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Voltage Stability and System Behavior of Cybernetic Loads in Vehicular Power Nets

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Abstract

Voltage stability has to be ensured within automotive power buses in order to reliably supply all components with sufficient energy. Especially in modern vehicles (conventional, hybrid electric, or electric), the stability is endangered due to electric loads with high dynamics, for example chassis control systems. In this paper, a power distribution management based on cybernetic principles is described. To manage the power flow efficiently, it is reasonable to distribute some intelligence from the central control unit to the system's components such as loads. A load's control algorithm is presented that is able to fulfill the power management functions autonomously. Its stability is examined both in theory and in real cases.
Therefore, evaluation criterions are derived from the component's system behavior. Based on the algorithm's equations, the transfer function is defined in order to proof the stability. Furthermore, over 200 test cases had been conducted and analyzed at a power net test bench that contains the whole vehicular power net, including wiring harness and chassis ground. The impact of all variables and influence factors on the stability is checked and, likewise, malfunctions are examined, such as measurement errors or data transfer with long dead times. By this means, the most critical variables could be detected.
Based on the results, some improvements of the control algorithm are made and, as a result, a stable implementation is realized.

Keywords: component, energy consumption, load management, power management, reliability

1 Introduction and Motivation

The main function of all electric power nets is to supply all components reliably with energy. Therefore, voltage stability has to be ensured within the power net. Especially in the case of a mobile, isolated power net, it is a major challenge to provide (voltage) stability with limiting specifications (e.g. weight and space) of both energy storages and power supply. In this way, several analyses about the voltage behavior may be found in the literature, for instance in the power buses of space shuttles [1] or all-electric cruise liners [2].

Recently, the challenge of voltage stability has become an issue of growing importance in automotive engineering. In the last years, an increasing number of components in vehicles have been electrified. New electrical systems have been developed to improve the safety and comfort of the passengers as well as the car's driving performance. In addition, a continuous electrification of previously mechanically driven components—e.g. the cooling water pump or power steering—

can be observed and new systems are established. Looking at hybrid electric vehicles and electric vehicles, even more or all components are electrified, which means that vehicles are more and more dependent on the stability of their power nets.

As the electric power demand increases, so do the load peaks of the components in the electric power net. Currently several auxiliaries and other electric loads with a peak power of almost 2 kW are installed in vehicles, e.g. electrical power steering or chassis control systems [3–5]. Due to the high power peaks, it is becoming increasingly difficult to guarantee voltage stability. Stability issues are known especially in the 12 V power net [6,7], for instance in low velocity driving situations (and thereby driving situation having low power supply by the alternator) [8] or in power demanding driving situations such as a slalom driving maneuver. In order to illustrate this, Fig. 1 depicts the voltages, measured in a slalom driving maneuver of a state of the art luxury class vehicle. The continuous power demand of more than 600 W due to consuming loads—e.g. entertainment electronics, heating, or the electric engine control unit—is augmented by the power demand of four electric chassis control systems: Electric Power Steering (EPS), Antilock Braking System (ABS), Electronic Stability Control (ESC), and rear active steering. The occurring peak currents cause voltage drops because of losses at the internal resistance of the battery, the resistances of the wirings, distribution and fuse boxes, and at the car body serving as return conductor. The minimum voltage at the load is about 7 V.

For many years, the introduction of multi-voltage systems has been discussed for the numerous benefits it would bring [9]. The advantages of higher voltage power nets, e.g. the proposed 42 V system, were shown in [10, 11], but the automotive industry mainly stuck to the conventional and reliable 12 V power net.

Establishing hybrid electric vehicles and electric vehicles, a new high voltage necessarily has to be introduced. Thereby, the currents as well as the voltage drops become lower and, at first glance, the voltage stability problems seem to be solved automatically. 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. Therefore, all automotive power nets have to operate close to their limits, no matter whether implemented in conventional or electric vehicles.

However, it is possible to reduce the voltage instability by establishing a power distribution management system without implementing additional components and thus weight. The main objectives of this system are to distribute the power most efficiently within the power net and to balance the supplied and demanded power. Ideas of such a system are described in [12, 13], for instance. In [14] is shown that cybernetic methods are suitable for an automotive power distribution management system. One of these methods is the distribution of the intelligence towards the single components as loads or alternator. Ref. [15] also shows that a distributed approach is more appropriate for big and complex systems.

