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Automotive Intelligence for/at Connected Shared Mobility

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Table of contents

1 Executive/ Publishable summary

This document is intended to describe the activities and results from Task 1.4 – "Requirements and specifications for the robust propulsion and energy storage system". This task spans the activities of creating the fundamental specifications for the numerous demonstrators, prototypes and algorithms that are part of Supply Chain 4. These include key components of the HV electrical system, like inverter, battery system and wireless charger, as well as microelectronic devices like Parallel Processing Unit and Power Management IC. It also contains the specification on the novel control and diagnostic algorithms as well as an advanced mission profile model for reliability simulations.

The developments considered in this task contribute to the AI4CSM objectives by increasing robustness and reliability of the drive train and the battery system (O1), by providing specialized processors for the execution of AI algorithms (O3), and improving the attractiveness of ECAS vehicles by means of efficiency and reliability (O6).

The defined requirements lay the foundations for the subsequent activities in Work Package 2.

2 Non publishable information

The following parts of this document are not to be published:

- Chapter 4.1.4 – High-speed sensor interface
- Chapter 4.4 – Safety Power Management IC
- Chapter 4.8 – Advanced Mission Profile Model

3 Introduction & Scope

3.1 Purpose and target group

This document describes the component specific high-level requirements for the different demonstrators and technologies developed in Supply Chain 4. They are meant to indicate a tangible approach of reaching the Key Performance Indicators of each development and their contribution to fulfilling the objectives of the AI4CSM project.

The requirements are collected individually for each development and serve as "spec book" for the subsequent work in the Work Packages 2, 3 and 4 where these requirements will be broken down to a more detailed level. They are also meant to define the scope of work of each demonstrator and activities that are related to them. Finally, they are meant to provide an easy way of assessing the results of the work by stating clear and measurable claims.

3.2 Contributions of partners

The following table indicates the contributions of each partner. It is organized by chapters and provides an overview where each individual contribution is located in the document.

TABLE 1 - PARTNER CONTRIBUTIONS

Chapter	Partner	Contribution
1, 2, 3, 4.1, 5	MBAG	Coordination of Supply Chain 4, Work Package 1 and Task 1.4 Introduction, Summary, OEM-requirements for drivetrain
4.1.1.5, 4.1.1.6	BUT	AI controlled redundant powertrain software, cognitive diagnostic system.
4.3, 4.6	FHG	Description of machine failure detection and intelligent battery system
4.7	HSO	Description of FPGA and phase-based control algorithms
4.2	IFAG	Description of Microcontrollers (MCU), Parallel Processing Unit (PPU) and Power Management Unit (PMU); Accelerating AI with PPU, AI algorithms
4.1.4	IFAT	Description of High Speed Sensor Interface
4.4	IFI	Descriptions of SCD 4.4 in the related section
4.5	TUD	Description of Foreign Object Detection for Wireless Charger
4.1.1.4, 4.1.1.5	TUDO	Description of gate driver
4.8	TUWIEN, IFAT	Description of Advanced Mission Profile Model
4.1	ZF	SCD4.1 owner, description and requirements

3.3 Relation to other activities in the project

This document describes activities from Work Package 1 which is the first work package of the project, so no inputs other than the ambitions from the full project proposal/grant agreement have been used. The results will be taken on by the subsequent tasks in Supply Chain 4, namely Task 2.4 – "System level design for the robust propulsion and energy storage system", Task 3.2 – "Components design for the robust propulsion and energy storage system" and Task 4.3 – "Embedded HW/SW development for the robust propulsion and energy storage system". A close cooperation with Supply Chain 2 is inherently established as all of these tasks are also linked to SC2.

A certain relation also exists to Task 3.1 – "Components design for L3 driving and multimodal CSM" of Supply Chain 3, as the Power Management IC (PMIC) and parts of the PPU development will be used there.

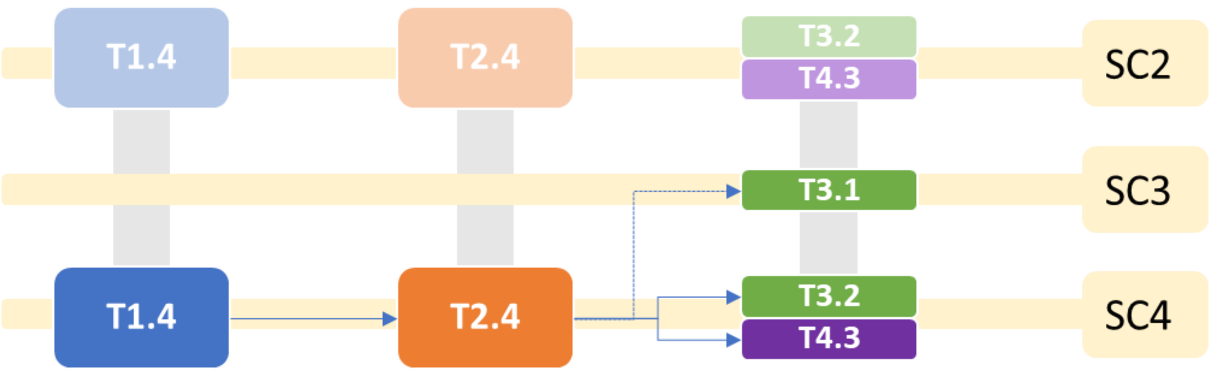


FIGURE 1 - RELATION TO OTHER ACTIVITIES IN THE PROJECT

The requirements as result of this task will serve as design guidelines and boundaries for the activities listed above and ensure their link to the overall project's objectives. They will also serve as starting point for defining the test and validation procedures in Work Package 6 – "Validation & Test".

4 Description of the technical work

Supply Chain 4 is dedicated to the different aspects of the drivetrain of battery electrical vehicles. These include naturally the electrical drivetrain, comprising an electrical machine, a reduction gear and the traction inverter, as well as the high-voltage battery as the main energy storage, including the battery management system. Charging technologies, as a crucial feature of electric mobility, are represented by a wireless charging system in Supply Chain 4. The powertrain controller as the platform for the vehicle's operating strategy is another important part of the drive system, as well as Power Management devices to ensure the low-voltage power supply of microcontrollers, gate drivers etc.

These devices form the Supply Chain's scope within the AI4CSM project and will be the main field of application for the developed technologies, algorithms and methods.

The mission of the AI4CSM project is to develop the functional architectures for next generation ECAS vehicles based on electronic components and systems (ECS), embedded intelligence and functional virtualization for connected and shared mobility using trustworthy AI. For Supply Chain 4, this translates to the following challenges:

- Increase efficiency
- Improve robustness and reliability
- Reduce resource consumption

The expected results will contribute directly to the project's overall objectives, namely

- O1: Develop robust and reliable mobile platforms
- O2: Develop scalable and embedded intelligence for edge and edge/cloud operation
- O3: Design silicon for deterministic low latency and build AI-accelerators for decision and learning

The developed solutions will be presented by means of demonstrators. These demonstrators are either hardware prototypes, software algorithms or simulation models. Supply Chain 4 is going to present five demonstrators (SCD = supply chain demonstrator) that represent key components of an electric vehicle's driving and energy storage system:

- SCD4.1: AI-controlled redundant powertrain
- SCD4.2: AI-accelerated powertrain controller
- SCD4.3: Intelligent battery by AI
- SCD4.4: Safety power management IC
- SCD4.5: Wireless Charger with AI-enhanced foreign object detection

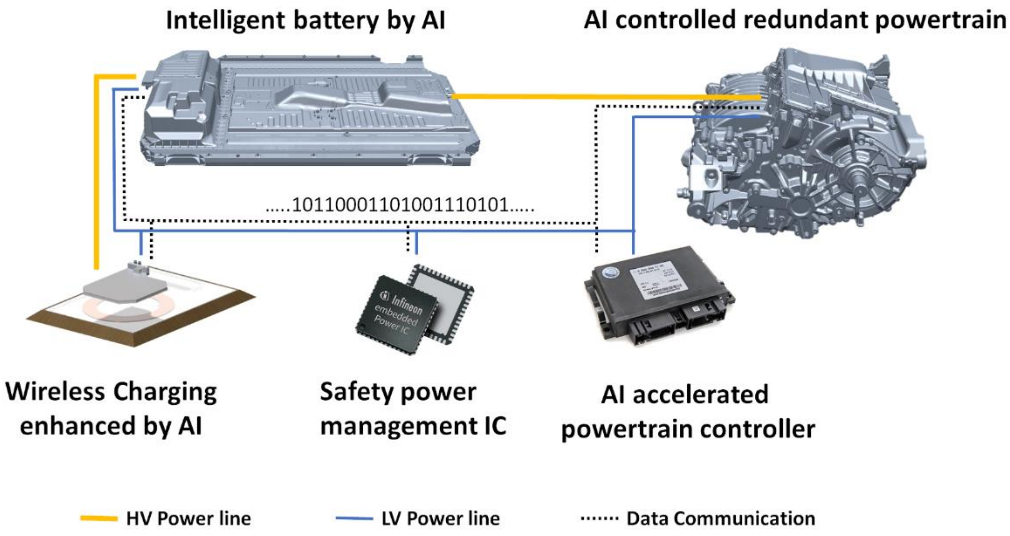


FIGURE 2 - OVERVIEW OF SC4-DEMONSTRATORS

In addition, Supply Chain 4 comprises three activities, that can be seen in the context of the aforementioned demonstrators but are described separately in this document due to their extent. The activities are

- Cognitive Diagnostic System
- Phase-based control algorithms
- Advanced Mission Profile Model

The feasibility of integration of these activities into the demonstrators will be evaluated during the design phase of the project.

