Simulation-Based Optimization of Multi Voltage Automotive Power Supply Systems

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***Abstract*—Complex multi-voltage automotive power supply systems are difficult to optimize. In this paper a simulation-based method to optimize multi voltage power supply systems is presented. With an electrical-thermal wire model the ampacity and the voltage drop of a cable can be determined. With these criteria cables of the power supply system can be dimensioned. By extending the electric-thermal models with functions defining costs, weight and space of the wires and DC/DC-converter models evaluation and optimization of multi-voltage vehicle systems is possible.**

***Keywords*—multi voltage power supply, cable, simulation, optimization, ampacity**

I. Introduction

The power supply system has a big impact on the electrical functions and also on the manufacturing cost of the vehicle. The electrification of the drive train and the steady increase of electrical components cause a more complex power supply system. To minimize the cost, weight and space efficient optimization methods are needed. Based on the complex topology and the high amount of variable configurations the usage of simulation methods to determine the optimum becomes more important. The simulation has to fulfill different requirements. Not only the electrical properties such as the dynamic voltage drop over the cable have to be regarded but also the thermal properties such as the temperature of the wire have to be determined.

For a simulation of the entire power supply system, models for all components such as battery, alternator, electrical components, contacts, fuses and cables are necessary. New voltage levels should be considered in the simulation. In addition to the standard 12 V power supply system, higher voltages (for example 48 V and more) for high power components and lower voltages (for example 5 V) for electrical components can be useful. To integrate the different voltage levels dc/dc-converters are required. In this paper different investigations on the design and optimization of multi voltage power supply systems are done.

II. Simulation Models

A. Cable Models

In [1] the calculation of the radial temperature distribution for automotive cables was shown. In addition, this paper extends this method to model the axial temperature distribution for automotive cables. To model this behavior the analogy between the electrical and thermal physical behavior is used. The heat flow can be considered as equivalent to an electrical current and the temperature as equivalent to the voltage. Thermal resistances model the heat transfer capability of a structure and thermal capacitances represent the thermal energy storage capability [2].

To build a thermal circuit model for the axial and radial temperature distribution, analogies of the transmission line theory can be used [3]. The equivalent thermal circuit is shown in figure 1. For a short cable segment the important elements are the thermal axial resistance R_{th}’, the thermal capacitance C_{th}’, and the dissipated power P_i’.

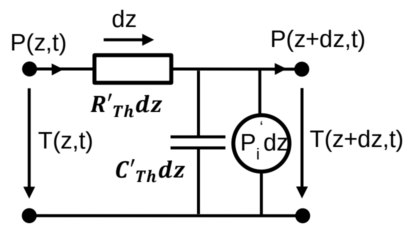

Fig. 1. Equivalent thermal circuit for a short cable segment [3]

As the resistance and the capacitance only depend on material and geometry, the power P_i’ has to consider the power sum from the electrical current, the power dissipated through convection, radiation and the power conduction over the different parts of the cable.

The resulting equation for the temperature T can be calculated for a small part dz of the wire

$$\frac{\partial T(z,t)}{\partial t} = \frac{1}{C'_{th}}\left(\frac{\partial^2 T(z,t)}{\partial^2 z}\frac{1}{R'_{th}} + P_i'\right) \quad (1)$$

The power P_i’ can be computed with [1]:

$$P_i' = I^2\frac{\rho l}{A}\left(1+\alpha_T\left(T-T_{ref}\right)\right) - \left[\frac{\lambda_i \alpha_{ges} 2\pi l r_i}{\alpha_{ges} r_i \ln\left(\frac{r_i}{r_l}\right) + \lambda_i}\right]\left(T-T_{env}\right) \quad (2)$$

To solve the partial differential equation above the spatial component of the equation needs to be discretized by lumped elements. The resulting differential equation can be finally solved using Matlab Simscape.

TABLE I. LIST OF USED SYMBOLS IN THIS PAPER

I	Current through the wire	[A]
ρ	Specific resistance of wire	[Ωm]
A	Cross section of wire	[m²]
r	Radius of wire r_l or insulation r_i	[m]
α_T	Linear temperature coefficient	[1/K]
T_{ref}	Reference temperature for ρ	[K]
λ_i	Heat conductivity	[W/Km]
α_{ges}	Heat transfer coefficient	[W/Km²]

B. Electronic Component Models

The electronic components are modeled as controlled current sources with rated currents and minimum voltage requirements. To ensure the compliance with the threshold the voltage is monitored.

