth that of conventional reactors and has excellent heat dissipating properties. This technology has enabled the downsizing of the reactor.

Introduction

With the recent global rise in environmental awareness, hybrid electric vehicles (hereinafter, HEVs) and electric vehicles (hereinafter, EVs) are spreading rapidly, thanks to their low CO_2 emissions. An HEV/EV system comprises more than one electric motor for driving and for generating power and requires the downsizing of the motors and batteries to improve the energy efficiency. To this end, each system mainly employs a power unit with a boost circuit (**Fig. 1**) that increases the battery voltage of 200-300 V to the motor-driving voltage of 400-800 V[1)-3)].

The reactor in a booster circuit is a core component that serves to boost the input voltage from the inverter with the action of, switching devices that turn on and off to alternately charge and discharge magnetic energy, and to smooth the ripple in the electric current generated during the voltage conversion. Such a reactor is required to keep its inductance at, or higher than, a predetermined value (in general, an L-value of 200-300 μH) even under a high current of several hundred amperes. Hence, it is designed to have large gap spacing so as to avoid the saturation of its magnetic core. Large gap spacing, however, increases the leakage flux from the gap and the amount of interlinkage flux into the coil conductor, increasing eddy current. As a result, the gap must often be separated into several sectors so as to minimize the amount of gap spacing per sector. Otherwise, the distance between the gap and coil must often be increased. These efforts inevitably cause an increase in the number of components and/or the upsizing of the coil.

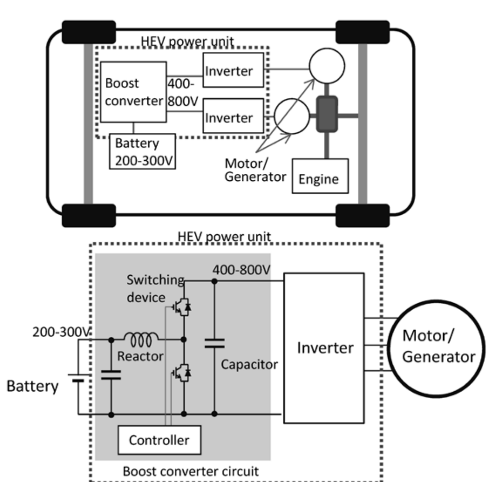

Fig.1 HEV system with boost converter circuit

Downsizing and weight reduction are imperative for any automotive components. To this end, studies are being conducted to decrease the required inductance by increasing the operation frequency (≧20 kHz) of boost converters[4)]. Increasing the frequency, however, leads to an increased loss in the reactor, posing a problem.

These problems have been solved by combining a pot-type reactor having a magnetic core made of iron powder (hereinafter, dust core) with a flatwise coil made of a copperbelt. Numerical analysis and a model experiment have demonstrated that the combination can decrease the coil loss while improving heat dissipation and thus enable the downsizing and weight reduction of the reactor. The following presents the outline.

1. Design concept and numerical analysis

1.1 Downsizing of reactor and improvement of heat dissipation performance

The basic structure of a conventional reactor is shown in **Fig. 2**. The inductance L, a major characteristic, is expressed by Equation (1):

$$L=\frac{\mu_0 \cdot S \cdot N^2}{\dfrac{\ell_c}{\mu_c}+\ell_g} \quad \cdots\cdots (1)$$

wherein S is the cross-sectional area of the flux path; ℓ_c, flux path length; ℓ_g, gap length; μ_0, vacuum permeability; μ_c:, relative permeability of magnetic core; and N, the number of turns in the coil.

