Overview of Power Loss Measurement Techniques in Power Electronics Systems

Chucheng Xiao, Gang Chen, and Willem G. H. Odendaal, *Senior Member, IEEE*

***Abstract*—Measuring power loss accurately is of great importance for power electronics systems design and for assessing system performance and reliability. This paper reviews various power loss measurement techniques in power electronics systems. A brief overview of electrical methods for loss measurements is given. Calorimetric methods, which are considered the most accurate of this purpose, are described along with their implementations. The pros and cons of various techniques are discussed and compared for estimating the losses in integrated power electronic modules.**

***Index Terms*—Calorimetric methods, power loss measurement.**

I. Introduction

THE NEED of a quantitative knowledge of power loss in any power electronics system is self-evident. Due to the increasing use of power electronics in a wide range of applications, power loss measurement with high accuracy is of great importance in the design process to assess system performance and optimize design characteristics. Driven by recent advances toward integration, higher densities, and higher operating frequencies in power electronics systems, accurate estimates of power losses have become more important for proper thermal management and for ensuring reliable operation. Although sophisticated numerical modeling methods are often available to predict power losses, the validity of the models needs to be verified experimentally, particularly where complex loss mechanisms exist in some parts, for instance magnetic materials for power conversion.

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C. Xiao was with the Center for Power Electronics Systems, Bradley Department of Electrical and Computer Engineering, Virginia Polytechnic Institute and State University, Blacksburg, VA 24061 USA. He is now with Vicor Corporation, Andover, MA 01810 USA (e-mail: cxiao@vicr.com).

G. Chen was with the Center for Power Electronics Systems, Bradley Department of Electrical and Computer Engineering, Virginia Polytechnic Institute and State University, Blacksburg, VA 24061 USA. He is now with ON Semiconductor Hong Kong Design Center, Hong Kong (e-mail: gang.Chen@onsemi.com).

W. G. H. Odendaal is with the Center for Power Electronics Systems, Bradley Department of Electrical and Computer Engineering, Virginia Polytechnic Institute and State University, Blacksburg, VA 24061 USA (e-mail: hardus@ieee.org).

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The task of measuring losses becomes more challenging with ever increasing efficiencies and operating frequencies in power electronics applications.

In this paper, two categories of power loss measurement techniques are discussed: 1) electrical methods and 2) calorimetric methods.

The electrical measurement [1]–[6] uses the product of voltage and current, which gives an electrical quantity equivalent to power. Power measurement can be performed by measuring the voltage drop across the device and the current flowing through it using electrical instruments. In dc and low-frequency ac circuits, it is common to measure power directly by using analog electronic equipment: voltmeters for voltage measurements and ammeters for current measurements, or a combined measurement using a wattmeter. However, for high-frequency signal and highly distorted signals, such as pulsewidth modulation, conventional meters are no longer suitable because of their limited bandwidth and dynamic frequency response. Digital instruments have gained popularity for obtaining the required resolution. This kind of digital meter takes simultaneous samplings of voltage and current waveforms, digitizes these values, and provides arithmetic multiplication and averaging using digital techniques to obtain a power measurement. An appealing advantage of the electrical methods is that they are easy to perform and to reproduce a measurement. It is suitable for steady state as well as transient measurements. However, high di/dt and dv/dt introduce serious radio frequency interference/electromagnetic interference (RFI/EMI) problems since digital instruments are very sensitive to noise. The accuracy of digital measurement is also affected by the delays introduced between probes, phase shifts between sampling channels of digitizer, sampling errors, and nonlinearities of analog-to-digital converter. No instrument known to man can accurately record the hard-switched output voltage waveforms when dv/dt is very high [7].

To date, the most common methods of determining power loss have been the conventional input–output procedure by taking the difference between the measured input and output power. From the basic definition of losses, this is a natural choice. There is always considerable error associated with the subtraction of two nearly equal numbers for high-efficiency system, whichever method is used to measure input and output power.

For example, a 1-kW device with an efficiency $\eta = 93\%$, input power $P_{\rm in} = 1000$ W, output power $P_{\rm out} = 930$ W, $P_{\rm loss} = P_{\rm in} - P_{\rm out} = 70$ W, and assuming $P \propto V \cdot I$ and a $\pm 1.5\%$ error distribution in voltage and current measurements for the input and output power, then the maximum error of

