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Analyzing Critical Resonances Within Automotive Power Supply Systems Affecting the Transient Voltage Stability

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***Abstract*—Future automotive power supply systems must be fail-operational. Therefore, supply voltage stability has to be ensured for safety-relevant components even in case of a single fault within the system. Otherwise, single faults could affect redundancy concepts that take over the functionality of a failed part of the system. As power system faults can cause disturbing transient voltage pulses propagating through the overall power system, this is not guaranteed. Critical transients have to be identified and then compensated by appropriate measures, such as capacitive or inductive circuits. Identifying all critical transients in an extended system is a challenging task. Accurate network simulations in time domain could find critical configurations, but tend to be time-consuming. Therefore, this work assesses an alternative frequency domain method to reveal critical resonances that lead to over-voltages. Established modal analysis approaches developed for AC power delivery systems are discussed and adapted to investigate resonant coupling paths within automotive DC supply systems. Finally, an exemplary supply system is analyzed to demonstrate the presented method and evaluate its potential.**

***Keywords*—*Automotive power supply; voltage stability; simulation; frequency domain; resonances*.**

I. Introduction

Automated driving requires future vehicles to be fail-operational, which means safety-relevant functions have to be available, even in case of a failure [1]. Redundant hardware, that provide the same function by two independent components, is the most common approach. If one component fails, the other component takes over. In case of a power supply failure, such as a short in a component or a wire, the fuse separates the faulty component. Both the short and the separation of the component by the fuse cause voltage transients in the power supply system, that might affect the supply voltage of other connected components. This is exemplarily depicted in Fig. 1. In the worst case, the voltage transient leads to a failure of the redundant component and safety-relevant functions are completely lost. Interactions of failures have to be investigated. Each fault and fault propagation path must be analyzed and safeguarded so that other functions are not affected.

Current development processes do not consider these complex interactions in power supply systems. Past research on supply system stability was mainly focused on slow events and static consequences of failures on the on-board voltage stability, e.g., [2, 3]. Some recent works also focus on the propagation of transients within the system caused by dynamic loads [4] and switching events [5, 6]. Using these approaches, the transient system behavior can be simulated in the time-domain with well-known network simulation programs, like SPICE or MATLAB/Simscape. However, these are usually very time-consuming.

To investigate all possible system failures, a large number of configurations need to be evaluated. Therefore, efficient alternative methods are required. In AC power delivery systems, modal analysis is a common approach to investigate resonance phenomena that affect power quality and voltage stability. A common method to

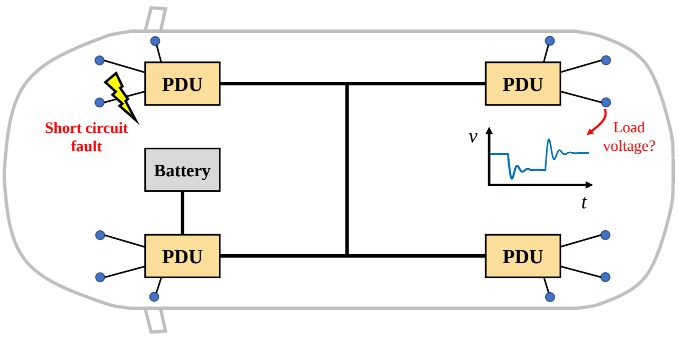

Fig. 1: Simplified illustration of an exemplary power supply system with four power distribution units (PDUs) and several loads (blue circles)

investigate the issue of harmonic resonances in these supply systems is based on a nodal description in frequency or s-domain and eigenvalue decomposition. Methods have been presented in, e.g., [7–10], and have been applied to systems such as wind farms [11], power-electronics-based systems [12, 13], HVDC-coupled grids [14] or photovoltaic systems [15].

In this paper, the application of modal analysis to failures in DC automotive power supply systems is analyzed. Specifically, the resonant behavior during switching processes is analyzed to identify critical voltage oscillations and reveal potentials for optimizing the voltage stability.