For every technical development it is important to define the objectives that are to be achieved by the activities. Furthermore, these objectives need to be specific, explicit and measurable. This is approached by defining Key Performance Indicators for each demonstrator and by linking these to the project's objectives. Thus, a tangible contribution of each demonstrator (and hence the activities in the Supply Chain) to the objectives can easily be retrieved.

TABLE 2 - KEY PERFORMANCE INDICATORS

AI4CSM objective	Means of validation (delivery of e.g. demonstrator)	Key Performance Indicators (KPIs)
O1: Develop robust and reliable mobile platforms	AI controlled redundant powertrain (SCD4.1)	Efficiency comparable to SiC at reduced semiconductor costs. Gate Driver contribution: 20% reduction of drive inverter losses Fail-operational with 50% power in low-speed range after switch failure
	Intelligent battery by AI (SCD 4.3)	Identification of temperature sensor degradation with balanced accuracy better than 90 %.
	Wireless Charging Enhanced by AI (SCD 4.5)	Enhancement of FOD capabilities over state of the art technology expected: - metallic and non metallic-metallic object detection with one sensor principle - simplified sensor layout, without "blind-spots"
O2: Develop scalable and embedded intelligence for edge and edge/cloud operation	Next-generation AURIX™-Microcontroller with Parallel Processing Unit for AI acceleration (SCD4.2)	Improved latency and pattern recognition speed Lower total energy and resources consumption
	New High-Speed-Sensor-Interface and its Reliability and Health prediction aspect	- Single master, multiple sensor concept (e.g. LIN) - Four wire interface - data transmission security according to ISO26262 standard (ASIL-D) - Synchronization of a single or multiple sensors

		- Broad range of data transmission rates form 125 kbps up 5 Mbps (10 Mbps) - Up to 8 sensors per bus - low cost silicon implementation based on common UART interface hardware - bidirectional communication - constant latency time, very low jitter - stray filed robustness (by using CAN physical layer for differential data transmission) - Min. update rate 25µs (40kHz) @ 2 Mbit/sec data transmission speed - 3 different level diagnostic (status bit, diagnostic frame, diagnostic sensor read out)
	ANN based autodiagnostics of sensing platform for mechanical faults using virtual sensors approach	Identification of individual sensing component fault better than 90 %.
	Cognitive diagnostic system for detection of system faults of the propulsion system (model based, ANN based)	- stator short circuit fault detection with 95 % classification accuracy in less than 30 ms time from fault occurrence - Identification of open transistor faults
	Nonlinear MPC algorithm running in PPU of Next-generation AURIX	- Execution time lower than 90 us enabling 10kHz PWM operation
	Motor Winding Fault Detection	-Analysis of detection methods for winding/stator faults of traction machines - Evaluation of the usability of internal inverter sensors. Identification of limitations - Development and validation of detection algorithms and machine/inverter co-simulation tools for fault detection - Detectability rate > 95%
O3: Design silicon for deterministic low latency and build AI-accelerators for decision and learning	Power Management IC (PMIC) (SCD 4.4)	Increase power handling of the PMIC from state of the art 10W to 50-60W to support new generation microcontroller capable of parallel processing (e.g. Aurix3G). This will be proven with a physical device. Improve the basic fault recognition currently in place to support an enhanced anomaly detection of failures related to PMIC and/or supplied users. This will be proven at model/simulation level.

A significant part of the work conducted in this task was to derive the requirements that need to be satisfied in order to reach the abovementioned Key Performance Indicators. For the sake of a systematic and uniform approach, the requirements were collected by means of a requirement database. For each demonstrator and activity a set of requirements is defined that contribute to the achievement of the top-level objectives. Each requirement is characterized by

- A **description**, defining the requirement more precisely

- A **rationale**, explaining the necessity of the requirement
- A **metric** or a measurable value to be able to verify whether the requirement has been satisfied, as well as the means of validation

As the main result of this Task, these requirements will then form the foundation for the design activities in the subsequent work packages.

The following chapters contain a description of the individual demonstrators and activities as well as the corresponding requirements.

4.1 SCD4.1 – AI controlled redundant powertrain

4.1.1 Description

The goal of this activity is to create a powertrain (inverter and electric motor) with inherent redundant elements to achieve fail-operational behaviour and a high system efficiency. To reach this goal, development of both hardware systems and software algorithms is necessary.

The block structure of the demonstrator is shown in Figure 3. The main block Power Inverter consists mostly of the components which have already been described, namely control board with software, gate drivers and GaN power transistors. Additionally, a DC-link capacitor as well as filters for the HV networks are to be implemented, as well as HV voltage and current, and temperature sensors.

The complexity of this prototype is covered by the collaboration of several partners. ZF acts as the demonstrator owner and is also in charge of the development of the mechanical components, such as cooling system and HV interfaces, as well as the power stage. TUDO contributes to the demonstrator development by developing the gate drivers for the GaN power stage, as well as implementing the necessary voltage and temperature measurements. On the software side BUT is responsible for creating the control and diagnostic algorithms for the inverter. In addition, IFAG and IFAT contribute by providing semiconductor components for the powertrain. Namely, IFAG provides the 3G AURIX with a Parallel Processing Unit (PPU) for the acceleration of linear operations, while IFAT contributes a rotor position sensor with a high-speed digital communication interface.

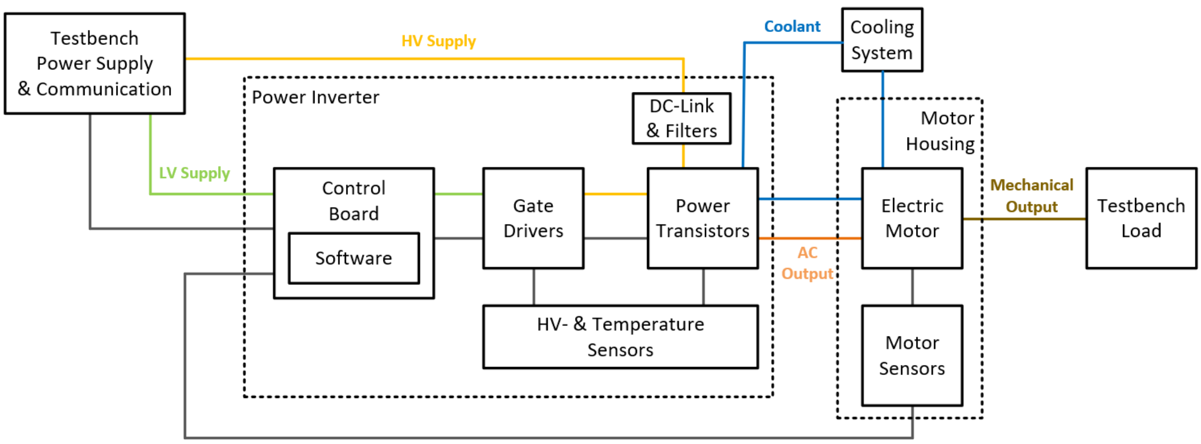


FIGURE 3 - SCD4.1 BLOCK DIAGRAM

An electric motor is needed to test the inverter; this is also shown in the diagram together with relevant sensors (temperature, rotor position sensor) needed to realize the control and safety functions of the inverter. Figure 4 shows the output characteristics of this motor, which has a peak power rating of 200 kW, and a continuous power rating of 78 kW. The inverter must be designed in such a way that the current supplied to the electric motor can satisfy the defined power diagram.

There are several elements which are not part of the demonstrator itself but must be provided by the testbench. These are the HV (800 V) and LV (12 V) power supplies, a CAN communication interface, a liquid cooling system including pump and heat exchanger, and a load to be connected to the rotor of the electric motor.

