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# Development of a Computer Platform for Visualization and Simulation of Vehicular DC Distribution Systems

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**Abstract:** Contrary to other in-car engineering systems where the use of simulation tools is highly extended prior to a prototyping stage, the simulation of vehicular electrical distribution systems (EDS) is not still a common practice as manufacturers so far have mainly relied on laborious empirical procedures for technical validation. However, to provide flexibility in EDS design and procure even faster endorsement, the development of computation tools on this subject is compelling considering the intricacy of these networks. To face this challenge, this work provides guidelines and experiences to develop a customized platform for EDS visualization and simulation within the automotive industry context. The use of agile techniques for software development, visual analytics and tailored power flow methods is highlighted among other aspects. Realistic case studies are presented to discuss the attributes of the implemented computational tool. To also provide relevant perspectives on how future EDS visualization and simulation platforms will be developed, latest research is discussed in topics such as new electric/electronic architectures, electro-thermal analysis, electronic fuses, mild hybrid power trains, hardware in the loop and high voltage networks.

## 1 Introduction

The complexity in electrical distribution systems (EDS) of vehicles has significantly increased in the last years due to the use of new electronic devices and sensors, advanced safety functionalities, higher user needs, superior efficiency demands and the continuous electrification of traditional mechanical functions including the insertion of electrically-powered traction systems. Moreover, to ensure reliability, wires in automobiles are usually oversized to avoid temperature increase so that insulation integrity is maintained, and also to warrant an acceptable mechanical resistance to withstand the manufacturing process [1]. For these reasons, more and bigger power supplies, Electronic Control Units (ECUs) and wires are required. This raise in system intricacy and weight provokes more time spending and energy in the manufacturing process as well as efficiency reduction in daily fuel or battery consumption [2]. On the other hand, the amount of information that planning engineers must handle is huge as today's vehicles may contain hundreds of power consumers, up to ten thousand possible wiring combinations and more than a thousand wires having a total extension close to 3 km and a weight above 50 kg [3, 4]. Consequently, these networks (See Fig. 1) demand a variety of protections, harnesses, ECUs and splices to properly transmit signals or power supply to the different components.

Despite the aforementioned requirements, these electrical networks are not only intended to be flexible and robust, but also they are expected to be aligned to fulfill efficiency standards [5, 6], design challenges [7] and emerging environmental policies on greenhouse gases reduction [8]. Besides, the pursue of Original Equipment Manufacturers (OEMs) to add augmented comfort and customized options to consumers has provoked a significant increase in assembly logistics due to the great amount of possible harnesses architectures. To overcome these augmented demands, the use of software platforms at the design stage to suitably visualize, simulate and analyze the vehicular DC distribution systems is crucial. In this respect, a variety of visualization and simulation tools exist for the majority of other systems in modern vehicles like chassis, air conditioning, engine, power train or electrical drive. The use of simulation tools at the design stage enhances productivity and reduces prototyping costs in these systems. However, this is not the case of EDS in automobiles, where in most cases real prototyping exists at early stages and thus increasing time-to-market. This is a consequence of three main factors: (i) The massive amount of electrical components and wiring harnesses paths and configurations, (ii) the large complexity on integrating disperse and vast data from automotive manufacturers and their suppliers and (iii) the lack of tailored software tools able to carry out a user-friendly yet reliable power flow simulations.

To overcome this information overload, facilitate human-information interaction and permit the electrical simulation of vehicular EDS, the development of versatile computational platforms is compelling to face these demands. In this regard, software tools such as Power Net Simulation and Simulink permit to

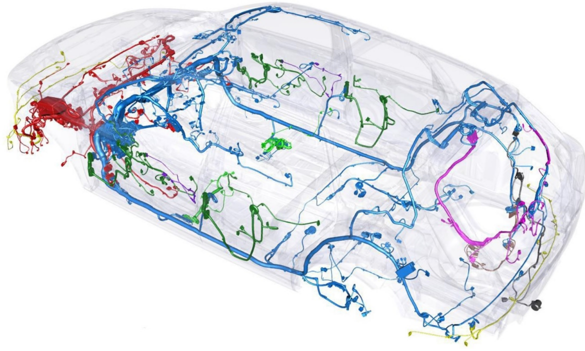

**Fig. 1**: Electrical network harnesses of a vehicle, adapted from [1]

examine overall energy optimization strategies considering general models for the battery and the loads but lack on analyzing in detail the on-board EDS in full network models containing all wires, fuses, ECUs, loads and other components. Other tools like EBCable, Vesys, Eplan Harness proD and LDorado are commonly employed in the automotive industry but only permit automobile EDS design. Beyond the design tasks, other software like Harness Studio, Siemens Solid Edge and Saber RD have recently included additional modules to perform EDS simulation. However, the latter computational packages do not provide detailed information regarding those add-ons, they neither specify the modelling parameterization of the different components and the included numerical methods to perform power flow analysis.

To address the aforesaid challenges, in a previous work from the authors, the automobile wiring design process, the required manufacturing data preprocessing and a detailed methodology to perform power flow analysis were presented [9]. Also in the context of vehicular EDS simulation, the main contributions of this work deal with the aspects of software development, user interface and visualization. To contextualize, Section 2 exposes the characteristics inherent to these networks from the automotive product development viewpoint and contrasts their peculiarities with those from conventional power distribution systems. Afterward, Section 3 and Section 4 dive into the proposed software development techniques. The first details the guidelines and experiences to deploy a computer platform for the visualization and simulation of on-board EDS, where the automotive industry framework conditions the particularities of the selected approach. The latter exposes examples of visual representations and simulation results based on realistic vehicular electrical harnesses. Elements to enhance the user experience are discussed all along. Section 5 elaborates on future research and its impact on prospect visualization and simulation platforms, while Section 6 gathers the conclusions drawn from the work.

