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Parametric Transient Thermo-Electrical PSPICE Model For A Single And Dual Conductor Power Cable

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ABSTRACT:A parametric macro model for a single and dual conductor power cable for transient thermo-electrical coupled simulation in PSPICE will be derived. The articledepicts the modelling of a simplified, single- and dual conductor cable and its use during simulation. Its verification against experiment and finite element simulation shows a good agreement. The derived single- and dual conductor PSPICE cable macro model enables a quick modelling at system level. It offers a time saving transient thermo-electrical simulation under various thermal conditions and cable geometries and to optimize e.g. size, weight. The approach support the engineer to overlook the thermal influences and temperatures along the power cable under real 'thermal' assembling conditions in an e.g. car engine room or aircraft.

Keywords: multi conductor power cable;coupledelectro-thermal macro model; transient, PSPICE

I. INTRODUCTION

With the increasing use of hybrid and electric vehicles, new challenges arise for the high-voltage electrical system.Power cable should therefore be able to conduct high currents with the lowest possible weight and under the increasing thermal stresses of the cable sheathing material. To optimize the electrical, weight and reliability demands, it is useful to know the conductor core and the cable surface temperature in respect to application conditions. These include the installation (conduction, convection and radiation), the ambient temperature and the transient electrical load (e.g. PWM).Transient analytical temperature calculations are only incompletely possible and numerical FE simulations cause high computing costs.

In literature [1 -5], the main motivation for research efforts has been the determination of the steady-state and transient temperature rises in electric conductors carrying, constant loads, cyclic loads or short overloads. In [6, 7], the partial differential equations for radial heat conduction in circular insulated conductors have been solved by the use of Bessel functions. The complexity of this approach makes it difficult to apply it in a comprehensive manner, e.g. to handle several conductors. Another approach to solve the heat transfer in electronic components is based in the usage of lumped equivalent thermal models. The results provided by this models have shown a good correlation[8-11]. The IEC 60287 Standard [12], which is well established in the industry, described the use of this modelling approach. Itis based on electro-thermal analogy and has the great advantage of intuitively understanding and can be easy implemented in a circuit simulator. It allows an easy modelling of more complex electric systems.

This lumped equivalent thermal model approach will picked up to implement a library element for a multi conductor cable to the application in a common network simulator,e.g. PSPICE.

In the following the approach, the results and the modelling for a single [13] and dual conductor cable will be given. The approach will be verified by a numerical ANSYS model and by experiment. For the experimental verification, a set-up to measure thetemperatureswas developed. It allows to determine the conductor core, cable isolation and cable surface temperature by using thermocouples and an infrared camera.

A. Approach

The approach is to divide a cable into segments, which can be described as macro modules in a circuit simulator (Figure 1). Each segment then can be assigned with the same or different thermal boundary condition, depends on its build-in location during its course through an e.g. vehicle.

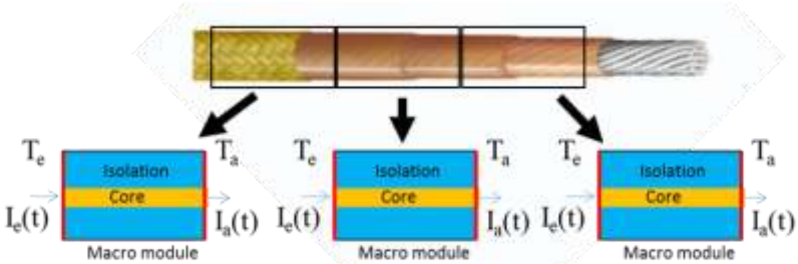


Fig. 1: The cable is divided into segments to describe its build-in location during its course.

Figure 2a and 2b show the modelling for a single and a dual conductor cable over the cable course. Each segment is assigned by the same material and geometry properties, but can be assigned with different thermal boundary condition, like conduction or convection and radiation.