C. DC/DC- Converter Models

The DC/DC-Converters are modeled as two-ports. For the evaluation of the power supply network the power loss has to be considered. Therefore the efficiency of the DC/DC-Converter is integrated in the model. Fig. 2 shows the model with the basic equations.

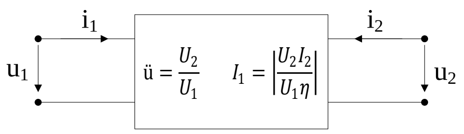

Fig. 2. Simple behavioral model for DC/DC-Converter

The efficiency of the converter is modeled depending on the nominal power P_{nom} of the converter, based on values given in [4] and [5].

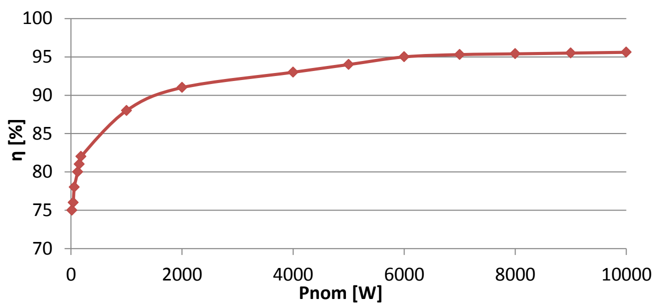

Fig. 3. Efficiency for DC/DC converter depending on the nominal power

III. STRUCTURE OF POWER SUPPLY SYSTEMS

In this investigation different types of power supply systems are regarded. For the structure of the power supply systems with multi voltage levels different design approaches exist. One option is to have each converter connected directly to the alternator or for electrical vehicles to the battery. Another is to have one dc/dc-converter and the other voltages are directly converted from there, see Fig. 4 [4]. For three voltage levels the optimized design approach considering cost, weight and power loss has to be determined.

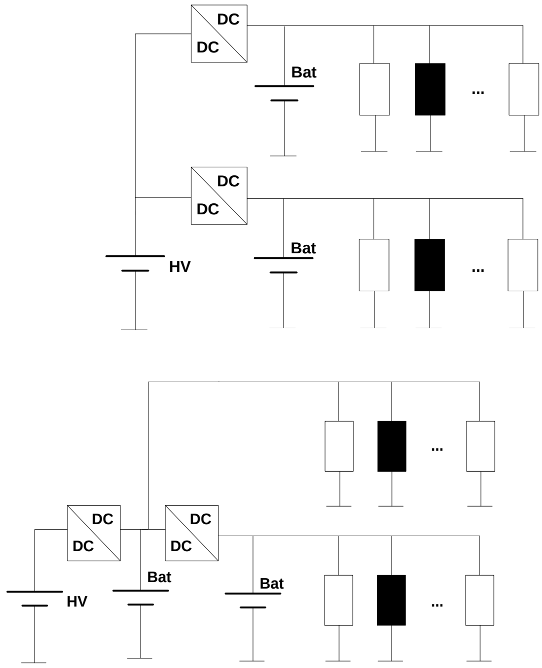

Fig. 4. Different achitectures

Additionally due to the limited space in the vehicle only a certain amount of installation spaces for the dc/dc-converters is available. In Fig. 5 the main principle of the limited installation spaces is visualized. In this example only six places for the dc/dc-converters exist. Each installation space has a predefined distance to a component or the next installation places $l_{n,m}$.

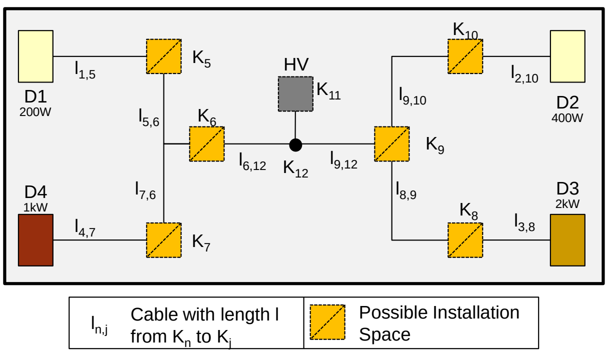

Fig. 5. Principle of installation spaces

To find the optimal structure for the power supply system the available options have to be taken into account. With the possible choices regarding the architecture and the topology, finding the optimized power supply system is a complex process.