## 2 Vehicular EDS Characteristics

In the automotive industry organization, all the wires and the different components (electrical and mechanical) that allow energising every single consumer within the vehicle are considered as part of the EDS. Additionally, from a product development point of view inside an OEM, vehicular EDS do not include the battery and alternator as these elements are regarded as subjects of the energy systems division. Sizing of the energy systems is performed on a previous stage based on the technical concept design of the vehicle. The on-board EDS, similarly to any other kind of electrical network, is dimensioned as a function of the allocated loads. Thus, an starting point for planning the EDS is the study of the current consumption of every load, which is then documented and stored in a database saving primarily the average and peak current values under nominal voltage conditions. Then, the EDS design takes into consideration several aspects such as optimization of cable lengths, integrity of the wiring harnesses, electromagnetic compatibility and risk prevention. These aspects condition the peculiarities of the electrical network, for instance, the quantity and location of fuse boxes inside the vehicle, the type of protections that should be used on the harnesses depending on temperature, humidity and friction, among others. To establish a trust-worthy operation of the vehicular EDS components, standards with clear specifications are also considered. That is the case of the ISO 8820 which details the general test requirements for fuse-links in the DC electrical network of road vehicles. Being fuses the key protective elements, their proper selection is of main importance for a fail safe operation of the system. Their main function is to protect the wiring. Automotive fuses evolved from glass tube fuses to the current common blade fuses and slow blow fuses among others. In particular, blade fuses usage is widespread in the industry due to their compact size, lightweight and durability.

The EDS itself has to respond to the activation and deactivation of the power consumers depending on the many functions that are available within the vehicle and are triggered either automatically or manually by the driver. Nowadays, a vehicle can register around 300 functions. This introduces the need for intermediate control devices that coordinate and extend the right signals shapes to the different components. Such intermediate control devices are the Electronic Control Units (ECU). Moreover, the power delivery in ECUs must be guaranteed to also provide a physical-media fail safe communication in all data buses. EDS as of today connect many decentralized ECUs that manage the operation of specific systems. Almost for every particular system that we can identify in a vehicle, there is a primary ECU managing the corresponding functions. For instance, for the window motor, the battery charging, the lighting, braking system, transmission motor, acclimatization, and so on.

In urban networks, the concept of electrical distribution systems usually include substations, transformers, protections, feeders and consumers. Although vehicle EDS are appreciably smaller than metropolitan urban grids, they are representative of what one typically finds. There is: (i) a main energy supply, in this case a battery, (ii) electro-mechanical protection devices (fuses and relays) safeguarding the integrity of the system, (iii) elaborated wiring paths to efficiently transport energy to loads within a range of acceptable voltage levels for variable current consumption and (iv) there might be DC energy conversion stages between high and low voltages as in the case of electric and hybrid vehicles. Validation of the components' quality and the correct network design is cyclically addressed all along the vehicle EDS development process and includes a set of experimental procedures on real prototypes. Contrary, experimentation within the development of metropolitan electrical networks to guarantee their correct operation is inherently difficult. Typically, once the infrastructure in these grids is deployed, they are expected to be immediately "plugged" and launched to favor immediate energy supply for a given community. Therefore, simulation is a mandatory step for urban electrical networks. In this regard, power flow numerical methods are widely used tools to calculate the electrical variables all along the network, anticipate proper energy balance and quality assurance of the voltage feed and identify the conditions deriving to instabilities in the system.

In turn, simulation in vehicular EDS is still not a common practice as manufacturers so far have usually relied on empirical procedures with step-by-step regulation guides to size cables, select protections and estimate voltage drops assuming mainly steady-state conditions. The inclusion of simulation in EDS would be of high significance to test different architectures and configurations, anticipate unwanted voltage drops and detect design failures in an early stage of the design process. Hence, the prototyping phase would just be focused to validate the optimized EDS design earlier attained via simulation. This design includes the correct selection and dimension of all the wires, protections and auxiliary coupling elements. Beyond the electrical aspects, the thermal response of the wires and electrical components become of paramount importance. As an example, a wire should never reach temperatures leading to melting of the isolation. Hence, to properly assist EDS designers, it is particularly relevant the development of a computer tool able to infer temperatures from the estimated electrical parameters and thus assist the appropriate match between a fuse with its wire-load combination. To analyze this match it is not enough to rely on standards, but to take into account the maximum peak energy that the fuse has to withstand during its operation. To evaluate this, it is necessary to have the amplitude and duration of peak currents for loads presenting this behaviour. As an example, every time a motor axis is blocked, its current experience peaks. For instance, an scenario could be the case of a driver in a highway under heavy rain or snow and thus using the wipers. Due to the freeze on the windshield the current consumption of the wiper motor will be higher than under regular conditions. The deployment of a tailored simulation tool would allow the verification of the previous scenario and many others, beyond to what is feasible through on-the-road characterization.


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## 3 Software Development

To develop a tailored EDS visualization and simulation platform, six main pillars (represented in Fig. 2) have been considered. These foundations benefited: (i) rapid software prototyping (Agile methodologies, user-centered design, open-source tools), (ii) a clean and intuitive visualization (Visual Analytics) and the incorporation of numerical methods (data pre/post processing, power flow simulation). These guidelines are described hereafter.

### 3.1 Agile methodologies

Plan-driven traditional software development, where sequential and rigid temporal stages exist for the different phases of the process, has been reported to present some drawbacks such as focusing on goals rather than teamwork, delayed working versions and reduced adaptability to rapid-changing requirements [10, 11]. Based on these evidences and the aim to develop a rapid-testing yet robust computational tool to be used in a daily basis by engineers related to on-board EDS, agile methodologies [12] were considered as a cornerstone to leverage team productivity and collaboration. Moreover, these approaches have proved to shorten the process in automotive software development [13]. For these reasons, in the present work the targeted Scrum agile tactic framework [14] was chosen and adapted according to the time-constraints and profile of the personnel assigned to this project. Nevertheless, the Scrum methodology premises were tried to be satisfied as much as possible to take advantage of its benefits. In this regard, the Scrum Team consisted on a small, multi-disciplinary group of researchers and software developers organized in different roles:

- The Product Owner who decided what was required to be done and prioritized the Product Backlog which is an ever-evolving list containing all the software requirements.
- The Scrum Master who removed impediments, facilitated meetings and guaranteed that Scrum practices were satisfied.
- A Development Team that generated product increments.

Scrum splits a project into cyclical increments named as Sprints. For medium-high complexity projects, a two week Sprint is suggested to procure rapid iteration and incorporation of new functionalities. Depending on the Scrum Team members availability, the so-called Daily Scrum meetings were conducted onsite or remotely to review the advancements (activities done or in progress), comment any obstacles, find solutions and share future planned work. In every first Daily Scrum, the Sprint Planning took place to socialize the Sprint Backlog, being this the set of Product Backlog items (User Stories) chosen for the Sprint. For every item, the corresponding daily activities were listed in a spreadsheet that served as the Scrum Board. In the last Daily Scrum of the Sprint, the results of the work were evaluated and accepted if they fulfilled the expectations; this as part of the Sprint Review. Finally, a Sprint Retrospective took place when needed to propose improvements in the Scrum process. All the previously described Scrum methodology is exposed in Fig. 3.