Fig. 3 shows a known pot-type reactor, in which a coil is wrapped in a dust core. Such reactors have

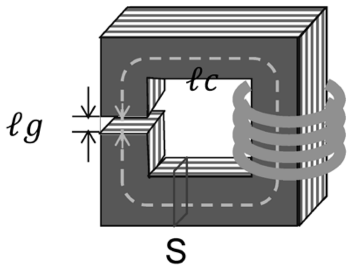

Fig. 2 Basic structure of reactor

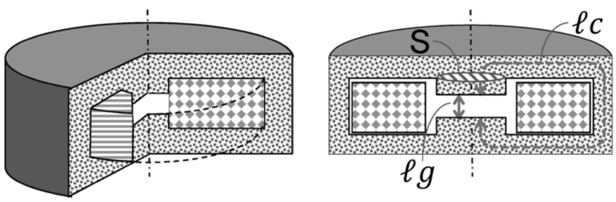

Fig. 3 Structure of pot-type reactor

been applied to noise filters with small capacities. Compared with a conventional reactor as shown in Fig. 2, a pot-type reactor has the advantage of allowing a shorter flux-path length ℓ_c and a greater flux-path cross-sectional area S. Hence, despite its smaller volume, a pot-type reactor can achieve inductance comparable with that achieved by a conventional reactor.

A pot-type reactor, however, has a coil wrapped by a magnetic core, which allows the coil to be cooled only through the magnetic core. Thus, when it comes to cooling, the pot-type reactor is at a disadvantage compared with the conventional structures. The reactors for HEVs and EVs are subject to high current. Thus it is most important for the coil to have high performance in heat dissipation. This has restricted the use of pot-type reactors.

Reactor coils are conventionally made of sheathed round wires, which have excellent workability and are inexpensive. On the other hand, from the aspect of coil cooling, the reactors for HEVs/EVs employ edgewise coils made of rectangular copper wires with large cross-sectional areas and low resistances. **Fig. 4** illustrates the heat-transfer structure of a pot-type reactor to which an edgewise coil has been adapted. This structure has an increased thermal conductivity in the radial directions; however, it suffers from inevitably poor thermal conductivity in the axial directions due to the increased number of heat transfer interfaces. Therefore, a pot-type reactor adapting an edgewise coil inevitably has the shape of an extended cylinder, which is a shape that is disadvantageous for inductance, and must be cooled from its outer circumferential surface or from the side of its central axis.

Against this backdrop, a structure was contemplated having a copperbelt wound flatwise as shown in **Fig. 5**. A heat transfer structure with a coil end in contact with the magnetic core results in low thermal conductivity in the radial direction of the reactor, but increases thermal conductivity in the axial direction, enabling cooling from the top and bottom surfaces of the reactor. This enables the reactor to have a flat shape, which is advantageous in securing inductance. In the cases of HEVs and EVs, downsizing as a whole can more easily be achieved by placing heat-generating components, such as reactors and switching elements, in contact with planar-shaped water-cooled heatsinks. Hence, the cooling structure adapting a flatwise coil is more suitable.

1.2 Reduction of coil loss during high-frequency operation

Reactor losses are classified into hysteresis loss/eddy-current loss occurring in magnetic cores and Joule loss/eddy-current loss occurring in coil conductors. As has been described, a reactor for an HEV/EV has large gap spacing, which is indispensable for avoiding the magnetic saturation of the core. This makes significant the loss due to the eddy-current generated in the conductor by the leakage flux from the gap. It is thus important to reduce the eddy-current loss in the coil to achieve, *inter alia*, downsizing and high-frequency.

Eddy current is generated in a coil when external magnetic flux intersects with the copper wires of the coil. The eddy current can be minimized if the copper wire is made sufficiently smaller in diameter than the skin depth of the eddy current; however, there is a trade-off in that the smaller the cross-sectional area of a lead the greater the direct current

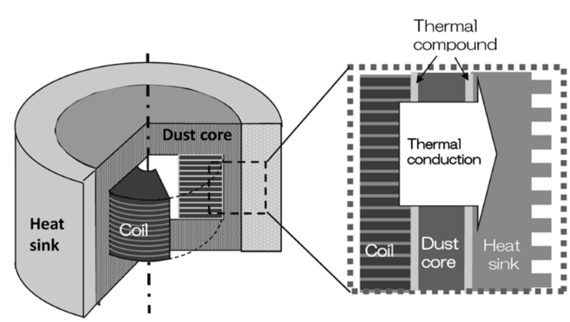

Fig. 4 Heat transfer structure of edgewise coil

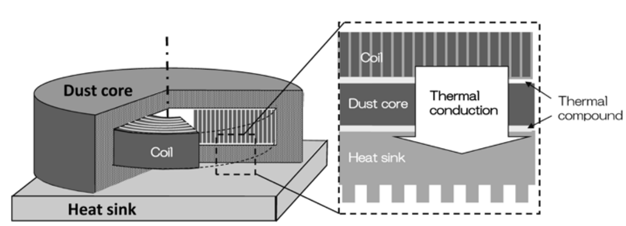

Fig. 5 Heat transfer structure of flatwise coil

(DC) resistance, which increases copper loss (i.e., Joule loss).

