Optimizing Multi-Voltage Automotive Power Supply Systems Using Electro-Thermal Simulation

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Abstract

Due to the ongoing rise of the number of electronic components and the electrification of the powertrain the importance of an optimized cable harness grows. The cable harness has a great influence on electric functions, weight, needed installation space and costs. To gain an optimized power supply system with minimal costs and at the same time achieving full functionality, new methods have to be developed. The virtual analysis of the cable harness in early stages of the development process is necessary. Not only is the detection of problems required but also new techniques and architectures shall be investigated and optimized. Considering electrical vehicles, one of the new ideas are multi-voltage power supply systems. Additional voltage levels, for example $48\,V$ for medium power consumers or $5\,V$ for logic components, can be investigated and evaluated with simulation. An optimized architecture can be found by using optimization algorithms.

In this paper a method for virtual investigation and optimization of multi-voltage power supply system is presented. System simulation models for all components such as converters or wires were developed. Not only has the electrical behavior to be considered but also the ampacity of the cables. Therefore thermal-electrical models are inevitable for the simulation. The parameters necessary for the optimization are the voltage drop, dissipation loss, temperature, and also costs and weight of the cable harness, making the problem highly complex. The proposed method analyses the different architectures and returns an optimized system.

Kurzfassung

Bedingt durch den stetigen Anstieg der Anzahl der elektrischen Komponenten im Fahrzeug und der Elektrifizierung des Antriebsstrangs gewinnt ein optimierter Kabelbaum an immer mehr Bedeutung. Die Verkabelung hat einen großen Einfluss auf die elektrischen Funktionen, das Gewicht, den benötigten Einbauraum und die Kosten. Um einen optimierten Kabelbaum mit minimalen Kosten unter gleichzeitiger Berücksichtigung der elektrischen Funktionen zu bekommen, müssen neue Methoden entwickelt werden. Die virtuelle Analyse des Bordnetzes im frühen Stadium des Entwicklungsprozesses ist dabei notwendig. Nicht nur die frühzeitige Fehlererkennung ist damit möglich, auch können neue Technologien und Architekturen untersucht und optimiert werden. Nicht nur bei Elektrofahrzeugen werden Ideen wie Mehrspannungsbordnetze diskutiert. Zusätzliche Spannungsebenen, wie beispielsweise $48\,V$ für Hochleistungsverbraucher oder auch $5\,V$ für die Logikkomponenten, müssen untersucht und bewertet werden. Hierfür ist die Simulation ein notwendiges Hilfsmittel. Aufgrund der hohen Parametervielfalt und Problemkomplexität können Optimierungsalgorithmen verwendet werden.

Eine neue Methode zur virtuellen Untersuchung und Optimierung von Mehrspannungsbordnetzen wurde entwickelt. Um die Simulation zu ermöglichen, müssen Modelle für alle Komponenten, wie zum Beispiel Wandler und Kabel erstellt werden. Neben dem elektrischen Verhalten, wie dem Spannungsabfall über den Leitungen, muss auch die Strombelastbarkeit der Leitungen untersucht werden. Daher sind thermo-elektrische Modell notwendig für die Simulation der Mehrspannungsbordnetze. Die für die Optimierung notwendigen Parameter sind der Spannungsabfall, die Verlustleistung, die Temperatur und ebenso Kosten und Gewicht der Variante. Unter Berücksichtigung dieser Parameter wird deutlich, dass es sich um ein komplexes Problem handelt. Die vorgeschlagene Methode analysiert verschiedene Topologien und berechnet und bewertet die Einsparpotentiale.

1. Introduction

The standard architecture for electric power supply systems in a conventional vehicle consists of a 12 V battery, an alternator and the components. Due to the ongoing increase of the power demand of electrical components, the necessary high reliability, and the electrification of the power train, this architecture reaches its limits. Hence, new concepts and methods are necessary. One option is the usage of multi-voltage power supply systems with higher voltages.

Already one big aspect is the application of $48\,V$ as discussed since 2010 intensively. Due to the fact that currents of $200\,A$ can be defined as difficult to handle, while $300\,A$ are already critical. Considering these options, the power limits depending on the voltage level can be defined as $3\,kW$ for $12\,V$ and $12\,kW$ for $48\,V$, see Fig. 1. [1]

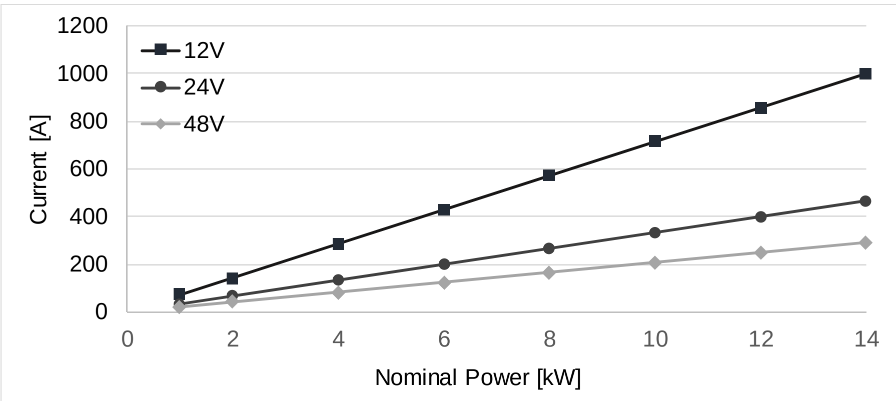

Fig. 1: Power limit due to current for different voltage levels [1]

Additionally, the $12\,V$ level cannot be neglected because a lot of the consumers are available and optimized for this level. As an extra option, a $5\,V$ level could be integrated to focus on the logic components. Normally this voltage is converted directly in the control unit of the components. Hence, the idea is to use one or more centralized converters for all components. For the resulting power supply system different approaches are possible, for example a simple system consisting of only of the battery and a converter for the other voltage levels or a complex system with several batteries and converters. Typical consumers for the $48\,V$ level are the heating functions in the vehicle [2]. Fig. 2 shows two examples for the layout of a multi-voltage power supply system for an electrical vehicle.

