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Voltage Stabilization in Vehicle Power Nets by Power Distribution Management

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Abstract

Due to more and more electric devices, electrical power consumption in modern vehicles has increased. This development will continue within upcoming electrically powered cars. To ensure reliability, efficient measures have to be developed to handle increased power consumption and to avoid critical voltage drops within the vehicular power buses. Especially in critical driving situations, voltage drops can occur, which may reduce the functionality of affected loads.
Within this paper, a power distribution management system is introduced, which is aimed to avoid critical voltage drops by predictive countermeasures without adding additional components to the vehicle's power net.
For this purpose, a general model for the power distribution management system is developed. It reflects the physical power net setup as well as different cybernetic principles and methods. Based on this model, a prototype is implemented on a real time prototyping unit that is able to ensure voltage stability within a subnet consisting of three intelligent, cybernetic loads. The prototype is verified on a real power net test bench that consists—among other things—of the wiring harness and car body of an actual car.
Thereby, it is shown, that the power distribution management system is effectively able to fight against critical voltage drops in vehicular power nets.

Keywords: control system, controller, efficiency, load management, power management

1 Introduction

In recent years, more and more components in vehicles were electrificated. New electrical systems are installed to improve safety and comfort of the passengers as well as the car's driving performance. Nowadays, up to 80 electronic control units (ECUs) are implemented in a vehicle [1, 2]. As the electric power demand increases, so do the load peaks of the electric power net. Loads as electrical power steering or chassis control systems with 1 to 2 kW peak power are installed in the 12 V power net [3–5]. Due to high power demand and the resulting currents, guaranteeing voltage stability in the 12 V power net becomes difficult and the danger of voltage instability increases [2, 6–8].
For example, a sudden braking and swerving maneuver occurs at $t = 6$ s in Fig. 1. Thereby, several peak loads like Electric Power Steering (EPS), Anti-lock Braking System (ABS), and Electronic Stability Control (ESC) are simultaneously activated causing a transient current demand in addition to the constant current of the base load.

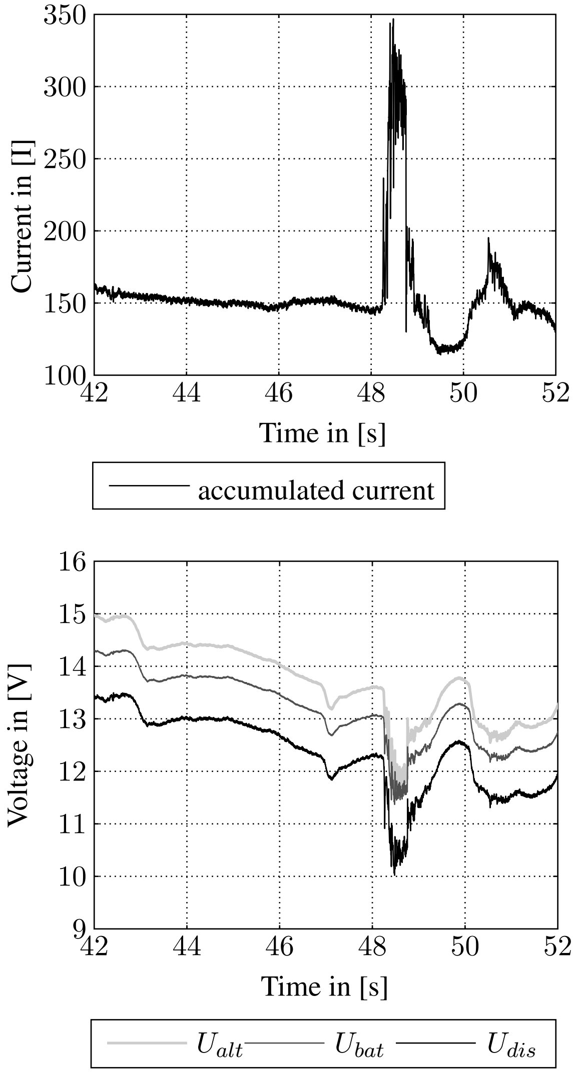

Figure 1: Cut-out of a braking and swerving maneuver: The accumulated current of all loads is shown at the top. It can be seen that the current of the constant loads is superposed by the current of loads like ESP and ABS that are activated during the braking and swerving maneuver. The voltages (bottom) of the alternator (V_{alt}), the battery (V_{bat}), and a power distribution box (V_{dist}) drop significantly in the case of high power demand. The voltages of the loads are even lower.

