Implementation and Performance of a Current Sensor for a Laminated Bus Bar

Yoshikazu Kuwabara, Student Member, IEEE, Keiji Wada, Senior Member, IEEE, Jean-Michel Guichon, Jean-Luc Schanen, Senior Member, IEEE, and James Roudet

Abstract—This paper proposes a current sensor embedded in a laminated bus bar. The proposed sensor is based on the Rogowski coil principle: the sensor can detect the magnetic flux corresponding to a derivative waveform of the current in a laminated bus bar. The electrical stray elements of the sensor depend on its geometry. The magnetic flux generated by the bus bar depends on the current repartition which is a function of the equivalent frequency during current transients. Both phenomena are discussed using partial element equivalent circuit (PEEC)-based software. Thanks to these investigations, the sensor is designed to measure switching waveforms. It is confirmed that the verification of the proposed current sensor embedded in a laminated bus bar can perform the measurement of switching waveform using a buck converter circuit rated at 50 V and 8 A.

Index Terms—Current sensor, Frequency characteristic, Laminated bus bar, Rogowski coil.

I. INTRODUCTION

Power converter circuits are widely used in several applications for realizing higher-efficiency power converter circuits. Modern converters use high-speed SiC and GaN power devices that are highly sensitive to stray inductances [1][2]. Therefore, it is difficult to insert a current sensor or probe in the circuit because the stray inductance is increased by inserting these sensor or probe. Current sensors may be used for several purposes. For example, device protection, control loop, or even switching losses determination [3][4]. The specific feature of the proposed sensor is that it can measure the current with very few modifications of the inductance of the switching cell because it is embedded in the bus bar circuit.

Recently, integrated current sensors for power converter circuits have been proposed based on the giant magnetoresistive (GMR) effect [5][6] or on shunt resistors [7][8]. In addition, current sensors based on the Rogowski coil principle [9] have also been proposed for power converter circuits. These current sensors of Rogowski coil are considered to measure accurate current waveforms[10]. The structure of the sensors and the electronic circuit are also discussed[11]-[15]. Although this solution has been used to measure the drain current of MOSFETs [16][17], it is very sensitive to external fields around the sensor; therefore, its measurement accuracy is sometimes limited. This paper proposes to use a detection coil inserted in the insulation thickness of the DC laminated bus bar [18]-[21] widely used in high-power-density converters. Therefore, the bus bar will act as a magnetic shield against external fields. The current repartition inside the bus bar may vary with increasing frequency; therefore, this effect should be taken into account in the sensor design to carefully choose its geometry and location according to possible variations in the gain against frequency. Finally, owing to the high proximity of the bus bar, capacitive effects cannot be neglected, and have been considered in order to study the limitations of the bandwidth.

The paper is organized as follows. A brief discussion on the detection principle is presented in Section II. Section III proposes a modeling method for both the inductive and capacitive parameters, and investigates whether the proposed design allows obtaining a constant gain and robustness against an external field. All inductive and capacitive parameters are modeled in Section IV to provide an equivalent circuit of the sensor in order to investigate its bandwidth. Section V will validate the proposed concept and compare previous results with an experimental implementation in printed circuit board (PCB) using a buck converter circuit rated at 50 V and 8 A.

II. CURRENT DETECTION

A. Current Detection Principle

Fig. 1 shows an example of a power converter circuit using a laminated bus bar. A laminated bus bar between power devices and DC capacitors is used to provide a connection, while maintaining a low stray inductance. In order to detect the bus-bar current, this paper proposes a current sensor based on the Rogowski coil principle without any magnetic component. The structure of the proposed current sensor is shown in Fig. 2(a). Fig. 2(b) shows the sensor embedded in a laminated bus bar. To simplify the realization in this preliminary study phase, the bus bar and the sensors have been realized using multilayer PCBs. The top and bottom layers include the wiring of the laminated bus bar, while the middle layers include the detection coil of the proposed current sensor. This sensor is fabricated using a double-sided PCB, and the connections between both sides are made using via.

Fig. 3 shows the wiring structure of the detection coil. The relationship between the current direction in the laminated bus bar and the magnetic flux direction crossing the sensor is orthogonal. The output voltage of the sensor corresponds to the derivative waveform of the bus-bar current. In order to calculate the bus-bar current, a numerical integration of
Fig. 1. Example of power converter circuit using a laminated bus bar.

(a) Exploded view. (b) Structure of the current sensor.

Fig. 2. Illustration of the PCB implementation.

Fig. 3. Detection coil wiring structure.

