Mission Profile Aware Robustness Assessment of Automotive Power Devices

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***Abstract*—In this paper we propose to exploit so called Mission Profiles to address increasing requirements on safety and power efficiency for automotive power ICs. These Mission Profiles constrain the required device performance space to valid application scenarios. Mission Profile data can be represented in arbitrary forms like temperature histograms or cumulated drive cycle data. Hence, the derivation of realistic verification scenarios on device level requires the generation of environmental properties as e.g. temperatures, board net conditions or currents. For the assessment of real application robustness we present a methodology to extract finite state machines out of measured vehicle data and integrate them in Mission Profiles. Subsequently Markov processes are derived from these finite state machines in order to automatically generate Mission Profile compliant test scenarios for the design and verification process.**
As a motivating example we show industry fault cases in which missing application fitness to power transient variations finally results in device failure. Verification results based on lab data are outlined and show the benefits of a fully mission profile driven IC verification flow.

***Keywords*—Automotive Powers, Mission Profile, Markov Process, Finite-State Machines, Robustness, Power Transients**

I. Introduction

Today, CO_2 reduction is a major focus all over the world. Since several years the reduction of fuel consumption and hence of CO_2 emission is no longer only driven by the improvement of *Internal Combustion Engines (ICE)* and drivetrains. A comprehensible and complete analysis and optimization of energy consumption for all subsystems within a vehicle is an essential step towards an economic handling of resources in the automotive sector. Hence in the automotive field the development of electric powertrains is currently being strongly pushed by *Original Equipment manufacturers (OEM)*, suppliers and governments in parallel.
Therefore next generation of cars within the automotive sector will be represented by *Fully Electric Vehicles (FEV)* [1]–[6]. Nowadays, there is experience built up over decades regarding the stresses and functional loads for components within traditional cars. This is a very important base for the actual high level of reliability in cars with ICE. Nevertheless, this knowledge needs to be rebuilt for fully electric cars in record time. However, with the introduction of this new generation of cars a variety of new challenges [7], [8] for the automotive sector are associated, for example:

- New vehicle architectures and new electronic architectures
- New boundary conditions regarding high voltage in cars
- Management of Li-Ion batteries
- Electric powertrains with 100kW

Therefore it is inevitable, that the new requirements are reliably passed from the OEM over tier 1 to the IC manufacturer and thereby considered and reviewed. Hence, it is absolutely necessary to develop new methods to achieve the current high level of robustness. Thus, it is essential to specify robustness as target dimension and to consider the robustness right from the start along the entire development process.
Therefore, a new form of standardized stress, operating and load profiles are defined, so called Mission Profiles. The Mission Profiles can be an integral part of the electronic component specification and will be passed from the OEM to the tier 1 down to the semiconductor manufacturer. The use of Mission Profiles along the entire supply chain requires new methods to derive stimuli from these formalized and standardized Mission Profiles.
In this paper we address this challenge and introduce a novel methodology to extract *Finite-State Machines (FSM)* out of measured vehicle data and integrate them in Mission Profiles. Therefore, we analyze real vehicle data and identify several formal operating states. Afterwards, these FSMs are derived in order to automatically generate Mission Profile compliant test scenarios for the design and verification process.
We motivate these efforts by showing industry relevant fault cases on smart power component level. The fault cases related to the part of the OEM LV124 guidelines [9], which specify guidelines for the power supply net.
We finalize with an outline, on how system robustness values in terms of Worst-Case-Distance [10], [11] can be synthesized to form component robustness values.

II. Related Work

In [12], the authors examine a process qualification and characterization strategy that can extend the foundry process reliability potential by using specific automotive mission profiles. They conclude, that the use of specific automotive

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Mission Profiles increases the reliability of the foundry process significantly.

For stimuli generation based on Mission Profiles, several approaches have been proposed [13]–[15]. In [13] an approach to validate the new European mission profiles [16], [17] on an electric vehicle simulator is presented. During the simulation different drivetrain components of the FEV are taking account for example, the control unit of the electric motor/generator and the braking system. The results for each simulation are the sizing of the drivetrain components. Compared to our definition of Mission Profiles in Section III, the Mission Profiles within this context are mainly driving cycles and don't define the application specific requirements for a component.

