Modeling of the Automotive Power Supply Network with VHDL-AMS

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Abstract — **Considering the ongoing increase of the amount of electronic components in vehicles the optimization of the power network is essential. To optimize the cable harness the ampacity, the voltage drop and the temperature of every cable have to be determined. In this paper stationary and transient ways of modeling cables are presented and compared. All simulation models are created in VHDL-AMS and validated with several measurements. The benefit of exact cable models is the possibility to analyze and optimize the cable harness in an early stage of development. A method to generate a simulation model of a power supply system is presented. The complete benefit of the method is illustrated with a simplified model of a typical automotive supply cable harness. The simulation results of the model are compared to vehicle measurements.**

Keywords- heat transfer, cable, ampacity, automotive cable harness modeling, VHDL-AMS

I. Introduction

In the last years the amount of electrical components in vehicles has increased due to improvements in safety, comfort, and entertainment. The automotive power supply cable harness system has a great importance regarding the electrical functions and is one of the main factors to reduce the manufacturing costs. To cost and functionally optimized cable harness with simultaneously a maximum amount of reliability, the use of elaborated development methods and processes is necessary. Therefore the different parts such as battery, generator, electronic components and cables of the power supply harness have to be modeled. The aim is to optimize the cable harness during the development process. Optimization is done by choosing the size of a wire while taking into consideration various parameters for example the cross section area of a conductor or the ambient temperature.

To gain a reliable model of the cable harness the ampacity of the cables, under consideration of the material and geometry, has to be determined. Hence a temperature dependent model of the cable is developed. The temperature of the isolation is determined with three different approaches:

- direct solution of the heat transfer equation [1],
- thermal equivalent approach [2],
- solution with power flow [3].

The three different models are investigated according to the steady state and transient behavior. The models are validated with measurement results.

Finally, a simplified model of a power supply system is modeled and the results are compared to vehicle measurements. The developed cable model is used in the system and the potential of the method for the dimensioning of the harness is investigated.

The models are simulated in VHDL-AMS (Very High Speed Integrated Circuit Hardware Description Language – Analog and Mixed Signal) which is standardized (IEEE 1076.1-1999 [4]) and supported by simulation software tools. The modeling language can describe digital, analog and mixed analog/digital systems. A high abstraction level and great flexibility, which result from the equation-based structure of the language, are important advantages. Mixed domain systems such as electrical, thermal or mechanical components can be described and simulated. The VHDL-AMS modeling language has become more and more famous in the automotive industry in the last years. Model extensions and changes can easily be realized. The different models can be connected with defined terminations.

Furthermore a free library of typical components is available from the Research Association for Automotive Technology (FAT) in the German Association of the Automotive Industry (VDA) [5]. Existing models can be used to build complex automotive systems.

II. Modeling of Cables

Cables are mainly routed in bundles. For thermal considerations, the bundle is not the most critical configuration. Here the surrounding cables can conduct the heat and cool down an overloaded cable. Detached cables surrounded only by air are most crucial. Air is a good thermal insulator and it is most likely that a cable will be destroyed when there is no contact to other cables or parts, which is the case close to a connector. Due to this reason cable bundles will not be considered in this paper. The worst case is often represented by a single cable in air.

The electrical conductor can also be regarded as a perfect heat conductor. Considering the long length of the wire compared to the small radius, only the heat flux in radial direction has to be considered in the model. The principle of the model follows from the interaction between the thermal and the electrical part. The inner heat source results of the consumed electrical power in the wire driven by the voltage and the current.

A. Solution of the heat transfer equation

The heat transfer equation for a cylindrical wire with the length l and the cross section A simplifies according to [1] to

$$\frac{\partial T}{\partial t}=\frac{\lambda}{\beta}\cdot\frac{1}{r}\cdot\frac{\partial}{\partial r}\left(r\cdot\frac{\partial T}{\partial r}\right)+\frac{1}{\beta}\frac{P_e}{A\cdot l}\cdot \tag{1}$$

with

β	heat capacity	[Ws/(Km³)]
λ	thermal conductivity of insulation	[W/(mK)]
r	radius of cylinder	[m]

P_e is the electrical power and is also dependent on the current temperature

$$P_e=I^2R_{wire}\left(1+\alpha_T\left(T-T_{ref}\right)+\beta_T\left(T-T_{ref}\right)^2\right)\cdot \tag{2}$$

