15th International Power Electronics and Motion Control Conference, EPE-PEMC 2012 ECCE Europe, Novi Sad, Serbia

Experimental Analysis on Precise Calorimetric Power Loss Measurement Using Two Chambers

Jun-ichi Itoh[1], Atsushi Nigorikawa[2]
[1]Nagaoka University of Technology, Nagaoka, Japan, itoh@vos.nagaokaut.ac.jp
[2]Nagaoka University of Technology, Nagaoka, Japan, nigori@stn.nagaokaut.ac.jp

Abstract — **In this paper, a low cost and simple structure power measuring system for a high efficiency power converter is proposed. The Calorimetric Power Loss Measurement (CPLM) uses the heat quantity which is generated by the power converter to measure losses. The proposed system is a low cost and simple structure without complex control circuits, which will increase the cost of the CPLM system. The measurement of the power consumption can be calculated by the increased temperature. The features of the proposed method are that the power consumption of the power converter is measured from the transient state of the rise in temperature. As a result, the measurement time of the power loss of the power converter is reduced by 86.1% in comparison with a conventional method. In addition, all of the maximum errors of the measuring power consumption are within 10%. Moreover, another method that can reduce the measurement time is discussed. In particular, the temperature in the container B is controlled to follow in the temperature in the container A for the transient state of the rise in temperature. As a consequence, the measurement time of the power loss of the power converter is reduced by 87.5% in comparison with a conventional method.**

Keywords — **Calorimetric determination, Power loss analysis, Thermostatic chamber**

I. INTRODUCTION

Recently, power converters become relatively high efficiency and high switching frequency due to the advanced semiconductor devices, such as SiC and GaN, and magnetic materials [1]. The power loss analysis of the very high efficiency power converter becomes difficult because the power losses are buried in the measurement error. One of the loss measurement methods is to measure the input and output power using a power measurement instrument (EPM) [2]. The EPM uses the products of voltage and current, which gives an electrical quantity equivalent to power. The power measurement can be performed by measuring the voltage drop across the device and the current flowing through it using electrical instruments. This method is commonly used to measure power directly by using analog electronic equipment. However, this method contains certain error because the ratio of the power loss to the total power is very small. That is, the full scale error of the measurement range is buried in measurement results. Furthermore, the measurement results by EPM are also affected by the delays between the probes. The phase shifts between sampling channels of digitizer, sampling errors, and voltage offset [3]. Even if the digital meter which has the required resolution is used in this method, problem such as the radio frequency interference and electromagnetic interference are very sensitive to noise.

To overcome these problems, there is another power loss measurement method, which uses two power converters to measure losses [4]. Two power converters are connected in parallel. The first converter is operated as a generator. The second converter is used as a receptor. The power is circulated by using two converters. The input power is equal to two converter losses from this circuit configuration [5]. Therefore, the measurement range of the power meter becomes smaller. As a result, the higher accuracy measurement results are obtained. However, since this method requires two power converters, consequently this method takes longer configuration time and cause higher cost.

On the other hand, another loss measurements method using the heat quantity of the power converter is known as the Calorimetric Power Loss Measurement (CPLM) [6]. A measured power converter is activated in the thermostatic chambers. The water or air is circulated in the thermostatic chambers. The power converter loss is obtained from the temperature change of the circulating water or air. This method can reduce the measurement error because of measurement of only the power loss. Therefore, this method provides higher accuracy than the EPM. The advantage of this method is measuring the power losses under normal operating conditions and independent of electrical quantities of a measured converter [7]. Moreover, the CPLM requires low sensitivity and less complicated device [8]. This system uses a thermostatic chamber to achieve the precise measurement of heat quantity and use the circulatory organ to circulate the water or air inside the thermostatic chambers [9]. However, the thermostatic chamber is required complex control circuits to control the water or air. Therefor thermostatic chamber systems are expensive. Also, the CPLM method takes longer time to complete a measurement due to the low sensitivity.

This paper proposes a low cost and simple structure CPLM system using two chambers to overcome the disadvantage of the conventional CPLM. The proposed system uses two simple chambers [10]. Also, the complex controlling water or air for measuring the temperature in the thermostatic chambers is not required in the proposed system. Therefore, the proposed system becomes low cost and simple structure. Besides, the power loss will be calculated by transient state data of the rise temperature inside the chamber. Therefore, this method can be measure quickly. Moreover, the measurement time will be short time to design the PI controller.

This paper is organized as follows, firstly, the calorimetric principle is described, next, the proposed system is introduced and the measurement principle of the proposed system is explained. At last, the prototype system will be demonstrated with experimental results. The experimental results indicate the validity of the proposed system.

