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Experimental Investigations on Voltage Stability in Multilevel Power Nets

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Abstract

In recent years, more and more components in vehicles have been electrified in order to improve the safety and comfort of the passengers as well as the driving performance. Owing to these developments, it has become increasingly difficult to guarantee the voltage stability within the 12 V as well as the high voltage power bus.
However, a new degree of freedom arises, as the two power nets are connected in order to exchange energy. As a consequence, they are able to stabilize their voltage reciprocally. This paper deals with the analysis of how two voltage levels can be coupled actively in order to stabilize their voltages in power demanding situations.
A power net test bench consisting of a 12 V power net and a high voltage power net is built. In the 12 V power net, original chassis and wiring harness are used in order to achieve the most realistic behavior. Furthermore, there are two control modes presented. In the power control mode, the power flow is increased preventively when the prediction model detects a critical situation that is likely to occur in the near future. In the voltage control mode, the voltage controller of the DC chopper converter is used to stabilize the power net voltage in real time. Both control methods can easily be implemented into a universal power distribution management system.
The voltage control mode is experimentally investigated at the power net test bench and it is shown that the minimum voltage in very power-consuming driving situations is increased by about 1.5 V per 1000 W of applied power supplied by the DC chopper converter.

Keywords: chopper, control system, DC-DC, power, power management

1 Introduction and Motivation

In recent years, there has been a movement toward increasing electrification in conventional automotive vehicles. Both the quantity of electronic control units and the dynamics of the power consumption of the loads power have increased:

- In today's luxury class vehicles there are up to 80 ECUs [1, 2]. More and more components, which were previously mechanically driven, are now electrically operated [3].

- Loads such as electrical power steering or chassis control systems consume up to 2 kW peak power [4, 5].

Due to these developments, it has become more and more difficult to guarantee voltage stability within the 12 V power system [6–9].

These developments lead to voltage instability in situations when a sudden power increase occurs such as swerving maneuvers or parking maneuvers (see Section 4, Voltage Drops, for further explanations). These voltage drops in the power nets of conventional vehicles can be noticed by the passengers, for example by light flickering or malfunction of electric control units. As a result, there have been a lot of considerations on how to modify the architecture of the automotive electrical power systems in the past twenty years [10–12]. About ten years ago, the introduction of an additional 42 V level was being discussed in order to reduce the currents drawn from the power net as well as the voltage fluctuations that are caused by high power loads [13, 14].

Furthermore, in the development of hybrid electric vehicles and pure electric vehicles that is currently happening, the electric peak power has reached a new level again. On the other hand, the voltage level is much higher than in conventional vehicles and, at first glance, the currents as well as the voltage drops are lower. However, efficiency plays an important role in electric cars. So in fact, all components of the power buses—e.g. wirings or the battery—are designed to take as little space and weight as possible. In this case, efficiency is defined so that the relation between consumed power and installed power is as high as possible. Therefore, automotive power nets must operate close to their limits, no matter whether implemented in conventional or electric vehicles.

In this context, it becomes apparent that voltage drops are a real challenge in both 12 V and high voltage power nets. However, a new degree of freedom arises, as the two power nets are connected in order to exchange energy. As a consequence, they are able to stabilize their voltage reciprocally.

Therefore, there are two central questions in the focus of this paper:

- How significant is the stabilizing effect of two power nets with different voltage levels stabilizing each other in power demanding situations?

- How can a power distribution management system be designed that efficiently manages the coupling between the voltage levels?

2 Goals and Approach

This paper deals with the coupling of two voltage levels in automotive power buses, in order to stabilize their voltage. For this purpose, a power net test bench is built up that provides a realistic replication of a multi voltage level power net. After the occurrence of voltage drops is described, suggestions are made on how an active power distribution management may control the power flow between the two voltage levels, in order to improve the voltage stability.
Furthermore, it is examined in practical tests at the test bench, to what extend both power nets are able to stabilize each other. Finally, a conclusion and an outlook are provided.

3 Test Benches

This section briefly describes the set-up of the two power net test benches and their connection. Ref. [15] provides a description of the 12 V power net test bench in detail.
Initially, the components involved in the 12 V power net test bench are described, followed by the components of the second voltage level. Finally, control and measurement as well as the connection between both of the voltage levels are presented.

3.1 12 V Power Net Test Bench

The goal of the 12 V power net test bench is to provide a realistic replication of a vehicular power net that can be "virtually cruised around" in arbitrary driving situations and environmental scenarios. The whole installation is shown in Fig. 1. In the following, the components of the test bench are briefly described:

3.1.1 Storage/Battery

Real batteries are used for the test bench. Several commercial battery sizes can be employed to model all car sizes, ranging from compact to luxury class cars.

3.1.2 Source/Alternator

The alternator is emulated by a physical model, which is executed on a real time system and a regulated 300 A power supply unit. Moreover, it is possible to integrate real alternators powered by a electric machine that emulates the behavior of the internal combustion engine.

