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Analysis and Classification of Validation Environments – A Case Study in Advanced Engineering of Electric Traction Drives

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Summary

"Which test configuration is best suited to meet the current validation objective?" Model-based development and validation approaches support modular and fast evolving validation environments. However, setting up or finding suiting test configurations highly depends on engineers' experience. To enhance the credibility of virtual or mixed virtual-physical test configurations, we provide systematic support for the continuous analysis and objective classification regarding the validation objective starting in early product development phases. The application of the proposed methods at the advanced engineering department of an automotive supplier provides detailed insides of its applicability and suitability during the development of mechatronic systems.

Keywords: data acquisition, electric drive, hardware-in-the-loop (HIL), emulation, modelling

1 Introduction

Advanced Engineering projects are often characterized by a high degree of novelty concerning the System in Development (SiD) and uncertainties regarding stakeholder needs. Besides, changing or multiple customers in business-to-business (B2B) relationships demand a high degree of development flexibility [1]. With the transformation towards electric mobility, complexity and interconnectedness of mechatronic systems increases, while development cycles are shortening. To face these challenges, model-based development and validation approaches are widely utilized [2–4].

Validation environments for the development of interdisciplinary systems such as electric traction drives consist of multiple test configurations (TCs) at different integration levels such as Model-in-the-Loop (MIL), Software-in-the-Loop (SIL) or Hardware-in-the Loop (HIL) [5, 6]. These modular validation environments are designed to address various validation needs. Initially set up to shift validation activities to earlier development phases and thus help understanding system behavior as well as to detect errors and failures, nowadays virtual TCs are also used for qualification and certification for example in the field of automated driving systems [7].

2 Background

Based on Ropohl's [8] general system theory, the development of products and systems can be described by different shares of carryover of existing systems and the particular development of new systems [9]. The variation of (sub-)systems raises the need for validation of the SiD. In the course of development cycles, different needs can be observed. While in early phases, knowledge generation regarding system behavior and examination of system properties/functions is apparent, the need for qualification and certification is raising close to the start of production. According to the development phases, various factors like for example the available resources determine the validation objectives. Consequently, the extent and maturity of test configurations to meet these objectives varies. Ehrlenspiel and Meerkamm's [10] 'rule of ten', which describes the increase of changing costs by a factor of ten for every design phase, reinforces the importance of early validation.

To enable validation of subsystem, X-in-the-Loop approaches consider the context of the SiD in the overall system and its interactions with the Connected Systems [11, 12]. In Figure 1 the architecture of a TC for an electric traction drive system according to the IPEK-X-in-the-Loop approach [4] is displayed.

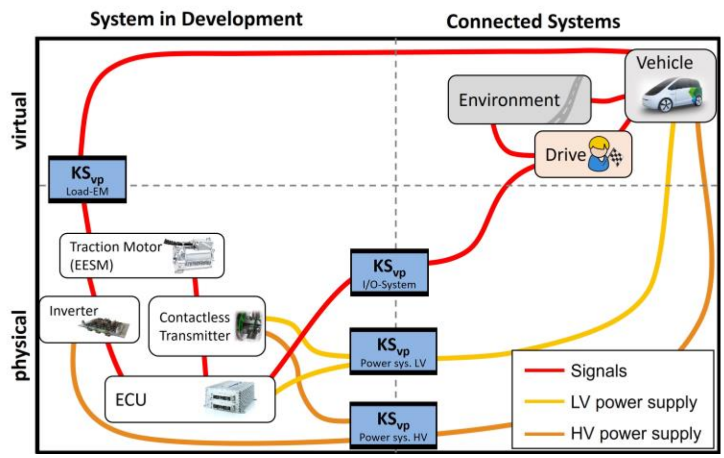

Figure 1: Architecture of a Test Configuration with physical representation of the System in Development (TC 4)

In the displayed example, the entire SiD is physically mounted on the testbed, while the Connected Systems are emulated. Koppelsystems (KS) are implanted to connect systems and to overcome incompatibilities between systems. However, these systems are not intended to add any relevant system behavior to the TC [13]. The colored lines represent the flow of information, energy and materials.

