Experimental Investigation on Voltage Stability in Vehicle Power Nets for Power Distribution Management

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***Abstract*— The power demand and the complexity of vehicle power nets has increased continuously during the last years. Especially the high demands of chassis control systems can cause voltage drops that endanger the power net's stability. A power net test bench that enables experimental research on voltage stability in vehicular power nets is presented in this paper. Thereby the relevance of voltage stability issues in today's and future vehicles was analyzed. Furthermore, proposals on counteractions using a power distribution management system are pointed out and the possibility of verifying dynamic power net simulation tools is provided.**

Keywords—Vehicle Power Net; Voltage Stability; Power Distribution Management; Power Management; Test Bench

I. INTRODUCTION

Recently, a trend of increasing electrification became clearly recognizable in automotive engineering. One reason for this is the increase of safety and comfort function. In today's luxury class vehicles there are up to 80 electronic control units (ECUs) [1, 2] varying from small electric loads like communication technology functions to great loads like power steering showing a peak power of almost 2 kW.

As the electric power demand increases, so do the load peaks of the electric power net and the danger of voltage instability [2-5]. In the example of the luxury class vehicle the continuous power of heating in winter, air conditioning in summer, ECUs, sensors, and consumer electronics can be more than 600 W. If this load is augmented by electric chassis control systems, voltage drops will be inevitable—especially in slow driving phases, when the alternator is not able to supply adequate power [4]. Furthermore the increase of electrical power demand will be strengthened by hybrid and electric vehicles, in which all functions from propulsion to heating or consumer electronics are driven electrically.

The different methods to counter the loss of control over the voltage stability can be subdivided into three approaches:

a.) The easiest method is to adapt the dimensioning of energy storage and wiring harness, but this causes additional costs, weight and installation space, of course.

b.) In various papers the stability problem is reduced by assembling additional power supply or optimizing existing components. Capacitive energy storages, like electric double layer capacitors, are used in [2] and [6] to increase the peak power capability of the power net. Furthermore they help reducing the demands placed on the battery and thereby extend the battery's lifetime. In [7] the control strategy of the alternator is optimized to obtain maximum energy efficiency and stability within the vehicle. Another approach is to analyze the electric loads: In [8] a stabilizing control strategy for power nets with constant power loads is developed. Ref. [9] compares load modeling with mathematical models and neural networks to emulate the dynamic behavior which is necessary to develop voltage stability effects. Stabilizing strategies by controlling the speed of the internal combustion engine or by reducing the availability of power loads are discussed in [4].

c.) Eventually, the control of the power distribution in the entire power net stabilizes the voltage by using the power reserves remaining in the power net's components. A rule-based strategy is developed in [5] considering both storages and dynamic loads. A holistic system approach, to actively balance the power distribution in the vehicle's power net with a prediction of the future driving pattern is introduced by [10].

In some of the mentioned papers several components were tested in test benches, e.g. in [2, 8], but more often simulation was the basis of verification [5, 7, 8]. However, to realize an optimized power distribution management and to achieve voltage stability, a profound knowledge of the effects in distributed power nets obtained by experimental analysis is required.

II. OBJECTIVES AND APPROACH

This paper describes a power net test bench, which enables to research into a real power net (consisting of alternator, energy storage, wiring harness, car body and electric loads) in a virtual environment. With this test bench, the effects of the distributed wiring harness on voltage stability are pointed out.

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A further goal is to show the significance of voltage stability problems in today's and future vehicles by experimental results. Finally, possibilities to stabilize the power net are presented.

III. POWER NET TEST BENCH

This chapter describes the set-up of the power net test bench. Thereby, the focus lies on analyzing which elements of a real power net are essential to emulate all effects realistically. For this purpose, the components involved in the voltage regulation are briefly described.

However, the first decision is selecting the voltage levels. Without loss of generality in the first stage of development only the 12 V DC level is implemented. Although the impact of voltage fluctuations are different—problems with the availability and resets of the ECUs in the case of 12 V; inaccuracies in control in the case of high-voltage levels—the issues and effects are the same in both cases and can be studied at the 12 V level as well. Another advantage of 12 V power net is the good availability of the components. The extension of different voltage levels is not needed until an advanced multi-level power distribution management is established.