The skin depth δ of eddy current flowing in a conductor is given by Equation (2):

$$\delta=\sqrt{\frac{2}{\omega\mu\sigma}} \quad \cdots\cdots (2)$$

wherein ω is angular frequency, μ is the magnetic permeability of the conductor, and σ is the electrical conductivity of the conductor. That is, the higher the frequency the shallower the skin depth δ. **Fig. 6** shows the relationship between skin depth in copper coil and frequency $f\,(=\omega/(2\pi))$.

Now let us compare the eddy currents in the conventional and in the newly proposed structures used for pot-type reactors with large gap spacing. A copperbelt having a thickness of 0.3 mm and a width of 20 mm was made into a edgewise coil (DC resistance, 16 mΩ), which was adapted for a pot-type magnetic core with a gap spacing of 10 mm. As shown in **Fig. 7** (a), the flux crosses the wide surface of the coil, generating eddy current in the coil.

The magnetic field created by the eddy current in the coil is applied in the direction that cancels the magnetic flux of the reactor, which, as a result, decreases the inductance of the reactor. For this setting, the relationships of the operating frequency, inductance and alternating current (AC) resistance were analyzed using electromagnetic-field-analysis software (ANSYS Maxwell). The results are shown in **Fig. 8** and **Fig. 9** (blue line).

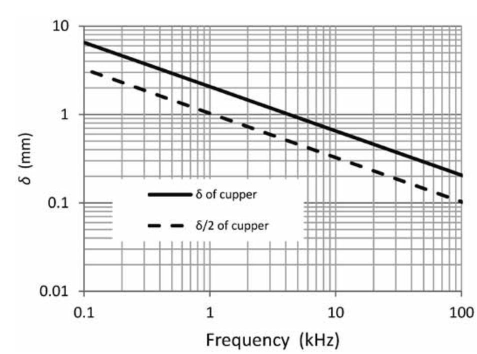

Fig. 6 Relationship between skin depth in copper coil and frequency

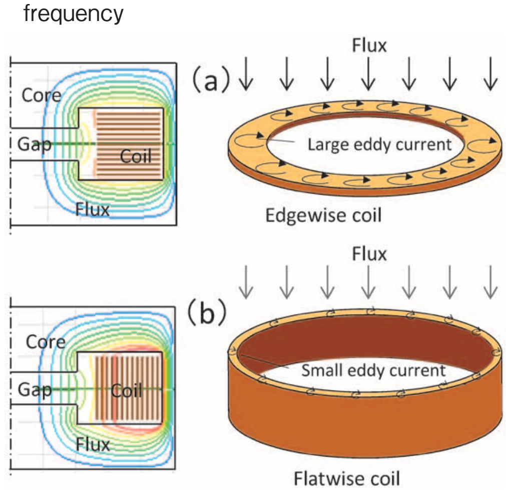

Fig. 7 (a) Eddy current in edgewise coil
(b) Eddy current in flatwise coil

In the case of the edgewise coil, the inductance decreases with increasing frequency. As shown, the inductance at the operating frequency of 10 kHz is almost 15% smaller than that at low frequency (100 Hz). The AC resistance at the operating frequency of 10 kHz becomes as high as 0.2 Ω, which is a factor of 12 greater than the direct current resistance of 16 mΩ.

Next, we studied eddy-current loss *Pe* occurring in the coil. As expressed by Equation (3), the value of *Pe* is calculated from the second power of the alternating current flowing through the reactor, and the AC resistance:

$$P_e=R_{ac}\cdot I_{ac}^{\,2} \quad \cdots\cdots (3)$$

wherein R_{ac} is the AC resistance, and I_{ac} is the effective value of the alternating component of the current flowing through the reactor.