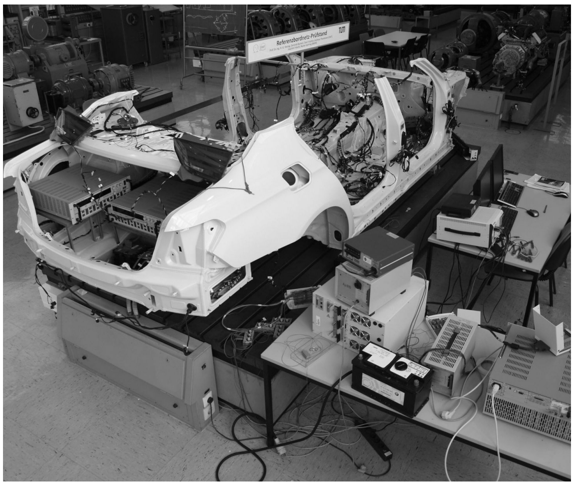

Figure 1: The power net test bench bases on a luxury class car body and wiring harness. Further components are battery, alternator, and several regulated electronic loads with high dynamics.

3.1.3 Electric Loads

Since only the terminal behavior of the ECUs and not the internal functionality is of interest, the ECUs and actors themselves are not built in. They are substituted by regulated electronic loads instead, which can demand specific power profiles and emulate the behavior of the real loads.
The structure of up to 80 electric loads is very complex in today's cars. However, it is possible to reduce the complexity retaining nearly constant accuracy as presented in [7]. For example, two loads using the same distribution box and grounding bolt can be substituted by a common load module or, in other cases, several smaller loads can be combined to form a larger load module. While placing the electric loads, the power bus' structure is strictly taken into account.
On the whole, there are 24 load modules built in. Some of these are implemented with very high dynamics (200 A per 1 µs), emulating the actors with highest dynamic demands like the power steering actor, chassis control systems, and the audio amplifier.

3.1.4 Wiring Harness and Chassis Ground

For a realistic analysis of the behavior of the voltage, the distributed structure must be reproduced as accurately as possible: Thus, the exact location of loads, power distribution units, fuse boxes, and clamp control is important. In this test bench, a real wiring harness of a luxury class vehicle is used. The negative terminals of all components are connected via wires to grounding bolts that are welded to the car body, which serves as the return conductor to close the circuits between the negative terminals of components and the battery. Fig. 1 shows all components integrated in the car body.

3.2 Second Voltage Level Test Bench

3.2.1 Wiring Harness and Architecture

In contrast to the 12 V power net, the high voltage power net is not a replication of the power net architecture of a real car. The reason for this is that the focus lies on the coupling between the two voltage levels and not on the voltage effects within the wiring harness. The voltage behavior can be studied at the 12 V power net test bench and the results can be transferred to other voltage levels (detailed investigations can be found in [7, 15]).
Since the absolute voltage level is not relevant to analyze the coupling of voltage levels, a voltage level of about 48 V is chosen for reasons of safety and convenience.
The dimensioning of the components like storage or loads follows those of today's commercial mild hybrid electric vehicles. In doing so, a market analysis is carried out considering the power net's components of different hybrid electric vehicles as the BMW ActiveHybrid 7 (2009). The average values of the found data are used to dimension the components of the test bench.

3.2.2 Battery

A lithium iron phosphate battery consisting of 64 single cells is built in (see Fig. 3). Its capacity is 40 Ah and the open-circuit voltage is 51.2 V (16 3.2 V cells in series). The most important battery parameters like temperature, state of charge, and charge are monitored by a control unit, which is directly integrated into the battery housing.

3.2.3 Source

A regulated 10 kW power supply unit with very high dynamics (min. 267 W per µs) is integrated.

3.2.4 Loads

A regulated electronic load functions as energy and power sink, respectively. It can emulate loads up to a power of 7.8 kW. Due to the dynamics of up to 240 A in 50 µs, high dynamic loads can also be emulated. Thus, in combination with the power supply unit and a real time model, the

behavior of the electric machine of a hybrid electric or pure electric vehicle can be emulated. For this purpose, an interface to a vehicle simulation tool [16] is currently being developed.
All components are built in a switch cabinet that is shown in Fig. 2.

3.3 Control and Measurement

Both control and measurement of the the test bench is realized in LabVIEW [17]. The LabVIEW program controls the load's power profiles, as well as the real time model of the alternator.
A grid of over fifty voltage and current measurement points reports the state of the 12 V power net. That amount of sensors is necessary because of the potential drops within the wiring harness and the car body. Furthermore, there are nine additional voltage and current measurement points built in the high voltage power net. The interface to the system's environment allows simulating recorded driving cycles as well as critical situations like the braking and swerving maneuver mentioned in the next chapter.