Due to the low velocity of 15 km/h[1], the alternator is not able to serve the power (see Fig. 1 top) and the voltages decrease from t = 1 s on. When this maneuver occurs, the resulting voltage at the loads' terminals can be lower than 8 V. In order to guarantee the proper functioning of all electrical components, a stable voltage supply has to be realized.
In order to avoid additional weight, cost and a wasting of installation space, different approaches of power management systems have been developed in the last years. Using central approaches [9, 10] or decentralized approaches [11, 12], the basic concept of all approaches is to adjust the balance between the supplied power, the consumed power, or both of them within the power net.
Some approaches have the aim to smooth the power of the consumer loads like [13, 14], others to increase the capability and the dynamics of the alternator [8, 15]. In [6, 16] predictive models are used to enhance the effectiveness of the power management systems. Ref. [17] presents a holistic system approach of a cybernetic power distribution management system that is able to stabilize the power net voltage effectively.

2 Goals and Approach

In this paper, a power distribution management system basing on cybernetic principles is developed. The system's goal is to guarantee a stable and reliable voltage supply within a vehicle power net. First of all, an overview of automotive power buses, the challenges of voltage drops as well as countermeasures against those is given. Thereafter, concept, requirements and assumptions of the power distribution management system as well as the realization are explained. Moreover, the system is implemented on a real time system at a power net test bench and verified in the following section. Finally, a conclusion and an outlook are given.

3 Vehicular Power Buses

3.1 Topology

At first, the power net's topology is presented. Therefore, a 12 V power net of a conventional car is used as an example. In Fig. 2, the schematic topology is shown [18]. Alternator (Alt.) and battery (Bat.) are connected with up to 80 loads

[1] around 9 mph

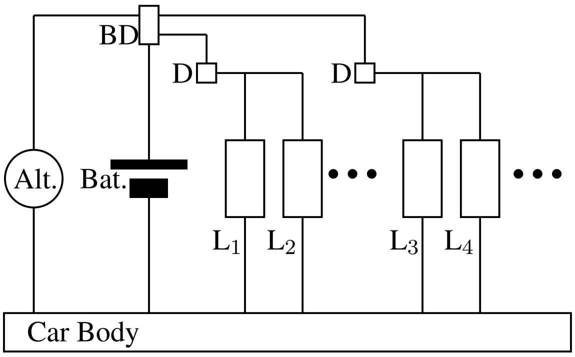

Figure 2: Schematic topology of 12 V vehicle power net [18]. Alternator (Alt.) and battery (Bat.) are connected with loads ($L_1 - L_6$) via battery distribution box (BD), further distribution boxes (D) and wiring harness. The car body serves as return conductor to close the circuit.

[1, 2]. via the battery distribution box (BD), further distribution boxes (D) and the wiring harness. The car body serves as return conductor to close the circuit. Here, the recursive structure is recognizable: In each level a distribution box redistributes the power to the branches of the next level. Normally, there are two (maximum three) hierarchical levels in conventional cars. In hybrid and electric vehicles there is an additional, higher voltage power net and the number of levels increments by one. In this way, the power net's topology can be arbitrary complex, but it consists of recurrent structures that are hierarchically structured.

3.2 Voltage Drops

The voltage within the power net depends on the balance between supplied and consumed power. During normal operation, the alternator is able to supply all power demands, and the battery's terminal voltage is between 13 and 14 V. So, there is a zero current control of the battery's current or the battery is charged. If the power demand of all loads exceeds the alternator's supply, the power is unbalanced and the battery has to take the power differential. Now, the battery's terminal voltage falls below 12 V.
From the battery's internal voltage to the terminals of the load, there is a fall of voltage at the internal resistance of the battery, the power distribution units, fuse boxes, the wiring harness, and even in the car body. These losses are significant, and can not be neglected—especially in critical situations as shown in the example of the sudden braking and swerving maneuver in Section 1.