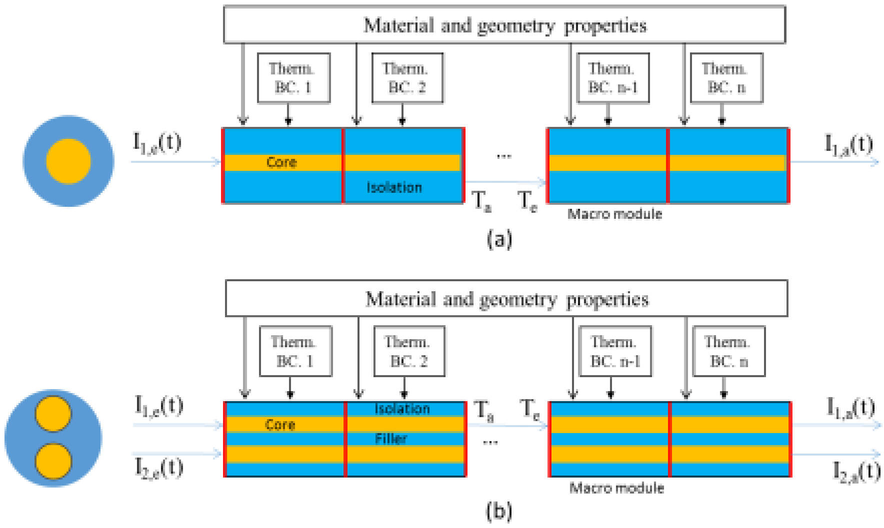


Fig.2: The segments, in form of the macro modules, can be piece wisely connected in series to modelthe cable under different thermal boundary conditions a) single conductor cable, b) dual conductor cable.

Table 1 sums up the considered module parameter to describe the parametric input variables, like the current (static, transient), the temperature depend material properties, the geometric dimension and the boundary conditions. At the cable ends the terminal temperature will be also considered.

Table I: PSPICE cable module input parameters and thermal boundary conditions.

Electrical parameter	**Thermal parameter**	**Geometry parameter**	**Boundaryconditions**
κ	λ_{core}	l	$T_{Terminal}$
α	λ_{iso}	d_{core}	T_{Amb}
I (static, transient)	c_p	t_{iso}	h_{conv}
	ρ		h_{rad}

To model and simulate the coupled behavior,the circuit simulator PSPICE was chosen. A circuit simulator offers the advantage to model electrical and thermal behaviour and to have a time-saving transient simulation on one simulator platform. This is possible, because the electrical and thermal behavior depends of the same physically analogy.So, the thermal behaviour can be describedeasily in anequivalent thermal network and the heat flux asa result of the electrical power loss of the temperature depended electrical conductor resistance. Connecting both, the electrical and thermal network, a macro modulecan be realized.

In addition to the discrete temperatures of the cable conductor and the cable sheath, the temperature-dependent voltage drop and the core resistance can be supplied via each cable module. 1 V represents 1 ° C.

Figure 3 presents the principle approach for the parametric thermo-electric coupled macro module of a single and double ladder cable. Table 2 shows the electrical, thermal, geometry and boundary parameters involved.

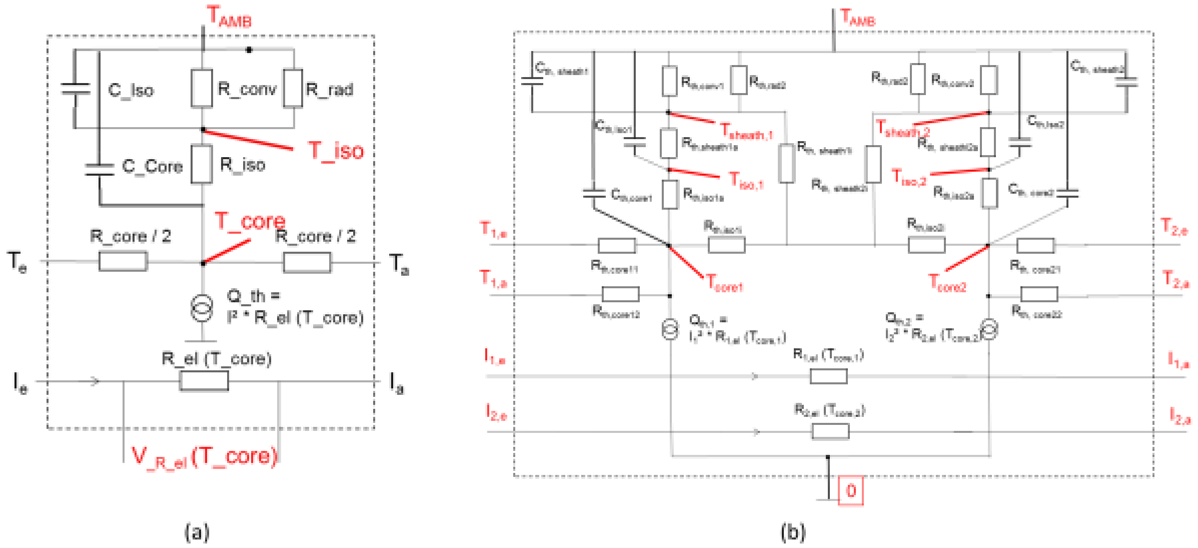


Fig.3: Principle approach for the parametric thermo-electric coupled macro module for a) single conductor cable and b) a dual conductor cable.

