Minimization of EMC Filter for Interconnection Inverter by High Switching Frequency

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***Abstract*—This paper proposes a design method of a common-mode current feedback type EMC filter in an interconnection system. First, the relationship between the switching frequency of the PWM inverter, the common-mode feedback current and the volume of the filter reactor is theoretically estimated. Moreover, the switching frequency and the current capacity of switching devices which are necessary in order to estimate the volume of the EMC filter is determined by this relationship. Second, the inverter loss is calculated based on the experimental result. After that, the relationship between the cut-off frequency of the EMC filter and volume of the cooling system is calculated. As a result, the minimum total volume of the EMC filter estimation and the design method of the cooling system are clarified. From the experimental result, the design point of the maximum power density is clarified. Moreover, the conduction noise of the switching frequency component suppresses below the prescribed by CISPR11.**

Keywords—EMC Filter; High-Frequency Switching; Wide Band-Gap device

I. INTRODUCTION

Recently, attentions are focused on miniaturization of the power conversion for interconnection system. In particular, it is necessary to reduce volume of an EMC filter because the EMC filter accounts for a considerable proportion of the power conversion system. The EMC filter comprised of a normal-mode filter and a common-mode filter. Furthermore, by increasing the switching frequency, passive components in the normal-mode filter are downsized and consequently the volume is reduced. Besides, in order to achieve a high frequency switching operation, the inverter requires fast-switching devices to be used because slow-switching devices cause a large switching loss and a dead time error. Thereby, the switching device using a wide band-gap semiconductor such as gallium nitride (GaN) or silicon carbide (SiC) is used to the PWM inverter, instead of the silicon based switching device [1-3]. However, the performance and the miniaturization effect have not been discussed in previous studies when wide band-gap semiconductors are applied to the PWM inverter for an interconnection system. Moreover, when the switching loss is increased by considering a high switching frequency, the volume of a cooling system becomes large. Therefore, there is a trade-off relationship between the EMC filter volume and cooling system volume. In order to solve this problem, the design method for minimization by using Pareto front curve has been discussed [4].

On the other hand, when the switching frequency is increased, electromagnetic noise is also increased. Therefore, a common-mode filter increases in volume in order to avoid incorrect operation of peripheral equipment by the conduction noise [5]. Furthermore, in order to solve this problem, the common-mode current feedback type EMC filter has been proposed [6-7]. In the past work, the normal-mode filter and the common-mode filter for PWM inverters are discussed [6]. Ref.[6] considers the design method of the normal-mode and common-mode filters and the effect of the harmonics suppression by experiments. Moreover, Ref.[6] clarify a design method of the common-mode reactor. The common-mode current which flows between the PWM inverter and the EMC filter becomes small and to be negligible due to increase the inductance of the filter reactor. When the switching frequency is larger than the cut-off frequency, the common-mode current is determined by the inductance of the filter reactor. In addition, the volume of the filter reactor accounts for a considerable proportion of the volume of the EMC filter because the energy density of the filter inductor is lower than one of the filter capacitor. Thus, it is important to consider the relationship between the common-mode current and the filter reactor from a viewpoint of a miniaturization. On the other hand, detail analyzes of a LC filter and simple design procedures along with a design example are presented in [7]. Furthermore, Ref.[7] have analyzed a single phase equivalent circuit of the LC filter. However, common-mode equivalent circuit and the effect of the power loss of the inverter by the filter current have not been discussed. Moreover, the miniaturization effect and the effect of reducing conduction noise have not been discussed in previous studies.

In this paper, a design method for miniaturization of the common-mode current feedback type EMC filter with high switching frequency is proposed. First, the switching frequency and the current capacity of switching devices which are necessary in order to estimate the volume of the EMC filter are determined. These factors are determined by considering 1) the current flowing between the inverter and the EMC filter, and 2) the relationship between the switching frequency and the volume of the filter inductor. Second, the inductance of the filter inductor is varied, and the relationship between the volume of the EMC filter and the cooling system is considered. Next, the minimum value of the total volume of the EMC filter and the cooling system is derived due to the trade-off relationship between the volume of the filter inductor and the inverter losses. Finally, experiments with a prototype of the GaN-FET inverter are conducted to verify the validity of the proposed design method. As a result, the design point of the maximum power density is clarified. Thus the validity of the proposed design method is confirmed.