3.3 Countermeasures

If critical situations—having a short rise time of power—are predicted in due time before the event, a few countermeasures can be initiated: For instance, the power supply of the alternator can smoothly be increased. On the other hand, the power demand of non-critical loads can be temporarily reduced. Most of all, heating elements are predestined because a function failure is not recognizable for some seconds.
If these measures are planned properly and prepared in advance to become fully effective at the moment of the critical situation, the voltage drop can be stabilized.
In the next section a power distribution management system is presented that monitors the environment, conducts and coordinates countermeasures in order to stabilize the power net voltage.

4 Concept and Requirements

In order to reduce voltage drops in vehicle power nets, a power distribution management system is developed. This system receives data about future driving situations that may affect voltage stability. With this data, the power distribution management system can calculate the future power demand within the vehicle. If it detects upcoming voltage drops, countermeasures, like the ones mentioned above, are taken to ensure voltage stability within the vehicle's power net.

4.1 General Assumptions

To make the system work, two assumptions have to be made: Predictions about future driving situations have to be available to the power distribution management system and the power net's components like loads, alternator, and so on need some kind of intelligence to perform certain actions.

4.1.1 Prediction Module

To provide data about future driving situations, a prediction module is developed in parallel to the power distribution management system. This module evaluates different kinds of sensor data in order to predict power critical driving situations like the example in Section 1. For the development and validation of the power distribution management system, the prediction module was replaced by a dummy, which provides suitable input data to the power distribution management system.

4.1.2 Intelligent Loads

The vehicle's electrical loads need extended capabilities to interact with the power distribution management system. On the one hand, they need to provide data about their actual power consumption and power reserves. On the other hand, they have to be able to prepare cooperatively for upcoming voltage drops. Such loads were introduced and implemented in [19].

4.2 Requirements based on the Application of Cybernetic Principles

In [17], it was suggested to consider the following cybernetic principles for the development of a power distribution management system in order to achieve a lean und efficient system well suited for vehicle applications:

1. **Detachment of object and management layer**: This is necessary to enable uniform and recursive system definition.
2. **Introduction of hierarchy and recursive definition**: Due to the complexity of the vehicle power net, a hierarchy has to be introduced. Recurrence describes a modular system architecture, in which every subsystem is only responsible for its subjects.
3. **Principle of subsidiarity**: The subordinated subsystems are only responsible for their sections. If they cannot achieve their goals (e.g. local voltage stability), superior subsystems step in.
4. **Interaction between the system and its environment**: Modeling of the environment is necessary to consider sudden driving situations or weather conditions.
5. **Fuzzy modeling**: Within the vehicle, there is a high degree of uncertainty due to the amount of sensor data or different ways of driving. This uncertainty has to be modeled accordingly.
6. **Reduction of the complexity by abstraction and data compaction**: To enable efficient power distribution management, information has to be abstracted and condensed deliberately.

Based on these principles, requirements for the power distribution management system can be deduced (numbers in brackets indicate the cybernetic principle considered for the respective requirement):

- **Depiction of the vehicle's power net (2):** The power distribution management system should depict the physical architecture of the vehicle's power net (see Section 3). Thereby, the system can be structured according to the hierarchical setup of the power net and a division into suitable subsystems is possible.
- **Enclosure and modularity (1 and 2):** Division into subsystems should enable a recursive system structure. Through uniform interface definition, modularity can be achieved, which enables a flexible and extensible system structure.
- **Uniform variables (3, 4, 5, and 6):** To create a modular architecture across all hierarchical levels of the system, it is necessary, that every subsystem works with the same variables. Thereby, the system can be tailored easily to any power net topology. The variables do not need to include every detail, but should indicate the condition of the respective subsystem.
- **Local responsibility (2 and 3):** Hierarchy should be used to achieve local responsibility for every subnet of the vehicle's power net. In every subnet, voltage should be stabilized locally. Only if local stabilization fails, countermeasures across several subnets should be taken. This saves communication traffic between the power distribution management system components and modules.
- **Information compaction (5 and 6):** Vehicle power nets are complex architectures. Therefore, information should be compacted intelligently to enable efficient power distribution management.