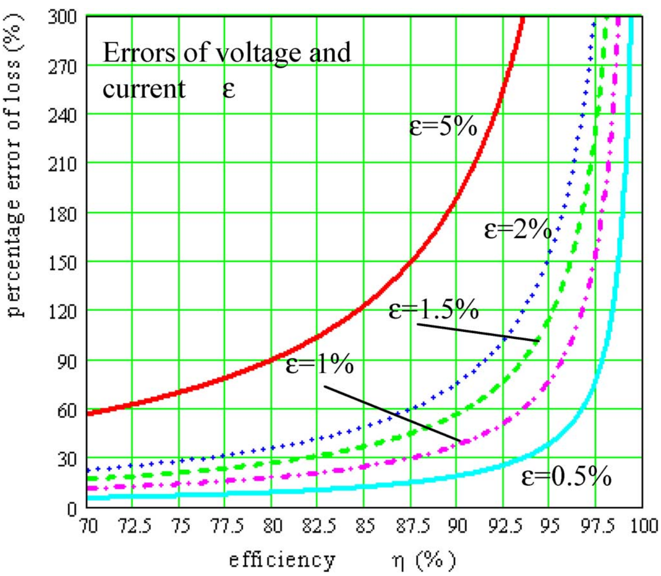

Fig. 1. Percentage error of loss measurement versus efficiency for given error of voltage and current.

loss measurement can be ±57.9 W with respect to the nominal 70 W. In other words, under these idealistic conditions, the absolute percentage error of loss is 83%. If the efficiency increases to 95%, the maximum error percentage can be 117% (Fig. 1). Clearly, there is a high degree of inaccuracy, which makes the loss figure totally unacceptable. To achieve a maximum absolute error of 5% in the total loss measurement using this method, an error as small as 0.09% in each of the voltage and current measurements is required. Such a small error is difficult to achieve, even employing the most sophisticated metering equipment.

In theory, higher accuracy is possible by measuring loss directly. Since the total power losses dissipate as heat, the effect caused by the heat can be measured to determine the losses. This can be achieved by calorimetric methods. Consequently, calorimetric method based on direct loss measurement provides a more accurate measurement technique. Calorimetric methods have been widely used in power electronics to measure the power losses of magnetic components [8]–[12], capacitors [13], switching semiconductors [14], [15], power converters [16], and electrical machines [7], [17]–[25]. Consequently, the calorimetric principle is the most promising of the methods available for accurate power loss measurements [25], [26]. This method has the advantage of being able to measure the power losses under normal operating conditions and being independent of electrical quantities of the device under test (DUT). The disadvantages are that it is usually limited to steady state and that measurement procedure is time consuming.

Note that measurement uncertainties are usually expressed in terms of a standard uncertainty, which is evaluated by either statistical methods or an assumed probability distribution. Since definitions of measurement uncertainty are often subjective and even unique among different standards, the discussion herein will focus more on the independent sources of error than their interpretations and distributions.

In this paper, we briefly review the electrical methods for power loss measurement. Various calorimetric methods are presented, and their operational principles are described in detail with their relative advantages and disadvantages. Therefore, it is expected that this paper will pave the way to evaluate the implementation of the best loss measurement technique for integrated power electronics module (IPEM).

II. Electrical Method

A. Direct Wattmeter Measurement [9]

In this method, the traditional electromechanical wattmeter is used directly to make measurements of the electrical power of the device or circuit under test. The wattmeter accuracy quickly deteriorates as a function of increasing frequencies, particularly when voltage and current waveforms are nonsinusoidal and contain high-frequency harmonics. This kind of wattmeter usually has low bandwidth and poor frequency response; therefore, it is only applicable to dc and low-frequency sinusoidal measurement and is unsuitable for high-frequency and nonsinusoidal conditions.

B. Digital Measurement Techniques

Digital instruments, particularly digital oscilloscopes, are some of the most widely used measuring tools in power electronics systems today. Estimating losses digitally is based on the high-frequency sampling of voltage and current waveforms. For periodical power signals with voltage $v(t)$ and current $i(t)$, having a period of T, the average power P_0 is expressed as

$$P_0 = \frac{1}{T} \int_0^T v(t) \cdot i(t) dt. \tag{1}$$

The voltage and the current waveforms are simultaneously sampled at a sampling rate $f_s = 1/T_s$ and are converted to digital values. The instantaneous power is the product of the digital values. If $v(t_i)$ and $i(t_i)$ are the instantaneous samples of the voltage and current at time $t_i = (iT/N)$, then the average power P_0 can be approximated by

$$P_d = \frac{1}{N} \sum_{n=0}^{N-1} v(t_i) i(t_i) \tag{2}$$

where N is the number of samples used for computing the average.

High-speed digital acquisition of voltage and current data using modern digitizers along with PCs makes this technique a powerful tool for power loss measurement.