(c) Middle layer (d) Side view of the sensor

Fig. 4. Consideration parameters of bus bar embedded Rogowski coil.

Fig. 5. Mutual inductance $M$ at each $h_{coil}$.

Fig. 6. Laminated bus bar inductance $\ell_{bus}$ at each $h_{bus}$.

Fig. 6 shows the impact of the thickness $h_{bus}$. The $h_{coil}$ affects the mutual inductance because it modifies the Rogowski coil cross section and the amount of magnetic field captured by the coil. However it is worth noting that $h_{coil}$ also impacts the distance between the two sheets of the bus bar, leading to a potential increase of its stray inductance, which has to be limited. There is thus a trade-off for this $h_{coil}$ parameter. In case of changing $h_{coil}$, the distance between the bus bar and the Rogowski coil $h_{cb}$ is kept to 1.6 mm. From Fig. 5, the thickness of the Rogowski coil $h_{coil}$ has a proportional tendency and the mutual inductance is changed directly. From Fig. 6, the laminated bus bar inductance $\ell_{bus}$ is increased when the thickness of laminated bus bar $h_{bus}$ is extended. From these results, it is confirmed that the ratio of the change in the laminated bus bar inductance is less than that of the mutual inductance. Therefore, it is possible to use the current sensor with keeping the laminated bus bar inductance low if the thin structure current sensor is used. TABLE I. shows the summary of the relationship between sensor geometry and the stray parameters. In the proposed application, the expected $\frac{di}{dt}$ is about few kA/μs, and the sensor maximum voltage has been limited to 5 V, in order to keep it compatible with future measurement system. Therefore, the mutual inductance between the sensor and the bus bar has been designed in order to reach 10nH. The thickness of the sensor is set to 4.8 mm and $h_{coil}$ is 1.6 mm,

the output voltage $v_{coil}$, is be applied. To design the sensor, the mutual inductance between the laminated bus bar and the proposed current sensor has to be evaluated.

III. EQUIVALENT CIRCUIT MODELING OF THE PROPOSED CURRENT SENSOR

A. Sensor design

Fig. 4 illustrates the various parameters defining the sensor’s geometry. The thickness of the Rogowski coil $h_{coil}$, distance between the bus bar and the Rogowski coil $h_{cb}$, length $l_{c}$, width $w_{c}$, and number of turns $N$. Fig. 5 shows the evolution of the mutual inductance depending on the thickness $h_{coil}$, and
TABLE I
SUMMARY OF GEOMETRICAL IMPACT

<table>
<thead>
<tr>
<th>Thickness $h_{coil}$ (mm)</th>
<th>$M$ (nH/mm or nH/turn)</th>
<th>$\ell_{bus}$ (nH/mm)</th>
<th>$\ell_{coil}$ (nH/mm)</th>
<th>$C_{bus}$ (pF/mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>very effect (7.66)</td>
<td>effect (1.47)</td>
<td>very effect (216)</td>
<td>very effect (-21.4)</td>
<td></td>
</tr>
<tr>
<td>Distance $h_{cb}$ (mm)</td>
<td>effect (-0.414)</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Length $l_c$ (mm)</td>
<td>neglect (-0.011)</td>
<td>no effect</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Width $w_c$ (mm)</td>
<td>effect (0.430)</td>
<td>no effect</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Number of turns $N$</td>
<td>effect (0.657)</td>
<td>no effect</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>

C. Inductive modeling

Inductive components of the sensor and bus bar, which are the mutual and stray inductances, are evaluated using simulation software based on a partial element equivalent circuit (PEEC) method [22]. The simulation software is realized by Altair’s software InCa3D [23]. In addition, the parameters of Fig. 6 are measured using a measuring instrument.

1) Mutual Inductance: The mutual inductance between the laminated bus bar and the sensor is the key factor influencing the sensitivity of the circuit. Fig. 11 shows the circuit diagram of the sensor, including the inductive components. The sensor can be represented as an ideal transformer, including a mutual inductance and two stray inductances. The mutual inductance represents $M$, and the stray inductances are $\ell_{bus}$ and $\ell_{coil}$.

