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THERMOGRAPHIC ANALYSIS OF A BRIDGE POWER CONVERTER

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Any loss of power in converters is dissipated as heat in the components of the circuit. The article presents a new approach to measuring heat dissipation in a bridge power converter with hard switches using infrared thermography. Parallel measurements by thermocouples have been carried out. The experimental results are compared and used from the both cases. The proposed approach can be used for various circuit implementations of the converters in a similar manner.

K e y w o r d s: thermal analysis, power conversion, switching loss, inverters

1 INTRODUCTION

Powerful energy converters (inverters) are now widely used in renewable energy sources, induction heating, adjustable speed motor drives, uninterruptable power supplies and many others [1]. The simplest form of an inverter is the bridge-type and a very large number of inverters are "hard-switched" voltage source inverters. Besides IGBTs, power MOSFETs are also used especially for lower voltages, power ratings, and applications that require a high efficiency and a high switching frequency.

Research related to determination of heat losses in the electronic converters of electrical energy is closely connected to improving their energy performance and quality [2–4]. Most of the problems occurring at the end of the design cycle are associated with poor thermoregulation. Thermal management is crucial for the reliability of the system since 53% of failures are related to overheating [5].

As it is known, thermal qualification is particularly important for power semiconductors for two reasons [6]. Firstly, they work with high density currents with a steep temperature gradient between the junction and the environment. Secondly, their thermal mass is very small and the heat spreads for parts of a millisecond. Therefore, optimizing the efficiency or reducing the loss of the inverter is an important part of the design process and of the choice of components. One way to assess the losses in the inverter is by measuring the temperature difference of the components during the off state and steady state operation.

Infrared Thermography (IRT) is a technique capable of revealing the presence of thermal anomalies in various objects. This technique begins to be used widely to monitor the temperature field of the power electrical components and systems. Recently, a number of articles have been published regarding the use of IRT for contactless thermal measurements to verify the results of thermal simulations of power electrical components and systems [7–9].

The article presents a new approach to evaluating the thermal losses in power converters using IRT. Experimental measurements are conducted using a laboratory setting of a bridge power converter with an AC output (inverter). Results are presented of evaluating the heat losses in the case of hard switching.

2 DETERMINATION OF LOSSES IN THE TRANSISTORS

The simplest form of an inverter is the bridge type (half and full). Therefore, most methodical basic researches are performed for this type of power converters. It is known that the loss of power and the dissipation of heat in devices are made up of the following components: in set state (conductivity), in off state (in most cases it is ignored) and from switching (switching operations) [1]. The selected operating mode of the DC/AC converter is a voltage inverter with an active load. In this case, the output current and output voltage have shapes similar to rectangular.

Two types of switching occur in the electronic converters: soft switching and hard switching [1, 6]. Typically, in soft switching the semiconductor devices (transistors) are switched on and off at zero voltage and/or zero current. This in turn leads to a reduction of the switching losses in power converters, and therefore reduces the warm-up of the devices. This allows to achieve significantly higher operating switching frequencies and reduction of the sizes of the converters. In soft commutations the harmonic compositions of current and voltage are improved, which results in weaker electromagnetic interference.

In hard switching, the voltages and currents are applied to semiconductor devices during their transition from the on to off state and vice versa. Typically, the current through the device is changed at a high speed from the maximum value to zero when switching off, and from zero to the maximum value when switching on. This creates large switching losses and electromagnetic interference.

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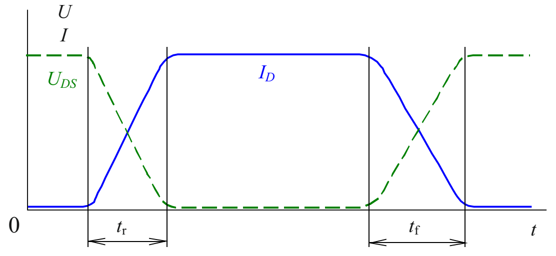

Fig. 1. The shape of current and voltage during switching

The losses in the MOS transistors are primarily due to their parasitic capacitance. The energy accumulated in the parasitic output capacitor of the transistor C_0 is given by formula

$$W_{C_0} = \frac{1}{2} C_0 V_{\mathrm{OFF}}^2 \tag{1}$$

where V_{OFF} is the voltage on the transistor in the OFF state.