First, an overview of existing modal analysis methods is given. Then, adaptions are discussed to investigate the effects of switching events on safety-relevant loads. The resonant behavior of an exemplary supply system is examined to demonstrate the possibilities of frequency domain analysis. Finally, the performance of the proposed method compared to accurate time domain simulations is assessed.

II. Methods of Modal Analysis

In AC power systems, parallel resonances are of particular interest. A nodal current injection that stimulates the system at a parallel resonance frequency can lead to particularly high voltages within the system. Modal analysis techniques have been developed to investigate and mitigate these potentially problematic resonance phenomena. These methods usually include the eigenvalue decomposition or the calculation of poles of the system's transfer impedances.

A. Resonance Mode Analysis

The method of resonance mode analysis (RMA) is proposed in [7] and is based on the frequency dependent nodal admittance matrix $\boldsymbol{Y}(f)$ of a power supply system. The vector of nodal voltages $\boldsymbol{V}(f)$ can be calculated by:

$$\boldsymbol{V}(f) = \boldsymbol{Y}(f)^{-\mathbf{1}}\boldsymbol{I}(f) \tag{1}$$

The vector $\boldsymbol{I}(f)$ contains the currents injected at the individual nodes. In the following, the frequency dependence is omitted in the notation for the sake of simplicity. The $\boldsymbol{Y}$ matrix can now be decomposed into the matrix $\boldsymbol{\Lambda} = \mathrm{diag}(\lambda_1, \dots, \lambda_N)$ of its N eigenvalues and its left and right eigenvector matrices $\boldsymbol{L}$ and $\boldsymbol{T}$, respectively, where $\boldsymbol{L} = \boldsymbol{T}^{-\mathbf{1}}$ [7]. Equation (1) then yields [7]:

$$\boldsymbol{V} = \boldsymbol{L}\boldsymbol{\Lambda}^{-\mathbf{1}}\boldsymbol{T}\boldsymbol{I} \tag{2}$$

The inverse eigenvalues λ_i^{-1} are considered the modal impedances and have the unit of Ohm. A significant parallel resonance occurs if the magnitude of one of the eigenvalues becomes very small, resulting in a large modal impedance. By investigating the individual eigenvalues, the different resonance modes of the system can be analyzed separately. Furthermore, a measure for the participation of a specific system node to an observed resonance can be defined; these so-called participation factors PF_{nm} where introduced in [8] and describe how strong a mode m can be excited and observed at a node n [7]:

$$PF_{nm} = L_{nm}T_{mn} \tag{3}$$

L_{ij} and T_{ij} are the entries of the i-th row and j-th column of the left and right eigenvector matrices, respectively.

B. S-Domain Modal Analysis

Another modal analysis approach that is based on a nodal formulation of a system is presented in [9]. Here, the nodal admittance matrix $\boldsymbol{Y}(s)$ is investigated in the Laplace domain. In comparison with (1), the node voltages $\boldsymbol{V}(s)$ can again be calculated given the injected currents $\boldsymbol{I}(s)$:

$$\boldsymbol{V}(s) = \boldsymbol{Y}(s)^{-\mathbf{1}}\boldsymbol{I}(s) \tag{4}$$

The transfer function between a current injection at node i and the observed voltage at node j is therefore described by the element in the j-th row and i-th column of the inverse admittance matrix $\boldsymbol{Y}(s)^{-1}$. The complex poles of these transfer impedances can now be determined to reveal resonances within the system.

III. Adaption to Automotive Supply Systems

The presented modal analysis approaches are now adapted to investigate the transient behavior of DC automotive supply systems. Specifically, the frequency domain information shall be used to determine critical switching events that can result in significant voltage pulses at safety-relevant loads.