TABLE III shows the analysis results of the mutual inductance. These simulations have been performed at 1 MHz, which is a good estimate of the equivalent switching frequency for conventional components. The main point is that the mutual inductance has to be constant over the entire frequency range. Indeed, the frequency distribution of the bus-bar current may change between low and high frequency. However, as illustrated in Fig. 12, the change in mutual inductance occurs in the low-frequency range, thus leading to a constant value between tens of kHz to tens of MHz. The variation in the mutual inductance owing to the redistribution of the current lines with the frequency occurs in the low-frequency range (between 1–10 kHz) and results in a negligible change in the mutual inductance value (less than 5%). Fig. 13 illustrates the distribution in the current density. The negligible change in the magnetic field between 10 Hz–1 MHz is the reason for the non-variation in the inductance with the increase in frequency. Fig. 14 illustrates the change of the induction. The change of the induction between 10 Hz–1 MHz is also negligible. From Fig. 13 and Fig. 14, it should also be noted that the sensor has been located in an area where the field is uniform.

To validate the mutual inductance value obtained in simulation, an experimental measurement has been carried out. A sinusoidal waveform has been injected in the bus bar, from 7 kHz–10 MHz using a power amplifier (HSA4101, NF Cooperation). The induced voltage $v_{coil}$, is calculated as follows:

$$v_{coil} = M \frac{dq}{dt} + \ell_{coil} \frac{di_2}{dt}. \tag{1}$$

Owing to the fact that the output resistance $R$, is set to 1 kΩ, the detection coil current $i_2$, is assumed to be zero. Therefore, only the mutual inductance $M$, is determined.
If the sinusoidal current $i_S$, flows through the wiring of the laminated bus bar, then $v_{coil}$ is induced by the flowing current. The measured $v_{coil}$ is substituted in (2).

$$M = v_{coil} \frac{1}{\text{dis/dt}}. \quad (2)$$

Fig. 15 shows the frequency characteristics of the mutual inductance from 7 kHz–10 MHz. The frequency bandwidth of these measurement results is determined by the characteristics of the power source and the resolution of the measurement instrument. From these measurement results, the average mutual inductance $M$, can be calculated as 11.6 nH in the frequency bandwidth of 1–10 MHz.

### Table III

<table>
<thead>
<tr>
<th>Inductive Stray Components on the Laminated Bus Bar and the Detection Coil of the Sensor</th>
</tr>
</thead>
<tbody>
<tr>
<td>Inductance [nH]</td>
</tr>
<tr>
<td>-----------------</td>
</tr>
<tr>
<td>Mutual inductance</td>
</tr>
<tr>
<td>Laminated bus bar inductance</td>
</tr>
<tr>
<td>Detection coil inductance</td>
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</tbody>
</table>

![Fig. 12. Variation of the mutual inductance with frequency in simulation.](image)

2) Stray Inductance of Laminated Bus Bar and Detection Coil: The stray inductances mean the inductances of the laminated bus bar and the detection coil. The stray inductances of the sensor may affect the bandwidth of the sensor. Using three PCBs for realizing the laminated bus bar with the current sensor increases the distance between the positive and negative copper plates, resulting in an increase in the laminated bus bar inductance.

From the analysis result, as shown in TABLE III, the laminated bus bar inductance is calculated to be 17.4 nH and the detection coil inductance is computed to be 751 nH.

The time-domain reflectometry (TDR) method is used for measuring the inductive components. A TDR can measure inductance of several nH and capacitance of several pF accurately[24]. Fig. 16(a) shows the circuit for measuring the laminated bus bar inductance, and Fig. 16(b) shows the circuit for measuring the detection coil inductance. The laminated bus bar inductance is measured when the sensor is fabricated. The detection coil inductance is measured using only the middle PCB. As a result, the laminated bus bar and the detection coil inductance were measured as 15.5 nH and 850 nH, respectively. The measurement results are summarized in TABLE III.

### D. Shield Effect

In order to verify the shield effect of the bus bar on the sensor, Fig. 17 shows the simulation model. An external wire is placed above the laminated bus bar with the current sensor. It is assumed that the distance between the external wire and the laminated bus bar is 5 mm and the external wire length is infinite. Fig. 18 shows the inductive coupling between the sensor and the external wire with and without the presence of the bus bar. When frequency increases, eddy currents are generated in both positive and negative bus bar conductors. These currents induce a voltage in the sensor that is opposite to the external origin of the field. Therefore, this coupling
Fig. 13. Illustration of the distribution in the current density between low and high frequency.

Fig. 14. Illustration of the change in the induction between the low and high frequency.

Fig. 15. Frequency characteristics of mutual inductance in measurement.

is greatly reduced as soon as the frequency reaches some kHz. It even becomes negative, because in the considered example the geometrical disposition of the external conductor is asymmetric (closer from positive bus bar sheet than from negative bus bar sheet). Positive or negative coupling is no issue since the most important result is that the coupling is reduced because the laminated bus bar acts as magnetic shields. As a result, the current sensor is robust against an external magnetic field.

