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Transient Emission Analysis of EV- and HEV-Powertrains using Simulation

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***Abstract*—As one consequence of the increasing grade in electrification of vehicle powertrains the electromagnetic interference (EMI) potential of these components becomes increasingly relevant. The conducted disturbances caused by high-voltage (HV) and high-energy pulses originating from the DC/AC-inverter have to be analyzed, as they can easily couple from the HV-DC traction-network to the low-voltage (LV) onboard-systems-network, where they could cause malfunctions. Consequently technical standards are revised concerning these problems (ISO7637 [1] or CISPR25 [3]). As the required or proposed measurement setups within these standards can be very time and fund consuming, it is desirable having the ability to repeatedly analyze a configuration's or device's disturbance potential by simulation techniques, prior to real hardware-testing. This contribution presents one method, which fulfills these requirements. The method is demonstrated, exemplary, according to a voltage transient emission test along high voltage supply lines as proposed in the new draft standard ISO7637-4 [1].**

Keywords—electric vehicle; electrical powertrain; conducted emissions; simulation-based analysis; ISO 7637

I. INTRODUCTION

Along with current and future developments for hybrid-electric (HEV) and full-electric (EV) vehicles new powertrain concepts and components are integrated into vehicles that still contain on-board systems which are mainly designed following principles evolved for combustion-engine driven vehicles using only low-voltage devices. These low-voltage devices now become part of an on-board system containing high-voltage and high-power devices. System-immanent electromagnetic disturbances, especially high-power transients, originating from the high-voltage system can couple to the low-voltage system and interfere with the functional reliability of the LV-devices. This makes it extremely important to precisely analyze these disturbances and their coupling behavior in order to evaluate their interference-potential and to develop preventive technologies. As research and developing in this domain is very time and funds consuming when only hardware test-setups are used, it is preferable having the possibility to use precise and modular simulation-models, instead of the necessity to construct a large variety of prototype-systems. Therefore, this paper presents a method for analyzing and evaluating cable-conducted transient disturbances in (hybrid-) electrical vehicles' onboard systems originating from the electrical powertrain by using simulation-based analysis.

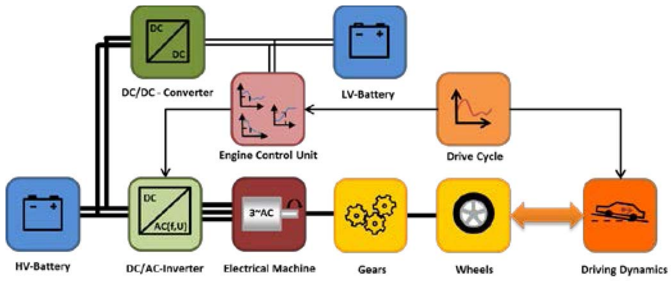

Fig. 1. Symbolic structure of an EV-powertrain system

II. MODULAR SIMULATION LIBRARY AND DRIVETRAIN-TEST-BENCH

The foundation of the above mentioned simulation-based analysis is a modular simulation library, created considering the particular properties of (hybrid-) electrical vehicles as well as the special requirements of standardized emission tests. The contained models are parameterized and verified by using a drivetrain-test-bench to ensure a valid transfer of the obtained results to real vehicle on-board systems.

A. Development of a modular Simulation Library

Since the library's main operation purpose is the analysis of the electrical quantities and behavior of an (partly) electrified vehicle powertrain, the main focus in model development is set to the electrical physical domain. This means, that all other physical domain quantities involved are only considered as a behavioral abstraction and merely as accurate as needed – e.g. only the longitudinal driving dynamics are considered.

The library itself is created regarding a modular but hierarchical approach. This means that on the top level all components are represented by a model class type, comparable to abstract or interface classes in object orientated programming (OOP). For any class type the physical and logical connections are defined hard, as a reasonable compromise of real physical connections and simulation abstraction necessities. The model developer has then only to ensure the presence and use of the defined interface and a correct functional behavior regarding the model's particular abstraction level. These top classes are considered equal among each other. Within a model class however the different models are order hierarchically regarding their functionality and abstraction levels. Thereby models of the same hierarchic level have to be fully compatible and exchangeable against each other. E.g. if a DC/AC-inverter on abstraction level-X has been modeled as structural model, on the one hand, and as behavioral model, on the other hand, an exchange of the two models within the context of a drivetrain simulation model should be possible without any other necessary changes to the rest of the system.