First, the differences compared to the modal analysis of AC systems shall be pointed out. In AC power delivery systems, nonlinear loads may produce harmonics at multiples of the fundamental frequency. If these harmonics excite resonance frequencies of the system, they may, for example, affect power quality. In DC automotive power supply systems, harmonics do not exist. In contrast, switching slopes stimulate the system in a wide frequency range. Moreover, the effects of these stimulations are primarily relevant at the supply nodes of safety-relevant loads.

A. System Modeling

Many power supply systems can be modeled with sufficient accuracy by only passive components. The components attached to the supply system often show a purely resistive or a resistive-capacitive behavior and can be modelled as RC elements [5]. Wires can be modeled by their resistance and inductance. DC voltages do not influence the AC behavior and can be considered as simple short.

The nodal admittance matrix $\boldsymbol{Y}(f)$ (respectively $\boldsymbol{Y}(s)$) of the resulting model can then be formulated according to the well-known nodal analysis method [16].

B. Consideration of Switching Processes

In general, switching processes are events that result in a time-invariant admittance matrix. Assuming ideal switching, a triggering fuse or a breaking wire leads to its respective resistance to be modified from a low to a high value. The switched-off current is the stimulus of the system. The generated transient voltage pulses then propagate through the system described by the admittance matrix. Therefore, the admittance matrix needs to be analyzed regarding its resonant behavior. By calculating the spectrum $\boldsymbol{I}(f)$ of the switching slope, the resulting node voltages $\boldsymbol{V}(f)$ can be calculated according to (1).

C. Observation at Safety-Relevant Loads

When considering the transient voltage stability of power supplies, safety-relevant loads are of particular interest. Beyond the general occurrence of resonances within the system, it is even more important how these transients propagate through the system and how they can be observed at safety-relevant components.

As introduced in section II.A, participation factors describe a combined measure of modal excitability and observability at a specific node. Based on this concept, a generalized measure is defined to describe the coupling of a mode *m* that is excited at node *l* and observed at node *n*. According to the eigenvalue decomposition in (2), the voltage at node *n* during an excitation at *l* can be expressed by:

$$V_n = (\lambda_1^{-1} \cdot L_{n1} T_{1l} + \lambda_2^{-1} \cdot L_{n2} T_{2l} + \cdots) I_l \qquad (5)$$

Therefore, the coupling factor of a specific mode *m*, hereafter referred to as coupling factor CF_{lmn}, is defined as:

$$CF_{lmn} = L_{nm} T_{ml} \qquad (6)$$

Furthermore, the weighted transfer impedance Z_{lmn} of each mode is defined as:

$$Z_{lmn} = \lambda_m^{-1} L_{nm} T_{ml} = \lambda_m^{-1} CF_{lmn} \qquad (7)$$

The summation of this impedance for all system modes therefore leads to the total transfer function $Z_{ln,\text{total}}$ from node *l* to node *n*:

$$Z_{ln,\text{total}} = \sum_{m=1}^{N} Z_{lmn} = Y_{ln}^{-1} \qquad (8)$$

This transfer function simultaneously corresponds to the *l*-th row and *n*-th column entry of the original inverse nodal admittance matrix $\boldsymbol{Y}$. Analogous, the s-domain transfer function of this scenario corresponds to the same entry of the inverse s-domain nodal admittance matrix (refer to (9)). However, modal decomposition in s-domain is a complex task [10].

$$Z_{ln,\text{total}}(s) = Y_{ln}^{-1}(s) \qquad (9)$$

An example for the described coupling is shown in Fig. 2. Here, load 2 is shorted and fuse 2 trips. Therefore, the load path is switched off and the resulting current slope $i(t)$ stimulates the remaining system, causing a voltage oscillation $v(t)$ at load 1. The frequency domain coupling between this switching event and the load voltage is described by the transfer function $Z_{2,5,\text{total}}$.