The sum of all planned and existing TCs to address a specific validation need can be described as the validation environment. In a modular environment, subsystems of both physical and virtual forms can be seamlessly exchanged and integrated. To ensure compatibility and exchangeability, models and systems are designed according to common interface rules (e.g. [14]). Based on the formulated validation objectives, appropriate TCs must be selected or designed. Yan *et al.* [15] propose to consider four perspectives to support the choice of suiting TCs:

1. Technological perspective,
2. Organizational perspective,
3. User perspective and
4. Economical perspective

While the organizational-, user- and economical-perspective can be objectified and evaluated by the available resources in time, personal and cost, the technological perspective highly depends on the specific validation objective [15].

3 Research objective and environment

According to the model of SGE - System Generation Engineering, new TCs are alike systems always based on a reference system [16]. In the early phases of the development process, TCs are most often set up subsequently to the non-/availability of physical components. However, with the availability of physical prototypes and multiple virtual models of a subsystem, the question “which configuration is best suited to meet the validation objective?” is raised. While the flexibility and reproducibility in virtual setups is unreachable by physical setups, it has been observed, that most of the time only the latter are trusted by stakeholders for development decisions [17]. In addition, virtual systems tend to develop in smaller but more frequent increments. Yan *et al.* [15] as well as our observations in advanced engineering projects have shown, that the assessment of modelling uncertainties is often based on the engineers’ experience. However, when seeking development decisions and convincing stakeholders based on results from mixed virtual-physical TCs, objectification is necessary. Consequently, we see a need to support the continuous evaluation of the technical uncertainty by the engineers.

The objective of this contribution is to increase the consistency among the various integration levels and TCs to reduce technical uncertainties regarding virtual or mixed virtual-physical systems. Consistency enables seamless development and validation iterations. Thus, supporting error detection or the identification of deviating behavior between models. Moreover, traceability within the validation should be aspired to meet ASPICE requirements [18] without losing necessary flexibility in the advanced engineering phase. Alike Carson [19], we will describe the decisionmakers confidence in a specific TC as ‘model credibility’. A systematic analysis allows objective evaluation of possible configurations for testing and thus, should increase credibility of virtual or mixes virtual-physical configurations. Therefore, a systematic support for continuous analysis and classification of TCs is presented in the following chapter. The presented work is structured according to the following two research questions:

1) Which systematic approach supports the consistent and traceable validation?
2) How can TCs be analyzed and classified to increase suitability of validation environments?

The proposed systematic approach has been implemented and evaluated at the Corporate Research and Advanced Engineering department of the automotive supplier MAHLE. The analysis and classification of several TCs as parts of a modular validation environment [5] has been conducted in the scope of an electric traction drive project [20].