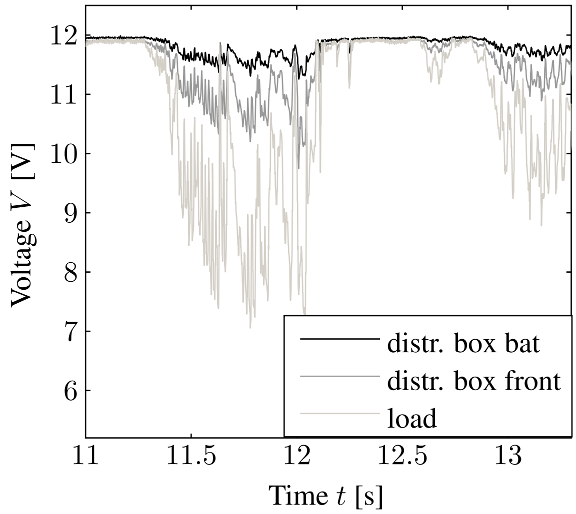

Figure 1: Cut-out of the slalom driving maneuver with measurements at the battery distribution box (distr. bat.), the distribution box in the front driver floor (distr. front), and one load (EPS). The voltage drop can be seen at all measuring points.

2 Goals and Approach

In this paper, cybernetic and intelligent loads are analysed in order to verify their stability in all possible situations.

After introducing the main features of the power distribution management system and presenting the power net test bench, the proof of stability is conducted: Firstly, the evaluation criterions are discussed. Secondly, the stability of the transfer function of the control algorithm is checked by the rules of control systems. Thereafter appropriate test cases for the practical stability analysis are developed and conducted. Finally, a conclusion and an outlook are provided.

3 Power Management

3.1 Voltage Stabilization

A predictive power distribution management system, as proposed in [8], is able to actively control and stabilize the voltage during the drive. If a power-critical event is predicted in the near future, it is possible to initiate countermeasures and to condition the power net and its components in advance. In addition to measures that are concerning the supply side (alternator), the consuming loads can be affected: In order to provide enough power for high priority consumer loads and to stabilize their voltage, lower priority loads can be degraded or switched off to allocate their power elsewhere.
The effectiveness of this measure depends on the installation position of the load that is stabilized and the one that is switched off. In [8] it is presented that 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. Therefore, a precondition for switching off a particular load in order to stabilize the power net is an exact knowledge of the power net's architecture, and the voltage's resulting behavior. If a power request's amplitude, location, and time are known, enough loads can intelligently be degraded by the power distribution management in order to provide the power for other loads, and to stabilize their voltages thereby.

3.2 System Requirements

However, the development of such a power distribution management system which is well-suited for its application in vehicles poses some challenges, which have to be mastered, e.g.:

- Resources: There are short resources such as processing time, memory usage, and communication transfer in the vehicle.
- Local distribution: As mentioned above, a power distribution management system necessarily has to consider the local power supply and demand within all branches of the wiring harness.
- Complexity: Caused by the complex structure of today's power nets, many voltages and currents have to be monitored and a multitude of ECUs has to be controlled.

Due to these three reasons, a centralized system is not suitable for automotive applications. It is a necessity to find methods, which can master and reduce the complexity in order to create a system being suitable to mobile application.

3.3 Cybernetic Methods

Ref. [14] shows that a management system that is based on cybernetic principles is able to perform the mentioned objectives.
Transferring the ideas of other cybernetic management systems, for instance in business administration, to a vehicle's energy and power management results, amongst others, in the two cybernetic principles:

- Hierachization: By stringent hierarchization, communication channels can be well-defined and the communication traffic between the objects can be minimized.
- Subsidiarity: That is the organizing principle in which a central authority only performs tasks, which cannot be fulfilled effectively at a more local level [16].

Applying these two principles provides a local power management by itself. Each difference in supply and demand of power will be balanced on local levels without any superordinate and extensive control.
The central authority only provides a global control target and will not be involved until the problems exceed the capability of the local, subordinated level. All components (e.g. loads) autonomously try to obtain the control target in the scope of their possibilities. They report their key figures to the central authority that may deduce new control targets.

3.4 Intelligent Loads

3.4.1 Functionality

In order to establish such a system, at least the most important components must have a local intelligence that enables the execution of cybernetic functions. They have to be able to ...

- ... receive target values by the central authority and to report their key figures to the central authority.
- ... reduce their power to reach a voltage set point that is provided by the central authority autonomously. As a result, they have to resume their functionality—that means increase their power—without disturbing the system's voltage.
- ... coordinate their power changes with other loads to guarantee stability.

3.4.2 Control Algorithm of cybernetic Loads

In [8], cybernetic, intelligent loads are introduced that are able to fulfill the tasks mentioned above. Without loss of generality, a system of three loads that are connected with the same distribution box is considered.[1]

Due to the same connection, the voltage of the node (distribution box) V_n is chosen as process variable. All loads can calculate that voltage

$$V_n[n] = V_{L_{meas}}[n] + R_W \cdot I_{L_{meas}}[n] \quad (1)$$

knowing the resistance R_W of their supply line as well as their own voltage and current. Therefore, communication is not necessary between the components.