II. SYSTEM CONFIGURATION

Fig.1 shows the circuit configuration of an Three-phase inverter with the common-mode current feedback type EMC filter. The natural point of a Y-type capacitor in the common-mode current feedback-type EMC filter is connected to the natural point of the DC link bus because it is possible to increase the allowable current i_c in comparison with connecting to the ground case. In this paper, the current i_c flowing between the inverter and the EMC filter is called as the filter current. Furthermore, the volume of the filter inductor accounts for the majority of the EMC filter volume because the energy density of the filter inductor is lower than one of the filter capacitor. Hence, the filter inductor volume is discussed with a special emphasis in this paper.

III. ESTIMATION OF VOLUME AND POWER LOSS

A. Volume of reactor

In this paper, the reactor volume is focused because the energy density of the filter inductor is lower than one of the filter capacitor. In addition, the reactor of the EMC filter is designed by the Area product concept using a window area and a cross-sectional area [8]. Then volume of the reactor is given by (1).

$$vol_L = K_v \left(\frac{2W}{K_u B_m J} \right)^{\frac{3}{4}} \tag{1}$$

where K_v is the constant value depending on the shape of a used reactor core. W is the maximum power of the reactor. K_u is the occupancy of the window area of core. B_m is the maximum flux density of the core. J is the current density of the wire which is used to the reactor. From (1), the volume of reactor is proportional to the power of 3/4 of maximum energy of the reactor.

B. Power loss of Inverter and Volume of Cooling system

A power loss of the inverter is separated into the conduction loss and the switching loss of the switching devices. Generally, the conduction loss of the switching devices is calculated by the on-state resistance R_{on} and the switching loss is calculated by turn-on loss P_{on} and turn-off loss P_{off} according to the datasheet. In this paper, loss analysis is based on the experimental results of the simplify estimation of volume of the cooling system.

Table 1 shows the circuit parameters on experiment. The GaN-FETs (V_{DSmax} = 600 V, I_{D_max} = 10 A) are used for the PWM inverter in order to achieve the 300-kHz switching

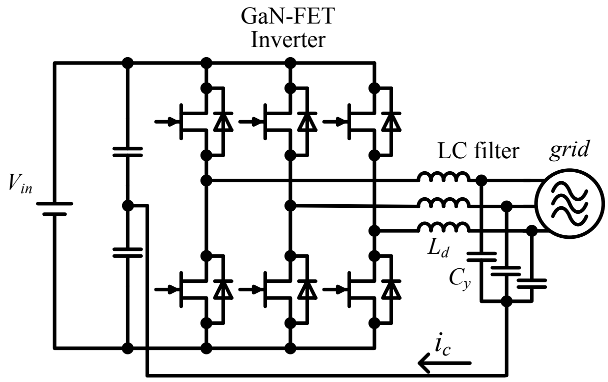

Fig. 1. Three-phase inverter system with the common-mode current feedback type EMC filter.

Table 1. Conditions of Experimental for measurement the power loss of GaN-FET inverter with RL load.

Input voltage V_{in}	141 V
Modulation ratio α	1
Output frequency f_{out}	20 Hz
Load impedance Z_{load}	51 Ω
Power factor cosϕ	0.99
Ambient temperature T_a	25 ℃
Dead time T_d	100 ns

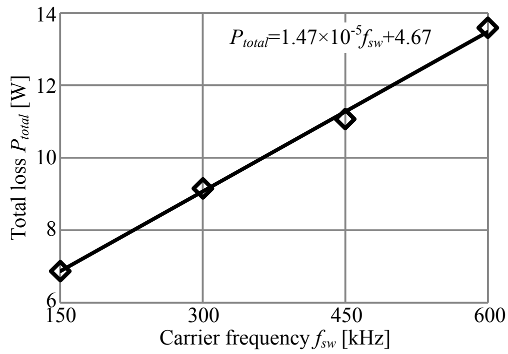

Fig. 2. Measurement result of relationship between switching frequency and power loss of GaN-FET inverter.

frequency. The PWM signals are generated by comparing the output voltage command with the triangle wave.

