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Transient Phenomena in Automotive High-Voltage Systems

Electrical transients affect the high-voltage (HV) supply systems of Battery electric vehicles (BEV), which is an integrated electrical power system. The study of the electric transients on this systems requires a detailed system level modelling approach. In automotive HV-systems, transients challenge the system designer, in terms of their impact on the protection, measurement and the communication systems. We propose a summary of the effects of voltage and current transients on the automotive HV supply systems, and the critical design, integration challenges with respect to stable operation. Furthermore, we evaluate of the relevant electrical characteristics on device and system level to guarantee the safe and stable operation of the automotive HV supply system is, and validate on MATLAB/Simulink/Simscape models.

Az elektromos autó nagyfeszültségű rendszerei egy integrált DC elektromos hálózatot alkotnak. Ezt a rendszert a villamos tranziens jelenségek ugyan úgy befolyásolják, mint minden más villamos energia rendszert. A tranziensek vizsgálata részletes modellezési és szimulációs módszereket igényelnek. A mérési, a kommunikációs és védelmi rendszerek területén ezek a jelenségek komoly kihívások elé állítják a rendszer integrátort. Munkánkban bemutatjuk a fellépő kritikus tranziens jelenségeket, kialakulásukat és hatásaikat. Továbbá bemutatjuk az összefüggéseket a rendszer paraméterek és a fellépő tranziensek között, valamint egy módszert a biztonságos és stabil működés garantálására, majd a validálást MATLAB / Simulink / Simscape modellek segítségével végezzük.

Keywords: Electric vehicle, transients, electric charging, high-voltage systems

1. INTRODUCTION

With the growing functional complexity and power demand in battery electric vehicles, complex high-voltage system architectures are developed, designed to operate with 400V or with 800V, and show architectural and physical similarities to low voltage DC micro grids. In the context of transient phenomena and their impact on DC micro grids readers can find description in [1], [2], [3].

In this paper, we focus on the 800V systems of a newly developed high performance battery electric vehicle, in the use case of DC charging, especially the impact of connecting the vehicle to the charging station. Nowadays the complexity of HV-systems of BEVs is growing with the functional requirements, besides drive and comfort applications also the variety of charging functions is large.

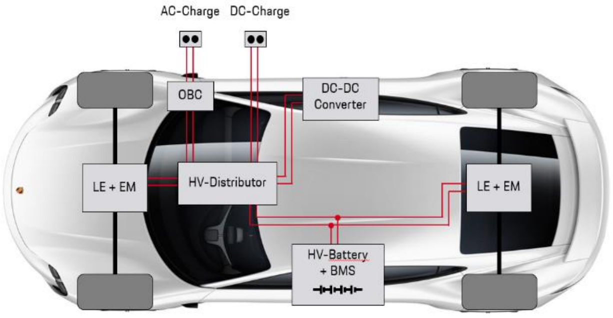

Figure 1 The high-voltage system of a BEV

DC charging can occur with a charging station with nominal voltage of 400V or with 800V. We examine the transient effects caused by the connection of the charging station and the high-voltage system of the vehicle. Charging standards like CHAdeMO or CSS/COMBO define the exact technical procedure the connection [4],[5]. However, every vehicle and every charging station have different internal parameters like grounding capacitors (Cy) and wiring length and voltage levels at the time of the connection event. Due to these parameter differences, every vehicle configuration with every charging station have different transient behavior. In this work, we summarize the parameter dependencies, identify the possible worst-case scenarios and the disturbances caused on device and on system level.

The examined transient phenomena cause short time over voltage and over currents that can disturb communication and measurement systems as well in the vehicle as in the charging station as well. In order to design the devices to be able to handle the transient voltage and current, analytical a numerical examination of the possible events are required. This paper provides a model in the loop simulation implemented in MATLAB/Simulnk/Simscape environment and some example parameter studies.

The reminder of this paper organized as follows. In section II. we briefly define the physical origin of the examined transient events and their critical influences. Section III. gives an analytical calculation method for the peak voltage and peak current with parameter dependencies caused by these transient events, and we define the worst cases. In section IV. we highlight the developed simulation program with its features, with use cases. Section V. shows simulation results validated on real prototype vehicles.