During transition from the cut-off state to the active state this energy is dissipated in its structure and leads to heating of the transistor. The power loss during turn-on can be expressed as

$$P_{\mathrm{SW(FET)}} = \frac{1}{2} f_{\mathrm{S}} C_0 V_{\mathrm{OFF}}^2 \,, \tag{2}$$

where f_{S} is the switching frequency of the power semiconductor devices.

The voltage drop on the transistor in the ON state is determined as

$$U_{\mathrm{ON}} = R_{\mathrm{DS}} I_{\mathrm{D}} \,, \tag{3}$$

where R_{DS} is the drain-source resistance of the transistor and I_{D} is the average value of the current through the transistor. On inserting $R_{\mathrm{DS}} = 0.055\,\Omega$ and $I_{\mathrm{D}} = 20$ A one has $U_{\mathrm{ON}} = 1.1$ V.

The losses in the transistor are defined from the datasheet of the investigated transistor, model IRFP260, and from the operating mode of the converter. The emitted power in the ON state is

$$P_{\mathrm{ON}} = \delta U_{\mathrm{ON}} I_{\mathrm{D}} \,, \tag{4}$$

where δ is the duty cycle. In our case of symmetrical operation of the devices it is 50 %. For $U_{\mathrm{ON}} = 1.1$ V and $I_D = 20$ A one obtains $P_{\mathrm{ON}} = 11$ W.

When working with a load with a value close to the active load, the current through the transistor has a form very close to rectangular. Most often, in calculation of the power loss from the process of switching it is assumed that the current and the voltage across the device change linearly as shown in Fig. 1.

Under the above assumptions of a linear change of variables during switching, the following expression is used to determine the power of switching [2, 3].

$$P_{\mathrm{SW}} = 0.167 \times (t_{rise} + t_{fall})\, f U_{\mathrm{DSmax}} I_{\mathrm{Dmax}} \,, \tag{5}$$

where times t_{rise} and t_{fall} are catalogue data of the transistor.

On inserting $t_{rise} = 130$ ns, $t_{fall} = 100$ ns, $f = 30$ kHz, $U_{\mathrm{Dsmax}} = 20$ V and $I_{\mathrm{Dmax}} = 30$ A one obtains $P_{\mathrm{SW}} = 0.69$ W.

The total power dissipated by the transistor is obtained by summing up the individual components identified above:

$$P_{\mathrm{D}} = P_{\mathrm{ON}} + P_{\mathrm{SW}} = 11.69\ \mathrm{W} \,. \tag{6}$$

Using the results obtained, the cooling radiator of the transistors can be selected [8]. The permissible temperature of the transistor packaging T_{CASE} can be defined by [5, 6]

$$T_{\mathrm{CASE}} = T_{\mathrm{J}} - R_{\mathrm{thJC}} P_{\mathrm{D}} \,, \tag{7}$$

where T_{J} is the maximum junction temperature, R_{thJC} is the junction-to-case thermal resistance and P_{D} is the dissipated power.

In a similar way, if the entire thermal system is taken into account, the above equation assumes the form

$$T_{\mathrm{AMB}} = T_{\mathrm{J}} - (R_{\mathrm{thJC}} + R_{\mathrm{thCA}}) P_{\mathrm{D}} \,, \tag{8}$$

where T_{AMB} is the ambient temperature and R_{thJC} is the case-to-ambient thermal resistance. On inserting ambient temperature $T_{\mathrm{AMB}} = 50\,^{\circ}\mathrm{C}$ and permissible junction temperature $T_{\mathrm{J}} = 100\,^{\circ}\mathrm{C}$ one obtains the maximum thermal resistance of the cooler 4.3 K/W.