II. Calorimetric Principle

The measurement error ε of the power loss in the power converter may be expressed

$$\varepsilon = \frac{\Delta P_{loss}}{P_{loss}} = \frac{\Delta P_{in} + \Delta P_{out}}{P_{loss}} \quad (1)$$

where, ΔP_{loss} is the error of the measured power loss of power converter. P_{loss} is the error of the power consumption of the power converter. ΔP_{in} is the measured input power and ΔP_{out} is the error of the measured output power. If a measured power converter which has the 99% efficiency is measured to use the power meter which have the 0.15% accuracy, the worst case of the measurement error is 29.85%. Besides, this method does not provide high accuracy due to the limited bandwidth and dynamic frequency response. Therefore, it is required to measure the power loss directly.

The power consumption of the power converters is exchanged to heat. Therefore, the calorimetric method used the controlled water or air to take over the heat from the power converters. P_{loss} can be described by

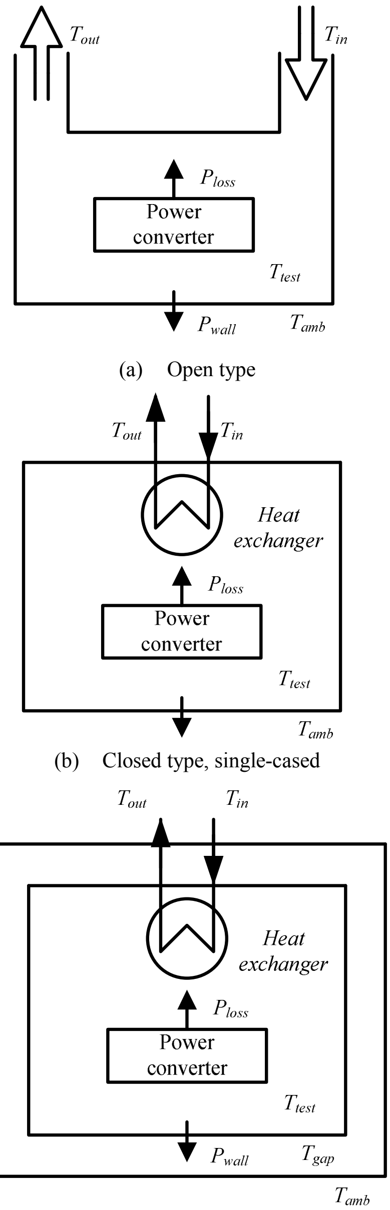
$$P_{loss} = \rho c_p V (T_{out} - T_{in}) \quad (2)$$

where, ρ is the mass density, c_p is the specific heat capacity of the fluid, V is the flow rate of the coolant, and T_{in} and T_{out} are the temperature of the inlet and outlet water.

In the past, several types of the calorimeters have been proposed. Figure 1 shows the three basic calorimeters [11], [12]. Fig. 1. (a) depicts the open type calorimeter system. In this system, the electrical power converter is placed directly in the measurement circuit. Using air for the coolant, this system is a simple construction and a fast response time. However, this system has significant defect that it is difficult to measure heat capacity, the rise in temperature and the volume flow of the air. Additionally, air is very sensitive to environmental changes such as the humidity, the temperature and density. Therefore, the accuracy of this system is very affected from the environment. This calorimeter type is often used for measuring induction machines with power losses up to several kilowatts [13], [14].

One the other hand, Fig. 1. (b) depicts closed and single-cased type calorimeter system. This system employs a separate cooling loop for the heat exchange with the ambient. Using water for a coolant, this system is higher accuracy than the open type calorimeter.

Moreover, in order to increase the measurement accuracy, closed and double-cased type calorimeter system have been proposed as shown Fig. 1. (c) The measurement accuracy is affected by the heat leakage through the walls of the calorimeter [15]. The power consumption for the heat leakage through the walls of the



(a) Open type

(b) Closed type, single-cased

(c) Closed type, double-cased

Fig. 1. Three kind of conventional calorimeters systems.

calorimeter P_{wall} on closed and single-cased type is expressed as

$$P_{wall} = \frac{T_{test} - T_{amb}}{R_{th,wall}} \quad (3)$$

where, T_{test} is the temperature in the chamber, T_{amb} is the ambient temperature, $R_{th,wall}$ is the thermal resistance of the calorimeter walls. In the contrast, P_{wall} of the closed and double-type system is expressed as

$$P_{wall} = \frac{T_{test} - T_{gap}}{R_{th,wall}} \quad (4)$$

where, T_{gap} is the air temperature in the gap between the inner chamber and outer chamber. The double-cased calorimeter controls T_{gap} equal to the temperature in the inner chamber. Therefore, the power consumption for the heat leakage through the walls of the inner chamber can be zero. Therefore, the double-cased calorimeter is highest accuracy in the three types. However, this system uses the circulatory organ for the coolant, complex control circuits and sensor. Therefore, these systems are expensive. Additionally the controlling the coolant and T_{gap} on this system is difficult. Moreover, these closed systems (Fig. 1. (b) and Fig. 1. (c)) are required to take the long measurement time because the heat capacity of the water is higher than that of the air.