E. Capacitive Modeling

Fig. 19 shows a circuit diagram, including capacitive components of the proposed current sensor. The stray capacitances of the sensor may also affect its frequency bandwidth. The stray capacitances are considered to be composed of three capacitances: the laminated bus bar capacitance $C_{bus}$, and the
From TABLE IV, the capacitance values obtained from simulation and measurement are also quite well. In order to evaluate the frequency characteristics of the sensor, the characteristics of the sensor are calculated using the circuit simulation.

\[
i_{\text{cal}} = \frac{1}{M} \int v_{\text{coil}} dt. \tag{3}
\]

From Fig. 22, the frequency bandwidth is approximately 35MHz. It could be improved by considering the theoretical transfer function instead of a simple integration in (3). Since both experimental and simulated transfer functions are in good accordance, it could help in increasing the frequency limit. This work will be carried out in further papers.

V. Experimental Results

A. Experimental Circuit

Fig. 23 shows the diagram of a buck converter circuit for experiment, and Fig. 24 shows the prototype of a buck converter circuit. In order to keep the current distribution in the laminated bus bar, four capacitors are almost uniform in parallel in the circuit. The proposed current sensor was fabricated with three PCBs, as shown in Fig. 2(b), and they are connected by soldering. The PCBs on the outer surface were used in the circuit simulation.

IV. Frequency Characteristics of the Current Sensor

Fig. 21 shows the equivalent circuit of the proposed current sensor. The measured values, which were obtained from the measurement conditions in Section III, are used in the equivalent circuit. The stray inductance of the laminated bus side is represented as laminated bus bar inductance and mutual inductance. The stray inductance of the detection coil side \( L_{\text{coil}} \) is represented as detection coil inductance. The output resistance \( R \) is connected to 1 k\( \Omega \) in the actual circuit. However, the stray inductance of the detection coil side and the output resistance \( R \) should be considered as the square of the number of turns because this circuit is considered from the laminated bus bar side, so the inductance and resistance should be set to 1/400 (=1/20\(^2\)) because the number of turns of the detection coil is set to 20. Therefore, the stray inductance of the detection coil side is changed from 850 nH to 2.1 nH, and \( R \) is converted from 1 k\( \Omega \) to 2.5 \( \Omega \). Fig. 22 shows the transfer function (gain and phase shift) \( I_{\text{cal}}(s)/I_{\text{S}}(s) \). The blue point shows the result using simulation value and the black point shows the result using experimental value. \( I_{\text{cal}} \) is the current detected by the sensor and calculated by (3) and \( i_S \) is the bus-bar current. The characteristics of the sensor are calculated using the circuit simulation.

capacitances between the laminated bus bar and the detection coil \( C_{T-S} \) and \( C_{B-S} \).

When the dielectric constant is equal to 5.0, using the FR-4, the analysis results as shown in TABLE IV indicates that \( C_{\text{bus}} \) is 92.4 pF, \( C_{T-S} \) is 42.1 pF, and \( C_{B-S} \) is 43.8 pF. The stray capacitances will be affected to the frequency bandwidth of the sensor. Therefore, the capacitances should be considered for considering the frequency characteristics of the sensor.

Fig. 20(a), (b) show the circuits for measuring the stray capacitances of the sensor. When the stray capacitance is measured, the other side is set as an open circuit. The stray capacitances are also measured using the TDR. TABLE IV summarizes the measurement results of the stray capacitances. From TABLE IV, the capacitance values obtained from simulation and measurement are also quite well. In order to evaluate the frequency characteristics of the sensor, the measured values were used in the circuit simulation.

![Fig. 18. Frequency characteristics of the shield effect.](image1)

![Fig. 19. Circuit diagram of the actual proposed current sensor.](image2)

![Fig. 20. Circuit for measuring the capacitive components.](image3)

![Fig. 21. Frequency characteristics of the shield effect.](image4)

![Fig. 22, the frequency bandwidth is approximately 35MHz.](image5)
Fig. 21. Equivalent circuit of the proposed sensor.

Fig. 22. Frequency characteristics of proposed current sensor.

Fig. 23. Circuit diagram of buck converter.

constitute the laminated bus bar for connecting the power devices and the DC capacitors. In addition, the PCB in the middle layer is the detection coil of the sensor consisting of a double-sided board.