Table II: Material and geometry data as input for ANSYS and PSPICE models

l_{Cable} [m]	d_{Core} [mm]	d_{Iso} [mm]	d_{Sheath} [mm]	λ_{Cu} [W/Km]	λ_{iso} [W/Km]	λ_{sheath} [W/Km]	ρ_{Cu} [g/m³]
0.4	2.5	5	12	400	0.3	0.3	8950

ρ_{iso} [g/m³]	ρ_{sheath} [g/m³]	C_{pCu} [Ws/kgK]	C_{p_Iso} [Ws/kgK]	C_{p_sheath} [Ws/kgK]	κ_{Cu} [S/m]	α_{Cu} [1/K]
950	950	381	1400	1400	59	0,00385

To enhance the accuracy a segment can be easily described by several sub-divided modules. To implement the electrical and thermal network in a handynetwork simulator library element, figure 4shows the in PSPICE realized macro modules for a single and a dual conductor cable. The given necessary model parameter belongs to the library element.

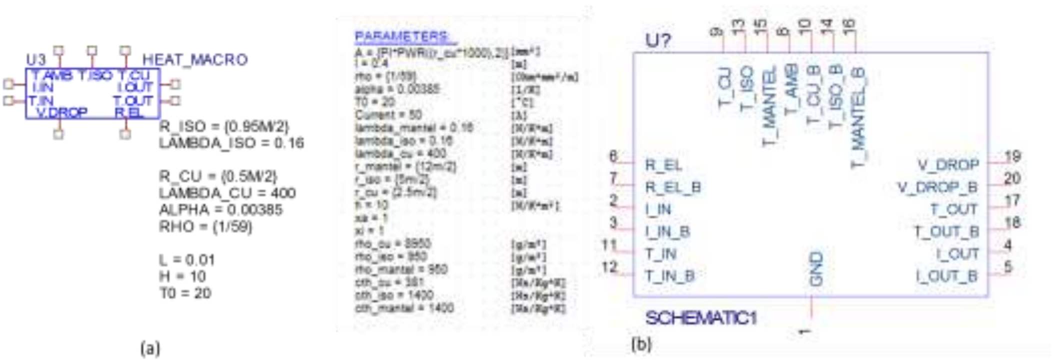


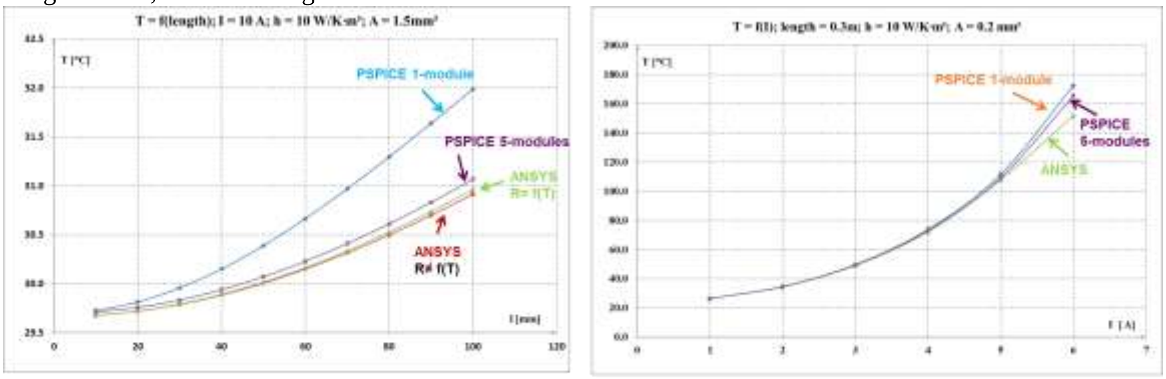
Fig.4: Implemented PSPICE library elements for a) single conductor cable and b) a dual conductor cable.

II. RESULTS

In the following the results and itscomparisonand accuracy will be given for the single and dual conductor cableapproach.

A. Single conductor cable model

Figure 5adelivers the temperature behavior with respect to conductor length. To show the temperature dependent electrical behavior of the resistance(R = f(T) and R≠ f(T)) the results of a finite-element simulation, using ANSYS, is additional given.



(a) (b)

Fig.5: Conductor core temperature with respect to a) cable length (R = f(T) und R≠ f(T)) and b) to current through the cable.

With increasing conductor length the temperature depending effect can be noticed, as expected. Withincreasing the discretization of the conductorthe temperature behavior fits smoother to the ANSYS result. The use of 5 modules (PSPICE 5- modules) in series instead of only one module (PSPICE 1-module) leads here to a better accuracy.

Figure 5bdelightsthe temperature behavior with respect to the current through the cable. Here can be noticed that up to I = 5 A,a discretization is neglectable.