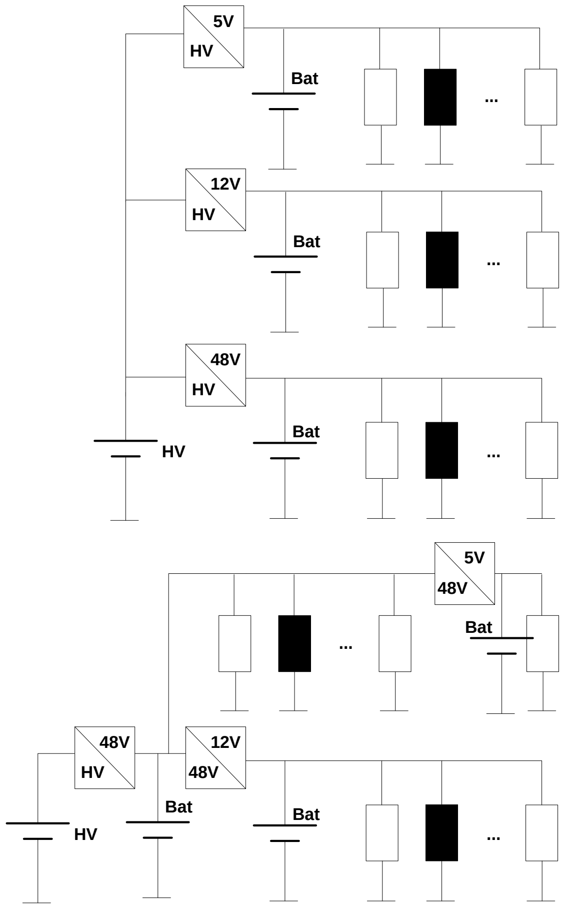

Fig. 2: Possible layout of multi-voltage Power Supply Systems

2. Power Supply Systems

To find the optimal architecture of a power supply system different design rules have to be applied in a first step, the design rules will define a set of alternative architectures that have to be tested. Considering four voltage levels (400 V, 48 V, 12 V, and 5 V), six architectures with single central converters are possible (Fig. 3). Depending on the architecture the necessary nominal power for each converter changes. For each option the cost, weight and power loss have to be determined. The architectures shown in Fig. 3 diversify from the alternative, that all converters are directly connected to the high voltage level to alternative that all converters are in series.

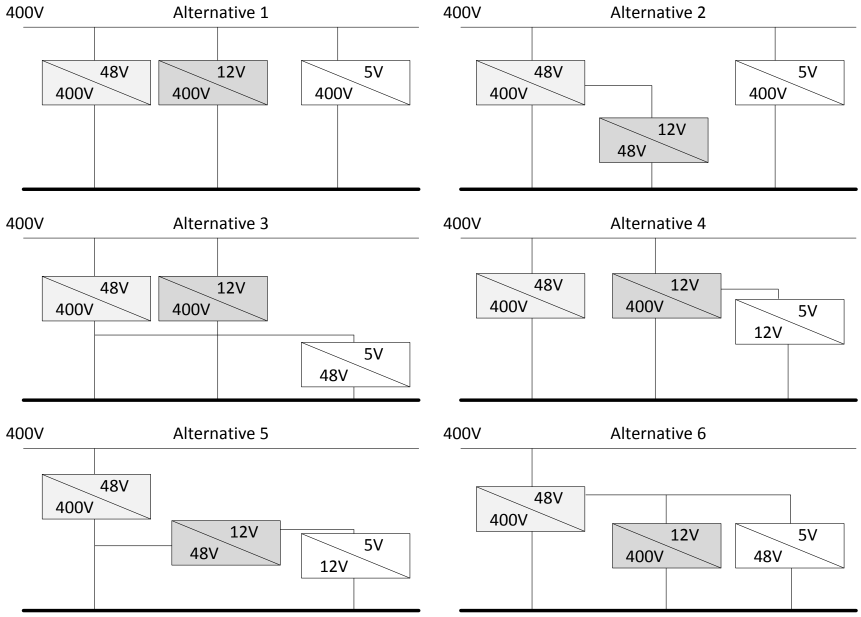

Fig. 3: Possible architectures for 4 voltage levels, with single central down-converters

Due to the limited installation space in the car only a certain amount of installation spaces for the three converters is feasible. The schematic of a possible power supply network with some predefined installation spaces is shown in Fig. 4. A certain amount of components Cn has to be supplied from the battery. Only predefined installations spaces Km are available. The distances between components and installation spaces is specified with the cable lengths $l_{Cn,Km}$.