This method was used for high-frequency magnetic core loss measurement in [27] and [28]. In [27], an automated measurement system for core loss characterization, under sine-wave or square-wave voltage excitation, is presented (Fig. 2). The core loss of a toroidal core in a temperature-controlled chamber is obtained by computing the mean of the product between primary current (through current-sensing resistor or current probe) and open-circuit secondary voltage referred to

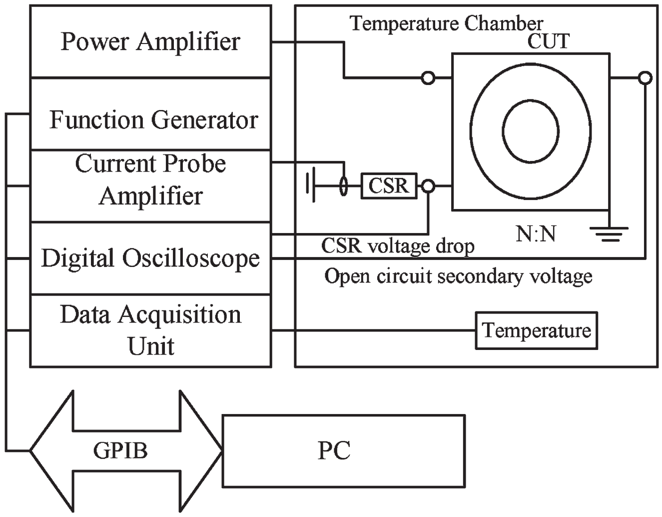

Fig. 2. Automated measurement system for core loss [27].

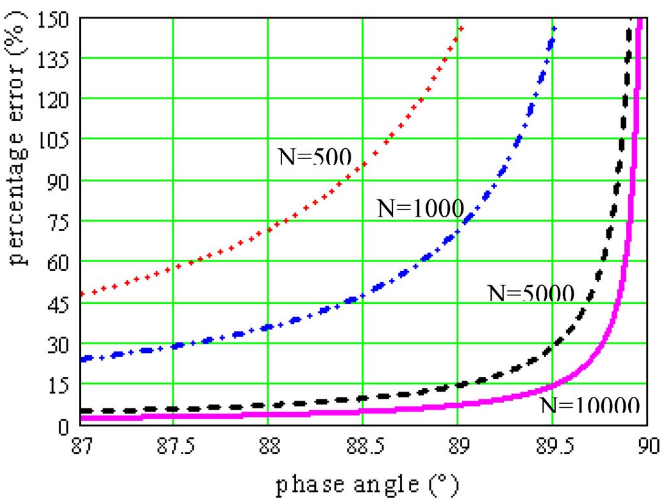

Fig. 3. Percentage error caused by sampling uncertainty in phase angle versus phase angle for different N.

the primary, over an integer number of acquired cycles. Under sinusoidal excitation, the core loss is given by

$$P = \frac{1}{T}\int_0^T v(t)i(t)dt = VI\cos\theta \qquad (3)$$

where θ is the phase angle between voltage and current. The percentage error in the loss measurement due to uncertainty in the phase is obtained as

$$f(N,\theta) = \frac{\Delta P}{P} = \tan\theta\cdot\Delta\theta\times 100\%. \qquad (4)$$

The phase error per data sample $e = 360°/N$ causes a maximum phase difference error $\Delta\theta = 2e$, where $N = f_s/f_0$ denotes the ratio of the sampling rate to the excitation frequency. Fig. 3 shows the percent error versus phase angle for different sampling number N over a cycle.

The plots in Fig. 3 illustrate that when θ is close to 90°, the error can be quite large, even for high sampling rate. The graph in Fig. 3 represents the maximum percentage error in the loss estimation due to the limited phase resolution only. If the amplitude error caused by the resolution of the digitizer and the delay introduced between current and voltage waveforms due to the probe and the cable are considered, the error will be larger [28].

TABLE I
SOURCE BANDWIDTH VERSUS SYSTEM BANDWIDTH

Ratio of Source Bandwidth to Probe/Scope System Bandwidth	Risetime Slowing Amplitude Attenuation
1:1	41%
1:2	12%
1:3	5%
1:5	2%

A computer-based data acquisition system coupled with a digital oscilloscope to create a virtual instrument for instantaneous and average power measurements on resistors, capacitors, ac/dc power converters, and bipolar junction transistor inverters is described in [29]. The same technique was adopted in [30] to measure the power loss of transformer. This kind of instrument shows good accuracy for operating frequencies up to 100 kHz. However, when a digital oscilloscope is used for measuring losses in high-frequency switching power devices, large errors may occur [31]–[34]. During high-speed measurements, parasitic parameters that exist within the measurement system introduce significant aberrations into the measured waveforms. First, different propagation delays due to the different construction of voltage and current probes are noticeable for megahertz signals [35]. Although compensation and correction are recommended to reduce these delays, it is pointed out in [35] and [36] that simple compensation is not sufficient for overshoots and distortions that are introduced by probes and cables, particularly when the probe's input capacitance is of the same order of magnitude as the capacitance of the DUT. Second, the bandwidth and rise time of oscilloscope/probe system also affect measurement accuracy. The equations used to approximate scope/probe system rise time and bandwidth are as follows [37]:

$$\text{System rise time} \approx \sqrt{\mathrm{tr}_{\text{probe}}^2 + \mathrm{tr}_{\text{scope}}^2} \qquad (5)$$

$$\text{System bandwidth} \approx \frac{0.4}{\sqrt{\mathrm{tr}_{\text{probe}}^2 + \mathrm{tr}_{\text{scope}}^2}}. \qquad (6)$$

Table I shows how the ratio of source bandwidth to system bandwidth affects amplitude attenuation of the measured waveforms. It shows that for reasonable accuracy, the probe/scope system bandwidth should always be three to five times larger than measured signal bandwidth.