The developed control algorithm is a combination of feedback or error-driven control and feed-forward control (compare Section 5.2). When a critical situation is detected, the central authority estimates suitable counteractive measures and transmits a control command to the cybernetic loads. Using this information, the loads stabilize the voltage in coordination with the other intelligent loads. The control command includes the target node voltage called V_{target}, the time to the predicted voltage drop t_{target}, and the time how long the voltage should be held. The loads adapt their power considering their actual internal status. During every iteration of the algorithm, a new current $I_L[n]$ is created by calculating

$$I_L[n] = I_{grad}[n-1] \cdot t_{loop} + I_L[n-1]. \quad (2)$$

Herein, t_{loop} is the cycle duration of one iteration of the algorithm. The variable I_{grad} has the most significant effect on the linear equation. It is the gradient

$$I_{grad}[n-1] = \frac{V_n[n-1] - V_{target}}{R_W \cdot t_{target}}, \quad (3)$$

which is calculated from the voltage difference that should be stabilized. According to the behavior of the other loads, this gradient is adapted during each iteration. Fig. 2 shows the voltage and current chart in the last step before the target voltage is reached.[2] The last step is marked with a dashed line. Insignificant differences to a linear voltage increasing are regular, because no load knows exactly in what scope the other loads are able to reduce their power consumption.

After the given voltage V_{target} is reached, it should be held for a given time. Maintaining this

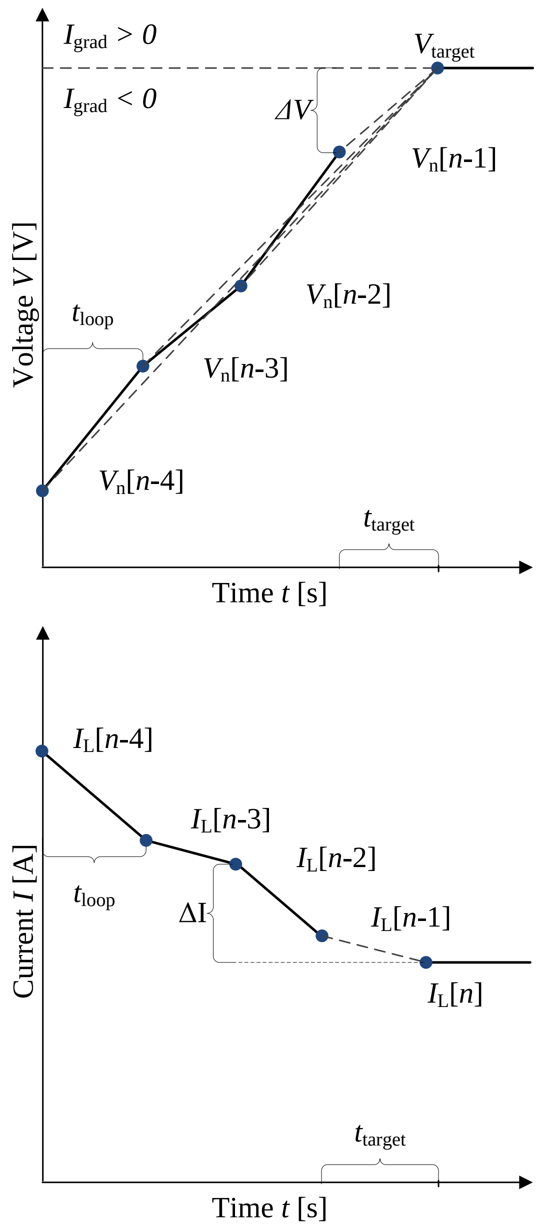

Figure 2: Control algorithm of the intelligent, cybernetic loads: To reach a subnet voltage of V_{target}, the actual current has to be decreased in t_{target}. In doing so, the gradient of the current has to be adapted in each iteration. The closed-loop control forces to follow the target trajectory defined by the feed-forward control.

[1]The power management consists of several hierarchical layers, described in [17]. Therefore a transfer to arbitrary power net topologies can easily be done.

[2]Measured characteristics can be seen in Figures 6 to 10.

voltage is done by the same control algorithm, using new target values. Now, the difference

$$\Delta V = V_n[n] - V_{target} \quad (4)$$

should be minimized as fast as possible.

4 Power Net Test Bench

All testing is conducted at the power net test bench described in detail in [18]. The test bench consists of several regulated electronic loads, a real battery and an alternator, as well as an original wiring harness and car body (return conductor). That is necessary because the voltage behavior is only emulated correctly in a realistic power bus. The whole installation is shown in Fig. 3. Every experiment was conducted using several loads that were connected to the same distribution box.