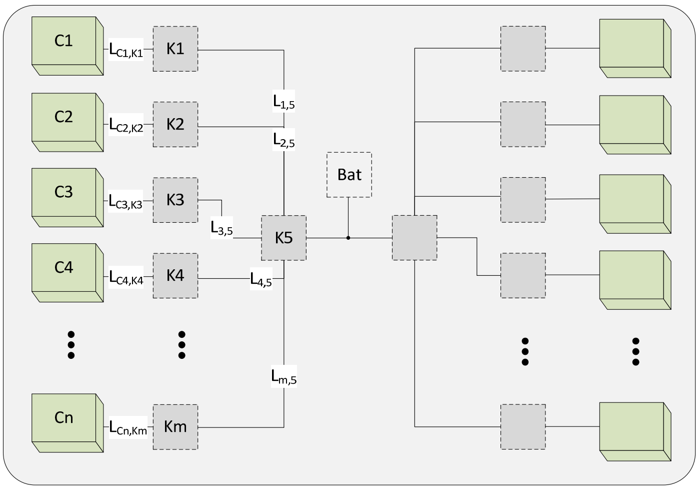

Fig. 4: Schematic for installation spaces

To find the optimal structure for the complex problem means taking all available options into account. For every possible option the optimal cross section for each wire has to be determined. With the numerous possible choices, regarding the number of architectures v and the installation spaces K, finding the optimized power supply system is a complex process. The possible combinations N can be calculated using the number of converters c, the possible cross sections cs and the number of wires w. For the cross sections only standardized values should be used, which leads to fifteen possible cross sections.

$$N = v \cdot \frac{K!}{(K! - c!)} \cdot cs^w \quad (1)$$

For example, a power supply system with two converters, ten installations spaces, nine wires and fifteen possible cross sections leads to 70 billion possible combinations.

3. Simulation Models

3.1. Cables

Modeling the thermal behavior using electrical descriptions

The ampacity of a cable and the power loss have to be determined. Therefore a cable model needs to be a physical model including both temperature and voltage drop calculation. Hence the analogy between the heat transfer and the electrical behavior can be used to derive a thermal model. [3]

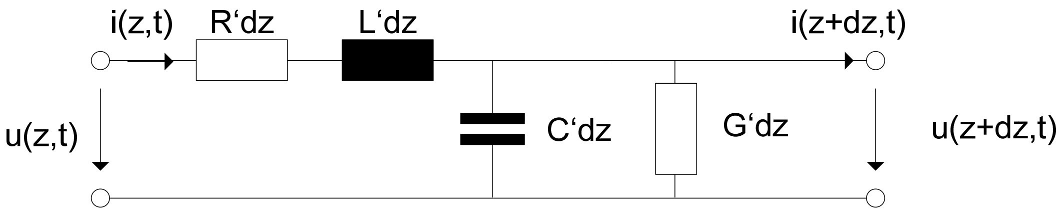

Fig. 5: Electric equivalent circuit of a transmission line

Using constant per unit length parameters, the derivation of the differential equation, describing the equivalent circuit shown in Fig. 5, can be done as following. Using Kirchhoff’s law the equation for the voltage is

$$u(z,t) = R' dz\, i(z,t) + L' dz \frac{\partial i(z,t)}{\partial t} + u(z+dz,t). \quad (2)$$

With Kirchhoff’s current law one gets the following equation:

$$i(z,t) = G' dz\, u(z+dz,t) + C' dz \frac{\partial u(z+dz,t)}{\partial t} + i(z+dz,t) \quad (3)$$

Substituting the differential quotient for voltage with

$$\frac{\partial u(z,t)}{\partial z} = \frac{u(z+dz,t) - u(z,t)}{dz} \quad (4)$$

in equation (2) and the differential quotient for the current in (3) leads to

$$\frac{\partial u(z,t)}{\partial z} = -R' i(z,t) - L' \frac{\partial i(z,t)}{\partial t} \quad (5)$$

$$\frac{\partial i(z,t)}{\partial z} = -G'u(z,t) - C'\frac{\partial u(z,t)}{\partial t}. \qquad (6)$$

Decoupling both equation results in the following partial differential equation:

$$\frac{\delta^2 u(z,t)}{\delta z^2} = R'G'u(z,t) + (R'C' + L'G')\frac{\delta u(z,t)}{\delta t} + L'C'\frac{\delta^2 u(z,t)}{\delta t^2} \qquad (7)$$

The inductance L' and the conductance G' do not exist in the thermal area. Therefore the equivalent circuit and equation (7) simplify to

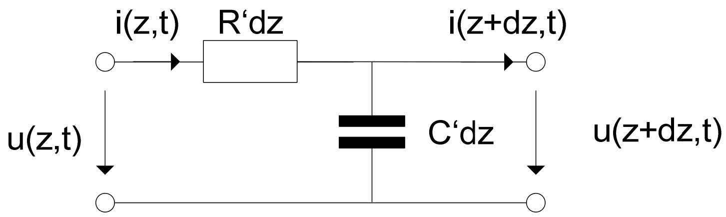

Fig. 6: Simplified electric equivalent circuit of a RC-transmission line

$$\frac{\delta^2 u(z,t)}{\delta z^2} = R'C'\frac{\delta u(z,t)}{\delta t} \qquad (8)$$

