Simple Hybrid Electrothermal Simulation Procedure

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***Abstract*— Electrothermal models of power semiconductor components are often too complex and requiring a long simulation time. Besides, there can be a situation that electrical and thermal behaviour of the circuit are not analyzed within the same department of a company. This necessitates an appropriate procedure of electrothermal simulation, sufficiently quick, accurate and simple, allowing an efficient exchange of data of electrical and thermal parts of the system. Presented in this article is a simple calculation procedure for the time course of silicon equivalent temperature in power semiconductor components, based on the previously calculated current loading. This hybrid procedure allows the exchange and use of simulation results in case of separated procedures of current and thermal dimensioning of power semiconductor components.**

I. Introduction

The models of power semiconductor components integrated in electrical simulators are used for the calculation of voltage and current waveforms as well as on-state and switching losses in the process of current component selection. The recent models enable us also to calculate the time course of virtual junction temperature [1].

The use of electrical simulators and built-in models ensures more than the simulation of electrical and thermal behaviour of converter circuits. They are used for forecasting and analysis of critical circuit conditions.

The models of power semiconductor components built into electrical simulators are of various structures and accuracy levels. These models are, however, often too complicated for use and require a large number of measured parameters and a long simulation time. In that case, it is possible to use in-house macromodels [2]. The existing simulators offer various tools for the design of macromodels of power semiconductor components. One of the simplest approaches is to make a macromodel by the use of a network of active and passive electrical components and dependent voltage and current sources.

This article describes such an approach in the developing of a simple macromodel for the calculation of losses and heating of a power IGBT module integrated into a converter circuit.

II. Basic Information about a Converter Circuit and Operating Conditions

Within the scope of the project of Zagreb low-floor tram *TMK2200*, a converter of the main drive was designed. The main part of the main drive converter is a three-phase inverter made with six IGBT modules (1700 V, 1200 A, FZ 1200 R 17 KF6C B2). Within these modules, there is an anti-parallel diode. All the 6 modules are fixed onto a common heatsink with forced ventilation.

In order to assess the converter reliability, it is necessary to know the course of virtual junction temperature in the module, separately for IGBT and diode, at the highest current load. According to the data for Zagreb tram network (slope of tracks, average time between stops, average stopping time), a start-stop cycle of a tram under full load between two stops has been established as the worst case scenario.

By means of a dedicated program for converter simulation developed in the programming language C, the course of current and voltage load of IGBT and diode of the module was calculated in the interval of one start-stop cycle. In order to calculate the voltage and current load, catalogue data regarding the dependence of the switching losses on current and voltage, and the dependence of on-state voltage on current were used for the given IGBT and diode of the module. In order to obtain a conservative calculation, the data were taken for junction temperature of 125 °C.

Output from this program is the course of module IGBT and diode losses in the interval of one start-stop cycle. The program calculates these data with various averaging interval and stores them into a file as pairs of time and loss values, separately for IGBT and separately for diode, Fig. 1 and 2.

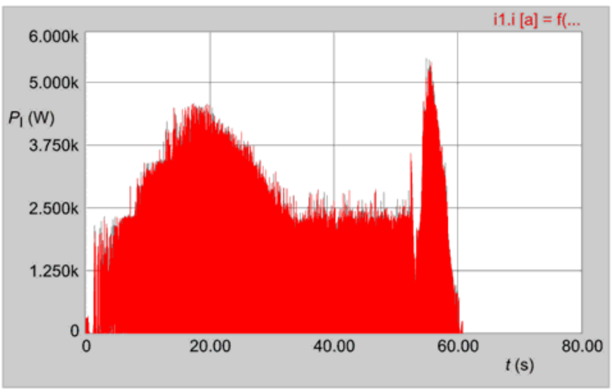

Fig. 1. IGBT loss waveform (averaging interval 0.5 ms).

III. Hybrid Electrothermal Simulation Procedure

The above described simulation program for calculation of time course of IGBT and diode losses does not make possible the calculation of the time course of the components silicon equivalent temperature. The program presupposes a constant silicon temperature for the total simulation time. For conservative reasons, the maximum silicon temperature of 125 °C was presumed.