5 Stability

In order to proof the stability of the control algorithm, it is important to analyze it both theoretically and practically.
The idea is to analyze the control algorithm within the range of validity. Using the known equations of the algorithm (cf. section 3.4.2), a stationary transfer function can be determined by the rules of control systems. Thereafter, all variables are classified in various categories to create appropriate test cases for the practical stability analysis. In the last passage, some test cases are explained in detail.
First of all, the requirements and the evaluation criterions for the implementation of the intelligent loads should be discussed.

5.1 Requirements and Evaluation Criterions

The intelligent loads should help to reach the voltage stability of a electrical power net. Therefore it is important that the following requirements are fulfilled properly. The requirements are:

- to decrease the subnet voltage nearly linearly to guarantee a good power gradient
- to avoid oscillation if all components try to obtain the control target
- independence from system reaction time
- to compensate errors in measuring

In order to check if all these requirements are already satisfied by the implemented intelligent loads, it is important to define important evaluation criterions for the success of the control intervention. These five criterions are checked in order to decide whether the intervention is successful or not:

1. no control deviation ΔV
2. reaching of the desired voltage in the given time
3. linear decreasing of the current and voltage characteristics during the control process
4. sensitivity to changes in the desired voltage during the "hold"-case
5. no control against each other during the entire intervention

Moreover, it is essential to check stability by looking at the control algorithm theoretically.

5.2 Theoretical Stability Verification (stationary[3])

After introducing and explaining the equations of the control algorithm, they are now used to extract the transfer function.
The content of the transfer blocks is unknown, but it is likely that in this case a fixed command control is given. The desired voltage is the command variable and the subnet voltage is the controlled process variable of the system. The variable ΔV equates to the control deviation. Based on the assumption that in this case no typical control mode exists (in principle the developing of current values is known and slope limit is set), a feed-forward control is discussed.
In Fig. 4 the structure of the feedback control system with feed-forward block is illustrated.

In contrast to the real model, it is necessary to calculate the subnet voltage for the theoretical stability analysis. For this purpose,

$$V_n[n] = V_n[n-1] + \{I_L[n-1] - I_L[n]\} \cdot R_W \quad (5)$$

replaces (1).

[3] This linear time-invariant system (LTI-System) cannot be evaluated continuously for all time steps. It has to be assessed stationarily step by step.

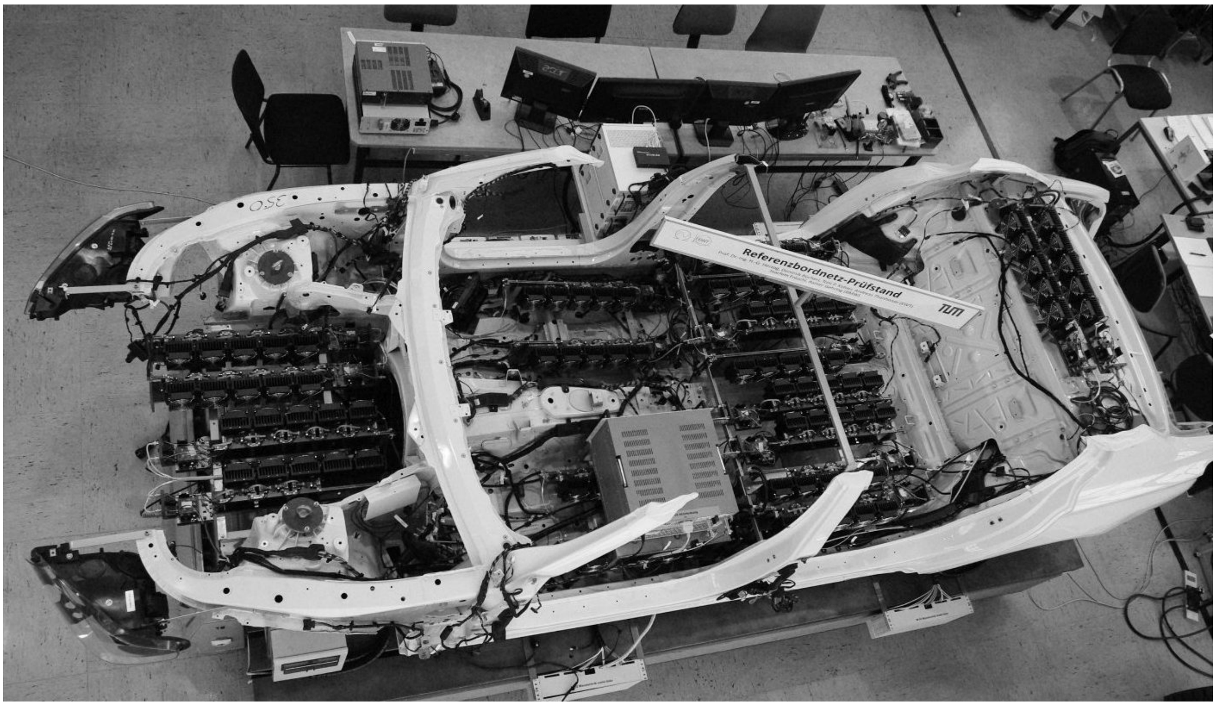

Figure 3: Power net test bench based on a luxury class car body and wiring harness including battery, alternator and several regulated electronic loads with high dynamics. Control and measurement equipment is not shown.