To overcome this drawback, we propose the unique technic and simple structure CPLM system. In the proposed CPLM system, the heat quantity is obtained by comparing between the two chambers. Therefore, the measurement accuracy of the proposed system is not affected by P_{wall} and the coolant parameter. As a result, the proposed system becomes significant low cost and simple structure. Moreover, the proposed system can be measured accurately the heat quantity to use the air as the coolant. Therefore, the proposed system becomes high accuracy and a fast response time. The specific is described in the next chapter.

III. CPLM System Using Two Chambers

Figure 2 shows the control block diagram of proposed system which is composed by two chambers and a heater. The chambers, which are made from insulator materials, are illustrated as the container A and container B in Fig. 2. A measured power converter is placed in the container A. The temperature in the container A is increased by power loss of the power converter. The temperature in the container A saturates when the amount of heat consumption from heater equals to the amount of heat consumption from the container surface.

The temperature in the container B is controlled by a feedback control using the PI regulator. It should be noted that the air in the container B is heated by a heater, which is controlled by the buck converter. The temperature in the container A is set to the command temperature of container B. The sensitivity error of the temperature sensor is corrected in the control circuit. When the temperature in the container B reaches the command value that is the saturated temperature in the container A, the heat generation from the heater in the container B equals to the heat generated from the power converter in the container A. In this way, the power consumption of the heater equals to the power loss of the power converter. This system does not require complex control circuit. Therefore, the proposed system becomes significant low cost and simple structure. The heat leakage of the walls of the container B is same the container A. Therefore, in the proposed system, the measurement accuracy of the power consumption does not be influenced by the heat leakage through the walls of the container.

The room temperature and the heat discharge for the two chambers must be the same in order to ensure high accuracy measurement. Therefore, in this paper, the developments of the measurement system will be discussed from the theoretical formula in the next chapter.

IV. Theoretical Discussion

The power converter is put and works in the container A.

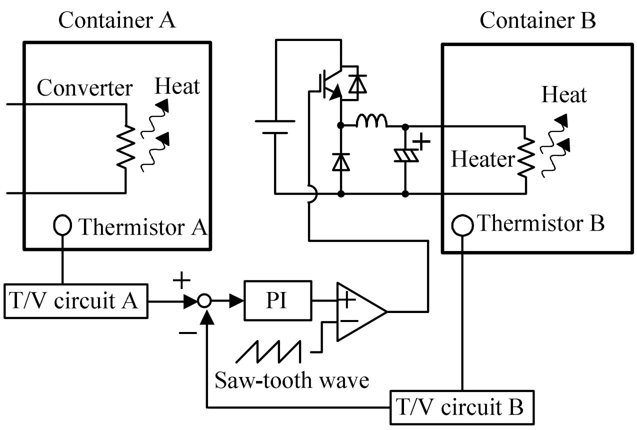


Fig. 2. System configuration of proposed CPLM using two chambers.

The temperature of the air in the container A rises, due to the heat quantity produced by the power loss of the power converter. The air in the container A is circulated by a fan in order to balance out the temperature in the container A. From heat conduction equation, the heat quantity Q_{in} is led to

$$\rho_{air}\, c_{pair}\, V_{con} \frac{dT_{inA}}{dt} = Q_{in} - Q_R - Q_{cool} \tag{5}$$

where, the density of the air is ρ_{air} (kg/m^3), the specific heat of air is c_{pair} (J/gK), the inner volume of the container A is V_{con} (m^3), the temperature of the air in the container A is T_{inA} (K) and Q_{in} is the heat quantity from the inside of the power converter to the converter surface in the container A. Q_R is the heat quantity from the converter surface to the measurement point of the air temperature in the container A. Q_{cool} is the heat discharge from the container A.

Then Q_R and Q_{cool} can be expressed as

$$\begin{aligned}\rho_{air}\, c_{pair}\, V_{con} \frac{dT_{inA}}{dt} &= Q_{in} - \frac{T_R - T_{inA}}{R_r} - \frac{T_{inA} - T_{amb}}{R_{conA}} \\ &= Q_{in} - \frac{(Q_{in} R_r + T_{inA}) - T_{amb}}{R}\end{aligned} \tag{6}$$

where, T_R is the inner temperature of power converter, R_r is the thermal resistance from inside of the power converter to the measurement point of the room temperature, R_{conA} is the thermal resistance of the container A, R is the total thermal resistances.