3.4 Coupling of the two Voltage Levels

Both voltage levels are coupled by a DC chopper converter. DC chopper converters for automotive applications are an object of research and development as in [18, 19]. The maximum transfer power of the used device is 1.2 kW, i.e. the maximum currents are 200 A on the 12 V side and 50 A on the 48 V side.
The wiring between the two voltage levels is implemented using low-inductive wires because of a distance of about four meters between the 12 V test bench and the switch cabinet that contains all components of the high voltage test bench. The ohmic resistance of the wirings can be compensated by the control algorithm.

4 Voltage Drops

During normal operation, the alternator (Alt.) is able to supply all power demands. In case of a superposition of the power peaks of several loads, the alternator can reach its limits—especially in driving situations of low velocity. In such cases, the battery has to supply the difference between the alternator's power supply and the power demand of all consumer loads. Furthermore, the alternator is not able to follow the dynamics of the loads and the battery generally has to buffer the transient power peaks. In these situations,

Figure 2: The components of the second voltage level test bench that are built in a test bench. The battery is separately placed, see Fig. 3.

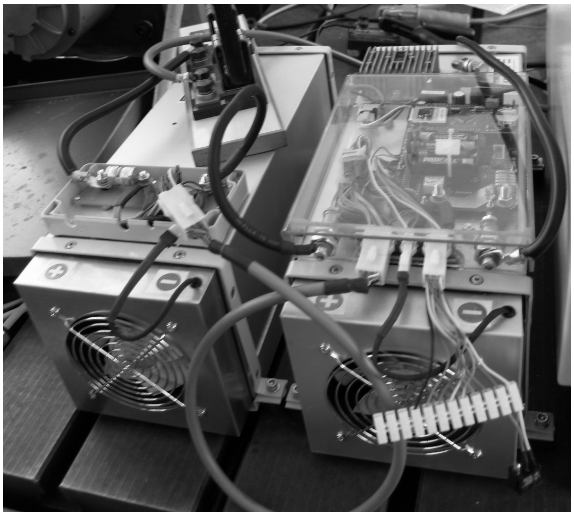

Figure 3: The lithium iron phosphate battery of the high voltage power net.

the voltage drops from about 14 V to less than 12 V (depending on the load of the internal resistance battery). Further voltage drops occur in the wiring harness, the distribution and fuse boxes, and the car body as return conductor. Fig. 4 shows the test sequence of the experimental investigations (Section 7), which consists of several critical driving maneuvers.
Using a fully charged battery, the minimum voltage is about 11.9 V at the battery (see Fig. 4) and less than 10 V at the load in the braking and swerving maneuver. More significant voltage drops occur if the battery is discharged. At voltages below 9 V, most loads encounter difficulties fulfilling their functions or even lead to malfunctions that can be perceived by the passengers as described in the introduction (Section 1).

5 Power Distribution Management

Plenty of countermeasures exist to stabilize the voltage in critical situations (these measures are described in [7] in detail):

- increasing the alternators power predictively
- equalizing of power peaks
- degrading of loads such as heating elements temporarily

Due to the limited dynamics of the alternator and the loads, most of these measures can only be initiated in advance.

In [20] a power management system was presented that is able to coordinate the mentioned measures efficiently using cybernetic methods. Cybernetics was coined by Norbert Wiener learning from nature and transferring control methods and processes from nature into engineering and technology [21, 22]. Ref. [20] and [23] show that the control of a complex system with an unknown control path becomes more effective using decentralized, intelligent components. Cybernetic, intelligent loads that can autonomously react to the power situation are presented in [24].
When dealing with more than one voltage level, another countermeasure exists: The power flow of the DC chopper converter between the two power nets. The current of the DC chopper converter commonly depends only on long term energetic key figures such as the state of charge of the battery. In the next part of this paper, it is discussed whether and how a cybernetic and intelligent DC chopper converter is able to stabilize the voltage of each power net. In this way, short term power and stability figures become part of the control strategy of the DC chopper converter that is integrated in the cybernetic power distribution management system.

6 Cybernetic DC Chopper Converter

In the cybernetic power management, the DC chopper converter is modeled as a bidirectional electric-electric energy converter.[1] It can be used in two operation modes:

6.1 Current/Power Control Mode

If the power distribution management predicts a power-critical event in the near future, it will be possible to condition the power net and its components. Without having a second power net, the alternator's current can be increased, for instance.[2] Here, the current of the DC chopper converter can be predictively increased. Likewise, the voltage at the terminals of the battery and in the whole power net increases. While the critical event is occurring, the absolute voltage drops are the same, but their minimum is on a higher voltage level, which results in a stabilization effect on each component of the power net. Due

[1] Loads are analogly modeled as electro-mechanic converter, electric-thermal converter and the like. The alternator is modeled as a mechanic-electric energy converter.

