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An Accurate Method For Power Loss Measurements In Energy Optimized Apparatus And Systems

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Keywords

»Efficiency « , »Measurements « , »Test Bench « , »Thermal Design «

Abstract

A calorimetric wattmeter has been built at Aalborg University, Institute of Energy Technology. The wattmeter is designed to measure power losses in power electronic components and applications at fixed temperatures. High accuracy has been achieved by using active constraints and optimizing flow and temperature conditions in the cooling circuit.

Introduction

The need for improved techniques capable of accurate measurement of power losses in power electronics, electrical machines and electro-technical devices, is becoming increasingly important. This is a result of the increasing use of power electronics in a wide range of applications, combined with the emergence of far more efficient and versatile power electronic components.

However, power electronics are often characterized by inductive circuits, currents and voltages with waveforms containing high frequency harmonics. It becomes difficult to measure power accurately due to a demand for measuring instruments with a high sampling rate and a wide bandwidth.

When measuring the efficiency, one needs two measurements, based on a combination of P_{in}, P_{out}, and P_{loss}. Classical methods use P_{in} and P_{out}. However, since the overall efficiency of power electronics apparatus is usually high, direct measurement of P_{loss} would increase the accuracy of the efficiency measurements. Classical methods uses equation (1) to determine the efficiency:

$$\eta = \frac{P_{out}}{P_{in}} \tag{1}$$

Whereas power loss methods uses:

$$\eta = 1 - \frac{P_{loss}}{P_{in}} \tag{2}$$

If P_{in} is determined to be 500 W±2%, P_{out} 450 W ±10%, and P_{loss} 50 W ±1%, classical methods would measure the efficiency to be 0.90±0.11, while measurement of the power loss would predict the efficiency to be 0.90±0.03.

Consequently, measurement of the power loss gives the possibility of more accurate measurements:

- On inductive circuits, or circuits characterized by a high frequency waveforms.
- Of efficiencies of power electronic components and apparatus.

Internationally, the calorimetric principle is the most promising of the methods available for accurate power loss measurements.

The objective of this project has been to design and build a calorimetric test rig capable of measuring power losses in the range between 1 and 50 W in electrical components. The test rig is to generate a required, predetermined, ambient temperature between 20°C and 70°C, and maintain it during the tests. The constructed test rig can measure power losses in components with a physical size up to 200 mm × 200 mm × 300 mm.

Method

Calorimetric methods make use of the fact that all losses in electrical applications are dissipated as heat, which results in an increase in machine temperature above the ambient level. The heat is then transferred to the surroundings by the three processes of conduction, convection, and radiation. [1]

Design

In order to maintain a steady ambient test temperature, heat dissipated from the device under test must be transported outside the control boundary of the system. Consequently, the system must be equipped with some kind of cooling system.

The power dissipated from the device under test is then found by:

$$P_{Coolant} = c_p \cdot \rho \cdot \dot{V} \cdot \Delta T_{Coolant} \tag{3}$$

The various types of calorimeter can be sorted into two basic categories termed open or closed circuits.

These terms refer to the way in which heat is exchanged with the surroundings. The open type exchanges heat directly with the surrounding air, whereas a heat exchanger is employed for the closed type. In the closed system, a coolant is needed and most frequently, water is chosen for this purpose.

The open circuit is relatively simple to implement and has a short response time. In this case, the coolant must be air. This gives rise to some disadvantages in such a system, since it is difficult to acquire integral measurements of both heat capacity, density, volume flow, and temperature rise of the coolant.

A heat exchanger is used to absorb the dissipated heat from the closed circuit inside the test chamber, and a liquid is used as coolant. This leaves only the mass flow, and the temperature rise of the coolant to be measured, since the temperature only affects the integral heat capacity of the coolant.

Calorimetric rigs operating with closed circuits have proved to be far more accurate than those with open circuits. Consequently, the design chosen was the closed circuit.

An important source of error was the heat leakage through the walls of the system. The total heat balance for the system is:

$$P_{loss} = \underbrace{c_p \cdot \dot{m} \cdot \Delta T_{Coolant}}_{\text{Heat loss through the cooling circuit}} + \underbrace{kA \cdot \Delta T_{Wall}}_{\text{Heat loss through the walls}} \tag{4}$$

During regular measurements of a power loss of 10 W at a test temperature of 30°C and an ambient temperature of 20°C, the heat flux through the calorimeter walls would be the major part of the total flow at approximately 8 W. In order to avoid this, and reduce the response time of the system, active regulation of the outer surface temperature, of the test chamber is provided. This method ensures practically zero heat flow through the wall, because the averaged temperature gradient across the wall is maintained at 0°C. The response time of the system is reduced, as only half of the wall material is now heated from the interior.

