Autonomous Load Shutdown Mechanism as a Voltage Stabilization Method in Automotive Power Nets

Florian Ruf*, Andreas Barthels†, Gregor Walla‡, Michael Winter*, Tom P. Kohler*, Hans-Ulrich Michel§,
Joachim Froeschl¶, and Hans-Georg Herzog*
*Institute for Energy Conversion Technology, Technische Universitaet Muenchen, Munich, Germany,
Email: florian.ruf@tum.de
†Chair for Operating Systems, Technische Universitaet Muenchen, Munich, Germany
‡Institute for Integrated Systems, Technische Universitaet Muenchen, Munich, Germany
§BMW Group Research and Technology, Munich, Germany
¶BMW Group, Munich, Germany

***Abstract*—The power demand in 14 V automotive power buses has steadily increased in recent years. Due to the high peak power of electrified chassis control systems, significant voltage drops can occur within the power net. These voltage drops can lead to malfunctions of ECUs (Electronic Control Units). This paper describes the influence of an autonomous load shutdown mechanism on voltage stability in automotive power buses. The mechanism is applied to heating systems, which feature a combined peak power demand of over 1 kW in modern luxury class vehicles. A temporary shutdown of these heating systems for a few seconds is unnoticeable for the costumer due to large time constants of these systems. The influence of the mechanism on the voltage stability is investigated within a physical power net simulation. It is shown, that the mechanism allows the neglection of power-hungry heating systems in the design process of the power bus regarding peak power scenarios.**

***Index Terms*—Vehicle power net, voltage stability, autonomous mechanism, cybernetic system**

I. INTRODUCTION

In recent years, the number of electrical systems in cars has steadily increased [1]. To reduce fuel consumption, lots of previously mechanically driven components are now electrically driven [2], [3]. Especially electrically driven chassis control systems require a high transient peak power. In electric vehicles (EVs), the use of electromechanical systems is essential in any case. The electric power steering (EPS), for example, demands up to 2 kW. In addition, today's cars feature a high number of comfort functions. In a luxury class vehicle, the continuous power demand can be more than 600 W [4]. Regarding special use cases in wintertime, the combined power consumption of interior fan, seat heating systems, auxiliary heating systems and rear window heating can exceed 1 kW. If such a use case is superposed by the high peak power of chassis control sytems, the power net voltage drops down to less than 10 V. Due to ohmic losses and parasitic inductances of the wiring harness, the occuring voltage drops vary significantly within the wiring harness [4]. These voltage drops can lead to malfunctions and undervoltage lockout resets of ECUs.

In the nineties, multivoltage topologies were discussed to counter these problems [5]. The advantage of a 42 V power net was shown in [6], but the automotive industry continued to use the established 14 V power net. To improve voltage stability in 14 V power nets, electronic double layer capacitors (EDLCs) were introduced as a transient energy buffer [1]. The use of EDLCs in the power net can also extend the battery's lifetime or even lead to a reduction of the battery size, but causes additional costs, weight and installation space.

Since the 14 V power net is reaching its limits and the complexity of power nets will further increase, it becomes more and more complicated to supply all loads with sufficient power and to guarantee voltage stability. One method to improve voltage stability is to adapt the power net's topology, using additional energy storages, for example [1]. Some papers propose new power management strategies and cybernetic methods in order to encounter this problem [7], [8].

II. OBJECTIVES AND APPROACH

Due to the rising number of electronic systems, especially the consideration of power-demanding use cases superposed by the high peak power of chassis control systems becomes more and more difficult. This paper describes a simple autonomous load shutdown mechanism for automotive loads. The shutdown mechanism reduces possible high load system states during peak power scenarios. Due to large time constants in heating systems, the shutdown mechanism is applicable to automotive heating sytems, where a temporary shutdown of a few seconds can not be noticed by the passengers. The influence of the mechanism on voltage stability is analysed by simulation.

Firstly, the problem of voltage stability in vehicular power nets is explained in the next section. After this, an autonomous load shutdown mechanism and the eligible loads are presented.

Based on a physical power net simulation, the effect on voltage stability is investigated.