2. DEFINITION OF TRANSIENT EVENTS

2.1 DC charging of an electric vehicle

The charging of a BEV can vary between AC and DC power source with different voltage levels. The variety of charging functions challenge the robustness of the high-voltage system of the vehicle against different charging conditions. In this work, we focus on the properties of DC charging which allows fast charging functions, with respect to the turn on behavior, and its impact on the high-voltage system of the vehicle. DC charging of an 800V vehicle can occur of a charging station with the nominal voltage of 400V and 800V

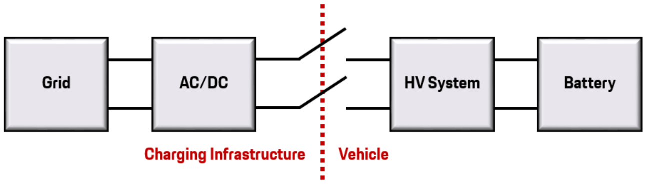

Figure 2 Schematic DC-Charging of a battery electric vehicle

The DC charging function of the vehicle begins with connection of the vehicle to the charging station. Firstly, the customer plug in the vehicle, in this moment the ground of the vehicle and the ground of charging station connects by a cable. After that, the cable connects with a contactor with respect to the charging protocol, this event means joining two electric power system. The research area of micro grids obtains the questions of connection of DC power systems. However the meaning of the connecting a vehicle to the charging infrastructure for the electric vehicle is a newly discovered area, since 800V prototype vehicles are only recently available.

2.2 Physical description of the transient events

We consider an 800V DC charging station and an 800V vehicle; a plus a minus such as a ground cable connect them. Electric contactors are on the plus and minus cable. After plugging the vehicle, they connect the vehicle with the charging station. Each electric cable behave as a serial R-L element. In the high-voltage system of the vehicle one can find capacitors between the plus and minus (C_x) and between the conductors and the ground (C_y). The charging station also contains C_x and C_y capacitors. We assume that $C_x >> C_y$, to give a feeling to the reader the C_x capacitors are usually in the dimension of some *mF* meanwhile C_y capacitors are in the dimension of some μF.

The battery of the vehicle and the charging station are the voltage sources that define the voltage levels in the system. Therefore, the whole system is a compound RLC network. The closing of an electric contactor provides the shock response of the compound RLC system. The transient events in the focus of this paper are described by the shock response of a complex RLC system. As known from undergraduate engineering education, the step response of the RLC system includes harmonic oscillations. For further investigations, we need to identify the properties of a step response, like peak voltage, peak current, time constant, damping and frequency as well.

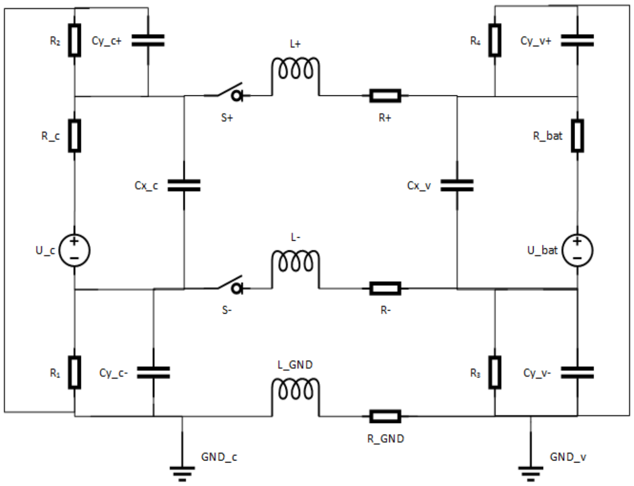

Figure 3 Network of interconnected vehicle with a charging station

We consider the electrical network in *Figure 3.* consisting a vehicle and a charging station side network, disconnected by two contactors while connected by the ground cable, the RLC circuit in the case of charging a 800V vehicle with a 800V DC charging station. The step response of this system is a high frequency oscillation with the natural frequency of the system. Every capacitor and cable inductivity in the system determine the natural frequency.

Table 1 System parameters

Parameter/ elements	**Meaning of parameters**
	Physical meaning
U_bat	Battery voltage of the vehicle
U_c	Voltage of the chaging station
R_bat	Internal resistance of the battery
R_c	Internal resistance of the charging station
C_x_c	DC-link capacitor of the charging station
C_x_v	DC-link capacitors in the vehicle
C_y_c+	Capacity against ground in the charging station
C_y_c-	Capacity against ground in the charging station
C_y_v+	Capacity against ground in the vehicle
C_y_v-	Capacity against ground in the vehicle