Finally, the ground lead and probe input capacitance could adversely affect the accuracy of measurement by inducing high-frequency resonance. Common-mode noise may also couple into the measurement system through the ground lead. Susceptibility to RFI/EMI is therefore another important source of uncertainty.

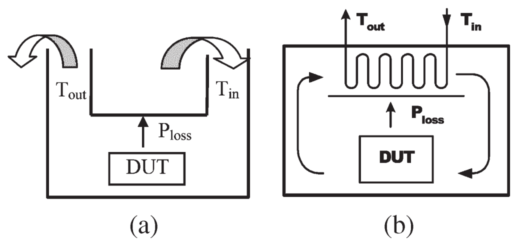

Fig. 4. (a) Schematic of open-type calorimeter. (b) Schematic of closed-type calorimeter.

III. Calorimeteric Method

The aforementioned electrical methods are all based on indirect loss measurements. Consequently, good accuracy is not easily achieved.

Calorimetric methods provide the means for measuring losses directly and are therefore considered to have better accuracy. In addition, they are less dependent on electrical peculiarities of the devices being tested. One remaining challenge is the ability to measure losses of power electronics modules, components, or subsystems accurately under their actual operating conditions.

A. General Principle of Operation

The calorimetric method is essentially aimed at measuring the total power P_{loss}, which the DUT dissipates as heat within a measurement chamber. This heat results in a temperature rise of a controlled environment (coolant) surrounding the DUT, and the temperature rise is, in turn, an indication of the total power losses of the DUT if the heat is completely absorbed by the coolant. Under steady state, the power dissipated by the DUT can be calculated from measured values of the mass flow rate $\dot{m}$ and temperature rise ΔT of the coolant as follows:

$$P = \frac{c_p \cdot m \cdot \Delta T}{dt} = c_p \cdot \dot{m} \cdot \Delta T \tag{7}$$

where c_p is the specific heat of the coolant. The calorimeter can be either of the open or closed type, as depicted in Fig. 4.

The open-type calorimeter exchanges heat directly with the surrounding air, whereas the primary coolant is circulated in a closed loop inside of the closed-type calorimeters that require heat exchangers to remove the heat. The closed-type calorimeter is usually much more accurate than the open type [17].

Some calorimeters based on (7) have been presented in [10] and [11] for transformer loss measurement and in [24] for electrical machines. In [10], the transformer is placed in thermal contact with a calorimetric mass having known weight and specific heat values. Assuming that the system is isolated from the environment, the transformer loss can be calculated based on an energy increment, which is a product of the mass, specific heat, and temperature rise within a specific time interval. However, in practice, the calorimetric mass and transformer are not perfectly isolated from the environment. It is therefore necessary to compensate for the energy that leaks to the surroundings through the insulation and through the transformer leads. The thermal connection between two bodies is also critical since the error caused by poor thermal contact cannot be compensated for.

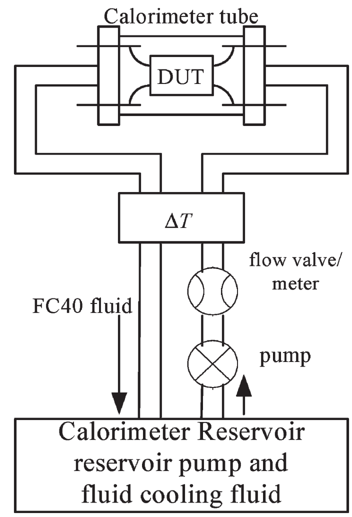

Fig. 5. Block diagram of calorimeter illustrated in [11].

In [11], the coolant of dielectric fluid FC-40 is circulated in the closed cooling system, which consists of a reservoir, pump, and cooling coils near an adiabatic calorimeter tube (Fig. 5). A delta-T thermocouple pile is used in this system for measuring the temperature difference, and a flowmeter is used for measuring the flow rate. It is important to maintain a constant flow rate through the chamber, minimize the heat leakage through the walls of the chamber, and control the temperature of the FC-40 fluid in the reservoir.

The water coolant of the calorimeter in [24] is gravity fed from a 300-L water supply tank with a pressure valve for adjusting the flow rate.