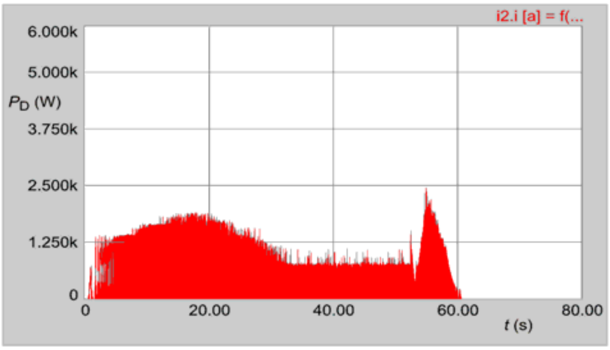

Fig. 2. Diode loss waveform (averaging interval 0.5 ms).

The proposed hybrid electrothermal simulation procedure offers the use of another simulation program and electrical model of power components thermal system, so that the time course of losses calculated in this way is used for calculation of the time course of equivalent silicon temperature, Fig. 3. In our case we have used simulation program Simplorer, Ver. 6.0.

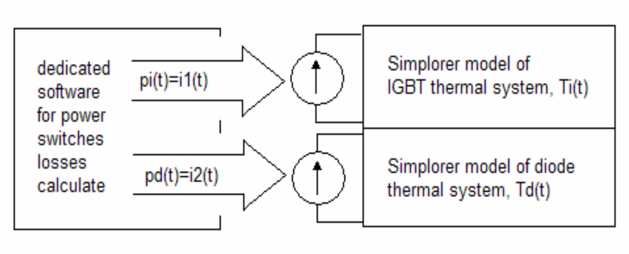

Fig. 3. Hybrid electrothermal simulation procedure.

Electrical models of power semiconductor components thermal system were developed on the basis of analogy between electrical and thermal systems. They are well known and documented in literature, e.g. (3). Basically, it is a question of chain or ladder RC network which can be built in any commercially obtainable electrical simulator. Electric resistances and capacitances are analogous to thermal resistances and capacitances. The current time course of current sources at the RC network input is analogous to the time course of losses. The voltage time course at the RC network input is analogous to the temperature time course.

The accuracy of such a simple electrothermal modelling is experimentally confirmed in previous works (6, 7), while within the frame of the project described herein, the experimental verification of the proposed method is planned for the next stage. The electrical model of module FZ1200R thermal system and heatsink is shown in Fig. 4.

The RC pairs from R_1C_1 to R_4C_4 model the thermal system of IGBT. The RC pairs from R_5C_5 to R_8C_8 model the thermal system of the diode. The remaining RC pairs model the thermal system of the heatsink. Current sources connected at the input port of these RC networks model the courses of losses within IGBT and diode, which are calculated by previously mentioned dedicated software. The values of the current of such sources are described in *Simplorer* by the use of *data-pair* tables. The data pairs in these tables correspond to the losses and time points in which these losses are averaged.

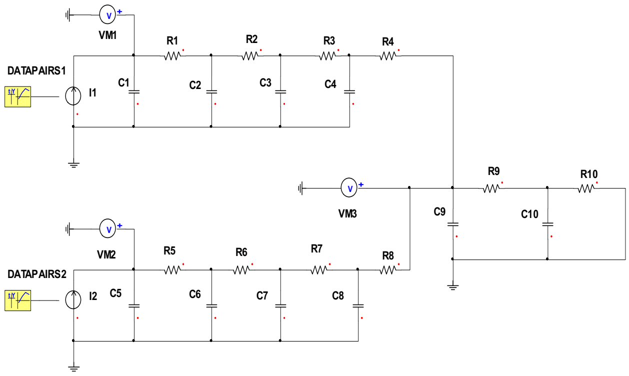

Fig 4. Ladder model of the thermal system of module and housing.

Voltmeters VM1, VM2 and VM3 measure the course of voltages which are analogous to the virtual junction temperature of IGBT, diode and the hottest place of the heatsink.

IV. Parameter Values of Thermal System Electrical Model

The values of RC pairs in the model belonging to IGBT and diode are identified on the basis of catalogue data. The catalogue data for thermal resistance and thermal time constants of the model module belong to the chain RC model of the thermal system. By the use of *Therm* [5] software, the values of RC pairs were transformed for the ladder model, required for proper thermal system integration, both for IGBT and for diode. By the use of calculated values, the transient thermal impedance curve was simulated for IGBT and compared with the similar curve in the catalogue, Fig. 5.