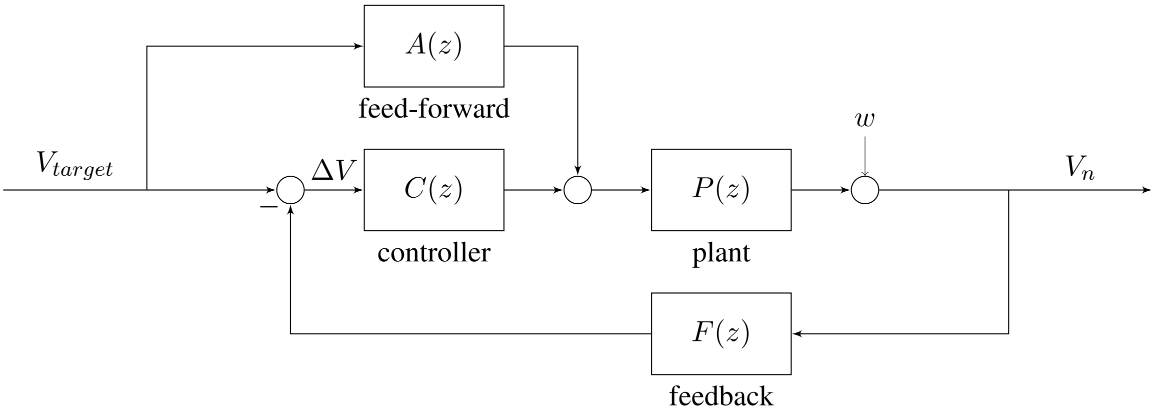

Figure 4: Structure of the feedback control system with feed-forward block.

Inserting (2) into (5) yields the following finite difference equation of order one:

$$V_n[n] = V_n[n-1] + \left\{ I_L[n-1] - \frac{V_n[n-1] - V_{target}}{|R_W \cdot t_{target}[n-1]|} \cdot t_{loop} - I_L[n-1] \right\} \cdot R_W \tag{6}$$

After some conversion steps, the output is exhibited by the weighted sum of the previous values of input and output:

$$V_n[n] = V_n[n-1] \cdot \underbrace{\frac{|t_{target}[n-1]| + t_{loop}}{|t_{target}[n-1]|}}_{a_1} + V_{target} \cdot \underbrace{\frac{-t_{loop}}{|t_{target}[n-1]|}}_{b_0} \tag{7}$$

Under consideration of the displacement law (8):

$$\mathcal{Z}\{f[n-k]\} = z^{-k}F(z)$$
$$R_x\text{: All}z\text{−valuesinsteadof0 for } k > 0 \tag{8}$$

the finite difference (7) can be transformed using the z-transformation

$$V_n[n] \equiv y[n] \qquad V_{target} \equiv u[n]$$
$$y[n] \circ\!\!-\!\!\bullet\ Y(z) = \mathcal{Z}\{y[n]\} = \sum_{n=0}^{\infty} y[n]z^{-n} \tag{9}$$

into the z-plane:

$$Y(z) - z^{-1}Y(z) \cdot a_1 = U(z) \cdot b_0$$
$$Y(z) \cdot [1 - z^{-1}a_1] = U(z) \cdot b_0 \tag{10}$$

The result is the transfer function of the time-discrete LTI-Systems:

$$H(z) = \frac{Y(z)}{U(z)} = \frac{b_0}{1 - z^{-1}a_1} = \frac{z \cdot b_0}{z - a_1} \tag{11}$$

By setting the numerator equal to zero, the zero is found. The denominator defines the position of the pole. Hence, the position of the pole depends on the time step we are looking at. For any time t_{target} near to zero the pole position goes to infinity. Otherwise the pole is close to one. Fig. 5 shows the pole and zero position in the z-plane.

Due to a rectangular pulse input signal, the area of convergence includes the whole z-plane without zero. Therewith, the theoretical stability is proofed for every instant of time.

5.3 Classification of the Variables

All the used variables of the equations presented in subsection 3.4.2 can be separated into four classes. The first class includes the *target specifications* with the requirements of the power distribution management. This class leads to an estimation for the potential of the intelligent loads in the following subsection.

Another class contains the *absolut terms* which are not changing during the entire program execution. Within this class, an inaccurate set point selection can be simulated for one or two loads, or for all intelligent loads.