B. Open-Type Balance Calorimeter

A single-chamber calorimeter was demonstrated by Turner *et al.* [20] for the measurement of losses in a 5.5-kW induction motor. This open-type calorimeter uses air as the coolant, and loss measurement is based on the balance method. Losses are determined in two steps, namely: 1) a main test and 2) a calibration test. In the main test, the motor is driven under the normal load conditions, and the steady-state temperature of the air is recorded. Next, the supply to the motor is removed, and an exact amount of power is injected into the calorimeter by heaters. All other conditions (flow rate, temperature, specific heat, humidity, etc.) of the calibration test have to be maintained as close as possible to those in the main test in an attempt to keep the same flow distributions in the calorimeter. Assuming that the physical properties of the air remain constant during the two tests, the measured losses then can be determined from the product of known power and the ratio of the steady-state temperature rises in the two tests. For the same temperature difference in the air, the total motor losses are assumed to be equal to the power injected into the heater. In [20], a worst case accuracy of 1.45% was reported at full load. The main test and the calibration test lasted between 6 and 8 h. This simple balance calorimetric technique has also been successfully implemented for measuring the losses of power electronic

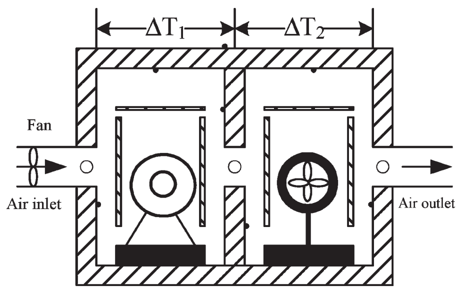

Fig. 6. Block diagram of a DCC in [21].

systems in permanent-magnet machines [7] and magnetic components in power converters [9] with good accuracy.

The balance calorimeter is easy to implement. The drawbacks are as follows: It is time consuming and costly; it has difficulty in maintaining constant coolant temperature and pressure for the duration of the test; and heat leakage can vary greatly between the main test and the balance test. Generally, accurate controls over the airflow, temperature, and humidity are required during the whole test, which requires expensive equipment and advanced control such as described in [22] and [23]. An improved calorimeter was designed with advanced computer control in [22] to minimize the heat leakage, ensure constant air properties, and keep uniform temperature distribution inside the calorimeter and across the air exit duct. Accurate measurements of air temperature, humidity, pressure, and volume flow rate were recorded with high-precision instruments to correct the power loss measurement and to provide control information to the computer. Because of the high repeatability and accuracy, there is no further need for the balance test once calibrated. An accuracy within as little as 0.2% was reached for a loss measurement of a 30-kW induction motor, but at the expense of complicated control, a large and complex configuration, and high cost.

Another balance calorimeter presented by Turner is an open-type double-chamber calorimeter (DCC) [21], as shown in Fig. 6. The DCC can perform a motor test and a calibration test simultaneously. The ratio of the measured losses to the reference heat losses is proportional to the ratio of the respective air temperature rise. Since the same air is used for both tests, errors are reduced by removing the uncertainty of air's thermal properties between tests. Also, the DCC simplifies the calorimeter operations and shortens the test time, although it doubles the chamber size. An overall accuracy of ± 15 W was obtained in [21] for 1-kW losses in a 7.5-kW machine, and $\pm 2\%$ error based on the 600-W total losses was reported in a flow calorimeter [38], which is a variation of DCC technique, as shown in Fig. 7.

Polyurethane foam of 48-mm thickness, having a thermal conductivity of 0.028 W/K · m, was used as the insulating material in the calorimeter shown in Fig. 7. A labyrinth structure was constructed to improve mixing of the air for measuring average temperature and to hide the thermistor from infrared emissions coming from the DUT and the heater.

The DCC method is an improved technique over the conventional single-chamber balance test by reducing the testing time. However, the problem of difference in heat leakage between the two chambers still exists. Again, there is no guarantee that the airflow conditions inside two chambers are similar.

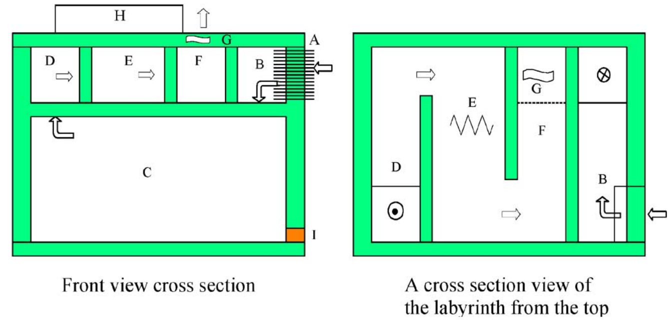

Fig. 7. Flow calorimeter. A: temperature equalizer; B: inlet room; C: test room; D: outlet of test room; E: reference heater; F: outlet of reference heater; G: regulated fan; H: supply, control, and readout; I: cable.