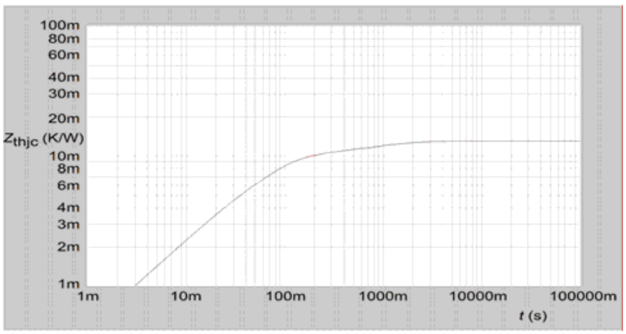

Fig. 5. Simulated transient thermal impedance curve (IGBT silicone-case)

In order to determine the values of RC parameters of the heatsink thermal circuit, the transient thermal impedance curve of the heatsink was measured. This was achieved by heating of the common heatsink of the converter directly beneath the IGBT module, which is the warmest (at the exit of the cooling channel). All the six modules were connected electrically into a series and loaded with direct current so that all of them were approximately under equal load with the assumed mean dissipation for the given operating conditions.

Based on the measured transient thermal impedance curve, the values of RC pairs of ladder heatsink thermal model were calculated, Table 1. Program for the calculation of the course of IGBT module losses calculates the losses with the intervals of 12.5 µs, 0.5 ms and 2s.

The calculation interval of 12.5 µs ensures the maximum accuracy, but also brings the maximum amount of data to be incorporated in Simplorer data-pair tables, and in current sources of the model from Fig. 4. Besides, for the required module heating simulation time of 80 s, the loss averaging interval of 12.5 *us* results in a long simulation time. The losses averaged within a longer time interval result in a shorter simulation time but also in lower accuracy. In order to test the accuracy, a comparison of simulation responses was done, first with module losses averaged in interval of 12.5 us and 0.5 ms. Fig. 6 shows the characteristic waveforms of IGBT module losses averaged within interval of 12.5 us and 0.5 ms. By simulation of IGBT module heating in duration of 50 ms, an equivalent silicon temperature of approx. 250•10^{-3} °C was obtained with negligible difference in response for the mentioned loss averaging intervals, Fig. 7.

TABLE I. CALCULATED HEAT RESISTANCE AND CAPACITANCE OF THE LADDER MODEL OF IGBT, DIODE AND HEATSINK

R_{th} (IGBT)	C_{th} (IGBT)	R_{th} (diode)
2.2848E-03	1.7580E+00	4.5924E-03
7.5235E-03	5.5872E+00	1.2786E-02
1.1511E-03	1.0908E+02	7.1616E-03
2.0405E-03	3.2940E+02	4.5952E-04
C_{th} (diode)	R_{th} (heatsink)	C_{th} (heatsink)
8.8153E-01		
2.7539E+00		
7.0703E+01	2.9995E-02	1.5476E+01
1.3730E+03	4.2704E-02	5.2186E+01

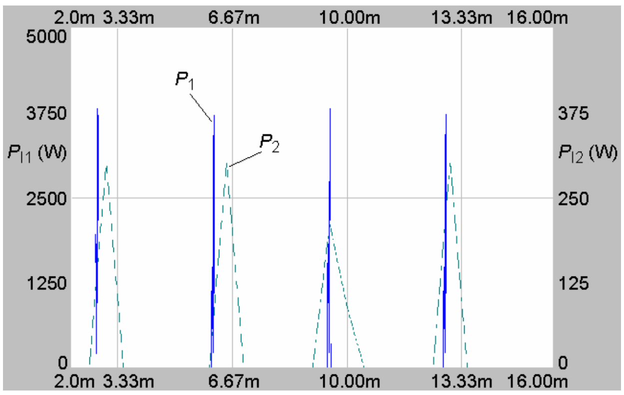

Fig 6. IGBT loss impulse waveforms averaged in the intervals of 12.5 µs and 0.5 ms.

Further simulations of virtual temperature of IGBT and diode started with the use of losses waveforms averaged in the 0.5 ms interval. For this loss waveform, virtual temperature of IGBT and diode was calculated for simulation time of 80 s, Fig. 8 and 9.