A modular simulation model library following this approach is currently developed. Additionally to the vehicle components, also the measurement equipment needed for standardized tests is modeled, as far as necessary. But as this contribution focuses on the analysis of conducted disturbances, this general description of the simulation library is considered to be sufficient.

B. *Model Verification and Parameterization Process using a Drivetrain-Test-Bench*

To ensure each model's correct functionality within the simulation library, each model has to be verified and parameterized in a two-step process. At first the component model is considered individually. Therefore the input- and output-behavior and its functional characteristics are measured in a laboratory test setup. The result of this primary step is a quite accurate default configuration or parameter-set. Especially simulation models created regarding more to their physical-structure instead of a behavior-abstraction benefit most from this first step.

Subsequent, the single component is integrated into a drivetrain-test-bench (Fig. 2) as device under test (DUT), the same way it will be used during the co-analysis. The drivetrain-test-bench sufficiently represents an electrical vehicle powertrain-system. It consists of a modular electrical drivetrain (electrical machine, inverter, electrical energy source, traction control unit), an electrical machine emulating the dynamic drive-load and a PC for control, measurement and computational purposes. So the drivetrain test-bench can be seen as an advanced version of a dynamometer.

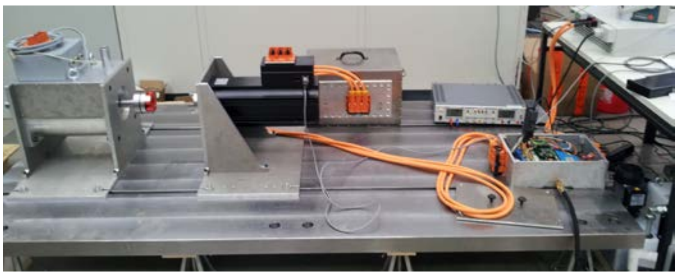

Fig. 2. Drivetrain test bench

One major advance over a classical dynamometer is the possibility to directly integrate the low-voltage onboard-system into the test-bench setup. This is especially useful when the coupling influences between all three voltage domains (HV-DC, LV-DC, HV-AC) should be investigated within a fully controllable and configurable environment. One particular configuration of this test-bench has been defined as reference configuration, which should be used to analyze and compare distinct variations of one type of component or to perform the model verification process.

In this reference setup the DUT can be evaluated once again and – if possible – the same measurements as in the primary step are executed. Hence the component's behavior regarding to different operating points can be qualified or complete characteristic curves can be recorded. These results are then used to further optimize the model parameters and to verify the simulation models in an almost realistic operative environment. Obviously simulation models which are mainly based on the system behavior benefit most from this secondary step.

Depending on the type of component under test – e.g. DC/DC-converter, DC/AC-inverter – it is possible to create the same operating points in both verification procedure steps. Both results together can then be used to derive the influence of the drivetrain-system to the single component's behavior, which is comparable to the creation/interpolation of a transfer function. This transfer function can then be used as a correctional factor when analyzing a component in a laboratory test-setup, to validly transfer obtained results to the components performance within the complete drivetrain system.

III. Transient Emission Test of HEV-Powertrain

As mentioned before the analysis methods presented in this contribution focus on conduction-coupled electrical disturbances, especially those caused by transient emissions. In an proposal for a new standard (ISO 7637-4 [1]) several tests are defined for qualifying emissions and device's immunities. So this use case will be our demonstration basis for the comparison of simulation-based vs. real-hardware analysis.

A. *Analysis Setup*

In general the emission-tests discussed currently might rely on a test setup as shown in Fig. 3. It consists of a HV-power source (battery or power supply) and an optional HV-battery load on the left side. Attached to the energy source is a standard two-phase line impedance stabilization network (HV-LISN), which is terminated with 50 Ohms at its measurement output against the reference potential.