[2] Current and Power can be converted into each other by multiplying by the power net voltage.

to the similarity of the DC chopper converter increasing its current, the alternator increasing its current, or the loads decreasing their current, the same interface can be used by the power management in all cases. Hence, the power management system does not need to distinguish between the components. From the perspective of the power management, all components are only assessed by their capability to increase (sources) or decrease (loads) their current and can be addressed by using the same control commands. Therefore, the DC chopper convertor can be operated by using the control algorithm presented in [24] for intelligent, cybernetic loads. Getting the input values

- delta current to stabilize,
- time to the critical event (e.g. a driving maneuver, and
- duration of the critical event,

the DC chopper converter can stabilize the voltage in coordination with the other components (alternator and power reducing loads).

6.2 Voltage Control Mode

In contrast to the other components, each DC converter mandatorily has a voltage control unit included.[3] Obviously, this feature can be used to stabilize the power net voltage: The power distribution system provides a voltage set point to the DC chopper converter that tries to force the power net voltage to that specific set point. If a power load is applied, the DC chopper converter will adjust the voltage within its possibilities.
In the next section, experimental analysis on these two operation modes is conducted and the results are presented.

7 Experimental Results

The goal of this analysis is to identify the factors that influence the stabilization of the vehicular power net as well as their sensitivity. Therefore, the settings of the DC chopper converter are varied and the resulting effect on the voltage stability is analyzed. In the first part of this section, the set-up of the sensitivity analysis is described. Following, the results of the voltage stability test at the power net test bench are presented.

[3]The alternator has a voltage control included as well, but its dynamics are limited to avoid unwanted retro-activity to the internal combustion engine.

7.1 Set-up and Test Sequence of Sensitivity Analysis

To achieve significant results in the sensitivity analysis, it is necessary to simulate the environment of the power net of a real car as authentic as possible. For this purpose a regulated 300 A power supply unit, set to an output voltage of 56 V, is coupled to the 12 V power net test bench (see Section 3) using a DC chopper converter. Furthermore, the built-in power supply of the power net test bench that emulates the 12 V alternator is removed so that all the power is fed into the system via the DC chopper converter.
In order to evaluate the occurring voltage drops, a realistic test sequence is used rather than generating a synthetic power profile as it provides more accurate results. This test sequence was produced by taking measurements of the current flow in a car that drove specific, pre-defined maneuvers. The most significant maneuvers therein are those that are very power consuming and, consequently, critical for voltage stability, such as the braking and swerving maneuver mentioned above. Herein, power peaks of Electronic Power Steering (EPS), Electronic Stability Control (ESC), and rear active steering occur.
Thus, the test sequence is composed of a turnaround maneuver, followed by a sudden braking and swerving maneuver, a short synthetic section (ramp function), and finishes with a repetition of the turnaround maneuver from the beginning (see one cylce in Fig. 4). The turnaround maneuver, which lasts for about twelve seconds, contains three peaks of high current demand over 100 A. The braking and swerving maneuver begins at a speed of 15 km/h[4] at t = 27 s and lasts for about 4 s. Herein, the maximum current peak of nearly 190 A occurs. The 20 s ramp function is added to require the power net's capability to provide a high constant power demand. Finally, the turnaround maneuver is repeated to be able to compare the voltage behavior after some changes in the state of charge of the batteries. The complete test sequence is about 70 s long.
The current peaks yield voltage drops as shown in the voltage characteristic of the test sequence in Fig. 5. The thick black line (lowest curve) ist the voltage when the 12 V power net is not stabilized by the high voltage power net. Eight local minima (A to H) are used as characteristic points of the sensitivity analysis. All tests are evaluated at these characteristic points. Hence, a comparison becomes possible.

