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Application-specific micro Rogowski coil for power modules -Design tool, novel coil pattern and demonstration-

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Abstract

We developed a printed circuit board "Rogowski coil" to improve the reliability of power modules and packages. For the design, we used a new tool for sensitivity and adopted a fishbone coil pattern to realize design sensitivity. The developed coil demonstrates flat sensitivity that is as good as that of commercialized current probes/sensors because the proposed coil pattern successfully cancels noise from an outside current with flat signal sensitivity by an inside current.

1 Introduction

Power devices and modules require high reliability because they are increasingly demanded as key devices in an energy-saving society. To realize highly reliable power modules, the current distribution of each chip and the total current of modules should be measured.

Current transformers (CT) and Rogowski coils, as representative commercialized current sensors (see Figure 1), are widely applied in many power electronics equipment as built-in sensors or used in experiments. However, they are too large to put in power modules, even considering the recent low-profile modules for low stray inductance [1,2]. In addition, it is difficult to utilize many sensors because they are expensive. In previous studies, the influence of outside current was theoretically large or not discussed [3-7]. Therefore, we developed a small, thin, low-cost Rogowski coil with Printed Circuit Board (PCB) technology. The PCB Rogowski coil can be put on chips or bonding wires. Therefore, it can be used for chip current monitoring as a built-in sensor in power modules/packages or applied for current distribution analysis in modules (see Figure 2).

	Commercialized Sensor 1 (Rogowski coil)	Commercialized Sensor 2 (CT)
Size of the sensor	25, 1.7 [mm]	16, 28 [mm]
Flexibility of the sensor	Have some flexibility	Solid
High frequency characteristic	~30MHz	~70MHz
Uniformity of sensitivity inside current	±3%	No data
Noise by outside current	No data	No data
Size of the amplifier	Need a large amplifier (18.3cm×9.3cm×3.2cm)	Amplifier unnecessary
Cost	expensive	expensive

Figure 1 Features of a typical commercialized current sensor

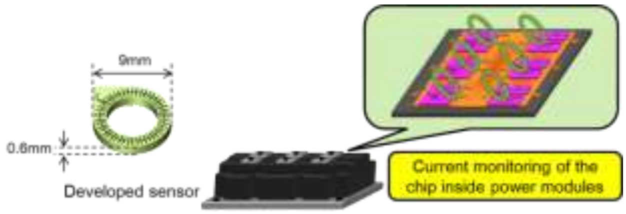


Figure 2 Application example of the power modules of the developed sensor

2 Original design tool development

We developed an original design tool using MATLAB to calculate the mutual inductance between the coil and hundreds of thousands of current flow points. The calculation speed is at least one hundred times faster than the speed of commercialized tools, which means that the developed tool is able to perform the calculation in 30 minutes, while it takes a couple of days using commercially available tools. In the design tool, the mutual inductance per turn of the Rogowski coil is calculated by Neumann's formula. The mutual inductance of the Rogowski coil is calculated by adding together the mutual inductance per turn of the Rogowski coil (see Figure 3). Furthermore, for improving calculation speed, the design tool incorporates two approaches. The first approach is that mutual inductance is calculated by using a simplified model of the Rogowski coil to reduce complicated calculations with the connecting line of each turns and the return line. The second approach is that the mutual inductance is calculated in advance and tabulated as a function of the distance

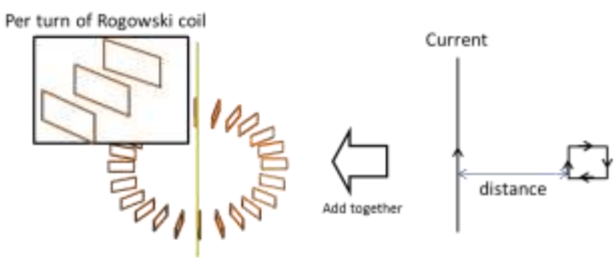


Figure 3 Simplified model for calculating mutual inductance of the Rogowski coil

in order to eliminate integral calculation including Neumann's formula. With this tool, the sensitivity and some of the noise can be estimated in advance and developed to a practical level despite the arbitrary geometry (see Figure 4).