The solution of the differential equation can be found for example with using Laplace Transformation. For further details on solving the differential equation see [4].
For standard automotive applications most wires consists of the inner conductor and the insulation. Considering both, axial and radial heat conduction the simplified equivalent circuit is composed of the thermal resistance for axial heat transfer R_{ax} in the conductor and for the radial heat transfer in the insulation R_{ins}.

$$R_{ins} = \frac{1}{2\pi\lambda}\ln\frac{d_i}{d_l} \qquad (9)$$
$$R_{ax} = \frac{1}{\lambda A}$$

The storage behavior is modeled with the thermal capacitance for the conductor C_{con} and the insulation C_{ins}. The thermal capacity cannot be seen as a linear function of the gauge of the insulation. Hence, a factor has to be used to model the total heat stored in the insulation. The assumption is a steady state logarithmic distribution. Depending on short or long duration transients the coefficients can be calculated. For normal vehicle applications the short duration coefficient can be used, as seen in equation (10) [5].

$$p = \frac{1}{\ln\frac{d_i}{d_c}} - \frac{1}{\frac{d_i}{d_c} - 1} \qquad (10)$$

The thermal capacities can then be derived with the specific heat capacity and the diameter of the conductor and insulation as:

$$C'_{ins1} = \frac{\pi}{4}(d_i d_l - d_l^2) \cdot c_i$$
$$C'_{ins2} = \frac{\pi}{4}(d_i^2 - d_l d_i) \cdot c_i \quad (11)$$

Regarding those components the resulting thermal equivalent circuit can be described as shown in Fig. 7.

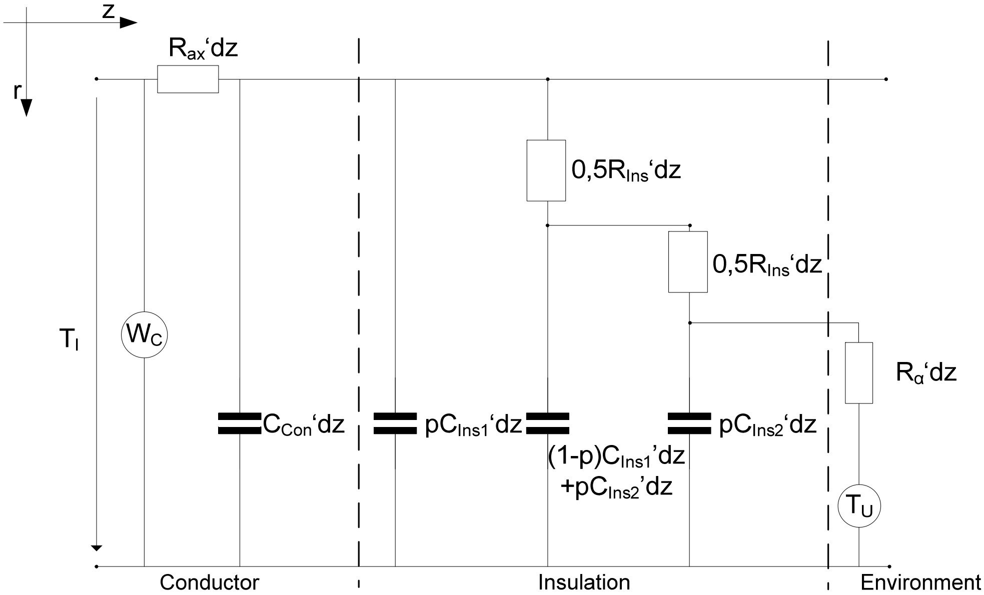

Fig. 7: Thermal equivalent circuit of a simple isolated cable for axial and radial heat conduction

The source W_c of the thermal equivalent circuit is the heat generated in the conductor due to the electrical current I. Depending on the electrical resistance R_0 the heat source can be calculated. Due to the fact, that the expected temperature difference between the conductor and the reference temperature is small, only a linear dependency is used here.

$$W_C = I^2 \frac{R_0}{A}\left(1 + \alpha\left(T - T_{ref}\right)\right) \quad (12)$$

In comparison to the equivalent circuit model, the partial differential equation resulting from the Fourier heat equation in cylinder coordinates for the wire is [6]

$$\frac{\delta T}{\delta t} = a\left(\frac{\delta^2 T}{\delta r^2} + \frac{1}{r}\frac{\delta T}{\delta r} + \frac{\delta^2 T}{\delta z^2}\right) + \frac{\dot{W}_C}{c\rho} \quad (13)$$

Under consideration of the initial and boundary conditions, the partial differential equation can be solved using numerical methods.
Matching the calculated temperature with both models for a 4 mm² cable with silicone insulation for different currents shows that the results are very similar (see Fig. 8).

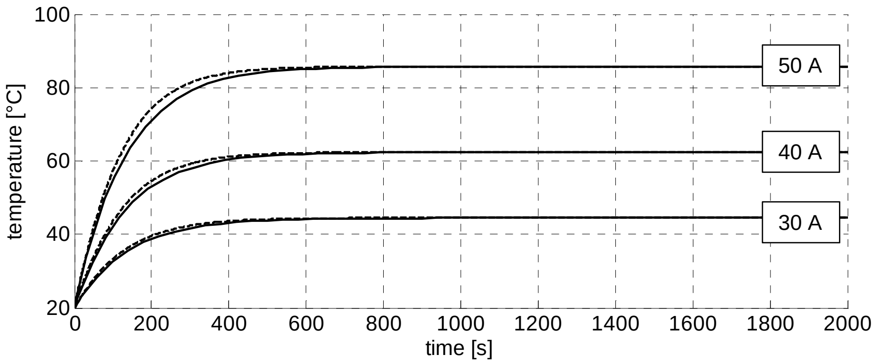

Fig. 8: Comparison of calculated temperature for both approaches of a 4 mm² wire with silicone insulation (dotted line for equivalent circuit model, solid line for Fourier partial differential equation)

The difference during the temperature rise is due to the separation of the capacities in the equivalent circuit.