III. VOLTAGE STABILITY IN AUTOMOTIVE POWER NETS

The automotive power net provides electric power for all electrical systems in the vehicle. A schematic topology of a typical power net is shown in Fig. 1. Especially chassis control systems such as an electric power steering feature very dynamic load behavior with a peak power demand of up to 2 kW [4]. Due to its field-winding time constant of 100 ms and more, the Lundell alternator is not able to ramp up its output power during a very dynamic peak power scenario [9]. This leads to a decrease of the power net voltage down to the batterys terminal voltage. Due to ohmic losses within the wiring harness and the battery's internal resistance, the terminal voltages of some electric loads can drop down to 10 V and less [4]. Also, the terminal voltages of electric components can significantly vary within the power bus. Fig. 2 shows the terminal voltages of three exemplary loads during a peak power scenario. In EVs, the 14 V power net is supplied by a DC/DC converter. A typical design criterion of the rated power of these DC/DC converters is the maximum average power consumption of the power net. Although the dynamic behavior of DC/DC converters is much better than the dynamic behavior of the Lundell alternator, peak load scenarios can exceed the rated power of the converter and a system state occurs, which is similar to the case, where the alternator is not able to ramp up its power (see above).

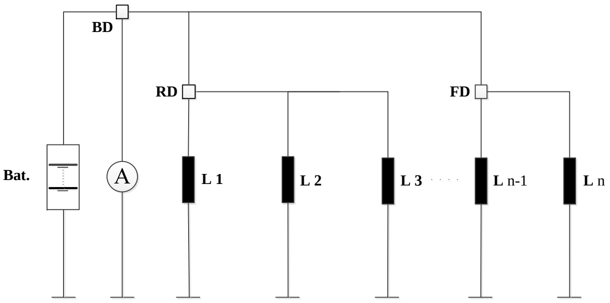

Fig. 1. Schematic of the basic 14 V automotive power net. The alternator (A) is connected to the battery (Bat.) via a battery distribution box (BD). Further distribution boxes (RD and FD) are used in order to supply the electrical loads (L1, L2, ... , Ln). The car body is used to close the circuit to the alternator and battery.

IV. PHYSICAL POWER NET SIMULATION

To examine the terminal voltages of ECUs in the power net under extreme load conditions, a Dymola-based simulation tool is used [10]. The simulation tool contains the following models of power net components, which are presented or derived in the indicated references:

1) Chassis ground and wiring harness [11]
2) Battery [12], [13]
3) Alternator [14], [15]
4) Loads [16]

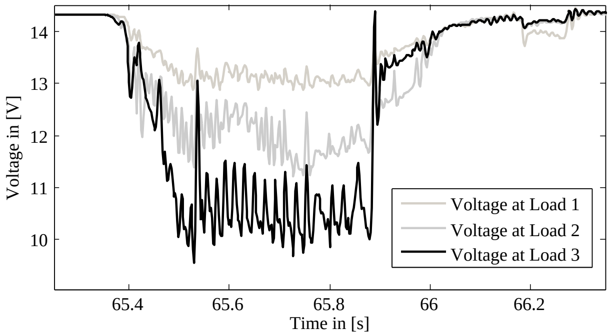

Fig. 2. Voltage characteristic of Load 1, 2 and 3 during load scenario

5) DC/DC converter [17]

The load scenario within this simulation is based on measurements from very dynamic driving maneuvers in a real car. In these driving maneuvers, chassis control systems as the electric power steering and the electronic stability program demand high peak power at the same time as described in the next section. The superposition of these peak loads and other electric loads can cause voltage drops down to less than 10 V in the power net [4].

V. AUTONOMOUS LOAD SHUTDOWN MECHANISM

Heating systems in todays luxury class vehicles feature peak power demands of more than 1 kW. Due to time constants of several seconds and more, a temporary shutdown of these systems during peak load scenarios is unnoticeable for the customer. Typically, todays heating systems are driven by a semiconductor power switch, which enables a fast on/off switching time. This circumstance offers the possibility of implementing an autonomous hysteresis-based shutdown mechanism, which immediately shuts down a heating element when the ECUs terminal voltage drops below a critical level. To avoid oscillation, the system remains off for a certain time period, before it is turned on again.

After the terminal voltage of an ECU falls below a configured threshold, the shutdown is delayed for a certain time period, depending on the actual hardware realization of the mechanism. While analog comparator based circuits can detect a shortfall below the threshold and proceed a shutdown within a few microseconds or less, the shutdown delay of microcontroller based realizations depends on the analog to digital converter sample frequency. In this paper, the delay time of the mechanism is set to 0.5 ms in the simulation, which emulates the average dead time of a microcontroller based ECU with an analog to digital converter and a sample frequency of 1 kHz. This sampling frequency is even possible with the smallest microcontrollers available and thereby can be considered as a worst case configuration.