Eq. (6) is then transformed with Laplace transformation and presented as

$$\rho_{air}\, c_{pair}\, V_{con} \left(s\, T_{inA}(s) - T_o\right) = \frac{Q_{in}}{s}\left(1 - \frac{R_r}{R}\right) - \frac{T_{inA}(s)}{R} - \frac{T_{amb}}{sR} \tag{7}$$

where, T_o is the initial temperature in the container A. The heat quantity of the power converter is assumed as the step input. Eq. (7) is derived in term of the T_{in}, and then it is applied with inverse Laplace transformation, which is shown in (8).

$$\begin{aligned}T_{inA} &= \{Q_{in}(R - R_r) + T_{amb}\} \cdot \left\{1 - \exp\left(-\frac{1}{\rho_{air}\, c_{pair}\, V_{con}\, R} t\right)\right\} \\ &\quad + T_o \exp\left(-\frac{1}{\rho_{air}\, c_{pair}\, V_{con}\, R} t\right)\end{aligned} \tag{8}$$

If the parameters are known except Q_{in}, (9) is derived by differentiating (8) and translating into logarithm.

$$Ln\left(\frac{dT_{inA}}{dt}\right) = \ln\frac{Q_{in}\left(R-R_r\right)+T_{amb}-T_o}{\rho_{air}\,c_{pair}\,V_{con}\,R} - \frac{1}{\rho_{air}\,c_{pair}\,V_{con}\,R}t \quad (9)$$

As a result, the Q_{in} can derive by (9) before temperature becomes saturated. The rise of the measured temperature is differentiated and both sides of equation are expressed logarithmically. Moreover, the regression curve is analyzed from the experimental results. The measurement results are expressed by 1st order equation. The R and the R_r is showed by (10) and (11) by using the slope a and the intercept b, respectively.

$$R = -\frac{1}{\rho_{air}\,c_{pair}\,V_{con}\,a} \quad (10)$$

$$R_r = R - \frac{\rho_{air}\,c_{pair}\,V_{con}\,R\exp(b)}{Q_{in}} \quad (11)$$

V. Experimental Results

A. Identification of the Thermal Resistance

Figure 3 shows the prototype of the proposed CPLM system. The measurement accuracy is evaluated using the prototype. Table I shows the used materials for the calorimeter. Two chambers are made from the expanded polystyrene. The heater cement resistor of 10 Ω is used. For simplicity of the experiment, a heater is used instead of the power converter. The power converter runs in the container A. The power loss measurements with the power consumption between 5 W and 25 W are demonstrated. The thermal resistances are identified from the experimental results of the rise in temperature in the container A. The volume of the container is V_{con} = 3.17×10^{-2} m^3 (inner dimension of container; long 447 mm, width 322 mm, height 220 mm). The error rate set up within 10% based on the power consumption between 5 W and 25 W.

Figure 4 shows the temperature characteristic of the container A that the power converter is placed. Figure 5 shows the natural logarithm of differential rise in temperature at P_{loss} = 25 W where P_{loss} is the power consumption of the power converter in the container A. The noise of the rise temperature is removed by the moving average method. The slope a and the intercept b is obtained by using the regression analysis. The thermal resistances are obtained by using (10) and (11).

Table II shows the slope a and the intercept b which is obtained from the temperature characteristic of the container A. The thermal resistances are obtained from this experimental result by (10) and (11).

The permissible temperature deviation range (ΔT_{inA}) is derived by substituting the permissible power consumption range and the thermal resistances to (8).

Table III shows the thermal resistances and the permissible temperature deviation range. Then, it is assumed that T_o equal to T_{amb}. From Table III, if the power consumption is small, the control of the temperature is shown accurately. When the temperature is saturated, (8) become (12).

$$T_{inA} = Q_{in}\left(R - R_r\right) \quad (12)$$

ΔT_{inA} is obtained by substituting the acceptable range of the power loss (error rate:10%). R and R_r that are shown in Table III are used.

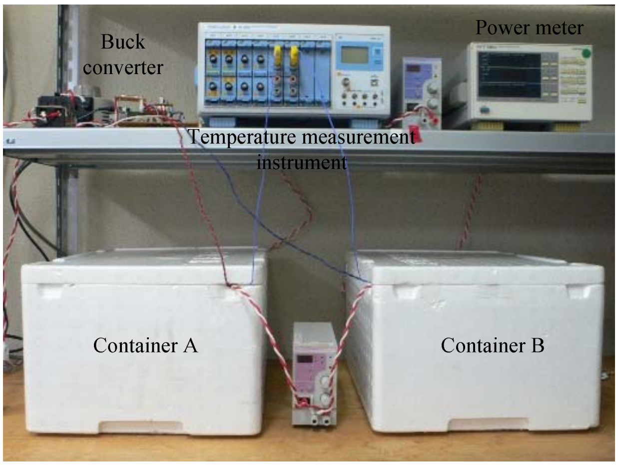


Fig. 3. Prototype of proposed CPLM using two chambers.