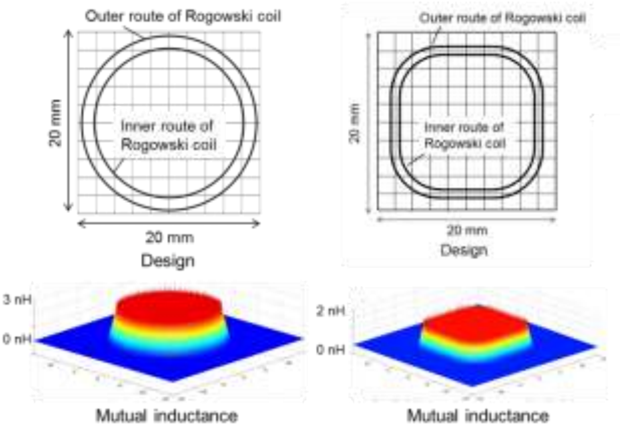


Figure 4 Mutual inductance to current path for arbitrary geometries with original MATLAB based design tool

3 Novel Rogowski coil

3.1 Novel Rogowski coil pattern

We propose a fishbone coil pattern with PCB technology to cancel the noise by outside current. The coil board is composed of the PCB in four layers. The main pattern is made up of the first layer, the fourth layer and through-holes.

We produced four coil patterns such as fishbone, triangle, saw, and fishbone without a return line experimentally in order to evaluate noise by the outside current and sensitivity by the inside current (see Figure 5). The influence of the outside current is reduced by removing unnecessary magnetic flux pathways with a novel pattern and return line. The concept of the proposed fishbone coil pattern is to eliminate unnecessary magnetic flux pathways to the utmost limit of the PCB technology. The other triangle and saw coil patterns cancel out the noise of the outside current by unnecessary magnetic flux. The coil board is sufficiently small and thin compared to the commercialized current sensor/probe (see Figure 6). Non-clamp and clamp sensor types have been developed.

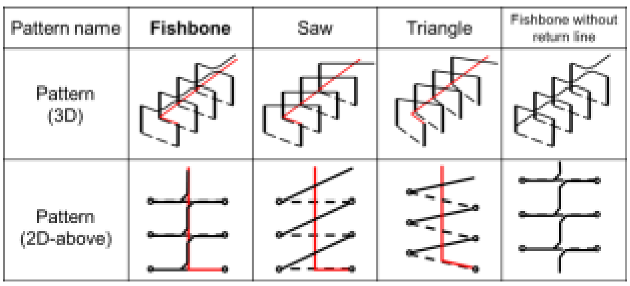


Figure 5 Proposed fishbone pattern and typical coil pattern with PCB technology

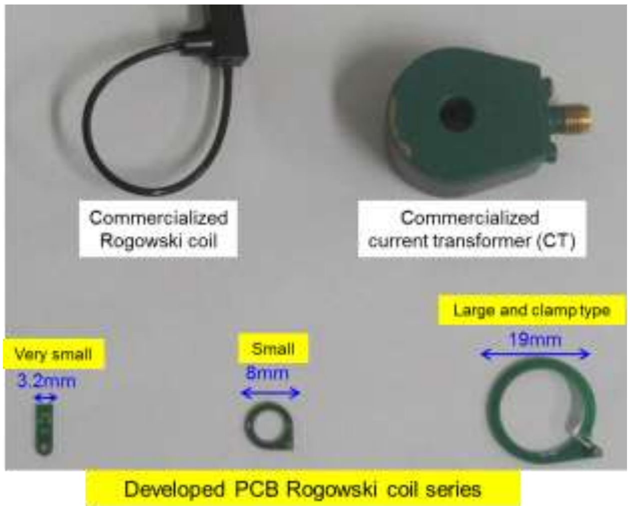


Figure 6 Developed PCB Rogowski coil and commercialized sensors/probes (The size is the outer diameter of the Rogowski coil)

3.2 Experimental evaluation of noise and sensitivity

The noise and sensitivity were evaluated by scanning in every direction with a 9-mm diameter coil (see Figure 7). Figure 7, (a) - (d) show the evaluation method of the influence of the outside current of the coil board and (e) is the evaluation method of the sensitivity by the inside current of the coil board. All values of the evaluation were the signal ratio to the center of the hole in the coil board. In the case of the outside current of the coil board, the coil and the current wiring were evaluated in contact through a 0.1-mm thick insulation sheet.