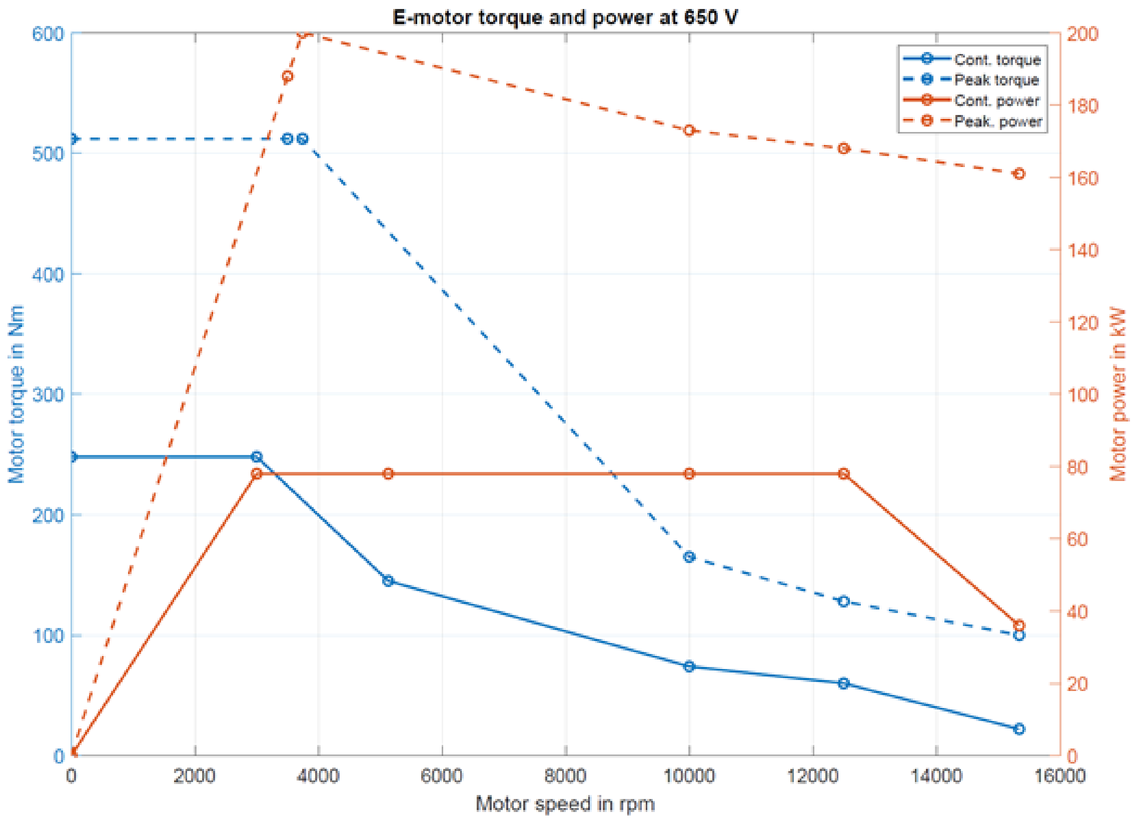


FIGURE 4 - MOTOR OUTPUT CHARACTERISTICS

The efficiency target can be achieved by using Wide Bandgap (WBG) materials, such as Silicon-Carbide (SiC) or Gallium-Nitride (GaN). Although SiC is already being used in automotive series development, its high cost when compared to Silicon (Si) makes the search for alternatives such as GaN necessary. Section 4.1.1.1 explains in more detail why GaN is an interesting material to use in traction inverter, as well as its advantages and disadvantages when compared to Si or SiC.

An increased availability of the system and the possibility of operation after the fault of a component (fail-operational behaviour) must be achieved with a combination of hardware and software. On the hardware side, multi-level inverter topologies such as three-level inverters are interesting, since their structure has an intrinsic degree of redundancy. At the component level, at least four transistors are used in each phase; at a functional level, the AC output is realized with several voltage output levels instead of the two output levels of a typical inverter. The combination of these properties makes a limited inverter operation after a component fault possible since the AC output can be reduced to a two-level operation after a fault. Further details to this topology are given in sections 4.1.1.2. For coverage of all possible motor faults, the powertrain should additionally be designed as a two three-phase system, with electrically separate but magnetically and mechanically joined three-phase systems. Considerations on the switching logic for the gate driver, such as the valid switching states and how transistors may theoretically fail, are provided in sections 4.1.1.3 and 4.1.1.4 respectively. Finally, sections 4.1.1.5 and 4.1.1.6 provide more details on the control algorithm for the powertrain in healthy and faulty scenarios, as well as on the diagnostic system for the detection of mechanical and electrical faults or degradations.

Section 4.1.3 provides more information about the high-speed sensor interface from IFAT. Although this was originally planned as a separate demonstration unit, it is well suited for integration in the powertrain and its performance can be shown after its integration in a system.

4.1.1.1 Gallium-Nitride semiconductors

Power inverters for high-voltage (HV) electric mobility are usually realized with Si-based Insulated Gate Bipolar Transistors (IGBTs). In recent years new WBG materials have become relevant in this field, with inverters based on SiC starting to become available. WBG materials are used instead of Si due to its superior material properties, which allow a faster and more efficient switching, as well as a better thermal performance. Thus, higher efficiencies at inverter level can be achieved. The main disadvantage of SiC comes from its much higher costs when compared to Si. For this reason, other WBG materials are under consideration for use instead of SiC.

One of these materials is GaN, which is used to create High Electron Mobility Transistors (HEMTs). Such transistors offer several advantages (Beheshti, 2020). On the one hand, they have even faster switching speeds and lower switching losses than SiC, providing a clear advantage in high-frequency systems. The HEMT structure lacks the intrinsic body diode typical of MOSFETs, leading to no reverse recovery when turning-off this diode. Finally, cost forecasts for this technology place it at a similar cost to traditional Si devices once the technology has matured.

Nevertheless, there are several limitations of GaN devices. HEMTs are usually available as depletion-mode devices, i.e., they are turned on when no control voltage is applied. Such a functionality is undesired in safety-critical applications, where enhancement-mode (e-mode) devices are preferred; these must actively be turned on. For this reason, GaN producers have created several approaches to create e-mode devices such as cascaded transistors, where a Si-MOSFET is connected in series to a GaN HEMT. The approach to be considered in this project is the use of p-GaN HEMTs, which achieves e-mode functionality by adding a p-doted area below the gate contact. Although functional, special care must be taken when designing the gate-driver stage to achieve a fast, efficient, and especially safe switching performance in all operation scenarios.

A further limitation of GaN is its maximum voltage rating of 650 V, which makes impossible their use in a traditional (two-level) inverter topology. An approach to deal with this limitation is discussed in section 4.1.1.2. Furthermore, GaN HEMTs are not available in complete power modules, as is the case when dealing with Si or SiC for automotive applications; instead, HEMTs are available either as dies or discrete devices which must be electrically and thermally connected individually. Finally, discrete GaN HEMTs typically have a higher on drain-source resistance R_{DS} as SiC, requiring a parallelization of devices to achieve the required currents.

4.1.1.2 Three-level inverter topology

The voltage limitation of actual GaN semiconductors can be overcome by using a multilevel inverter topology, namely a three-level topology. These three levels refer to the possible output values of a single phase. While standard inverters can only deliver $\pm\frac{1}{2}$ the DC-link voltage (when referenced to the middle point of the inverter motor), three-level inverters deliver these two values as well as a 0-voltage output, as shown in Figure 5.

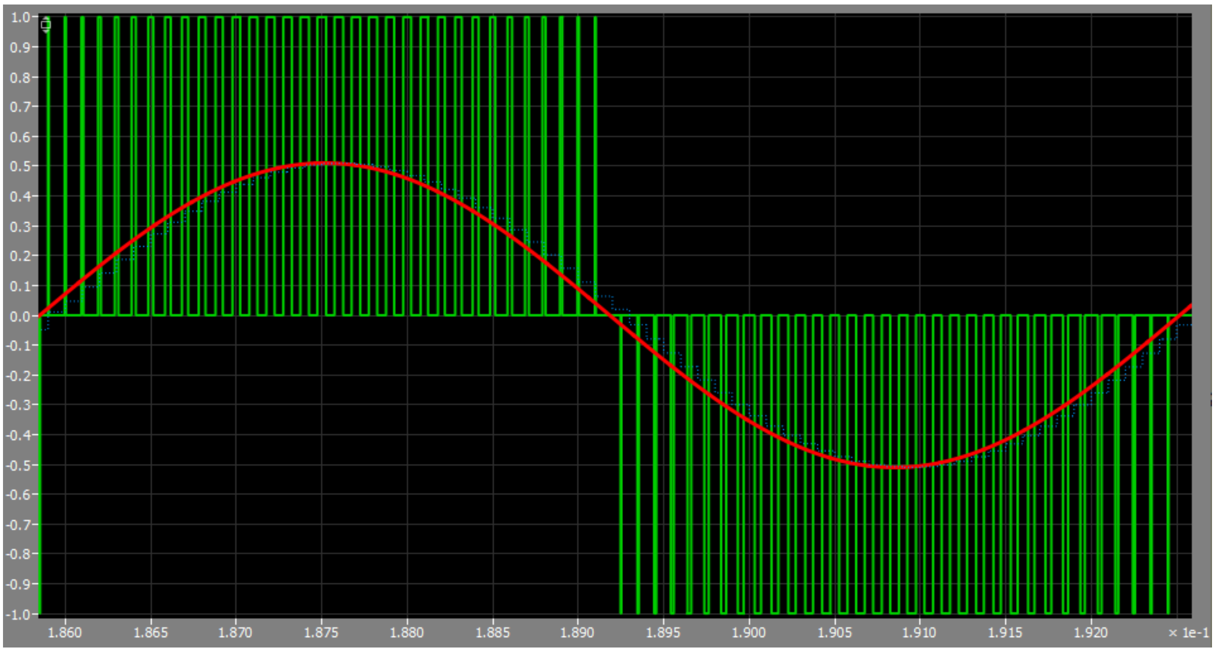


FIGURE 5 - THREE-LEVEL PWM SWITCHING; GREEN: PWM SIGNAL; RED: REFERENCE SINE SIGNAL

There exist a multitude of three-level inverter topologies which could be implemented, such as Flying-Capacitor, T-Type, Neutral-Point-Clamped (NPC), or Active-Neutral-Point-Clamped (ANPC) (Kouro, et al., 2010). 650V GaN devices can be used with most of these topologies in 800V systems due to the series connection of transistors between a HV potential and the AC output, as can be seen in Figure 6. By adequately selecting the active devices, each transistor is subject to maximum 400V, well below the maximum voltage rating of the device.