Figure 6 and table 3 validates the results of the experiment and the ANSYS simulation with the results of the PSPICE simulation. In this case a discretization of four over the cable length was chosen.

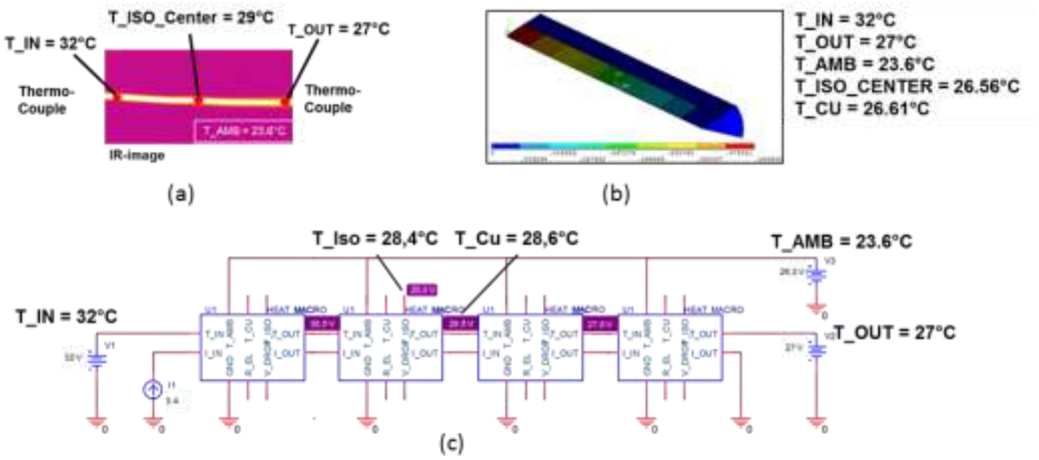


Fig. 6: Validation of the results between a) the experiment using an IR-camera,b) the ANSYS Model and c) the PSPICE model

The temperatures at the cable terminals are determined by experimental investigation and were used as input parameters for the ANSYS and PSPICE model setup. The temperatures were measured by using thermo-couples assembled at the terminals, the centre of the cable surface by IR-thermography.

Table III. Comparison between the experiment, the ANSYS Model and the PSPICE model(T_{Amb} = 23.6 °C).

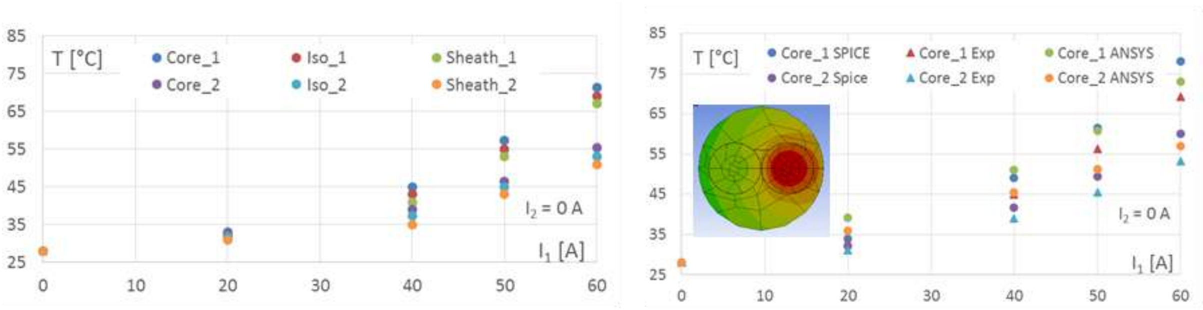
variable	Experiment	ANSYS	PSPICE
$T_{core, center}$[°C]	-	26.61	28.6
$T_{Iso,center}$[°C]	29	26.56	28.4
T_{IN} [°C]	32	32	32
T_{OUT} [°C]	27	27	27

In case of the temperature different between the T $_{\text{core, center}}$ to T $_{\text{Iso, center}}$, the results show a quite good agreement between the ANSYS and PSPICE simulation. And even the measured T $_{\text{Iso, center}}$values fit quite well to the simulated ones.

B. **Dual conductor cable model**

Figure 7a verifies the experimental setup,which is described more in detail in section IV. It shows the cable temperatures at different load currentsthrough conductor core 1,I_1,for natural convection.The temperatures were measured by thermo-couplesinstalled in different regions of the cable. The current through conductor core 2 was off, $I_2 = 0$ A. The used cable length was l = 1 m and the cable surface had an area of A = 12 mm².

The temperature behaviors show, as expected, a grading from the conductor core 1 over the isolation layer in direction to the cable sheath 1 andas well as the grading behaviour of the inactive conductor 2 compared the active conductor 1.



