Calorimetric Measuring Systems for Characterizing High Frequency Power Losses in Power Electronic Components and Systems

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Abstract - **High frequency power losses in power electronic components and systems are very difficult to measure. The same applies to the efficiency of high-efficiency systems and components. An important method to measure losses with high accuracy is the calorimetric measuring system. This paper describes two different calorimetric measuring systems, one for power losses up to 50 W and one for power losses up to 1500 W. These differ in size and also the systems which can be analysed. The basic concept of calorimetry is discussed and the overall performance of the two systems is specified. Methods to calibrate such systems are proposed and different applications of the systems are given. Two practical examples end the description of the research. It is concluded that such systems have a relative long time-constant but they are accurate and useful for precise power loss measurement**.

I. INTRODUCTION

Power electronics remains an emerging technology. New materials, new devices and new circuit topologies reduce the cost, weight and volume for important applications [1]. Two important factors in power electronic circuits are the switching speed of the devices and the total power losses in the system. If the switching speed can be increased improvements may be possible e.g. current ripple in an electrical machine or physical size of passive components may be reduced. On the other hand increased switching speed may cause additional losses in a power electronic system, and increase the system cooling requirement. A common problem is that high frequency phenomena like proximity effect, skin effect, hysteresis losses and eddy current losses appear in the systems. These losses are very difficult to treat both theoretically and in practice. It is often difficult to measure the effect of increasing the switching frequency electrically, because the system efficiency is high and a pure input-output measurement gives an unsatisfactory resolution and accuracy.

A promising solution is to use a calorimetric measuring system. This has been reported in the literature in a number of versions and applications. In [2] a double chamber air-based system is used to determine power losses particularly for motor drives. A simpler method is presented in [3], using a two body mass principle to determine power losses in a transformer using a known mass and the specific heat. Other versions are presented in [4] and [6] to determine the power losses in electrical machines. Determination of losses in a capacitor is also difficult by using the measurement of electrical power and [5] uses isothermal calorimetry. The applications of calorimetry are many, e.g. soft-switching of high power devices [7], AC loss test of super conductors [8], stray losses in induction machines [9], deflection coil in a television [10], [11] and a diode split transformer in a television [12] and more.

Several issues are important in calorimetric system design. The temperature around the device under test has to be fixed to maintain constant losses. The system must respond quickly to yield many measurements in a given time. Interface to a load may be necessary. The same measurement should be repeated without a significant error. Finally, the system should be user-friendly.

Two calorimetric wattmeter systems have been designed and built based on these criteria. One system [13] is useful for low power measurements (< 50 W) and the other system can measure up to 1.5 kW. A rotating load is provided on this system. This paper describes the two systems with demands and specifications. Methods are described to promote high accuracy. Different applications and some measuring examples are described.

II. BASIC PRINCIPLE OF OPERATION

The calorimetric principle is a most promising method for accurate power measurements. A calorimetric wattmeter provides a useful tool for use in the development of new, energy efficient, electrical components for industrial and consumer products.

The overall efficiency of any component is defined by the power supplied to it, and the useful power output as shown in

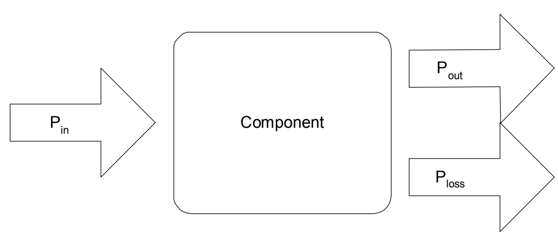

Fig. 1. The overall power balance for an electrical component

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The overall power balance may be expressed as:

$$P_{in} = P_{out} + P_{loss} \tag{1}$$

where

P_{in} is the power supplied to the component
P_{out} is the usable power from the component
P_{loss} is the power loss from the component

For example, when measuring P_{in} for a motor drive supplied with DC, P_{in} is characterized by a constant voltage level and highly alternating currents. In this configuration P_{in} may normally be determined with an accuracy of 2%. For the drive, P_{out} comprises a wide spectrum of harmonic waveforms both for voltage and for current. P_{out} may be measured with an accuracy of 10 %. P_{loss} is the heat lost to the surroundings from the device during operation.