### 3.2 User-Centered Design (UCD)

In order to enhance intrinsic knowledge from experts and design software for a very specific target group, user-centered design (UCD) [15] perspectives were incorporated into the SCRUM methodology as suggested in [16]. Therefore, to develop a functional tailored software by means of a proper understanding of the nature of the problem, workshops were carried out to gather all the user needs, suggestions and perspectives concerning the computational tool. The kick-off workshop took place prior to the beginning of the Scrum process and gathered potential users and engineers related to vehicular EDS design and testing. In this meeting, some context on the project was initially exposed by the Scrum Team to the assistants regarding the time planning, development software tools, the need for users involvement, expected outcomes in virtue of preceding related work, among others. Then, a simple software process-flow [17] was conducted to propose a basic procedure to upload, visualize and simulate an electrical harnesses. This was achieved by means of low-fidelity prototypes (wireframes) [18] which are graphical representations (layouts) of the computer tool containing the most relevant interface elements and content. After this, comments from the participants were received regarding their impressions and suggestions on the process-flow, the wireframes and the corresponding interface elements. This was highly useful as it permitted to understand the users' needs and therefore make a proper initial definition and item prioritization of the Product Backlog (See Fig. 3).

Also, regular feedback workshops were organized to receive opinions and validation of the interface process-flow and the proposed (general and detailed) EDS graphical representations. On this, for the general illustration (harness level visualization), it was agreed to exhibit schemes familiar to other software tools commonly employed by EDS engineers. On the other hand, for the detailed representation (wire-by-wire visualization), the regularly used electrical layouts were not considered as an starting point as they did not permit and straightforward understanding of the electrical routes and connections.

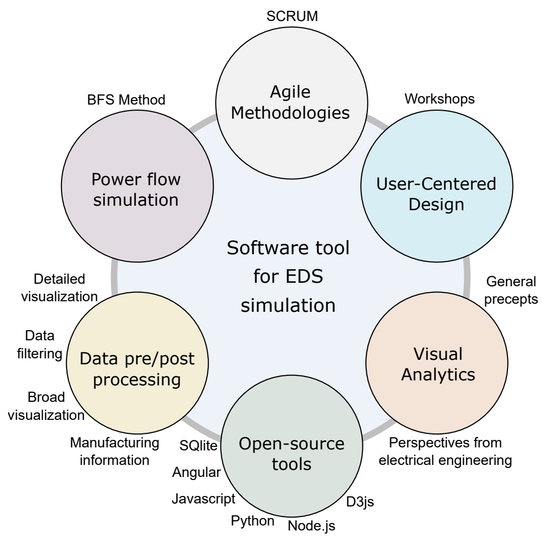


**Fig. 2**: Developed computer tool foundations

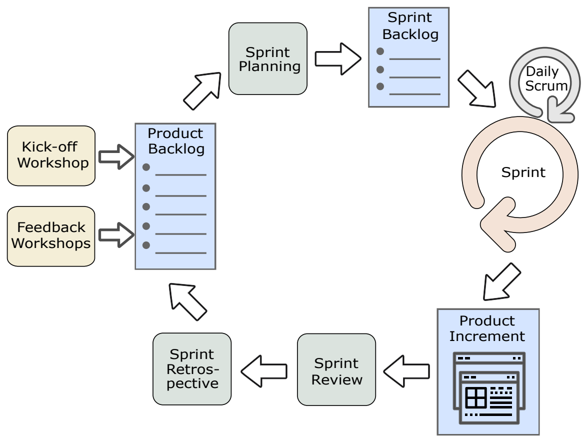


**Fig. 3**: SCRUM process

### 3.3 Visual Analytics

As denoted by [19], “large companies provide a lot of interesting challenges and complex real-world datasets for information visualization research". This statement and the needs of this project motivated the inclusion of Visual Analytics (VA) precepts. Moreover, VA has been remarked as a useful framework for software development in the automotive industry [20]. Indeed, it is a multidisciplinary field that merges different research areas such as visualisation, data analysis, data mining, human-computer interaction, data processing, geo-spatial analytics, statistics and others [21]. Despite the fact that user experience and efficient human machine interfaces (HMI) are of great significance in the automotive industry, only few academic attempts to use VA in varying depth exist. So far they have been mostly engaged in the domain of computed-aided-design [22], artificial vision [23], vehicle collision [24, 25], engine multibody dynamics [26], virtual reality [27], aerodynamics [28], sensor data [29] and electric vehicle charging analysis [30]. Additionally to the previous references, it is worth to highlight the contributions performed in [20] regarding the systematic deployment of visualisation systems for vehicle communication networks in a large automotive company. In the present work, attributes such as proper manufacturing data preprocessing, color coding, clear appearance, easy navigation, zooming and panning, boxes for elements search, interactive data visualization and simulation results tabulation have been incorporated.

### 3.4 Open-source libraries and database managers

Well supported programming languages (Javascript, Python), robust data-base managers (SQlite [31]) and open-source and specialized libraries and frameworks (D3 Data-Driven Documents [32], Node.js [33], Angular) have been used in this project. Furthermore, Javascript-based library D3 is being highly employed in a broad variety of information visualization projects as it permits with ease to add interaction and animation to complex datasets by using Scalable Vector Graphics (SVGs). Recently, D3 has even been used to increase the awareness on power distribution infrastructure [34]. Despite the fact that the deployed software platform is oriented to local execution, it could easily be upgraded in the future to operate in a cloud computing environment. This may represent an effective alternative to minimize costs, increase accessibility, provide elasticity to customer’s demands and promote resource sharing and agile development [35].