The negative side of the buck converter circuit is set to a common ground for differential measurement. Therefore, two SMA connectors are connected between each sensor output and the negative side of the buck converter circuit. This is just for validation purpose; other differential measurement method could be used in the future. The output voltage $v_{\text{coil}}$, of the sensor is the derivative waveform of the bus-bar current $i_S$. In order to remove the common-mode voltage of the experimental waveforms, a differential measurement method is applied, as shown in Fig. 25. With reference to the negative side of the buck converter circuit, the voltages between each sensor output and the negative side of the buck converter circuit are defined. The voltages between the negative side of the buck converter circuit and each sensor output are set to $v_{\text{coil}+}$ and $v_{\text{coil}^-}$. In order to confirm the effectiveness of the proposed current sensor, the output voltage $v_{\text{coil}}$, is measured with an oscilloscope (Lecroy HD4096). The sampling rate is set to 2.5 GS/s, and the vertical resolutions are 12 bits without using any digital filters. In addition, the attenuators (Radiall R411810121) are connected to each sensor output. The damping ratio of the attenuators is 10 dB.

The output voltage, $v_{\text{coil}}$, is given by (4).

$$v_{\text{coil}} = v_{\text{coil}+} - v_{\text{coil}^-}. \quad (4)$$

Through numerical integration, the detection current that flows through the laminated bus bar $i_{\text{cal}}$, is calculated using the following equation:

$$i_{\text{cal}} = \frac{1}{M} \sum_{n=0}^{N} \{ T_S \times v_{\text{coil}}(n) \times \alpha \} \quad (5)$$

where $T_S$ is the sampling period of the oscilloscope and $N$ is the number of data points. In this experiment, the sampling period $T_S$, was set to 0.4 ns and the number of data points $N$, was set to 500. $\alpha$ is the coefficient for the attenuator and is $10^{-2}$. The mutual inductance used for the calculation (11.6 nH) is shown in Fig. 15.

B. Experimental Results using Buck Converter Circuit

Fig. 26 shows the experimental waveforms during the turn-on operation and Fig. 27 shows the experimental waveforms.
during the turn-off operation. The differential voltages $v_{\text{coil}+}$ and $v_{\text{coil}}$, the induced electromotive force with the attenuators, $v_{\text{coil}}$, and the current waveforms are shown in these figures. These waveforms have been obtained by numerical integration, performed off line on recorder signals. In each figure $i_{\text{cal}}$ is the calculated waveform from $v_{\text{coil}}$, and $i_{S}$ is the current waveform measured on the same point using a conventional current probe. The conventional current probe is used with a DC current probe (IWATSU SS-250) and the frequency bandwidth is from DC–100 MHz. The proposed current sensor can be calculated from the terminal voltage using passive voltage probes. On the hand, the conventional current probe has an electronic circuit inside the probe. Therefore, the current waveforms using the conventional current sensor is occurred the propagation time delay compared with the proposed current sensor.

The damping oscillation waveform is occurred to the differential voltages $v_{\text{coil}+}$ and $v_{\text{coil}}$ with irregular oscillation components, however, the induced electromotive force with the attenuators $v_{\text{coil}}$ is occurred with a single frequency oscillation component. In order to compare $i_{\text{cal}}$ and $i_{S}$, DC bias component is added to $i_{\text{cal}}$ in Fig. 27. The current waveforms in Fig. 26 have frequency components of 62.5 MHz in each waveform and the current waveforms in Fig. 27 have frequency components of 33 MHz in each waveforms.

In addition, the $\text{di/dt}$ of $i_{\text{cal}}$ at turn-on is 0.42 kA/s and the absolute value of the maximum $\text{di/dt}$ of $i_{\text{cal}}$ at turn-off is 1.24 kA/s. It is confirmed that the sensor can measure the switching current which is the $\text{di/dt}$ of 1 kA/s. From these experimental results, it can be seen that the proposed current sensor actually captures the current waveform quite well. From TABLE V, it is confirmed that the oscillation frequency both the current sensor and the conventional current probe is the same. However, the peak-currents are different because the frequency characteristic of the sensor is smaller than the the conventional current probe. However, this drawback can be improved in future work, using the knowledge of the transfer function.

**VI. Conclusion**

This paper proposed a current sensor for a laminated bus bar based on Rogowski coil principle. The proposed current sensor was embedded in the laminated bus bar for a buck converter circuit. The relationship between the sensor geometry and the stray component is discussed. The sensor, including the stray inductances and capacitances, was modeled and the frequency characteristics of the sensor were discussed using an equivalent
circuit model. In addition, experimental results were presented under turn-on and turn-off operation at input voltage of 50 V and output current of 8 A.

REFERENCES


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