TABLE I
USED MATERIALS FOR THE CALORIMETER.

Senser	Temperature	SL1000 : Thermocouple : type K (-200 ~ 1300℃)
	Power meter	WT130 : accuracy 0.35%
Chamber	Expanded polystyrene : Dimensions : 447 mm × 322 mm × 220 mm Wall Thickness : 200 mm	
Heater	Cement resistor : Resistance 10 Ω Dimensions 190 mm × 550 mm × 20 mm	

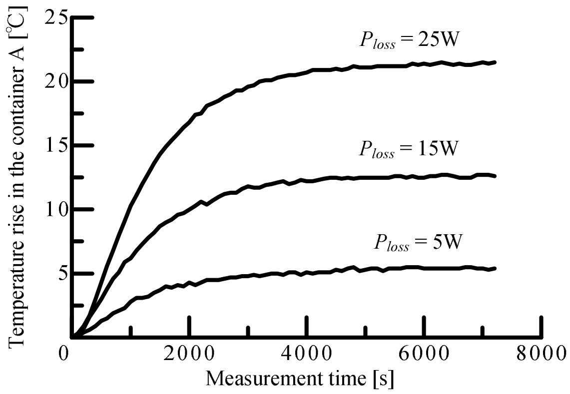


Fig. 4. Temperature characteristic of the container A.

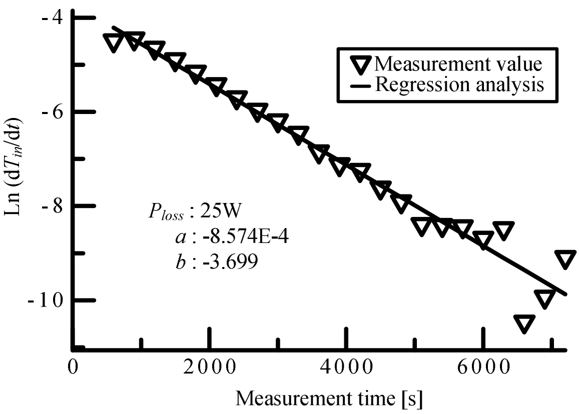


Fig. 5. Relation between the differential of temperature and time in log scale.

$$\Delta T_{inA} = \pm 0.1 Q_{in}(R - R_r) \quad (13)$$

When the power consumption is 5 W, the allowance of the temperature deviation is ±0.635 degrees Celsius in order to keep within 10% measurement accuracy.

B. *Power Loss Measurement Based on Steady State Condition*

The power loss of the power converter is evaluated from the power consumption of a heater in container B. The temperatures of the air in the two containers are affected by the same ambient temperature because two containers are placed in same place.

Figure 6 shows the experimental result of the temperature control by using PI regulator at P_{loss} = 5 W. From Fig. 6, it is confirmed that the temperature in the container B is equaled to the temperature in the container A by using PI control.

Figure 7 shows the fluctuation band of the measurement error rate. The power consumption of the power converter is measured three times at the each power consumption. The ambient temperature is different with respect to each measurement. As a result, the measurement error rate is changed. From Fig. 7, it is confirmed that the maximum error of power loss is 8.0% at P_{loss} = 5 W. The measurement error rate of the power consumption is within 10% in the proposed system.

In theory, when the temperature deviation of the container A and container B is 0 degrees Celsius, the measurement error became 0% in this system. However, there are measurement errors in the experimental results. This reason is the difference of the ambient temperature between the container A and the container B.

C. *Power Losses Measurement Using Heat Conduction Equation Formula*

The CPLM methods spend a lot of measurement time until the temperature in the container A is saturated. In the experiment shown in previous section, the measurement is over three hour. In this section, the method that can reduce the measurement time is discussed. In particular, the power consumption of the power converter is introduced from the transient state of the rise in temperature.

However, the error of the measurement power loss increases because the thermal resistance of the container varies with the power loss of the power converter. Therefore, the thermal resistance of the container A can be corrected by using the rise in temperature of the container B in order to reduce the error of the measurement power loss.

From Fig. 4, the temperature saturation time is approximately 7200 s. In addition, the change of the temperature is confirmed from 0 s to 4000 s. The power consumption of the power converter is obtained by (10) and (11) in the measurement time of up to 4000 s. It should be noted that the measurement results below 500 s is not accurate because time delay occurs in the results.