A. Voltage stability in a 12 V power net

A schematic topology of a 12 V power net is shown in Fig. 1. In normal operation the alternator is able to supply all power demands and forces the maximum voltage to its setpoint of about 14 V. If the power demand of all loads exceeds the alternator's supply, the battery has to take the power differential and the maximum voltage decrease to the battery's terminal voltage of about 12 V. Due to the internal resistance of the battery, the terminal voltage depends on the battery current and further voltage reductions occur in case of high current demands. These voltage fluctuations can be noticed by the passengers, for example by light flicker or changes in noise of the blower fans [4]. Since the alternator's dynamics are limited in order to avoid a reduction of customer's driving comfort those voltage drops occur especially at short rise time of current. Additionally the loads' voltage is reduced by losses in the distributed system of the

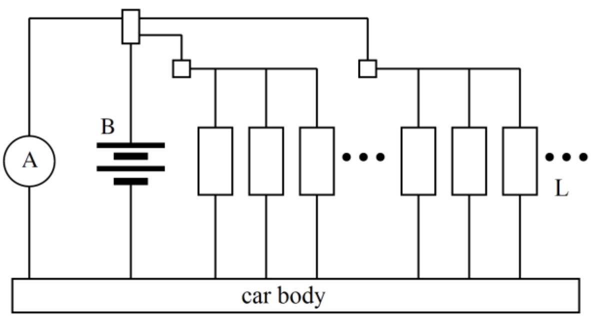

Figure 1. Schematic topology of 12 V vehicle power net [11]. Alternator (A) and battery (B) are connected with loads (L) via wiring harness, power distribution and power distribution boxes.

wiring harness, in power distribution units, and in fuse boxes. Especially these losses are significant and can't be neglected in many situations as shown in chapter IV.

B. Components

In the following the components necessary to emulate a realistic behavior of the power net in the test bench are described. Fig. 2 presents the whole topology of the test bench.

Storage/Battery: Although a battery simulation system has the advantage that the measurements and tests are easily repeatable and configurable [12, 13], real batteries are used. Since the electrochemical processes in batteries are very complex, it is not easy to model especially the transient processes in the required accuracy. Several commercial battery sizes can be employed ranging from compact to luxury class car's batteries (C_{bat} = 60...90 Ah) in this test bench. The state of charge (SOC) can be precisely adjusted at an own battery conditioning test bench in order to provide equal conditions in the experimental procedure.

Source/Alternator: In the first stage of development, the alternator is emulated by a physical model executed on a real time system. Input parameters are the battery's voltage, the engine speed and the alternator's start temperature. The real time system controls a regulated 300 A power supply unit.

A separate alternator test bench is under way, at the moment. Here, alternators from mass-production can be powered by a machine that emulates the behavior of the internal combustion engine. The alternator's output can be coupled with the power net test bench. A coupling with a hybrid power train is contemplated in the next developmental stage.

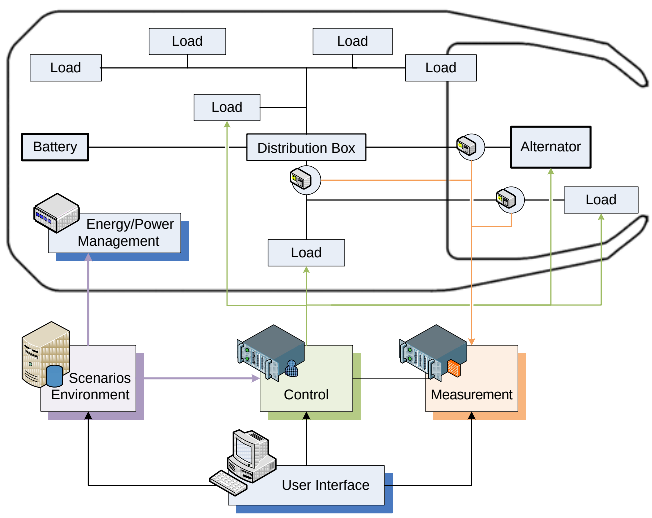

Figure 2. Schematic topology of the power net test bench with the power net's components—some loads, power distribution boxes (only one is on display), battery and alternator—in the top and the control and measurement periphery (bottom).