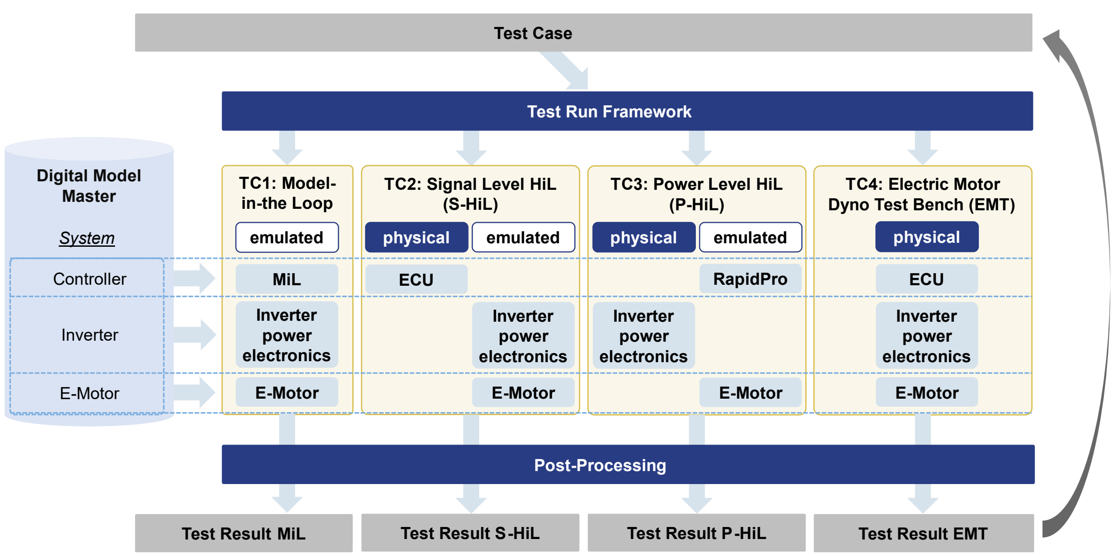

Figure 2: Excerpt of a modular validation environment for the development of electric traction drive systems

4 Analysis and Classification of Validation Environments

Figure 2 visualizes an excerpt of the implemented modular validation environment for electric traction drive systems in the research environment. The displayed environment consists of four different integration levels from MIL to different HIL setups. For simplification only one TC (1-4) at each of the four integration levels is displayed. The share of emulated and physical components varies from a complete simulation of the SiD to a highly integrated physical system.

In the following chapters, two different perspectives to achieve consistency are addressed by the systematic approach. Firstly, vertical consistency is targeted to ensure consistency and traceability of test conduction and interpretation. Secondly, horizontal consistency is addressed to guarantee exchangeability of subsystems within the TC. In chapter 4.4 the second research question is addressed.

4.1 Vertical Consistency – Testing Framework

Albers *et al.* [21] suggest to model identified potentials to address stakeholder needs in form of product profiles. Building on the initially formulated objectives, the potential user-, customer- and/or provider benefits of the SiD must be continuously refined and validated. In this work the focus is placed on the validation of the technical ideas, prototypes and solutions according to the identified potentials.

Consequently, the starting point of this contribution is subsequent to the initial system design. Test cases are defined based on customer requirements and thus initiate the technical verification on component and system level. Requirements and test cases are commonly stored in application life cycle management tools and serve as a basis for the testing activities regardless of the integration level. On the left side of Figure 3 a functional description of a test case according to ISO/IEC/IEEE standards 29119 & 24765 [22, 23] is displayed. On the right side a more detailed description of our understanding of the test procedure is displayed.

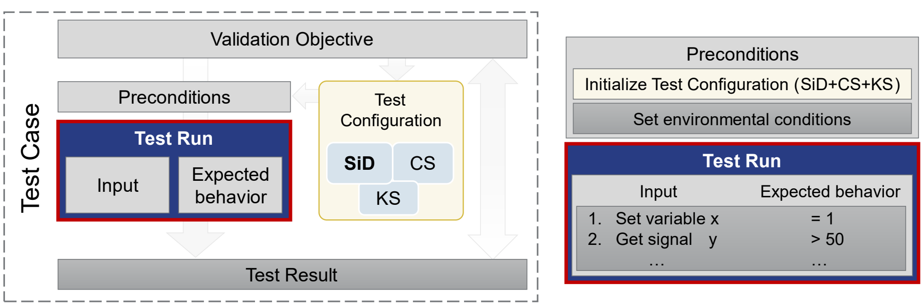

Figure 3: left: Test Case description according to [22, 23], right: schematic overview of a test procedure

In general test cases are meant to address validation needs. The specific purpose and expectations are defined by the validation objective. Commonly, a test case is a representative model of use cases and thus is designed to verify requirements [4]. X-in-the Loop approaches allow a variety of TCs to perform similar test procedures. To predict behavior of further integrated systems or to reproduce observed patterns in lower integration levels, comparability of test runs conducted in different configurations is necessary. In practice, validation environments consist of multiple tools to address a broad variety of testing purposes and thus impedes seamless comparability.