Fig.2 shows the measured power loss of the GaN-FET inverter in Fig.1. The conduction loss is given by y-intercept of approximation formula b because it is not related to the switching frequency. On the other hand, the switching loss of PWM inverter is given by slope of the approximation formula. As a result, the conduction loss and the switching loss on arbitrary output power are calculated by (2) and (3).

$$P_{SW} = a f_{sw} \frac{V_{DC\_calc}}{V_{DC\_test}} \frac{I_{out\_calc}}{I_{out\_test}} \tag{2}$$

$$P_{CON} = b \times \left(\frac{I_{out\_calc}}{I_{out\_test}} \right)^2 \quad (3)$$

where I_{out_calc} is the output current on arbitrary output power, I_{out_test} is the output current when the power loss is measured in experiment, V_{DC_calc} is the DC link voltage on arbitrary output power, and V_{DC_test} is the DC link voltage when the power loss is measured in experiment. Thus, the power loss is given by the following equation.

$$P_{loss} = P_{SW} + P_{CON} \quad (4)$$

The switching devices that used for the PWM inverter is heated by the loss of the conduction loss and the switching loss. The rising in temperature causes a breaking the switching device. Hence, the PWM inverter requires a cooling system such as heatsinks and fans. In this paper, consideration of the cooling system is the heatsinks only. Generally, a thermal resistance is used in order to evaluate the cooling system performance. However, it is not enough because the evaluation based on thermal resistance does not consider the volume of the cooling system. In this paper, CSPI (Cooling System Performance Index), which is a reciprocal of the product of the volume and the thermal resistance, is introduce for the volume of the cooling system estimation. The CSPI indicates the cooling performance per unit volume of the cooling system. Thereby, it means that a high CSPI shows a high performance cooling system. Therefore, in order to downsize a cooling system, PWM inverter needs a cooling system which has high CSPI. The volume of the cooling system is given by the relationship between the power loss and the rise in temperature by the following equation [9].

$$vol_{cooling} = \frac{1}{R_{th} \times CSPI} = \frac{P_{loss}}{(T_j - T_a) \times CSPI} \quad (2)$$

where R_{th} is the thermal resistance of the cooling system, T_j is the junction temperature of switching devices, T_a is the ambient temperature, P_{loss} is the power loss of the switching devices that used for PWM inverter.

IV. Design Consideration of EMC Filter

Fig. 3 shows the part of common-mode equivalent circuit of GaN-FET inverter and the EMC filter in Fig.1. The filter current i_c flows between the GaN-FET inverter and the EMC filter. The filter current i_c and cut-off frequency of the EMC filter are given by the following equations.

$$i_c = \left| \frac{j\omega(3C_y)}{1 - \omega^2 (L_d/3)(3C_y)} \right| = \frac{\omega v_{inv}}{(\omega^2 - \omega^2{}_c)(L_d/3)} \quad (5)$$

$$\omega_c = \sqrt{\frac{1}{L_d C_y}} \quad (6)$$

where ω is the switching angular frequency, ω_c is the cut-off angular frequency of the EMC filter, L_d is the inductance of the filter reactor and v_{inv} is the common-mode voltage of the inverter.

