Frequency Characteristics of Power Transformer for Isolated DC-DC Converter

TAKAYUKI. NAKAMURA¹, Member, IEEE AND TOSHIYUKI.MURKAMI², Senior Member, IEEE

¹Railway Technical Research Institute, Kokubunji, Tokyo 185-8540 JAPAN
²Keio University, Yokohama, Kanagawa 223-8522 JAPAN

Corresponding author: Takayuki Nakamura (e-mail: nakamura.takayuki.68@rtri.or.jp).

ABSTRACT The operational frequency of a transformer is an important factor in the configuration of an isolated DC-DC converter. However, discussions regarding this frequency are inadequate. This study focuses on the frequency characteristics of the transformer. The authors obtained the frequency characteristics of the impedance and the loss of the transformer to explain its fundamental attributes. When the transformer is employed for a power electronic transformer (PET), the waveform of voltage is rectangular. The loss under this waveform was observed to be due to the ringing.

INDEX TERMS Power transformers, Impedance, Magnetic losses, Magnetic resonance, DC-DC power converters,

I. INTRODUCTION

Transformers are electrical machines used for voltage conversion and isolation. The size and weight of a transformer depends on the frequency at which it operates. As the frequency increases, the transformer is lighter and smaller in size. Developments in semiconductor technologies have enabled us to fabricate a power electronic transformer (PET) that is operated at arbitrary frequencies [1]. PET is employed not only for AC-AC conversion system, but also DC-DC conversion system [2][3].

The study in this area is largely conducted in Europe for railway vehicles. The feeding system with specifications of AC 15 kV 16.7 Hz is common in Germany, Austria, and Switzerland where the size of the transformer is an important issue. The effort in increasing the frequency of the traction transformer has been conducted from 1980s. These efforts are summarized in [4]-[6]. ABB and ALSTOM, European manufactures, already developed the prototype vehicles, which employ PET [7][8]. However, there are few vehicles employing PET for commercial service. Some “FLIRT (Fast Light Intercity and Regional Train)”, named and produced by STADLER, a Swiss railway manufacturer, employs isolated DC-DC converter with PET for commercial operation. To achieve interoperability of DC and AC 15 kV 16.7 Hz feeding sections, these vehicles employ isolated DC-DC converter with PET. The traction converters are manufactured by ABB, and the vehicles, by STADLER. The operational frequency of the transformer is 100 Hz [9].

The study on PET is largely configured by its system such as control and operation of the semiconductors. However, there is little study on the transformer itself. There are many studies dealing with losses and efficiency. Loss and efficiency are important factors, which determine performance of isolated DC-DC converter. However, these studies are not discussed comprehensively but only individually. The determination of operational frequency is an important factor in terms of efficiency and electromagnetic compatibility for configuring a system. Operational frequency is a given parameter according to application system in many related studies. This is the reason why there are only few studies on the determination of operational frequency. However, the characteristics of a
transformer depend on its frequency. Due to the stray capacitance, prevalent amongst the windings everywhere, a transformer possesses frequency characteristics and resonant frequencies. An understanding of the frequency characteristics is essential for the configuration of the isolated DC-DC converter. Moreover, the transformer used for the isolated DC-DC converter is operated under voltage with a rectangular waveform and not a sinusoidal one. The characteristics of the loss under the voltage with a rectangular waveform is to be verified practically owing to the shortage of data from previous works in the domain.

With these notions, the authors focus on the frequency characteristics of transformer in this study. The definition of inductance and loss is reviewed in Chapter II. The determination of transformer used in the experiment, measurement configurations and conditions are presented in Chapter III. The results of the experiment are presented in Chapter IV. The obtained results are discussed in Chapter V and the application for the isolated DC-DC converter is mentioned in Chapter VI. Finally, conclusion is described in Chapter VII.

II. GENERAL DEFINITION AND MEASUREMENT
In this chapter, we confirm two parameters, inductance (reactance) and loss. The procedures for their measurements are described.