IV. Optimization of Power Supply System

To optimize a power supply system rating functions have to be developed. The factors for the evaluation of the different architectures and topologies are cost, weight and power loss. For cables and converters rating functions are developed and used for the optimization process.

A. *Rating Functions*

1) Cables

Weight and cost of cables can be determined using the density of the material. The insulation of a wire can be neglected due to the small amount of weight in comparison to the conductor (ρ_{CU}: 8.92 g/cm³, ρ_{PVC}: 1.4 g/cm³) [5]. With the density and the cross section the weight of the cable can be calculated. To integrate the weight of the insulation and the connectors 50 % of the conductor weight is additionally added. Fig. 6 shows the weight of a cable per meter, valid for cables with cross sections from 1 mm² to 120 mm².

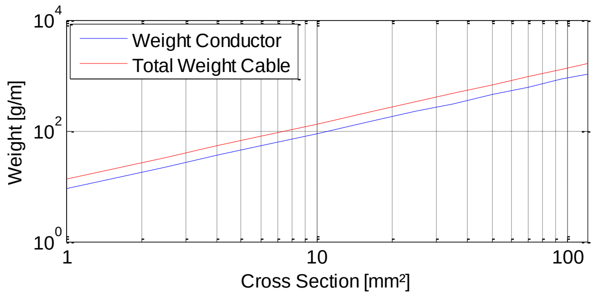

Fig. 6. Weight function over Cross-Section for the cables

The costs of a cable are calculated with the weight of the cable. As price for copper 5.85 €/kg (February 2013) is assumed here. The cost of the insulation and the fabrication cost are considered with a correction factor of 2. The costs per meter are shown in Fig. 7 and are only valid for cross sections from 1 mm² to 120 mm².

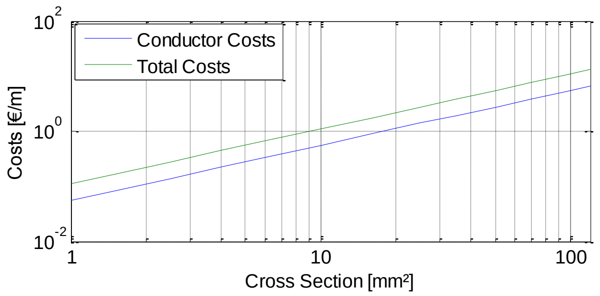

Fig. 7. Cost function over Cross-Section for the cables

2) DC/DC-Converters

The calculation of the converter weight is done with the values given from different datasheets. The weight can be calculated depending on the nominal power. Fig. 8 shows the values given from several datasheets and the fitted quadratic function.

$$G(P_{nom})_W = -2\cdot 10^{-6}\cdot {P_{nom}}^2 + 0{,}37\cdot P_{nom} + 1459 \quad (3)$$

The calculation of the converter cost is done with the calculation of the different elements of a converter. For the transistors and diodes the cost are taken from datasheets. Additionally the package, cooling and other element costs are added. The resulting converter cost is shown in Fig. 9. The given evaluation functions for the converters are only valid for a nominal power range from 0.1 kW to 50 kW.