Another approach [14] uses the same Mission Profiles for an online estimation simulation of energy recuperation. Within these approaches, the Mission Profiles are not derived in order to generate stimuli but the Mission Profiles are driving cycles, which are applied as stimuli for the simulations.

The authors in [15] are exploring inverter designs considering Mission Profiles. The presented approach computes the component temperature based on mission profiles within an adequate amount of time and with satisfying accuracy. The Mission Profiles, which are used within this approach, are the FTP-72 driving cycle. The component temperatures are generated for a static ambient temperature of 65 °C. Note, that our approach generates temperature and velocity profiles based on Mission Profiles, which are created from vehicle measurement data. Due to that fact, we are able to generate profiles representing the correlation of velocity and temperature at different mounting points within the car.

III. Definition and Modelling of Mission Profiles

Mission Profiles (MP) define the application specific context for a certain component. It contains application-driven requirements, which are refined as design specifications down to the circuit level within semiconductor components. These requirements are expressed as a set of relevant environmental stresses, functional loads and operating conditions regarding this component. Therefore, measurements and specific data transformations are used, which are significant for the life cycle. Due to the increasing complexity of these application-driven requirements, it is necessary, to formalize and to standardize Mission Profiles.

In a first step towards the formalization and standardization of Mission Profiles, we specify three hierarchical structured Mission Profile Meta Models, see Fig. 1. The layered Meta

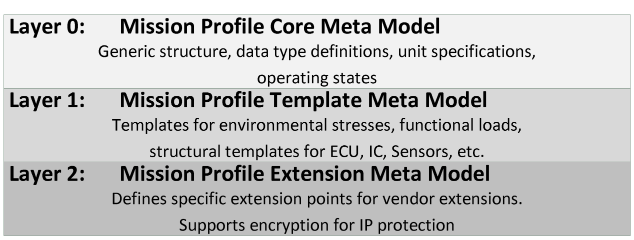

Fig. 1. Hierarchically structured Mission Profile Meta Models

Models define the structure of a Mission Profile document and its data handling. The first layer specifies the core structure and different generic data structures like values, vectors or standard data types. The second layer describes specific templates for environmental stresses or functional loads as well as hierarchically structured operating states. Operating states describe common and special application conditions for a vehicle like the defrosting for a potentially frozen throttle valve which leads to an excess current at very low temperatures or the high load for the power assisted steering motor by steering against the curb.

The third layer defines extension points and mechanisms in order to add company specific templates, data structures and data types. Likewise it provides elements to support encryption to guarantee IP protection. In the following sections we demonstrate a Mission Profile driven stimuli generation using information obtained from automotive power ICs.

IV. Finite-State-Machines in Mission Profiles

As mentioned in the introduction, Mission Profiles are exchanged along the entire supply chain to ensure robustness and reliability of a certain component, see Fig 2. Due to that

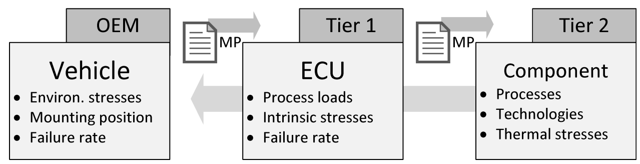

Fig. 2. Exemplarily Mission Profile exchange on the supply chain

exchange, Mission Profiles are a promising approach to reduce over-specification. Nowadays Mission Profiles are predominantly used in the automotive context to specify thermal loads, functional loads and other stresses, depending on specific operating states for *Electronic Control Units (ECU)*, ICs, etc. Therefore, expressive driving cycles are correlated with temperature loads or functional loads. Commonly, these data are provided in the form of histograms or *n*-dimensional distributions. Hence, the variability to make robustness statements based on these data is restricted, for example the alternation of loads is not displayed properly.

Due to that fact, we present an approach to encode Mission Profiles in the form of hierarchical FSMs. This representation of driving cycles and loads enables a more precise stimuli generation than based on histograms.