The overall efficiency may be expressed variously:

$$\eta = \frac{P_{out}}{P_{in}} \tag{2}$$

$$\eta = \frac{P_{out}}{P_{out} + P_{loss}} \tag{3}$$

$$\eta = 1 - \frac{P_{loss}}{P_{in}} \tag{4}$$

where

η is the overall efficiency

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

Two measurements are required, based on a combination of P_{in}, P_{out}, and P_{loss}, to measure the efficiency. The common method uses P_{in} and P_{out}. Since the overall efficiencies of power electronics are often high, the use of a direct measurement of P_{loss} in the efficiency measurement would improve the accuracy of the efficiency determination. In a drive system, an accurate measurement of P_{loss} would enable a determination of P_{in} and P_{loss}, eliminating a relatively large error from the efficiency measurement.

A calorimetric measurement of the power loss facilitates more accurate measurements for:

- Inductive circuits, or circuits carrying high frequency waveforms.
- Losses in power electronic components.

Fundamentally, the calorimetric method is based on measurements of the heat dissipated, P_{loss}, inside a measurement chamber. Use is made of the fact that all losses in electrical apparatus are dissipated as heat, resulting in an increase of machine temperature above the ambient. Heat is then transferred to the surroundings by the three processes of conduction, convection, and radiation. The ideal calorimetric measurement system has adiabatic walls, ensuring that the total power loss from the Device Under Test (DUT) may be detected as an increase in temperature inside the measurement chamber.

However, this measurement is unsuitable for measurements below a given ambient temperature. Since the temperature is not predetermined, but varies with the heat loss supplied, the method also implies precise knowledge of the thermal characteristics of the materials enclosing the measurement chamber, i.e. the heat storage capacity.

To maintain a steady ambient test temperature, heat dissipated from the device under test must be transported outside the control boundary of the chamber. The system requires a method of cooling.

The power dissipated $P_{coolant}$ from the device under test is then given by:

$$P_{coolant} = c_p \cdot \rho \cdot \dot{V} \cdot \Delta T_{coolant} \tag{5}$$

where

C_p = the specific heat of the coolant
ρ = the mass-density of the coolant
$\dot{V}$ = the volume rate of flow of the coolant
$\Delta T_{coolant}$ = the temperature change of the coolant

The various types of calorimeter may be sorted into two categories termed open or closed circuit. These terms refer to the method of heat exchange 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. Most frequently, water is chosen.

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

In the closed circuit type, a heat exchanger is normally used to absorb the heat dissipated inside the test chamber, using a liquid as coolant. The mass flow, and temperature rise of the coolant must be measured, since the temperature merely affects the integral heat capacity of the coolant.

Closed circuit calorimetric systems have proved to be far more accurate than those with open circuit. The closed circuit design was chosen.

A major source of error is heat leakage through the walls of the chamber. The total heat balance for the system is:

$$P_{loss} = \underbrace{c_p \cdot \dot{m} \cdot \Delta T_{coolant}}_{\text{Heat loss through cooling circuit}} + \underbrace{kA \cdot \Delta T_{wall}}_{\text{Heat loss through the walls}} \quad (6)$$

where

$\dot{m}$ = the mass rate of flow of the coolant

kA = the coefficient of conductive heat loss of the walls

ΔT_{wall} = the temperature gradient through the wall

During measurements with of a power loss of 10 W, at a test temperature of 30°C, in an ambient temperature of 20°C, the heat flow through the chamber walls would be approximately 8 W, the major part of the total flow. To avoid this, and to reduce the system response time, active control of the outer surface temperature of the test chamber is provided. This method ensures practically zero heat flow through the wall, as the average temperature gradient across the wall is maintained at 0°C.

III. Small Power Calorimetric System

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

· Use lightweight materials to minimize the system time constant.
· Provide a high degree of thermal insulation; minimize stray heat flow to the surroundings.
· Design the test chamber suitably, ensuring versatile mechanical use of the measurement system.
· To prevent eddy current losses minimize the use of electrically conducting materials in the chamber. Eddy current losses could be caused by radiation of AC electromagnetic fields from the DUT, thus changing the power dissipated in the chamber during a test.
· Produce an automatic test rig, using a PC and data acquisition cards to read and control the wide range of sensors and equipment in the system, at powers between 1-50W. Fig. 2 shows the system developed and Fig. 3 shows a diagram of the system.