Wiring harness and chassis ground: For a realistic analysis of the power net's behavior the distributed structure has to be reproduced as accurately as possible. Especially the exact location of power distribution units, fuse boxes, and clamp control is important. So a real wiring harness of a luxury class vehicle is used. The car body serves as return conductor to close the circuits between the negative terminals of components and the battery. Therefore it is part of the power distribution network, too. Especially, if several loads are using the same grounding bolt, interactions may be caused. Here, a car body of the BMW 7 series is applied (Fig. 3 and Fig. 4).

Electric loads: The structure of up to 80 loads is very complex in reality. Therefore it is sufficient to consider only a representative selection to analyze voltage stability. While placing the electric loads, it is necessary to regard the power system's structure. This includes the choice of the power distribution and fuse boxes, the wire's lengths and cross sections as well as the grounding bolts. With an accurate placement, it is possible to analyze all real kinds of request on the power net with considerably fewer loads.

Figure 3. Detail of the wiring harness (driver floor) with wires of communication busses and the power suppy as well as some grounding bolts on the car body.

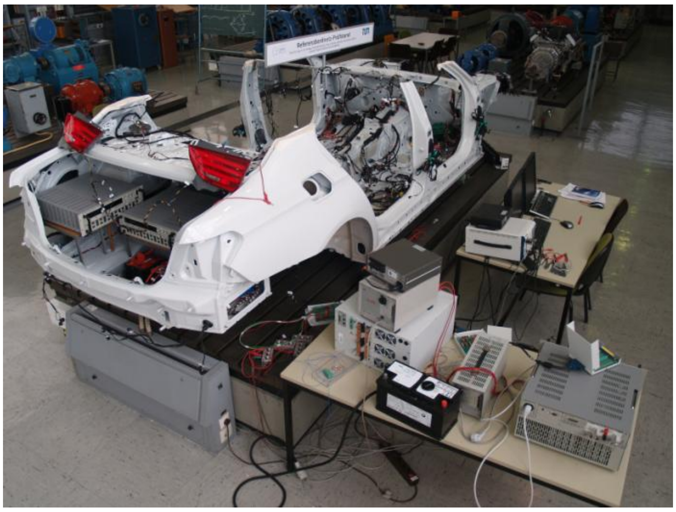

Figure 4. Complete installation of the power net test bench.

The ECUs in itself are not built in, but substituted by regulated electronic loads having high dynamics, which can demand arbitrary power profiles and emulate the behavior of the ECUs. In this way the experimental studies are more flexible, for example worst cases can be conducted.

Control and measurement: The test bench's control is realized in LabVIEW [14]. Environmental data and driving cycles are passed by a CAN[1] interface. Based on this information, the LabVIEW program controls the load's power profiles as well as the real time system of the alternator. A grid of voltage and current measurement points reports the state of the power net.

It is feasible to "virtually cruise around" the power net with the presented test bench. Fig. 4 shows the complete installation. The universal interface to the system's environment allows driving logged driving cycles as well as critical situations, for example a breaking and swerving scenario or the slalom driving maneuver, shown in Fig. 7.

IV. VOLTAGE CHARACTERISTICS AND STABILITY PROBLEMS

All measurements clearly show that it is not sufficient to consider only one voltage supply but that the voltages in many different places have to be taken into account at any time. This can be examined at the test setup of Fig. 5: Two loads at different places of installation are connected at the same distribution box and supplied by the battery.

A constant current demand of 40 A by *Load A* at $t = 1$ s involves a voltage jump at the battery's internal series resistance, which describes internal and contact losses. This jump is recognizable in Fig. 6a. Between $t = 1$ s and $t = 10$ s the voltage describes an exponential curve caused by the electrochemical processes in the real battery or the RC members in the battery's equivalent circuit [15, 16].

The measurement close to *Load A* shows a similar characteristic at a lower voltage level (Fig. 6b). The voltage difference of about 1.1 V is caused by losses in the wiring harness as well as in the distribution and fuse boxes. Additionally, *Load B* superposes a peak power demand at $t = 9$ s

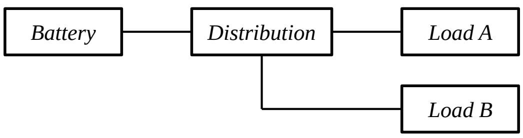

Figure 5. Test setup to study the impacts of the superposed power demands of two loads at different locations of the power net.