The active wall regulation can maintain an instantaneous temperature gradient across the walls of 0.7°C or less. See Fig. 1.

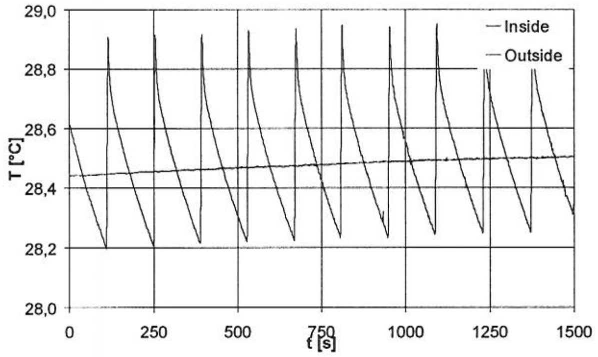

Fig. 1 Active temperature control of the test chamber walls.

Measuring method

The proposed measurement system uses the direct calorimetric measurement method. This method is based on the determination of the power transferred to the coolant by measurements of coolant mass flow rate and temperature increase. Heat is not transported from the measurement chamber by any other means.

Both the direct method and a balanced method were considered as measurement options. The balanced method uses a second measurement during which the conditions inside the chamber are carefully reproduced, and with DC heater as the source of heat. This power may be easily measured. However, the main obstacle against using the balanced method was the ability to reproduce exactly the same conditions for both tests.

Implementation

In the design of the measurement system the key matters of interest have been:

- Use of lightweight materials in order to minimize the time constant of the system.
- To provide a high degree of thermal insulation, to minimize extraneous heat flow to the surroundings.

- To design the mechanical arrangements of the test chamber in order to provide versatile use of the measurement system.
- To minimize the use of electrically conducting materials in the design, in order to prevent eddy current losses. These could be caused by radiation of AC electromagnetic fields from the device under test, and thus change the power dissipated in the chamber during the test.

Physical design

The measurement system is in the form of two concentric boxes. The internal box is the test chamber and is of thermal insulation material. The surfaces of the box are coated with glass fiber and epoxy. A photograph of the overall design of the measurement system is given in figure 2.

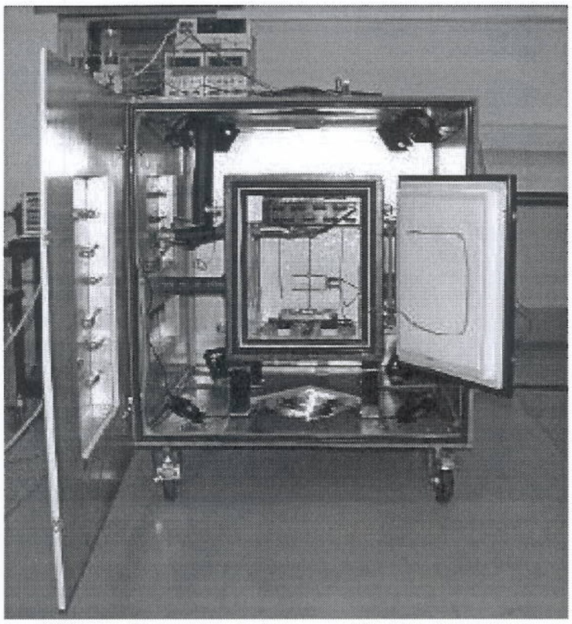

Fig. 2 The calorimetric measurement rig at Institute of Energy Technolog y, Aalborg University.

Internal Heating

The measurement system is equipped with an internal heating system. This is both used to initialize the desired test temperature, and for measurements to verify the accuracy of the measurement.

Temperature control

The surface temperatures are measured with two arrays of 24, Pt100 sensors. The test chamber temperature is measured by one Pt100 sensor and the internal surface sensor array. As heat source for the outside surface, an array of 68 light bulbs was used. This ensures fast response, since the heat is transferred from the sources to the surface by radiation. To reduce the effect of natural convection on the surface, 8 fans ventilate the outer surfaces. The temperature gradient of the lead-throughs to the inner box is also reduced by this method.

Cooling circuit

A cooling circuit absorbs the heat dissipated in the device under test. The cooling circuit consists of a heat exchanger inside the box, two Pt100 temperature sensors placed at the lead-throughs in the wall, a gear pump to ensure controlled steady flow, a flow sensor, and a refrigeration unit, which combined with a heater, placed before the inlet produces a controlled inlet temperature. The overall circuit design of the measurement system is given in Fig. 3.