The measurement system takes the form of two concentric boxes. The inner box forms the test chamber and is of thermally insulating material. The surfaces of the box are coated with glass fibre and epoxy. The measurement system is equipped with an internal heating system. This is used both to initialise the test temperature, and as a DUT to verify the accuracy of the measurement.

Fig. 2. The 50 W calorimetric measurement system

Inner box surface temperatures are measured using 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 outer surface, an array of 68 light bulbs was used. This ensures fast response, since 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-through to the inner box is also minimised by this method. A cooling circuit absorbs heat dissipated by the DUT.

The cooling circuit comprises a heat exchanger inside the chamber, a gear pump to ensure controlled steady flow, a refrigeration unit, and a heater, placed before the inlet. This produces a controlled inlet temperature. A flow sensor, and two Pt100 temperature sensors are placed at the lead-throughs providing measurements.

A PC with LabView™ was used to control the system and store all data. An extensive program was developed to make operation of the system both accurate and user-friendly. The measured power loss was found as an average, of the data acquired from four hours measurement, while the DUT is at the defined steady state condition. The system may be programmed to perform a measurement series of different power losses, and test temperatures. Preliminary reactions from users of the system so far report that these goals have been accomplished.

Experiments so far show a system error of about 59 mW in the measurement region from 1 W to 10 W, at 30°C. The error increases to about 180 mW for measurements in the region 10 W to 50 W, at 30°C. There is still insufficient data measured at above 10 W, or at other temperatures than 30°C, to be conclusive. So far, the data acquired suggests using an offset of 60 mW at 30°C. This will shift the error range to ±30 mW. Results of tests at 45°C suggest an offset of 315 mW, and at 70°C, an offset of 749 mW.

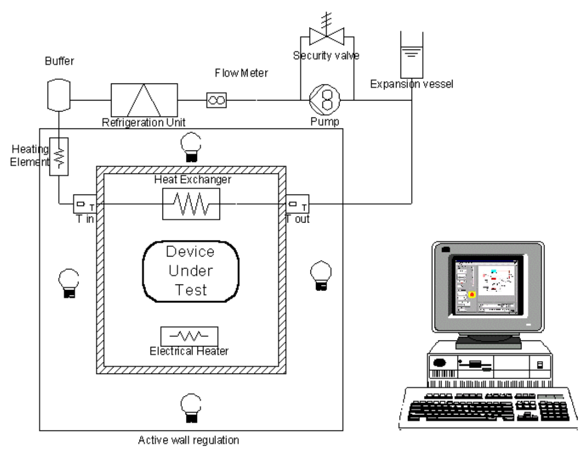


Fig. 3. Schematic describing the 50 W calorimetric measurement system

IV. High Power Calorimetric System

The measurement system for calorimetric measuring of power losses between 200 W and 1500 W uses many of the design ideas from the 50 W system. The 1500 W system operates with a closed cooling circuit very similar to that of the 50 W system, but rated for more cooling. For initial temperature control, the 1500 W system is fitted with resistors to supply the heat required to change the test chamber temperature. The 1500 W system also uses active walls to reduce stray heat flow. In contrast to the 50 W system, heat conductive alumina plates were used extensively throughout the construction. The purpose of this is to distribute the temperature, from the top to the bottom of the test chamber, more evenly. The active wall components are integral to the wall design in a more compact form than for the 50W version. The test chamber walls are arranged as a sandwich construction with electric heater elements and temperature sensors integral to the structure as shown in Fig. 4.

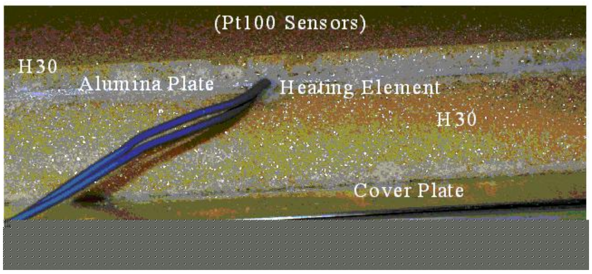


Fig. 4. The integration of the temperature sensors and the heating element in the wall construction.