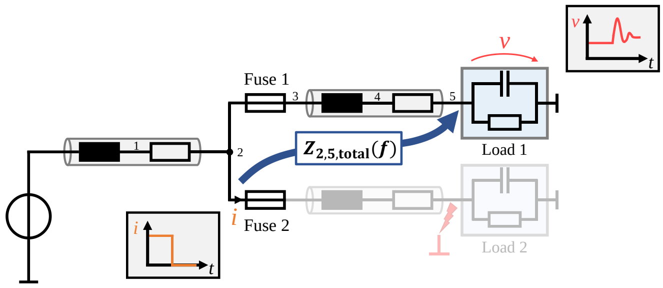

Fig. 2: Example network with a short at load 2, the resulting pulse at load 1 and the relevant transfer function

IV. Analysis of Exemplary System

In this section, the resonant behavior of an exemplary automotive power supply system is analyzed. Fig. 3 and Table *1* show the topology and the load and wire parameterization of the investigated example. The topology consists of four power distribution units (PDUs) with two exemplary loads connected to each and a redundant supply. The nodes that are especially relevant in this section are denoted by green numbers. The following scenario is considered: PDU 3 is switched off at node 10 because of an internal short circuit fault. The transient effects of this switching event are to be observed at safety-relevant loads 2 and 3.

Table 1: Load Parameterization of Investigated Power Supply System

PDU	Load	Impedance	Wire (cross section, length)
1	1	0.15 Ω	25 mm², 2 m
	2	100 Ω ‖ 220 µF	0.35 mm², 2 m
2	3	1 Ω ‖ 440 µF	1.5 mm², 2 m
	4	0.5 Ω	4 mm², 2 m
3	5	0.75 Ω ‖ 440 µF	2.5 mm², 2 m
	6	1 Ω ‖ 440 µF	1.5 mm², 2 m
4	7	0.5 Ω ‖ 440 µF	4 mm², 2 m
	8	10 Ω ‖ 220 µF	0.35 mm², 2 m

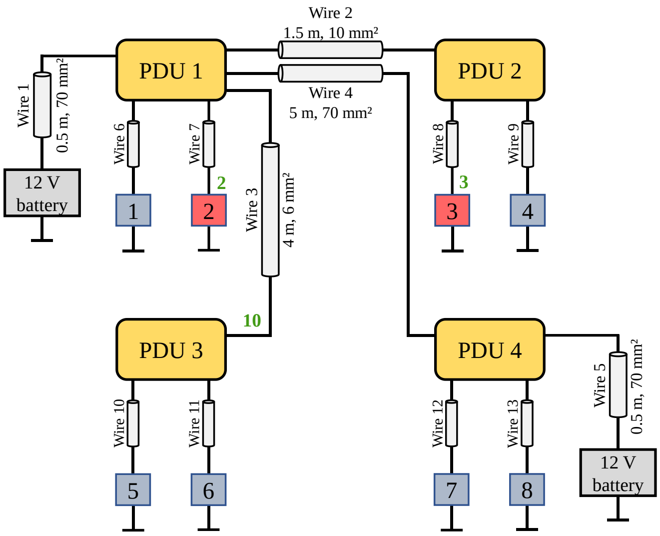

Fig. 3: Investigated power supply system

The RMA method is applied to the nodal admittance matrix of the system with switched off PDU 3; an eigenvalue decomposition is performed (see II.A). The twelve largest modal impedances, i.e., inverse eigenvalues of the $\boldsymbol{Y}$ matrix, are depicted in Fig. 4 for frequencies up to 50 kHz. Three distinct resonance peaks can be observed in mode 8 ($f_1 = 3.73$ kHz), mode 3 ($f_2 = 5.02$ kHz) and mode 6 ($f_3 = 33.7$ kHz), respectively. Note that the order of the depicted modal impedances depends on the eigenvalue calculation algorithm and has no direct physical relation.