For the project, the ANPC topology shown in Figure 6 has been selected due to its intrinsic redundancy. Its main disadvantage lies on the high number of devices needed, with 6 functional transistors per phase, each one in turn composed of one or more real devices to achieve the required current demand. In turn, six signals from the control unit are required per phase.

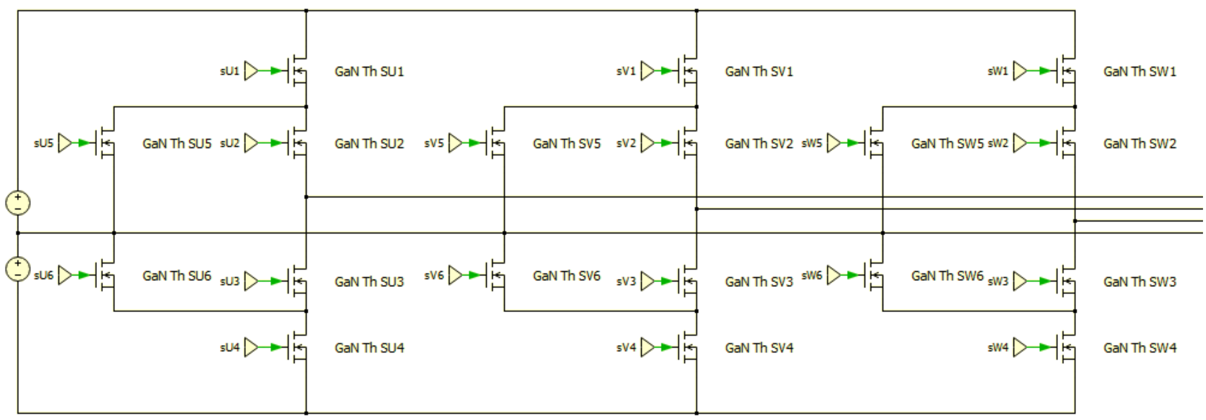


FIGURE 6 - THREE-PHASE ANPC INVERTER

Although the ANPC inverter is considerably more complex than a standard power inverter, it offers several advantages. Several of these are common to three-level inverters (Krug, Kume, & Swamy, 2004). As shown in Figure 5, the output sine signal is now approximated by a three-level PWM signal, which allows a better approximation of the sine signal. This results in a smaller current ripple on the load/electric motor, which in turn results on smaller torque ripples at the motor output, and thus a better noise vibration harshness (NVH).

The existence of the 0-voltage output value as a middle step has several electrical advantages. Firstly, the voltage steps are smaller, since now the 0-voltage value serves as a middle point. This smaller voltage change results in smaller voltage overshoots at the phase output, which in turn degrade the isolation of the electric motor stator. Secondly, the smaller voltage changes also result in smaller common-mode voltage at the middle point of the three-phase system. These changes in the common-mode voltage are responsible for leakage currents are, more critically, for bearing currents, which mechanically degrade the bearings of the electric motor. In summary, by using a three-level topology, we can expect an increase of the powertrain lifetime due to reduced degradation of stator isolation and bearings.

An advantage which is particular to the ANPC topology is its full fail-operational capabilities in case of a transistor fault. No matter which transistor fails, there is always a strategy to continue the operation of the broken phase with a specially selected switching pattern. For critical faults, in which the phase operation is no longer possible, the generation of a rotating magnetic field on the electric motor is still possible. Figure 7 shows the phase-to-phase voltage Uab in such a fault scenario (Xu, Wang, & Wang, 2019). When a fault occurs, phase A is set to its 0-voltage output; nevertheless, the phase-to-phase voltage is still non-zero thanks to the other two healthy phases. In this case, the inverter degrades to a two-level operation with limited power.

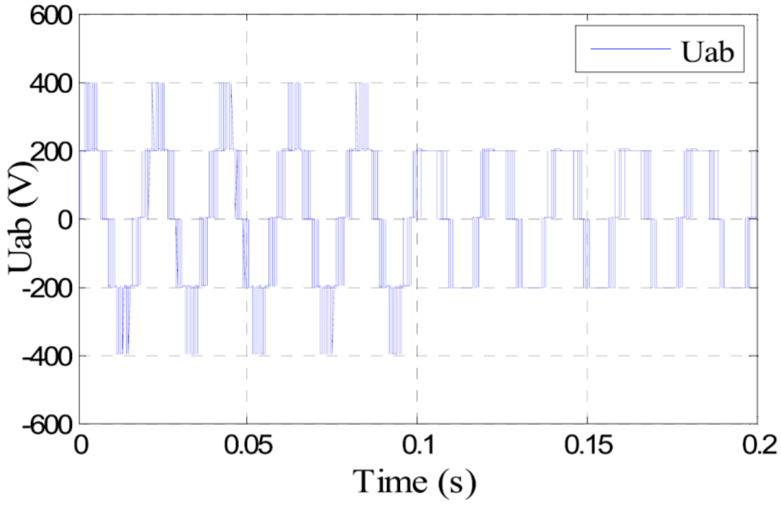


FIGURE 7 - PHASE-TO-PHASE VOLTAGE WITH FAULT INJECTION AT T=0.1S (FROM (XU, WANG, & WANG, 2019))

4.1.1.3 Switching states

One of the 3L-ANPC phases is shown in Figure 8.

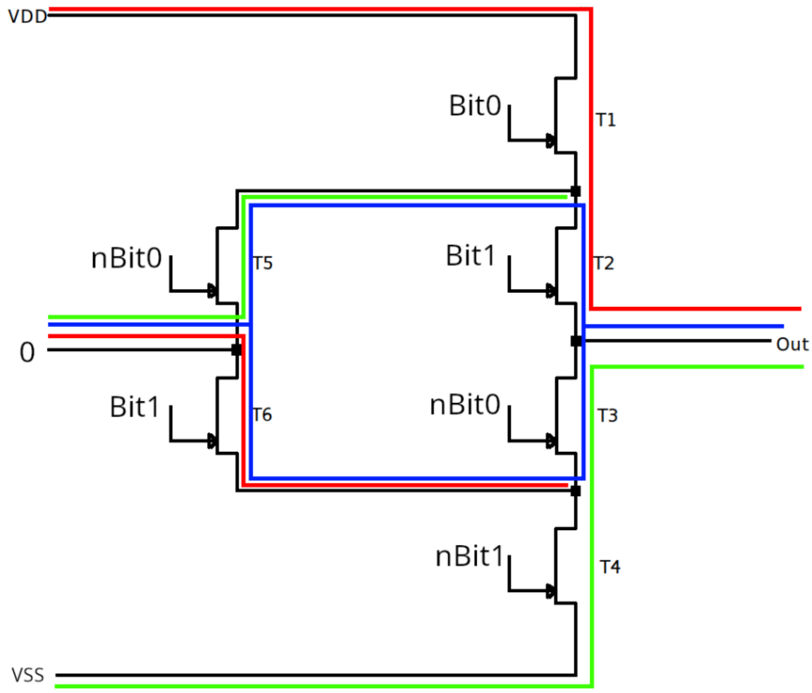


FIGURE 8 - ONE PHASE OF THE 3L-ANPC-TOPOLOGY. HV OUTPUT (RED), 0-OUTPUT(BLUE), AND LV OUTPUT (GREEN)

It should be able to output the high voltage level (HV), a neutral level (0) and a low voltage level (LV). For a HV output (red line), T1 and T2 are turned on, as also T6 to clamp the zero voltage between T3 and T4. For the LV output (green line), T3 and T4 are turned on, as also T5 to clamp the zero voltage between T1 and T2. Now in addition, for the zero voltage output, all of the four middle transistors T2, T3, T5 and T6 should be turned on to reach maximum efficiency by means of to parallel conducting paths. These three conditions can be encoded by a two bit signal as shown in Figure 9 to reduce the complexity of the communication data lanes from microcontroller to gate driver.