3.2. DC/DC-Converters

For the DC/DC-converter, a simplified two-port model is used (Fig. 9). The nominal power, the voltage and the efficiency of the converter are defined.

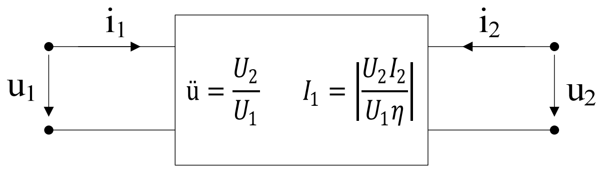

Fig. 9: Simplified behavioral model for DC/DC-Converter

For the efficiency of the converter the values given in [7] and [8] are assumed and shown in Fig. 10.

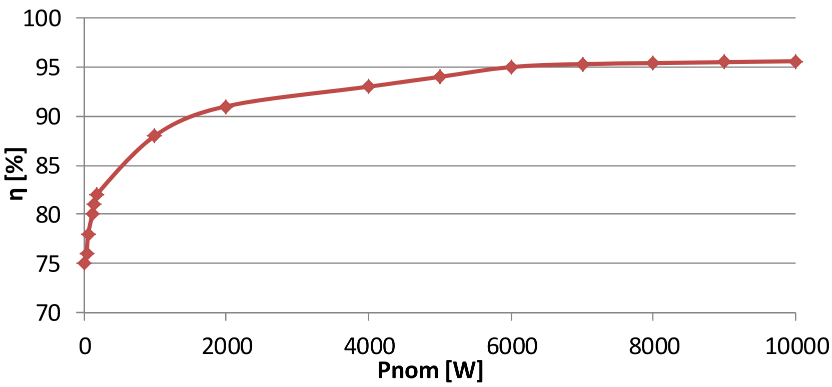

Fig. 10: Efficiency for DC/DC converter depending on the nominal power

3.3. Electronic Components

The components are modeled always as controlled current sources with defined currents and voltage thresholds. The critical voltage is monitored and in case of falling below a given value the architecture is assumed to be not sufficient.

4. Optimization Algorithms

Due to the large amount of possible parameters the calculation of every alternative could be too long. Hence, optimization algorithms have to be used. Here two methods, Ant Colony Optimization (ACO) and Particle Swarm Optimization (PSO), were used.
The *Ant Colony Optimization* is based on an ant colony as a nature example. The optimization problem is constituted as a graph, which is passed through by the ants. The ants pass a way and leave a certain amount of pheromones on the edges. The next ant will more likely take the way with the highest pheromone trail. For every optimization step a determined number of ants will take a certain possible way through the graph. After every cycle the results are calculated and the pheromones are distributed accordingly. Solutions with better results will have a higher pheromone rate. Simultaneously the pheromones evaporate on the ways. Due to the natural model over time the pheromone trail will be highest on the best way which than will be preferred more likely by the following ants. The difficulty with this algorithm is to define the graph for the problem and the rate of pheromones [9].
For the given problem the graph will be split into two parts as shown in Fig. 11. First the architecture, the installation spaces and the cross sections for the cables between the converters will be found. Then the cross sections for the other cables will be defined. Dividing the graph into this two parts leads to a faster calculation.

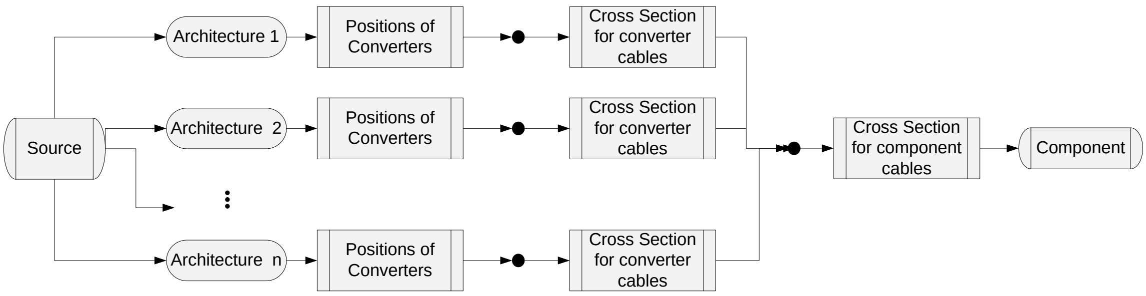

Fig. 11: Simplified graph for ACO

The *Particle Swarm Optimization* is based on the swarm behavior of animals, such as birds or fishes. A swarm is defined as an association of multiple individuals, which share information and hence have the option to solve a complex problem. Here, a determined amount of particles, representing the swarm, is used to find the optimum. While optimizing, the particles move with decreasing speed in the search space. The new positions of the particles depend on the actual position, the speed, a random number, and the current best global solution and solution of the particle. At first the particles are distributed equally. After a while the particles concentrate on the area of the optimum. The behavior of the particles depends on the size of the neighborhoods. A greater neighborhood leads to a faster convergence of the algorithm, where as a smaller neighborhood results more probable into a global optimum. [10]

5. Optimization of Power Supply System

Starting the optimization process is only possible after defining rating functions for the investigated parameters. In this case, the weight and the cost of the power supply system are the main coefficients. Hence, for the individual devices, such as wires and converters, evaluation factors have to be determined.