1) Steady state

An analytical solution can be achieved by considering the steady state behavior. The heat transfer equation simplifies to

$$0=\frac{\lambda}{\beta}\cdot\frac{1}{r}\cdot\frac{\partial}{\partial r}\left(r\cdot\frac{\partial T}{\partial r}\right)+\frac{1}{\beta}\frac{P_e}{A\cdot l}\cdot \tag{3}$$

To determine the temperature of the conductor the ordinary differential equation has to be integrated twice. The overall solution is

$$T=\frac{P_e}{2\pi r_2}+C_1\ln(r)+C_2\cdot \tag{4}$$

The constants of integration C_1 and C_2 can be found using boundary conditions. The temperature of the conductor for the steady state is

$$T=\frac{P_e}{2\pi r_2\alpha}+\frac{P_e}{2\pi\lambda}\ln\left(\frac{r_2}{r_1}\right)+T_{env}\cdot \tag{5}$$

The heat transfer coefficient α is calculated according to [6] and depends on the convection α_c and radiation α_r factors.

2) Transient state

The heat transfer equation for the transient state cannot be solved analytical. Numerical solutions have to be applied. Therefore the MATLAB® function *pdepe* is used. The partial differential equation is discretized in space and the resulting set of ordinary differential equations is solved. To use this function the wire has to be separated into the conductor and the insulation part. The initial value and the initial-boundary values used for this problem are

$$T(r,0)=T_{env}, \tag{6}$$

$$\left.\frac{\partial T}{\partial r}\right|_{r=0}=0\ , \tag{7}$$

and

$$\alpha(T_{env}-T_{r2})=\lambda\left.\frac{\partial T}{\partial r}\right|_{r_2}\cdot \tag{8}$$

B. Thermal equivalent circuit approach

Considering the similarity between heat flow and electrical current in the thermal part of the equivalent circuit the electrical power is used as the initial current of the circuit [2]. The resulting temperature is given back to the electrical part and influences the temperature dependent resistor R_{wire} of the wire. The scheme of the model is shown in figure 1.

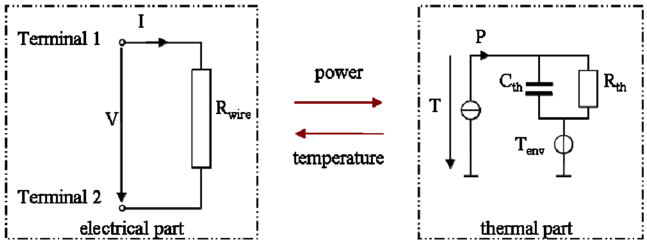

Figure 1. Scheme of the cable model

The environmental temperature T_{env} is given by the DC voltage source. The equation for the temperature can be derived analogically to an electrical circuit to

$$P_e=C_{th}\frac{dT}{dt}+\frac{1}{R_{th}}T \tag{9}$$

The thermal resistor R_{th} and capacitor C_{th} have to be determined as a function of the geometric and thermal properties of the cable.

The thermal resistance R_{th} describes the fact that a material is not a perfect conductor [1]. For an electrical wire with the conductor radius r_1 and the insulation radius r_2 the formula for the thermal resistor results from the heat transfer through a multilayered wall [7]. Assuming that the heat transfer between the insulation and the conductor is perfect the calculation formula for the thermal resistor is expressed as

$$R_{th}=\frac{\lambda_i+\cdot r_2\cdot\alpha\cdot\ln\left(\frac{r_2}{r_1}\right)}{\lambda_i\cdot 2\cdot\pi\cdot r_2\cdot\alpha\cdot l}, \tag{10}$$

The thermal capacitance C_{th} describes the ability of the material to store heat and depends on geometrical and material properties [1].

$$C_{th}=\beta_l\cdot\pi r_1^2+\beta_i\cdot\pi r_2^2, \tag{11}$$

The differential equation for the temperature according to the thermal equivalent circuit can be expressed as

$$C_{th}\frac{dT}{dt}=I^2R_{wire}\left(1+\alpha_T\left(T-T_{ref}\right)+\beta_T\left(T-T_{ref}\right)^2\right)-\frac{1}{R_{th}}T\cdot \tag{12}$$

C. Solution with power flow balance

The heat energy balance according to [1] for the transient state of the cable is

$$P_e = P_r + P_c + \frac{dQ}{dt} \quad \textbf{(13)}$$

Disregarding the axial heat conduction along the length of the wire, the only effects important for the heat distribution is the heat dissipated by convection P_c and radiation P_r. Convection and radiation depend on the temperature difference between the wire and the environment. The part of the heat not emitted to the ambience is stored in the conductor depending on the heat capacitance of the material and increases the temperature of the wire.