To face this challenge, we propose a generic test run framework. Test runs, which define the input and expected behavior of the system, are implemented generically in a centralized test automation tool instead of local implementations at each TC. To model user and system interactions, test runs consist of control (set) as well as feedback (get) functions. Thus, test runs are implemented independent of the specific TCs. To perform a test, the centralized test automatization tool translates these generic test runs to the specific controls on the regarded platforms. Thus, a consistent communication of control and feedback functions is ensured throughout the entire validation environment. [24]

In addition to a consistent system stimulation by the generic test run framework, comparability of results is essential for quick development and validation iterations. For vertical consistency standardized data postprocessing, independent of the utilized tools and platforms is needed. The basis of our analysis approach (see chapter 4.4) consists of uniform test data handling, synchronization and visual preparation. As a result, automatization of testing is enabled while ensuring consistency and comparability of test results of all TCs. Furthermore, the generic test run framework allows to define standard test procedures, which promotes reusability beyond the scope of one development project.

4.2 Horizontal Consistency – Digital Model Master

Modern development of interdisciplinary systems such as electric traction drives is accompanied by numerous, simultaneously evolving virtual and physical models of the system. Models are rarely isolated and normally interact with other models within the developed system. Varying model purposes and maturity levels complicate not only the choice of suiting models in regard to the considered validation objective but also to maintain an up-to-date overview. Thus, the frequent exchange of modelling and parameter data is prone to error. To avoid errors based on faulty or non-up-to-date data exchange between the disciplines (Systems Engineering (SYS), Software (SW), Hardware (EE), Simulation (SIM), Mechanical Design (MECH), Validation (VAL)) the Digital Model Master is introduced (see Figure 4).

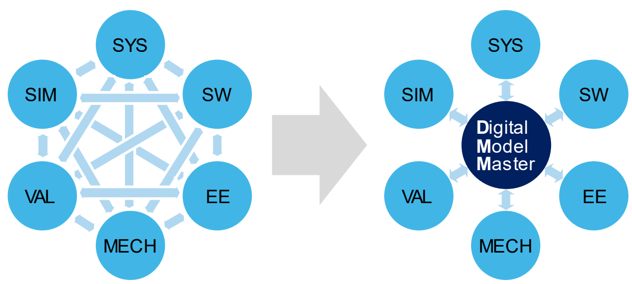

Figure 4: Centralized modelling and parameter-data management with the Digital Model Master [25]

Instead of a decentral exchange of system information between disciplines and models, the Digital Model Master serves as a unique, interdisciplinary platform for modelling and parameter data exchange. Consequently, input or parametrization of models for development or validation activities regardless of the affected discipline is always based on data provided by the Digital Model Master. [25]

To ease usability and traceability of data exchange, the Digital Model Master is closely linked to the system model and structured according to the physical architecture. Thereby, not only supporting horizontal consistency for the systematic setup of TCs but also creating an essential link between the descriptive system model (systems engineering) and the predictive models of the developed (sub-)systems. Thus, providing and establishing a system-oriented development approach starting in the early phases of the development process. Consequently, the Digital Model Master serves as a basis for the subsequent development and usage of Digital Twins later in the products life cycle [26].

4.3 Interim Conclusion on Consistency

The presented systematic approach, consisting of a generic test run framework, standardized post-processing and the Digital Model Master (see Figure 2) supports consistent and traceable validation from the start of development process. The combination of the test run framework and the centralized post-processing approach ensure comparability of test results from different test cases [24]. Regardless of the utilized tools and models in the TC as well as differing preconditions, immediate feedback between two test cases is enabled.