5 Realization

Based on the requirements from Section 4, the power distribution management system was developed. An overview is given in Fig. 3. The power distribution management system consists of three different kinds of components: Interfaces, conversion layers and power distribution management layers. In this section, the functionality of the different components is explained. In certain equations, e.g. when power demand is subtracted from power supply, negative results have to be avoided by additional provisions. In order to focus on the main calculations, this is not described within the following explanations. To illustrate the functionality of the power distribution management system an exemplary intervention to prevent a voltage drop is described in Section 5.4 (Example).

5.1 Interfaces

The power distribution management system has to be able to communicate with the prediction module and the intelligent loads within the vehicle's power net. Therefore, interfaces for every subpart of the power net are necessary to receive and transmit the actual signals.

The intelligent loads provide actual voltages v_{actj}, currents i_{actj} and minimal-currents i_{minj}. After calculating necessary countermeasures, the power distribution management system sends a target voltage value v_{tarSN} as well as start point t_{tarSN} and length of the target interval T_{tarSN} to the intelligent loads. With this data, the loads are able to raise the voltage within a subnet to a certain target value for a specified interval, by reducing their power consumption up to the limit of their individual possibility.

The prediction module provides types k, intensities I_k as well as start points t_k and interval length T_k of the two most likely predicted driving scenarios. More the one scenario is transmitted because there may exist different scenarios with the same indicators. The number of two was chosen because it is a compromise between incomplete and too much information.

5.2 Conversion Layers

Conversion layers translate the received signals from the interfaces into the uniform variables with which the power distribution management layers work. Furthermore, the calculated results from the power management layers have to be translated into signals the intelligent loads are able to handle.

With the received data from the intelligent loads actual power consumption P_{actSN} and power reserves P_{resSN} can be calculated for every subnet:

$$P_{actSN} = \sum_{j=1}^{n} (v_{actj} \cdot i_{actj} + R_{Lj} \cdot i_{actj}^2) \quad (1)$$

$$P_{resSN} = \sum_{j=1}^{n} [(i_{actj} - i_{minj}) \cdot v_{actj} + \\ + R_{Lj} \cdot (i_{actj}^2 - i_{minj}^2)] \quad (2)$$

R_{Lj} describes the line resistance of the cable that supplies load $j \in \{1, \ldots, n\}$. Thereby, power consumption and power reserves caused by these resistances can be considered. In (2) it is neglected that, because of line resistances, currents would change if voltages change. Therefore, a complete physical model of the vehicle's power net, including the exact behavior of all components, would necessary, which is on the one hand difficult to develop and on the other hand far too complex to realize an efficient power distribution management system.

Input data from the prediction module gets processed in the conversion layers, too. Based on the predicted driving scenarios and their intensities, the additional power consumption in the subnet P_{addSN} during the future driving situation is calculated:

$$P_{predj} = P_{maxj} \cdot \max_k (b_{kj} \cdot I_{kj}) \quad (3)$$

$$P_{addSN} = \sum_{j=1}^{n} (P_{predj} - P_{actj}) \quad (4)$$

In (3), the predicted power consumption of every load is calculated. For every scenario k (and every subnet), there exists a vector b_k which indicates which loads are affected by this specific scenario. Every element b_{kj} of this vector, either one or zero, is multiplied with the intensity I_k of the respective scenario. Using the maximum for every predicted scenario and multiplying it with the maximal power consumption the predicted power consumption for each load is calculated [2]. In (4), the difference of predicted and actual power consumptions gives the additional power consumption for every subnet P_{addSN} within the critical driving scenario.

Furthermore, starting point and interval length during that the additional power consumption applies is needed. Therefore, the minimal starting point t_{pred} and the maximal timeframe T_{pred} of the scenarios is used:

$$t_{pred} = \min_k (t_k) \quad (5)$$

$$T_{pred} = \max_k (T_k) \quad (6)$$

Moreover, the conversion layers have to translate commands from the power distribution management layers into signals the intelligent loads can process. Power distribution management layers

[2] In general, the computing effort is low because the prediction has to cover only a few loads like electrical power steering or chassis control systems.