When the switching frequency is much larger than the cut-off frequency of the EMC filter, $(\omega^2 - \omega^2{}_c)$ can be approximated to ω^2 . Therefore, the changes of the filter current due to the effect of resonant is negligibly small. Hence, the approximation formula of the film current i_c is given by the following equation.

$$i_c = \frac{1}{\omega(L_d/3)} v_{inv} \quad (7)$$

Fig. 4 shows the relationship between the filter current and the volume of the filter inductor from (7), when the switching frequency is varied. Table 2 shows the calculation condition for the designed EMC filter. In order to eliminate the effect of resonant of the EMC filter, the cut-off frequency is set as 1/10 of the switching frequency. As a result, when the switching frequency is high, the volume of the filter inductor is small. Moreover, the relationship between the filter current and the filter reactor volume is a trade-off relationship. Therefore, the switching frequency and power loss of the switching devices are necessary in order to estimate the volume of the EMC filter and it is determined by this relationship.

Table 2. Simulation and calculation parameters.

Input voltage V_{in}	282 V
Output voltage v_{out}	200 V
Output frequency f_{out}	50 Hz
Load resister R_{load}	26.67 Ω
Load reactor L_{load}	1 mH
Switching frequency f_{sw}	600 kHz
Modulation Ratio α	1
CSPI	3
Ambient temperature T_a	20 °C
Junction temperature T_j	100 °C
Slope in Fig.2 a	1.47×10^{-5}
y-intercept in Fig.2 b	4.67

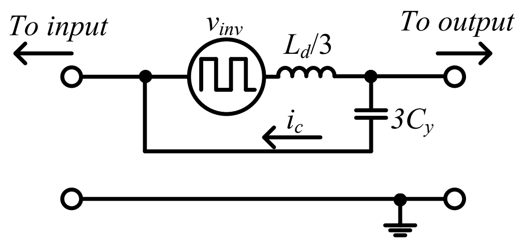

Fig. 3. Interconnection system with the common-mode current feedback type EMC filter. The filter current is calculated by use of the filter reactor L_d, the filter capacitor C_y and the common-mode voltage v_{inv}.

Fig. 5 shows the relationship between the cut-off frequency of the EMC filter and the power loss of the GaN-inverter, when the filter capacitor is 100 nF, and the switching frequency is 600 kHz. Fig. 5 is based on the simulation results by referring to (3) and (4). When the cut-off frequency increases, the filter current becomes large due to the decreasing of the inductance of the filter reactor; therefore, the power loss of the inverter becomes large.

Fig. 6 shows the relationship between the cut-off frequency of the EMC filter and total volume of the filter inductor and the cooling system, when the switching frequency is 600 kHz. In this paper, the total volume is sum of the volume of the heatsink and the filter reactor. When the cut-off frequency decreases, the inductance of the filter inductor becomes large, and the volume of the filter inductor also becomes large. On the other hand, when the cut-off frequency increases, the filter current becomes small, whereas the volume of the cooling system becomes large due to the increasing of the inverter losses. As a result, the relationship between the cut-off frequency and total volume is established as a downward convex function. Therefore, the minimum value of total volume is clarified.

V. Experimental Results

Fig. 7 shows the relationship between the cut-off frequency of the EMC filter and total volume at 300-kHz switching frequency. In the simulation, the EMC filter is designed based on switching frequency of 600-kHz. However, switching frequency is 300-kHz in experiment. Therefore, the EMC filter needs to be redesigned. As a result, the relationship between the cut-off frequency and total volume is established as a downward convex function and similar to Fig. 6. Therefore, the minimum value of total volume is clarified. At this point, total volume can be estimated at minimum point when the percentage of an impedance of the filter inductor %Z is 0.8% as the cut-off frequency is 50-kHz.

Fig. 8 shows the circuit diagram for conducting experiment. From the experiment setup, in order to simplify experiment, the load resister is used, instead of the grid. Furthermore, in order to reduce the conduction noise, the EMC filter is connected to the earth via grounded capacitor C_{yg}. Moreover, the RL load is connected to the earth via capacitor C_s. The capacitor C_s imitates stray capacitance.