These simulation results for IGBT virtual temperature were compared again with the waveform of IGBT virtual temperature obtained with the losses averaged in the interval of 2 s. The acceptable correspondence of results in this case was the reason for approaching the simulation of IGBT and diode virtual temperature in a longer characteristic cycle of 640 s with losses averaged with 2 s.

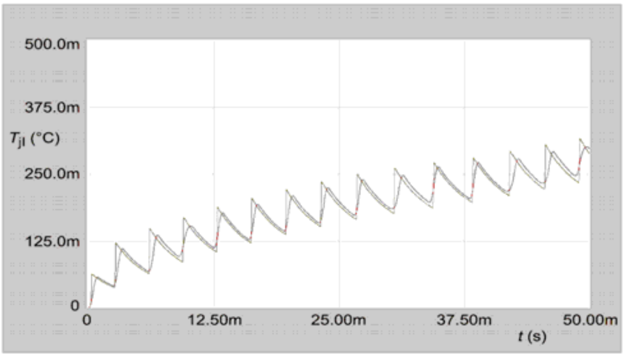

Fig 7. Virtual temperature of IGBT for losses calculated in intervals of 12.5 µs and 0.5 ms.

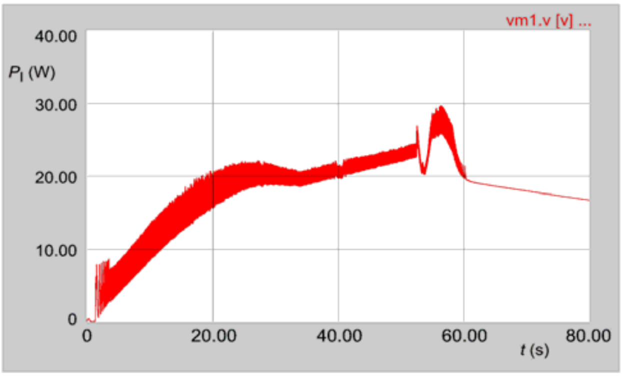

Fig. 8. Waveform of IGBT virtual temperature calculated with losses averaged in the interval 0.5 ms.

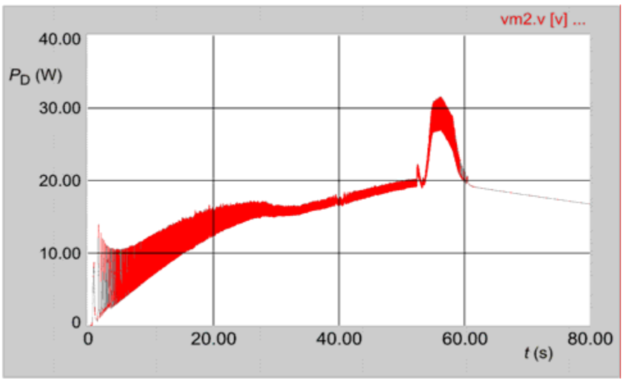

Fig 9. Waveform of diode virtual temperature calculated with losses averaged in 0.5 ms interval.

V. Simulation Results

After the satisfactory simulation accuracy was established by using the time course of losses averaged in a time interval of 2 s, the final simulation was performed. The virtual temperature of IGBT, diode and heatsink was simulated until reaching the stationary state, i.e. in duration of 640 s.

Fig. 10. shows the current waveform of current source I1 from Fig. 4, i.e. the waveform of losses averaged in time interval of 2 s. Fig. 11. shows the waveform of IGBT silicon equivalent temperature. Fig. 12. shows the waveform of diode silicon equivalent temperature. In a stationary state, the peak value of IGBT silicon and diode silicon equivalent over-temperature rise amounts to approx. 50 °C. Fig. 13 shows the waveform of heatsink equivalent temperature. In a stationary state, the peak value of heatsink equivalent over-temperature rise amounts to approx. 44 °C.