3 INFRARED MEASUREMENTS

Thermography measurements of a specially developed circuit have been performed to verify the analytical assessments. Figure 2 shows a simplified bridge circuit of the inverter and a block scheme of the experimental set-up on which experimental studies are conducted. The bridge circuit includes four transistors type IRFP260 with integrated reverse diodes. CS denotes the drivers of the transistors which perform their switching. An active-inductive load (Z) is included in the AC part of the bridge. The power factor of the load is close to 1 (minor part of the inductive component of the load). Operation in the hard switching mode is realized (with simultaneous presence of current through the device and voltage during its switching). Thus increased switching losses and the necessary heat to conduct the experiment are obtained.

The results from two modes are presented: Mode I at 22 V supply voltage and current consumption 18.6 A, and Mode II at 15 V supply voltage and current consumption 12.8 A. The active load is water cooled because of the significant power (more than 400 W). The operating frequency is 40 kHz. Measurements have been made with an infrared camera and thermocouples (for transistors, heat sink and active load). When placing the thermocouples on the drain terminals of the transistors or between the

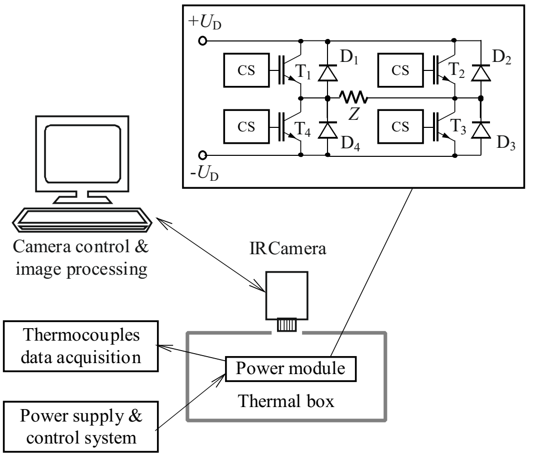

Fig. 2. The inverter (simplified circuit) and block scheme of the experimental set-up

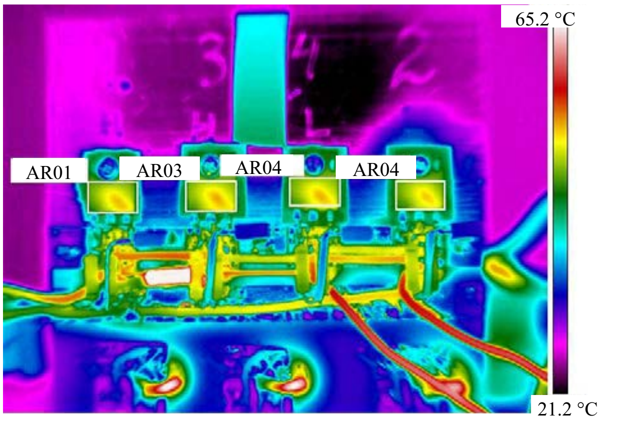

Fig. 3. Thermogram of the power module with marked evaluated areas on the surface of the MOS transistors

Table 1. Results in steady-state of Modes I and II (ROI means "region of interest") at $T_{\mathrm{AMB}} = 25\,^{\circ}\mathrm{C}$

ROI	$T_a = 25\,^{\circ}\mathrm{C}$	Measured temp, °C				Temp St dev
		Min	Max	Max−Min	Avg	
AR01	Mode I	61.5	70.6	9.0	67.1	1.8
	Mode II	52.7	59.4	3.8	58.1	0.8
AR02	Mode I	62.3	70.4	8.1	67.2	1.6
	Mode II	55.8	59.6	3.8	58.1	0.8
AR03	Mode I	63.5	72.1	8.6	68.8	1.6
	Mode II	55.9	60.5	4.6	58.9	0.8
AR04	Mode I	62.6	72.0	9.4	68.5	1.7
	Mode II	55.8	60.4	4.6	58.8	0.9

drain and the heat sink, only minor changes are reported. 2D measurements of the surface temperature of the transistors and the heat sink are made by an infrared camera ThermaCam SC640 with FPA detector, 640 × 480 pixels, and IP link using FireWire. Close-up 50 mm and 24° lenses are used.