(a) (b)

Fig.7: a) Evaluation of measured temperature values for a dual conductor cable for different load currents in conductor core 1(I_1) using thermo-couples, $I_2 = 0$ A b) Comparison between the experimental results and the ANSYS and PSPICE simulation results for different load currents in conductor core 1 (I_1), $I_2 = 0$ A.

Figure 7b compares the experimental results for the investigated dual conductor cable with the ANSYS and PSPICE simulation results for different load currents in the active conductor core 1 (I_1), $I_2 = 0$ A.Depending on the load current intensity, the deviations between simulation and measurement results were up to 10%. However, this can be reduced by a more detailed discretization.

Figure 7b shows additional the centre cross section of the ANSYS model and the mesh for a two-core cable with the insulation layer and its sheath as well as the temperature distribution at the electrical loads $I_1 = 50$ A and $I_2 = 0$ A. The thermal boundary conditions were set to $h_{conv} = 10$ W/m²K and $T_{Terminal} = 33$ ° C (symmetry axis on half the cable length).

Figure 8 shows the transient temperature behavior in both cable conductors, with a stepwise current increase from $I_1 = 0$ A to 50 A, $I_2 = 0$ A. The boundary conditions of the experiment were determined for the PSPICE simulation so that they corresponded to the values of the external temperature sensors.

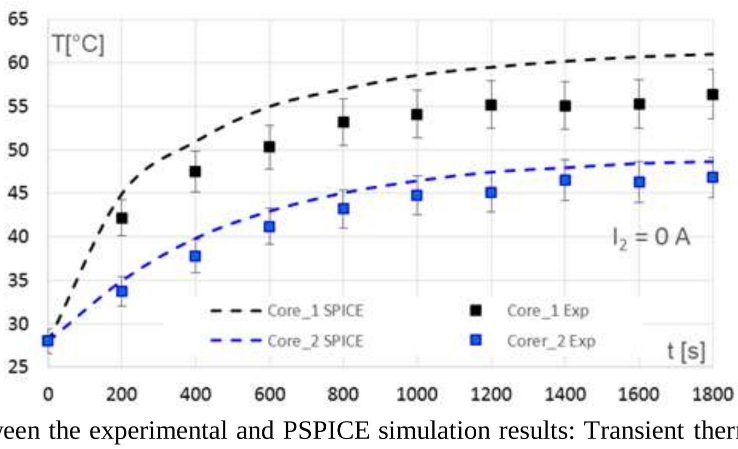


Fig. 8: Comparison between the experimental and PSPICE simulation results: Transient thermalstep responseat the middle of the cable length (l = 0.2 m) for $I_1 = 50$ A, $I_2 = 0$ A, l = 0.4 m, $h_{conv} = 10$ W/m²K, $T_{Terminals} = 33$ °C, $T_{Amb} = 28$ °C.

Figure 9 shows the PSPICE model for this transient investigation. In this case a discretization of two was chosen.The comparison shows a relatively good agreement between the temporal behavior of the temperatures in the active and passive conductor core (table 4). The deviations are between 4% (passive conductor) and 10% (active conductor).

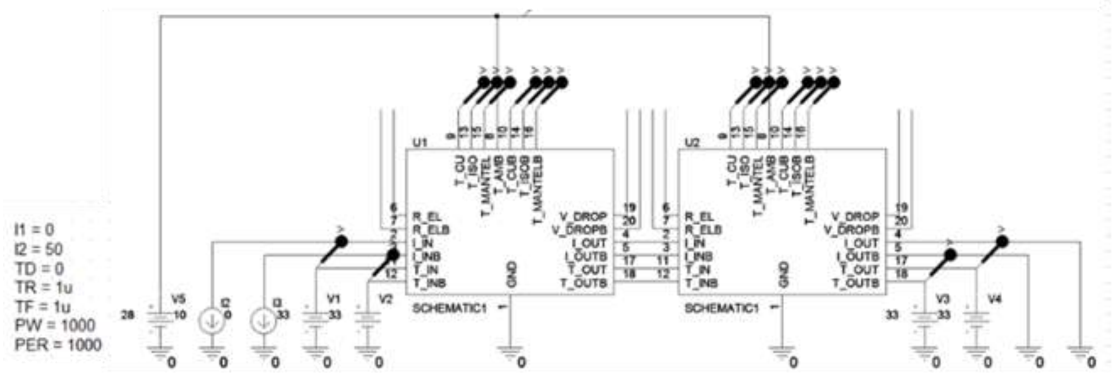


Fig.9:PSPICE model for transient investigation with a discretization of two modules.