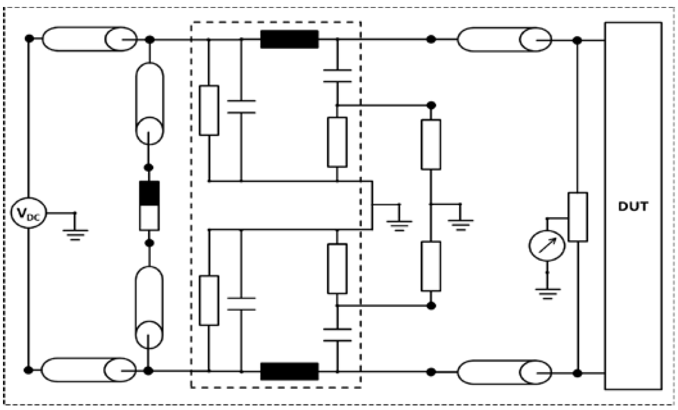

Fig. 3. Possible transient emission analysis test-setup

To the right of the LISN two HV-supply lines establish a connection between the DUT-component and the test-setup. The entire test- setup is placed on a metal ground plane to ensure a uniformly distributed reference potential.

B. Hardware and Drivetrain-Test-Bench Setup

In the emission test hardware-setup presented a laboratory power supply is used as HV-energy source instead of a battery, in order to provide a reliably constant voltage supply and invariant operational conditions. The used HV-supply cables and traction cables are compliant to [ISO 6722] and [LV 216].

As DUT and origin of the transient emissions/disturbances an INFINEON HybridPACK2 (Fig. 4) is used as DC/AC-inverter. This inverter was especially created for the use in (hybrid-) electrical vehicles. It can be supplied with DC-voltages up to 650 V and provides powers up to 80 kW generated with a switching frequency of up to 20 kHz [10],[11]. The IGBT-module has be cooled actively with a water cooling system to ensure proper heat dissipation and required operational conditions.

Fig. 4. INFINEON HybridPACK2 with enclosure and measurement equipment

In order to generate stable load conditions at the AC-side of the test-setup two different hardware configurations are used. The first load configuration is a basic electrical machine replica (EMR) for EMC-investigations; the second is an 18 kW permanent-magnet synchronous machine (PMSM) (Fig. 5). As metal ground plane, as required by the ISO-standard, the countertop mounting for the electrical machines can be used, as it consists of a polished steel plate.

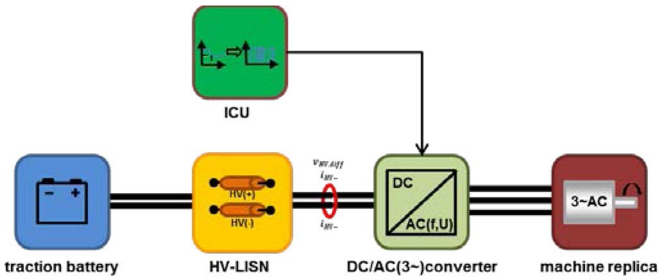

Fig. 5. Test configuration 1

The most relevant hardware parameters of the test setup are given in TABLE I.

TABLE I. RELEVANT TEST-BENCH PARAMETERS FOR TEST-SETUPS

DC-supply voltage	$V_{DC,1}$ = 50 V; $V_{DC,2}$ = 300 V;
HV-supply cables	Length(DC) = 1,5 m; Length(AC) = 2,5 m; Cable-conductor: 35 mm^2
Intermediate capacitor values	C_{imc} = 500 µF; R_{ESR} = 1 mΩ
DC/AC-inverter settings	m_1 = 0.10; f_1 = 50 Hz; m_2 = 0.50; f_2 = 50 Hz; f_{SVPVM} = 20.0 kHz
IGBT-drivers	$V_{Gate,off}$ = -8.0 V; $V_{Gate,on}$ = 15.0 V;
EMR-inductances	L_s = 90 mH; $R_{s,DC}$ = 0.4 Ω

C. Simulation models and Parameterization

The above presented test-bench setup is reproduced with simulation models of different complexity within the modular simulation library. The simulation models used in this paper are created and computed using MATLAB Simulink/Simscape; but models were also created in VHDL-AMS and Modelica for alternative use or model verification reasons. As the focus is set on the transient emissions generated by the DC/AC-inverter the simulation models of this device and the used EMC-electrical machine replica are shortly presented.