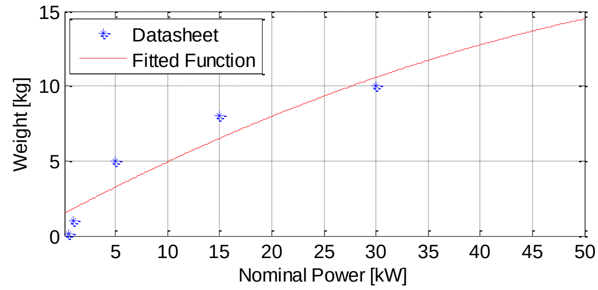

Fig. 8. Weight for DC/DC converter depending on the nominal power

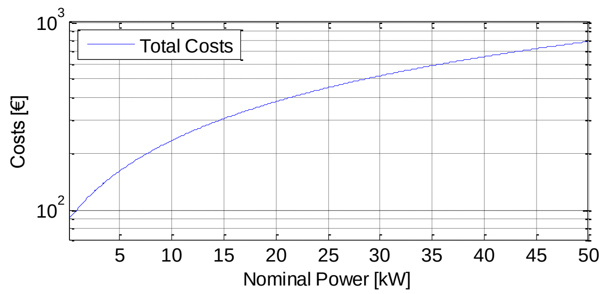

Fig. 9. Cost for DC/DC converter depending on the nominal power

B. *Optimization Process for cables*

For finding the optimal topology the cables have to be optimized for each simulation step. With the model given in chapter II.A the temperature and the voltage drop over the wire can be determined. The optimal cross section for each cable is calculated. For the simulation process only the standardized cross sections for automotive applications can be chosen. The optimization process is shown in Fig. 10.

The developed algorithm compares the calculated temperature T with the maximal allowed temperature T_{max}. Is the calculated temperature lower than the maximal allowed temperature, the voltage at the component is checked. Depending on the voltage the next higher A_{n+1} or lower A_{n-1} cross section is selected. This process is repeated until the optimal cross section is found.

With the developed algorithm for the optimized cross section and the evaluation functions, an optimization of the multi voltage power supply system can be executed. The flow chart of the optimization process is shown in Fig. 11.

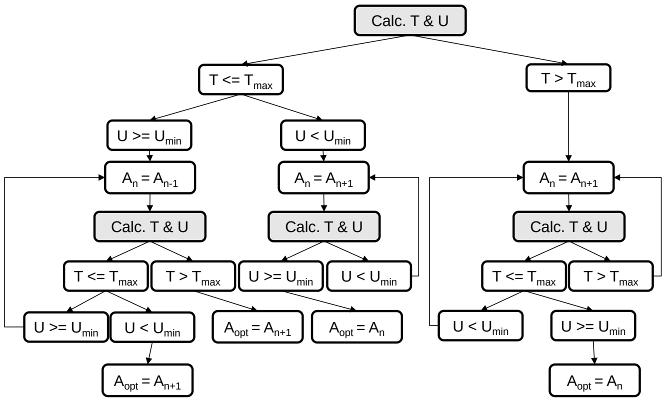

Fig. 10. Optimization process for cross sections

After defining the components for the power supply system the possible architectures and topologies regarding the possible installation spaces have to be determined. Every configuration is simulated and the cross section for every cable is optimized. The total cost and weight for every configuration are calculated and compared to the rest. With this method the optimal configuration for any given problem can be found.

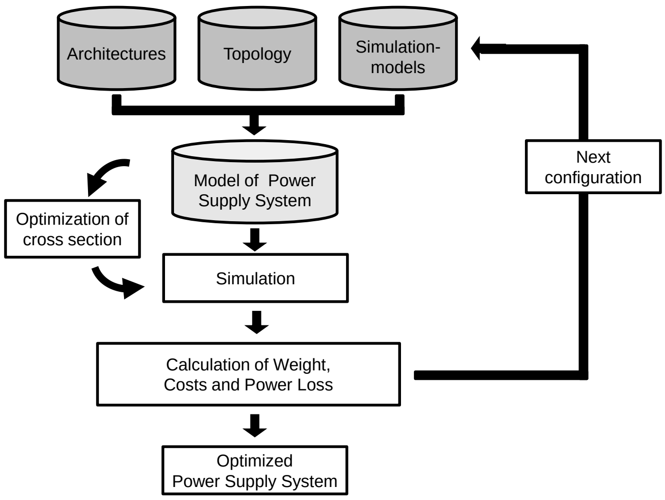

Fig. 11. Flow chart of optimization process

V. Results

To verify the developed method two multi voltage automotive power supply systems are analyzed.

A. Evaluation of Power Supply System

The first system is shown in Fig. 12. The power supply network consists of four components and three converters. Two electronic components (*D1*, *D2*) are connected to the 5 V power supply system, one electronic component (*D3*) to the 12 V power supply and one (*D4*) to the 48 V power supply. For this configuration all possible architectures, centralized and decentralized, are compared.