Parameter/ elements	**Meaning of parameters**
	Physical meaning
R_1	Isolation resistance in the charging station
R_2	Isolation resistance in the charging station
R_3	Isolation resistance in the vehicle
R_4	Isolation resistance in the vehicle
L+	Inductivity of the plus cable
L-	Inductivity of the minus cable
L_GND	Inductivity of the ground cable
R+	Serial resistance of the plus cable
R-	Serial resistance of the minus cable
R_GND	Serial resistance of the ground cable
S+, S-	Contactor in the plus and minus cable
GND_c, GND_v	Ground in the charging station, and vehicle

Ideally, the voltage levels in the vehicle and in the charging station are equal to each other. However there is no guaranty in the charging standards for symmetrical voltage levels against the ground, so there can be voltage difference between vehicle plus, minus to vehicle ground and between charging station plus, minus to charging station ground. Kirchhoff's laws determinate the voltage levels in the case of asymmetrical isolation resistance, or asymmetrically defined vehicle or charging station configuration.

According to the standards, the charging has to be functioning despite the existence of isolation fault. Isolation fault means lower isolations resistance against ground than specified. Transient events on plus and minus wire are not harming the system, but if the RLC circuit is closed by the ground wire, where normally there is no current or voltage measureable the system protection and measurements can be disturbed. The transient event occurs while *S+* such as *S-* are opened then *S-* closes and there is voltage difference $U(C_y\_c-)$ is not equal to $U(C_y\_v)$, because S- can close only if $|Uc\text{-}U\_bat|<\varepsilon$ where ε is defined by the charging protocol of the corresponding standard [4],[5].

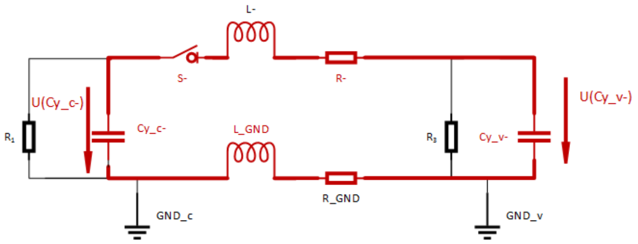

Figure 4 Network of interconnected vehicle and charging station with reloading capacitors.

The transient phenomenon is a shock response of the complex RLC circuit with the shock like input voltage $U(C_y\_c-)-U(C_y\_v-)$ at the *Y* capacitor of the vehicle side.

2.3 Ground shift between charging station and vehicles

The electrical ground of the vehicle and the charging station is connected via a cable, the cable behaves as a serial RL element, with low serial resistance. In shock response with high natural frequency, where the inductivity and capacity in the whole system determine the natural frequency of the system, the inductivity of the ground cable represents a higher impedance against high frequency electrical pulse.

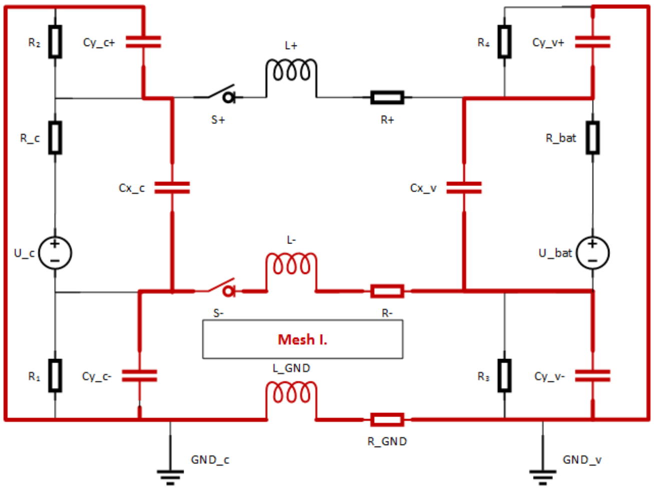

Figure 5 Oscillating RLC network while connecting vehicle to charging station

During the transient event between the two ends of the ground cable occurs a measurable voltage. Therefore, during the transient event the voltage between the ground of the vehicle and the charging station will not be zero. In the CCS/COMBO standard and in the CHAdeMO standard [4],[5] the system requires some communication wires between the charging station and the vehicle.

These communication wires are parallel to the ground wiring, so the same voltage is measureable between their two ends as on the ground wire. This ground shift between the vehicle and the charging station can disturb the communication systems and the protection system. We examine the events caused by the ground shift and the current pulse on the ground wire. [8] We examined the impact of different charging standards on the vehicle.