The power dissipated by convection and radiation depending on the length of the conductor can be expressed as

$$P_c = \alpha_c 2\pi r_2 l (T - T_{env}), \quad \textbf{(14)}$$

and

$$P_r = \alpha_r 2\pi r_2 l \left(T^4 - T_{env}^4\right). \quad \textbf{(15)}$$

The heat stored in the cable is

$$Q = \left(\beta_l \pi \cdot r_1^2 + \beta_i \pi \cdot r_2^2\right) l \left(T - T_{env}\right). \quad \textbf{(16)}$$

Considering a wire with insulation the temperature can be calculated to

$$\frac{\partial T}{\partial t} = \frac{I^2 R_{wire}\left(1 + \alpha_T (T - T_{ref}) + \beta_T (T - T_{ref})^2\right) + (-c2\pi r_2 l \alpha)\cdot(T - T_{env})}{\left(\beta_l \pi \cdot r_1^2 + \beta_i \pi \cdot r_2^2\right) l} \quad \textbf{(17)}$$

where c is the coefficient concerning the heat transfer through the insulation, depending on the size of the conductor and the insulation:

$$c = \frac{\lambda_i}{\lambda_i + (\alpha_k + \alpha_s) r_i \ln(r_2/r_1)}. \quad \textbf{(18)}$$

III. Validation of Cable Models

In order to verify the introduced models comparisons of the different approaches and experimental results are made.

A. Comparison of different approaches

A cable with a conductor size of 0.5 mm² and an insulation thickness of 0.35 mm installed in free air was simulated with each of the three approaches. The material of the conductor is copper and the insulation material is polyethylene. For all selectable parameters the same values were used such as the heat transfer coefficient and the heat conductivity.

Figure 2 shows the conductor steady state temperature for a current between 2 and 18 ampere computed with the formulas for the thermal equivalent circuit, the power flow and the solution of the heat transfer equation.

In figure 3 the radial temperature distribution is given. The thermal conductivity of the conductor is considered to be perfect and so the temperature in the conductor is the equal for all positions. For the insulation, the thermal conductivity is 0.4 W/Km. The insulation is not very thick and so the temperature difference between conductor and the outside is small.

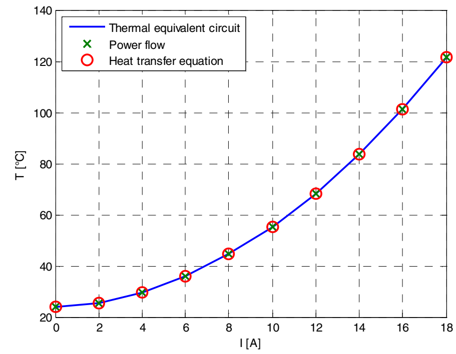

Figure 2. Comparison of different approaches for steady state

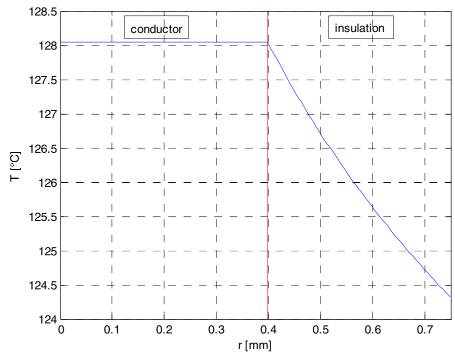

Figure 3. Radial temperature distribution in the wire

For the same configuration the transient models are investigated. In figure 5 the wire is fed with an 18 ampere current for 200 seconds.