In our approach we transform measured vehicle data to FSMs. In a first step we specify formal operating states based on OEM LV124 guidelines [9], which define the commonly used generally requirements for test in the automotive sector, and experiences of OEMs. Afterwards, we identify the transitions between these operating states by using cluster algorithms.

The operating states are classified by the following four parameters: *Speed (**V**)*, *Ignition Status (**I**)*, *Engine Status (**E**)* and *Prior Operating State (**PO**)* of the vehicle . This leads to the following eight operating states depicted in Table I. The

TABLE I. Formal Definition of Operating States

BZ	*01*	*02*	*03*	*04*	*05*	*06*	*07*	*08*
V (km/h)	0	0	0	0-30	30-100	>100	0	0
I	F	T	T	T	T	T	T	F
E	F	F	T	T	T	T	T	F
PO	F	F	F	*	T	T	T	T

T = True; F = False; * = Don't Care;

parameter **PO** is specified as a set of operating states: **PO** = $\{$*BZ-04, BZ-05, BZ-06, BZ-07, BZ-08*$\}$. This applies: **PO** = True (T), if the previous operating state is contained in **PO**. After the specification of the formalized operating states, the FSM is initialized and trained. This initialization and training process is done by the chronologically insertion of measured vehicle data into the formalized operating states.

The transitions between the different operating states are identified and weighted within this elaboration process. Hence, the weighted transitions can be classified with probability values. This process generated a set of networks, which are classified by mounting position and driving cycle (short-distance/long-distance commuter, family vehicle, etc.) because of the analyzed measurement data.

Due to the fact that the FSM should be used to generate stimuli for the input and environmental conditions for automotive power ICs, these rough operating states are not accurate enough. Likewise, they are classified by speed and not by temperature, which is a fundamental requirement for generating feasible stimuli for automotive power ICs. Hence, it is required to refine the formalized operating states. The refinement process is performed by a clustering of the data points stored in the operating states. We used the K means algorithm [18] to identify clusters within the operating states. Likewise, any other clusterig algorithm can be applied for this step like DBSCAN [19] or EM algorithm [20]. The input for the K means algorithm for each operating state is a set of data vectors of speed and temperature, which are derived from the stored data points. The K means algorithm defines cluster these data vectors by min/max tuples of speed and temperature.

Next, we have to generate transitions between the identified clusters. Therefore, we stored in our data structure the successor and predecessor of each data point. Hence, transitions between each sub state of the same operating state as well as between sub states of different operating states can be identified and weighted.

This fine-grained network forms the basis for generating stimuli for automotive power ICs. One of the main weaknesses of this approach is, that the generated FSMs are only as good as the measured data they are generated from. Therefore, it is necessary, to use a data set, which is significant for a life cycle of the component for generating these networks. Since OEMs commonly use accelerated test methods and test sets for components and vehicles, the obtained FSMs allow a robustness assessment of automotive power ICs under realistic operation conditions.

V. Generating Mission Profile Compliant Stimuli

The validation of a design-under-test, a device-under-test or a system-under-test with respect to a given Mission Profile requires to stimulate the device with specific stimuli and to assess the performance and functionality of the device with respect to these stimuli. In the case of automotive power ICs these specific stimuli can be transient, like the power net voltage. Finally, robustness values can be transported back to tier n-1 based on a sufficient coverage.

Stimuli derived from the FSM-coded mission profile as described in Section IV are highly beneficial, as they are compliant to the mission profile by construction. Besides, the verification and validation process can then be performed coverage driven, e.g. based on the mathematical framework of a Monte Carlo process [10].

We give an example for robustness with respect to power supply transients in order to outline the benefits of that approach. For motivation, we first discuss the industry relevance of that subject based on a survey of known fault cases.

VI. Example: Survey on Power Transient Fault Cases

A. *Power transient faults*

In order to increase the power supply robustness of automotive smart power devices with respect to variations and transients of the power supply voltage, known fault cases have been assessed and classified with respect to conditions of occurrence, root cause and coverage possibilities during validation.