### 3.5 Data pre-processing and post-processing

In the automotive industry, there is a systematic process to create a file container having all the possible electrical configurations for a particular car model [9]. This container has an Extensible Markup Language extension (.xml) and it was mainly designed for automotive industries and suppliers to share manufacturing data. To obtain from these .xml files all the required electrical information for visualization and power flow studies, laborious data preprocessing is firstly needed to extract the identifiers and characteristics from wires (sections, paths, lengths, insulators), protections, ECUs (topologies, input/output pins) and splices (solder joints). In order to filter the data and derive the electrical elements present in a particular car configuration, an extensive list (containing the arrangements of the different components) is also required. Additionally, the ratings and pattern consumption of the loads are obtained from components databases. The data pre-processing has a double purpose. On the one hand it prepares the information to arrange it in the necessary form to deploy a power flow simulator, and on the other hand, it outputs part of the information required for visualization. In a first stage, for the broad level visualization, a nodes map is constructed. Every node has associated an x-y coordinate and identifying information. The nodes are interconnected by harness segments. In the second stage, for the detailed wire-by-wire representation, all the wires in the harness are given their source and destination nodes along with the length, section, path and resistance. Once the power flow algorithm is executed and successfully achieves convergence, a third stage of visualization takes the results and integrates them into the already developed harness representations. The workflow indicating the data processing for visualization is sketched in Fig. 4.

### 3.6 Power flow simulation

To allow a rapid and reliable power flow simulation for the particular characteristics of vehicular EDS (complex weakly-meshed low-voltage DC networks), the Backward/Forward Sweep (BFS) method [36] was chosen as it has been exposed to outperform traditional approaches like Newton-Raphson and Gauss-Seidel in terms of computational intensity in radial or slightly meshed systems [37]. Additionally, the mathematical formulation for these kind of networks is more straightforward when BFS is employed. This method relies in the iterative use of Kirchhoff’s current and voltage laws (KCL and KVL). Algorithm 1 summarizes the implemented BFS strategy. However, a detailed explanation can be found in [9].

## 4 Interface Visualization and Simulation

This section exposes visual representations and simulation results attained with the implemented software tool. Realistic vehicular electrical harnesses have been considered for this purpose. Due to assembling requirements, vehicular EDS might be formed by a main harness (blue in Fig. 1) which delivers power supply as well as communication and control signals to different secondary harnesses (non-blue harnesses in Fig. 1) such as those related with the bumpers, doors or engine. Bearing this in mind, the general representation (broad level visualization) of the main harness for a particular car model can be seen in Fig. 5. There, it is shown the description of selected power consumers. This harness contains several nodes consisting on different components such as the battery, main and secondary fuse boxes, coupling connectors, ground plates, splices and power consumers. The main harness is connected to secondary harnesses by means of coupling connectors. For instance, Node 278 in the lower-middle part of Fig. 5 represents a coupling to a secondary harness. The general representation of this secondary harness can be observed in Fig. 6a where the aforementioned Node 278 has now been named as Node 1 for didactic purposes. Besides, Fig. 6b exhibits the detailed (wire-by-wire) representation of this secondary harness. The detailed layout was designed to provide the user with an intuitive understanding of the network by resembling the general scheme. To add interactivity and easy navigation to the interface, mouseover highlighting and tooltips, element search boxes, responsive legends as well as zooming and panning options have been included.

Regarding the power flow simulation, Table 1 details the voltage and current calculated for the different consumers in the secondary harness given a predefined power consumption and also considering Node 1 having 14.5 V in all its pins. The consumers can be predefined in active or inactive state. Consumers in Nodes 15 and

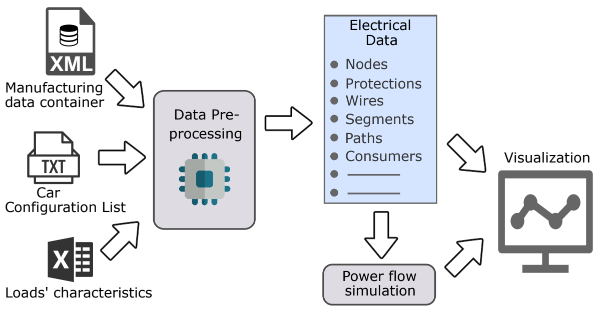


**Fig. 4**: Input data for visualization


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24 have been deactivated for this test. Voltage drops exist due to the physical characteristics of the lines (length, section, material, temperature) that are extracted and organized in the pre-processing stage and calculated during the power flow simulation. A single consumer may function as a multi-load element, demanding current from different pins. For instance, a headlight can have three loads associated: one for the blinker, one for the high beam and another for the dimmed beam. Additionally, Table 2 exhibits the line currents and voltage drops. As it can be seen, the results are coherent all along the network for the assumed power demands in the consumers' loads validating the implemented BFS power flow algorithm. The visualization and power flow analysis aforementioned described can be extended to other vehicle harnesses having their particular network topologies.

## 5 Future Research and Trends on Vehicular EDS

This section begins exposing future software functionalities and research regarding the inclusion of VA from the power engineering experience. On this, some context is provided to then comment possible forthcoming developments from these perspectives. Next, the analysis and visualization of thermal conditions is discussed. Later on, to also provide the reader with some insights and trends that will play a significant role in future on-board EDS and the way in which simulations platforms are developed for these systems, topics such as new Electric/Electronic (E/E) architectures, electronic-fuses (e-fuses), hardware in the loop, mild hybrid power trains, high voltage networks and power converters are discussed as well.

**Input:** Preprocessed electrical data
**Output:** Branch currents and node voltages

1. Network components categorization in correspondence to the type and identifier related to their pins
2. Partitioning of the network into a "positive" and "negative" grid to face complex paths to ground and improve the model accuracy
3. Incidence matrix creation. Rows represent branches while columns outline to nodes
4. Determination of the "cut" an "non-cut" branches
5. Calculation of the branch resistances matrix considering possible temperature variations
6. Computation of the Thevenin resistances in the "cut" branches by means of a unitary current sequential injection tactic
7. In view of the incidence matrix, withdrawal of unneeded branches having loops in the "positive" and "negative" grid
8. **for** i = 1 : Max. number of iterations **do**
9. Calculation of the "non-cut" branches currents as the nodal currents are already defined
10. Determination of the node voltages utilizing the "non-cut" branches resistances and the branch currents
11. Obtention of the voltage drops in the "cut" branches considering the node voltages
12. Obtention of the voltage drops in the "cut" branches considering the branch currents and the "cut" branches resistances
13. **if** The computed voltage drops from the previous two approaches are close enough **then**
14. Include a compensation algorithm based on the Thevenin equivalent resistance to improve the accuracy of the "cut" branches currents
15. Break
16. **else**
    Compute the new "cut" branches currents employing the new voltage profile
17. **end if**
18. **end for**