Another important difference is that the system is equipped to load and measure rotating machines. The system is provided with an integral mechanical load. Shafts may be loaded at up to 7.5 kW at speeds in the range 1500-4500 rpm, and with a maximum torque of 62.5 Nm. A Siemens controller and a PM synchronous machine provide the load. The load is led through the test chamber wall using a combination of a magnetic coupling and a carbon fibre shaft. This minimises stray heat flow along the shaft, as may be expected if a steel shaft were used. The 1500 W system is currently being prepared for acceptance tests and is expected to have accuracy better than 5 W.

Fig. 5. The 1500 W calorimetric measuring system. A motor is seen inside the chamber with a torque transducer hidden behind it.

V. Operation of the System

The calorimetric wattmeters can measure using the direct method, and the verification method. The 50 W system is able to test objects up to 200 mm x 200 mm x 300 mm in physical size. The 1500 W system measures both the load and the power losses, and can test objects up to a physical size of 1000 mm x 1000 mm x 700 mm. It is capable of measuring steady state conditions at test temperatures between 20°C and 70°C. Dynamic measurements were not intended and are not possible. A PC equipped with data acquisition cards from National Instruments™ and software designed using LabView 5.1™ performs all data acquisition and system control. The automated measurement assures that the power loss dissipated by the DUT is measured with the highest possible accuracy.

The DUT is mounted inside the inner box of the test system. For the 50 W system, two different mounting plates are available, one in aluminium and one in plastic. The plastic plate is recommended when there is a risk of eddy current power losses being induced in the aluminium mounting plate. The 1500 W system is provided with a more substantial, motor mounting system of steel.

The measured power input to the calorimeter system determines the control system parameters during the measurement. This also determines the accuracy of the measurement. The exact power dissipated by the DUT is of course unknown at the beginning of the test. If estimation of the power to be measured is difficult it may be necessary to calibrate the system using a known power, before starting the measurement.

A. Method of use

Though the materials for the chamber were chosen for their low density, the system is still fairly slow. From the test rig being configured and started to the time the measurement starts, 3-12 hours are often required, dependent on the specified test temperature. Fig. 6 illustrates the time sequence of a test. The system must be started and allowed time to reach the required test operating temperature. Typically, a measurement will then require about four hours to settle to a constant steady-state temperature, suitable to take a new reading. If subsequent readings are required at closely related operating points, then about one hour will be required for re-settling. After this, about four hours will be required for the system to settle to a new constant steady-state temperature suitable to take the new reading.

The test results of are written to two data files. A log file holds values of all signals, sampled once a minute. This offers an opportunity to verify the test sequence. The result file holds the most important measurement signals with samples every second.

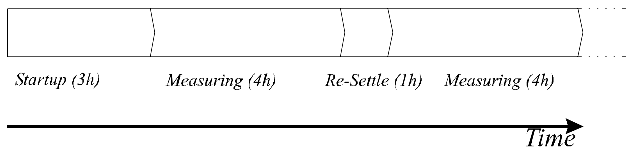


Fig. 6. Time sequence of operations during testing.

B. Measured errors

Verification tests of the 50 W system are still in progress, and new, accuracy-improving techniques are still being taken into use. However, current results already show a very high potential accuracy. Tests have been performed using the heaters fitted in the chamber. A DC current is used to supply the heaters, the power dissipated in the test chamber may be measured accurately.

In Fig. 7 some results are shown for measurements at test temperatures of 30°C and 70°C. However, since the measurement system continues to be improved, the measurement series are not entirely comparable. Nevertheless, so far the results indicate that measurements of power may be performed using the measurement system with accuracy better than ±0.2 % of full-scale deflection.

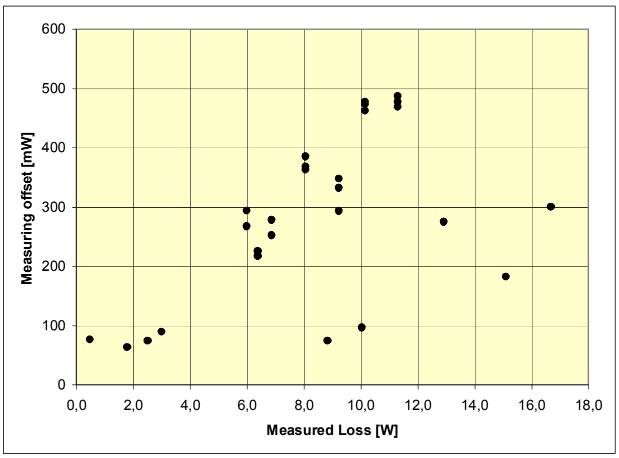


Fig. 7. Measurement offset as a function of the measured loss value (50 W system).