The measurements are carried out at ambient temperature $T_{\mathrm{AMB}} = 25\,^{\circ}\mathrm{C}$ (in laboratory conditions) and at $T_{\mathrm{AMB}} = 40\,^{\circ}\mathrm{C}$ (in a thermostat), and at relative humidity RH = 50 % for both modes.

Each pixel of a thermal image represents a temperature at the acquired scene. To minimize the error from the thermal measurement of the surface temperature and to avoid the effect of temperature spreading it is preferred to evaluate the average instead of the peak values. Figure 3 shows the thermogram with marked white contour areas of the four MOS transistors. The corresponding measured minimum, maximum, average and root mean square values of the surface temperatures in steady state for the marked areas in Fig. 3 are given in Tab. 1.

Transient phenomena of the heating due to switching losses were also monitored. Temperature variations in switching Mode I are shown in Fig. 4.

The measured transition time at switching on is 8.05 min (the rate of temperature change is 5.40 °C/min) for Mode I and 18.7 min (the rate of temperature change is 1.80 °C/s) for Mode II.

Figure 5 shows the change in temperature at switching in Mode II. The curves describe the change of the mean temperature of the marked areas (Fig. 3).

In Figs. 4 and 5 one can see that at switching in Mode I, the temperature of transistors T3 and T4 is by about 2 °C higher than the temperature of T1 and T2. This difference in Mode II is 2 °C for T2 and 4 °C for T1. When changing the length-to-width ratio of the radiator with a 1 cm the basis, this temperature difference is removed. The temperature profile during the steady state is excluded from the graphics.

To compensate the effects of emissivity of various materials into the structure of the inverter, an electric insulating tape and a pre-recorded emissivity map are used. Subtracting the reference thermal image from each image in sequence captured during the switching in Mode I and Mode II, comparisons (changes in temperature, position or shape) between thermal images can be made. The difference between the current frame and the background model can also be compensated. As a result of the subtraction pixel by pixel a new image is generated. The result of subtracting infrared successive images made at different times to compensate reflections is shown in Fig. 6(a), (b) and (c).

Figure 7 shows the thermograms of transistor T4 recorded at transient mode 3 min, 6 min and 8 min after switching on the power in Mode I.

Figure 8 shows the thermograms of T4 taken in the transient mode of switching off at the initial time, after 1 min and then after 3 min. The maximum temperature measured on the packaging of T4 (case temperature) is 72.0 °C in Mode I and 60.0 °C in Mode II. The junction temperature of T4 for Mode I is 77.9 °C and for Mode II 63.8 °C [11].

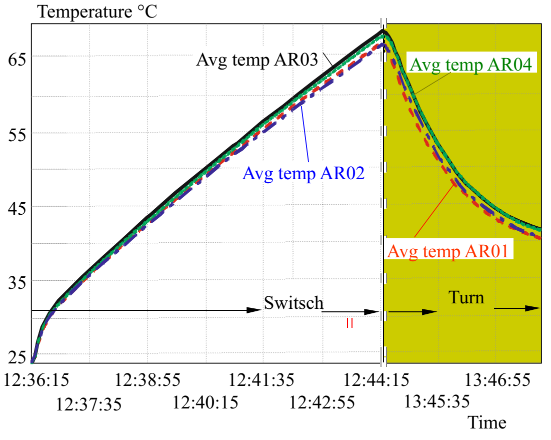

Fig. 4. Change in the average surface temperature of the marked areas of Fig. 3 in switching Mode I