Some variations occur in the measurement results. Therefore, the measurement results of the rise in temperature are approximated by the regression curve. After that, the regression curve is differentiated and both sides of equations are expressed logarithmically. Moreover, the regression curve is analyzed from the experimental results. The measurement results are expressed by 1st order equation.

Figure 8 shows the experimental results of the regression analysis at P_{loss} = 25 W. The regression curve is approximated by 1st order equation. The power consumption of the power converter is obtained from (10) and (11) by using the slope *a* and the intercept *b* of the 1st order equation. Similarly, the power consumption of the power converter is obtained when the measurement time is decreased.

Table IV shows the slope *a* and the intercept *b* which is obtained from the regression analysis. It is noted that the power consumptions of the power converter are

TABLE II
THE SLOPE AND THE INTERCEPT (0 – 7200 S).

	P_{loss} [W]		
	5	15	25
a	-8.574E-4	-9.360E-4	-7.348E-4
b	-3.699	-4.173	-5.367

TABLE III
TEMPERATURE ALLOWANCE ΔT TO KEEP WITHIN ±10% MEASUREMENT ACCURACY.

P_{loss} [W]	R [K/W]	R_r [K/W]	ΔT_{inA} [℃]
5.0	32.996	31.725	±0.635
15.0	25.910	24.813	±1.646
25.0	28.284	27.130	±2.885

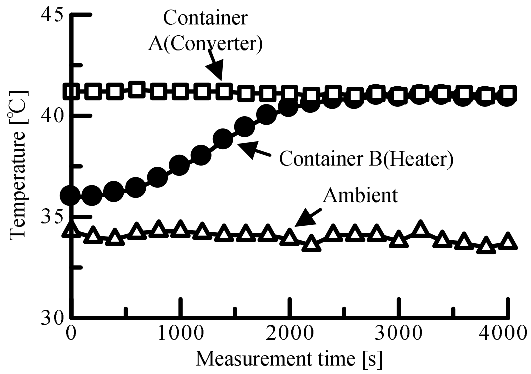


Fig. 6. Temperature control results for constant temperature command using PI control.

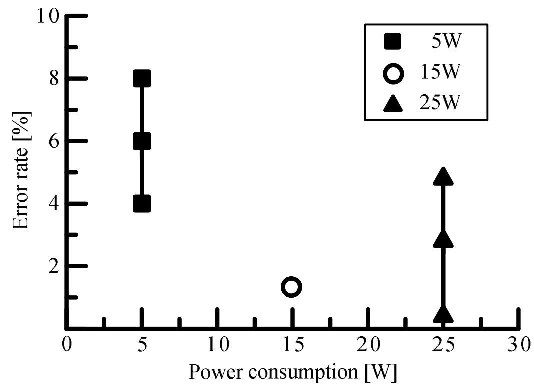


Fig. 7. Measurement error rate.

calculated when the data ranges of the rise in temperature are in the measurement times between from 500 s to 4000 s, 500 s to 2000 s and 500 s to 1500 s.

Figure 9 shows the error rate of the power consumption of the converter between the measurement values and the calculation values which is obtained by (10) and (11). As a result, the power consumption of the power converter is obtained from 500 s to 4000 s, the maximum error of the power consumption occurs as 5.8% at P_{loss} = 15 W. On the other hand, when the measurement range is from 500 s to 2000 s, the maximum error of the power consumption is 6.7% at P_{loss} = 15 W. Similarly, when the measurement range is from 500 s to 1500 s, the maximum error of the power consumption is 6.2% at P_{loss} = 25 W.

These results are compared with the experimental results in chapter *B*. As a result, the measurement accuracy by using the (10) and (11) is lower than that is measured from the steady state of the temperature described in the previous section. However, it is confirmed that the measurement error rate can be achieved within 10%. Therefore, a long measurement time is not required in the proposed method compared with conventional method. Moreover, it is confirmed that the measurement time is shortened by 86.1%.

D. Power Loss Measurement by Transient Response of Temperature Controller

As already mentioned, the CPLM methods spend a lot of measurement time until the temperature in the container A is saturated. In this section, another method which can reduce the measurement time is discussed. In particular, the temperature in the container B is controlled to follow in the temperature in the container A for the transient state of the rise in temperature. The overshoot of controlled temperature response in the container A happens easily because the heater does not have a cooling function. Therefore, the response should be the first order lag system, which has no overshoot. In order to achieve the response of first order lag system, the time constant of PI controller is design to the time constant of the heater. As a result, the transfer function of temperature response becomes the first order system.

Figure 10 shows that the temperature of the container B is controlled to the temperature of the container A for a short time. Note that the power consumption of the power converter is 25 W. According to Fig. 10, it is confirmed the temperature in the container B reaches to the temperature in the container A in the transient states of rise in temperature.