MIKROCONTROLLER PATTERN		
	Bit1 (SLOW)	Bit0 (FAST)
HH	1	1
H0 = L0	1	0
LL	0	0

FIGURE 9 - SWITCHING PATTERN FROM THE MICROCONTROLLER

4.1.1.4 *Fail safe modes*

If a transistor fails, both cases of an open-, or short circuit are possible. On GaN-HEMTs, the open failure most likely tends to appear as a shift in its threshold voltage due to electron trapping effects, which mainly appears as a result of high temperature and therefore appearing gate currents (gate stress) (Alamo, 2009). In this case, the HEMT is not directly defective, but it will not longer be turned on by the applied gate voltage. As also known from silicon MOSFETs, a high drain current combined with a high temperature can lead to a drain-source breakdown, resulting in a permanently conducting device (short circuit) (Meneghesso, 2014). Actually, experiences in using GaN-HEMTs for inverters are missing, so values from SiC-MOSFETs are used, which in case of a failure lead to 15% chance of an open failure and 85% chance of a short circuit. To reach the maximum flowing current into the motor, four GaN-HEMTs are paralleled in the inverter. Therefore as shown in Figure 10 the chance of a completely open-failed path is estimated as 0,0008%.

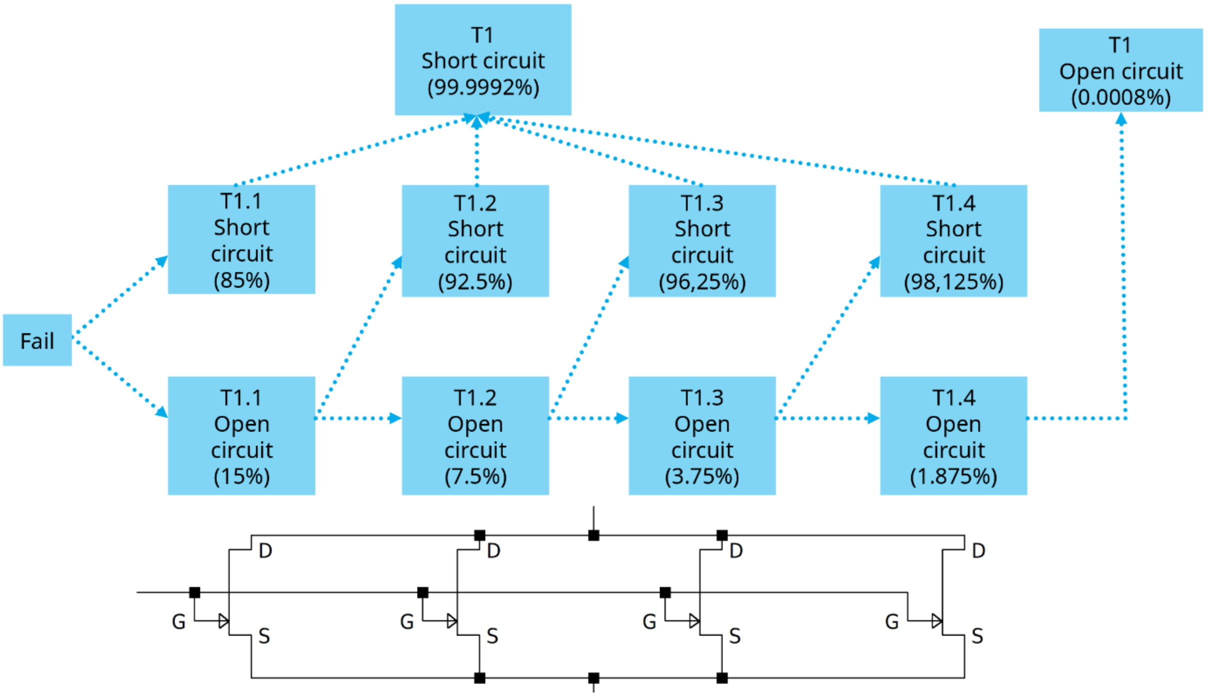


FIGURE 10 - STATISTICAL FAILURE ANALYSIS OF 4 PARALLELED GAN-HEMTS

Note, that for every open failed transistor, the remaining transistors have an advanced chance of a short circuit, as overcurrents will be the result. As it can be seen, the short circuit failure is significantly higher and therefore will only be considered in the failure safety feature. A shorting transistor in the inverter will result in a measurable drain-source voltage above at least another transistor while it is turned on. The failure-detection mechanism reports a failure, if a significant voltage VDS is applied, while also the gate is turned on (Figure 11).

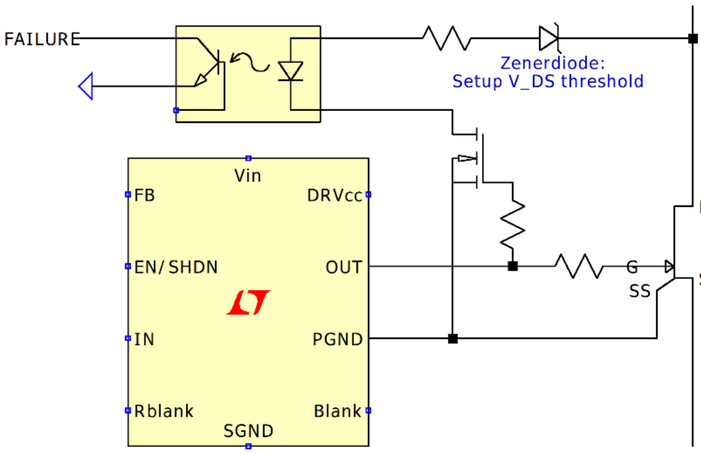


FIGURE 11 - FAILURE DETECTION CIRCUIT

For all possible short-circuit failures, the table in Figure 12 shows, which failure can be detected by which detection circuit on a contrary transistor.

State	HH	0	LL
T1 Short		Detection through V_DS (T5)	Detection through V_DS (T5) (T2 overvoltage)
T2 Short			Detection through V_DS (T5,T3,T4)
T5 Short	Detection through V_DS (T1)		
T4 Short	Detection through V_DS (T6) (T3 overvoltage)	Detection through V_DS (T6)	
T3 Short	Detection through V_DS (T6,T1,T2)		
T6 Short			Detection through V_DS (T4)

FIGURE 12 - DETECTION TABLE OF SHORT CIRCUIT FAILED TRANSISTORS

Every failure case will be reported to the microcontroller, which as a result will report the failure and its related phase to the motor management. As a result, the microcontroller will permanently switch to the zero-voltage output on that phase. Additionally, if T1 or T4 fail, the gate drivers for T2&T5 or respectively T3&T6 need to be powered off, because otherwise a short circuit between 0 and VDD/VSS will occur. Therefore, the T1, T2 & T5 gate drivers are fed by a flip-flop switched by the T5-detection-circuit and the T3, T4 & T6 gate drivers are fed by a flip-flop switched by the T6-detection-circuit. The marked cells in orange mean, that an overvoltage might occur by means of a negatively influenced zero voltage clamping. These cells do not likely happen, because their affected transistors are not active in that moment (for example T4 is turned off while the inverter switches between HV and 0). These transistors will be detected earlier while their path is active.

4.1.1.5 Control algorithm

The considered power inverter used in the project is conceived as a three-level inverter for a dual three-phase motor. Six three-level legs in the power inverter are needed for this reason. Each transistor is created as several GaN transistors connected in parallel to reduce the current flowing through it. Fail-operational features are achieved not only by using a redundant dual three-phase motor structure but also thanks to the three-level structure of the power inverter. This combination significantly increases the complexity of the control algorithm and fault detection mechanisms. The system should be able to provide complete functionality and power or partially reduced power even if the fault is presented in the system.

Two control methods will be developed for this motor. The first control strategy is based on Finite-Control-Set Model Predictive Control (FCM MPC) algorithms. The second control strategy will use enhanced Field-Oriented Control (FOC) algorithms. Both control algorithms need to reflect the dual three-phase structure of the motor and a multi-level power inverter. The possibility to operate under various fault conditions shall also be integrated.

FCS MPC uses a fixed sampling period. The GaN power inverter can use 50 µs or even a shorter sampling period. The algorithm calculates a new optimal combination of output states to follow the setpoint. Output signals change only in specified time intervals.

Finite-control-set used in model predictive control can reduce the effective switching frequency while keeping low current ripples. Fail-operational will be achieved by reducing the control set of the MPC algorithm. Harmful states are excluded based on detected faults of the power inverter. Fault detection will take place with the help of prepared hardware. The healthy monitoring part of the algorithm will modify the available MPC control set according to the severity of the detected inverter fault. MPC algorithm uses the available control set to achieve the required operational point. Thanks to the non-linear motor model and structure of the algorithm, the algorithm can automatically adapt to the impact of the reduced control set. Some less severe faults, such as a disconnected transistor, do not need immediate intervention because the inverter contains several transistors in parallel. Advanced derating algorithms need to be considered and prepared for these faults. The proposed system should be robust enough that one open transistor even leads to only a slight loss of efficiency, and no power limitation is required.

Model predictive control algorithm requires high computing power. Individual AURIX cores will probably not provide sufficient computing power. The parallel processing unit (PPU) of the new AURIX generation will be effectively used for the implementation of MPC algorithms.