1) DC/AC-Frequency Inverter Model

When modeling the DC/AC-inverter the work is concentrated on the power-electronic (Fig. 6) and its essential components – IGBTs, diodes and intermediate circuit capacitor. Precise modeling of the logic-board is impossible due to its complexity, so only the signal generating algorithms (triangular sine-PWM, space vector modulation PWM) have been reproduced. An accurate modeling of the driver-board is considered negligible at this stage, though a general driver model was created in order to achieve a more realistic switching behavior of the IGBTs. This generalized driver model will be extended at future stages in order to investigate the direct HV-LV-coupling path along the drivers' sense-circuits.

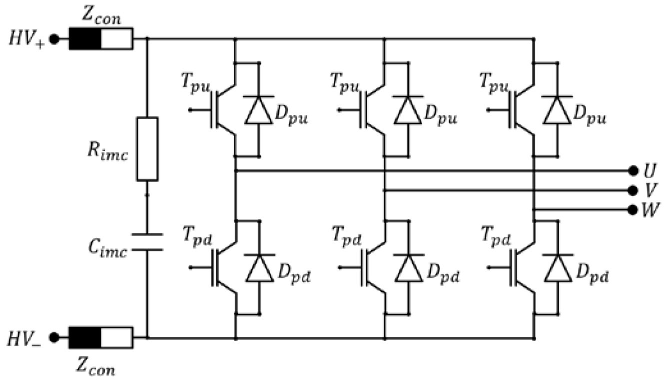

Fig. 6. Model of DC/AC-inverter power-electronic

The intermediate circuit capacitor (C_{imc}) model follows a commonly used equivalent circuit for high-frequency analysis purposes. The behavior of the antiparallel freewheeling diodes ($D_{pd/pu}$) is reconstructed using an equivalent circuit as shown in Fig. 7. Diode D^* is assumed to be ideal and modeled according to the Shockley-equation. But for numerical stability reasons maximum and minimum exponents for the exponential functions are defined, from which on the diode's behavior is linearized. The parallel capacitor-resistor branch works as a simplified model, which combines the diode's capacitive behavior and the reverse-recovery effect. The resistor size is calculated from the given reverse-recovery time τ_{RR} and junction capacitance C_J.

$$R_{CL} = C_J \cdot \tau_{RR} \tag{1}$$

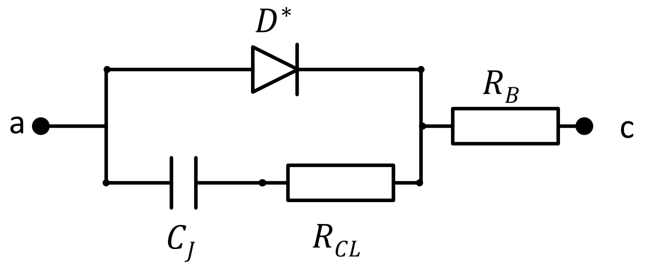

Fig. 7. Diode model

Modeling of the transistors is done with two variants according to the equivalent circuits shown in Fig. 8 and Fig. 9.