The survey does not only include devices supplied directly by the power net, but also devices using secondary supplies, a common case for smart power ICs, where analog and digital supplies are separated from each other. The relation between the primary and secondary supplies on ECU level requires an enrichment of the original OEM Mission Profile by the tier 1. We separated the survey into failure classes, related to:

- Direct connection to the power net or secondary supplies present (ECU conditions),
- Transient shape(s) and temporal relation,
- Temperature,
- Statistical occurrence over samples,
- Relevance of faulty behavior, transient or persistent, partial or complete functional failure.
- Root-cause of mixed-signal or digital type.

Major outcomes are summarized are summerized in the order of importance as follows:

- Root causes for most faults are related to analog or mixed-signal circuitry often including parasitic effects and meta-stable states
- Fault triggering often related to very high or very low supply slew rates or to slope reversals on the supply (partial reset)
- Fault triggering with multiple supplies related to temporal relation of supply transients
- Sometimes faults are temperature dependent

Finally, the summary of this work highlights the importance of Mission Profile generated stimuli for validation and verification.

1) Root cause analysis: In almost all functional failure cases, the root cause is complex and of mixed-signal nature, often including parasitic effects, thereby making it hard to give specific design guidelines for avoidance by simple design rules. As an example for an often used meta-stable circuit, the bare band-gap reference voltage should be mentioned. Without additional start-up circuitry the band-gap has 2 stable operating conditions, one with the desired stabilized output voltage and the other with 0 V outputs [21], [22].

In the following real life example of a smart power device, the temporal order of powering-up primary and secondary digital supplies triggered the partial functional failure, see Fig. 3. The root cause analysis of the failure revealed, that the issue is triggered by a parasitic capacitance at the input of a level shifter, which passes digital signals from one power domain to the other, see Fig. 4. Tests using an appropriate Mission Profile would have revealed this issue at an early stage of verification. This survey of power transient related faults also revealed that at least 10.000 randomly chosen profiles are needed for coverage, in case the verification process is not Mission Profile driven. This large number of required simulations is unfeasible to reach for practical designs of mid or high complexity. Again,

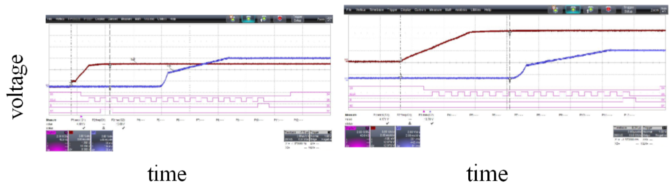

Fig. 3. Example of functional failure triggered by transient relation between power supply and secondary supply. Depending on the crossing or not crossing of primary (brown) and secondary (blue) power supplies the fault is triggered (left) or not (right).

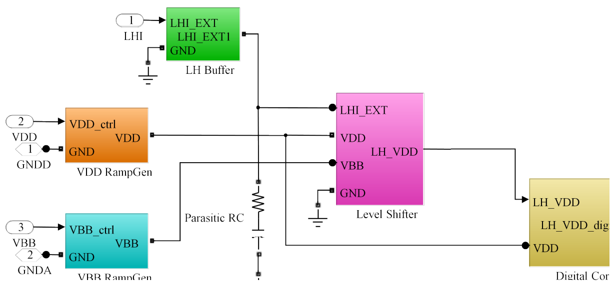

Fig. 4. Behavioral model with primary analog (VBB) and secondary digital supply (VDD) to reproduce the device failure in the digital core, observable on signal LH_SPI. Root cause is the parasitic capacitance at the entrance to the level shifter connecting two power domains.

simulations using the right Mission Profile can largely reduce this number to practical achievable limits.