C. Measured results

Until now, there have been two major problems with the results achieved from the measurement system. Although active wall regulation is utilized, there seems to be an unaccountable heat flow from the surroundings to the test chamber. This heat flow seems to be a function of the test temperature. Investigations to reveal the source are as yet inconclusive. Some investigations indicate that the temperature distribution on the inner surfaces may be a source of the error. The temperature profile on the surfaces is complex, and though the sensor arrays are dense, some cold spots may still be unobserved. Though the source of the heat flow is undiscovered, investigations to date have all showed that use of an empirical constant in the interpretation of the result improves the accuracy to ±0.2 % of full-scale deflection. Another important issue is to maintain a constant predetermined inlet temperature. Until now, the inlet temperatures fluctuate with a magnitude of 0.4°C causing reduced accuracy of measurements at low power levels, e.g. <10 W, see Fig. 8. The fluctuations have been reduced, and work is continuing to obtain a further reduction.

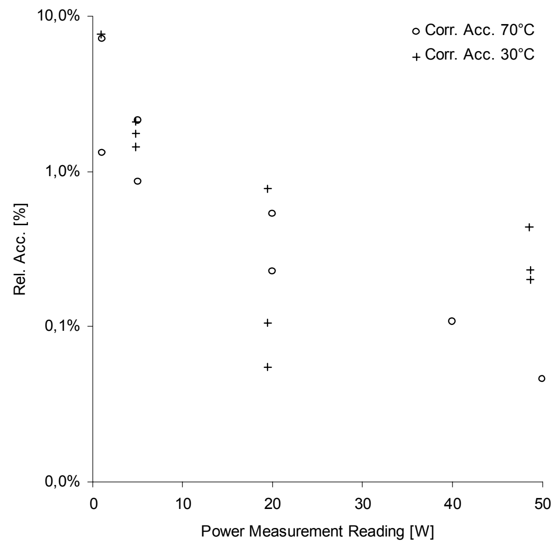


Fig. 8. Accuracy in power loss measurements (50 W system).

D. Thermovision to find elusive heat loss error

In order to investigate the heating principle of the active wall regulation, tests were carried out with infrared thermovision measurement equipment. This was an effort to find the elusive stray heat loss error. The tests were carried out at Grundfos' laboratory.

The purpose of the measurements was to investigate how the temperature was distributed on the surface of the chamber wall. It was of particular interest to investigate if the light bulb heaters generated hot spots on the surface. A sample of the temperature distribution is presented in Fig. 9.

The temperature distribution pictures revealed some interesting details. Two specimens were tested, representing different surface materials on the walls. Both the experiments performed on specimen I and on specimen II showed a homogeneous temperature distribution during the initial phase of heating. When maximum temperature occurred, the temperature distribution was very different at the boundaries. However, all tests showed a smooth distribution from the boundaries to the central region. For test specimen I, the structure of the surface was also reflected in the temperature distribution, especially during the initial phase of heating.

Surprisingly, none of the tests revealed any hot spots due to the presence of the lamps, neither during heating nor in the cooling period. The presence of the distinct fan-jets and fans in the images shows, that if spots caused by the lamps had been present, they would have been revealed.

To ensure taking accurate measurements of the average temperature from the surface temperature sensors, they should be place about one quarter from the boundary. If the sensors were placed in the centre region of the wall, the readings obtained would be too high.

The experiments showed that the method of heating the surfaces was satisfactory. Most of the energy distributed from the lamps was distributed to the surface of the test specimens and dissipated as heat energy.

The experiments showed that the heat was distributed very homogeneously across the surface, and the region below the surface. In addition, it was revealed that in order to make correct measurements the sensors should be placed around 100 mm from the edge of the box. Placing the sensors here ensures that they are placed where the approximate average temperature of the surface area appears.

These measurements give an indication of the temperature distribution of the outer surface of the test chamber. Because of the driving forces of the flow inside the test chamber, a more complex temperature distribution may be expected on the inner wall.