Starting with the given architectures, for every configuration, the possible topologies are compared. The evaluation of the configurations is done with cost and weight. The topologies consider the routing options and the installation spaces. With the predefined intersections the length of the wires are given and the optimal cross section for each cable has to be determined. The length of the wires between the installation spaces is assumed to be 1.5 m.

The possible installation spaces for this power supply system are shown in Fig. 5.

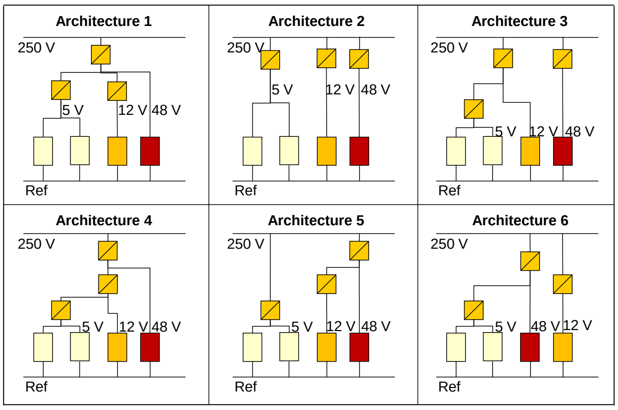

Fig. 12. Architecture of power supply system

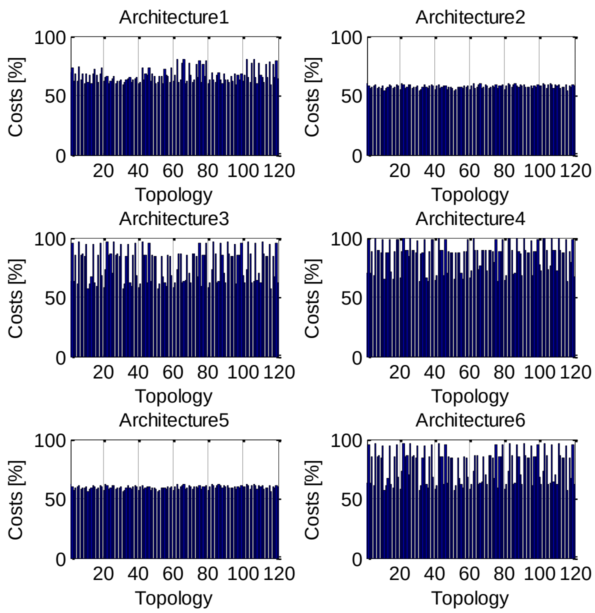

Fig. 13. Results for the different architectures and topologies

Fig. 13 shows the results of the costs of the simulation for the different architectures and the topologies. The optimal architecture is number 2. The optimal topology for this architecture is number 51. In this topology the 48 V converter is placed at the installation space K_7, the 12 V converter at K_8 and the 5 V converter at K_9. The results show that the best alternative to place the converter is close to the main consumer components. For the 5 V supply system the components are placed on both sides of the power source therefore the converter has to be placed in the middle.

B. Possible Investigation on Power Supply Systems

The first investigations show that the best option is to place the converter close to the component with the highest power requirements. Therefore the second multi voltage power supply system, shown in Fig. 14, has eight components with different power levels. This network consists of only two converters. To create a more realistic scenario for the converters only certain power levels are selectable. The used components have two contacts, one for the 48 V power supply voltage and one for the 5 V logic voltage. The length of the wires between the installation spaces is always 1.5 m.

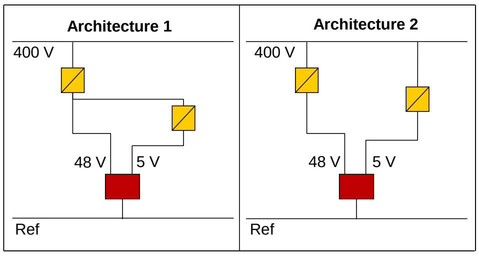

Fig. 14. Architecture of power supply system

The topology with the possible installation spaces for the dc/dc-converters is shown in Fig. 15. In total ten installation spaces can be chosen for the converters. For the given data the optimized installation space for the 48 V converter is K_{13} and for the 5 V converter is K_{14} using architecture number two.