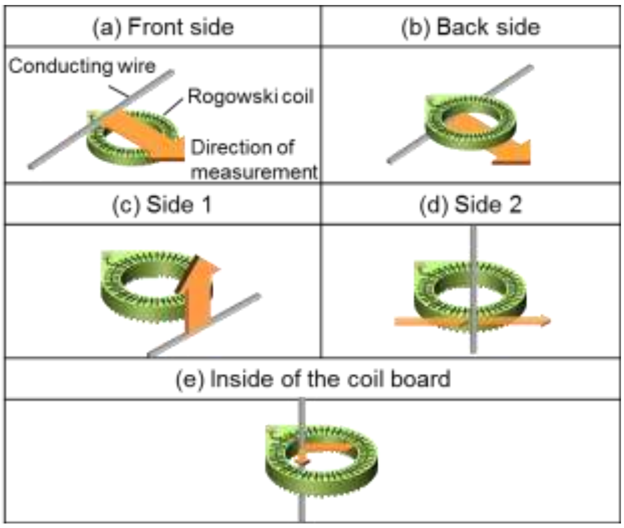


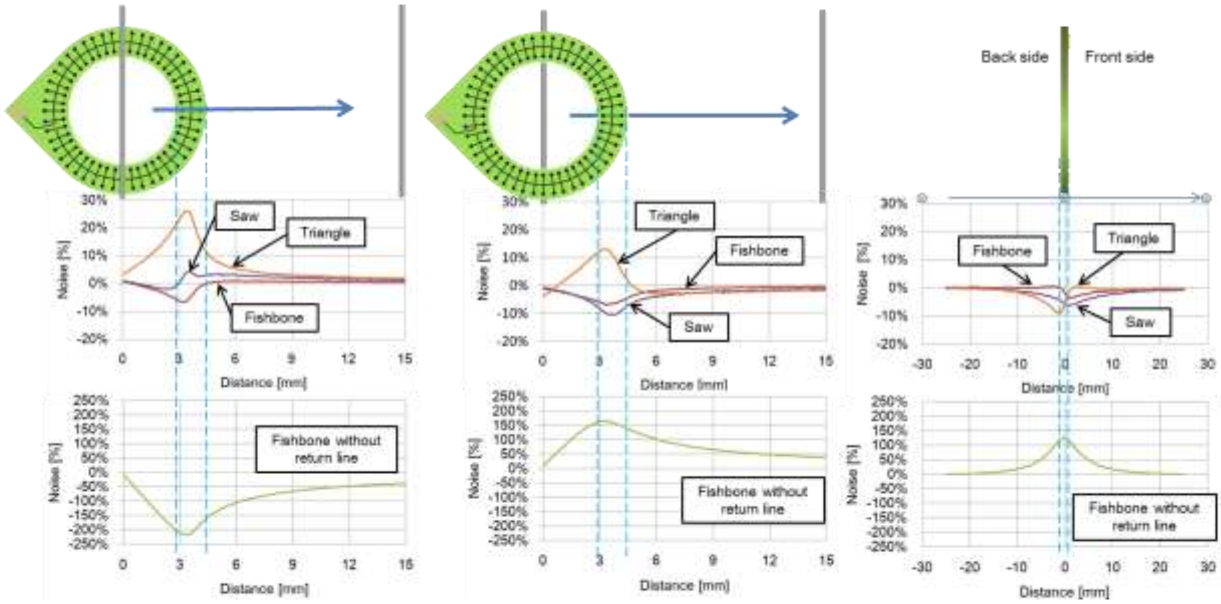
Figure 7 Noise and sensitivity evaluation methods by each direction scanning