Field-oriented control algorithm requires a different approach to achieve fail-operational behaviour. In this case, the algorithm calculates specific duty cycles, and the switching frequency is fixed. Duty cycles are calculated from required phase voltages. Space vector modulation (SVM) allows efficiently use DC-link voltage's full potential. A transistor short-circuit fault typically does not cause a malfunction of the whole inverter leg. Thanks to the three-level structure, the middle voltage can be used in the case of any short-circuited transistor. This state still allows the generation of a rotating voltage vector. However maximal amplitude of the output vector is reduced to one-half. Dummy DC-link voltage reduction is required during the transistor short-circuit fault. This reduction of DC-link voltage leads to reaching the field-weakening region at a lower speed. Above this speed, the power provided by the damaged three-phase sub-system is limited to one-half of the maximum power. Another essential modification required by active fault is the change of switching strategies for PWM signal generation. SVM modulation cannot be used during the fault, and the PWM signal for the damaged leg must be set to zero voltage (middle potential of the power inverter). Open transistor fault can be solved using a derating algorithm. The derating algorithm can be the same as for MPC algorithm.

FOC algorithm can be calculated individually for each sub-system. Separation can also be implemented on the microcontroller level. The control algorithm will use two separate microcontroller cores to calculate two PWM sets for each sub-system.

4.1.1.6 Cognitive Diagnostic System

Fault detection and health monitoring algorithms for the dual three-phase machine and multi-level inverter are much more complicated than commonly used algorithms for three-phase systems. Faults of the system can be divided into two categories. The first category represents severe faults requiring an immediate system response. The category of severe faults can be represented by motor interturn short-circuit, phase to phase short-circuit, or power inverter transistor short-circuit. Especially transistor short-circuit must be detected extremely fast—ideally within the ongoing PWM period. Transistor faults can be detected using the desaturation fault flag from the gate drivers. Better detection can be achieved using specially designed HW. Motor short-circuit faults should be detected in less than 30 ms to prevent additional thermal damage. A damaged motor sub-system can be field weakened by the control algorithm or switched into active short circuit mode to reduce fault currents amplitudes.

For this reason, a cognitive diagnostic system based on an artificial neural network (ANN) will be prepared to detect these types of faults. The fault affects motor currents which can be used as input for the ANN. Motor currents are closely related to voltages because current controllers use voltage to eliminate current disturbances. ANN can use a comparison of current and voltage waveforms of both sub-systems. Actual motor position and required currents can also be used to increase the fault detection reliability of ANN during transients. Analyses also suggest that one-dimensional convolutional layers can extract important features from input waveforms successfully. ANN consisting of several layers with hundreds of neurons will be sufficient for the purpose of fault detection.

However, inference time should be as short as possible. The neural network can be implemented in a dedicated microcontroller core, or the parallel processing unit can be used to reduce inference time. Expected implementation of control algorithm and diagnostic system into AURIX microcontroller can be seen in Figure 13.

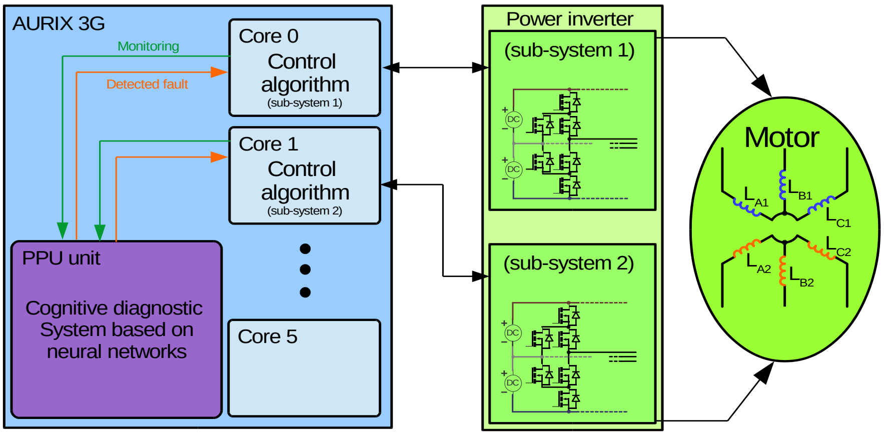


FIGURE 13 - EXPECTED COGNITIVE DIAGNOSTIC SYSTEM AND FOC CONTROL ALGORITHM IMPLEMENTATION INTO AURIX 3G MICROCONTROLLER

The second category of faults is less severe. Detection of these faults can be slower; however, in the long run, their detection is also necessary. This type of faults is represented by an open transistor fault. One open transistor increases current flow through other parallel transistors. The power inverter is constructed for high power efficiency, so one open transistor only partially reduces efficiency. In this case, modification of the control strategy is not needed. However, if multiple transistors are damaged, the maximum current should be reduced. The open transistor can be detected by the higher drain-source voltage on the healthy transistors or by increased temperature on these transistors. Power inverter temperatures should also be measured. The measured data will be used to derate maximum motor power if needed.

Description of all above mentioned faults in both severity categories and definition of suitable methods for their detection are based on their typical manifestations in measured electrical signals available in the system, and whose carry relevant symptoms linked to these faults. However, diagnostics purely based on the utilization of electrical signals can be extended by additional sensing of manifestations of those faults in other domains. Such prospective sensing domains, where faults of electrical components can also be potentially identified, are mechanical and acoustical domains, where measurement of related quantities can be performed, e.g., vibrations, sound, or ultrasound. These measurements can be an additional source of data that are rich in features that can be linked to the faults in the electrical components and can improve the performance and reliability of their detection. Typical components, where their faults could be possibly identified also in these domains, are specifically windings issues (short circuit, loose wires), magnets performance, or potentially a degradation of power electronic components in the inverter. Diagnostics utilizing sensing of mechanical manifestations can support decisions (their confirmation) resulting from diagnostics based only on sensing of the electrical signals and can also increase the detectability of electrical faults, where these faults could be identified earlier or more reliably. Nowadays, a typical propulsion system doesn't contain a device enabling sensing of mechanical or acoustical quantities, but previous research indicated that deployment of such a sensor in the system could be beneficial for diagnostic purposes.

Moreover, the presence of a sensor for mechanical or acoustical quantities measurement in the propulsion system can also allow to monitor the condition and diagnose faults of specific mechanical components (e.g., bearings, the rotor of the e-machine) whose health is also important for full operation of the system. Therefore, the cognitive diagnostic system can easily perform also mechanical components diagnostics to increase the overall reliability of the propulsion system. Continuous condition monitoring of these critical mechanical components can allow early detection of significant faults, e.g., unbalance or bearing faults, and potentially predict the remaining lifetime before the critical component failure.

Unfortunately, an additional sensor for the measurement of mechanical or acoustical quantities brings another component to the propulsion system that may fail or provide unreliable output information. Especially in the case of measurement of dynamic motion or acoustic pressure using modern MEMS-based sensors, these devices incorporate principles utilizing delicate sensing elements like miniature moving masses or tiny membranes which can be affected or even damaged during long-term operation in a harsh environment. Therefore, it is necessary that these components will perform internal auto diagnostics of their internal sensing elements to provide reliable output data incorporated with information about the credibility of these data. In other words, the sensor should inform the diagnostic system about the trustworthiness of such sensory data and consequently, these data will not reduce the reliability and safety level of the overall system. The success rate of detecting critical internal sensing components faults in the sensors must be better than 90 %.

4.1.2 Validation concept

As is typical with such complex systems, the testing and validation phase is divided first into component/subsystem test before integration, and afterwards a complete system validation on a testbench is to be performed.

4.1.2.1 Component tests

The design and functionality of the gate-drivers should be tested at first with a low-power inverter arrangement, as well as with emulation/injection of faults to be detected. Once the gate-drivers have been validated, they can be connected to the full-power inverter for common function test. This is achieved via a double-pulse experiment, which is a typical measurement to evaluate the switching performance of power semiconductors with a defined gate-driver stage under different voltage and temperature conditions. Such as experiment delivers first estimations about the inverter losses.

In parallel, the control board can be tested. Minimal tests are possible using only the control board hardware; for a full test it is necessary to have a (preliminary) version of the microcontroller software to be used. With dedicated testing functions, the functionality of the periphery/ports can be verified, and emulated gate-driver signals can be used to evaluate diagnostic functions. In addition, a complete control system can be simulated on the microcontroller to validate the correct functionality of the algorithm and ports before integration into the inverter.

After mounting of the inverter, tests can be performed in the HV laboratory with a static load, in which the correct functionality of the control board, software, gate drivers, and power state are evaluated together before the final integration together with the electric motor.

4.1.2.2 Testbench demonstration

The assembled powertrain demonstrator, consisting of e-machine and inverter will be tested on a testbench at Mercedes-Benz. The available testbenches are suited to directly evaluate electric machines and provide peak powers of up to 500kW. The setup consists of the dynamometer as the direct counterpart of the machine under test as well as a high-voltage DC-power supply as battery simulator. Both systems can be controlled automatically to simulate realistic vehicle operation in standardized driving cycles.