A full bus line or a transmission error can cause malfunctions in the *dynamic measuring*. To emulate these faults, this class of variables is changed constantly, proportionally and the data is transferred with reaction time.

The fourth and the last class consists of all variables which has to be *calculated* during the program execution. The new load current and the current slope are kept constant in the test cases. Furthermore, they are changed proportionally.

Table 1 illustrates the classification made above.

Table 1: Classification of the variables used in the control algorithm

Class 1 **Target spec.**	Class 2 **Absolut term**	Class 3 **Dynamic measuring**	Class 4 **Calculation**
V_{target} T_{target} T_{hold}	R_W t_{loop}	$I_{L_{meas}}$ $V_{L_{meas}}$	$I[n]$ $I_{grad}[n]$ $t_{target}[n]$ $V_n[n]$

In addition to the introduced class tests, situations that exist in reality are also implemented in test scenarios. Further constant loads are connected to the power distribution box and the already installed loads have to accomplish the control task alone in order to assess the potential of the control. To simulate a different load shutdown, the loads are turned off erratically. In this way, all possible error cases are covered.

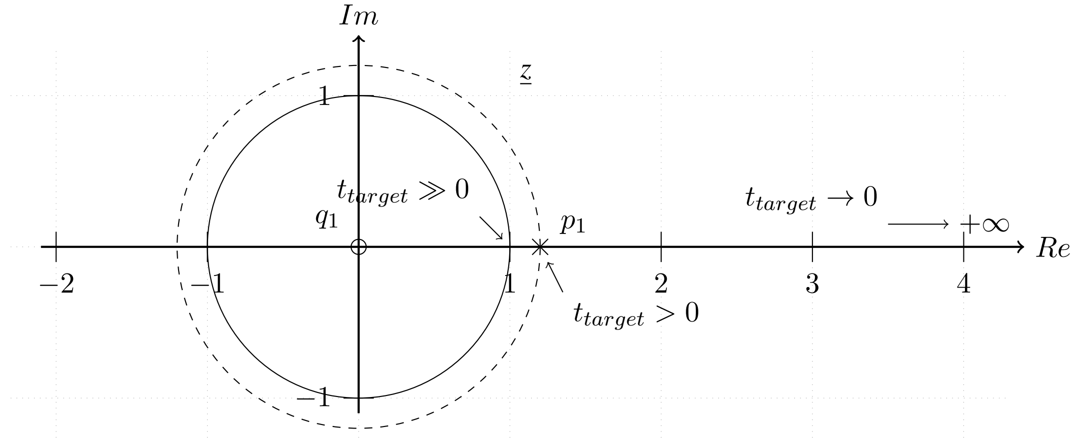

Figure 5: Position of the pole and zero in the $\underline{z}$-plane. The area of convergence is the complete $\underline{z}$-plane. The unit circle is part of the area of convergence. Pole p_1 and zero q_1 is figured at an instant of time near to $t_{target} = 0$.

5.4 Test Cases

All in all, over 200 test cases have been conducted and analysed at the power net test bench. The goal of every test cycle is to check the stability limit of the control. Moreover, very critical variables should be exposed to improve the intelligent loads at those points. The improvements are discussed in detail in Section 6.

5.4.1 Additional constant Loads

Often, it is not possible to reduce the current of every single load. Especially the lights cannot be switched off without loss of security. For this purpose, the intelligent loads are tested in an array with standard loads, which cannot be deactivated. In Fig. 6, two loads with a current consumption of 30 A are activated at about 1.3 s, which causes a voltage drop of 0.8 V. Nevertheless the three intelligent loads reach the preset voltage without disturbance.
The test case is fulfilled properly, hence the control has not to be improved.

5.4.2 Incorrect Wire Resistance

The resistance of every supply wire is affected by temperature and corrosion. In this test case, the wire resistance of load three is increased by 20%. According to (3), the current slope decreases. Moreover, the subnet voltage is not properly calculated (see (1)) and is always lower in reality. Thus, the loads are controlling against each other to reach the desired voltage. The fifth evaluation criterion cannot be fulfilled, which can be seen in Fig. 7.