Relevant information about the transient events are the duration of the transient, the positive and the negative peak voltage between vehicle and charging station ground, finally the peak current on the ground wire. On the other hand, we provide simulations showing the effects on the communication cables.

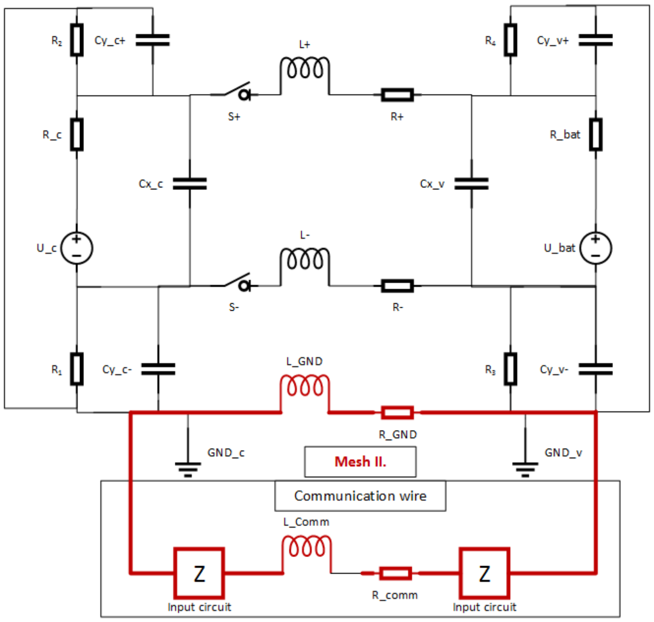

Figure 6 Oscillating network of communication wires and ground cable

3. ANALYTICAL DESCRIPTION

This section shows the analytical dependencies between system parameters and the main properties of the transient events. Consider the system parameters defined in *Figure 4.* meanwhile the transient events occur in mesh 1 in Figure 5 without the communication wires. The influencing parameters are the cable length yields to the cable inductivity, the C_y capacity on vehicle and on charging station side and the serial resistance that damps the transient phenomena, like the isolation resistance that yields to the voltage asymmetry against the vehicle and the charging station ground. The cable inductivity and the C_y capacitors set the natural frequency. The serial resistance and the C_y capacitors set the time constant such as the damping of the transient event. The isolation resistance sets asymmetry, which determines the voltage levels which yields to the energy of the transient oscillation [3].

The energy transfer between the C_y capacitors on vehicle and on charging station side determines the energy of the transient oscillations. While the transient phenomena this energy will be dissipated on, the serial resistance thought an oscillation with the natural frequency of this RLC network. The reload energy yields the following so the reload energy is a function of the C_y capacitor and the isolation resistance. The energy levels of the capacitors are depending from their voltage levels, before closing *S1*, the energy in the *Y* capacitors is the following:

$$E = \frac{1}{2}\mathrm{Cy\_c}\left[\left(U\frac{R_1}{R_1+R_2}\right)^2 + \left(U\frac{R_2}{R_1+R_2}\right)^2\right] + \frac{1}{2}\mathrm{Cy\_v}\left[\left(\mathrm{U\_bat}\frac{R_3}{R_3+R_4}\right)^2 + \left(\mathrm{U\_bat}\frac{R_4}{R_3+R_4}\right)^2\right] \qquad (1)$$

After switching *S1* and after following the transient event the new energy levels of the *y* capacitors in the system are according to Kirchhoff's law are the following:

$$E = \frac{1}{2}\mathrm{Cy\_c}\left[\left(U\frac{R_1R_3R_4}{R_1+R_2+R_3+R_4} + \mathrm{U\_bat}\frac{R_1R_2R_3}{R_1+R_2+R_3+R_4}\right)^2 + \left(U - U\frac{R_1R_3R_4}{R_1+R_2+R_3+R_4} - \mathrm{U\_bat}\frac{R_1R_2R_3}{R_1+R_2+R_3+R_4}\right)^2\right] + \frac{1}{2}\mathrm{Cy\_v}\left[\left(U\frac{R_1R_3R_4}{R_1+R_2+R_3+R_4} + \mathrm{U\_bat}\frac{R_1R_2R_3}{R_1+R_2+R_3+R_4}\right)^2 + \left(U_{bat} - U\frac{R_1R_3R_4}{R_1+R_2+R_3+R_4} - \mathrm{U\_bat}\frac{R_1R_2R_3}{R_1+R_2+R_3+R_4}\right)^2\right] \qquad (2)$$

The natural frequency of the transient phenomena is the natural frequency of the RLC circuit:

$$\omega = \frac{1}{2\pi\sqrt{(L_{GND}+L-)\left(\frac{Cy\_v * Cy\_c}{Cy\_v + Cy\_c}\right)}} \qquad (3)$$

The variables in (1)-(3) are defined in table 1. The y capacitors and the serial resistance are determining the time constant and damping ratio in the system.