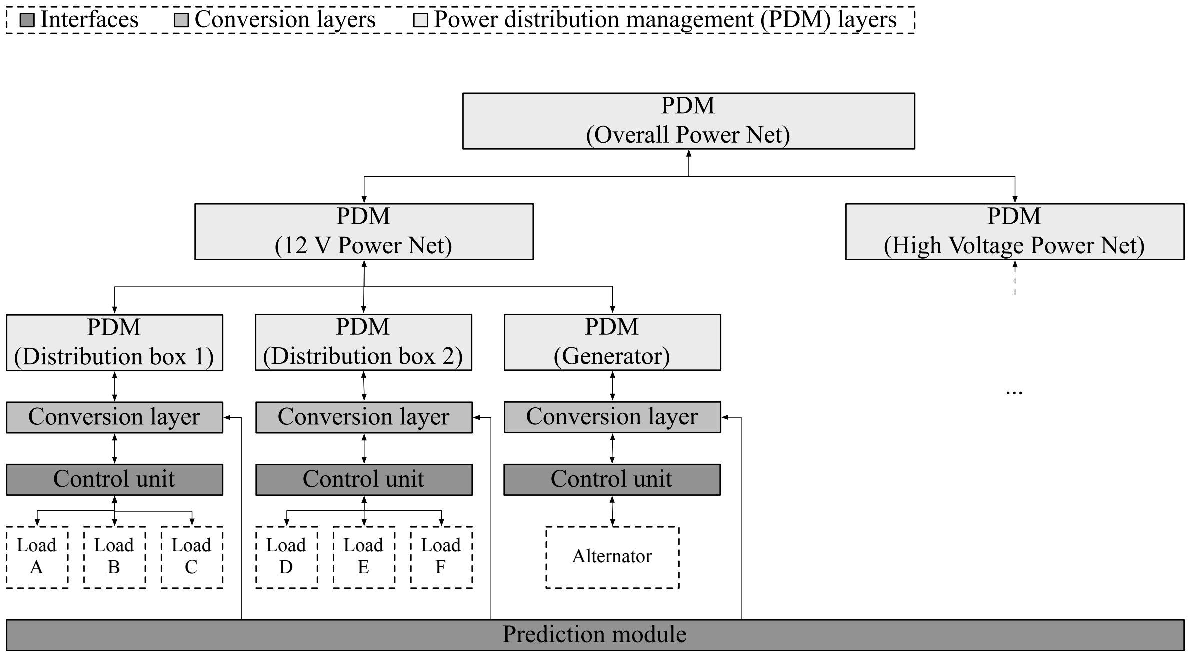

Figure 3: Overview of the hierarchical organized power power distribution management system. Power distribution is managed locally for each subnet. Overall coordination takes place at higher levels. Conversion layers are necessary to enable communication to cybernetic control units and the prediction module.

calculate a target power consumption P_{tarSN} for every subnet. This value can be translated into a target voltage v_{SN} by equations that result from analyzing the electric circuit:

$$v_{SN} = \frac{v_0 + \sqrt{v_0^2 - 4P_{tarSN}(R_L + R_i)}}{2} \quad (7)$$

R_L is the line resistance to the subnet, u_0 and R_i are the battery's open circuit voltage and internal resistance. Starting time and interval length are simply forwarded.

5.3 Power distribution management

For every subnet there is a respective power distribution management layer to stabilize voltage locally. Generally, signals are forwarded to the superior level, where overarching countermeasures can be initiated. The algorithms for every level are the same, resulting in a hierarchical and recursive organization of the power distribution management system.

Starting point and interval length for countermeasures are calculated similar to (5) and (6). However, on subnet level this is trivial, as there is in each case only one input value.