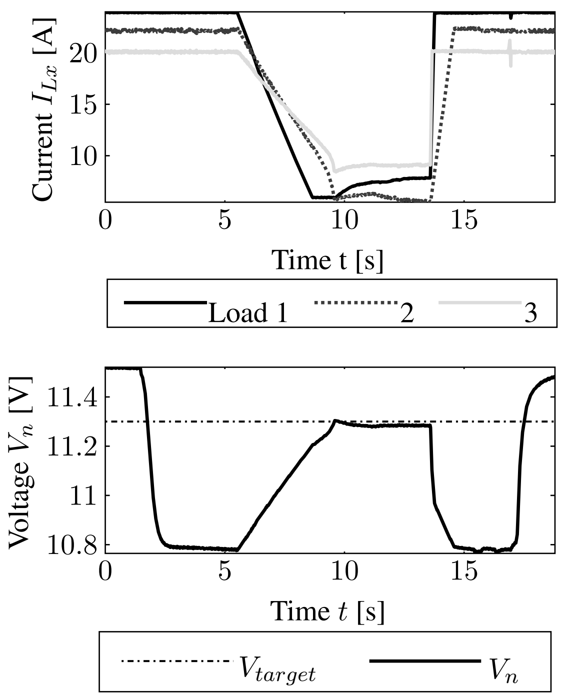

Figure 6: The measurement curve shows how a voltage of 11.3 V is reached in 4 s and is held over 4 s. Additionally two constant loads are part of the subnet. Each laod has a current consumption of 30 A. The control objective is achieved without disturbance.

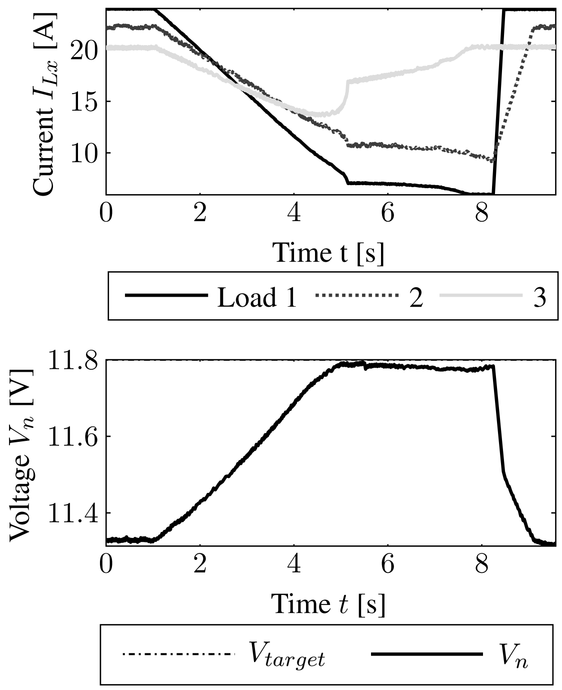

Figure 7: The measurement curve shows how a voltage of 11.8 V is reached in 4 s. In spite of controlling against each other the voltage can be held over 3 s. $R_{W,L3}$ is increased by 20%.

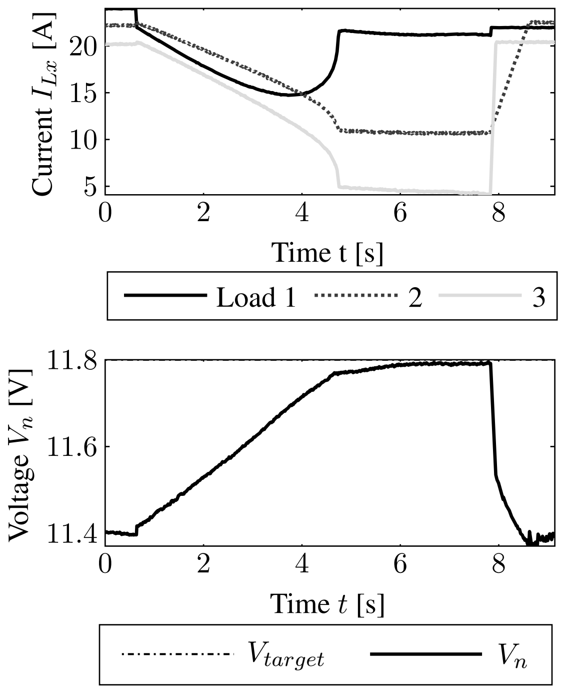

Figure 8: The measurement curve shows how a voltage of 11.8 V is nearly reached in 5 s and is held over 3 s. Load 1 measures a constant current of 22 A. All the remaining loads have to react to this misbehaviour.

To suppress this problem, the desired voltage can be changed to the actual voltage just before the "hold"-case. This improvement is discussed in Section 6.

5.4.3 Load Current Measurement Error

Voltage and current are constantly measured by the intelligent loads and are used to calculate the subnet voltage. Hence, they can reach the target voltage devoid of communication with the other loads or the central authority. Fig. 8 shows load one, which always measures spuriously a constant current of 22 A and runs counter the other loads. At about 3.8 s, the affected load calculates that the desired voltage is reached and stops to decrease current. Unfortunately, load two and three calculate the correct subnet voltage and decrease continuously their current. This causes a nonlinear decreasing of the current and voltage characteristics during the control process and should be improved.

6 Improvements of the intelligent Loads

The tests emphasize that variations and failures of variables, which are relevant for the calculation of the subnet voltage (load current, load voltage, load resistance), are most critical. Likewise, a delay of new current calculation is deemed critical. Hereupon, the control algorithm is extended and improved to stabilize or avoid critical situations. Loads with a defective management are suppressed or deactivated automatically to ensure that they are no longer interfering in the control sequence.