A. INDUCTANCE(REACTION)
The definitions of different types of inductances are shown in Table I. The value obtained by multiplying each inductance value by the angular frequency of the current is its reactance value. The following equation is derived from the definition in Table I.

\[ L = l + M \]  

(1)

The equivalent circuit of the short-circuit-inductance is represented in Fig. 1. The short-circuit-inductance of the first winding \( L_{s1} \) is represented by (2), using the leakage-inductance of first winding \( l_1 \) and that of second winding \( l_2 \).

\[ L_{s1} = l_1 + \frac{l_2 M}{l_2 + M} \]  

(2)

From (2), when the leakage-inductance of second winding \( l_2 \) is zero, the short-circuit-inductance of first winding \( L_{s1} \) is equivalent to the leakage-inductance of first winding \( l_1 \).

![FIGURE 1. Short-circuit-inductance (Equivalent circuit).](image)

B. LOSS
The parameters of a transformer are obtained by open and short circuit experiments. The open-circuit experiment is conducted under the condition that all windings except for the measurement windings are open. The connection in the open-circuit experiment is equal to the connection in the measurement of the self-inductance. The open-circuit experiment leads to the characteristics of the transformer under no-load condition. The short-circuit experiment is conducted under the condition that all windings except for the measurement windings are shortened. The connection in the short-circuit experiment is equal to the connection in the measurement of the short-circuit-inductance. The short-circuit experiment leads to clarifying the characteristics in load condition. Table II shows the relationship between loss, inductance, and connection in the measurement circuit.

The no-load loss \( P_0 \) is obtained using the measured power \( P_t \), the measured RMS current \( I_0 \) and the DC resistance of the winding \( R_{DC} \).

\[ P_0 = P_t - R_{DC} I_0^2 \]  

(3)

III. SPECIFICATIONS OF THE TRANSFORMER AND EXPERIMENT CONDITION

A. SELECTION OF THE TRANSFORMER FOR EXPERIMENT
The specifications of transformer used in experiment (NCT-F6 manufactured by DENKENSEIKI Research Institute Cooperation) are shown in Table III. The resistance of the winding, which is obtained by DC energization, is 0.126 Ω. The reasons for this selection are listed as follows:

--The rated frequency is the commercial frequency. This selection enables us to discuss the wide-frequency characteristic of the transformer. Since PET is not designed for operation at below the rated frequency, PET is inappropriate for our discussion.

| Connection  | Inductance | Loss     |
|-------------|------------|----------|
| Open-circuit| Self-inductance | No-load loss |
| Short-circuit| Short-circuit-inductance | Load loss |

| TABLE III  | THE DEFINITION OF INDUCTANCE |
|-------------|------------------------------|
| Input voltage (V) | 100  |
| Output voltage (V) | 100  |
| Rated capacity (kVA) | 1  |
| Mass (kg) | 16  |
--The ratio of winding is 1:1. This is the simplest configuration.

--Since the transformers used in isolated DC-DC converter generally possess leakage-inductance, the transformer for experiment possesses leakage-inductance.

B. MEASUREMENT ITEMS AND CONDITIONS

The quantities to be measured and the experimental conditions are elaborated in this section. Both the experiments are conducted in open and short circuit settings. Measurement winding is first winding of the transformer.

1) FREQUENCY CHARACTERISTIC OF IMPEDANCE

The frequency characteristics of the impedance is obtained using an LCR meter (HIOKI IM3533-01). The LCR meter is used as a 1 V voltage source.

2) FREQUENCY CHARACTERISTIC OF LOSS

The frequency characteristics of the loss is obtained using the bipolar power source. Fig. 2 and Table IV show the quantities to be measured and the experimental conditions. The function generator generates arbitrary frequency and waveform. The power supply is used as a voltage source. In general, when the transformers are employed for the isolated DC-DC converter, the waveform of voltage is rectangular. Therefore, to obtain the characteristics under voltage with a rectangular waveform, an experiment was conducted with this configuration of the waveform. RMS voltage value of the rectangular waveform is the same as that of the sinusoidal waveform. The loss characteristic with a rectangular voltage waveform is equivalent to the loss at the transformer for a DC-DC converter. The results of loss with a rectangular voltage waveform aid in understanding the loss characteristic of an actual DC-DC converter. Regarding the load condition, the result of open-circuit is equivalent to the characteristic of the no-load or the light-load condition, the result of short-circuit is equivalent to that of heavy-load condition. These correspondences are the same as those of the commercial transformer as shown in Table II. Table IV shows the experimental condition to obtain frequency characteristics of loss. Since the transformer used in the isolated DC-DC converter is largely operated in linear area, the voltage is set to be in linear area at 50 Hz (commercial frequency). The flux of the transformer in the experiment appears to be saturated at an input voltage, approximately 75 V (50 Hz).