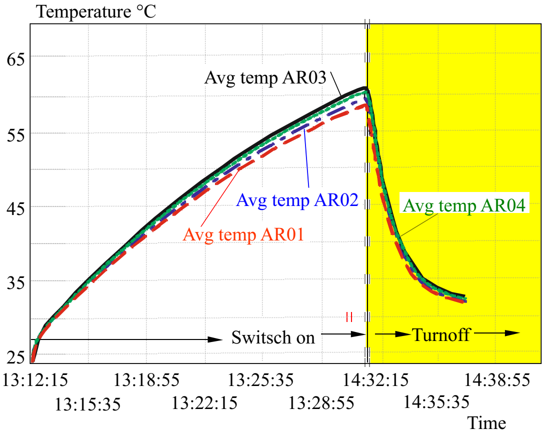

Fig. 5. Change in the average surface temperature of the marked areas of Fig. 3 at switching in Mode II

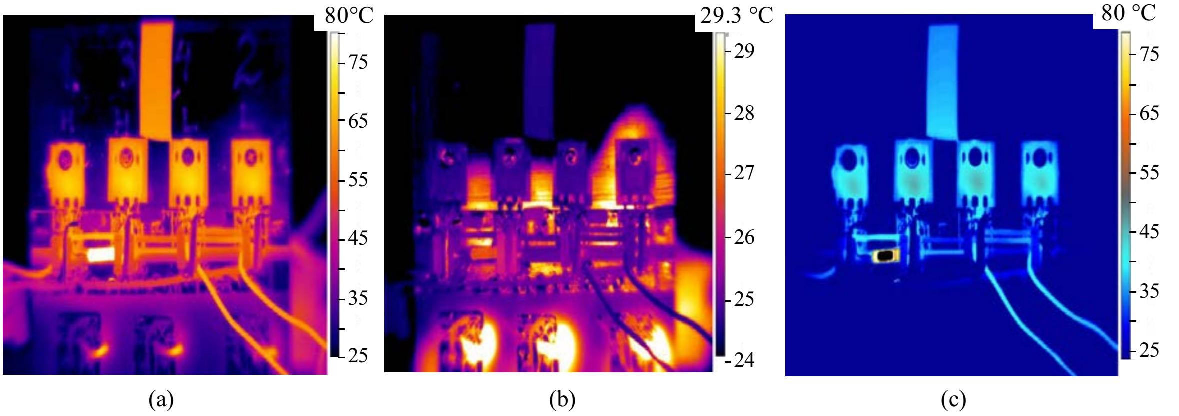

Fig. 6. Subtraction of thermal images in switching time for Mode I: (a) – source image, (b) – reference image (off state image), (c) – generated subtraction image