Furthermore, target power consumption for each subnet has to be calculated. To do so, the surplus power P_{spSN} is calculated first:

$$P_{spSN} = P_{actSN} + P_{addSN} - P_{critSN} \quad (8)$$

This is the power consumption that exceeds the critical power consumption, which indicates the maximal power consumption without resulting in a voltage drop below a critical minimal voltage v_{critSN}. By analyzing the electrical circuit, the following equation for the critical power consumption can be found:

$$P_{critSN} = \frac{(v_0 - v_{critSN})v_{critSN}}{R_L + R_i} \quad (9)$$

Based on the surplus power P_{spSN}, the target power consumption P_{tarSN} can be calculated:

$$P_{tarSN} = P_{actSN} - \min(P_{spSN}, P_{resSN}) \quad (10)$$

This is the power that may be consumed within the subnet so that the predicted upcoming power consumption does not result in a voltage drop below v_{critSN}.

5.4 Example

In this section, an exemplary intervention by the power distribution management system is described to illustrate its functionality.

During regular driving, the power distribution management system is in idle mode. Suddenly, the prediction module detects an upcoming critical driving situation as described in Section 1. At

the conversion layers, the predicted driving scenario is translated into power requirements. Together with actual power demand and reserves, it is forwarded to the lower power distribution management layers. One of the power distribution management layers recognizes an upcoming voltage drop in its subnet. As a countermeasure, all available power reserves in the subnet are freed. This instruction is forwarded to the subordinate conversion layer and from there to the cybernetic load control. The cybernetic load control presents its instructions and the connected loads adapt their power consumption autonomously.
However, these measures are not enough to prevent a critical voltage drop. Therefore, the subnet power distribution management layer consults its superior power distribution management layer. There, instructions to reduce power consumption are forwarded to other subnets. Furthermore, the generator is ordered to provide more power. By decreasing the power consumption in further subnets and by increasing the power supply of the generator, the critical voltage drop can finally be avoided.

6 Implementation

In order to verify the power distribution management system described above, a real power net including wiring harness and distributed loads is necessary. Since it is nearly impossible to replicate driving scenarios one to one in a real vehicle, a power net test bench is built up that faithfully reproduces the real power net:

- A real wiring harness and a real car body ensure a realistic voltage behavior in the supply and return conductors. The whole installation is shown in Fig. 4.
- Since only the terminal behavior and not the internal electric functioning of the consumer loads is relevant for voltage stability issues, the consumer loads are substituted by regulated electronic loads that emulate the behavior of actors and control units. Altogether, 24 loads are built in the test bench. These loads can demand arbitrary power profiles—measured in test vehicles or synthetically created.
- A real battery is included as energy storage.
- A regulated power supply unit emulates the alternator. It is controlled by a real time system that executes a physical alternator model.
- A grid of over fifty voltage and current measurement points monitors the power net. All measured data are recorded using a LabVIEW program [20].
- The control of the power net, switches, relays, loads, and alternator is also done by a LabVIEW program.
- The power distribution management system described above as well as the prediction model are implemented on a dSPACE MicroAutoBox. The interface between the cybernetic components of the power net and the power distribution management system is realized by a CAN bus.

In the next section experimental verification of the functioning of the power distribution management system are conducted on the power net test bench.

7 Verification

Test results indicate that the power distribution management system is able to reduce voltage drops in vehicle power nets. Two examples with different prediction horizons are shown in Fig. 5 and 6. In each case, Load C performs two sudden power consumption increases[3]. During the first ones, a voltage drop below $11.6\,\mathrm{V}$ at the distribution box occurs. During the second ones, the introduced power distribution management system is activated, avoiding a critical voltage drop. The power distribution management system receives prediction data about the approaching second power consumption increase. To compensate the voltage drop, a maximal power consumption for the subnet is calculated in the power distribution management layer, translated in the conversion layer and forwarded to the intelligent loads A and B. These loads cooperatively reduce their power consumption to avoid the critical voltage drop. Although, there is no communication between the two loads, the desired voltage value is reached in a stable manner.
It has to be remarked, that the critical voltage during that experiment was defined as v_{critSN} $=11.8\,\mathrm{V}$. As the capacitive behavior of the battery was not considered in the algorithms, the voltage at the distribution box rises above $12.2\,\mathrm{V}$—far more than necessary to compensate

[3] These power consumption increases are basically rectangular pulses of the current at load C. This is meant to resemble sudden current peaks at loads like the power steering or chassis control systems.