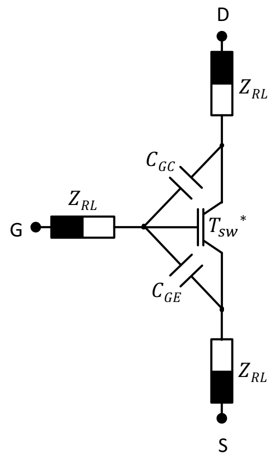

Fig. 8. MOSFET model

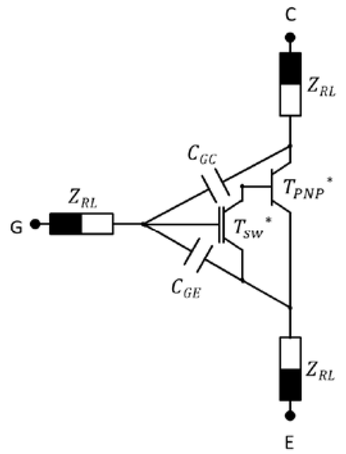

Fig. 9. IGBT model

The central element of both models is an ideal transistor switch (T_{SW}^*) according to the Shichman-Hodges model [7] for MOSFETs, which behaves as a voltage-driven current source. For performance reasons different models of each transistor exist with different abstraction-levels and precision. The level-0 model of the transistors solely contains the ideal transistor switch, while for level-1 the parasitic capacitances $C_{GE,}$ C_{GC} and for level-2 also the pin-impedances $Z_{RL,i}$ are added to the model. For performance reasons the parasitic capacitances are represented by static ideal capacitances, though one has to be aware that these capacitances are in fact variable relating to the applied voltages – with V_{CE} dominating. The IGBT-model (Fig. 9) contains an additional idealized bipolar junction transistor (T_{PNP}^*). Due to model-complexity and numerical stability issues it is more useful to use the MOSFET-model (Fig. 8) instead of the more complex and more critical IGBT-model. With a correct parameter-set the behavior of the MOSFET model provides a sufficient representation of an equivalent IGBT's behavior. But beyond that the solver stability is increased by smaller derivatives and the antiparallel diode could be neglected, due to the intrinsic "body-diode-behavior" of the MOSFET-switch (T_{SW}^*).

At the DC-side of the power-electronic the connector-impedances Z_{con} are integrated into the model. Thus achieves a more realistic behavior of the energy flow among the capacitor-bridge-combination by limiting the current flowing from an (ideal) DC-power supply into the intermediate circuit capacitor. Additionally it helps to stabilize the transient simulation-solver by limiting gradient and magnitude of the quantities' derivative values.

2) EMC-Electrical Machine Replica Model

The model of the applied electrical machine replica (Fig. 10) follows the idea of an equivalent circuit of an asynchronous machine. The three stator inductances $L_{s,i}$ and stator resistances $R_{s,i}$ are – in this case – connected as star-circuit. Parallel to each stator inductance $L_{s,i}$ a load resistor $R_{rLoad,i}$ is connected, whose resistance is approximated as a function (2) of the idle operating point resistance R_{r0} and rotor slip s.

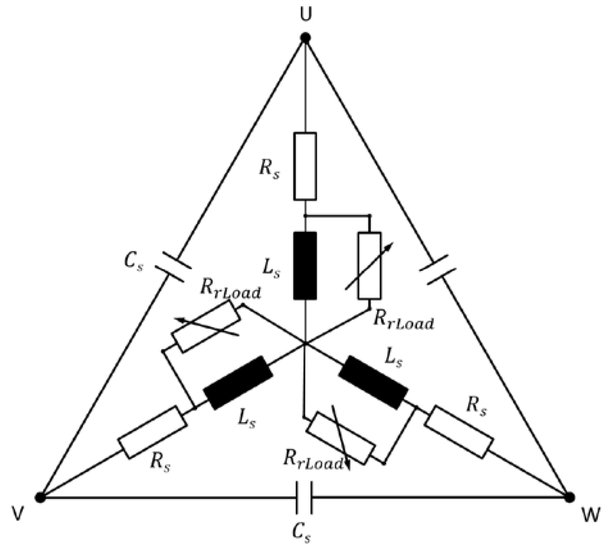

Fig. 10. Model of electrical machine replica

Thus it is possible to create different load operating points in order to vary the energy level of the transient emissions and the total drivetrain-system.

$$R_{rLoad,i}(s) = R_{r0} \,/\, (1 - s) \approx U_0 \,/\, I_0 \cdot (1 - s_0) / (1 - s) \tag{2}$$

Only stator side capacitive effects ($C_{s,i}$) are taken into account. Those between rotor windings are not taken into account, just as the transformer coupling behavior between stator and rotor is neglected. This is, on one hand, to limit the complexity of the replica model, and, on the other hand, to stick closer to the EMR-equipment used in the drivetrain test-bench.

IV. Pulse-Disturbance Analysis in EV-Drivetrains

To demonstrate the functionality and validity of the presented methodical procedure results of measurement-based and a simulation-based analysis are compared. A transient emission test along HV-supply lines compliant to ISO7637-4 draft [1](Fig. 3) is used as exemplary test-setup. The results of the hardware-based analysis presented here have been measured using a test bench-setup with an electrical machine replica (Fig. 5) and the configuration-1 parameter set as shown in TABLE I. Voltage measurements have been accomplished for all three differential AC-voltages and on the HV-DC-side close to the DC/AC-inverter – as proposed in draft version of ISO7637-4. Line currents have been measured with an inductive current probe.