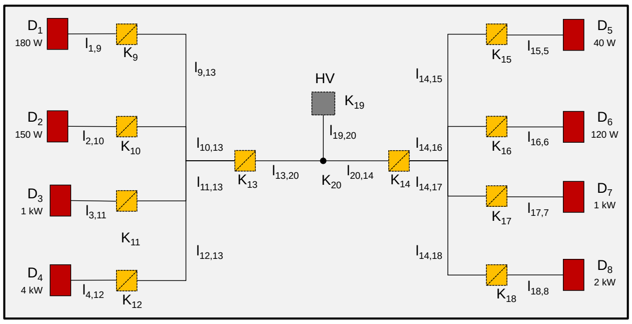

Fig. 15. Installation spaces (K_{xx})

In this supply network one component (D4) with 4 kW is on the left side and one component (D8) with 2 kW is on the opposite side of the vehicle. To investigate the influence of the size of the component D8 the nominal power is varied. Additionally the length of the wire $l_{12,13}$ is changed.

Fig. 16 shows the cost of the optimized configuration for the different length and nominal power values. With increasing power or length the cost of the network increases. The influence of the size of the converter is bigger than the influence of the wire length.

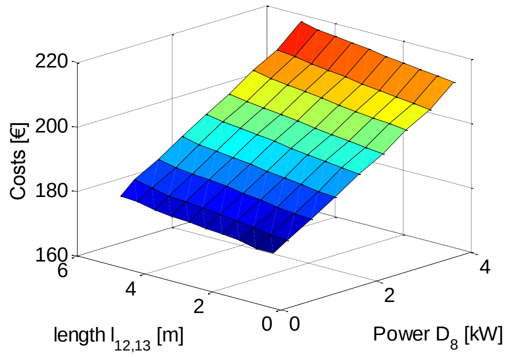

Fig. 16. Cost depending on the power of D8 and the wire length $l_{12,13}$

In Fig. 17 the power loss is shown. In comparison to the cost the distribution is cascaded. This results from the changing of the installation space of the converter and the different power levels. The different power levels require other cross sections and therefore the power loss varies depending on the selected parameters. Fig. 18 shows the installation space for the 48 V converter.

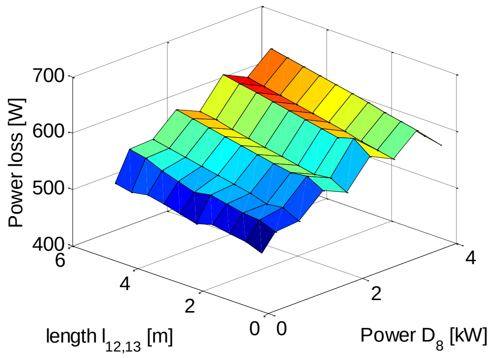

Fig. 17. Power loss depending on the power of D8 and the wire length $l_{12,13}$

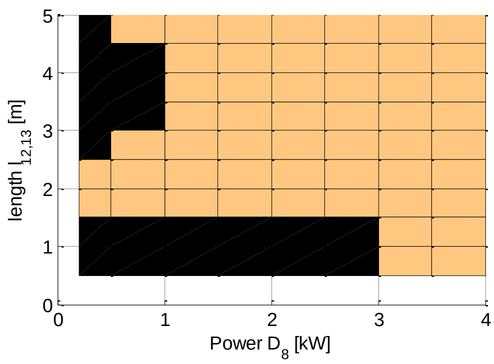

Fig. 18. Installation space for 48 V-converter (black: K_{12}; orange: K_{13})

Increasing the power of the component D8 results in a change of the installation space for the 48 V converter. Is the needed power larger than 3 kW the installations space changes from K_{12} to K_{13}. For smaller powers the installations space changes depending on the length of the wire.

Depending on the installation space of the 48 V converter the 5 V converter changes the installation space. Fig. 19 shows the installation spaces.