**Algorithm 1:** Pseudocode of the implemented BFS method

**Table 1** Voltage and current in the consumers' loads

| Node Pin | Power [W] | Voltage [V] | Current [A] |
|---|---|---|---|
| 15a | 0 | 14.5 | 0 |
| 17a | 1.16 | 14.4938 | 0.08 |
| 17b | 26.1 | 14.469 | 1.8 |
| 17c | 1.45 | 14.4983 | 0.1 |
| 17d | 0.72 | 14.4988 | 0.05 |
| 21a | 29 | 14.4857 | 2 |
| 21b | 29 | 14.4912 | 2 |
| 24a | 0 | 14.5 | 0 |
| 24b | 0 | 14.5 | 0 |
| 24c | 0 | 14.5 | 0 |
| 24d | 0 | 14.5 | 0 |
| 24e | 0 | 14.5 | 0 |
| 25a | 0.43 | 14.4983 | 0.03 |
| 26a | 391.5 | 14.289 | 27.4 |
| 26b | 391.5 | 14.289 | 27.4 |
| 26c | 391.5 | 14.289 | 27.4 |
| 26d | 391.5 | 14.289 | 27.4 |
| 28a | 2.9 | 14.4903 | 0.2 |
| 28b | 2.9 | 14.4903 | 0.2 |
| 28c | 2.9 | 14.4903 | 0.2 |
| 28d | 29 | 14.4028 | 2.01 |
| 28e | 116 | 14.103 | 8.23 |
| 28f | 87 | 14.2044 | 6.12 |
| 29a | 0.29 | 14.499 | 0.02 |
| 31a | 2.9 | 14.4893 | 0.2 |
| 31b | 2.9 | 14.4893 | 0.2 |
| 31c | 2.9 | 14.4893 | 0.2 |
| 31d | 29 | 14.3923 | 2.01 |
| 31e | 116 | 14.0589 | 8.25 |
| 31f | 87 | 14.1718 | 6.14 |
| 32a | 0.29 | 14.4989 | 0.02 |

**Table 2** Line currents

| From Node Pin | To Node Pin | Voltage drop [mV] | Current [A] |
|---|---|---|---|
| 1 | 6a | 3.71 | 0.08 |
| 24a | 6c | 0 | 0 |
| 1 | 15a | 0 | 0 |
| 6b | 17a | 2.48 | 0.08 |
| 1 | 17b | 30.96 | 1.804 |
| 1 | 17c | 1.2 | 0.05 |
| 1 | 17d | 1.72 | 0.1 |
| 1 | 21a | 14.26 | 0.776 |
| 1 | 21b | 8.84 | 0.481 |
| 1 | 21c | 14.26 | 1.226 |
| 1 | 21d | 8.84 | 0.76 |
| 1 | 21e | 0 | 0 |
| 1 | 21f | 8.84 | 0.76 |
| 1 | 24b | 0 | 0 |
| 1 | 24c | 0 | 0 |
| 1 | 24d | 0 | 0 |
| 1 | 24e | 0 | 0 |
| 1 | 25a | 1.67 | 0.03 |
| 1 | 26a | 210.97 | 27.398 |
| 1 | 26b | 210.97 | 27.398 |
| 1 | 26c | 210.97 | 27.398 |
| 1 | 26d | 210.97 | 27.398 |
| 1 | 28a | 9.66 | 0.2 |
| 1 | 28b | 9.66 | 0.2 |
| 1 | 28c | 9.66 | 0.2 |
| 1 | 28d | 396.97 | 8.225 |
| 1 | 28e | 295.6 | 6.125 |
| 1 | 28f | 97.18 | 2.013 |
| 1 | 29a | 0.96 | 0.02 |
| 1 | 31a | 10.7 | 0.2 |
| 1 | 31b | 10.7 | 0.2 |
| 1 | 31c | 10.7 | 0.2 |
| 1 | 31d | 441.07 | 8.251 |
| 1 | 31e | 328.17 | 6.139 |
| 1 | 31f | 107.71 | 2.015 |
| 1 | 32a | 1.07 | 0.02 |

### 5.1 Tailored Visual Analytics

Bearing in mind that VA techniques permit the user to rapidly and intuitively obtain insights and sufficient understanding of the electrical network in study, the adaptation of well-proven visualization precepts from power systems will be highly relevant. In this respect, color contouring [38, 39] (See Fig. 7a) would enhance

