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ELECTROTHERMAL SIMULATION METHODOLOGY FOR POWER DEVICES AND INTEGRATED CIRCUITS

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Owing to the increasingly compact integration in power electronics circuits, the dissipated energy has to be correctly evaluated to allow optimization of the thermal environment. General purpose simulation tools like SPICE, SABER, ESACAP have been developed to predict losses due to the device self heating. However, to address electrothermal simulation of circuits despite the huge difference between electric and thermal time constants, a new approach for the coupling of the thermal and electric simulators is required.

The electrothermal study of a power circuit encompasses all the interactions between the electronics components and the thermal environment in which they operate. During electric operation, heat generation in the structure originates from the on state and switching losses of the main power components. The latter's thermal response (ie, self-heating and thermal coupling with adjacent devices, if any) acts upon the device's electric parameters which consistently dissipate a different level of power until a possible final electrothermal equilibrium has been struck.

Simulation of the physical evolution of this straightforward system is nevertheless delicate to achieve in practice, because even if designers can take advantage of various tools (physical models for the device, efficient electric and thermal simulators), they are still faced with the difficult issue of coupling simulations of phenomena whose time constants are generally different for several orders of magnitude.

In this paper, an original method of electrothermal modeling of power electronics devices is proposed, the study being limited to a constant duty cycle operating chopper circuit. In order to overcome inherent problems in the implicit method and the "slowness" of the electric simulator, a supervisor software handles an interactive dialog between the thermal and the electric simulators so as to minimize the working time of the latter. Thus, the electric simulator is only used for computing the steady-state electric response of the circuit proposed and only specifically over a certain operating period so as to determine mean losses dissipated in the device at the temperatures imposed by the pseudo-computing step of the electrothermal simulator.

This method takes advantage of the fastness of the thermal simulator PYRTHERM [1] developed for electrothermal simulation of power devices or circuits and originally solving the 3D heat diffusion equation by applying a Fast Fourier Transform algorithm. Indeed, this software allows for the computation in just a few minutes (3 to 5 mn) of transient 3D thermal responses for the particular structures of power IC's.

The thermal software written in FORTRAN is started as a subroutine of the main supervising program itself written in FORTRAN. The electric simulator is activated through system calls; thereby calling for a multitask operating system so that the supervisor can regain control after each electric simulation. The interchange of data is done through file read/write in a UNIX environment.

The description of the methodology, schematically depicted in Fig. 1, makes use of a device dissipating a power which is an increasing function of temperature. Duration of the transient electric response being much less than the device's thermal equilibration time, the iterative procedure run by the supervisor directly starts with the steady-state electric response. Results of a first electric simulation yield a value p_o of the mean power dissipation in the device at ambient temperature Ta. Then the thermal simulator computes a thermal response which is necessarily underestimated as the device self-heating effects have not yet been taken into consideration (see curve p_o). The supervisor then carries out a prediction by searching for instant t_o corresponding to a temperature rise $\Delta\theta$, which stands for the accuracy criterion and pseudo computing step of the electrothermal simulator.

The electric parameters being computed at temperature $Ta+\Delta\theta$, a new electrothermal simulation leads to an overestimated thermal response (curve p_1). In fact, the temperature rise $\Delta\theta$ will then be reached by supplying a mean power value $P1=(p_o+p_1)/2$ for a mean time $T1=(t_o+t_1)/2$. The supervisor stores in a file the P1 and T1 values so that the thermal simulator keeps track of the temperature changes $\Delta\theta$ between instants 0 and T1.

The next step consists of determining power P2 and temperature T2 needed for a new temperature rise $\Delta\theta$ between the instants T1 and T2. The electric simulator having evaluated the losses p_2 dissipated at temperature $Ta+2\Delta\theta$ the supervisor can carry out two new thermal simulations: one underestimated beyond T1 for a constant thermal dissipation P1 (see curve P1) and the other overestimated beyond T1 (see curve p_2) for a variable power dissipation (P1 until T1, then p_2). The couple of points (P2,T2) being derived and stored, the iterative procedure used for prediction/correction purposes can then be alternated to reach a stable electrothermal equilibrium.

To validate this original approach for the electrothermal simulations of power circuits, we have selected a behavioural study of an IC for automotive applications. This circuit includes 6 VDMOS and a CMOS control logic. For the simulation purpose, the CMOS logic circuit which controls the VDMOS gate has been represented using a 0.83 mA current source connected in parallel with a 400 ohm resistance.

The electric circuit used consists of a (R, L) chopper (3.8 ohms and 15 mH respectively) supplied by a 20 volts voltage source.

The physical VDMOS model is embedded in the ESACAP software. It includes electric parameters which are not temperature-dependent (gate resistance, gate/source linear capacitances, drain/source nonlinear capacitances, weld resistances and inductances) as well as temperature-dependent electric paramaters derived from semiconductor equations (the slope factor K_P, threshold voltage V_T and drift resistance R_D).

$$K_P = K_{P0} \times \left(\frac{T}{T_0}\right)^{1.5} \quad \text{with } K_{P0} = 5.36\text{V}$$

$$V_T = V_{T0} \times \left(1 - 3.5 \times 10^{-3} \times \left(T - T_0\right)\right) \quad \text{with } V_{T0} = 2\text{V}$$

T_0 stands for the ambient operating temperature

$$R_D = 0.25 \times \left(\frac{T}{T_0}\right)^{2.2}$$

The channel resistance Rch is an implicit function of temperature through the drain current equation which itself depends on KP and VT

The overall dissipation losses (ON-state and switchings), are taken into account by a subroutine of the supervisor which reads the outpout results of the electric simulator in the dedicated output files and computes the mean value of the dissipated power.

Temperature measurements have been recorded using an IR camera, the package having previously been removed by "chemical etching".

The measured and computed heating curves obtained for a VDMOS and for two different gate controls are given in Fig. 2. The simulated solution necessitated approximately 10 minutes of computations on a SUN SPARC 10 station. This computational time being equally divided between the search for a steady-state electric response and the electrothermal computation.The good agreement between experiment and simulation allows us to envisage an upper level for the application of this original method of simulation: the study of the electrothermal coupling of several devices dissipating different amounts of power depending on the type of the load and the control sequence; the electrothermal study of rather complicated power circuits having complexe control sequences.

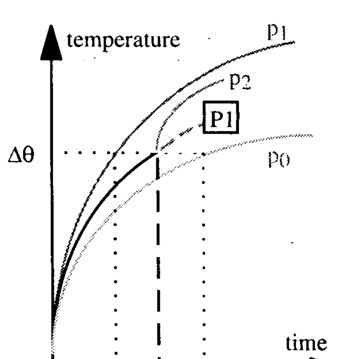

figure 1: methodologie

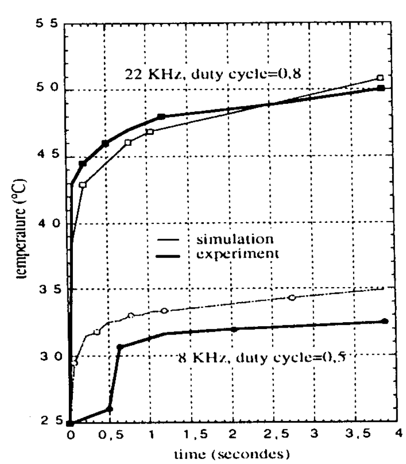

figure 2 : results

[1] D. Esteve et al, "L'intégration des systèmes électroniques dans l'automobile du XXIe siècle",CEPADUES Edition 1995, contribution of P. Tounsi et al;, pp 183,190.