One of the improvements is the possibility to suppress the loads to run counter in the "hold"-case. Therefore, the desired voltage of each intelligent load is simultaneously set to the actual calculated voltage at the end of the current decreasing. Thus, the erroneous load is inhibited and cannot disturb the control anymore. Fig. 9 shows the measurement of Fig. 7 with the previously mentioned improvement.

Another improvement enforces a defective load to stop the control sequence before the preset time t_{target}. This second opportunity enables to intercept a load if it calculates that it reached the desired voltage. From this time the load holds the most recently calculated current and is no longer interfering in the control. The remaining loads can decrease their current unimpededly. Fig. 10 shows the measurement of Fig. 8 with the early control stop.

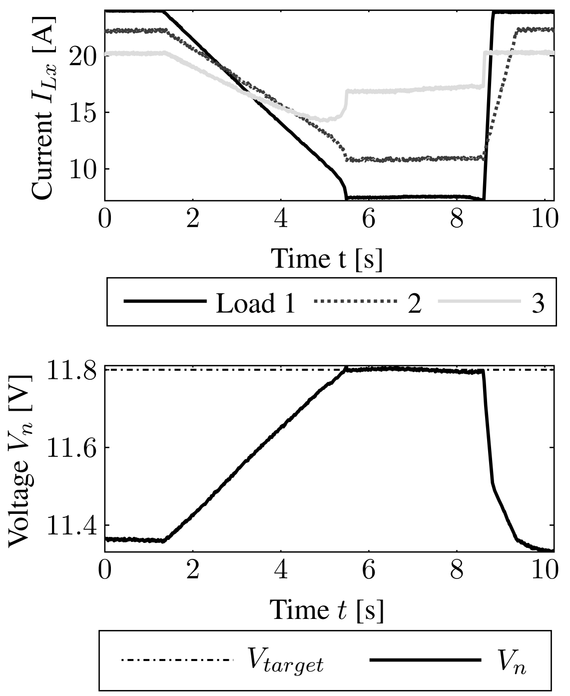

Figure 9: The measurement curve shows the affect of the counter-control improvement. The loads do not run counter in the "hold"-case (cf. Fig. 7).

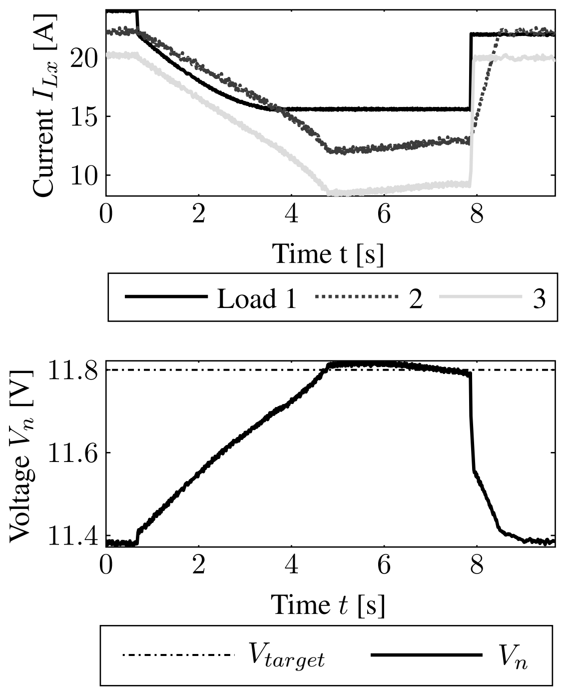

Figure 10: Defective loads are deactivated before they affect other loads negatively. As a result, there is no control against each other during the entire intervention (cf. Fig. 8). $I_{L1_{meas}} = 22\,\text{A}$.

7 Conclusion and Outlook

The algorithm of the control, the requirements and the evaluation criterions are the basis of the stability analysis. Based on the algorithm's equations, the transfer function of a time-discrete LTI-System can be calculated and the theoretical stability can be proofed for every instant of time.

Thereafter, all variables are classified in various categories to create appropriate test cases for the practical stability analysis. The tests emphasize the variables, which are less and most critical, and exhibit the important points for improvement. To avoid critical situations, the advancements inhibit an erroneous load to stop disturbing the control. Moreover, there is the opportunity to disable a load, when reaching the desired voltage before the target time.

As a result, a stable control algorithm implementation whose potential can be used for the voltage stability of the electrical power net is arisen. Now, the cybernetic control algorithm can be applied to other cybernetic objects, for example the alternator or a DC chopper converter coupling two voltage levels. In combination with a power distribution management prototype that is implemented on a real-time system, thus, the complete system can be verified.

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