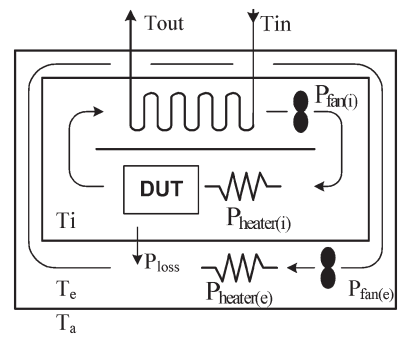

Fig. 8. Schematic of double-jacketed calorimeter.

C. Double-Jacketed Closed-Type Calorimeter

As mentioned previously, it is very important to minimize the heat leakage through the chamber walls and other parts of the calorimeter chamber. The concept of double-jacketed calorimeter was presented by Malliban *et al.* [17]–[19]. This is essentially a closed-type calorimeter that directly measures the power losses using (7), but in this design, a second thermally insulating enclosure is added to prevent the heat leakage through the walls and to ensure that all heat from the DUT is completely absorbed by the coolant. Therefore, the power loss through the chamber walls is less than the required absolute accuracy P_{acc}. In theory, the heat leakage in the closed-type calorimeter shown in Fig. 4(b) can be eliminated if the temperature inside the calorimeter is the same as that of the ambient. Thus, a significant improvement in the accuracy of loss measurement is possible in half of the time that is typically required by balance calorimeter. The operation principle of the double-jacketed calorimeter is depicted in Fig. 8.

The outer insulating enclosure isolates the calorimeter from the ambient. The air gap temperature T_e is controlled to be equal to the temperature T_i inside the calorimeter. To ensure that power loss through the inner calorimeter walls is less than the maximum permissible loss P_{acc}, the following relation must be satisfied:

$$|T_i - T_e| < P_{\mathrm{acc}} R_{\mathrm{th(cal)}} \tag{8}$$

where $R_{\mathrm{th(cal)}}$ is the thermal resistance of the inner walls.

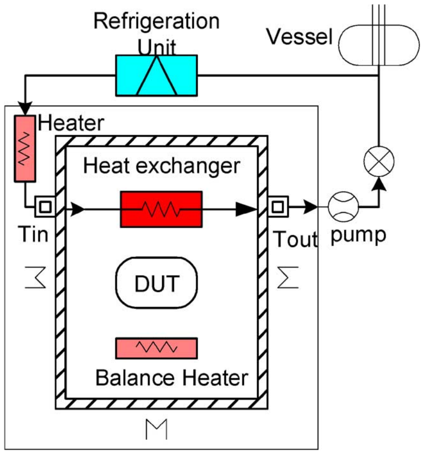

Fig. 9. Diagram of principle in [5].

Although the calorimeter of [17] was originally designed to test a motor up to 1.1 kW, it can be used to perform tests on a 2.2-kW induction motor [18]. An air/water heat exchanger inside the chamber withdraws the heat dissipated by the test motor from the calorimeter, and dc fans force air through the heat exchanger. A water tank is located above the calorimeter, and the flow rate can be measured by weighing the water at fixed intervals of time and can be adjusted by throttling the valve. The insulating wall and motor support structure were carefully designed to reduce the heat leakage. Heaters and fans are evenly placed in the air gap to ensure uniform temperature distribution on the surface and to avoid local cold or hot spots. With special attention paid to the potential sources of error and improved design, the calorimeter achieved 0.5-W accuracy on a full scale of 300 W. Malliband *et al.* [18] claimed that an accuracy of 0.1 W over 200 W is possible with smaller and more accurate calorimeters.

A calorimetric wattmeter (as shown in Fig. 9) that was constructed at Aalborg University is also a double-jacketed closed-type calorimeter [25], [26]. It consists of two concentric thermally insulated boxes. The surfaces of the inner test chamber are coated with glass fiber and epoxy. It is equipped with an internal heating system that serves the dual purposes of creating a desired test temperature and of calibrating. An array of 68 light bulbs in the air gap regulates the surface temperatures to minimize the heat flux through the walls. These bulbs also ensure faster response by radiating the heat to the surface. A gear pump controls water flow rate, and a flowmeter senses the flow rate. A refrigeration unit combined with a heater before the inlet controls the inlet coolant temperature. The heat dissipated from the DUT is absorbed by the flowing water through the heat exchanger. Numerous temperature sensors are installed in the measurement system for measuring temperatures in different locations. A PC with LabView is used to control, regulate, and store all the data. Ritchie *et al.* [25] and Hansen *et al.* [26] presented an empirical formula for computing the inlet temperature and mass flow in advance by using a predicted value of the power loss as an input. This calorimeter can measure power losses in the 1- to 50-W range with an error of less than $\pm 0.2\%$ at full load. The physical size of the DUT