Furthermore, the Digital Model Master provides essential guidance to promote consistency among the system representations. The consequent usage of the Digital Model Master allows to reduce model deviations between different TCs substantially [25]. Besides the enhanced consistency throughout tests in the validation environment, the approach supports full traceability from system design to validation.

4.4 Classification Approach for Validation Environments

Basing on consistency and traceability, the next step to further enhance utilization of model-based development and validation approaches is to extend the understanding and credibility of virtual or mixed virtual physical TCs. Especially in the early phases of the system development, when configurations are initially planned and built up, objective evaluation of the technical uncertainty is needed to increase the decisionmakers confidence in these (partially) virtual TCs. Furthermore, enabling continuous and objective evaluation of the built-up models allows their direct integration in subsequent validation and certification processes.

Therefore, this contribution proposes a systematic approach for target-oriented and objective description to build up model credibility beginning in the early stages of the development process. The approach basically consists of the following four steps:

1. Definition of the validation objective to address the present validation need
2. Identification of key performance indicators (KPIs) and test cases to evaluate the model credibility
3. Perform tests in available configurations
4. Evaluation of technical performance based on KPIs

To initiate the analysis and classification of a validation environment, a specific validation objective must be defined or identified. The validation objective is linked to product features, functions as well as requirements and thus, identification of KPIs is possible in a subsequent step. In general, these indicators can be described on a functional level and are attached to factors, variables or signals which provide a certain system feedback. The technical implementation and recording of these indicators might differ between TCs. For example, currents can be measured by hall sensors in physical setups and calculated within virtual setups.

The most important step for the classification of a validation environment is the realization of consistent and traceable tests in at least two different TCs. Based on the validation objective and the identified KPIs test runs must be defined and implemented across the validation environment. The presented approach in chapters 4.1 and 4.2 is designed to support this procedure. Depending on the validation need, moreover based on the required level of maturity, suiting statistical measures must be defined to evaluate the recorded performance. The measures to evaluate the model credibility for knowledge generation or initial error detections are most likely less extensive than for product qualification or certification needs. A comprehensive overview of extensive evaluation strategies for qualification and certification tasks as for example in the development of advanced driving systems can be found in [27]. The case studies presented in this contribution address needs during the advanced engineering phase which mainly focus on knowledge generation.

The described steps of the systematic approach function as a guideline for classification of validation environments. Due to frequent extensions and changes to the validation environment, the approach is understood as an iterative process. In practice, findings of the evaluation step can lead to a refinement of objectives or identification of additional KPIs. The continuous classification of existing TCs supports the identification and specification of needed TCs to address formulated validation objectives.

5 Case Studies in Advanced Engineering of Electric Traction Drives

5.1 Contactless Transmitter Current Control

Object of this case study is the development of the rotor current control strategy for an externally excited synchronous machine (EESM). A knowledge gap considering the electromagnetic coupling behavior between rotor and stator field is addressed. To optimize the rotor current behavior, a real time model of the contactless transmitter is set-up and integrated in the highly virtual TC displayed in Figure 5.

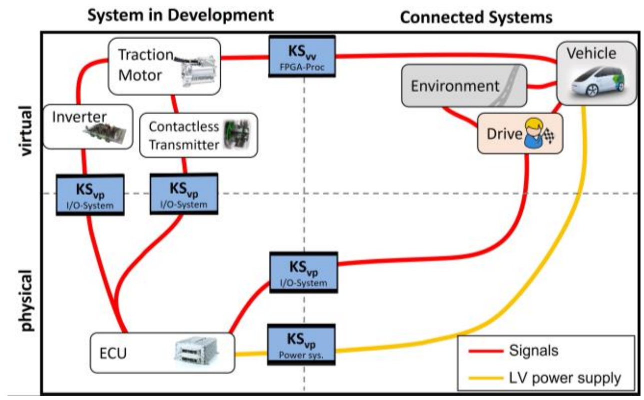

Figure 5: Test Configuration for real-time software test (TC 2)

The validation objective aims at the suitability of the presented TC for the design and parametrization strategy of the rotor current controller. Moreover, the coupling between rotor and stator currents is modelled within the newly composed TC. Subject to the influence of system requirements, like for example low torque ripple or sufficient torque control response time, various test runs with rotor and stator current changes are defined.