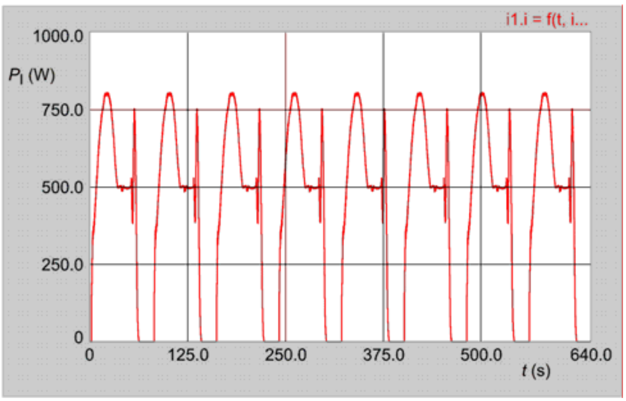

Fig. 10. Waveform of IGBT losses (averaging interval 2s).

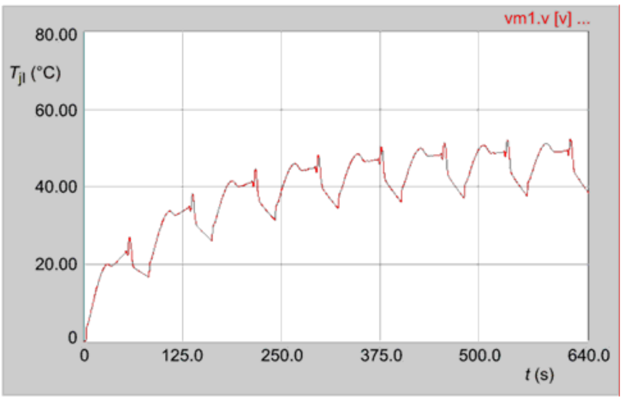

Fig 11. Waveform of IGBT virtual temperature.

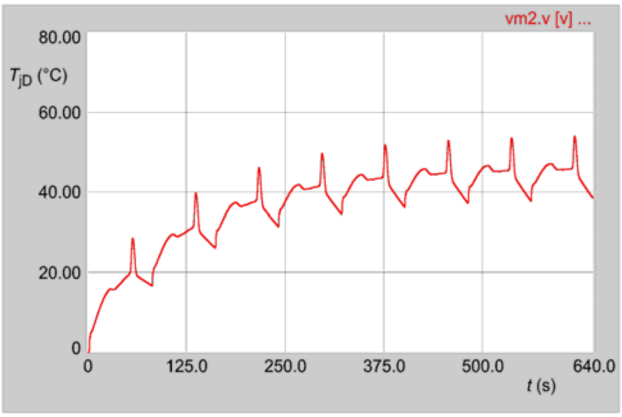

Fig. 13. Waveform of diode virtual temperature.

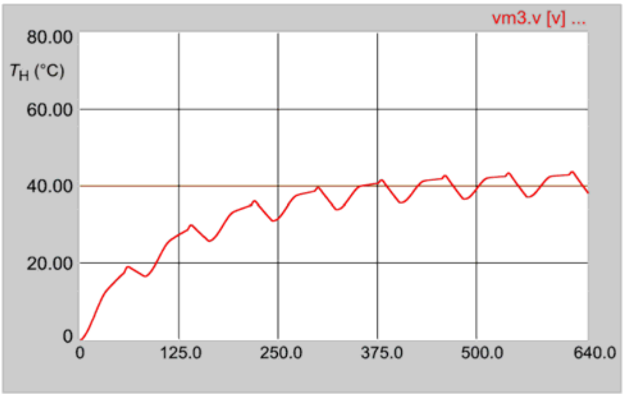

Fig. 14. Waveform of heatsink virtual temperature.

As already mentioned, the simulation results obtained have not been compared with the measurement results. However, a satisfactory accuracy of the procedure has been presumed (6,7), and an insight into oscillations of semiconductor switches silicon over-temperature and the time course of silicon over-temperature rise during characteristic tram operating cycles has been obtained. In the meantime, more than 20 tram vehicles have been successfully put into operation and have been running free of faults caused by excessive loading of converter.

VI. Conclusion

The proposed hybrid electrothermal simulation procedure makes possible a fast check of power switches thermal behaviour in converter circuits. It is possible to use different software tools, one for loss calculation and the other for junction temperature calculation. This facilitates teamwork in separate groups and the current dimensioning of power switches based on the losses calculated elsewhere. Power losses data need not be of high resolution, owing to the thermal system structure. The averaging interval of calculated losses determines strongly the amount of calculated data and the required calculation time.

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