Since the only input for the mechanism is the ECU's local terminal voltage, the mechanism equals a cybernetic

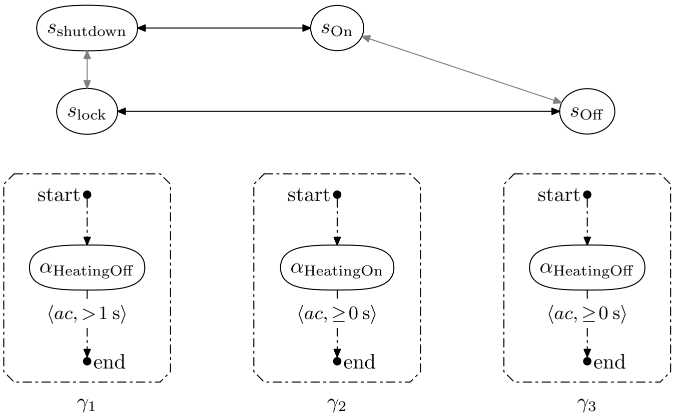

Fig. 3. Power management module as a transducing machine [19]. On top are the functional states of the autonomous subsystems; solid black transitions are based upon the measured supply voltage levels, whereas gray transitions are due to user input. Below are the respective power management plans γ_1–γ_3, the functional states activate the plans depicted in the same column.

load within a cybernetic system, where the ECU itself has a certain amount of local intelligence [18]–[20]. Thereby, the system is able to interact with its environment. The ECUs can autonomously process their shutdown without the necessity of a central coordinator. Thus, the mechanism is very fast and does not require bus traffic.

A. Cyber-Physical Model

The mechanism can be abstractly described in terms of the cyber-physical system modeling approach presented in [19]. Depicted in figure 3 is the system along with its states and transitions as well as the respective power management plans.

The system changes its state due to sensoric inputs which is processed. The processing model (functional chain) is omitted here for simplicity reasons. Each autonomous subsystem can be in one of the four states:

- s_{Off}: The heating system is turned off.
- s_{On}: The heating system is turned on.
- s_{shutdown}: The user chose to turn on heating, but it is autonomously shut down.
- s_{lock}: The user chose to turn off heating. Heating is prevented from being turned on during some interval.

The system states each call for the activation of one of the following three power management plans:

- Both s_{shutdown} and s_{lock} ensure the heating is turned off during the exemplary interval of 1 s in plan γ_1. The condition $\langle ac, > 1\text{ s}\rangle$ prevents any change in power management plan and thus power state of the system during the period.
- s_{On} and s_{Off} associate the power management plans to turn on and off the heating, the respective plans γ_2 and γ_3 can immediately be swapped and the heating be immediately affected either by user request, or by a voltage drop.

In [18], the authors describe how to reconfigure this mechanism as part of a layered cybernetic architecture. This way, both the criteria for detecting an undervoltage lockout scenario, as well as the reaction to it (the power management plans), may be affected.

VI. SIMULATION RESULTS

To investigate the influence of the autonomous load shutdown mechanism on voltage stability, the physical power net simulation described in chapter IV is extended by several heating elements such as seat heaters in the front and in the rear, a rear window heater, an electric auxiliary heating and the interior fan. Fig. 4 shows the position of dynamic loads and heating systems in the car body. Each simulation model of these systems feature a configurable shutdown threshold, a configurable shutdown delay time after the threshold shortfall and a configurable lock time. To ensure comparability, each simulation is proceeded with an alternator voltage of 13.8 V and an operating point, where the alternator is able to provide sufficient power for all systems. The shutdown threshold is set to 12 V and the shutdown delay time is set to 0.5 ms as described in chapter V.

In order to analyse the improvement on voltage stability, three different scenarios are simulated. In setup a), all heating systems are turned off. In setup b), all heating systems are turned on; in setup c), the heating sytems are turned on and the autonomous load shutdown mechanism described in section V is enabled. Fig. 5 shows the simulated minimum terminal voltage of the distribution boxes, the three most critical loads and the battery during the peak power scenario described in IV for all three setups.