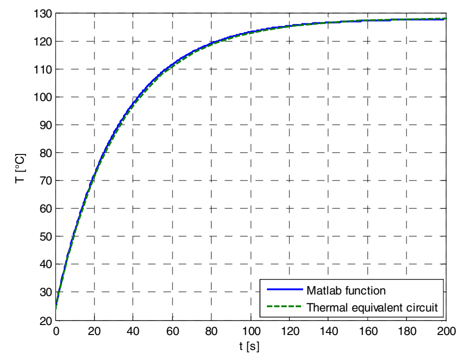

Figure 4. Comparison of pde solution to thermal equivalent circuit

B. Experimental results

The developed models have to be compared to measurement results. In [3] and [8] the temperature of the wire is determined by measuring the voltage drop through the electrical wire with a given current. The current temperature of the wire can be calculated according to equation (14). Figure 6 shows the measurement results for the 0.5 mm cable presented in [3] for different current loadings.

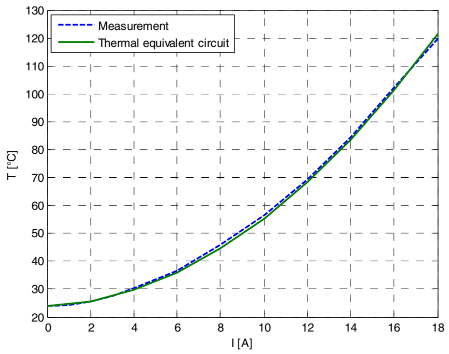

Figure 5. Comparison of temperature from simulation and measurement [3]

Figure 8 compares the transient temperature for a 1.5 mm² wire charged with 35 A.

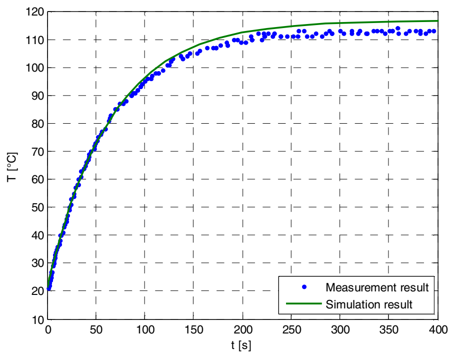

Figure 6. Comparision of the T(t) from simulation and measurement [8]

Additionally to the comparisons with the data from literature, measurements at the University of Dortmund have been made. Therefore the cable to be measured is placed in a conditioning cabinet and the environmental temperature is set. The current is impressed on the cable with a constant current source. The voltage drop is measured with a High Performance Digital Multimeter from Keithley. The used measurement setup is shown in figure 7.

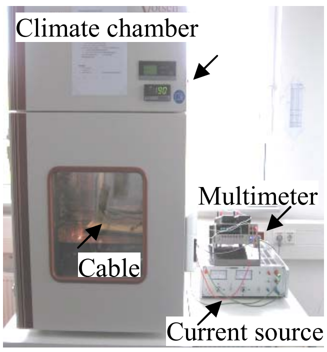

Figure 7. Measurement setup for voltage drop and temperature measurement

The voltage drop and the temperature results for a cable with PVC insulation and a cross section of 0.5 mm² are shown in figure 8 and figure 9.

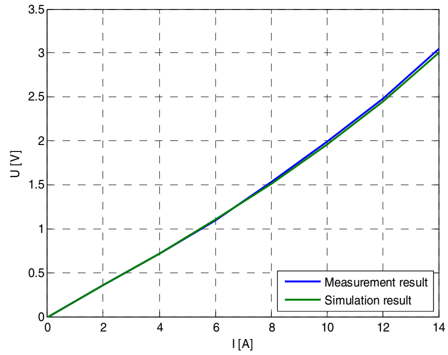

Figure 8. Comparison of voltage drop from simulation and measurement

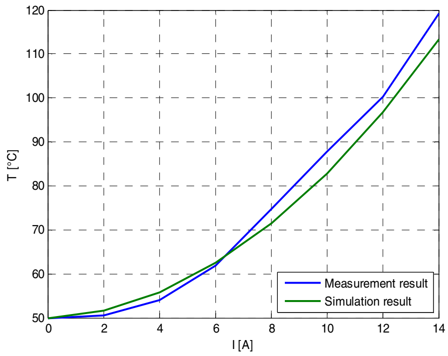

Figure 9. Comparison of temperature from simulation and measurement

IV. TYPICAL CABLE HARNESS INVESTIGATIONS

With the validated cable models various types of investigations can be made. Considering the cable harness, aspects such as the dependency on the ambient temperature and the heating time are important for the dimensioning of the harness.