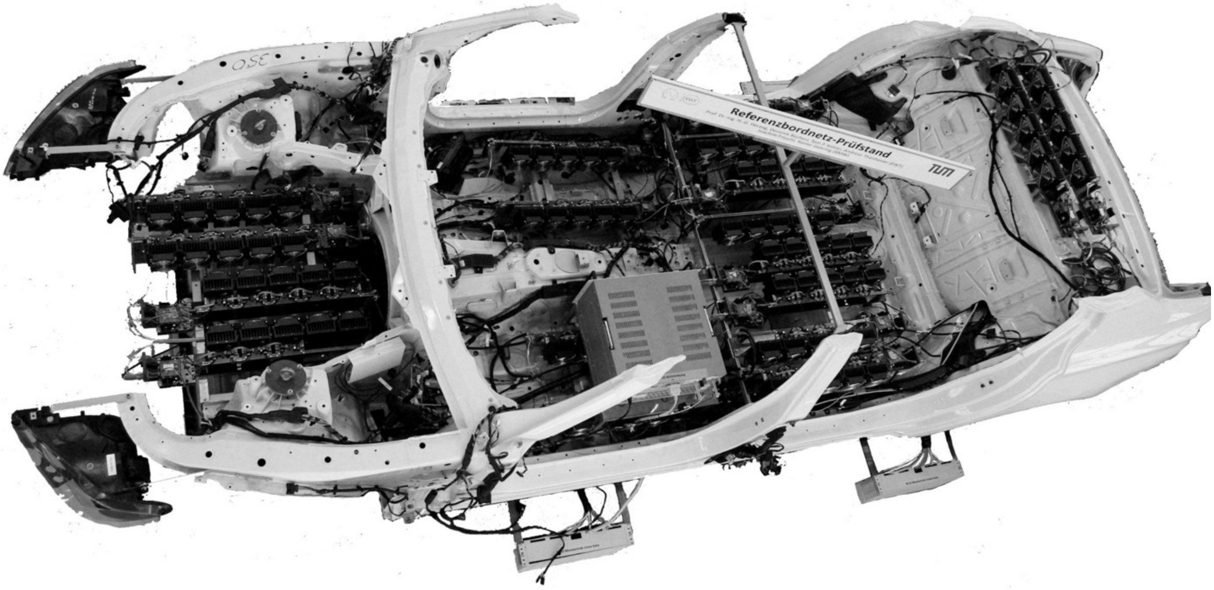

Figure 4: The power net test bench bases on a luxury class car body and wiring harness. Further components are battery, alternator, and several regulated electronic loads with high dynamics. The boxes in the lower part of the figure contain the measurement equipment. The control equipment is not shown.

the voltage drop. This overcompensation can either be used as an additional buffer to deal with uncertainties or be removed by considering internal capacities of the battery.

8 Conclusion and Outlook

To avoid critical voltage drops in vehicular power nets, a predictive power distribution management system was introduced in this paper. A prototype was implemented on a real time computer and verified on a power net test bench. Results indicate that the power distribution management system is able to avoid critical voltage drops and guarantee voltage stability within the vehicular power net.

In the next stage of development, more loads and subnets should be included into the power distribution management. Furthermore, the management interventions mainly bear on the consuming side at the moment.

As an extension to the introduced system, the alternator (supplying side) can be included in future works. Thereby, the alternator can be used to provide additional countermeasures to avoid critical voltage drops. In addition, the power distribution management system can be extended to a further hierarchical level. For this purpose, a higher voltage level is currently built up at the test bench. Using this, all effects of multiple voltage level cars, such as electric cars and hybrid electric cars, can be studied.

Finally, after the development of a system that covers the whole vehicular power net, it would be desirable to deploy a prototype to real vehicle in order to test the system on the road.