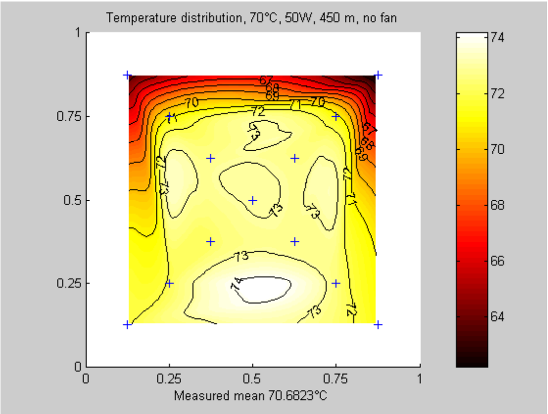


Fig. 9. Example of thermographic photograph showing temperature distribuiton on the outer surface of one of the walls of the 50 W calorimeter.

E. Test results

Fig. 10 shows results of a test in the 50 W system, with a 5 W dissipation, where the ambient temperature inside the test chamber was set to be 30°C. A clear impression of the time delays involved and the settling time is obtained.

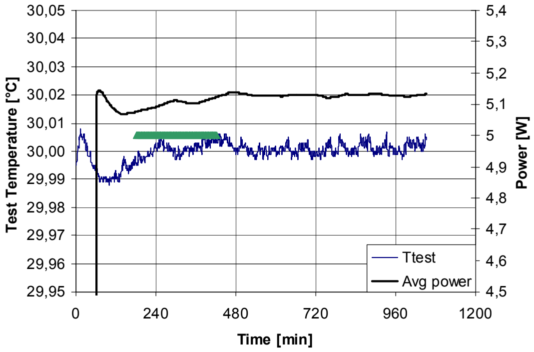


Fig 10. Results of 5W test at 30°C in the 50 W system.

F. Optimum mass flow

In order to determine the optimum point of operation for the measurement system an analysis of the accuracy of the key sensors has been carried out. This analysis has been carried out similarly for both measurement systems. The analysis is based on a model developed during the design phase. Briefly, the determination of the optimum mass flow rate is an optimisation of the function describing the accuracies for the flow sensor and for the inlet and outlet temperature probes in the cooling circuit.

Fig. 11 shows the calculated optimum mass flow in the cooling circuit to obtain the most accurate power loss measurements.

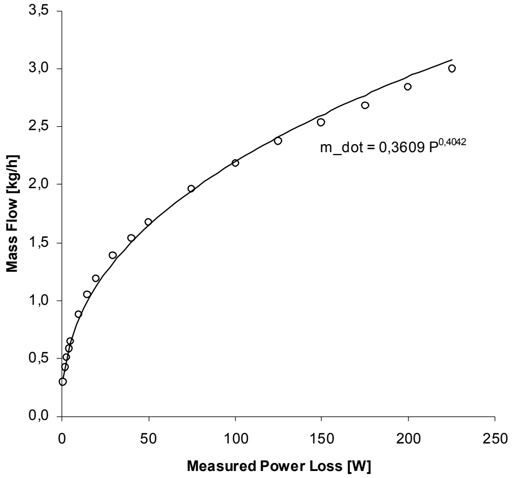


Fig. 11. Calculated optimum coolant flow for the 50 W system.

G. Heat exchanger efficiency

The purpose of this section is to describe the method used for mapping the heat exchanger performance. The method used is suited for mapping heat exchangers in the 50 W system as implemented. It forms the basis for a similar investigation on the 1500 W system.

The calorimeter is fitted with a heat exchanger inside the test chamber to absorb the generated heat from the DUT. It was important to estimate the performance of the heat exchanger since the accuracy of the measuring system is affected by the flow of the coolant and difference between the inlet and outlet temperatures. These figures are closely connected to the heat exchanger performance.

To measure the heat exchanger efficiency within the flow and temperature space, the test procedure was as follows: The test chamber temperature is fixed at a predetermined value. This was controlled by means of the balance heaters. The cooling circuit was then run with a series of flow rates corresponding to the cooling capacity of the refrigeration unit. Because the cooling capacity was limited to approximately 150 W, and the possible heat transfer capacity of the heat exchanger was significantly larger at high test chamber temperatures it was only possible, and necessary to measure the heat exchanger performance at low flow rates, and at high chamber temperatures. Each flow was maintained for four hours before changing conditions to the subsequent setting. Only data read during the final ten minutes of the measurements are used, since it is required to use data from steady state conditions. The heat exchanger efficiency was then estimated from the test chamber, inlet and outlet temperatures and the flow rate.