An excerpt of the detailed analysis is presented to demonstrate and evaluate the approach described in chapter 4. This example focusses on the impact of stator current (Id) steps on the rotor current (If) behavior. The following KPIs to classify the model credibility regarding the rotor current were identified: amplitude, rise time (duration of rising signal from reference value up to 90% of the maximum amplitude) and fall time (duration from maximum amplitude until 101% of reference value is reached).

The defined set of test runs is implemented within the subordinate test automation. Making use of the consistent validation approach (see chapter 4.1 & 4.2), automatized tests are performed in both the highly virtual TC (TC 2, Figure 5) as well as a mainly physical TC (TC 4, Figure 1). The configuration in Figure 1 is used as a reference for the analysis and classification of these TCs, where the SiD consists of virtual systems. The behavior of the rotor current If (open-loop control) during a positive step of stator current Id (closed-loop control) for both TCs is displayed in Figure 6

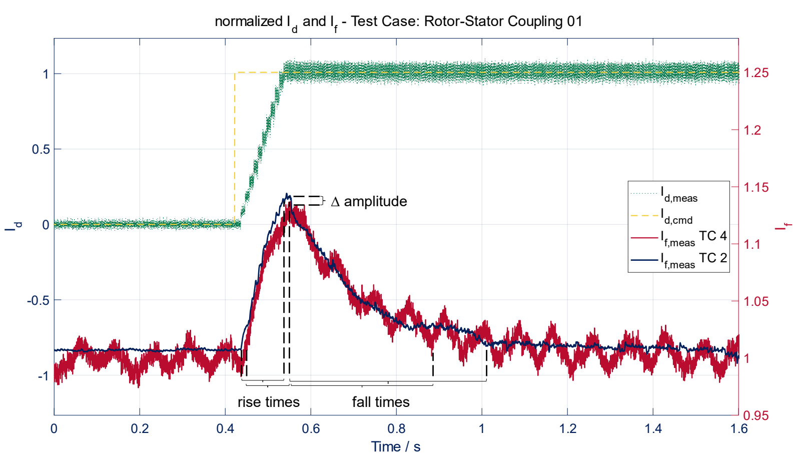

Figure 6: Excerpt of test run for investigation of rotor-stator coupling behavior
System stimulus – Id (left y-axis) and system feedback– If (right y-axis) in both Test Configurations

In Figure 6 the stimulation of the system – Id (left y-axis) as well as the systems reaction – If (right y-axis) is displayed over time. With a positive step in stator current Id, energy is added into the electromagnetic field between rotor and stator. To be more precise, the magnetic flux in the direction of the rotor flux (d-axis) is increased. As expected, the rotor current reacts with a slight overshoot. The differences between the reaction in both TC is analyzed with the previously defined KPIs, which are displayed in Table 1.

Table1: Performance analysis of rotor current behavior

TC/ KPI	amplitude (%)	rise time (ms)	fall time (ms)
TC 2	114,4	89.3	466.3
TC 4	113,7	90.2	324.9
Δ	0,7	0.9	141.4

At a first glance, no significant difference in amplitude and rise time can be identified. However, according to the data displayed in Table 1, the fall time of the displayed overshoot is significantly higher in TC 2. Here, the difference in fall time is subject to the signal noise of the measured current in TC 4. With the appearance of signal disturbances, either the analysis of the fundamental wave or averaging of multiple test executions is recommendable for the classification. Due to the fact, that in this case the TCs are used for knowledge generation, the advanced data analysis methods will not be performed to extend validity but might be necessary for qualification or certification tasks. The displayed comparison is representative for multiple operation points as well as for positive and negative steps to both stator currents. The significance of the displayed test run was verified by multiple repetitions in both TCs. Thus, TC 2 can be classified as suiting for knowledge generation regarding the rotor current controller design and parametrization.