IV. RESULTS OF EXPERIMENT

A. FREQUENCY CHARACTERISTIC OF IMPEDANCE

Fig. 3 shows the frequency characteristics of the impedance. From Fig. 3, the characteristics of the open-circuit impedance is interpreted as:

--To approximately 500 Hz: Inductive
--From approximately 500 Hz to 2.5 kHz: Capacitive
--From approximately 2.5 kHz to 45 kHz: Inductive
--From approximately 45 kHz: Capacitive

The characteristics of the short-circuit impedance is inductive up to approximately 45 kHz and capacitive above frequencies approximately 45 kHz. The characteristics of the short-circuit impedance agree with that of the open-circuit impedance above frequencies approximately 10 kHz. The definitions of inductive and capacitive do not change as conventional applications. The inductive mode is determined as follows:

--The impedance value increases as the frequency increases.
--The phase value is positive.

The capacitive mode is determined as follows:

--The impedance value decreases as the frequency increases.
--The phase value is negative.

B. FREQUENCY CHARACTERISTIC OF LOSS

Fig. 4 shows the frequency characteristics of the loss. From Fig. 4, the characteristics of the loss is interpreted as:

--In the open-circuit experiment, regardless of voltage waveform, the maximum loss is 22 W at approximately 2.5 kHz where the impedance is minimum.

--In the open-circuit experiment, the loss under voltage with sinusoidal waveform is smaller than that under voltage with rectangular waveform up to approximately 2.5 kHz. Regarding the rectangular waveform, the characteristic shows peak approximately 500 Hz and 800 Hz. These frequencies correspond to 1/5 and 1/3 of 2.5 kHz, respectively.

--In the short-circuit experiment, the loss under voltage with the sinusoidal waveform is larger than that with the rectangular waveform. The open-circuit experiment shows similar tendency over approximately 2.5 kHz.

--The loss characteristics of the short-circuit configuration agrees with that of the open-circuit over approximately 10 kHz. This tendency is similar to the characteristics of the impedance.
V. DISCUSSION

A. DEDUCTION OF COEFFICIENTS OF EQUIVALENT CIRCUIT AND RESONANT FREQUENCY

In this section, the authors derive the circuit constants of the transformer using the result of the characteristic of impedance. From Fig. 3, it is necessary to classify the cases based on the frequency ranges. The distribution of inductance and capacitance components in the transformer is shown in Fig. 5. The capacitance components of the transformer are prevalent everywhere, such as at each turn in the winding and between the first and the second winding. Hence, it is difficult to identify and measure individual capacitance. The capacitance components are described by dotted lines in Fig. 5, where $C_1$ is the capacitance of first winding, $C_2$ is that of the second winding, and $C_{12}$ is that between the first winding and the second winding.

1) FREQUENCY AREA UPTO APPROXIMATELY 500 HZ: INDUCTIVE

In this range, the characteristic of the impedance is inductive. The main factor contributing to the impedance is the self-inductance $L_1$, which is 99.5 mH calculated using the impedance ($Z = 31.261 \, \Omega$) at 50 Hz, open-circuit.

2) FREQUENCY AREA FROM APPROXIMATELY 500 HZ TO 2.5 KHZ: CAPACITIVE

In this range, the characteristic of impedance is capacitive. The main factor contributing to the impedance is the equivalent-parallel-capacitance $C_p$, which is 0.973 μF calculated using the impedance ($Z = 163.64 \, \Omega$) at 1 kHz, open-circuit. The equivalent-parallel-capacitance $C_p$ is composed of capacitance of the first winding $C_1$ primarily.

3) FREQUENCY AREA FROM APPROXIMATELY 2.5 KHZ TO 45 KHZ: INDUCTIVE

In this range, the characteristic of impedance is inductive. The main factor contributing to the impedance is the leakage-inductance $l_1$, which is 4.01 mH calculated using the impedance ($Z = 1.2609 \, \Omega$) at 50 Hz, short-circuit. The leakage-inductance $l_1$ of 2.41 mH is calculated using the impedance ($Z = 151.56 \, \Omega$) at 10 kHz, open-circuit. Since the characteristic of the leakage-inductance and that of the short-circuit-impedance match, the second leakage-inductance is regarded as zero.