Table IV: Comparison between the experiment, the ANSYS Model and the PSPICE model at t = 1800 s (T_{Amb} = 28 °C, h_{conv} = 10 W/mK).

variable	Experiment	PSPICE
$T_{core1, center}$ [°C]	56.4	61
$T_{core2, center}$ [°C]	46.8	48.7
T_{IN} [°C]	33	33
T_{OUT} [°C]	33	33

III. DISCUSSION

The modelling is based on a semi-analytical approach, which delivers an approximation of the real geometry and the boundary condition of a multi-conductor cable. In this case, a higher discretization of the cable length when using several macro modules leads to better results compared to e.g. ANSYS results. It can be noticed that a discretization up to five modules for cable length of one metre show satisfactory thermal simulation results for the investigated ranges of the electrical current and to heat transfer coefficient.

Acomparison with the experimental results shows satisfactory results as well.A first error estimate was made between the PSPICE model, the FE model, and the experiment. The error between the experiment and ANSYS model results was found to ~ 8% while the error between the experiment and PSPICE model was ~ 3%.

Also the transient comparison of a dual conductor cable PSPICE model shows a relatively good agreement between the temporal behavior of the temperatures in the active and passive conductor core. The deviations are conservative and between 4% (passive conductor) and 10% (active conductor).

It can be stated in principle that the approach can be used for further investigation of complex cable harnesses on system level. Future research activities are planned in the direction to transfer the approach to a real cable harnesses system installed in e.g. an engine compartment.

IV. MODELING

In order to model the electrical and thermal behavior of a single- or double-conductor cable, the electrical and thermal subsystem must be subdivided in consideration of the physical relationship between electrical power dissipation and core temperature. The analytical description of the physical behavior for each subsystem must be based on the assumption that each subsystem can be transformed into the PSPICE circuit simulator language.Afterwards, both subsystems are coupled and the PSPICE library model can be created.

First, the modeling for a single-conductor cable with simplified single-layer insulation is described below. After that the modelling of a dual conductor cable will be shown.

Equation (1) describes the equilibrium relationship between the thermal and the electrical quantities. Here, the thermal convection $\dot{Q}_{conv.}$ [W] and radiation $\dot{Q}_{rad.}$ [W] as well as the electrical power loss P_D [W]. The power loss can befurther described by the electrical current I [A] and the temperature-depended electrical resistance of the electrically conductive conductorR(T) [Ω].

$$\dot{Q}_{conv.} + \dot{Q}_{rad.} = P_D = I^2 \cdot R(T) \quad (1)$$

A. **Electrical system behaviour**

The electrical part of the system focusses on the simulation of the temperature-dependent electrical resistance of the electrically conductive conductor. The thermo-electrical behavior description of a single or dual conductor cable is identically. With the help of system-theoretical functions, the properties of the PSPICE network simulator could be reproduced.

Equations (2) and (3) describe the electrically temperature-dependent resistance behaviorR(T) and the electrically temperature-dependent power loss behaviour $P_D(T)$.

$$R(T) = \frac{\Delta l}{\kappa \cdot (\pi \cdot r_{core}^2)} \cdot \left(1 + \alpha \cdot \left(T - T_{Amb}\right)\right) \tag{2}$$

$$P_D(T) = I^2 \cdot R(T) = V(T) \cdot I \tag{3}$$

B. **Thermal system behaviour**

The thermo-electrical system description for a single and dual conductor cable is varying, because of different thermal paths. Therefore this subsection is divided into two parts.

B.1One conductor cable

Figure 10 shows the geometrical definitions for the analytical description of the thermal resistances in the longitudinal direction (a) of the conductor core and vertically (b) from the conductor core through the cable insulation to the environment.

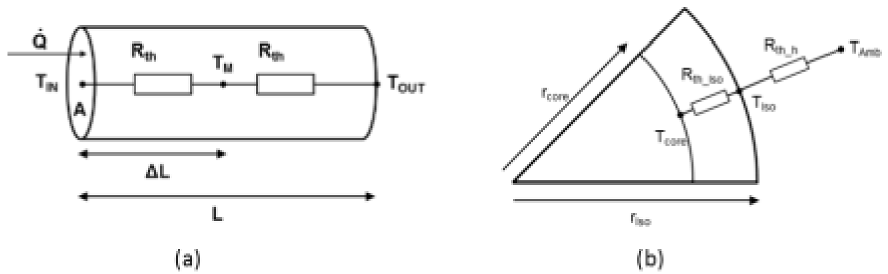


Fig.10: Thermal modeling of the cable behavior a) in longitudinal direction of the conductor core and b) vertically to the conductor core.