As a result, the proposed fishbone structure canceled the noise most by the outside current (see Figure 8). The details are shown below. Evaluations of the front side and the back side showed the peak of the noise on top of the return line (see Figure 8 - (a), (b)). The unnecessary magnetic flux path around the return line was easily affected compared to the other part. As shown in Figure 8 - (a), the saw pattern had the smallest noise of 4%. As shown in Figure 8 - (b), the fishbone pattern had the smallest noise of 5%. As shown in Figure 8 - (c), the fishbone pattern was excellent compared with the other patterns. As shown in Figure 8 - (d), all patterns with a return line had very small noise such as ± 0.7%. Evaluation of Side Path 2 showed very small noise compared with evaluation of the front side, the back side, and Side Path 1 because the unnecessary magnetic flux path was smaller than the other scanning direction. However, the fishbone without the return line showed noise at approximately 7% because the current wiring was not perfectly vertical to the coil board in the experiment. In total, the maximum noise in each of the coil patterns was 7% for fishbone, 10% for saw, 26% for triangle and 218% for fishbone without a return line. The noise of the proposed fishbone pattern will become smaller and smaller with advancement of PCB technology. The sensitivity error was from -1.1% to 0.7% thanks to the return line (see Figure 7 - (e)).

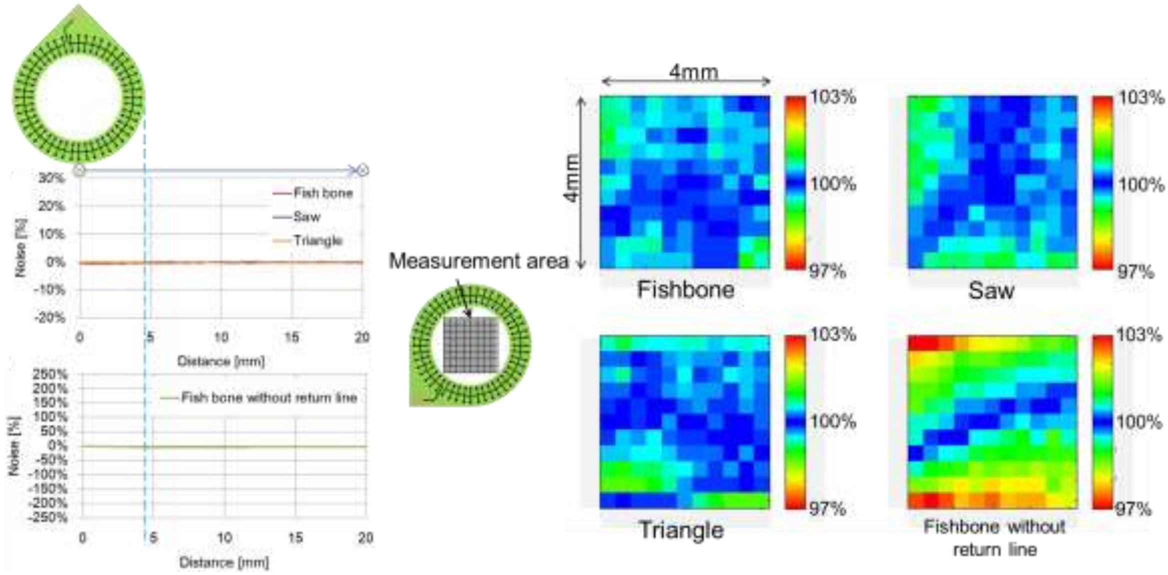
3.3 Frequency characteristic

The frequency characteristic was measured by using an impedance analyzer and the output voltage of the coil with the amplifier. The diameter of the measured coil was 9 mm and 3.2 mm.

The frequency characteristic of the coil's impedance was proportional to the frequency up to 110 MHz (see Figure 10). This indicates that the self-inductances of the coils were constant over 110 MHz. It was not possible to evaluate over 110 MHz with the maximum frequency of the impedance analyzer used in the experiment. The maximum output voltage of the coil was also proportional to



(a) Noise of the front side path **(b)** Noise of the back side path **(c)** Noise of Side Path 1



(d) Noise of Side Path 2 **(e)** Experimental evaluation of sensitivity in the hole

Figure 8 Experimental evaluation of noise and sensitivity in the hole (Central signal is 100 %)

the frequency over 10 kHz from several tens of kHz (see Figure 10). From this result, we can confirm the constant mutual inductance in the frequency range. The output voltage of the coil with the amplifier was constant from 10 kHz to over 10 MHz (see Figure 11). We could not measure frequency characteristics over 10 MHz because the measurement limit of the signal source in our laboratory was 10 MHz. The frequency region of the output voltage from the amplifier could be adjusted by the amplifier because the self-inductance of the sensor was constant in a wide frequency range. The features of the developed sensor were confirmed by actual measurement (see Figure 12). The frequency characteristics and sensitivity uniformity of the developed sensor were almost the same as those of a commercially available sensor. Therefore, it is sufficient for switching waveform measurement.