A. Dependency on ambient temperature

The vehicle can be divided in different temperature zones for example the engine or the passenger compartment. Depending on the ambient temperature the cables have to be selected. The continuous operating temperature for many types of PVC is 105°C. For example a cable with an environmental temperature of 85°C may only be heated 20°C more with the operational current.

Figure 10 shows the steady state temperature of a cable with a 2.5 mm² cross section and PVC insulation. Three different ambient temperatures are investigated (25°C, 50°C and 85°C).

Considering only this effect, the ampacity of a cable is more restricted with increasing environmental temperature. For dimensioning of the cable harness the ambient temperature of the wire has to be determined.

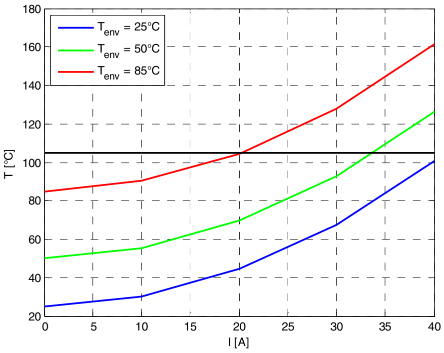

Figure 10. Influence of different ambient temperatures on the cable temperatur

B. *Heating time*

The heating time is the time till the allowed temperature of the cable is reached by a given ambient temperature. In figure 11 the heating time for a 1.0 mm² cable depending on the ambient temperature and the current is shown.

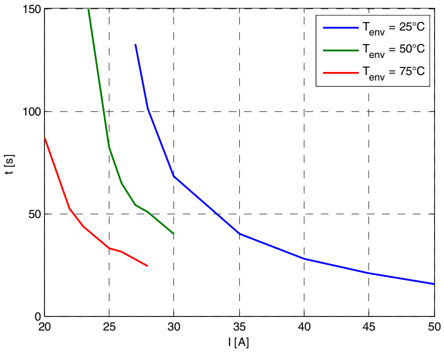

Figure 11. Influence of different ambient temperatures on the cable heating time

The heating time is important for dynamic analysis. Short high current peaks do not destroy the cable because of the inertia of the cable.

V. Validation of Complete On-Board System Model

With the cable models being validated it is now possible to create a cable harness model. To automate the process a tool is developed which automatically generates a simulation model. The information about the wires and the connectors is stored in a so called KBL-file. The format is standardized as STEP AP 212 [4]. The data sets for modeling the whole system were adjusted using the software Harness Studio by EMCoS [9].

A first preprocessor written in Matlab builds a data model from the KBL-file. All the necessary data such as the information about the pins or the mapping of the different parts of the model have been gathered. The second preprocessor creates the simulation model based on the data model. The created simulation models are assigned to the electrical components, the wires, and the contact points. The schema of the data process is shown in figure 12.

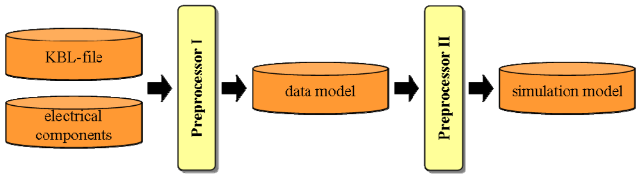

Figure 12. Scheme of data processing

The model can be generated automatically with the presented method. The generator and the battery are modeled as constant voltage sources with internal resistances to limit the current flow. The fuse and the contacts are represented as resistors. The electronic components are modeled as time dependent resistors. The value of the resistor is calculated from measurement results. Because experimental results were available for two dominant Electronic Control Units (ECUs), the other ECUs are modeled as one resistor R_{rest} connected directly to the battery. The current difference was used to estimate the resistance value. In figure 13 the created system model is shown.

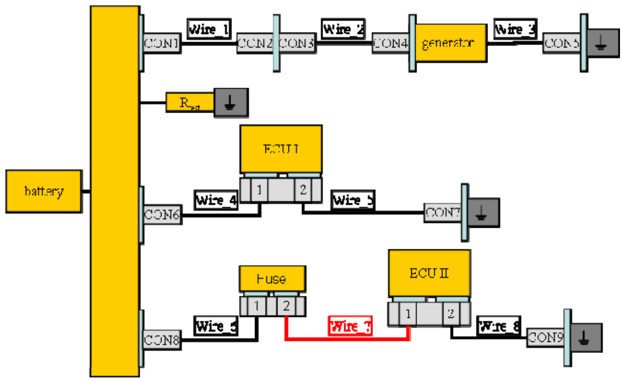

Figure 13. Example for a power supply system

In order to validate the created system a driving maneuver was investigated. The current and voltage at several points were measured. The cable parameters correspond to the actual vehicle parameters. Especially the dominant ECU II and wire 7 shall be investigated. Wire 7 has a conductor size of 4 mm² and the insulation thickness is 0.7 mm.