5.2 Control Stability and System Efficiency of new Torque Control Algorithm

The optimization of the overall system efficiency is one of the main objectives for the development of electric traction drive systems. In order to increase system efficiency while reducing software resource consumption an analytical torque control algorithm (ATA) for the EESM is implemented and validated. The initial validation objective regarding the newly developed algorithm is to proof its feasibility. In addition to basic commissioning and stability test cases, performance tests are conducted. It is expected to reach at least similar system efficiencies with the less resource intensive ATA compared to a previously developed look-up table-based control algorithm (LUTA), which is based on a state-of-the-art field-oriented control approach and optimized regarding the system efficiency of the EESM.

Initial development and verification of the developed algorithm are usually carried out in MIL configurations alike TC 1 (see Figure 2). Simultaneously, FEM simulations provide good accuracy regarding the efficiency of the electric machine. However, for the proof of feasibility of the ATA the consideration of system interactions in real time is demanded. Tests on system test beds (TC 4, Figure 1) depend on the availability of all physical system components and thus are costly, time consuming and only available in a late period of the development process. A trade-off between simulation accuracy and high resource demands are real time signal-HIL configurations (TC 2, Figure 5). The classification approach supports the reduction of uncertainties regarding their suitability for the proof of feasibility.

On the one hand, the conducted analysis and classification (extract in chapter 5.1) underlines the suitability of TC 2 for commissioning and stability test. On the other hand, the utilized models of the inverter and the electric machine are optimized for real time performance and thus lack detailed modulation of the losses. The following example concentrates on the part of the carried-out analysis regarding the evaluation of the system efficiency. Among other things it is investigated, to what extend TC 2 can be used for efficiency evaluations although, it is lacking detailed loss modulation. Consequently, the total power losses are defined as the KPI. In total, four performance tests are carried out. At first, tests in both TCs are performed with the LUTA for all operation points. Afterwards, the tests are repeated with the ATA. Before the actual performance test, a conditioning phase is conducted to ensure constant machine temperatures. The test run consists of 3 phases: 1) ramp up and stabilization of machine speed and torque for desired operation point, 2) power measurement for 2 seconds, 3) re-conditioning if necessary. The resulting efficiency maps in the base speed range are displayed in Figure 7.

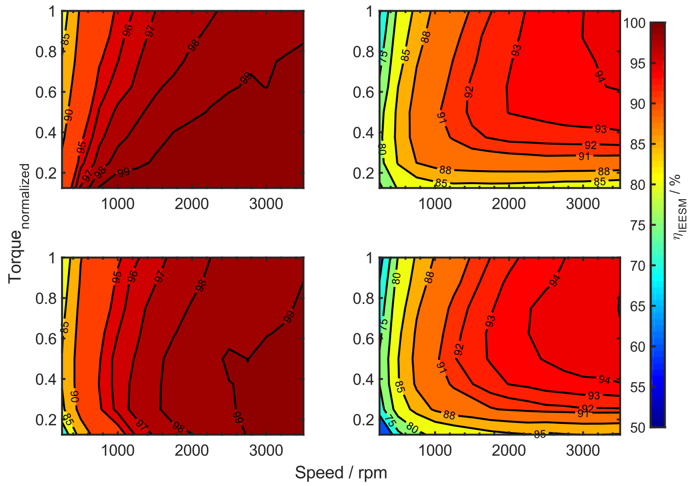

Figure 7: Efficiency maps – upper LUTA, lower ATA, left TC 2, right TC 4

On the left hand, efficiency maps from TC 2 are displayed, on the right-hand, TC 4 is displayed. Results from the conventional LUTA are shown on top, while the ATA is utilized in the ones below. The analysis of the performance tests in the physical test configuration (TC 4), display familiar efficiency characteristics. Moreover, a slight increase in system efficiency for most operation points with the ATA compared to the LUTA can be observed. Thus, expectations of the newly developed ATA are met. However, the efficiencies maps on the left show almost ideal system behavior. To understand the results of the performance tests carried out in TC 2 a detailed analysis of the KPI (system losses) is displayed in Figure 8.