Figure 11 shows the power consumptions of converter and heater when the temperature of the container B is controlled as shown in Fig. 10. In this experiment, the power consumption of the heater is equaled to the power consumption of the converter on 1350 s. As a result, it is confirmed that the measurement time is shortened by 87.5%.

VI. CONCLUSION

In this paper, a low cost and simple structure to measure the converter losses is discussed. The CPLM uses the heat quantity which is generated by the power converter

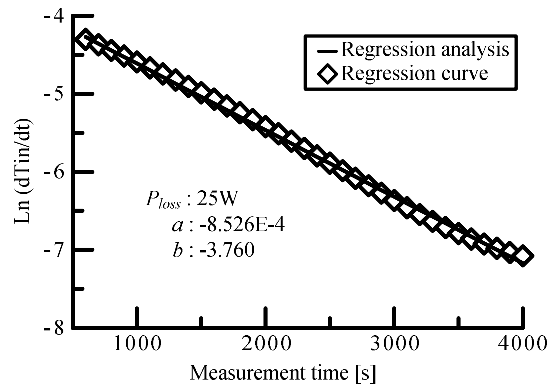


Fig. 8. Relation between the differential of temperature and time in 4000 s.

TABLE IV
THE SLOPE AND THE INTERCEPT (500 – 4000 S)

P_{loss} [W]		Time used for calculation [s]		
		500 - 1500	500 - 2000	500 - 4000
5	*a*	-8.295E-4	-10.752E-4	-8.105E-4
	b	-5.195	-4.931	-5.294
15	*a*	-6.156E-4	-8.792E-4	-8.465E-4
	b	-4.540	-4.305	-4.333
25	*a*	-5.552E-4	-7.639E-4	-8.526E-4
	b	-4.074	-3.871	-3.760

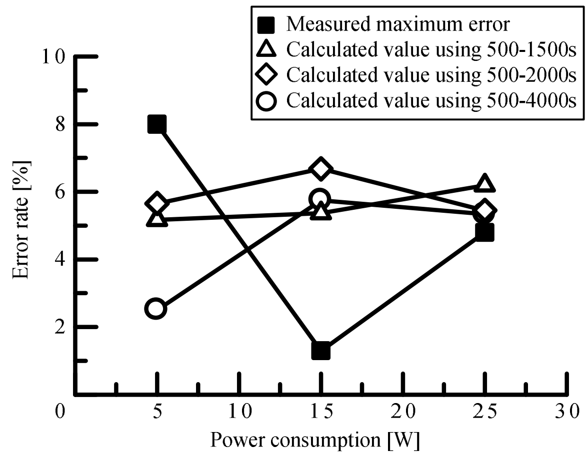


Fig. 9. Error rate of the power consumption between the measurement values and the calculation values.

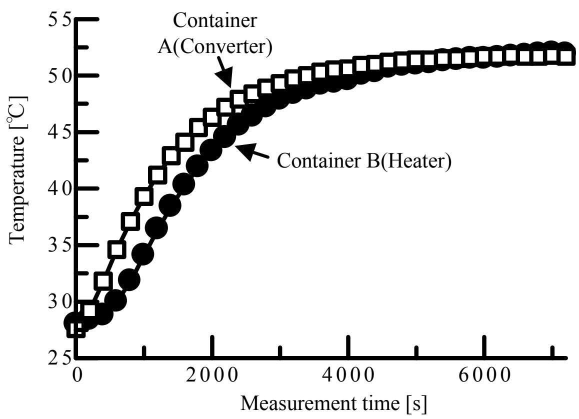


Fig. 10. Temperature of the container B is controlled to the temperature of the container A for a short time.

to measure losses. The proposed system is a low cost and simple structure without complex control circuits. The measurement method of the power consumption based on the rise in temperature is discussed. When the measurement uses temperature saturation, the measurement time becomes longer. In the proposed system, the power consumption measurement of the power converter is achieved from the transient state of the rise in temperature. As a result, when the measurement ranges are from 500 s to 4000 s, 500 s to 2000 s and 500 s to 1500 s, the maximum error of the power consumption are 6.2% at 25 W, 6.7% at 15 W and 5.8% at 5 W, respectively. In other words, the proposed method achieves approximately 10% measurement error rate. Moreover, the measurement time of the power loss of the power converter is reduced by 86.1% in comparison with a conventional method. Moreover, another method that can reduce the measurement time is discussed. In particular, the temperature in the container B is controlled to follow in the temperature in the container A for the transient state of the rise in temperature. As a result, the measurement time of the power loss of the power converter is reduced by 87.5% in comparison with a conventional method.