B. Various power transient profiles

The above mentioned survey also includes the coverage assessment for power-transient profiles based on several paradigms, which are:

- Based on OEM LV124 guidelines
- Pseudo-random *Piece-Wise-Linear (PWL)* and Pseudo-random wavelet
- Mission-profile generated

As mentioned in the previous section, there is no fault model available for power related faults due to the complexity and variety of root causes. Therefore, we propose to determine coverage for transients based on the coverage of the state space of voltage and slew rate, see Fig. 5 for respective coverage plots. The state space is only sparsely covered because of the directed bias of the LV124 test. The pseudo-random tests potentially cover the full state-space, yet random PWL transients (see Fig. 6) may be subject to random resistance. Therefore we propose to use so-called pseudo-random wavelets, composed of the mixture of primitives like steps, oscillations and spikes to avoid random resistance and to improve the understanding (see Fig. 7 for an example). For mission-profile generated stimuli, coverage targets can be calculated instead based on Markov theory.

C. Mission Profile compliant power transient tests

As mentioned in the previous chapter, applying the LV124 test set and in addition pseudo-randomly generated tests can strongly help in assessing device robustness with respect to power transients, though with excessively large effort due to the unconstrained nature of the pseudo-random tests. Instead, we can achieve an optimum coverage by using power transient tests, which are generated compliant to a given Mission Profile.

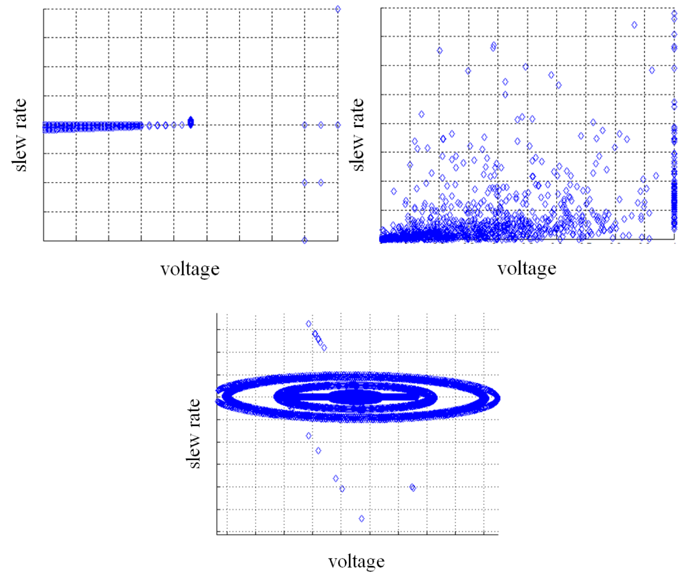

Fig. 5. Coverage plot in voltage slew rate plane from LV124 test set (upper left), pseudo-random PWL (upper right) and pseudo-random wavelet (lower left)

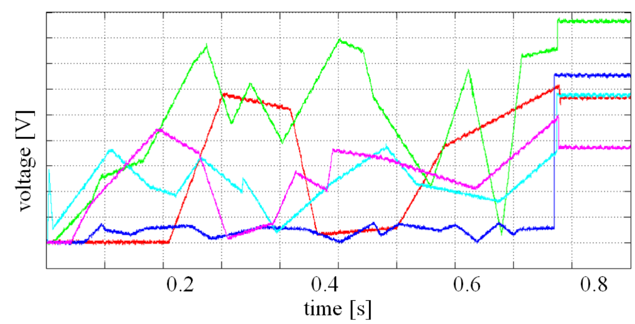

Fig. 6. Example of pseudo-random piece-wise-linear profiles.

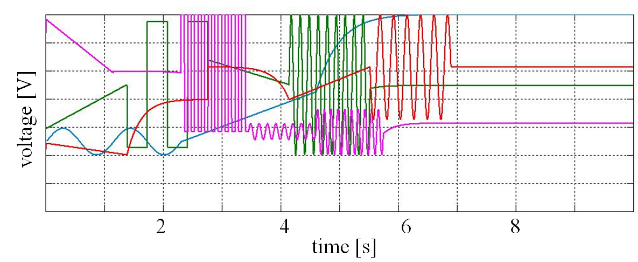

Fig. 7. Example of pseudo-random wavelets.