[1] CAN: *Controller Area Network*

that yields to a local voltage drop down to 10.3 V (Fig. 6c). The impact of that voltage fluctuation can be observed in the whole power net: The closer the measuring point and *Load B* are together the lower is the occurring voltage drop (Fig. 6a and 6b).

Therefore, voltages and power demands must not be considered isolatedly. With knowledge of the specific power demands in the power net, the critical voltage at the load u_{load} can approximately be calculated by

$$u_{load} = U_0 - \Delta U_{\text{bat}}(I_{\text{bat}}) - \Delta U_{\text{dist}}(I_{\text{dist}}) - \Delta U_{\text{wire}}(I_{\text{wire}}) - \Delta U_{\text{chassis}}(I_{\text{bat}}). \quad (1)$$

Besides synthetic power profiles, logged test drives can be reproduced at the test bench. In doing so, situations showing high and dynamic power peaks are particularly interesting to analyze the power net's reaction and to deduce methods stabilizing the voltage. Fig. 7 presents the voltages, measured in a slalom driving maneuver. In this case, resulting from the fast steering interventions a few systems showing high peak power like electric power steering or dynamic stability control are simultaneously activated and therefore particularly high power peaks occur in the whole system.

The vertical red line in Fig. 7 marks a moment of extremely high peak loads. Fig. 8 presents an analysis of the different voltages within the power distribution net at that very moment. The green line represents several measurements on the path from the battery's positive terminal to the load's positive terminal. The blue line represents the return conductor from the battery's negative terminal to the load's negative terminal. Comparing the battery's and the load's terminals the voltage decreased from 12.5 V to 7.1 V. However, to guarantee the proper functioning of the loads, a stable voltage supply is necessary. This problem leads to the need of developing methods for stabilizing the loads' voltages. Some of these actions will be discussed in the following chapter.

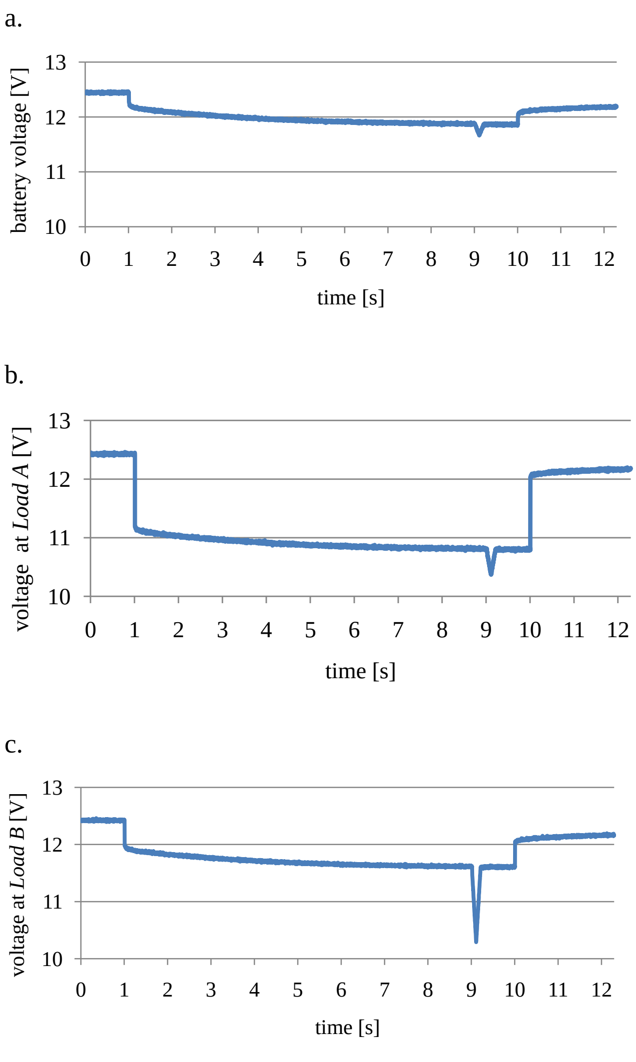

Figure 6. Synthetic local power demand and impacts at different locations of the power net.