FIGURE 3. The frequency characteristic of impedance.

FIGURE 4. The frequency characteristic of loss.

FIGURE 5. Equivalent circuit of the transformer.
4) FREQUENCY AREA FROM APPROXIMATELY 45 KHZ: CAPACITIVE

In this range, the characteristic of impedance is capacitive. The main factor contributing to the impedance is the equivalent-series-capacitance $C_s$ (5.02 nF), calculated using the impedance ($Z = 316.97 \, \Omega$) at 100 kHz, short-circuit. The equivalent-series-capacitance $C_s$ (5.02 nF) is calculated using the impedance ($Z = 316.99 \, \Omega$) at 100 kHz, open-circuit. The equivalent-series-capacitance $C_s$ consists of the capacitance of the second winding $C_2$ and that between the first winding and the second winding $C_{12}$ primarily.

The aforementioned deductions, 1) through 4) are summarized in Table V. The resonant frequency $f_r$ is generally determined by (4), as a function of inductance $L$ and capacitance $C$.

$$f_r = \frac{1}{2\pi\sqrt{LC}}$$

The resonant frequencies are obtained by using Table V. Table VI shows the obtained resonant frequencies. The obtained values agree with the resonant frequency in the impedance characteristic in Fig. 3.

B. LOSS CHARACTERISTICS UNDER RECTANGULAR VOLTAGE WAVEFORM

In the experiment with the short-circuit configuration, it is observed from Fig. 4 that the loss characteristics shows similar tendency regardless of the applied voltage waveform. This tendency is similar to that in the open-circuit experiment above frequencies of approximately 2.5 kHz. However, the characteristics of the loss with rectangular voltage waveform is different from that of the sinusoidal one below 2.5 kHz. The loss characteristics with the rectangular voltage waveform form some peaks for value below 2.5 kHz. Fig. 6 presents the waveform of voltage and current in the experiment with the rectangular voltage waveform (1 kHz). From Fig. 6 (a), the current waveform comprises a frequency approximately 2.5 kHz (open-circuit).

The current waveform is regarded as a second-order lag under a step response. It is equivalent to a general RLC series circuit, which has the natural frequency. The equation of the general RLC circuit is represented by (5).

$$E = Ri + \frac{di}{dt} + \frac{1}{C} \int idt$$

By means of the Laplace transform, the impedance of the circuit $Z$ is represented by (6), as a function of the Laplace operator $s$.

$$Z(s) = s \left( R + sL + \frac{1}{sC} \right) = \left( s + \frac{R}{2L} \right)^2 - \left( \frac{R}{2L} \right)^2 + \frac{1}{LC}$$

From (6), the square of the peak angular frequency $\omega$ is represented by (7).

$$\omega^2 = \frac{1}{LC} - \left( \frac{R}{2L} \right)^2$$

When the resistance is small enough, the peak frequency corresponds to (4). From Table VI, the resonant frequency, which determines the characteristics of Fig. 6, consists of the leakage-inductance $I_l$ and the equivalent-parallel-capacitance $C_p$. This paper regards the resonant frequency as “natural frequency.” The natural frequency is different from the “self-resonant frequency,” which consists of the self-inductance $L_I$ and the equivalent-parallel-capacitance $C_p$ (The self-resonant frequency of the transformer for the experiment is approximately 500 Hz).

The above discussion indicates that the consideration of the natural frequency is determined by the leakage-inductance $I_l$ and the equivalent-parallel-capacitance $C_p$ for configuring the isolated DC-DC converter. When the frequency of the

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TABLE VI

| Component | Frequency $f$ |
|-----------|--------------|
| Inductance | Capacitance | Resonant frequency $f_r$ |
| Self-inductance $L_1$ | Equivalent-parallel-capacitance $C_p$ | 512 Hz |
| Leakage-inductance $I_l$ | Equivalent-parallel-capacitance $C_p$ | 2.55 kHz |
| Leakage-inductance $I_l$ | Equivalent-series-capacitance $C_s$ | 45.8 kHz |

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FIGURE 6. The current waveform under the rectangular voltage waveform (1 kHz).
transformer is longer than the natural frequency, we regard the system as a conventional transformer with sinusoidal voltage waveform. Meanwhile, when the frequency of the transformer is less than the natural frequency, the current waveform contains the natural frequency due to ringing. The current with the natural frequency contributes to increasing the loss at light-load and no-load conditions. Therefore, the operation over the natural frequency is important from the viewpoint of the loss characteristics with the rectangular voltage waveform.