The effective value, I_{ac}, of the alternating component of the current flowing through the reactor is approximated by Equation (4):

$$I_{ac}\cong\frac{V_i\left(1-\frac{V_i}{V_o}\right)}{4Lf} \quad \cdots\cdots (4)$$

wherein V_i is the voltage before booster; V_o, voltage after booster; L, inductance; and f, operating frequency.

For the voltage before booster of 200 V, voltage after booster of 600 V, reactor inductance of 300 μH

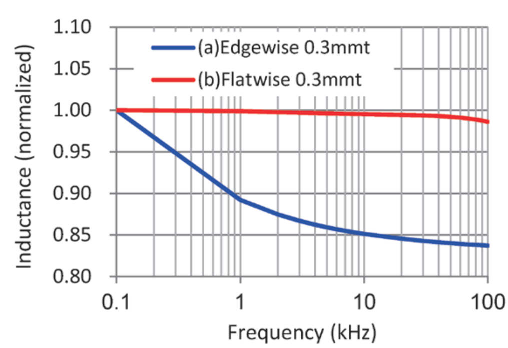

Fig. 8 Inductance frequency response (analysis)

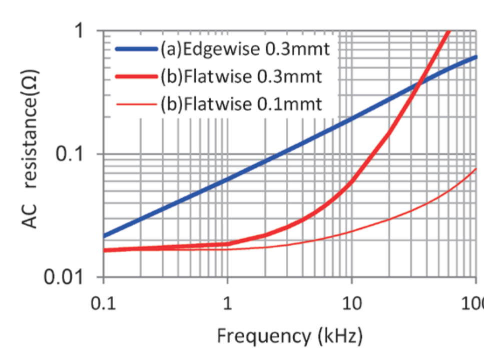

Fig. 9 AC resistance frequency response (analysis)

and operating frequency of 10 kHz, Equation (4) yields the alternating current I_{ac} of 11 A. Given the AC resistance of 0.2Ω, Equation (3) yields the coil eddy-current loss of 24 W.

In contrast, when a flatwise coil as shown in Fig. 5 is adapted for a pot-type reactor, the flux generated in the coil space of the reactor penetrates through the copperbelt in the transverse direction of the copperbelt, as shown in Fig. 7 (b). Here, the thickness, t, of the copperbelt is set to be equal or smaller than half the skin depth, which makes the eddy current in the copperbelt small enough to prevent the decrease in inductance and the increase in AC resistance, the aforementioned problems encountered when using an edgewise coil. The upper limit, $\delta/2$, for the copperbelt thickness is depicted by the broken line in Fig. 6. For example, in the case of a typical reactor for current HEV/EV, operating at a frequency of approximately 10 kHz, a copperbelt thickness of 0.35 mm or smaller should suppress the eddy current effectively. For the operating frequency of 40 kHz, envisaged in the further downsizing of reactors, a copperbelt thickness of 0.15 mm or smaller would serve the purpose.

As an example, a magnetic field analysis was conducted on the case where a copperbelt of 0.3 mm thick and 20 mm wide is fabricated into a flatwise coil (direct current resistance, 16 mΩ) and is adapted to a magnetic core with a gap spacing of 10 mm. The resulting inductance and AC resistance are shown in Fig. 8 and Fig. 9 (red line). Unlike the edgewise coil, the flatwise coil has an inductance that remains almost unchanged in the range from low frequency to 10 kHz. Its AC resistance at 10 kHz is about 60 mΩ, which makes the eddy-current loss of the coil in the aforementioned booster operating condition to be 7 W, the value suppressed to 1/3 or less of the loss for the edgewise coil. It should be noted, however, that the higher frequency decreases the skin depth; and, in the high frequency region where $\delta/2$ becomes smaller than 0.3 mm, the AC resistance increases rapidly.

Hence, operation in the higher-frequency region requires a copperbelt having a thickness of half the skin depth ($\delta/2$), or thinner, at that operating frequency. Fig. 9 (red thin line) depicts the AC resistance for a copperbelt thickness of 0.1 mm, in which case, the AC resistance is suppressed up to 100 kHz, the frequency corresponding to $\delta/2$.