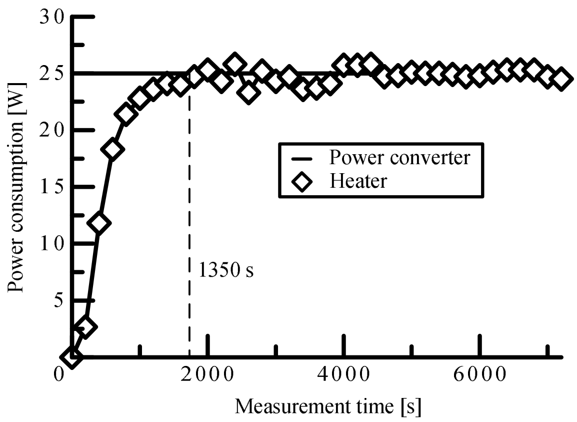


Fig. 11. Power consumptions of converter and heater when the temperature of the container B is controlled as show in Fig. 10.

REFERENCES

[1] R. Kamei, A. kawamura, T. kim, "Discussion on Highly Accurate Calorimetric for Power Loss Measurement", Annual Conference of I.E.E. of Japan, Industry Applications Society, pp.I-363-I-366 (2011)

[2] B. Szabados, A. Mihalcea, "Design and Implementation of a Calorimetric Measurement Facility for Determining Losses in Electrical Machines", IEEE tran. VOL. 51, NO. 5, pp902-907 (2002)

[3] A. Stafiniak, G. Kosobudzki, "Sources of Error in AC Losses Measurement Using V-I Method", IEEE tran. VOL. 19, NO. 3, pp3110-3114 (2009)

[4] W. Yu, H. Qian, J. S. Lai, "Design of High-Efficiency Bidirectional DC–DC Converter and High-Precision Efficiency Measurement", IEEE tran. VOL. 25, NO. 3, pp650-658 (2010)

[5] F. Forest, J. J. Huselstein, S. Faucher, M. Elghazouani, P. Ladoux, T. A. Meynard, F. Richardeau, C. Turpin, "Use of Opposition Method in the Test of High-Power Electronic Converters", IEEE tran. VOL. 53, NO. 2, pp530-541 (2006)

[6] D. Christen, U. Badstuebner, J. Biela, J.W.Kolar : "Calorimetric Power Loss Measurement for Highly Efficient Converters", I PEC2010, pp1438-1445 (2010)

[7] C. Xiao, G. Chen, W. G. H. Odendaal, "Overview of Power Loss Measurement Techniques in Power Electronics Systems", IEEE tran. VOL. 43, NO. 3,pp657-664 (2007)

[8] M. Yagi, S. Tanaka, S. Mukoyama, M. Mimura, H. Kimura, S. Torii, S. Akita, and A. Kikuchi, "Measurement of AC Losses of Superconducting Cable by Calorimetric Method and Development of HTS Conductor With Low AC Losses", IEEE tran. VOL. 13, NO. 2, pp1901-1905 (2003)

[9] S. Weier, M. A. Shafi, R. McMahon "Precision Calorimetry for the Accurate Measurement of Losses in Power Electronic Devices", IEEE tran. VOL. 46, NO. 1, pp278-284 (2010)

[10] A. Nigorikawa, Y. Nakata, K. Orikawa, J. Itoh, "Experimental Verification on Precise Calorimetric Power Loss Measurement Using Two Chambers", 2011 Japan-Korea Joint Technical Workshop on Semiconductor Power Converter, pp77-78, IEEJ-SPC-10

[11] G. Chen, C. Xiao, and W. Odendaal, "An apparatus for loss measurement of integrated power electronics modules: design and analysis", Conference Records of the 37th Annual Industry Applications Conference (IAS), 2002, pp222-226.

[12] P. Wolfs and Q. Li, "Precision calorimetry for power loss measurement of a very low power maximum power point tracker", Australasian Universities Power Engineering Conference (AUPEC), 2007, pp.1-5.

[13] D. R. Turner, K. J. Binns, B. N. Shamsadeen, and D. F. Warne, "Accurate measurement of induction motor losses using balance calorimeter", IEE Proceedings B Electric Power Applications, vol. 138, no. 5, 1991, pp.233-242.

[14] K. Bradly, A. Ferrah, R. Magill, J. Clare, P. Wheeler, and P. Sewell, "Improvements to precision measurement of stray load loss by calorimeter", 9th International Conference on Electrical Machines and Drives, 1999, pp189-193.

[15] S. Weier, R. McMahon, and P. Malliband, "Calorimetry for power electronics", Proceedings of the 41st International Universities Power Engineering Conference (UPEC), 2006, pp608-612.