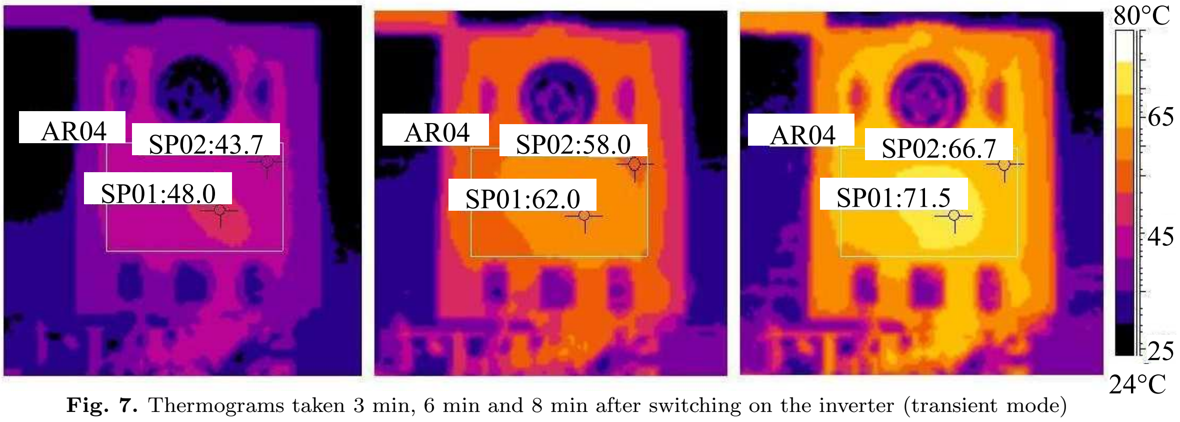

Fig. 7. Thermograms taken 3 min, 6 min and 8 min after switching on the inverter (transient mode)

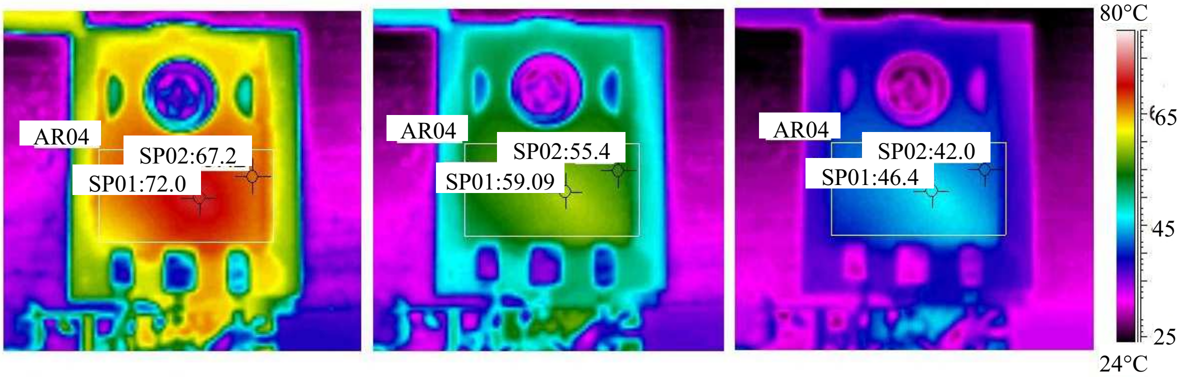

Fig. 8. Thermograms taken at steady-state, 1 min and 3 min after turning off the inverter (transient mode)

In fivefold repetition of measurements of the heat dissipation using the surface temperature profile, a temperature difference not more than 5 °C is observed between single measurements. When measured by a thermocouple the temperature at one point is detected, thereby the measuring error in the range of 10 % to 20 % for the various controlled elements is received. The total measured losses in % for the whole bridge for Mode I are 3.72 % and for Mode II 3.56 %. The calculated junction temperature of the transistors in the bridge based on the thermographic measurements for Mode I is not higher than 80 °C, and for Mode II not higher than 65 °C for the chosen operating frequency of 40 kHz. The measured thermal resistance of the heat sink is 5.36 K/W.

It is found that when measured by thermocouples during the operation of the inverter, considerable electromagnetic disturbances are obtained which depend on the length of the thermocouple wire. This effect leads to the introduction of errors in the measurement. This effect is missing when using IRT.

4 CONCLUSIONS

A methodology for assessing the heat losses measured by IRT is proposed. The conducted studies confirm the conclusion that in the selected transistor and operating frequency the switching losses are negligible compared to the losses by conduction and hence the use of soft switching in our case is not justified because of the associated additional loads of transistors. From comparing the results obtained from analytical expressions and by thermovision it is established that errors in the measurement of thermal distribution by IRT can be minimized. For this purpose, quantitative assessments with a prerecorded emissivity map must be compensated. Investigation by thermal cameras is a powerful tool for improving the mode of operation of power electronic devices, which can be used to optimize the cooling of active and passive components of powerful converters.

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