FIGURE 14 - E-MACHINE TESTBENCH

The testbench is able to provide a torque of up to 680Nm (positive and negative) as well as a speed of up to 20.000/min. The battery simulator is rated for voltages of up to 1000V. The setup is completed by thermal conditioning devices for both water-based coolant and oil, as well as state-of-the art measuring equipment for torque, DC-voltage and current as well as phase currents. The testbench also provides interfaces to include CAN-communication descriptions, allowing the use of vehicle-ready software.

4.1.3 Subdemonstrator: High-speed sensor interface

4.1.3.1 General description

The General-Purpose High-Speed Sensor Interface (GPHSSI) is a high-speed digital sensor interface for high performance automotive sensor applications. The interface data link layer is based on standard Universal Asynchronous Receiver Transmitter (UART) bit stream. The protocol is designed to support direct sensor-to-microcontroller connections as well as a broad range of standard automotive line drivers such as, classical CAN, CAN FD and FlexRay transceivers to implement a robust sensor connection scheme for remote sensor applications. Due to the lean protocol implementation, high sensor update rates can be achieved despite limited bandwidth especially with remote sensor interfaces. The GPHSSI is a low-cost sensor interface for high performance automotive applications. GPHSSI can be used as highly flexible interface for transferring sensor data or to control decentralized automotive applications. Main features are single master, multiple sensor concept, four wire interface, bidirectional communication and deterministic signal transmission with signal propagation time computable in advance. Additional to that data the transmission security according to ISO26262 standard achieves ASIL-D compliance. Also, synchronization mechanism of a single or multiple sensor for up to 8 sensors are specified.

4.1.3.2 System Setup

Communication concept

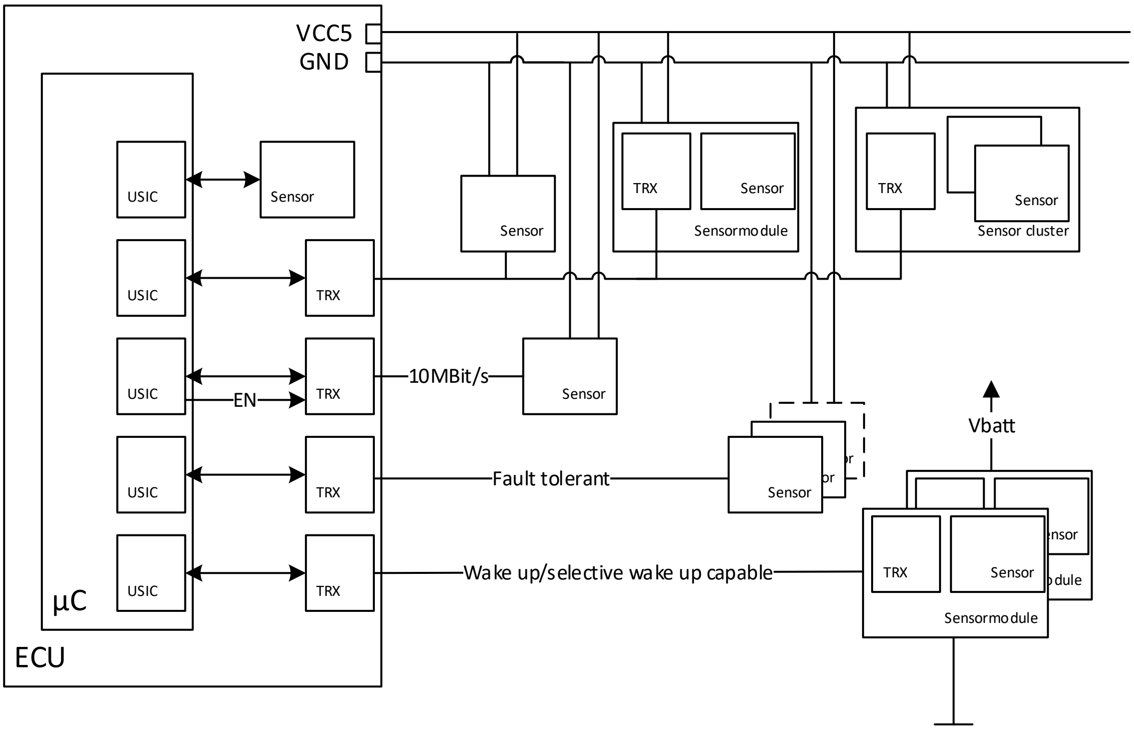


Figure 15 pictures several potential system setups for internal and external sensor modules. They are connected to an electronic control unit (ECU) through a dedicated high-speed sensor interface (GP-HSSI) with different physical layer (FlexRay, CAN ISO 11898-2, -3, -5). It provides addressing, synchronization and data transfer features via a serial communication protocol layer. The interface enables:

- Synchronization of one or multiple sensors to an external clock domain
- Connection of one up to eight sensors to a sensor bus
- High speed readout of multiple sensor registers

The sensor can be directly connected to microcontroller peripherals; however, depending on the application requirements a differential line driver/receiver (e.g. CAN-FD transceiver) can be inserted to improve the physical robustness of the interface.

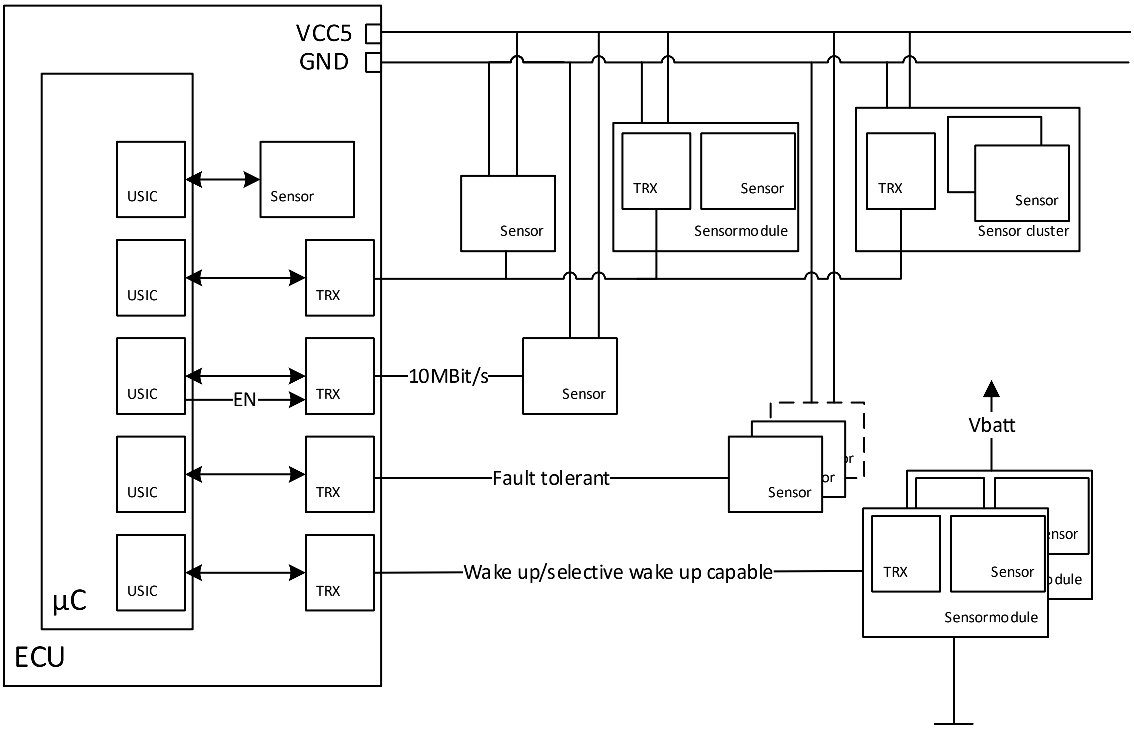


FIGURE 15 - CONNECTION FOR INTERNAL AND EXTERNAL SENSORS (EXAMPLE)

Sensor Application Circuits

The interface protocol is designed to support both local and remote sensor applications. The sensor can be either connected to the UART interface of a microcontroller directly (local application) or through a physical bus driver interface (remote applications) respectively. The usage a of a bus driver interface enables superior robustness against external disturbances while minimizing EME and EMI. The GP-HSSI protocol is designed to support a broad range of automotive grade bus transceivers; the usage of CAN-HS or CAN-FD transceivers provides an optimum cost over performance ratio for most high-performance applications.

Remote Application

For remote sensor applications (the sensor is located off-board), a line driver can be inserted between the sensor and the ECU to improve the robustness and susceptibility of the interface. For high-speed applications the use of standard CAN-FD transceivers (e.g. TLE9250) is recommended. The sensor provides and receives data on its RxD and TxD pins. Similar to the local applications, both, a single sensor as well as a sensor cluster configuration are supported.

Due to the nature of the CAN transceiver implementation, the information sent by a sensor's TxD on the CAN is read back on the sensor's RxD input. Therefore, the sensors receive their own transmitted information. To avoid that data information is interpreted as address or synchronization data, the sensors should feature an internal logic to distinguish between address and data information. Additionally, the sensor should check the data consistency between the transmitted and the received sensor data and if a deviation is detected the sensor should interrupt the communication and will wait for a new master request frame.