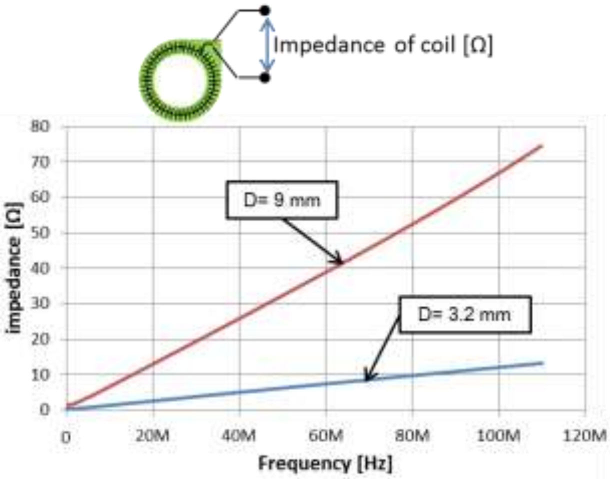


Figure 9 Experimental frequency characteristic of the impedance of the coil only

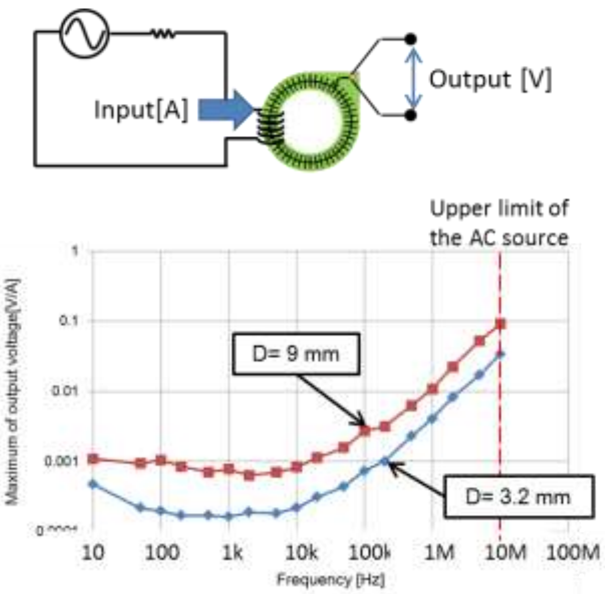


Figure 10 Experimental frequency characteristic of the output voltage of the coil only

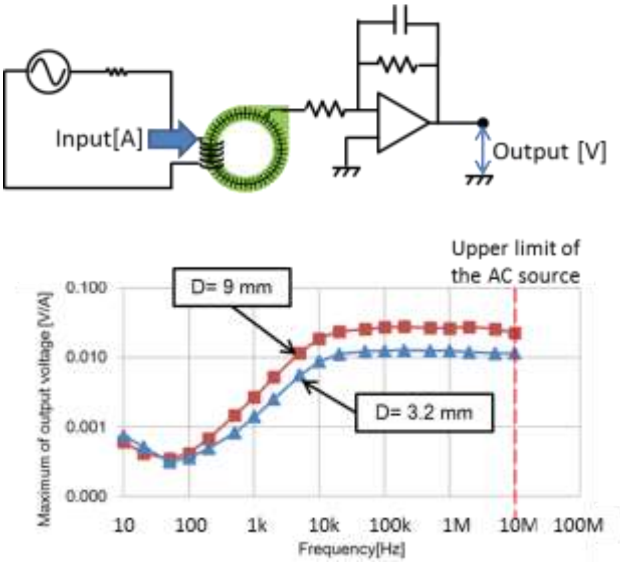


Figure 11 Experimental frequency characteristics of output voltage of the coil with the amplifier

Size of the sensor		0.3cm × 0.3cm × 0.06cm
Flexibility of the sensor		Solid but design is flexible
High frequency characteristic		~>100MHz(Rogowski coil only)
Uniformity of sensitivity inside current		±1%(circle geometry)
Noise by outside current		Maximum 7 %
Size of the amplifier	?	Under developedment
Cost		Inexpensive