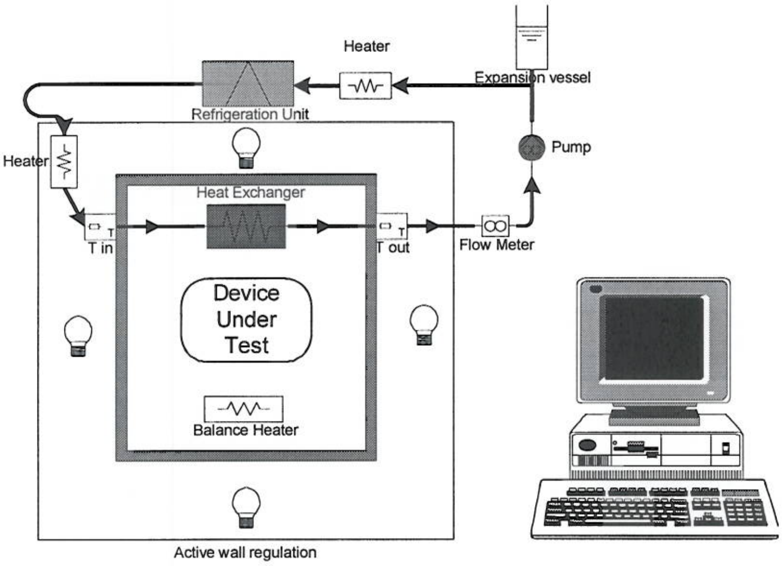

Fig. 3 Design of the measurement system

In order to acquire the most accurate results using the chosen instrumentation, a study to optimize the overall accuracy by correlating the different sub-measurements from the system. This study generated a prediction of corresponding mass flow in the cooling circuit and temperature rise of the coolant, for measuring an estimated power loss.

$$\dot{m}_{Opt} = 0.36 \times P_{Estimated}^{0.4} \tag{5}$$

Subsequently, the heat exchanger efficiency was measured, and the inlet temperature for a predicted power loss generated.

$$T_{Inlet} = T_{Test} - \frac{P_{Estimated}}{c_p \cdot \dot{m}_{Opt} \cdot \varepsilon} \tag{6}$$

Figure 4 shows the calculated optimum mass flow in the coolant circuit for most accurate power loss measurements. Figure 5 shows the measured efficiency of the heat exchanger within the possible range of operation.

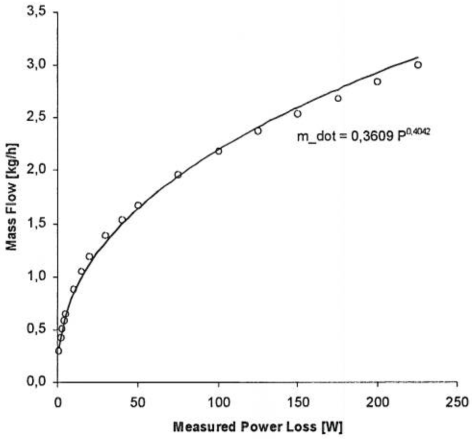

Fig. 4 Calculated optimum coolant flow

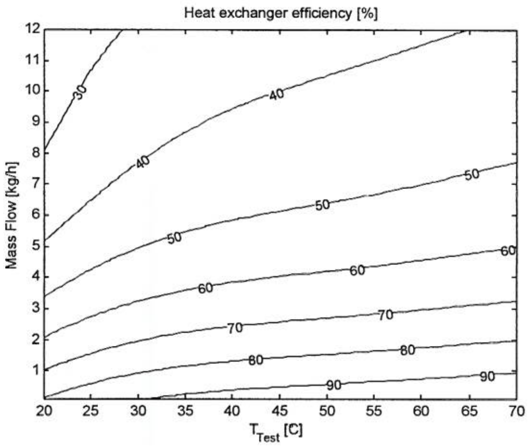

Fig. 5 Measured heat exchanger efficiency

Data acquisition and control

A PC with LabView™ was used to control the system and store all data. Based on a predicted power loss from the device under test, the inlet temperature, and an initial mass flow in the cooling circuit was derived. In order to maintain a steady test chamber temperature the mass flow in the cooling circuit was regulated until the desired test condition was achieved. Since the heat exchanger efficiency was measured directly, the settling mass flow was determined by the accuracy of the predicted power loss. However, an error in estimation of the power loss at up to ±20% does not influence the overall accuracy significantly.

Post processing of the acquired data is performed in LabView™. The measured power loss is found as an average, based on the data's acquired from four hours measurement, while the system is within the defined steady state condition. It is possible to set up the system for a series of measurements at different power losses, and test temperatures.

Results

The verification tests of the measurement rig are still in progress, and further accuracy improving techniques are still being implemented. However, the test rig shows already a very high potential accuracy.

So far, tests have been performed on the interior heaters in the test rig. When the interior heaters are supplied by DC current, the power dissipated within the test chamber may be measured accurately.