[4]about 9 mph

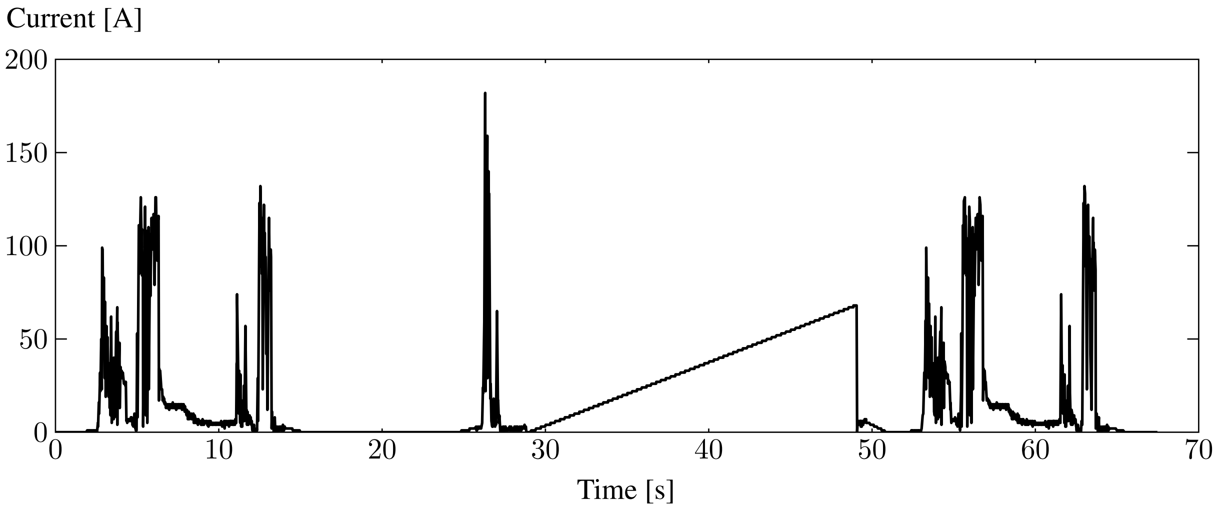

Figure 4: Test sequence consisting of cut-offs of a turnaround maneuver, a braking and swerving maneuver, a linear current increase (synthetic), and again the turnaround maneuver.

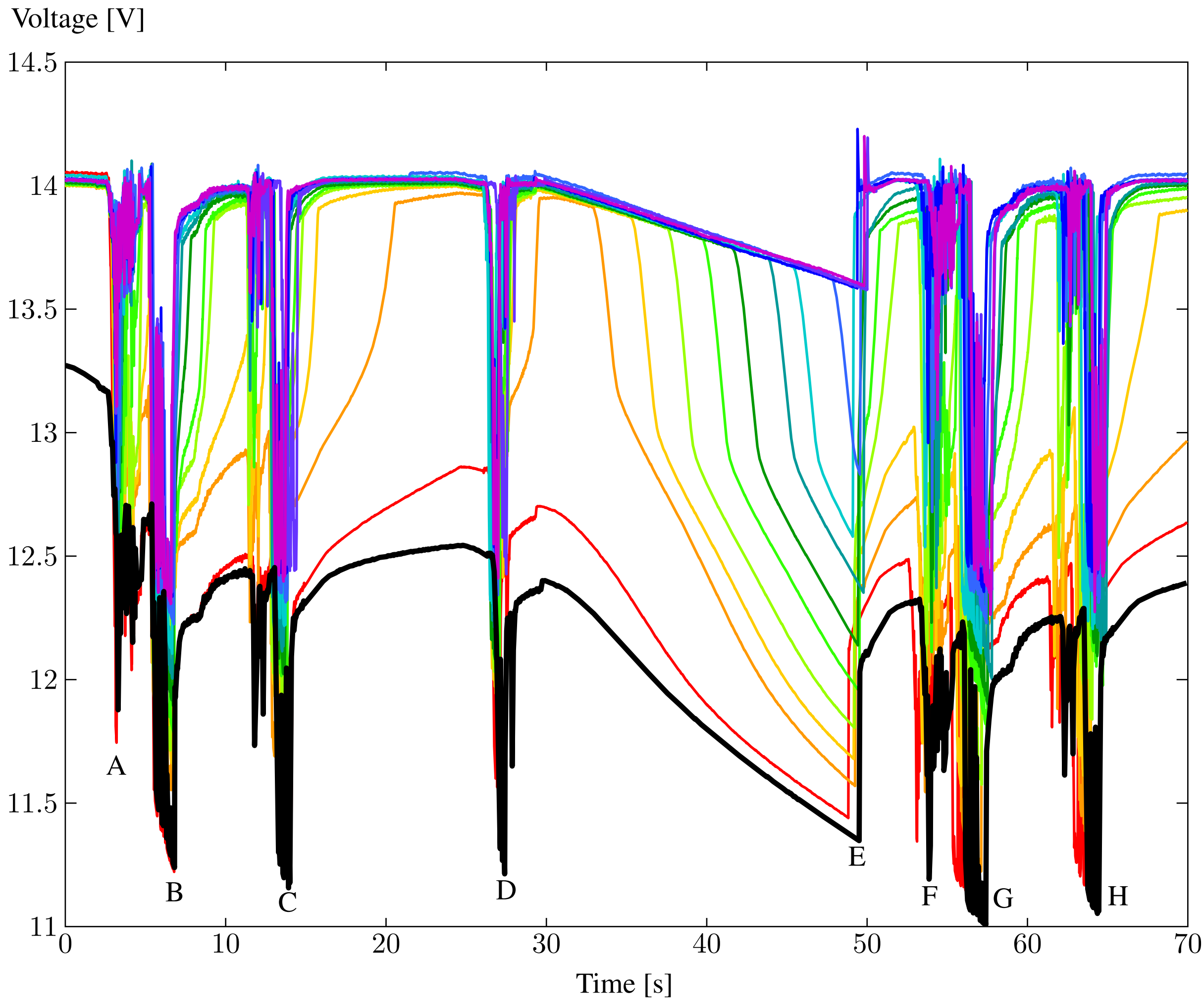

Figure 5: Voltage reaction to the test sequence of Fig. 4. The current peaks yield to voltage drops. Eight local minima (A to H) are used as characteristic points of the analysis. The thick black line is the voltage of the system without any supply by the DC chopper converter. From red to violett the maximum power of the DC chopper converter is increased in 100 W steps from 200 W to 1200 W.