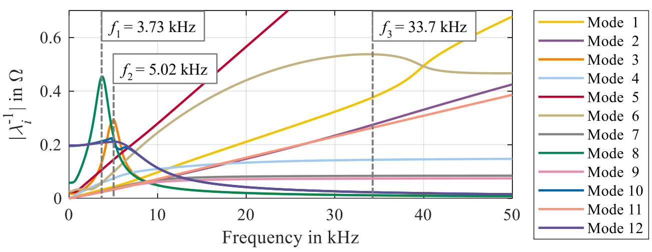

Fig. 4: Selected modal impedances (inverse nodal admittance matrix eigenvalues) of investigated system

To investigate how these modal impedances contribute to the coupling between the switching event at node 10 and the observed load voltages, the coupling factors need to be considered. Fig. 5(a) shows the coupling factors $CF_{10,m,3}$ of the selected modes between the excitation node 10 and load 3. Multiplied with the inverse eigenvalues, these result in the corresponding modal transfer impedances $Z_{10,m,3}$ (Fig. 5(b)). It can be seen that the strong coupling of modes 5 and 6 does not correlate with resonant peaks of their modal impedances. However, these two modes largely cancel each other out; the total coupling $Z_{10,3,\text{total}}$, as seen in Fig. 6(a), shows only one remaining distinct resonance peak at about 3.9 kHz that is primarily caused by mode 8.

In comparison, the simulated time domain load voltage that results from the switching event is depicted in Fig. 6(b). The switching triggers an oscillation of the load voltage that reaches up to 23 V. The frequency of this damped oscillation matches with the resonance peak observed in frequency domain.

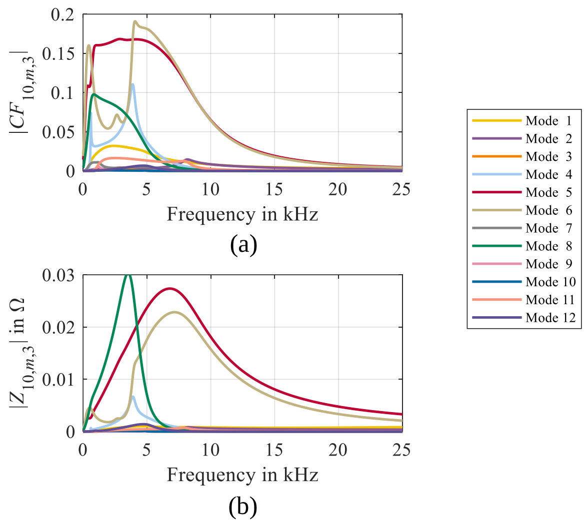

Fig. 5: Coupling between node 10 and load 3 for selected modes. (a) Coupling factors. (b) Modal transfer impedances

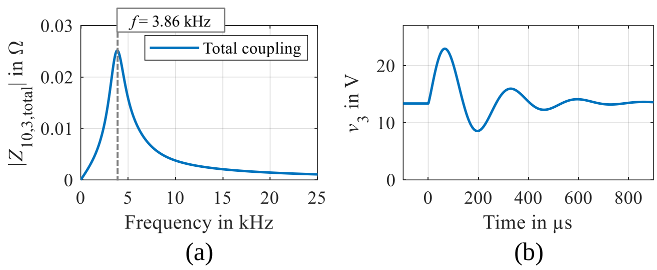

Fig. 6: (a) Total frequency domain coupling between node 10 and load 3. (b) Time domain voltage at load 3. Switching at $t = 0$

Next, the coupling between node 10 and load 2 is investigated. Fig. 7 shows the corresponding coupling factors $CF_{10,m,2}$ and the resulting modal transfer impedances $Z_{10,m,2}$. As can be seen, these are dominated by the resonance of mode 5. Therefore, the total coupling $Z_{10,2,\text{total}}$ (Fig. 8(a)) is also primarily determined by this mode. The resonance peak is located at about 7 kHz and is not correlated with a respective peak of mode 5's modal impedance (Fig. 4).

The time domain voltage of load 2 caused by the switching event is depicted in Fig. 8(b). The load voltage oscillates with the observed resonance frequency but is strongly damped. The amplitude of the first peak reaches more than 25 V and is therefore higher than the load 3 voltage. This can be explained by the resonance shape in the frequency domain. Compared to the coupling to load 3, the resonance is more attenuated and has a lower Q factor.