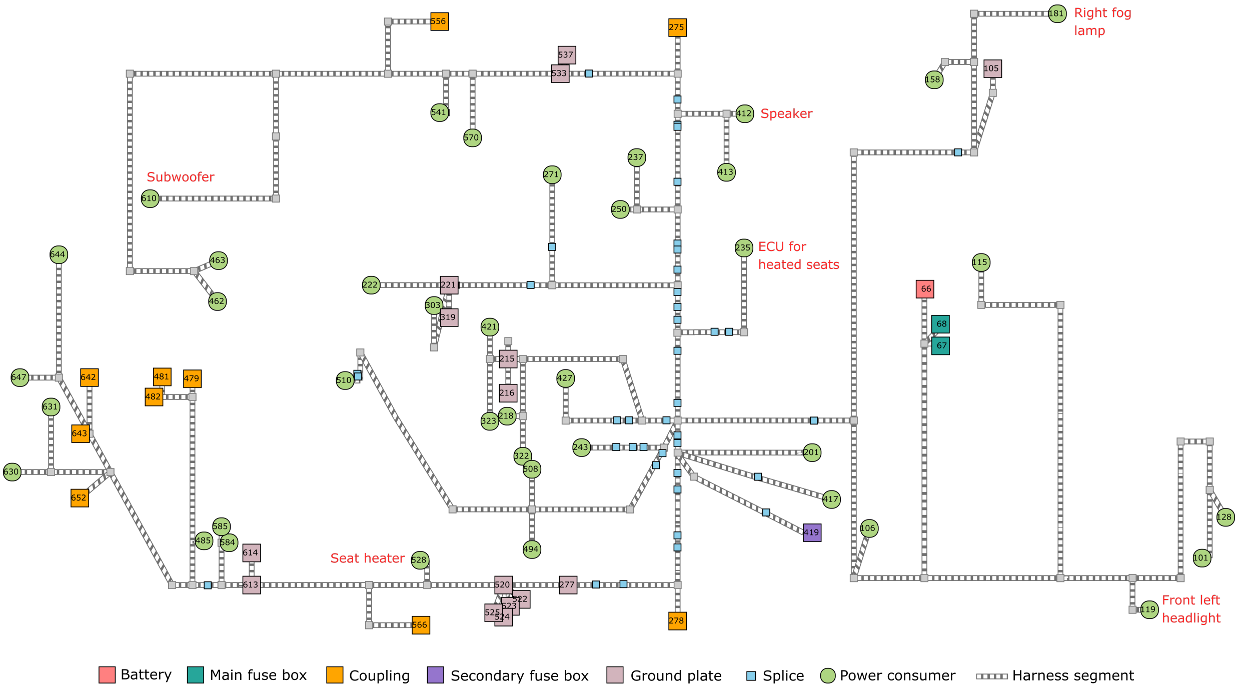


**Fig. 5**: Main harness general representation

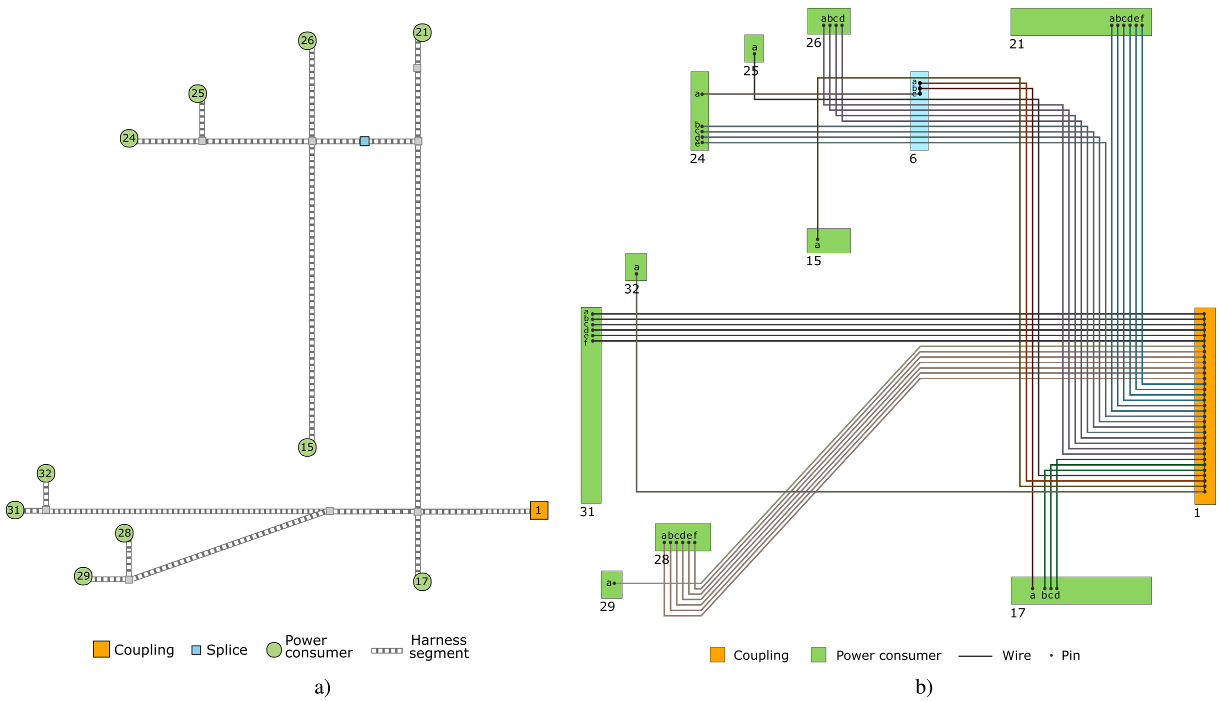


**Fig. 6**: Secondary harness: a) general representation, b) detailed representation

visual EDS diagnosis as color serves as an effective highlighting feature allowing a rapid localization of problematic zones or elements in large and complex networks [40]. Under this approach, nodes voltages and branch currents are usually employed to build the corresponding background color grid. A similar tactic to this strategy is color coding [41] where transmission lines or buses themselves are represented with discrete colors according to their voltage or current levels (See Fig. 7b). On the other hand, the incorporation of time plots will permit to observe the evolution of varying data (voltage, current, power) over time once temporal simulation is included in the software (See Fig. 7c). Additionally, as in vehicular-DC networks there is a vast amount of components, wires and paths; the automatic one-line diagrams generation [42–45] added to the inclusion of navigation panes (See Fig. 7d) will be beneficial. In these on-line