We considered two Mission Profiles so far: one being generic based the common *New European Driving Cycle (NEDC)* [16], [17] and the other Mission Profile based on recorded OEM drive data [1], see first sections for details. In both cases, the Mission Profile is first encoded as a state machine. The NEDC was encoded using the basic states STOP, ACCELERATE, CRUISE, BRAKE (and OFF). A Markov chain is generated for the NEDC simple FSM, see example state sequence in Fig. 8. A sample vehicle speed profile is subsequently generated based on accelerating, breaking and other states. The generation of relevant test cases requires knowledge of the power supply net, ideally provided by OEM or tier *n*-1. In this case, we were using heuristics for enrichment, because the original data was not available. Then the supply voltage has been directly used as input stimulus for smart power devices on emulation

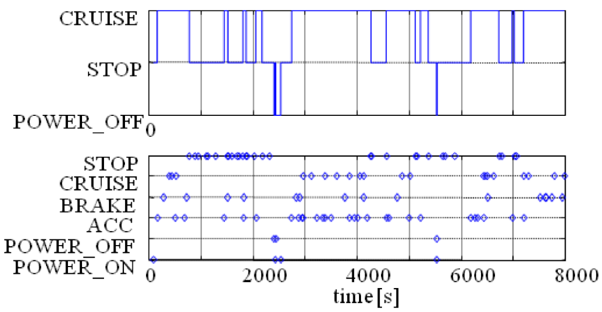

Fig. 8. States (upper) and state transitions (lower) over time from a Markov process.

equipment [23], see Fig. 9 and 10. We used real drive data

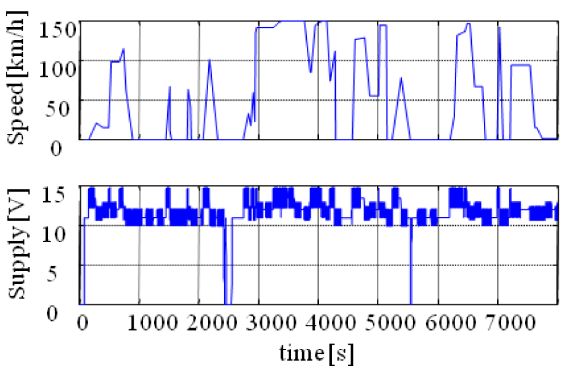

Fig. 9. Speed and resulting power supply voltage generated based on a Mission Profile.

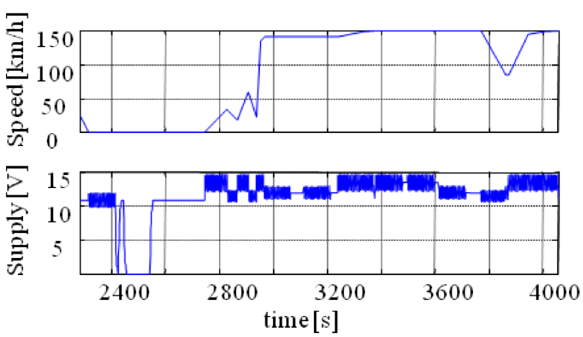

Fig. 10. Detail showing power drops and oscillations on the power supply net.

from recorded OEM drive tests as second Mission Profile.
We outlined in the first chapter the encoding of the Mission Profile as FSM. Here, drive speed was directly available in the Mission Profile FSM and did not needed to be deduced from heuristics.
A voltage regulator as exemplary automotive power device has then been subjected to the Mission Profile compliant profiles, using emulation equipment, see Fig. 11 for an example.

VII. Sythesis Of System Robustness Information

The next step has to be to provide the information of the device robustness, which is now quantified on component level, along the entire supply chain. Hence, the device robustness feedback has to be propagate upwards along the supply chain, from tier n to tier n-1 and finally to OEM, for assessing the robustness of the full system. We propose to use the *Worst Case Distance (WCD)* as metric to assess functional and parametric robustness [11] because the WCD is sensitive to parameter distance and parameter spread. Beside that, we briefly want to outline the possibilities to synthesize system robustness from individual component robustness values. This is necessary because an entire system WCD can only