These examples show that the observed time domain behavior can be identified by the investigated frequency domain methods. However, the inverse eigenvalues of the nodal admittance matrix do not offer all the necessary information, as the coupling between the individual nodes has to be considered too.

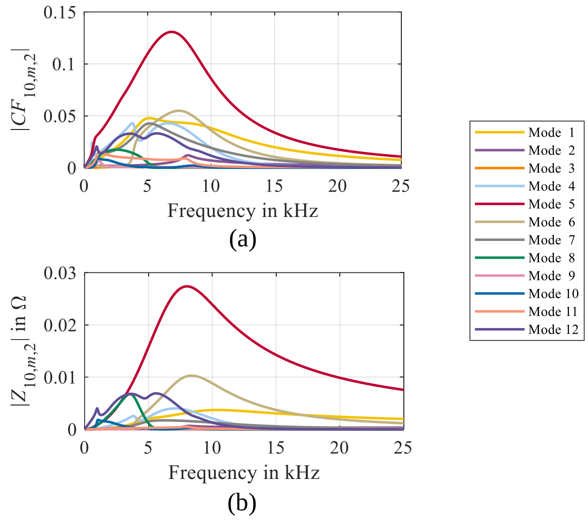

Fig. 7: Coupling between node 10 and load 2 for selected modes. (a) Coupling factors. (b) Modal transfer impedances

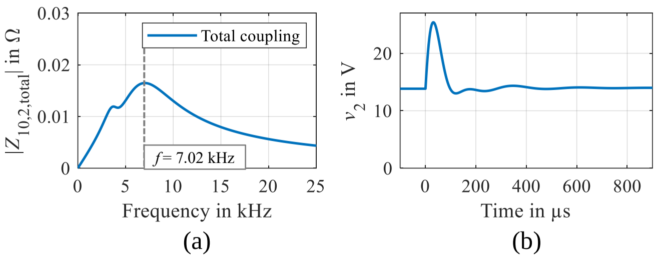

Fig. 8: (a) Total frequency domain coupling between node 10 and load 2. (b) Time domain voltage at load 2. Switching at $t = 0$

V. Performance Considerations

The aim of the investigated frequency domain approach is the faster evaluation of transient voltage stability within automotive power supply systems. Based on the presented exemplary, not optimized results, a final performance assessment is not feasible. However, basic runtime considerations can be made.

The automated formulation of the needed nodal admittance matrix based on a system description takes about 0.27 s on the used desktop PC. For the modal decomposition, i.e., calculation of eigenvalues and left and right eigenvectors, 2.0 s are needed in this example. The direct calculation of the total transfer impedance $Z_{ln,\mathrm{total}}$ based on the $\boldsymbol{Y}$ matrix (refer to (8)) takes only 0.07 s.

In contrast, an accurate Simscape simulation of the investigated scenario takes about 34 s on the same PC. This assessment shows that an optimized frequency domain approach might be a promising method for an efficient analysis of the transient voltage stability.

VI. Conclusion and Outlook

In this paper, the investigation of automotive power supply's resonant behavior based on modal analysis has been described. Existing methods of modal analysis for AC power delivery systems have been presented. Adaptions have been made to analyze the effects of switching events on the transient voltage stability at different system nodes. Based on an exemplary supply system, modal impedances and selected coupling paths have been investigated. It has been found that critical load voltage pulses can be identified in frequency domain; however, modal impedances alone are not sufficient to reveal all resonant coupling phenomena. More investigations are required.

A runtime analysis of the presented example showed a promising advantage of the frequency domain method.

Besides further elaboration of the proposed method, future research might apply sensitivity analysis to mitigate observed resonances. By selectively adjusting critical system parameters, the transient voltage stability could be improved. Finally, these methods shall support the design and optimization process of highly reliable power supply systems.

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