The lowest temperature producible from the refrigeration unit is determined the inlet temperature. This means that in order for measurements to be used by the control system it was assumed that the heat exchanger efficiency was governed mainly by the flow rate. This assumption has proven to be useful in the implementation of the control system.

From measurements, the performance of the heat exchanger was approximated to a polynomial function of the mass flow rate and the test temperature. Fig. 12 shows the measured efficiency of the heat exchanger within the possible range of operation.

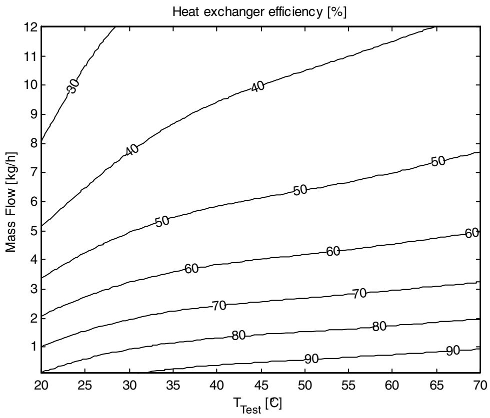


Fig. 12. Heat exchanger efficiency as function of Test temperature, and mass rate of flow (polynomial fit of measured results).

VI. EXAMPLES OF APPLICATIONS

The calorimetric wattmeter is of particular interest when measuring components or applications with:

- High efficiency
- High switching frequency
- Highly inductive circuits.

The calorimetric wattmeter has been used to assist in the solution of several industrial and research problems. Fig. 13 shows an example of a power supply unit by Grundfos, where the total loss was successfully investigated. Fig. 14 shows a test report from the 50 W system.

In recent years the development in television sets and computer monitors has been towards bigger picture screen size and faster screen updating, using a higher scanning frequency. At higher scanning frequencies, the power losses in the inductive components, such as the Extreme-High-Tension transformer and the deflection coils, are increased significantly because of the frequency-dependent eddy-current losses both in windings and core [12].

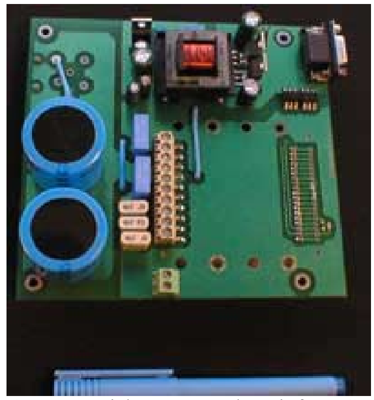
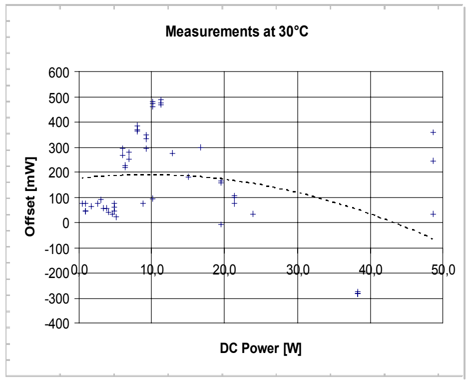


Fig. 13. A commercial power supply unit from Grundfos.



Entire domain		
Number of measurements	52	
Mean offset	162	mW
Deviation	196,84	mW
Max-Min	770	mW
Lower region (0-10W)		
Number of measurements	28	
Mean offset	163	mW
Deviation	128,59	mW
Max-Min	362	mW
Mid-range region (10-25W)		
Number of measurements	17	
Mean offset	255	mW
Deviation	182,99	mW
Max-Min	493	mW
Upper range region (25-50W)		
Number of measurements	7	
Mean offset	-70	mW
Deviation	280,57	mW
Max-Min	643	mW

Fig.14. A sample of the output showing test results from the 50 W system.