5.1 Rating functions

Fig. 12 shows the rating functions for the wires. For the cables the weight and cost can be calculated using the cross section as the main factor. The weight of the cable is calculated using the density of the material (ρ_{CU}: $8.92\ g/cm^3$, ρ_{AL}: $2.7\ g/cm^3$) and the cross section. The weight of the insulation and the connectors are regarded by adding a correction factor of $50\ \%$ of the conductor weight. The calculated functions are valid for cross sections from $1\ mm^2$ to $120\ mm^2$. The costs can be computed with the weight and the price for copper ($\sim 5{,}85€/kg$ [Feb. 2013]). The cost for the insulation and the manufacturing costs are added with a correction factor of 2.

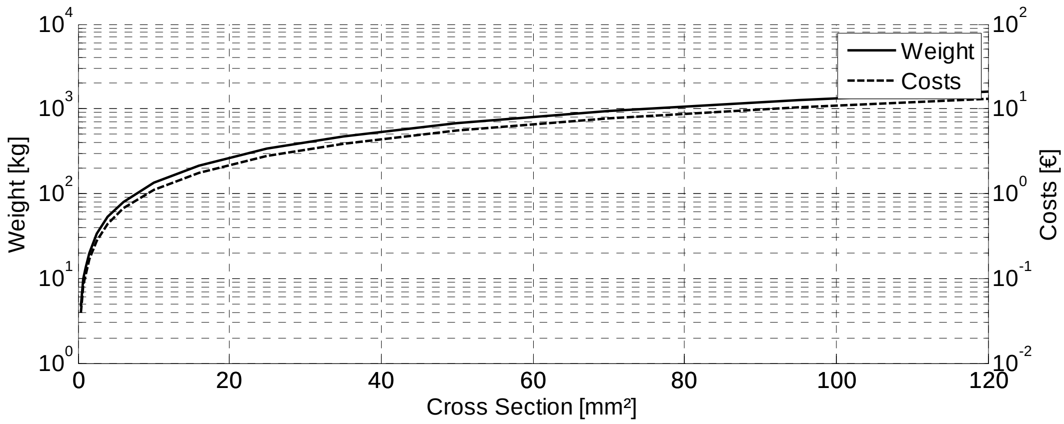

Fig. 12: Cost and weight function over Cross-Section for copper cables depending on the cross section

In Fig. 13 the rating functions for the converters are shown. The weights and prices of the converters were calculated using values from different datasheets and supplier informations [11].

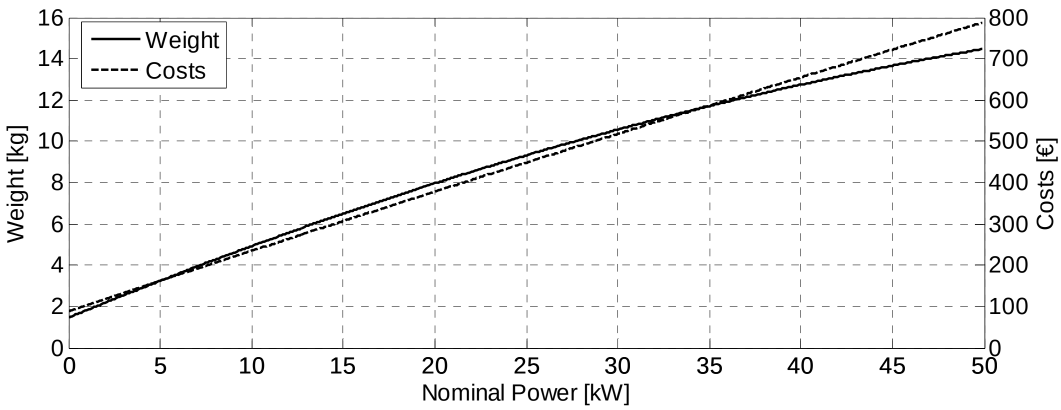

Fig. 13: Cost and weight functions for DC/DC converters depending on the nominal power

5.2 Optimization process

The optimal architecture can only be found when considering all devices. For the cables, the ampacity and the voltage drop have to be regarded. Solutions, where the calculated temperature is higher than the limit temperature are marked as non-functional, as well as solutions where the voltage at the component is too low. Those solutions will be evaluated with a lower fitness than working ones. All other solutions will be marked as valid and used for the optimization process.
The general process of the optimization is shown in Fig. 14. For the database all possible architectures, installation spaces, and simulation models will be used. For the cross sections only the standardized values are used. After each optimization step the abort criterion is checked. Is the criterion not met, the next parameter set is used.