Table 3 shows the experimental condition. In the experiment, the GaN-FET inverter is operated at 300-kHz switching frequency. The inverter is controlled by an open-loop control system. The conduction noise which be generated by control circuit is deducted to evaluate the conduction noise by main circuit.

Fig. 9 shows output waveforms of the inverter. The load current has low distorted sinusoidal waveform. The reactor current has large ripple current comparing to the load current because the reactor current is composed from the load current and the filter current. When the filter current is large, the reactor current ripple become large; thereby, the inverter loss and conduction loss of the filter reactor is increased. The maximum value of the filter current is 3.32A in the experiment. However, in the simulation, the maximum value of the filter current is 2.91A. The difference between experiment and simulation has occurred. The possible cause of the difference is the effect of the grounded capacitor. However, this paper does not consider this matter in details.

Fig. 10 shows the measurement result of the relationship between the cut-off frequency and the efficiency. In this case,

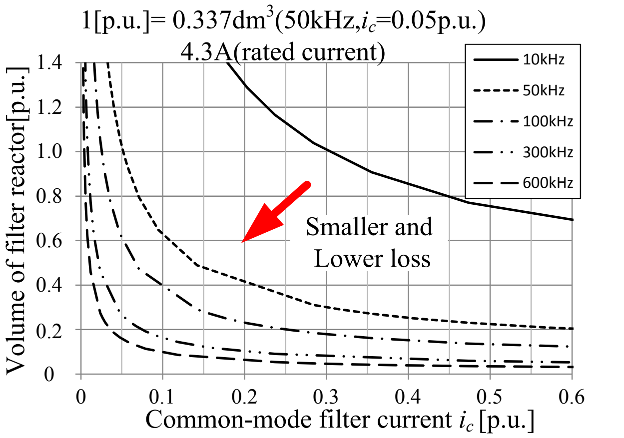

Fig. 4. Relationship between the filter current i_c and the volume of the filter inductor, when the switching frequency is varied.

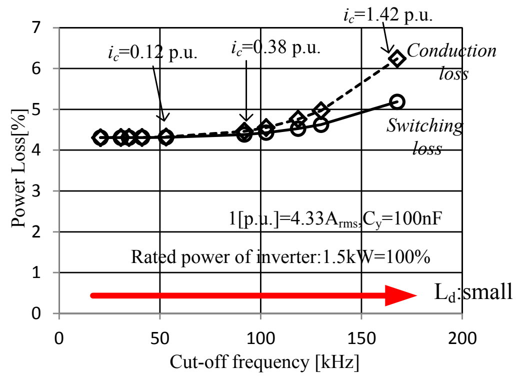

Fig. 5. Relationship between the cut-off frequency of the EMC filter and a power loss of the inverter.

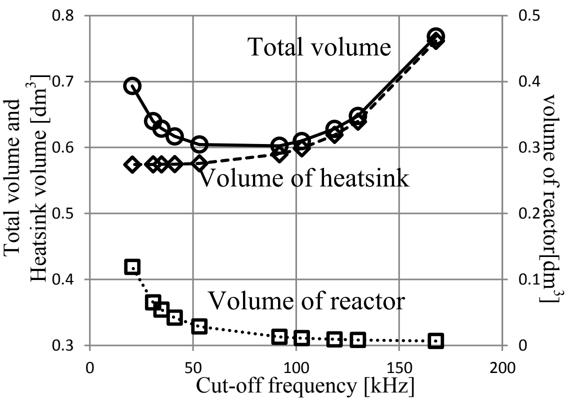

Fig. 6. Relationship among the cut-off frequency of the EMC filter and volume of reactor, heatsink and total. The relationship is established as a downward convex. Therefore, the minimum value of total volume is clarified.

the capacitance of the filter capacitor is kept at a constant value. Therefore, the cut-off frequency is varies by changing the inductance of the filter inductor. The efficiency includes total efficiencies of both the inverter and the EMC filter and it measured by the power meter of Yokogawa, WT1800. When the filter inductor is small, the loss of the inverter becomes large due to the increasing of the filter current i_c. In contrast, when the filter inductor is large, the core loss of the filter inductor becomes large. As a result, the efficiency can be represented into an upward convex function in experiment. Therefore, the maximum point of efficiency is clarified. Hence, the efficiency is clarified at the maximum point when the inductance of the filter inductor is 150-μH as the cut-off frequency is 49-kHz.