As has been described, winding a copperbelt with a thickness suitable for the operating frequency, in a flatwise manner makes possible a reactor with small eddy-current loss and excellent inductance characteristics at high frequencies.

2. Model experiment

Two models having pot-type dust cores with wide gap spacing, as described previously, were prepared, one including an edgewise coil (Coil a) and the other including a flatwise coil (Coil b). Their inductance, AC resistance and the heat transfer performance of their coils were measured. **Fig.10** shows the construction of the dust cores used in this model experiment. The specifications of the coils are shown in **Table 1**, and the design parameters of the reactors are shown in **Table 2**. Each dust core was made of insulated magnetic powder having an average grain size of approximately 100 μm or smaller so as to sufficiently minimize the eddy current loss that occurs in the magnetic core.

The analysis assumed a conductor model comprising an edgewise coil 0.3 mm thick and 20 mm wide; however, such a coil turned out to be difficult to wind. Hence, the measurement model adopted a thickness of 0.8 mm and a width of 10 mm.

2.1 Measurement results for electrical characteristics

The inductance-frequency responses of the coils were measured as their electrical characteristics when inserted in dust cores. The results are plotted in **Fig.11**. Also shown in the figure are the curves obtained by numerical analyses conducted under the same conditions as the experimental models.

The edgewise coil (Coil a, blue line) exhibits inductance decreasing as the frequency increases,

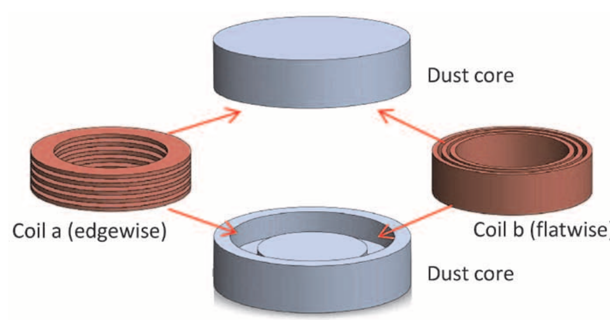

Fig.10 Construction of experimental models

Table 1 Coil specifications

	Inside diameter (mm)	Outside diameter (mm)	Wire diameter (mm)	Wire turns	weight (g)	DC resistance (mΩ)
Coil a (Edgewise)	60	80	0.8t×10	23	320	12.7
Coil b (Flatwise)	65	80	0.3t×20	23	260	16.5

Table 2 Design parameter of reactor

	S (mm^2)	ℓc (mm)	ℓg (mm)	μ_c	Wire turns
Design parameter of reactor	1,900	140	10	90 - 110	23

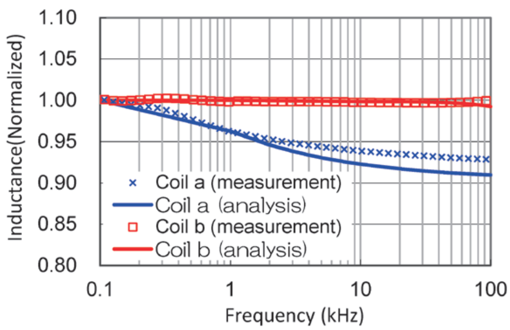

Fig.11 Inductance frequency response

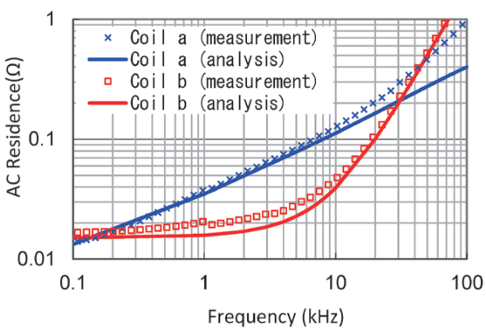

Fig.12 AC resistance frequency response

and the inductance at 10 kHz is approximately 6% smaller than that at a low frequency of 100 Hz. The flatwise coil (Coil b, red line), on the other hand, exhibits an almost constant inductance up to a frequency of 100 kHz. In the case of the flatwise coil, the experimental results agree well with what was predicted by the numerical analysis. In the case of the edgewise coil, the analysis and experiment agree in the frequency range lower than several kHz or so; however, the analysis cannot fully reproduce the behavior of the coil eddy current in the high-frequency range, causing an error of approximately 2%.