Figure 12 The features of the developed sensor

4 Demonstration

The current monitoring is demonstrated with parallel IGBT chips on Direct Copper Bonded (DCB) substrate (see Figure 13). The switching circuit has a resistive load of 5 Ω and DC voltage is set to 180 V. The PCB Rogowski coil of diameter 10.4 mm is put on the bonding wire of both IGBT chips, and a CT is put on the wiring of the total current path. The current waveform is changed with gate resistance (R_G). In the case of connecting the same R_G, the signals of PCB Rogowski coil show the same output results (see Figure 14). The signals of the PCB Rogowski coil show valid results for R_G value. The current difference during turn-off is larger with different R_G (see Figure 15). The sum of signal waveforms is the same as the current waveform. Current monitoring with a very small PCB Rogowski coil of diameter 3.2 mm is also successfully demonstrated (see Figure 16). The PCB Rogowski coil is put on the terminal of the TO-220 package.

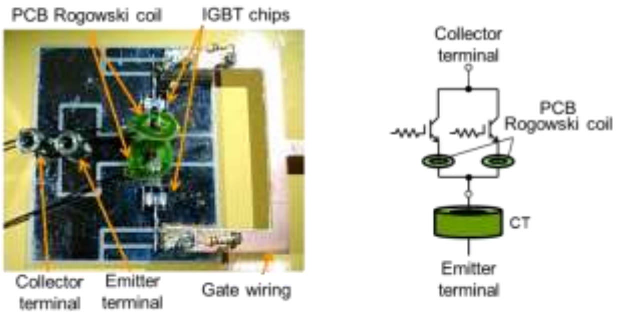


Figure 13 Setup of parallel IGBT chips with the position of the PCB Rogowski coil and CT for circuit

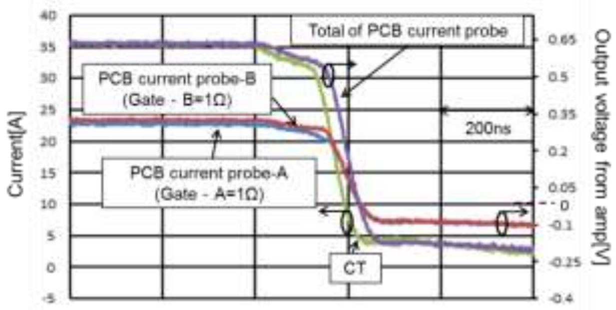


Figure 14 Current and signal waveforms under balanced R_G of parallel IGBT

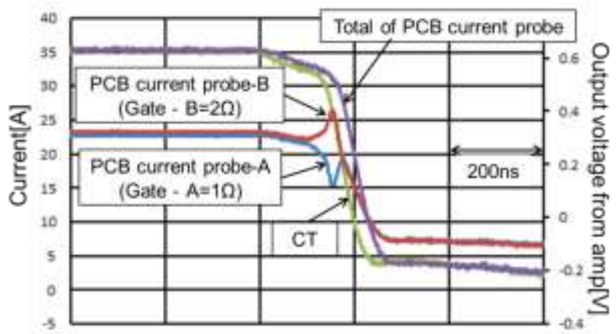


Figure 15 Current and signal waveforms under unbalanced R_G of parallel IGBT

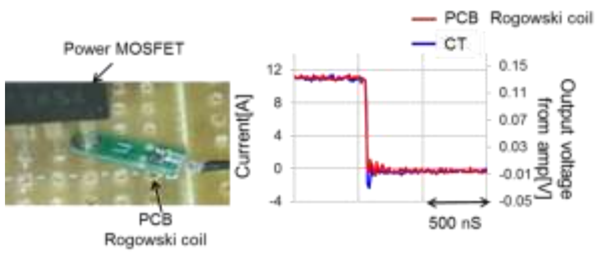


Figure 16 Demonstration with a very small Rogowski coil

5 Conclusion

We used a newly designed tool and proposed a fishbone coil pattern for design sensitivity of the PCB Rogowski coil and realization of the designed sensitivity. The developed coil thin, small, and low cost demonstrated flat sensitivity as good as commercialized current probes/sensors because of the proposed coil pattern cancel noise with flat signal sensitivity. The frequency band is substantiated that the coil is over 110 MHz. It can be used for chip current monitoring as a built-in sensor in power modules and package or applied for module current analysis.

6 References

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