Fig.11 shows the Pareto front curve of the relationship between power density and efficiency. The total volume is calculated as sum of volumes of the EMC filter and the cooling system. In particular, the volume of the inverter is calculated from the measurement results of inverter losses by using CSPI. The volume of the filter reactor is calculated from the inductance of the filter reactor which using is experiment by (1). From these results, the maximum point of power density of the interconnection system with the common-mode current feedback-type EMC filter is clarified. At this point, the power density can be clarified at the maximum point when the inductance of the filter inductor is 150-μH as the cut-off frequency is 49-kHz.

Fig. 12 shows the measurement result of the conduction noise of the prototype circuit of the inverter with the common-mode current feedback-type EMC filter. As a result, the conduction noise of the fundamental component of the switching frequency and the high-frequency components are less than 2MHz is generated by the main circuit and it mostly suppressed according to the regulation value of CISPR11. In order to suppress fully according to the regulation, the revising of cut-off frequency is needed. However, the conduction noise in the range of more than 2MHz has exceeded the limit of CISPR11. This problem occurs due to the device mounting such as a stray capacitor. However, this problem is not considered in this paper. Based on these results, the validity of the proposed design method for the common-mode current feedback-type EMC filter is confirmed.

VI. Conclusion

This paper proposes a design method of the common-mode current feedback type EMC filter in an interconnection system. In this paper, the relationship between the cut-off frequency of the EMC filter and the total volume of the GaN-FET inverter and the EMC filter is discussed based on a simulation and an experiment results. As a result, the design point of the minimum volume of the sum of the EMC filter and the cooling system is clarified. In the experiment, the designed point of the maximum power density is clarified. In addition, the load current has low distorted sinusoidal waveform. Furthermore, the conduction noise of the fundamental component of the switching frequency and the high-frequency components are less than 2MHz is generated by the main circuit and it suppressed according to the regulation value of CISPR11 by designed EMC filter. These results, the proposed design

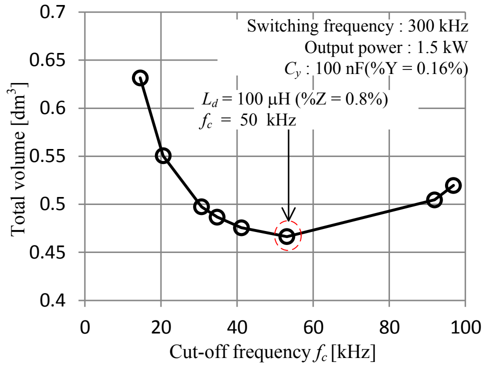

Fig.7. Relationship between the cut-off frequency of the EMC filter and total volume.

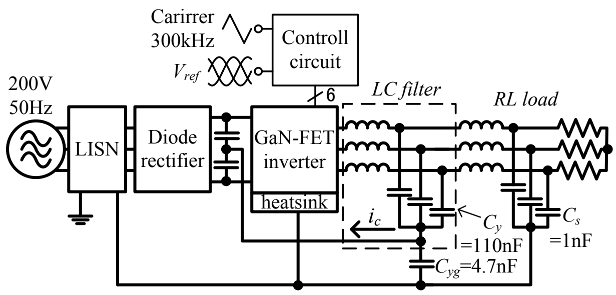

Fig. 8. Circuit diagram for the conduction noise evaluation.

Table 3. Experimental conditions.