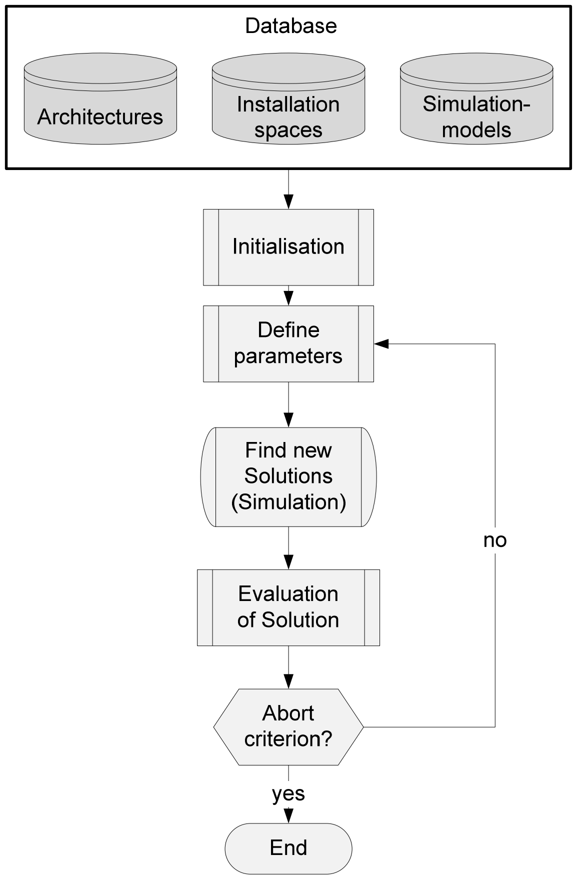

Fig. 14: Flow chart of optimization process

To validate the developed optimization process and the implemented optimization algorithms as introduced in section 4, a small topology was investigated (Fig. 15). In this example only two voltage levels ($48\,V$ and $5\,V$) are used. The eight components have one port for each voltage level. The two converters can be placed on ten different installation spaces $K9 \ldots K18$. Considering Fig. 2 with two converters only two architecture alternatives are possible.

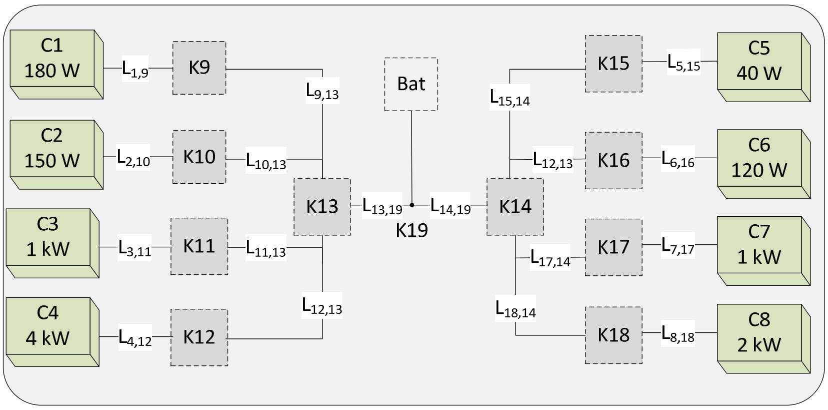

Fig. 15: Small topology for power supply system

To validate the algorithms, all combinations are calculated. The calculation of all alternatives shows that the optimal architecture has both converters directly connected to the source. The $48\,V$ converter must be placed on position $K13$ and the $5\,V$ converter on position $K14$. This result is given after 48600 iterations with the minimal cost of 794 €. Here all wires have the minimal possible cross section. The ACO reaches its minimum after 1500 iterations with the costs of 800 €. The PSO reaches the minimum after 1000 iterations and costs of 822 €. All minimums have the same alternative and converter positions but differ in the size of the cross section for the cables.

6. Results

The developed method was applied to a more complex power supply system. Hence, the topology in Fig. 15 is extended with further components and the third voltage level. Again every component has a $5\,V$ port and additionally either a $48\,V$ port (lighter) or a $12\,V$ port (darker). The power requirement of the 31 components varies from $40\,W$ (e.g. brake light) to $4\,kW$ (e.g. air conditioning compressor). Due to the rating functions and the influence of the converter costs architecture one (see Fig. 3) is the optimal architecture. The converters are placed centralized and close to the biggest power consumers, see Fig. 16.