Equation (4) derives the thermal resistancealong the conductor core using the input parameter thermal conductivity λ_{core} [W/ m K].

$$R_{th\_core} = \frac{l/2}{\lambda_{core} \cdot \pi \cdot r_{core}^2} \tag{4}$$

The thermal resistance between ambient and the cable surface (isolation layer) is given in (5).

$$R_{th\_Iso} = \frac{\ln\left(r_{Iso}/r_{core}\right)}{2\pi \cdot \lambda_{iso} \cdot l} \tag{5}$$

Equation (6) describes the heat resistance due to the heat transfer coefficient due to the convection over the cable surface using the macro model input parameterh_{conv} [W/m²K].

$$R_{th\_conv} = \frac{1}{h_{conv} \cdot A} = \frac{1}{h_{conv} \cdot 2\pi \cdot l \cdot r_{Iso}} \tag{6}$$

The heat transfer and the thermal resistance due to radiation over cable surface is given in (7) and (8).

$$h_{rad} = \frac{\varepsilon \sigma_S \left(T_S^4 - T_{Amb}^4\right)}{\left(T_S - T_{Amb}\right)} \left[\frac{W}{m^2 K}\right] \tag{7}$$

$$R_{th\_rad} = \frac{1}{h_{rad} \cdot A} = \frac{1}{h_{rad} \cdot 2\pi \cdot l \cdot r_{Iso}} \tag{8}$$

Equations (9) and (10) describe the transient properties using the thermal heat capacities of the conductor core and the insulation layer.

$$C_{th\_core} = c_{p,core} \cdot \rho_{core} \cdot l \cdot \pi \cdot r_{core}^2 \tag{9}$$

$$C_{th\_Iso} = c_{p,Iso} \cdot \rho_{ISO} \cdot l \cdot \pi \cdot \left(r_{Iso}^2 - r_{core}^2\right) \tag{10}$$

B.1.2**Singleconductor cable model in PSPICE**

Figure 11 shows the thermo-electric coupled model in developed in PSPICE and its input parameters (material and geometry data, electrical and thermal boundary conditions) and the designed library element.

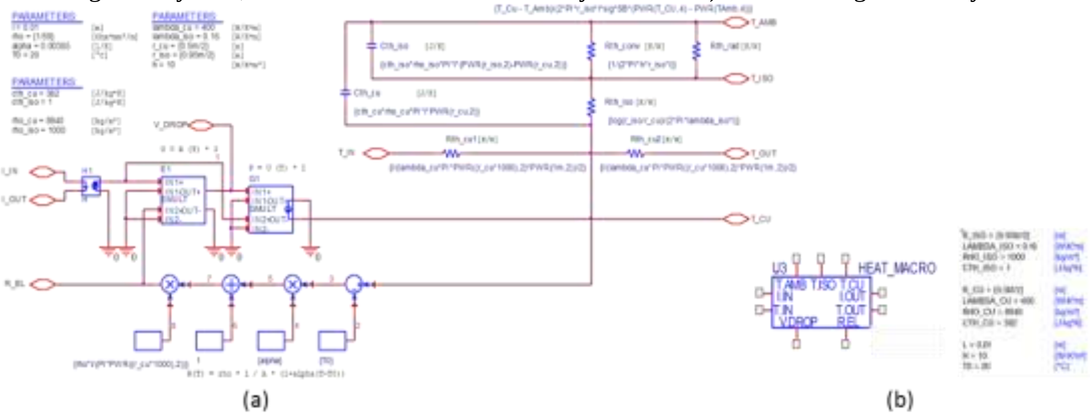


Fig.11: a) PSPICE model description, b) library symbol of the macro module.

B.2. **Dual conductor cable**

Equation (11) describes the thermal resistance of the conductor core between the cable end terminals.

$$R_{th\_core\ 1,2} = \frac{1/2}{\lambda_{core} \cdot \pi \cdot r_{core}^2}, \tag{11}$$

The thermal resistance for the cable isolation and the cable sheathing can be found by means of the equations (12) and (13).

$$R_{th\_Iso\ i,a} = \frac{\ln\left(r_{Iso} / r_{core} \right)}{x_{i,a} \cdot 2\pi \cdot \lambda_{iso} \cdot l} \tag{12}$$

$$R_{th\_sheath\ i,a} = \frac{\ln\left(r_{sheath} / r_{Iso} \right)}{x_{i,a} \cdot 2\pi \cdot \lambda_{sheath} \cdot l} \tag{13}$$

The parameters x_i and x_a(figure 12) describe the radial portion of the heat interactionbetween the conductor coresand to the cable surface.