Input voltage v_{in}	200 V
Input frequency	50 Hz
Modulation Ratio α	0.866
Load resister R_{load}	75 Ω
Load reactor L_{load}	1 mH
Switching frequency f_{sw}	300 kHz
Modulation Ratio α	1
Dead time T_d	100 ns

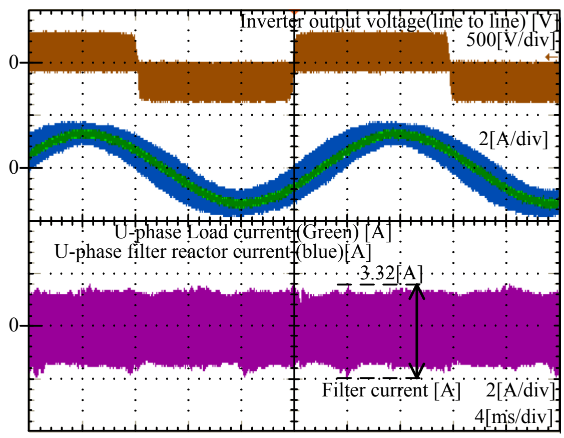

Fig. 9. Output waveform of the GaN-FET inverter at 300-kHz switching frequency. The load current obtains low distorted sinusoidal waveform.

method achieves minimization of interconnection system which include the EMC filter. In future work, the effect of suppression of conduction noise will be improvement.

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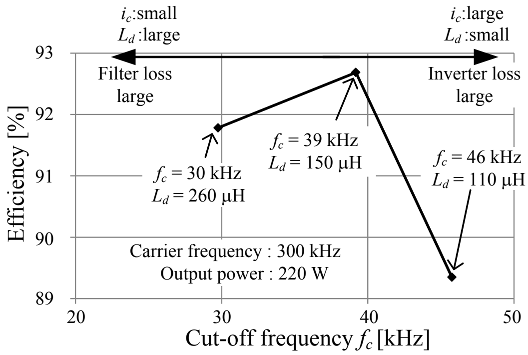

Fig. 10. Measurement result of the relationship between the cut-off frequency and the efficiency. In condition, the filter capacitor is kept at constant value, whereas the filter inductor is varied. The efficiency is represented into an upward convex function. Therefore, a maximum point of efficiency is clarified.

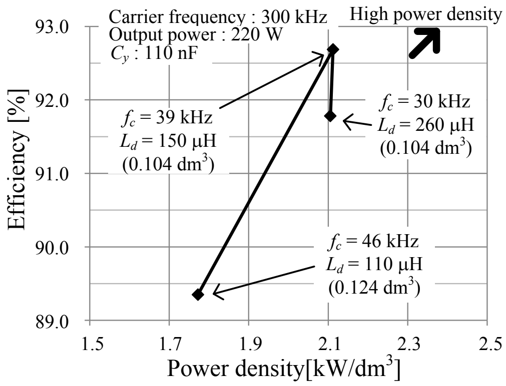

Fig. 11. Calculation result of the Pare to front curve of the relationship between the power density and the efficiency.

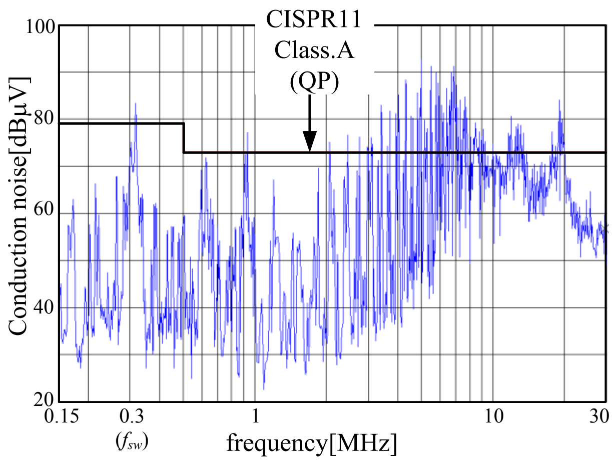

Fig. 12. Measurement result of the conduction noise of the prototype circuit with proposed EMC filter.