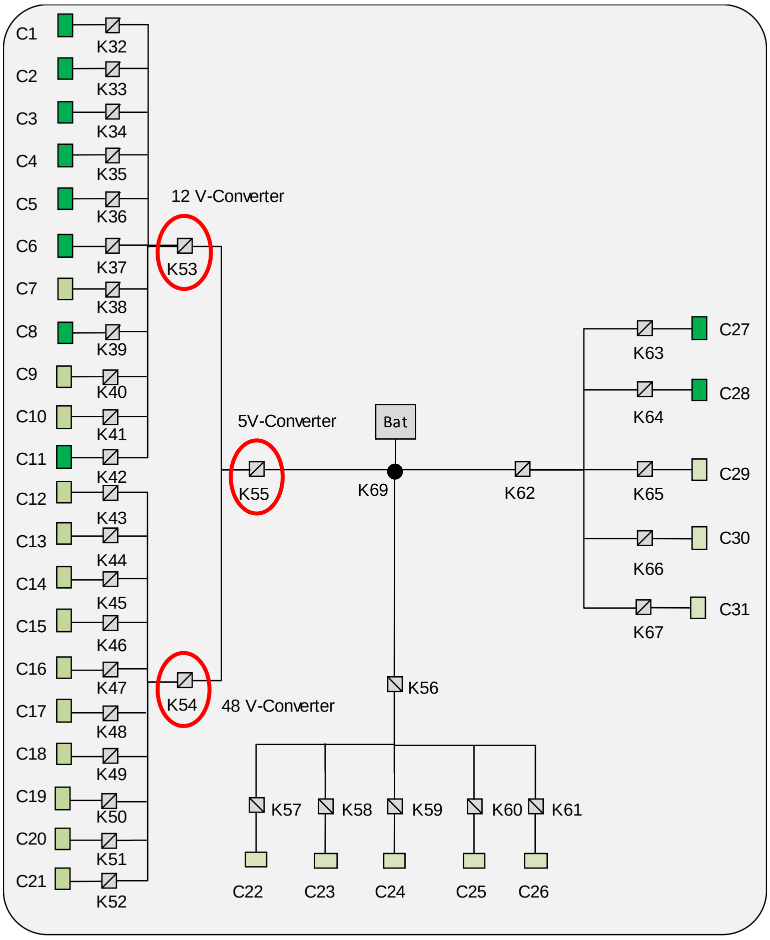

Fig. 16: Topology for power supply system with three voltage levels

With the introduced optimization algorithms the best-case and also the worst-case solutions can be found. For both solutions, the potential savings for the cost differ more than 8 %, for the power loss and the weight almost 20 %, see Fig. 17. This results show, how important the dimensioning and layout of the power supply system is.

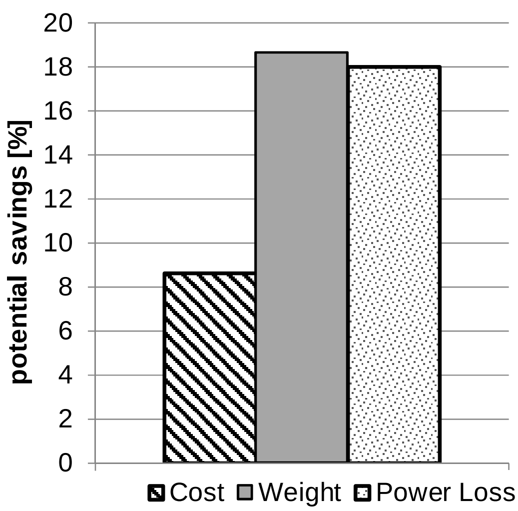

Fig. 17: Potential savings for cost, weight and power loss of complex power supply systems

The influence of the position of the dc/dc-converters was investigated. For the optimum in the previous investigations, the converters are placed centralized and close to the highest power consumers. For the parameter variation the power supply system shown in Fig. 15 is used. The nominal power from component $C8$ is varied from $500\ W$ to $4\ kW$ and the length of the wire $l_{12,13}$ from $0.5\ m$ to $5\ m$. Fig. 18 shows the optimal installation spaces for the two converters depending on length $l_{12,13}$ and the nominal power of component $C8$.

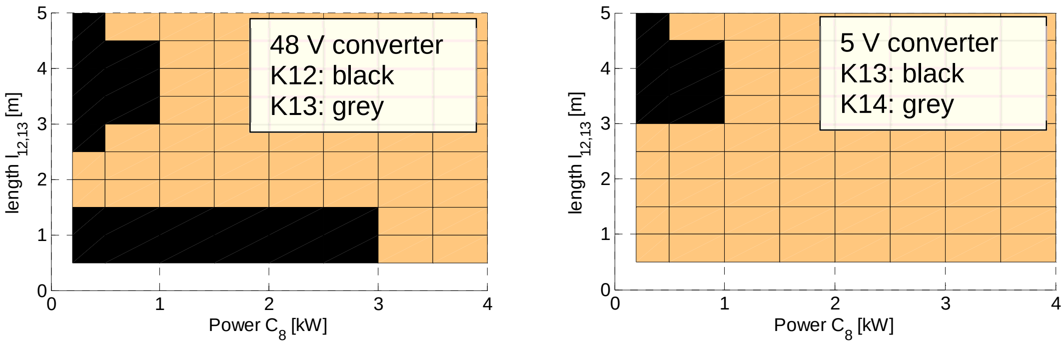

Fig. 18: Installation spaces for 48 V and 5 V converter

For short wire length $l_{12,13}$ and with higher power of the component $C8$ the installation space of the $48\,V$ converter changes from $K13$ to $K12$. With increasing length the influence of the nominal power decreases. Only for a long length and small power the installation space for the converter is directly in front of component $C4$ (installation space $K12$). Depending on the installation space of the $48\,V$ converter the $5\,V$ converter changes the installation space.

With this parameter variation the influence of the different parameters becomes obvious. Depending on the maximum power of the components, their place and the length of the wires the installation space of the converters changes. Therefore the use of optimization algorithms is necessary.

10. Summary and Outlook

Due to the electrification in the vehicle, the importance of the power supply systems grows. Hence, new methods and therefore simulation is needed to support and improve the development process. Simulation models for cables, converters and components are necessary. The development of the models was discussed, which consider the thermal and the electrical behavior of the cables and therefore allow to calculate the ampacity and the voltage drop.

The developed simulation methods allow the investigation and optimization of different power supply systems with regard to the architecture, the installation spaces, and the optimal size of the cross sections for the cables. For optimization two algorithms (ant colony and particle swarm optimization) were used. The method enables different parameter studies like cross section optimization.

For further investigation more parameters can be integrated in the optimization process and larger architectures have to be optimized. Here proof of function of the optimization algorithms is the major challenge. Also the power loss has to be investigated.

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