Fig.12 shows the AC resistance-frequency responses of the coils, including the analysis values and measured values. The flatwise coil made of 0.3 mm thick copperbelt exhibits lower AC resistances, which are suppressed lower than those of the edgewise coil, in the frequency range lower than about 10 kHz. Thus, appropriately selecting the copperbelt thickness for a flatwise coil in accordance with the operating frequency enables a significant reduction of eddy-current loss occurring in the coil. It should be noted, however, that although the results of experiment and numerical analysis agree with a high accuracy for the flatwise coil, the edgewise coil exhibits a significant discrepancy between the analyzed and measured values as the frequency increases to over 10 kHz. There remains an issue of analysis accuracy in the high-frequency range.

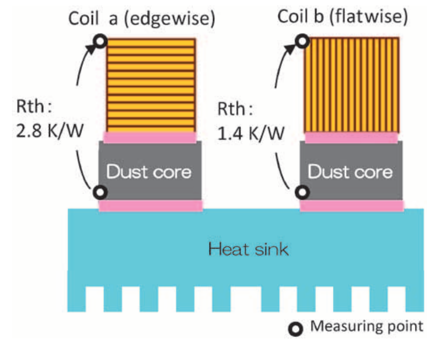

Fig.13 Thermal resistance of coils

2.2 Heat dissipation characteristics

The thermal conductance/resistance was measured for edgewise and flatwise coils and the results are shown in **Fig.13**.

In this experiment, a resin with a thermal conductivity of 1.1 W/mK was coated on the interface between the copperbelt in each coil and each dust core. Direct current of approximately 50 A was applied so as to induce a loss of 30 W in the coil. The resulting thermal resistance, *Rth*, between the top of the edgewise coil and the dust core was 2.8 K/W, and that between the top of the flatwise coil and the dust core was 1.4 K/W. The thermal resistance of the flatwise coil had decreased to half of that of the edgewise coil, confirming the excellent heat transfer characteristics of the flatwise coil.

3. Discussions

Table 3 summarizes, for comparison, the characteristics measured for both models. Compared with the currently predominantly-used edgewise model, the newly proposed flatwise model is superior in exhibiting smaller AC resistance at approximately 10 kHz, the frequency in the operating frequency range for current HEVs/EVs, and in heat transfer to heatsinks. As described in Section 1, selecting a copperbelt thickness of less than half the skin depth that corresponds to the operating frequency can further significantly reduce the AC resistance, i.e., the eddy-current loss of the coil, during high-frequency operation. Hence, adapting the newly proposed structure to reactors for the power units for HEVs/EVs, the units required to

Table 3 Summary of experimental results

	Inductance reduction rate(%)	AC resistance (mΩ)	Thermal resistance (K/W)
Condition	10Hz to 10kHz	@10kHz	From coil to core
Coil a (Edgewise)	−6	130	2.8
Coil b (Flatwise)	0	50	1.4

accommodate high current, which are to be downsized, will enable the gaps to be widened to suppress the magnetic saturation at high current and allow the operating frequency to be increased for downsizing.

Edgewise coils require special plastic working in the coil winding process, which makes thin copperbelts difficult to fabricate for use at high frequencies. By contrast, flatwise coils can be made by a simple tape-winding process and are more advantageous in terms of process cost.

The low-loss reactors herein proposed, comprising dust cores and copperbelt coils, are applicable not only to HEVs/EVs, but also to other booster reactors and AC filters for power conditioners used in renewable energy applications that are subject to power variation.

Conclusions

It has been demonstrated that combining a pot-type dust-core reactor with flatwise coil made of a copperbelt [5),6)] can realize a reactor that operates at high current with high-heat-dissipation and is suitable for HEV/EV applications. Also demonstrated was the fact that selecting a copperbelt thickness for the operating frequency can significantly reduce eddy-current loss occurring in the coil. The reactors for HEVs/EVs are expected to be downsized thanks to the proposed structure exploiting the features of dust cores.

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