Even if the operational frequency of an isolated DC-DC converter is already determined, it is worthwhile to obtain the natural frequency of the transformer. The natural frequency of the transformer is the basis for determining whether any additional circuit components (reactors/capacitors) are required. If no additional circuit components are installed for an isolated DC-DC converter, the resonant frequency of the transformer can be adjusted. To adjust the resonant frequency, the leakage-inductance is adjusted according to the natural frequency. Adjustment techniques are commonly used for this purpose. The leakage-inductance is increased by increasing the number of fluxes, which links solely the winding where we intend to increase the leakage-inductance. This technique decreases the coupling coefficient of the transformer. The technique is employed for the secondary winding of the traction transformer for AC railway vehicle [10].

C. CURRENT CHARACTERISTICS UNDER RECTANGULAR VOLTAGE WAVEFORM

This section deals with the current characteristics associated with the rectangular voltage waveform. When the RMS voltage is $E$ and the frequency of the voltage is $f$, the sinusoidal voltage and the rectangular voltage waveform is represented by (8) and (9), respectively.

$$V_s(t) = \sqrt{2}E \sin 2\pi ft$$

$$V_i(t) = \begin{cases} E & (0 \leq t \leq \frac{1}{2f}) \\ -E & (\frac{1}{2f} \leq t \leq \frac{1}{f}) \end{cases}$$

When the inductance is $L$, the slope of the current with the sinusoidal voltage waveform $\frac{di_s}{dt}$ and that with the rectangular waveform $\frac{di_t}{dt}$ are represented by (10) and (11), respectively.

$$\frac{di_s}{dt} = \frac{V_s(t)}{L} = \frac{\sqrt{2}E}{L} \sin 2\pi ft$$

$$\frac{di_t}{dt} = \frac{V_i(t)}{L} = \begin{cases} E & (0 \leq t \leq \frac{1}{2f}) \\ -E & (\frac{1}{2f} \leq t \leq \frac{1}{f}) \end{cases}$$

As these currents do not contain the DC component, the current waveforms are deduced by the integrating equation for one cycle. From (13), the current waveform with the rectangular voltage waveform is triangular in nature.

$$i_s(t) = -\frac{\sqrt{2}E}{2\pi fL} \cos 2\pi ft$$

Considering that the crest factor of triangular waveform is $\sqrt{3}$, its characteristics when the same RMS voltage and the same frequency are applied shown in Table VII. From Table VII, the magnetizing current (RMS) when the rectangular voltage waveform is applied is $E / \sqrt{3L}$. The ratio of RMS when the rectangular voltage waveform is applied to sinusoidal one is $\frac{\pi}{2\sqrt{3}} (= 0.907)$.

Fig. 7 shows the results of the frequency characteristics of the current. The characteristics of the current is similar to that of the loss. Regarding the result of the open-circuit, the current characteristics also changes according to the frequency, the branch point is approximately 2.5 kHz. The frequency is the natural frequency of the transformer discussed in Section B in this chapter. Below the natural frequency, the current with the rectangular voltage waveform exceeds that with the sinusoidal one. The result is caused by the current, which contains natural frequency. When the frequency is above the natural frequency, the characteristics of the current in the open-circuit is similar to that of the current in the short-circuit experiment. Both the characteristics agree in the short-circuit configuration. The ratio of the value when the rectangular voltage waveform is applied to that of the sinusoidal one is approximately 0.90 to 0.91 up to 1 kHz. The value is in good agreement with the deduced ratio of $\frac{\pi}{2\sqrt{3}} (= 0.907)$ . However, the value is approximately 0.95 near 10 kHz. The value with the rectangular voltage waveform exceeds that with the sinusoidal one from the resonant frequency by approximately 45 kHz. The result of the short-circuit is similar to that of the open-circuit experiment over the natural frequency. Fig. 8 shows the waveform when the rectangular voltage waveform with 5 kHz is applied. As shown in Fig. 8, the waveform of the current is triangle. 5 kHz is within the frequency area where the deduced relationship holds.