In the next step, the sensitivity analysis is conducted and the maximum output power of the DC chopper converter is varied. Starting at its maximum of 1200 W, the output power is decreased in 200 W steps down to 0 W, the last meaning no intervention of the DC chopper converter. In a second part, the maximum output power is left at a constant 1200 W but the parameters of the controller of the DC chopper converter are modified in order to observe its effect on the voltage stabilization. For this purpose, there are four different parameter settings for the controller each varying in speed, accuracy or overshoot.

7.2 Results

It can be considered that one factor that greatly influences the stabilization of the vehicular power net is the maximum output power of the DC chopper converter. Therefore, the output power of the converter is varied in between 0 W (that means, the DC chopper converter is switched off) and its maximum of 1200 W and, in steps of 100 W. For each output power setting, voltage and current are measured and recorded for a whole cycle of the test sequence mentioned above. Through these measurements, it is possible to evaluate to what extend the electrical properties of the DC chopper converter have an impact on the stabilizing effect. As a larger converter requires more space and weight, both limited within a vehicle, as well as more money to build it, information on this issue can be very useful.
The voltage curves of all the 13 power settings are shown in Fig. 5. Although it is not possible to give an accurate estimation on the development of the various voltage dips from this, there are two facts that can be recognized. Firstly, when the DC chopper converter is active (all but the lowest line in Fig. 5), the voltages are able to return faster to their adjusted level, here 14 V, as oppose to the unsupported case where the battery works alone. This can be seen in particular in between the second and the third voltage dip, when the lowest line only reaches its normal level just before the third dip, whereas most of the other lines level out very quickly. Secondly, it is possible to observe the characteristic with which the voltage drops when the DC converter is not able to provide the power demand. The voltage breaks in rapidly at first and slopes down continuously after that. This can be seen best at the ramp function. Interestingly, all the graphs show the same characteristic shape and gradient, only being delayed by an offset of the initial break-in according to their output power setting.

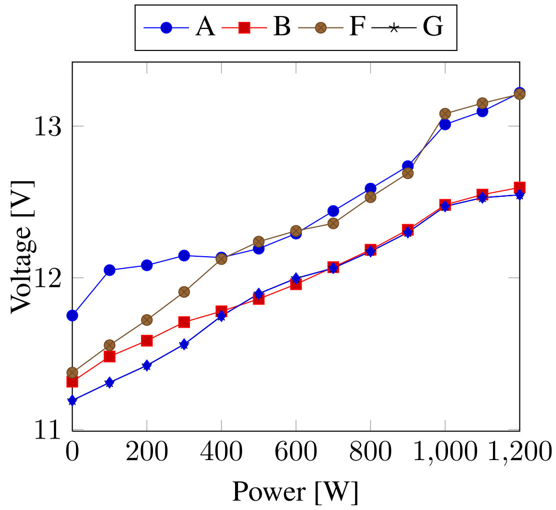

Figure 6: Minimum voltage at the characteristic points A, B, F, and G (compare the test sequence in Fig. 4) versus the applied power supplied by the DC chopper converter.

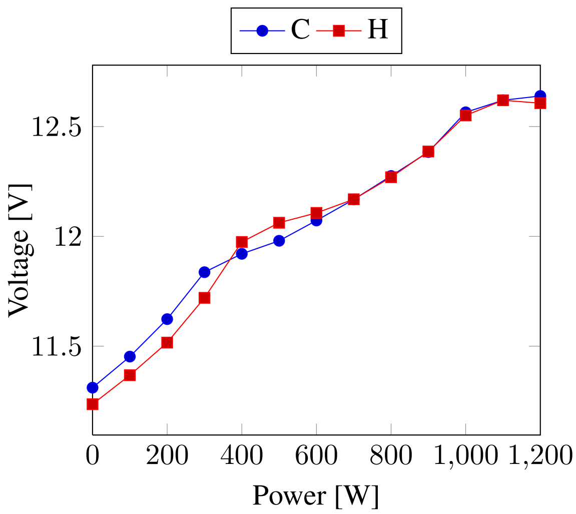

Figure 7: Minimum voltage at the characteristic points C and H (compare the test sequence in Fig. 4) versus the applied power supplied by the DC chopper converter.