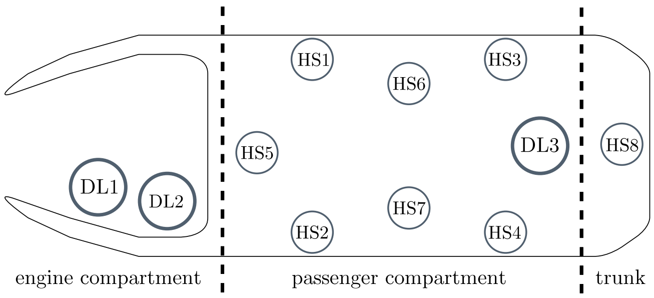

Fig. 4. Schematic of the car body with the location of dynamic loads (DL1 to DL3) and heating systems (HS1 to HS8)

In the simulation, setup b) shows the deepest voltage drop. Compared to setup a), where the heating systems are turned off, the additional load caused by the enabled heating systems leads to additional ohmic losses in the wiring harness and the battery's internal resistance during the peak power scenario. The minimum terminal voltages of the loads in setup c) (heating systems on and autonomous load shutdown mechanism enabled) are even higher than in setup a), where the heating systems are turned off. This circumstance can be traced back to the poor dynamic behavior of the alternator, which results from the field-winding time constant of 100 ms and more [9]: If the heating systems are enabled, the alternator is running

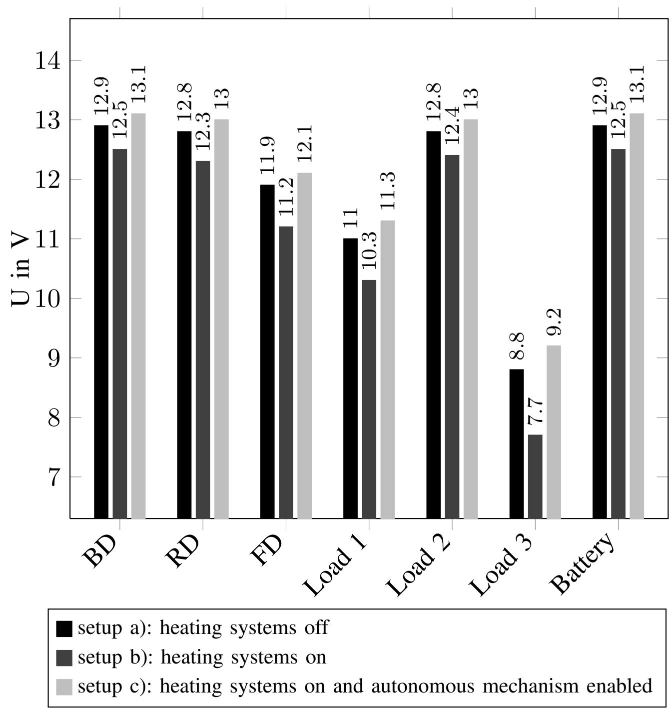

Fig. 5. Minimum simulated terminal voltages during peak power scenario at the terminals of Load 1, 2 and 3, the battery distribution box (BD), the front distribution box (FD), the rear distribution box (RD) and the battery. In setup a), the heating systems are permanently turned off; in setup b), the heating systems are permanently turned on; in setup c), the heating systems are turned on and the autonomous shutdown mechanism is active.

in an operating point with a higher output power compared to the case, where the heating systems are disabled. As soon as the dynamic loads demand high peak power and the terminal voltage of the heating system drops beneath the configured threshold, the power switches of the heating systems are turned off and the released alternator power is available for all other loads.

The simulation results show, that an autonomous load shutdown mechanism provides the advantage to neglect power-hungry heating systems during the design process of the power net regarding voltage stability. This leads to a reduction of the amount of critical high load systems states, which have to be considered.

In EVs, the 14 V power net is supplied by a DC/DC converter. Just as in a car with conventional drive train, a lead acid battery is used as energy storage and transient energy buffer. The DC/DC converter features much better dynamic behavior than the alternator, but to minimize costs and weight, the rated power of these DC/DC converters equates the maximum average power consumption of the power net. Thereby, the autonomous shutdown mechanism is also applicable to EVs, since the maximum power during peak power scenarios can easily exceed the DC/DC converter's rated power.

VII. CONCLUSION AND OUTLOOK

In this paper, an autonomous load shutdown mechanism and its influence on voltage stability in automotive power nets is presented and evaluated. It is shown, that the implementation of this mechanism can reduce the voltage drops during peak loads within the power net. Additionally, this mechanism can reduce the amount of critical load scenarios during the design process of the power net in respect to voltage stability. In further research, the described mechanism will be implemented and validated in an existing test bench consisting of a real car chassis with a wiring harness.