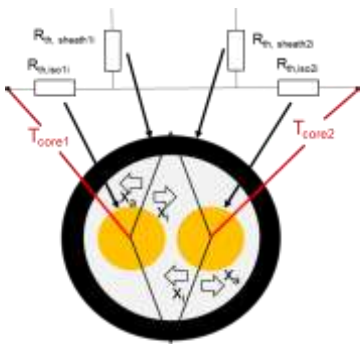


Fig.12: Modelling the thermal interaction between the conductors and to the cable surface.

It depends on the core and cable diameter as well as the conductor spacing. In a first approximation, $x_i = x_a = \frac{1}{2}$can be set here (equation 14).

$$1 = x_i + x_a \tag{14}$$

Equation (15) describes the convective heat resistance which acts across the cable surface, with the use of the heat transfer coefficient h_{conv} [W/m²K].

$$R_{th\_conv1,2} = \frac{1}{h_{conv} \cdot A} = \frac{1}{h_{conv} \cdot \pi \cdot l \cdot r_{sheath}} \tag{15}$$

According to [14], for natural convection the heat transfer coefficient h_{conv} can be described as a function of the cable surface diameter d [m] and the surface temperature difference to ambient ΔT [K] according to equation (16).

$$h_{conv} = \left[0.1254 \cdot \left(\frac{1}{d} \right)^{\frac{1}{2}} + 1.0932 \cdot (\Delta T)^{\frac{1}{6}} \right]^2 \quad (16)$$

The heat radiation across the cable surface is modelled by equations (17) and (18)using the emissivity ε [–], the Stefan-Boltzmann constantσ_S [W/K^{4}m²] and the surface temperature T_S [K] and the ambient temperature T_{Amb} [K].

$$h_{rad} = \frac{\varepsilon \sigma_S \left(T_S^4 - T_{Amb}^4 \right)}{\left(T_S - T_{Amb} \right)} \left[\frac{W}{m^2 K} \right] \quad (17)$$

$$R_{th\_rad\ 1,2} = \frac{1}{h_{rad} \cdot A} = \frac{1}{h_{rad} \cdot \pi \cdot \Delta l \cdot r_{Iso}} \quad (18)$$

Equations (19-21) determine the thermal capacitances $c_{th,xx}$ using the specific heat capacities $c_{p,xx}$ [Ws/kgK] and material densities ρ_{XX} [kg/m³] for the conductor core as well as the insulation and sheathing material.

$$C_{th\_core} = c_{p,Cu\ core} \cdot \rho_{Kern} \cdot l \cdot \pi \cdot r_{core}^2 \quad (19)$$

$$C_{th\_Iso} = c_{p,Iso} \cdot \rho_{Iso} \cdot l \cdot \pi \cdot \left(r_{Iso}^2 - r_{core}^2 \right) \quad (20)$$

$$C_{th\_sheath} = c_{p,sheath} \cdot \rho_{sheath} \cdot l \cdot \pi \cdot \left(r_{sheath}^2 - r_{Iso}^2 \right) \quad (21)$$

V. EXPERIMENTAL SET-UP FOR TWO-CORE CABLE

For the experimental verification of the simulation model, J-type thermos-couple sensors were inserted by drilling holes into the two conductor cable as given in figure 13. The diameter of a sensor is d = 0.5 mm.

Fi.13: Arrangement / assembling of the temperature sensors.

Additional temperature sensors were measuring the temperatures at the terminals of the cable ends as well as the ambient temperature.

VI. CONCLUSIONS

With the extended double core conductor cable PSPICE model, transient simulations can be investigated at system level under various thermal and electrical boundary conditions, as well as cable materials and geometries, taking into account the insulation and sheath structure. The static validation between the PSPICE, FE model and the experiment shows a suitable agreement. This is dependent on the discrediting of the cable length. The transient PSPICE model behavior has also shows an acceptable agreement.

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NOMENCLATURE

A area, m²
l cable length, m
d diameter, m
r radius, m
t isolation thickness, m
x parameter, -
P_D electrical power dissipation, W
R electrical resistive, □
V Voltage, V
I current, A
κ electrical conductivity, S/m
α electrical temperature coefficient, 1/K
Q_{conv}thermal convection, W
Q_{rad}thermal radiation, W
Q_{el} electrical power dissipation, W
T_{amb}ambient temperature, K
ΔT temperature difference, K
h heat transfer coefficient, W/m²K
R_{th} thermal resistive, K/W
λ thermal conductivity, W/mK
C_{th} thermal capacitance, Ws/K
c_p specific heat capacitance, Ws/kgK
ρ density, g/m³
ε surface emissivity, -
σ_s Stefan-Boltzmann constant, W/K^{4}m²

Subscripts

Coreconductor metal core
iso core isolation layer
sheathcover of cable
Ssurface
rad radiation

convconvection

Abbreviation

PWMPulse Width Modulation

BC Boundary Condition