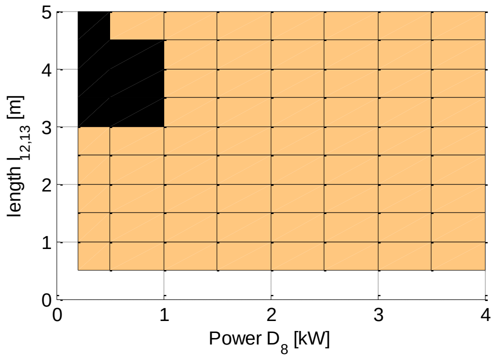

Fig. 19. Installation space for 5 V-converter (black: K_{13}; orange: K_{14})

C. *Optimiziation of complex automotive power supply system*

In Fig 20 a complex automotive multi voltage power supply system is shown. The network consists of 31 components varying in maximum power consumption from 40 W (e.g. brake light) to 4000 W (e.g. air conditioning compressor). All components consist of two voltage ports one for the supply voltage (either 12 V or 48 V) and one for the logic part (5 V). For this configuration all possible architectures are calculated. Comparing the worst-case and the best-case solution show potential savings for the cost of 8 % and for the weight and power loss of almost 20 % (Fig. 21).

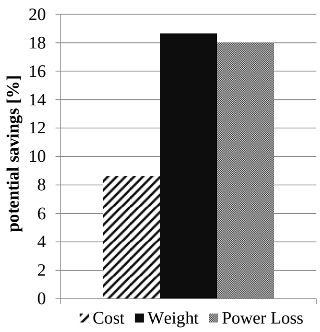

Fig. 21. Potential savings of power supply system

I. Conclusion

Accurate and fast electro-thermal models for the cable harness of automobiles were developed and extended with properties like weight, space consumption, or costs. With the models complex automotive multi voltage power supply systems can be rated.

Assuming a predefined number of converters different architectures are possible. Depending on the available installation spaces the best topology must be found. This problem was solved in this paper with simulation. A method for optimizing the complete system performance is presented and applied to example configurations. It could be shown that simulation, combined with optimization methods, can handle the complexity of future automotive multi-voltage supply systems and provide powerful, efficient, and economic solutions.

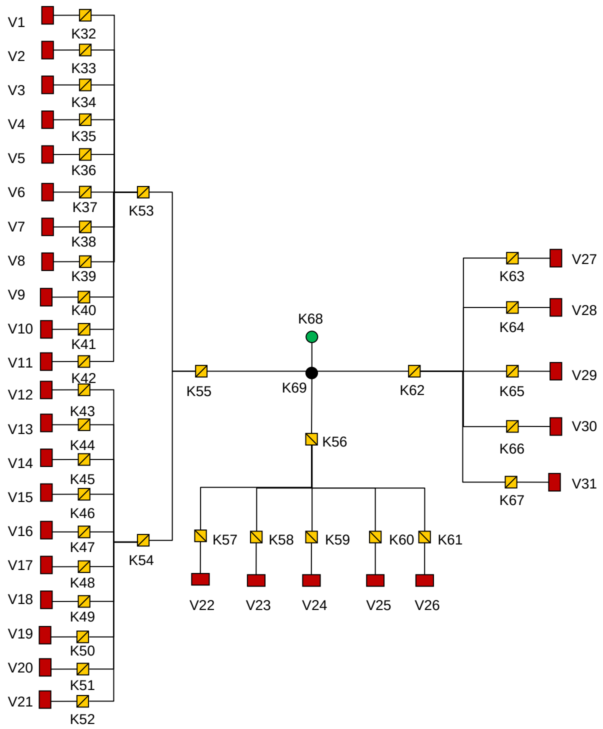

Fig. 20. Architecture of power supply system

References

[1] M. Diebig, S. Frei, H. Reitinger and C. Ullrich, "Modeling of the automotive power supply network with VHDL-AMS," in *Vehicle Power and Propulsion Conference (VPPC)*, Lille, 2010.

[2] G. Anders, Rating of electric power cables in unfavorable thermal environment, Wiley & Sons, 2005.

[3] C. Paul, Analysis of multiconductor transmission lines, New Jersey: Wiley & Sons, 2008.

[4] T. Power, "http://www.tracopower.com/," [Online]. [Accessed September 2012].

[5] P. One, "http://www.power-one.com," [Online]. [Accessed September 2012].

[6] P. Hartnett, P. Miller and M. O"Hara, "42 V Powernet enabling technologies: overview," in *Passenger Car Electrical Architecture (Ref. No. 2000/088) IEE Seminar*, 2000.

[7] N. Greenwood and A. Earnshaw, Chemistry of the Elements, Butterworth-Heinemann Ltd, 1997.