A. Transistor and power-electronics model verification

The transistor models and the power-electronics model are the central components of the transient-analysis measurement and simulation. Therefore it is most important to achieve a good accordance between the measured and simulated switching behavior of the power-electronics. In Fig. 11 a single pulse on AC-phase U is shown in comparison of measurement and simulation. The pulse is shown as clipping of the total PWM-switching period of $T_{PWM} = 50\mu s$, only during its on-state. The small ratio of the switching period T_{PWM} and the pulse active-state time of about $T_{Pulse,act} = 2.45\ \mu s$ is a consequence of the low voltage-modulation factor $m_1 = 0.1$.

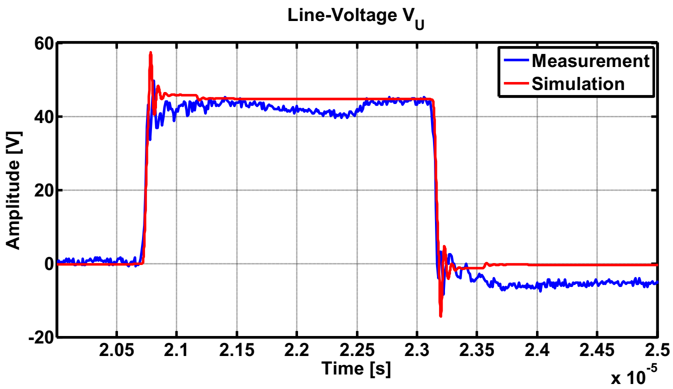

Fig. 11. Comparison of measured and simulated single pulse on AC-phase *U*

The general voltage drop to the full $V_{DC,1} = 50V$ is caused by the cables and internal impedances of the components used in the technical setup. In general a quite accurate reproduction of the measured pulse is achieved. Also the oscillating behavior at the switching-events is recreated quite correct. The voltage-dip on the measured signal's roof is caused by voltage V_W becoming active at $t = 21.70\ \mu s$. Notable are the voltage over- or undershoot with a maximum of 23% with respect to the applied DC-voltage. Especially for higher DC-voltages of about *300 V* to *400 V* in combination with the short rise- and fall-time this could result in severe transient emissions on the AC-side

In Fig. 12 a comparison of the amplitude spectrum is shown for the frequency range of *150 kHz* to *30 MHz*. The resolution bandwidth is $RBW = 9\ kHz$ and the detector mode was set to Peak-detection.

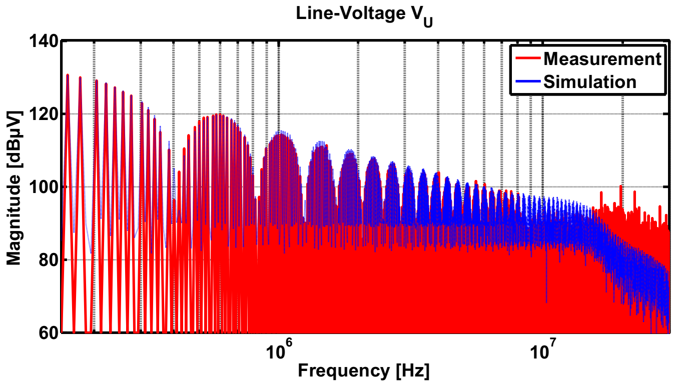

Fig. 12. Spectral comparison of measured and simulated single pulse AC-phase *U* (peak-detection mode)

Up to a frequency of *15 MHz* a quite accurate match of the amplitude spectrum is achieved for the simulated power-electronic behavior.

V. Conclusion

The approach presented in this contribution offers an effective possibility to analyze conducted disturbances, especially from transient events, in (hybrid-) electrical vehicle systems. The general functionality and validity of the approach have been proven; even if at this early stage some limitations apply. Future work will concentrate on enhanced model accuracy and the creation of variable load-conditions in order to investigate the failure, acceleration and braking behavior of the drivetrain-system. Since simulation models are created and parameterized not just under isolated laboratory conditions, but with direct use of a complete electrical drivetrain-test-bench, the validity-range of the developed models should be large.

With the transistor and power-electronics models showing a quite sufficient representation of the real devices, it is now possible to perform simulation-based analysis of transient emission tests in order to get reference points for a certain test-setup prior to time- and fund-consuming hardware tests.

Acknowledgment

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