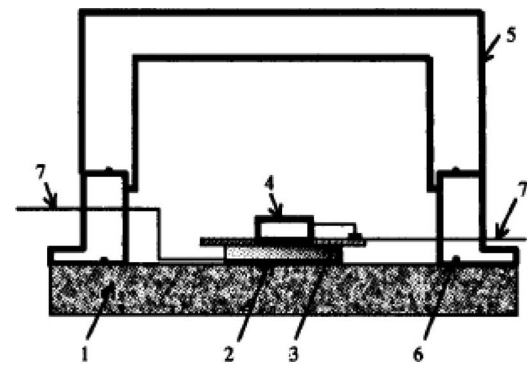

Fig. 10. Schematic of apparatus in [4]. 1: aluminum base plate; 2: heat flux sensor; 3: heat spreader; 4: DUT; 5: aluminum cover; 6: fitting; 7: lead wires.

was $200 \times 200 \times 300$ mm, but it could be up to $1000 \times 1000 \times 700$ mm for measuring losses of between 200 and 1500 W.

These tests demonstrate that the implementation of a double-jacketed enclosure in the calorimeter could increase the accuracy considerably by active control of the air gap temperature and by implementing automatic computer control.

D. Calorimeter Based on Heat Flux Sensor

A simple and accurate apparatus for measuring the losses in a magnetic component is presented in [8] (Fig. 10). A heat flux sensor is embedded inside a pedestal, on which the DUT is mounted. A liquid-cooled base plate serves as the heat exchanger. The heat passing through the sensor generates a temperature difference between the upper side and lower side of the sensor. The temperature difference is proportional to the heat flux through the sensor and is converted to a voltage signal. A heat spreader distributes the heat over the sensor area. The apparatus is designed such that almost all the heat generated in the DUT passes through the heat flux sensor. Accuracy of the instrument depends on how well this condition is satisfied.

The liquid-cooled base plate allows most of the heat to flow downward through the heat flux sensor. The chamber is evacuated to minimize convection heat loss, and inside surfaces are polished to minimize the radiation heat loss through the cover. Factors that affect the measurement accuracy were analyzed by using thermal analysis software. The apparatus is suited for measuring power losses of relative small components to within $\pm 5\%$ error. This method is easier to implement and operate in comparison with the aforementioned calorimetric methods. It does not need a liquid bath or a liquid flow system, and the thermal time constants are significantly shorter.

E. Summary

Based on the discussion of various aforementioned calorimeters, every method has its own features and advantages.

The open-type calorimeter uses air as a coolant, thus eliminating the risk of leaking fluids. The cooling system is very simple; however, the properties of air such as density and specific heat are easily affected by ambient temperature, pressure, and humidity. Air as coolant is also more prone to uneven temperature distributions inside the chamber. Therefore, the

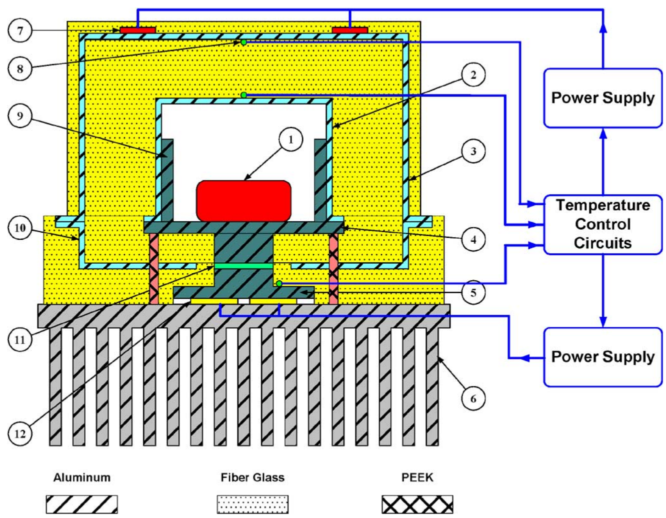

Fig. 11. Schematic of proposed apparatus in IPEM. 1: DUT; 2: inner Al cover; 3: outer Al cover; 4: Al base plate I; 5: Al base plate II; 6: heat sink; 7: heater; 8: thermocouple; 9: fins; 10: insulated material; 11: heat flux sensor; 12: TE module.

open-type calorimeter is unsuitable for a direct calorimetric measurement using (7). Although the balance calorimeter and the DCC improve and enhance the wider use of the calorimetric method by eliminating the need for direct measurements of air density and flow rate, problems such as heat leakage between two tests or chambers and great temperature gradients still exist. These problems were addressed in [22], but at the expense of significant increase in complexity and cost.