In figure 6 some of the acquired results are shown for measurements at test temperatures of 30°C and 70°C. However, since the measurement system is still undergoing further improvements the measurement series are not entirely comparable. Nevertheless, the results so far indicate that measurements of power losses may be performed using the measurement system with accuracy better than ±0.2% of full-scale deflection.

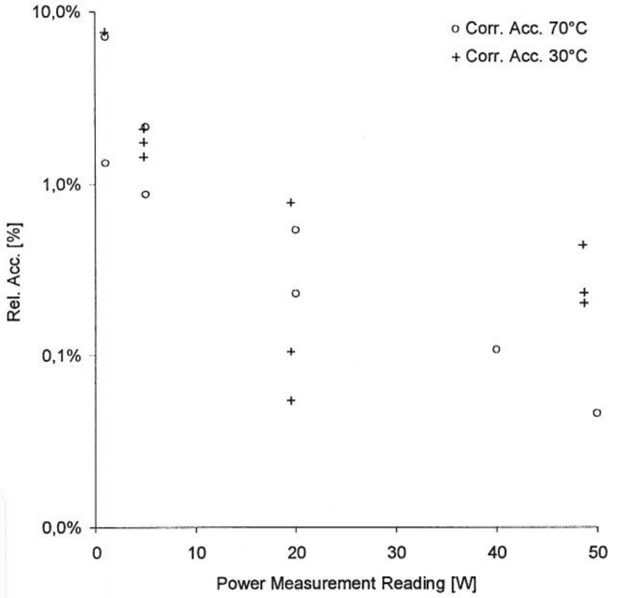

Fig. 6 Accuracy in power loss measurements

Though the materials in the design were chosen for their low density, the system has a long time constant. The time reach to stable conditions from one test temperature level to another is about 4 hours. If the test temperature is constant, the power loss may be measured after 2 hours following a step change in test device power loss.

Another important feature is that the design makes extensive use of modern available technology. In the implementation of the system it has not been necessary to develop a new, accurate, measuring device, or make use of special materials or technology.

However, there have been two major problems with the results achieved from the measurement system so far. Although active wall regulation is utilized, there seems to be an unaccounted heat flow from the surroundings to the test chamber. This heat flow seems to be affected of the test temperature. Investigations to reveal the source are as yet inconclusive. Some investigations indicate the temperature distribution on the inner surfaces may be the source of the error. The temperature profile on the surfaces is complex, and though the sensor arrays are dense, some cold spots may still not be measured. Though the source of the heat flux is undiscovered, investigations so far have all showed that use of an empirical constant in the result improves the accuracy to ±0.2% of full scale deflection. Another important issue is to maintain a constant predetermined inlet temperature. So far the inlet temperatures fluctuate with a magnitude of 0.4°C causing less accurate measurements at low power level, e.g. <10 W. Though the fluctuations have been reduced work is still continuing to obtain a further reduction.

Conclusion

Power measurements can be performed with good accuracy of 0.2% of full scale deflection using the proposed calorimetric measuring method. The constructed measuring system may be used to measure power losses between 1 W and 50 W at a constant determined temperature. Tests have shown that the implementation of active wall regulation increases the accuracy considerably. However, a satisfactory measurement technique for measuring the surface temperatures on the entire surfaces remains to be found.

The preliminary study of the correlation accuracy between the primary measurement components also resulted in a significant increase in the overall accuracy.

Further validation of the test rig, and more research in to the overall accuracy will be performed while conducting initial experiments on power electronic components.

The test rig is currently used in basic research at Institute of Energy Technology, Aalborg University. Another important task for the test facilities will be to perform tests on industrial components and consumer electronics for companies.

In this function, the calorimetric wattmeter is an effective tool in the development of and research into, the energy efficient electronics of tomorrow.

Nomenclature

P_{in}	input power to component	[W]
P_{out}	output power from component	[W]
P_{Loss}	power loss from component	[W]
η	efficiency of component [-]	
c_p	integral heat capacity of the coolant	[J/(kg°C)]
ρ	density of the coolant	[kg/m^3]
$\dot{V}$	volumetric flow of the coolant	[m^3/s]
$\Delta T_{Coolant}$	temperature rise of the coolant	[°C]
kA	heat transfer coefficient for the system	[W/°C]
ΔT_{Wall}	temperature gradient through the walls	[°C]
$P_{coolant}$	heat dissipated to coolant	[W]
P_{loss}	total heat loss of DUT	[W]
$P_{Estemated}$	estimated power loss to measure[W]	
$\dot{m}$	mass flow of coolant	[kg/s]
$\dot{m}_{Opt}$	mass flow for optimum accuracy	[kg/s]
T_{inlet}	inlet temperature of coolant	[°C]
T_{Test}	test chamber temperature	[°C]
ε	heat exchanger efficiency	[-]

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