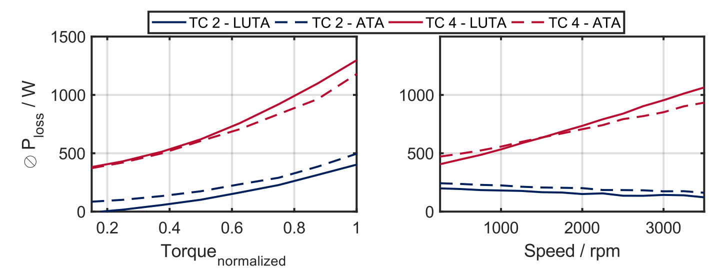

Figure 8: Average system losses for both control algorithms at both TCs;
left: average losses over torque, right: average losses over machine speed

The analysis shows that the system losses are not sufficiently modelled in TC 2. By the visualization of the average system losses over torque (left-hand), a deficit regarding on-state losses of the inverter and/or copper losses of the machine. However, the general quadratic relation between the applied torque and the losses is apparent. Major differences between the physical (TC 4) and the modeled traction drive system (TC 2) are recognizable at the right graph of Figure 8. While system losses increase with rising speeds (mainly due to friction, switching and iron losses) as shown by the measurements in TC 4 (red), a negative correlation between speed and system losses is apparent in TC 2 (blue). As the described behavior is apparent for the utilization of both control algorithms, the significance of the described model deficit is underlined. The following measures for modifications of TC 2 are derived: On the one hand, minor adaptions to the parametrization of the model can improve accuracy of the loss behavior in relation to the applied torque. But on the other hand, significant changes to the model are necessary to overcome the negative correlation between system losses and machine speed. Consequently, without further modifications of TC 2, predictions regarding the systems efficiency must be conducted in TC 4 only.

6 Conclusion and Outlook

The presented systematic approach enables consistency and traceability among heterogenous TCs. Thus, immediate comparability and modular validation of the systems in different TCs is supported. As a result, transparent and objective classifications of the validation environment are ensured and thus model credibility is significantly increased.

The case studies provide a deep insight into the potential of consistency among a diverse validation environment. In advanced engineering projects, validation needs for knowledge generation regarding the newly utilized systems have been addressed. Thus, model strengths and deficits regarding various validation objectives were identified. Based on these findings, the need to adapt or extend existing TCs regarding validation objectives is supported by objectification. The reference for the analysis and classification during the advanced engineering phase consists of prototypes and models of the system itself. As a consequence, the significance of the presented evaluation is limited to the maturity and credibility of these prototypes. For example, the signal disturbance of the reference shown in the first case study, must be taken into account.

To increase significance, extensive testing and evaluation strategies [27, 28] could be applied based on the introduced approach for consistency. Moreover, validation needs such as product qualification and certification must be addressed by extended classifications. Different needs regarding the evaluation of test results of the various integration levels should be further investigated. In addition, adequate methods [29] to store the generated knowledge regarding the classification of the validation environment have to be applied accordingly to facilitate reusability.

To sum it up, the presented approach for the analysis and classification of validation environments provides in-depth support for the task of finding suitable test configurations. In particular the credibility of virtual or mixed virtual-physical configurations is substantially increased by the application. The ongoing roll-out represents the consequential extension of the model-based development approach within the MAHLE Group.

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