VI. APPLICATION FOR ISOLATED DC-DC CONVERTER

DC-DC converters are classified into two types from the viewpoint of isolation: no-isolated type: and isolated type. The no-isolated type is called chopper, and the isolated type is called isolated DC-DC converter. Regarding the magnetic component, the chopper employs an inductor whereas the isolated DC-DC converter employs a transformer. This paper discusses the application of the transformer used in the isolated DC-DC converter. The isolated DC-DC converters are again classified into two. One of them utilizes a converter employing pulse width modulation (PWM) switching, and the other utilizes resonance between the inductance of the inductor or the transformer and the capacitance of the capacitor. To utilize isolated DC-DC converters, it is necessary to consider each type. Both types of the transformers possess leakage-inductance. The leakage-inductance of the transformer substitutes the input inductor in the isolated DC-DC converters. Therefore, the transformers, which possess
leakage-inductance, such as the transformer used in this study, are suitable for the discussion of the isolated DC-DC converter. The characteristic of loss with a rectangular voltage waveform is equivalent to that of the transformer of an isolated DC-DC converter.

### A. PWM Type

From inferences conducted in the study, when the system employs a transformer with the leakage-inductance, the operational frequency should be set over the natural frequency of the transformer. This operation enables the characteristics of PET to be the same as the conventional transformer at the commercial frequency. It is not necessary for us to consider the effect of ringing due to the natural frequency of transformer. On the contrary, when the operational frequency is set below the natural frequency of the transformer, the loss caused by ringing increases under light-load or no-load conditions.

#### TABLE VII

| Voltage waveform | Sine | Rectangle |
|------------------|------|-----------|
| Voltage (RMS)    | $E$  | $E$       |
| Voltage (Amplitude) | $\sqrt{2}E$ | $E$ |
| Current (RMS)    | $\frac{2\pi f L}{E}$ | $\frac{4\sqrt{3} f L}{E}$ |
| Current (Amplitude) | $\frac{\sqrt{2}E}{2\pi f L}$ | $\frac{E}{4 f L}$ |

### FIGURE 8

The current waveform under the rectangular voltage waveform (5 kHz).

### B. Resonant Type

Fig. 9 shows the equivalent circuit of the inductance and the capacitance parts of the resonant converter. The ratio of the output to input is shown in (14), where the impedance of the load is $Z_L$.

$$V_{out} = \frac{V_{in}}{1 + \frac{1}{M}} = \frac{1}{\omega L_0 f_r} \frac{1}{\omega Q L_0 f_r}$$  \hspace{1cm} (14)

Equation (14) is transformed to (15) by using $S = \frac{M}{f_r}$, $F = \frac{f_r}{f_0}$, $f_0$ is the self-resonant frequency of the transformer. Table VIII presents the relationship between the deduced frequency characteristic and the transformer used in this study. The operational frequency exists within the capacitive area as described in Chapter IV and V. From the result of the open-circuit configuration, since the current contains natural frequency, the loss increases under light-load or no-load conditions. Therefore, it is necessary to consider the current, in a situation where the frequency contains the natural frequency of the transformers for employing of resonant converter.
C. APPLICATION FOR RAILWAY AND REQUIREMENTS

This study refers to a vehicle, which employs the isolated DC-DC converter for traction circuit and discusses the application for railway. Since railway is an application of large load variation, railway vehicles are an appropriate example from the point of load variation. Two examples of the employment of the isolated DC-DC converter for traction circuit are listed:

--“Coradia LIREX” was developed by ALSTOM and DB (German railway). To achieve a hybrid of the power from the overhead contact line and the diesel engine, they employed the isolated DC-DC converter. The operational frequency was 5 kHz [7].

--The type of “Ee 933” was developed by ABB. The switcher locomotive was modified by conventional locomotive of “Ee 934” in SBB (Swiss railway) The operational frequency was 1.75 kHz [8].

Both vehicles are prototypes which employ the resonant converter. However, there is no subsequent reporting in this matter. The load on the converters in the traction circuit varies from no-load condition such as a standstill and coasting to the condition of over the rated load during acceleration. Therefore, the loss is caused by the current with the natural frequency under no-load and light-load conditions. Regarding the latter example, an attempt is made to improve the efficiency at light-load condition [11]. However, the problem under the light-load condition remains, as it appears that the prototype vehicles are not mass produced.