This from engineering studies known properties are describing the transient phenomena, however the proper analysis requires the calculation of effect of the with the ground parallel communication wires.

The parallel RLC circuit that contains the input and output circuit of the communication wire, which is an unknown black box with impedance Z, this coupled RLC circuit has also a natural frequency and there is internal oscillation in this part of the system. If at a time point between the two end of the ground wire the voltage is U_{GND} on the communication wire there is trivially $U_{GND}=U_{Z\_in}+U_{comm}+U_{Z\_out}$, meanwhile a hazardous value of U_{Z_in} can cause unwilled interrupt commands. Which can stop the charging, one of the main challenge is to robustly avoid that. Assume U_{GND} not zero than a voltage Kirchhoff's laws determine the proportion between U_{Z_in}, U_{comm}, and U_{Z_out} so the impedance of the input and output circuit is determining. From (1)-(3) the maximum value of U_{GND} and the maximum value of U_{Z_in} can be formulated as follows.

$$\max(U_{GND}) = \Phi(R1 \dots R4\ Cy_c-, Cy_c+, Cy_v-, \dots Cy_v+, L_{GND}, R_{GND}, L-, R-, U_{bat}, U\_c) \tag{4}$$

$$\max(U_{Z_{in}}) = \psi(R1 \dots R4\ Cy_c-, Cy_c+, Cy_v-, Cy_v+, L_{GND}, R_{GND}, L-, R-, U_{bat}, U_c, Z_{out}, Z_{in}, L_{comm}, R_{comm}) \tag{5}$$

The variables in (4) and (5 are defined in table 1. From a mathematical point of view, Φ spans a manifold in a 15 dimensional parameter space with 14 exogenous and 1 endogenous variable. Moreover Ψ spans a manifold in a 18 dimensional parameter space with 17 exogenous and 1 endogenous variable. In the parameter space of Φ, the vehicle system designer can determine *R3, R4,* C_{y_v-}, C_{y_v+} the other parameters vary between technically realistic boundaries, determined by the infrastructure designer. For the proper system design the boundaries of the exogenous variables has to be identified. We propose a numerical method; using model in the loops simulation to identify that detects the worst case parameter combinations of the independent variables. We focus on the analysis of Φ because it describes the transient phenomena, and Z has to be such designed, which can handle every possible values of Φ.

The transient voltage measured between the vehicle and the charging station side of the ground wire is a composite oscillation of two oscillations, one occurs in mesh 1 while the other occurs in mesh 2. The ground wire is the common part between mesh 1. Mesh 2 critical is the voltage between the two ends of the ground wire and the voltage occurs on the input circuit of the communication wires. This can cause hazardous signal levels on the communication wires, which could cause hazardous interrupt commands, which harms the robust functionality of the charging system.

4. SIMULATION

This section shows a numerical simulation method to evaluate the transient phenomena and their impact on the measurement as on the communication systems. We show the method of model in the loop simulation for providing parameter studies and identification of worst-case situations. The simulation uses parameters from vehicle measurements and tolerances according to the charging standards. The cable length is considered between the minimally and maximally allowed according to the charging standard.

We use noncausal modeling method for the simulation with in MATLAB/Simulink/Simscape tool. This method provides the fast analyze of electrical circuits and it can be embedded to MATLAB scripts to provide parameter studies or model in the loops simulations. The script parametrizes the simulation in every iteration, saves, such as plots the results of the calculations automatically [6],[9].