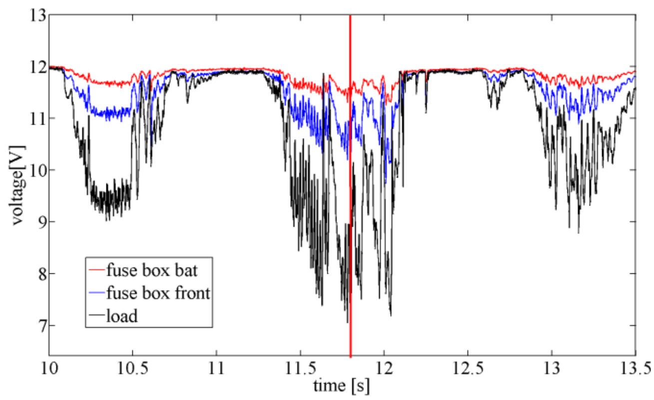

Figure 7. Cut-out of the slalom driving maneuver with measurements at different places in the power net. The vertical red line marks the moment for the following analysis.

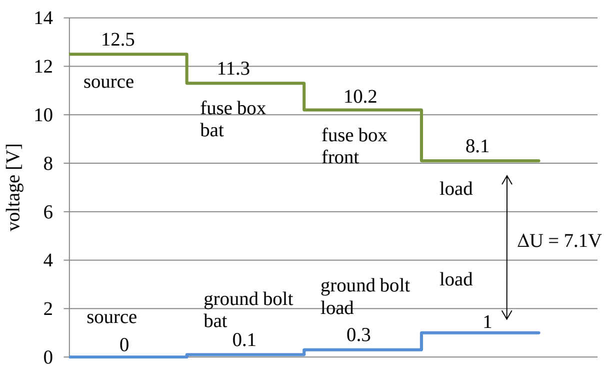

Figure 8. Voltage steps at different measurement points at $t = 11{,}8$ s of the slalom driving maneuver (Fig. 7). The resulting voltage at the terminals of the load is only 7.1 V.

V. Voltage Stabilization Possibilities

This chapter presents possible steps against the voltage drops. These measures include the application of an alternator, the usage of power reserves, the manipulation of load profiles and the application of capacitors.

A. *Voltage increase by alternator*

The alternator's actual purpose is to cover the mean power request. A further possibility is to use it for stabilization purposes, as presented in Fig. 9.

By increasing the alternators output voltage, the entire voltage level of the power net is enhanced. Although the absolute voltage drops are the same, their minimum is on a higher voltage level, which results in a stabilization effect on each component of the power net.

B. *Usage of power reserves*

In order to provide enough power for high prioritized consumer loads and to stabilize their voltage, lower prioritized loads can be switched off to allocate their power. Thus, power reserves describe a load's power demand that is not necessarily needed and that is required more urgently by another load. If a power request's amplitude, location and time are known, the power distribution management can switch off adequate loads to provide the power for other loads and thereby to stabilize their voltages.

Precondition for the switching off of a single load in order to stabilize the power net is an exact knowledge of the power net's architecture and the voltage's resulting behavior. As it can be seen in Fig. 10 the achievable stabilization depends on the installation place of the load that is stabilized and the one that is switched off. The example of Fig. 10 points out that the determining factor for the resulting effect of power reserves is their place of installation. In this case, six different 40 A loads were switched off. As a result, power reserves connected to the same power distribution box as the load that should be stabilized are more effective than other power reserves connected to different power distribution boxes.

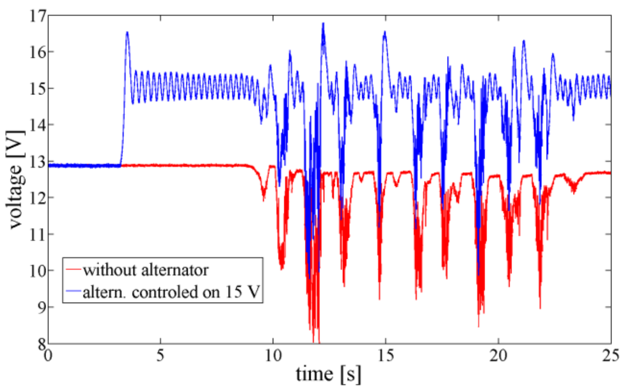

Figure 9. Comparison of a slalom driving maneuver without voltage increase by alternator to a scenario with voltage increase controlled on 15 V.