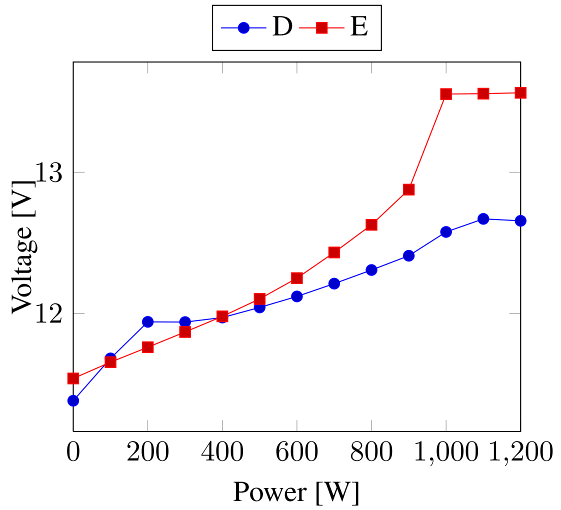

Figure 8: Minimum voltage at the characteristic points D and E (compare the test sequence in Fig. 4) versus the applied power supplied by the DC chopper converter.

For a detailed examination on this issue eight points of interest are defined within the test sequence, developments of these points are evaluated for the different output powers. The definition can be seen in Fig. 4.

Figures 6, 7, and 8 show the development of the voltage dips of the various points defined above for different output power settings. In Fig. 6 and Fig. 7, the development of the voltage drops of the turnaround maneuver can be seen. Thereby, the points A, B, and C are measured before, the points F, G, and H after the synthetic ramp function and thus can be considered to happen at a different state of charge of the battery. The reason for this is that during the ramp an additional current must be drawn from the battery for most of the output power settings, as the DC chopper converter is not able to provide all of the current. The graphs show an overall linear character that slowly flattens out toward the right end of the graph which can be seen as reaching saturation. Furthermore, it is easy to recognize that the graphs of the first (points A and F), the second (points B and G) and the third (points C and H) voltage dips start to diverge below about 400 W. This leads to the conclusion that above an output power of 400 W the draw of energy out of the battery can be fully compensated by the DC chopper converter before the second turnaround maneuver hits in. Below an maximum output power of 400 W the converter is still in the process of recharging the battery and thus cannot provide the same amount of current to support the demand as with the first maneuver.

The development of Point D in Fig. 8, which resembles the braking and swerving maneuver and which is shown in the third graph, gives a similar characteristic. As can be seen in the same graph, the curve of point E reaches saturation at about 1000 W. This means that above this output power the demand of current drawn by the ramp function is always fully carried by the DC chopper converter. Below that power the battery has to contribute to the current demand. The more current comes from the battery, the more the voltage drops, again in a linear development.

All in all, the minimum voltage increases about 1.5 V per 1000 W applied power supplied by the DC chopper converter. Or, in absolute figures, the minimum voltage is increased from 11 V up to about 12.5 V for instance in the braking and swerving maneuver.

8 Conclusions and Outlook

In this paper, the coupling of two voltage levels in automotive power buses is analyzed. First of all, a test bench with a multilevel voltage power net is described that enables researching into the active coupling of the voltage levels by a DC chopper converter in order to stabilize their voltages. In general, there are two possible control modes: In the current/power control mode, the power flow is increased preventively when the prediction model detects a critical situation probably occurring in the near future. In the voltage control mode, the voltage controller of the DC chopper converter is used to stabilize the power net voltage in real-time. In the experimental section, this stabilization method is analyzed. It is shown that the minimum voltage in very power-consuming driving situations is increased about 1.5 V per 1000 W applied power supplied by the DC chopper converter. Thus, there can be an appreciable stabilizing effect by the coupling of two voltage levels. In the future, these measures should be included in the power management system that is presented in [20]. At the moment, there are only measures like increasing the alternators power or degrading of low-priority loads implemented. The stabilization by coupling the two power nets would improve the effectiveness of the system.

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References

[1] M. Hillenbrand and K. Muller-Glaser, "An approach to supply simulations of the functional environment of ecus for hardware-in-the-loop test systems based on ee-architectures conform to autosar," in *Rapid System Prototyping, 2009. RSP '09. IEEE/IFIP International Symposium on*, Jun. 2009, pp. 188 –195.

[2] D. Polenov, H. Probstle, A. Brosse, G. Domorazek, and J. Lutz, "Integration of supercapacitors as transient energy buffer in automotive power nets," in *Power Electronics and Applications, 2007 European Conference on*, Sep. 2007, pp. 1 –10.

[3] S. Lukic, J. Cao, R. Bansal, F. Rodriguez, and A. Emadi, "Energy storage systems for automotive applications," *Industrial Electronics, IEEE Transactions on*, vol. 55, no. 6, pp. 2258 –2267, Jun. 2008.