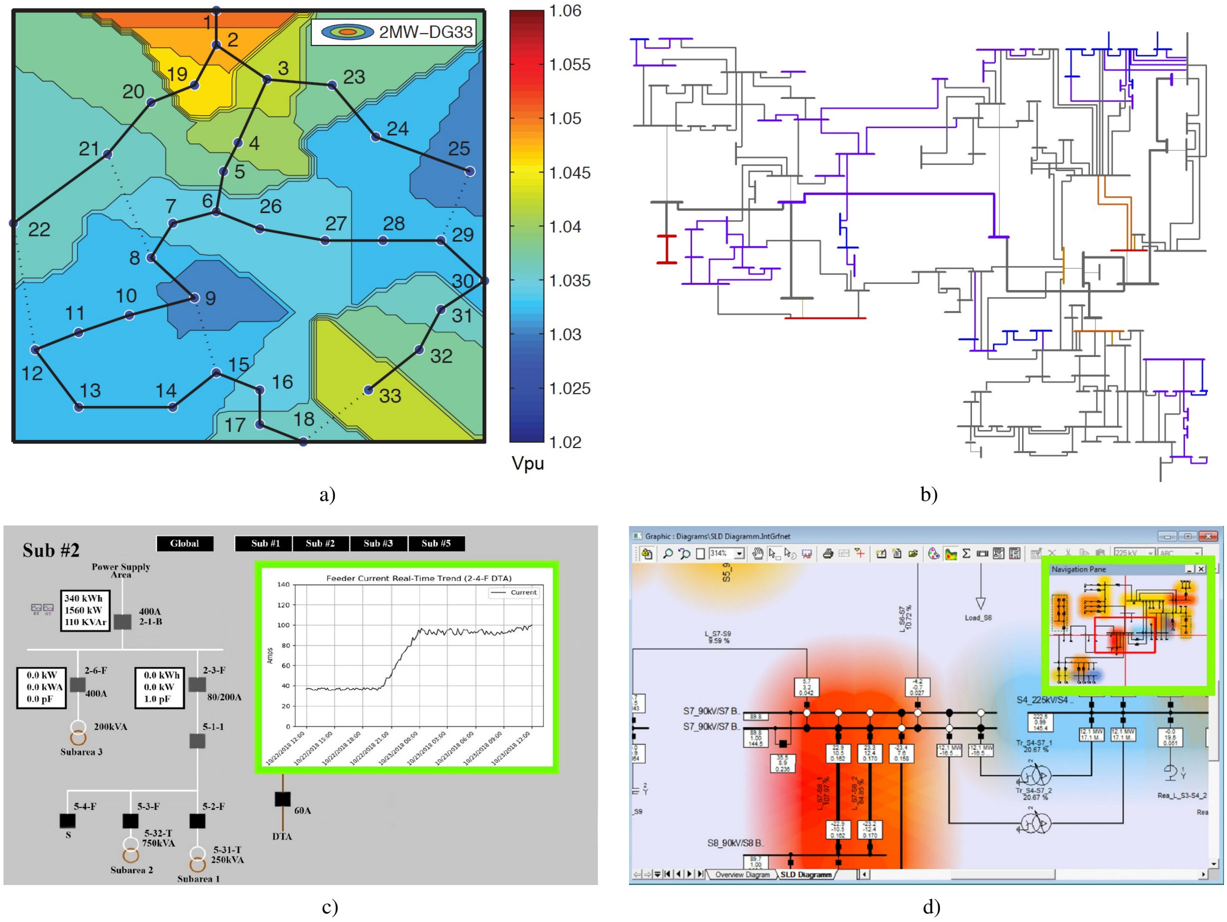


**Fig. 7**: a) Color contouring, taken from [49]. b) Discrete buses coloring (Blue$\leq$0.96 pu and Red$\geq$1.04pu), taken from [41]. c) Time plot, adapted from [50]. d) Navigation pane, adapted from [50]

layouts, the inclusion of animations representing the system power flow will emphasize the energy delivery correlation between the different elements. Taking into account that in on-board EDS the geographic or coordinate position of nodes is not compulsory for visualizing and understanding the network, the use of force directed graphs [46] to avoid overlapping of lines or the adoption of multi-dimensional scaling with "electrical distances" [47, 48] to infer electrical connectivity, could represent valid alternatives to be taken into account when analyzing troublesome or critical conditions. Nevertheless, all these aforesaid visualization techniques should be handled with care and given on-demand. Otherwise, the user could be overwhelmed with the amount of information visually given [40].

### 5.2 *Thermal Analysis*

The electrical simulation of vehicular EDS is closely tied to the inner thermal characteristics of the electrical components but also to the corresponding elements and environments surrounding them. For instance, the wires resistance can be linearly correlated with the temperature as in Equation 1, being $T$ the ambient temperature and $\alpha$ the temperature coefficient of resistance. This was the approach employed in this work to relate the electro-thermal interaction in wires.

$$R(T) = R(T_0) * [1 + \alpha(T - T_0)] \tag{1}$$

However, to achieve more accurate power flow simulations, there is room for future research regarding an improved estimation of the wires isolation temperature. Nonetheless, as wires in bundles transmit heat between each other, all the wires in their particular harness segment should be also taken into account. Indeed, the wires temperature inference is not trivial given [51]: (i) the great number of wiring harness paths and combinations, (ii) the random distribution of wires in bundles as they are manually assembled, (iii) the presence of wires carrying only control or communication signals, (iv) the non-uniform heat dissipation along the wire's section and length and (v) the difficulty to infer neighboring temperatures due to the thermal particularities of the different vehicle car compartments such as those which house the motor, doors, the bumper, the roof or the base platform. As an starting point, to simulate the thermal response in wire bundles in nominal conditions and during short-circuits, the use of finite element analysis has been presented as a reliable tool [1] suited to enhance user experience and understanding. For instance, Fig. 8 exhibits the radial thermal behavior in a harness for two different wire bundles configuration. This figure provides a brief insight on the complexity to perform accurate electro-thermal simulation when different elements and thermal environments are involved. However, the extension of this tactic to EDS zones or complete harnesses would provide the user with valuable information and intuitive representations of troublesome thermal areas, paths or elements in the electrical network given certain conditions or scenarios.

### 5.3 *New E/E architectures. E-fuses*

Contrary to isolated hardware-oriented architectures, future E/E systems will be designed to integrally merge the vehicle hardware

(ECUs, sensors, actuators, loads, protections, wires, communication and connecting devices) by means of a central computing platform and a unified software. In this respect, on-board EDS are moving towards standardization and scalability. To do so, the incorporation of robust power devices and a new conception of vehicular e-fuses is required [52]. Indeed, e-fuses will dramatically outperform typical electromechanical protection devices (fuses and relays) given their controlled short-circuit current, rapid precise reaction-time and fault-tolerance capability. For instance, specialized EDS software could permit engineers an intelligent parameterization of time-current curves for the different e-fuses in the network, allowing a robust protection coordination. Moreover, some work has been proposed toward enhanced reliability functions by means of safety mechanisms at device and system levels [52] and decentralised modular architectures [53]. Under this last approach, smart distributed power devices can be achieved with different DC/DC converters where conditions such as over-temperature and overcurrent are constantly informed to a master control. Despite some efforts on the initial development of e-fuses some years ago [54–56], it must be mentioned the lack of academic research regarding the integration of smart e-fuses into on-board EDS. Relevant information on this topic can be mainly found in manufacturers or vehicles societies websites as in [53, 57, 58].

In this context towards a paradigm shift favoring universal E/E architectures, significant efforts must be devoted to the development of modular software packages having combined design environments. This will permit to analyze the interaction and avoid conflicts between different vehicular subsystems which are currently designed independently such as the EDS, the high-voltage power conversion system, electric charging, communications network, battery energy management and electro-mechanical traction. This convergence will be reflected on an improved system reliability, programmability and coordination.