C. *Manipulation of load profiles*

It is particular difficult to stabilize the power net when the sum of peak loads is the highest. Thus, the aim is a minimization of peak loads and avoidance of interactions by rescheduling the load profiles. This has an influence on the single load's timing, but not on its amplitude. The higher the load's priority is, the smaller the allowed profile movement will be. E.g., it is not allowed to delay the stability control for more than several milliseconds, because of safety reasons.

D. *Application of capacitors*

While a battery's main purpose is the storage of energy, the capacitor's main purpose in cars is to provide and gain power peaks. Again, there is a dependency on the capacitor's place of installation. The higher the voltage drop at the capacitor's place of installation the higher is the resulting current the capacitor provides and therefore the stabilization effect. Since the voltage drops near the loads are the highest, the resulting stabilization is most effective there, too. Furthermore, all the current that is provided by the capacitor needs not to be provided by the battery and the parts of the wiring harness between battery and capacitor. Fig. 11 shows the resulting

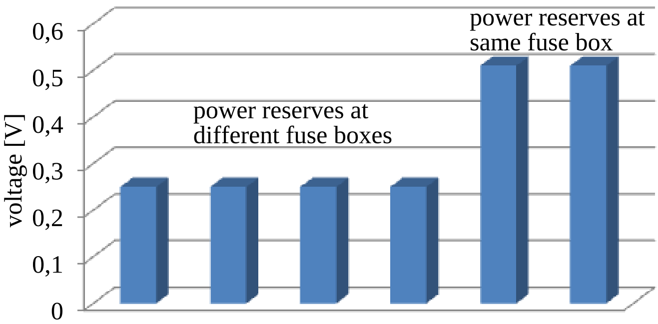

Figure 10. The determining factor for the resulting effect of power reserves is their place of installation. Power reserves at the same power distribution box as the load that should be stabilized are more effective than power reserves at different power distribution boxes.

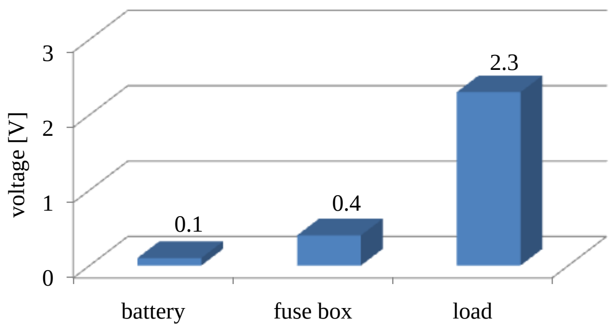

Figure 11. Voltage recovery for the capacitors' different places of installation exemplary presented for a slalom scenario.

voltage recovery at different positions of the capacitor exemplary presented for the slalom scenario of Fig. 7. In this scenario the resulting stabilization is very small, if the capacitors were installed at the battery. It is three times better, if they were installed at the power distribution box. But the most effective way is to install the capacitors right at the load that should be stabilized.

VI. Conclusion and Outlook

This paper describes the set-up of a power net test bench which enables experimental research on voltage stability in vehicular power nets. Thereby the problems of voltage stability's issues in today's vehicles are shown. Even while using components of a series-production vehicle, voltage drops down to 7.1 V can occur, if the different systems interfere inauspiciously with each other.

Accepting that the trends of increasing electrification and further safety and comfort systems can be extrapolated into the future, major problems will appear and methods to actively stabilize the power net's voltage will become more and more important. In the last chapter of this paper, a few proposals for stabilizing methods by a power distribution management system were pointed out. It was shown that the power net's voltage can significantly be increased only by an expedient combination of several methods to distribute electric power. This demonstrates the capability of active power distribution management in contrast to the installation of more energy storages or a heavier and more expensive wiring harness.

Furthermore, all analyses confirm that the complex set-up of the power net test bench using original wiring harness and car body is necessary to draw the right conclusions since the place of installation emerges as the main factor in all measurements. Therefore, only in this test environment, sustainable results in developing an active power distribution management can be achieved.

In the next step, a new power distribution management ECU has to be developed and added to the power net test bench. This system can execute the presented methods to counteract voltage drops. Besides, a high voltage level (and maybe a hybrid vehicle power train) shall be installed, generating new degrees of freedom for energy and power distribution management. Finally, dynamic power net simulation tools, like introduced in [17], can be validated at the power net test bench.

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