Regarding the PWM type, the operational frequency should be set over the natural frequency of the transformer as mentioned in Section A. The natural frequency range is in the order of kHz. The PWM type of isolated DC-DC converter for traction circuit requires semiconductors capable of operating in the frequency range of kHz. Moreover, the rated power of the semiconductor is required approximately several-100-kW area.

VII. CONCLUSION

As the transformers have frequency characteristics, the performances of the isolated DC-DC converters are determined by the operational frequency. To clarify the fundamental characteristics of the frequency, this study acquires the frequency characteristics of the impedance and that of the loss. As the PET largely operates with the rectangular voltage waveform, this study compares the rectangular voltage waveform with the sinusoidal waveform with regard to the characteristics of the loss. The inferences from the study are as follows:

--From the open-circuit experiment, the characteristics under no-load condition are determined by the natural frequency of the transformer, which consists of the leakage-inductance and the equivalent-parallel-capacitance. The natural frequency of the transformer for the experiment is approximately 2.5 kHz.

--With regard to the loss characteristics under the rectangular voltage waveform, when the operational frequency is larger than the natural frequency of the transformer, we regard the PET system as the conventional transformer with sinusoidal waveform.

--Furthermore, this study deduces the theoretical value of the current ratio of the rectangular voltage waveform to the sinusoidal voltage waveform under the same RMS voltage. The deduced ratio is approximately 0.9. This value matches the frequency from the natural frequency to approximately 10 kHz.

--When the operational frequency is less than the natural frequency of the transformer, the RMS current increases under the rectangular voltage waveform in the open-circuit experiment. This increase is caused by the current, which comprises natural frequency owing to the ringing.

--It is important that the operational frequency should be higher than the natural frequency of the transformer in the configuration of the PET system. Otherwise, the loss increases under no-load and light-load conditions.

--Even if the operational frequency of an isolated DC-DC converter has already been determined, it is worthwhile to obtain the natural frequency of the transformer. The natural frequency of the transformer is the basis for determining whether any additional circuit components (reactors/capacitors) are required. If no additional circuit components are installed for an isolated DC-DC converter, the resonant frequency of the transformer can be adjusted. To adjust the resonant frequency, the leakage-inductance is adjusted according to the natural frequency.

Furthermore, this study applies the inferences to the isolated DC-DC converter. The discussion in this paper leads to the determination of the operational frequency according to the type of the isolated DC-DC converter.

--PWM type: The operational frequency should be set over the natural frequency of the transformer. Otherwise, the loss increases under no-load and light-load conditions.
--Resonant type: The operational frequency is limited from the self-resonant frequency to the natural frequency of the transformer. The characteristics of the transformer in this area is capacitive. From the result of the open-circuit experiment, the loss increases under no-load and light-load conditions.

To increase in operational frequency of the isolated DC-DC converter, the determination of the operational frequency essentially requires the consideration of the frequency characteristics of the transformers. Therefore, this study acquires the characteristics of the transformer and clarifies the problem in the application for the isolated DC-DC converter. From the inferences, this study is the basis for the determination of the operational frequency of an isolated DC-DC converter. Furthermore, it contributes to the improvement in the technology regarding isolated DC-DC converters.

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TAKAYUKI NAKAMURA (M’16) received the B.S. and M.S. degree in system design engineering from Keio University, Yokohama, Japan in 2005 and 2007, respectively.

In 2007, he joined Railway Technical Research Institute, Kokubunji, Japan where he is currently an Assistant Senior Researcher with Traction Control Laboratory in Vehicle Control Technology division. His research interests include power electronics and electric machines.

TOSHIYUKI MURAKAMI (M’93–SM’13) received the B.E., M.E., and Ph.D. degrees in electrical engineering from Keio University, Yokohama, Japan, in 1988, 1990, and 1993, respectively. In 1993, he joined the Department of Electrical Engineering, Keio University, where he is currently a Professor with the Department of System Design Engineering. From 1999 to 2000, he was a Visiting Researcher with the Institute of Power Electronics and Electrical Drives, Aachen University of Technology, Aachen, Germany. His research interests include robotics, intelligent vehicles, mobile robots, and motion control. In the education project, he was a coordinator of EMARO (European Master on Advanced Robotics, erasmus program) from 2008 to 2018. From 2019, he is now a responsible person of JEMARO (Japan Europe Master on Advanced Robotics, Erasmus&MEXT program) in faculty of science and technology, Keio University.