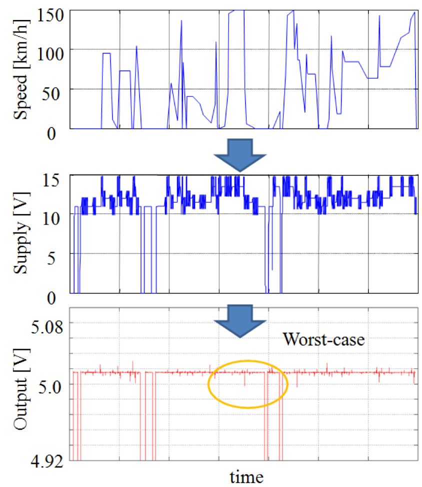

Fig. 11. Example of MissionProfile compliant transient test case with vehicle speed (upper), power net voltage (middle) and response of device-under-test (lower) to identify worst-cases. This Mission Profile compliant test is based on Mission Profile FSM, outlined in the first chapter.

be given if the specification holds for all components of that system because the WCD relates distance and spread of performance parameters to specification, i.e. tolerance body. This could happen in the case for an external temperature, but each component on an ECU may have a distinct thermal environment, making it more difficult to derive a system WCD. In this case the Mission Profile must be enriched by the tier n-1 to derive a useful Mission Profile for the tier n.
The calculation of the exact system WCD would require the full knowledge of *Probability Density Functions (PDF)* for the performance parameters, based on all operating conditions. It is unlikely, that such detailed information will be provided due to practical reasons.
If no additional knowledge is available concerning the exact PDFs, which were the basis for n component WCD calculations, at least a lower bound can be given by the following definition, where *erfc* is defined as complementary error function:

$$WCD(S) = erfc^{-1}\left(\sum_{i=1}^{n} erfc(WCD_i)\right)$$

A simplified expression, which may hold in most practical cases takes the minimum of all components WCDs:

$$WCD(S) = min(WCD(C_1), ..., WCD(C_n))$$

The minimum overestimates the system robustness if the system consists of n identical components, because then:

$$WCD(S) = erfc^{-1}(n * erfc(WCD_i))$$

In general, this fits to heuristics which assume that a highly uniform system is less robust than a heterogeneous system.

Though system robustness may be detracted by the use of many identical components, the absolute relevance is negligible in typical case. Fig. 12 shows quantitative robustness values for a 2-component system with respect to the WCD values of these two components.
With the assumption of a system consisting of 10 identical components with each WCD = 3.0, the complete system WCD will slightly be reduced to WCD = 2.6. We want to

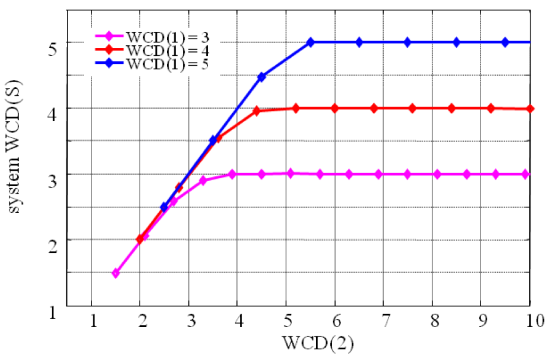

Fig. 12. Difference between systems WCD based on minimum or based on error function calculation for various WCD combinations. Simulated was a system built of 2 components. The small error region is marked by the arrow.

point out, that this calculation only holds, when there are no active measures on system level to correct missing robustness. Active measures could be implemented as redundancy, error correction etc. More accurate system WCD results may be achievable by using *n*-dimensional WCD information.

VIII. Summary and Outlook

We presented how Mission Profiles from automotive OEM can be consistently coded and transported through the supply chain down to the semiconductor manufacturer for automotive semiconductors with special focus on the assessment of the automotive power device robustness. An essential step is the encoding of the Mission Profiles in the form of state machines. From these state machines, transient stimuli can be generated which are compliant to the Mission Profile content, using a Markov chain generation process. We have shown an industrial motivation to follow this path for components connected to the power supply net and an exemplary test for one device based on real data from an automotive OEM. We conclude with a short summary how the extracted robustness values in the form of Worst-Case-Distance can be synthesized back to system robustness values.

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