[4] P. Pfeffer and M. Harrer, "Elektrohydraulische lenksysteme (ephs)," in *Lenkungshandbuch*, P. Pfeffer and M. Harrer, Eds. Vieweg+Teubner Verlag, 2011, pp. 325–344.

[5] D. Polenov, H. Proebstle, and A. O. Stoermer, "Integration of transient high power loads," in *Energy Management & Wire Harness Systems*, ser. Haus der Technik Fachbuch. Renningen: Expert Verlag, mar 2011, no. 117, pp. 182–190.

[6] T. Gerke and C. Petsch, "Analysis of vehicle power supply systems using system simulation," in *2006 SAE World Congress*, Apr. 2006.

[7] T. Kohler, T. Wagner, R. Gehring, J. Froeschl, A. Thanheiser, C. Bertram, D. Buecherl, and H.-G. Herzog, "Experimental investigation on voltage stability in vehicle power nets for power distribution management," in *Vehicle Power and Propulsion Conference, 2010. VPPC '10. IEEE*, 2010.

[8] L. C. Rosario, "Power and energy management of multiple energy storage systems in electric vehicles," Dissertation, Cranfiled University, 2007.

[9] E. Surewaard and M. Thele, "Modelica in automotive simulations - powernet voltage control during engine idle," in *4th International Modelica Conference 2005 by The Modelica Association*, Mar. 2005, pp. 309 – 318.

[10] J. Miller and P. Nicastri, "The next generation automotive electrical power system architecture: issues and challenges," in *Digital Avionics Systems Conference, 1998. Proceedings., 17th DASC. The AIAA/IEEE/SAE*, vol. 2, oct 1998, pp. I15/1 –I15/8 vol.2.

[11] J. Kassakian, H.-C. Wolf, J. Miller, and C. Hurton, "The future of automotive electrical systems," in *Power Electronics in Transportation, 1996. IEEE*, oct 1996, pp. 3 – 12.

[12] ——, "Automotive electrical systems circa 2005," *Spectrum, IEEE*, vol. 33, no. 8, pp. 22 –27, aug 1996.

[13] N. Jemaa, L. Doublet, L. Morin, and D. Jeannot, "Break arc study for the new electrical level of 42 v in automotive applications," *Components and Packaging Technologies, IEEE Transactions on*, vol. 25, no. 3, pp. 420 – 426, sep 2002.

[14] J. Neubert, "Powering up 42 v automotive electronics," *IEE Review*, vol. 46, no. 5, pp. 21 –25, sep 2000.

[15] T. Kohler, R. Gehring, J. Froeschl, D. Buecherl, and H.-G. Herzog, "Voltage stability analysis of automotive power nets based on modeling and experimental results," in *New Trends and Developments in Automotive System Engineering*, M. Chiaberge, Ed. InTech, Rijeka, Crotia, 2011, vol. 1.

[16] C. Haupt, D. Bucherl, A. Engstle, H.-G. Herzog, and G. Wachtmeister, "Energy management in hybrid vehicles considering thermal interactions," in *Vehicle Power and Propulsion Conference, 2007. VPPC 2007. IEEE*, sep 2007, pp. 36–41.

[17] National Instruments Corporation, "Labview user manual," Website, 2003, available online at http://www.ni.com/pdf/manuals/320999e.pdf;.

[18] G.-J. Su and L. Tang, "A multiphase, modular, bidirectional, triple-voltage dc-dc converter for hybrid and fuel cell vehicle power systems," *Power Electronics, IEEE Transactions on*, vol. 23, no. 6, pp. 3035 –3046, nov 2008.

[19] ——, "A reduced-part, triple-voltage dc-dc converter for ev/hev power management," *Power Electronics, IEEE Transactions on*, vol. 24, no. 10, pp. 2406 –2410, oct 2009.

[20] T. Kohler, J. Froeschl, C. Bertram, D. Buecherl, and H.-G. Herzog, "Approach of a predictive, cybernetic power distribution management," in *The 25th World Electric Vehicle Symposium and Exposition, 2010. EVS 2010. WEVA*, Nov. 2010.

[21] R. Ashby, *An Introduction to Cybernetics*. Chapman & Hall Ltd, London, 1957.

[22] N. Wiener, *Cybernetics or control and communication in the animal and the machine*. MIT Press, 1965.

[23] I. Alvarez, "Intelligent self assignment of resources for an optimal implementation of complex embedded distributed energy management algorithms," in *2. Aachener Elektronik Symposium: Energy Management – Today and tomorrow*, Aachen, sep 2004.

[24] T. P. Kohler, A. W. Ebentheuer, A. Thanheiser, D. Buecherl, H.-G. Herzog, and J. Froeschl, "Development of an intelligent cybernetic load control for power distribution management in vehicular power nets," in *Vehicle Power and Propulsion Conference (VPPC), 2011 IEEE*, sep 2011.

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