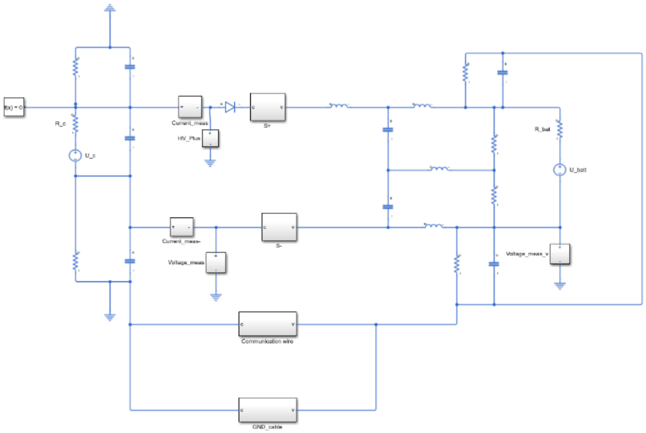

Figure 7 System model implemented in MATLAB/Simulink/Simscape

For the system modeling, we used the exact measured cable inductivity and the properties of the discrete capacitors. The simulation uses given battery models with a constant voltage source serial connected with the internal resistance. The model of the charging station is also a constant DC voltage source.

First, we verified the simulations with measurements on a real vehicle prototype; we checked the existence of the transient events and the behavior of the proposed RLC circuits in real prototypes with real charging stations. Secondly, we validated the parameters of the existing transient events on a real prototype measurement. We adjusted the cable inductivity like the connections of the communication wires as well as the discrete capacities against the ground.

We provided simulations that are examining an existing charging station and an existing real prototype vehicle with different cable length between vehicle and charging station, the cable length varies between 1m to 20m as in real charging infrastructure. We simulated the peak voltage on the ground cable such as the peak current on the ground cable as well as its damping as well.

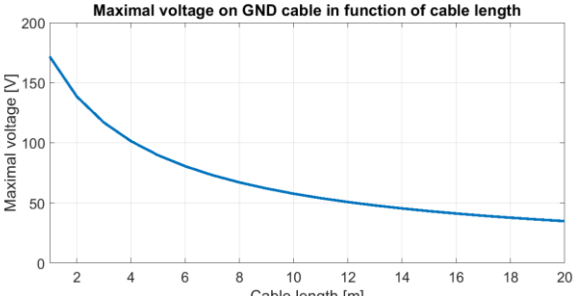

Figure 8 Effect of interconnecting cable length on voltage peak

The longer cable means larger inductivity so larger resistance in high frequency events and lower natural frequency but meanwhile larger serial resistance so better damping, smaller time constant.

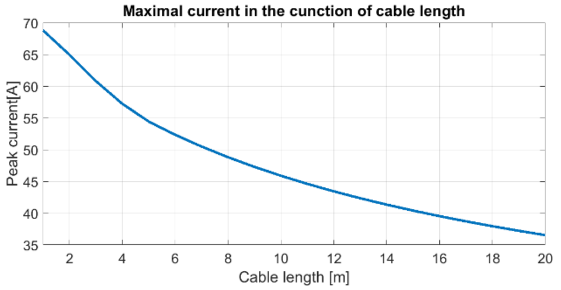

Figure 9 Effect of interconnecting cable length on current peak

The following simulations are examining the effect of asymmetrical vehicle voltage against vehicle ground and asymmetrical charging station voltage against charging station ground. The simulation provides the asymmetry by modifying the isolations resistance of the plus and minus cable against ground.

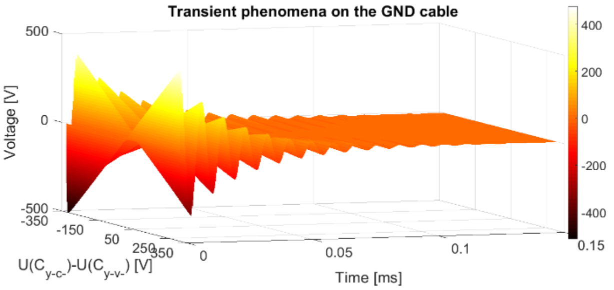

Figure 10 Transient voltage on ground cable with asymmetrically loaded capacitors

Our numerical results show strong dependency between cable length and peak voltage, and current, and small vehicle asymmetries can also cause undesired interrupts despite the duration of the transients is under 1ms without an additional protection system.

5. CONCLUSION

The validated simulations results show the possible occurring transient phenomena, as the possible voltage shifts between the ground of the vehicle and the charging station as well as the possible voltage on the input circuit of the communication wires. The definition of the worst-case transient events yields to new definition of robustness specification of the charging system. The new charging system of the vehicle is such designed that it can handle every possible transient phenomena due to asymmetry of the voltage levels against ground, with respect to any possible charging station configuration.

Our developments were centered around the definition of the possible pulses on a concrete vehicle configuration and validation of real vehicles with respect to robustness against transient voltage and current phenomena. Our results are essential for robust circuit design and for the development of stable charging functions.

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