For the closed-type calorimeter, water or another fluid is used as coolant. The density and specific heat of such coolants can be determined more accurately and are not as dependent on changes in the environment. The volume and flow rate can also be determined with ease. Since the density and specific heat of such coolants are much higher than those of air, the volume flow rate is much smaller for a given power loss, resulting in smaller duct sizes and slower flow velocities. This method may therefore be used for a direct calorimetric measurement or a balance test with better accuracy than that of the open-type calorimeters. Active temperature control by adding another insulating enclosure and automatic computer control increases the measurement accuracy considerably. However, liquid coolant and a heat exchanger are needed in the closed cooling system, making this system complex and expensive.

The dry calorimeter based on heat flux sensors is an effective and simple construction. Fewer accessories are required as compared to the other calorimeters, and the testing time can be reduced because of small time constants.

A calorimeter combining the advantages of double-jacketed closed-type calorimeter and calorimeter based on heat flux sensor is presented in [39] for accurate loss measurement of IPEMs. The schematic diagram of the proposed calorimeter is shown in Fig. 11.

The power converter based on IPEMs (or another DUT) is placed inside the internal enclosure of the double-jacketed calorimeter. The temperature difference between two polished covers is controlled to minimize the heat escaping through the two covers. A heat flux sensor placed under the conductive pedestal measures the total heat generated in the DUT. A pair of thermoelectric (TE) modules are introduced to keep the plate II (as shown in Fig. 11) at constant temperature and direct the generated heat in the DUT to flow down through heat flux sensor, or alternatively, the temperature of the DUT can be controlled. The heat sink, TE modules, and heat flux sensor together replace the liquid cooling system necessary in other types of calorimeter. The proposed calorimeter is easy to setup and operate, and less than 5% error in 50-W loss measurements can be achieved.

IV. Conclusion

Various loss measurement techniques, including electrical methods and calorimetric methods, are described in this paper. The electrical methods are briefly introduced, and sources of measurement errors are discussed. The emphasis of this paper is placed on the description of various calorimeters. The basic principles of operation of various calorimetric methods have been presented. From the descriptions of electrical and calorimetric methods, it can be concluded that calorimetric methods are more accurate than indirect electrical measurements of losses, particularly for high-frequency and nonsinusoidal conditions. It can be expected that with further investigation of calorimetric methods and the development of modern technology, calorimetric method will gain more popularity in power electronics systems.

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Chucheng Xiao received the B.S. and M.S. degrees from Huazhong University of Science and Technology, Wuhan, China, in 1995 and 1998, respectively, and the Ph.D. degree from Virginia Polytechnic Institute and State University, Blacksburg, in 2006.

From 1998 to 2001, he was an Engineer at Dongfang Electronics Company, Yantai, China. He is currently a Senior Design Engineer at Vicor Corporation, Andover, MA, where he designs VI chips. His research interests include high-frequency high-power-density dc–dc power converters, thermal management and measurement of power electronic systems, integrated current-sensing techniques, and integration of passive components.

Gang Chen received the B.S., M.S., and Ph.D. degrees from Zhejiang University, Hangzhou, China, in 1994, 1997, and 2001, respectively, all in electrical and electronics engineering.

He was a Research Assistant during his Ph.D. program in the Department of Electronic and Information Engineering, Hong Kong Polytechnic University, Hong Kong. From 2001 to 2004, he was a Postdoctoral Research Scholar in the National Science Foundation Engineering Research Center for Power Electronics Systems, Virginia Polytechnic Institute and State University, Blacksburg. He is currently an Application Engineer at ON Semiconductor Hong Kong Design Center, Hong Kong. His research interests include power conversion, soft-switching techniques, modeling and control of power converters, and thermodynamic analysis and processing in power electronics systems.

Willem G. H. Odendaal (M'98–SM'04) received the B.Eng., M.Eng., and D.Eng. degrees from Rand Afrikaans University, Johannesburg, South Africa, in 1992, 1995, and 1997, respectively, all in electrical and electronics engineering.

He spent one year in a postdoctoral position under two fellowships at the Virginia Power Electronics Center, Virginia Polytechnic Institute and State University (Virginia Tech), Blacksburg, before joining Philips Research North America, Briarcliff, NY, as Senior Member of Research Staff. Since the fall of 2001, he has been an Assistant Professor in the Bradley Department of Electrical and Computer Engineering, Virginia Tech, as well as a Faculty Member of the National Science Foundation Engineering Research Center for Power Electronics Systems. His research interests include electromagnetic and thermodynamic energy processing and packaging of power electronic circuits, EMC/EMI, and relativistic electrodynamics.

Prof. Odendaal is a Member-at-Large of the ADCOM of the IEEE Power Electronics Society and a Past Chairman of the Power Electronics Devices and Components Committee of the IEEE Industry Applications Society.