VIII. ACKNOWLEDGMENT

The represented research and development work is carried out in a project within the framework of the cooperation CAR@TUM ("Munich Centre of Automotive Research") between the BMW Group and the Technische Universitaet Muenchen. This particular research was supported by BMW Group Research and Technology. The responsibility for this publication is held by authors only.

REFERENCES

[1] D. Polenov, H. Proebstle, 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*, September 2007, pp. 1 –10.

[2] H. Akhondi, J. Milimonfared, and K. Malekian, "Performance evaluation of electric power steering with ipm motor and drive system," in *Power Electronics and Motion Control Conference, 2008. EPE-PEMC 2008. 13th*, September 2008, pp. 2071 –2075.

[3] S. Mir, M. Islam, and S. T, "Role of electronics and controls in steering systems," in *Industrial Electronics Society, 2003. IECON '03. The 29th Annual Conference of the IEEE*, vol. 3, nov. 2003, pp. 2859 – 2864 Vol.3.

[4] T. Kohler, T. Wagner, A. Thanheiser, C. Bertram, D. Buecherl, H.-G. Herzog, J. Froeschl, and R. Gehring, "Experimental investigation on voltage stability in vehicle power nets for power distribution management," in *Vehicle Power and Propulsion Conference (VPPC), 2010 IEEE*, sept. 2010, pp. 1 –6.

[5] J. Kassakian, H.-C. Wolf, J. Miller, and C. Hurton, "Automotive electrical systems circa 2005," *Spectrum, IEEE*, vol. 33, no. 8, pp. 22 –27, aug 1996.

[6] 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-7 nov 1998, pp. I15/1 –I15/8 vol.2.

[7] T. Kohler, A. 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*, sept. 2011, pp. 1 –6.

[8] 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*, November 2010.

[9] D. Perreault and V. Caliskan, "Automotive power generation and control," *Power Electronics, IEEE Transactions on*, vol. 19, no. 3, pp. 618 – 630, may 2004.

[10] Dassault Systems, *Dymola - Dynamic Modeling Laboratory - User Manual*, 2010.

[11] R. Gehring, J. Froschl, T. Kohler, and H.-G. Herzog, "Modeling of the automotive 14 V power net for voltage stability analysis," in *Vehicle Power and Propulsion Conference, 2009. VPPC '09. IEEE*, September 2009, pp. 71 –77.

[12] M. Ceraolo, "New dynamical models of lead-acid batteries," *Power Systems, IEEE Transactions on*, vol. 15, no. 4, pp. 1184 –1190, Nov. 2000.

[13] H. A. H. Kiehne, Ed., *Battery technology handbook*, 2nd ed., ser. Electrical and computer engineering ; 118. New York: Dekker, 2003, includes bibliographical references and index.

[14] E. Lange, M. van der Giet, F. Henrotte, and K. Hameyer, “Circuit coupled simulation of a claw-pole alternator by a temporary linearization of the 3d-fe model,” in *Electrical Machines, 2008. ICEM 2008. 18th International Conference on*, sept. 2008, pp. 1 –6.

[15] H. Bai, S. Pekarek, J. Tichenor, W. Eversman, D. Buening, G. Holbrook, M. Hull, R. Krefta, and S. Shields, “Analytical derivation of a coupled-circuit model of a claw-pole alternator with concentrated stator windings,” *Energy Conversion, IEEE Transactions on*, vol. 17, no. 1, pp. 32 –38, mar 2002.

[16] 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.

[17] D. Polenov, J. Lutz, J. Merwerth, and H. Proebstle, “Evaluation of topologies for bi-directional dc/dc-converters with overlapping input and output voltage ranges,” in *Proc. of the PCIM Europe 2006 Conference*, 2006.

[18] A. Barthels, J. Froeschl, H.-U. Michel, and U. Baumgarten, “An architecture for power management in automotive systems,” in *Architecture of Computing Systems - ARCS 2012*, ser. Lecture Notes in Computer Science, A. Herkersdorf, K. Roemer, and U. Brinkschulte, Eds. Springer Berlin / Heidelberg, 2012, vol. 7179, pp. 63–73.

[19] A. Barthels, F. Ruf, G. Walla, J. Froeschl, H.-U. Michel, and U. Baumgarten, “A model for sequence based power management in cyber physical systems,” in *1st International Conference on ICT as Key Technology for the Fight against Global Warming – ICT-GLOW*, 2011, pp. 87–101.

[20] T. Kohler, A. 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*, sept. 2011, pp. 1 –6.