The losses dissipated in other electronic components in the television set do not increase accordingly. Technological development tends towards High-Definition-Television, where the scan frequency may be 67.5 kHz. Allowing for this development and the amount of time TV-sets run in homes throughout the world, there is good reason for optimising the energy dissipated in future television sets.

The objective was to develop a predictive tool with the purpose of modelling the deflection coil power losses during the design process, see Fig 15. This will make it possible to design deflection coils with regard to minimising the power loss. The approach was to model existing deflection coils and verify these models by calorimetric power measurements. The deflection coil type, which forms the basis of the simulation model, was production coil from a 32´´ TV. The prototypes were deflection coils from a 17´´ monitor, but with various wire types and core materials. The results will give ideas as to how to reduce deflection coil power losses.

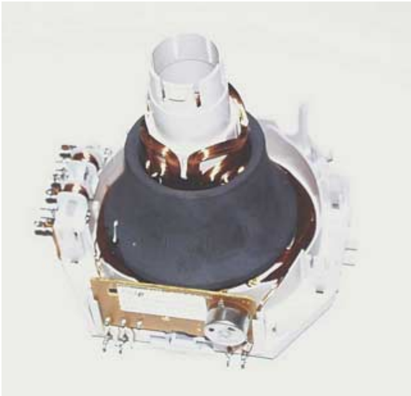


Fig. 15. Deflection coils on a cathode ray tube by Bang & Olufsen/Philips.

In order to compare the simulated and measured power losses of the 32´´ TV deflection coil, the same conditions should apply in both cases. Therefore, the amplitude and frequency of the drive current, and the winding temperatures during measurement must be known. During the measurements, only the high frequency line coil was driven. The line coil was driven with a saw-tooth current with amplitude 6 A and frequency 32kHz. To obtain a better verification of the simulation model, measurements were performed on several variants of the deflection coil. For example, some measurements were made with the yoke ring removed. This alters the magnetic field of the coil, which must be

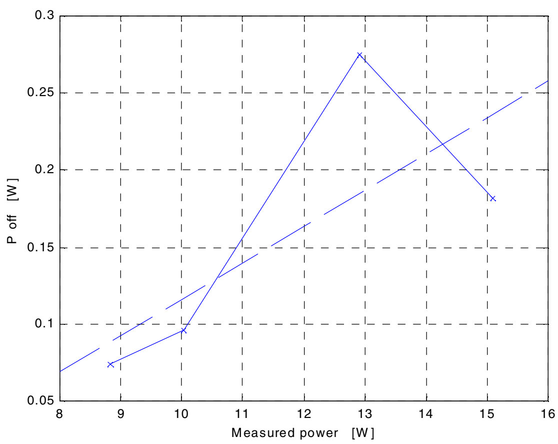


Fig. 16. Calibration measurements for a 32´´ TV deflection coil.

considered in the simulation model. The calculated results of the complete 32´´ TV deflection unit show good agreement with measurements.

Further calorimetric power measurements were performed on several deflection coils of a 17´´ monitor. These were prototypes with various coil wire types and core ferrite materials. The measurements showed variations in power losses. According to theory: thinner wires gave a reduction in power loss, and the core losses were dependent upon the magnetic properties of the ferrite material used. By conducting calorimetric measurements on the deflection coils, it was concluded that a calibration measurement must be carried out directly after each measurement to ensure the accuracy of the system. Fig. 16 shows an example of such a calibration curve.

VII. CONCLUSION

Power measurements can be performed with an accuracy of 0.2% of full-scale deflection using the proposed calorimetric measuring method. The constructed 50 W measuring system is useful to measure power losses between 1 W and 50 W at a constant determined temperature. Tests show that the active wall regulation improves the accuracy considerably. However, a satisfactory measurement technique for measuring the wall surface temperatures on the entire surfaces is still sought.

The preliminary study of the correlation accuracy between the primary measurement components resulted in a significant increase in the overall accuracy. Further validation of the calorimetric wattmeter, and more research into the overall accuracy will be performed while conducting experiments on power electronic components.

The test rig is currently used in basic research at Institute of Energy Technology, Aalborg University.

The 1500 W system is currently being installed and will be ready for commissioning and acceptance tests shortly.

An important task for both 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 and drive systems of tomorrow. It is expected to make a significant contribution to the general understanding of loss functions and the interaction between power supply and load system.

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