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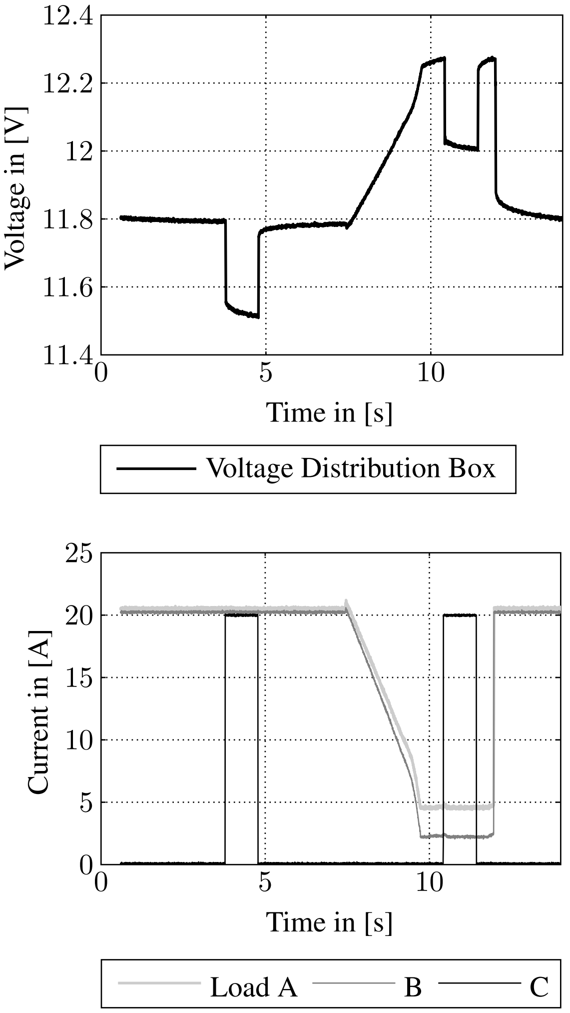

Figure 5: Effects of a 20 A peak on the voltage at the distribution box. Three seconds before the second peak, the power distribution management system calculates countermeasures to compensate. As a result, power consumption of load A and B are reduced to compensate the voltage drop.

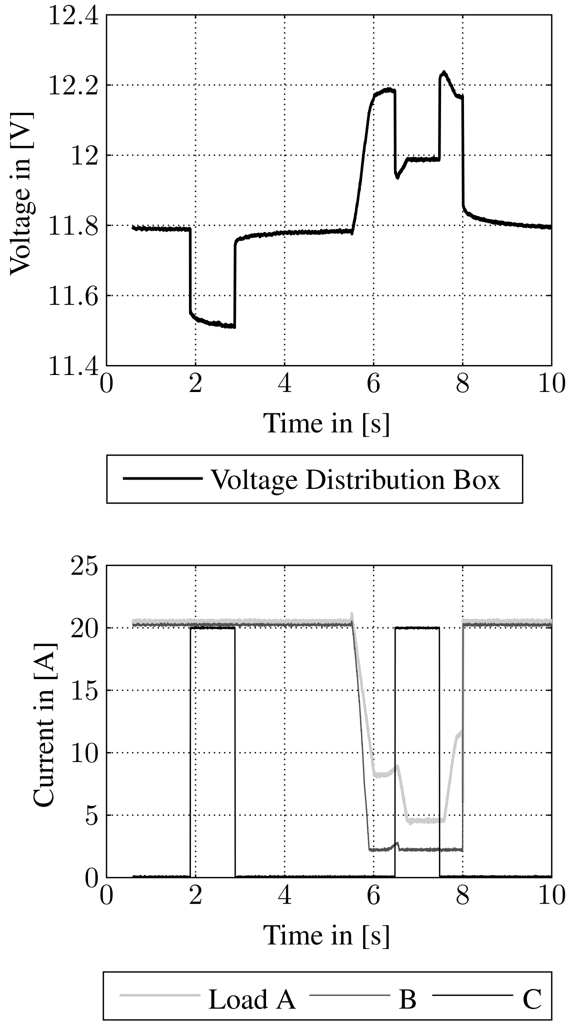

Figure 6: Effects of a 20 A peak on the voltage at the distribution box. One second before the second peak, the power distribution management system calculates countermeasures to compensate. As a result, power consumption of load A and B are reduced to compensate the voltage drop.

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