### 5.4 Mild Hybrid Electric Vehicles (MHEVs)

In 2019, the amount of fully electric vehicles (EVs), hybrid electric vehicles (HEVs) and plug-in hybrid electric vehicles (PHEVs) sold worldwide (around 2.2 million) represented a 2.5% market share over all vehicle sales [59]. However, by 2030 it is expected to raise up to a 30% share [60]. Hence, until HEVs and EVs get consolidated in the market, sustained efforts are taking place to improve the conventional internal combustion engine (ICE) technology and fulfill European regulations such as the limit of 95 g/km of carbon-dioxide emissions in new passengers cars [61]. In this respect, the incorporation of mild hybrid powertrains have been exposed as a convenient approach to improve fuel efficiency up to 20% with reduced costs [62]. It consists on adding to the conventional 12V battery system, an additional 48V supply. This higher voltage availability in MHEVs permits the extraction of sufficient power to use a small electric motor/generator intended only to assist and act as a power booster for the ICE. By doing so, no insulation upgrades are required and the fuel consumption is reduced by decreasing the engine idling time when the vehicle is stopping, braking or cruising. Moreover, the electric motor can guide the ICE to efficient operating points and even accomplish

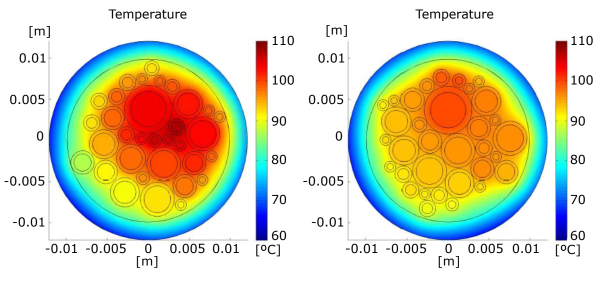


**Fig. 8**: Thermal response for two different wire bundles configuration, adapted from [1]

partial regenerative braking [63]. Given these benefits, automakers are showing high interest in the mild hybrid technology. This is evidenced with some international industrially oriented conferences and expositions which have been taking place in the last years with the aim of consolidating the 48V power supply systems [64].

From the software design point of view, simulation capabilities can be leveraged by considering recent related academic contributions. Between these we have an optimal hybrid energy management [63], low-cost 48V switched reluctance drive [64], DC/DC converter architectures [65, 66], hybridization degree levels [67], motor-inverter power module for electric compressor [68], modelling and validation of lithium-ion battery packs [69] and integrated converters for mild hybrid starter-generators [70, 71].

### 5.5 Vehicular high voltage networks and power converters

In the last years, as the literature reveals, most of the academic effort related to electrical systems in vehicles has been devoted to the development of new power conversion and charging systems towards electrified traction. On this subject, towards electric mobility, two main scenarios are being witnessed: (i) the short-term migration from internal combustion engine vehicles (ICEVs) to MHEVs, already contextualized in the previous subsection and (ii) the progressive strengthening of PHEVs and EVs in the market. For this second scenario to promptly unfold, the design of future on-board E/E architectures and powertrains must be reformulated to suitably integrate high voltage machines (beyond 200 V) requiring high torque and power densities such as those based on permanent magnet materials [72]. The DC-link voltage is nowadays normally designed around 400 V but it is expected to raise up to 800 V where wide-bandgap or silicon-carbide devices are used on the power inverters [73]. Furthermore, automotive manufacturers have started integrating in common enclosures the inverter with the other vehicular power electronics systems in order to minimize connections, reduce size and weight and reuse common functionalities [73]. Additionally, the use of multi-phase and multi-level drivers have been exhibited as an attractive solution to improve torque-density and handle DC-link voltages higher than 800 V respectively [74]. On the other hand, regarding the energy storage in batteries and their charging systems, consistent work has been exposed towards fast and wireless charging [75, 76] and flexible vehicle/grid interaction [72]. As the actual litium-ion based technologies are arriving their theoretical specific energy limits, some research on the use of solid-electrolyte based litium batteries and hybrid energy storage systems (including supercapacitors or fuel cells) has been proposed to favor longer operating cycles, improve power density and increase lifetime [77]. It is also noteworthy the relevance of battery management systems (BMS) to monitor and control proper states of charge (SOC) and state of health (SOH) in the battery packs [77]. In future vehicular EDS, the BMS will be required to be a functional aspect of a universal software able to monitor and control all the relevant low and high voltage electrical components and systems part of the entire E/E architecture. Finally, to enhance resiliency on vehicular EDS, some efforts have been proposed to achieve energy assistance from the high-voltage to the low-voltage side during normal operation modes [78, 79]. Nevertheless, these approaches should be extended to critic or extreme conditions.

### 5.6 Hardware in the loop (HiL)

On-board EDS design and simulation platforms can also take significant advantage from HiL systems in order to attain accurate dynamic models for the different electrical elements, emulate if needed some system components (sensors, ECUs, actuators, mechanical parts) and thus refine and validate the numerical methods. To do so, some HiL experiences in vehicles should be considered and adapted. For instance, HiL has been employed to emulate vehicular ECUs, improve plant models, facilitate rapid-prototyping and perform standardized tests [80, 81]. Research on the use of HiL for assisted and autonomous driving has also been presented [82–84]. An analysis on mechanical-electrical traction shift in HEVs is exhibited in [85]. Additionally, an Internet-based HiL testbed for HEVs, able to integrate distributed vehicular subsystems can be found in [86].

## 6 Conclusions

As a consequence of new regulations, novel electrification trends and higher user demands, the complexity in vehicular EDS has significantly increased in the last years. Hence, EDS design represents a highly demanding stage in the automotive industry manufacturing. In this respect, EDS conception should incorporate versatile interfaces to test different architectures and configurations, anticipate unwanted voltage drops and detect design failures in a prompt stage of the design process. Moreover, computational platforms would permit the analysis of demanding EDS scenarios, beyond to what is feasible through prototyping or on-the-road characterization. This paper has reported strategies and experiences to develop a specialized computer tool for EDS visualization and simulation. Regarding to the software development methodology, some cornerstones such as the SCRUM agile framework, user-centered design (UCD) and open-source libraries have been exposed to leverage teamwork productivity and facilitate rapid software prototyping. By means of the implemented computer tool, broad and detailed level visual representations have been exhibited for realistic EDS harnesses. Consistent power flow simulation results have also been presented given predefined power demand in the consumers. On the other hand, visual analytics (VA) has been exposed as a promising research field able to enhance user experience by means of aesthetic yet functional interfaces. Besides, the adaptation of well proven VA techniques from conventional power systems represent promising alternatives to permit users a rapid and intuitive understanding of the on-board electrical network. As it has been elaborated in virtue of recent research, future simulation and visualization platforms for EDS must be developed to face new challenging technological trends being witnessed by the automotive industry.

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