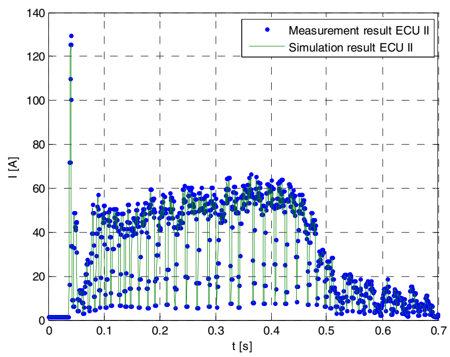

Figure 14. Comparision of measured and modeled current for ECU II

In figure 14 the simulated and the measured currents through ECU II are presented while figure 15 compares the voltages. For the time of the maneuver ECU II consumes a current of 130 ampere. The maximal current through wire 7 exists only for one millisecond. After the maneuver the current needs about five milliseconds to return to the initial value. The voltage drops about 1.2 volt.

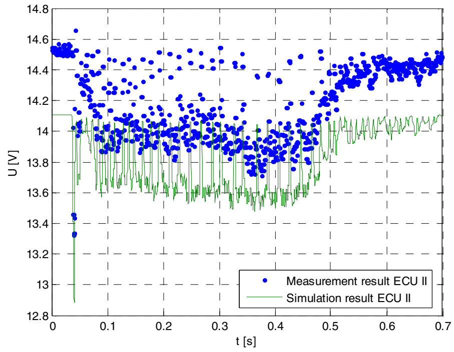

Figure 15. Comparison of measured and modeled voltage for ECU II

Because of the long heating time of the temperature the effect of the heating in the cable is small due to the short period.

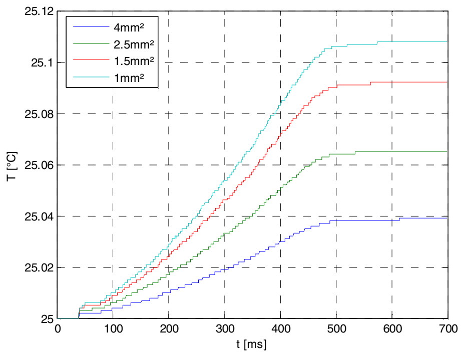

Figure 16. Parameter varation of conductor size of wire 7

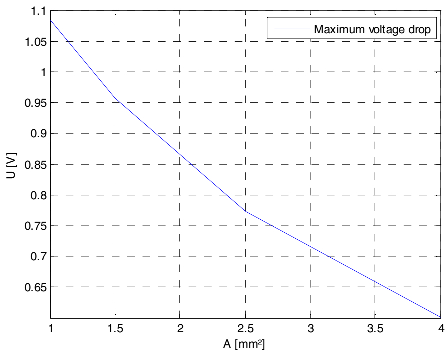

Figure 17. Maximum voltage drop depending on the conductor size

To obtain an optimized harness several loadings have to be investigated. In this paper the optimization process exemplarily is shown for only one maneuver and an environmental temperature of 25°C. Different conductor sizes are used for wire 7. The results of this parameter variation are shown in figure 16 and figure 17.

VI. Conclusion

Different ways of modeling a cable were presented in this paper. It was shown that all investigated methods lead to the same results. Comparisons with the experimental data validate the introduced models. Therefore the models can be used in a power supply system model to estimate the diameter of a conductor and optimize the cable harness.

A method to simulate the power supply system was described. The simulation shows suitable results which have been validated by measurements. The presented approach gives car manufacturers the possibility to run worst-case examinations on the harness and to optimize the cable conductor sizes. The optimization process has to be performed for several driving maneuvers and environmental temperatures to obtain an optimized harness.

For more accurate results the simulation models have to be modified in order to take the real cable environment into account. The assumptions for power consumer and source models which have been made need to be validated in further studies.

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