Similar to the local network configurations, it is required that all sensors connected to the sensor network are assigned a unique sensor address to prevent from bus conflicts caused by multiple sensors transmitting their sensor information at the same time.

Protected Remote Sensor Module

Depending on the individual specifications, remote sensor applications may require an overvoltage and/or a reverse polarity protection. While standard CAN transceivers support high overvoltage capability on the communication pins, the supply input of both the sensor as well as the CAN transceivers are rated for a 5V nominal voltage. Therefore, it is required to provide an additional protection scheme to achieve typical supply ratings for remote components (-18V … +24V) as e.g. stated in LV124. An example of a protected remotes sensor module circuit implementation is shown in Figure 16.

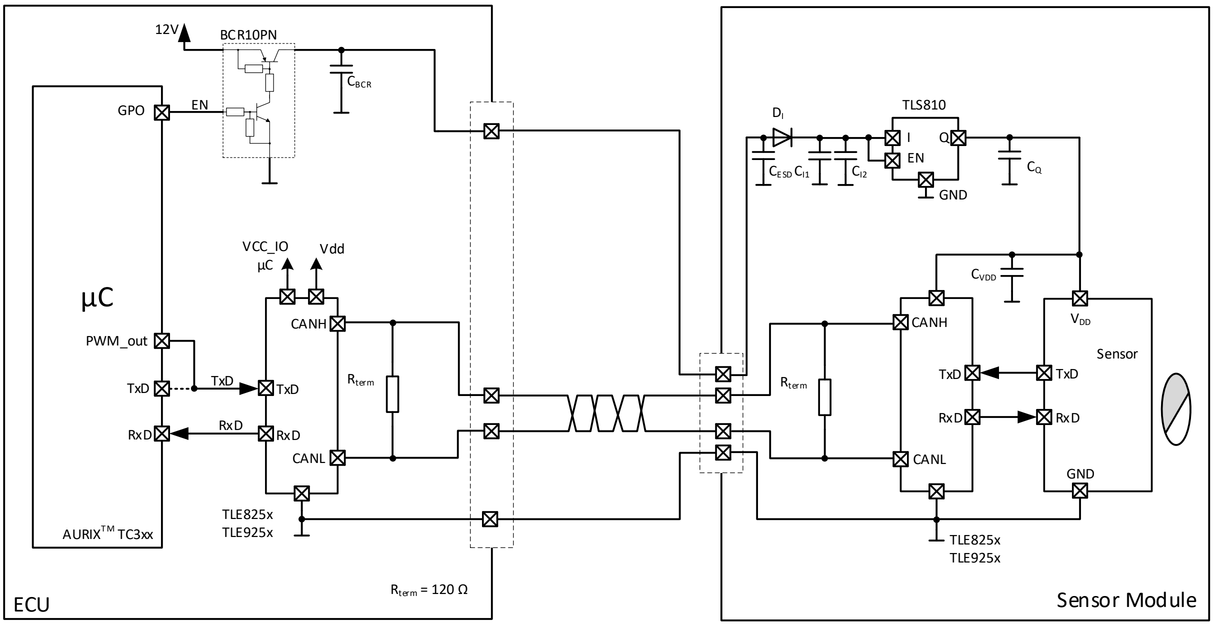


FIGURE 16 - PROTECTED SENSOR MODULE

4.1.4 List of requirements

ID: AI4CSM_WP1_SCD4.1_1

Name: Output power and torque

Description: The powertrain at the electric motor rotor must provide a maximum power of 200 kW, maximum torque of 512 Nm at 3740 rpm for 30 seconds. Continuous power is defined as 78 kW, with a torque of 248 Nm at 3000 rpm without time limitaton

Rationale: Powertrain design should be able to propel an electric vehicle with the desired acceleration and speed

Metrics: Speed, torque and power measurements on testbench

Owner: ZF

ID: AI4CSM_WP1_SCD4.1_2

Name: HV-safety

Description: The powertrain shall fulfill the HV-safety requirements as described in UN R 100 / MBN20123

Rationale: Safe operation at high voltages requires components that fulfil state-of-the-art electrical safety requirements to avoid hazards for users and operators

Metrics: Validation of insulation resistance, discharging duration, withstand voltage, ground resistance, active safety measures (discharge, open connector detection)

Owner: MBAG

ID: AI4CSM_WP1_SCD4.1_3

Name: Fail operational behaviour

Description: The powertrain must be able to remain in operation after a single fault in the inverter or electric motor, with a maximum loss of 50% of the total power at low speeds

Rationale: Automated vehicles do not have driver as a fallback state for emergency operation. Vehicle should be able to drive itself to workshop even after a fault

Metrics: Power measurements after injection/emulation of a fault

Owner: MBAG

ID: AI4CSM_WP1_SCD4.1_4

Name: Power transistors and gate drivers

Description: 650V, ~60A GaN eMode transistor from GaN Systems. Specific device subject to availability. Transistors will be driven by a dedicated gate driver stage in order to satisfy the switching requirements

Rationale: GaN has similar low losses to SiC, while having a lower cost. GaN requires a specially designed gate-driver to ensure safe and efficient switching

Metrics: Dynamic analysis (double pulse test) with designed gate-drivers and selected GaN transistors

Owner: ZF

ID: AI4CSM_WP1_SCD4.1_5

Name: Rotor position sensor and its communication.

Description: The position of the electric motor rotor must be measured using an external rotor position sensor located at the motor shaft. The communication between rotor position sensor and microcontroller shall be achieved using a digital communication interface

Rationale: The position of the rotor is necessary to realize the control of a PMSM. Digital communication is reliable and reduces the number of communication lines. In addition, some sensor evaluation functions can be moved from the microcontroller to the sensor itself

Metrics: Rotor position sensor functional test

Owner: IFAT

ID: AI4CSM_WP1_SCD4.1_6

Name: Microcontroller

Description: Main processing unit is an Infineon AURIX 3G TC49x

Rationale: AURIX 4G generation contains a Parallel Processing Unit well suited for efficient implementation of AI algorithms and linear operations

Metrics: Non-functional, must be considered in design

Owner: ZF

ID: AI4CSM_WP1_SCD4.1_7

Name: Software functions

Description: • Multiphase motor control algorithm for healthy powertrain

• Routines for diagnostics based on redundant measurements

• Algorithms for model based diagnostics

• Decision making algorithms changing the way of operation in case of faults

• Control algorithms for identified faults

• Safe disconnection of faulty subsystem

• Decoupling algorithms for elimination of influence of faulty parts on healthy ones

• Algorithm for speed and torque estimation

• Algorithms for signal processing of sensing and perception subsystems

• Emulation of faults on a software level to be able to test fault detection algorithms

Rationale: Software is responsible for fulfilling the main powertrain function of controlling/providing a desired torque at a desired motor speed. In addition, the fail-operational behaviour depends and influences the control strategy realized in software. For the realization of these functions, sensor information is needed, as well as information regarding any faults. The controller provides PWM signals to the gate-drivers, which in turn interact with the power transistors

Metrics: Microcontroller/software function test in laboratory conditions

Owner: ZF

ID: AI4CSM_WP1_SCD4.1_8

Name: Real-time inverter diagnostics

Description: The three-level Active Neutral-Point-Clamped (ANPC) inverter faults should be analysed and methods for their detection must be proposed both in hardware and in software.

Rationale: The fault detection leads to control strategy mitigation which must be realized as soon as possible.

Metrics: Execution time below 100 us or 50 us depending on selected PWM sampling period.

Owner: BUT

ID: AI4CSM_WP1_SCD4.1_9

Name: Real-time motor diagnostics

Description: Common stator faults should be detected before they lead to further motor damage.

Rationale: To keep the motor in operational mode.

Metrics: Detection time below 30 ms from fault occurrence.

Owner: BUT

ID: AI4CSM_WP1_SCD4.1_10

Name: Model-based diagnostics of motor faults

Description: Provide the models of motor faults ideally as a combination of healthy and faulty part to simplify diagnostic algorithms.

Rationale: Suppresses complex signal pre-processing for successful fault detection.

Metrics: Comparison with other existing methods.

Owner: BUT

ID: AI4CSM_WP1_SCD4.1_11

Name: Diagnostics based on multiple sensing domains (electrical, mechanical) including autodiagnostics of sensing components

Description: Extension of pure electrical based diagnostics with additional sensing of mechanical/acoustical quantities (vibration, acoustic, ultrasonic) to improve performance and reliability of faults detection (e.g. in windings, magnets, power electrical components) manifesting typically in electrical domain and to additionally diagnose mechnical components (bearings, rotor) including information about thrustworthiness of provided diagnostic data.

Rationale: Diagnostics based on sensing of the mechanical manifestations can support diagnostics based only on sensing of the electrical signals to increase its reliability and credibility.

Metrics: Increase the detectability of electrical faults and detectability of critical mechanical faults. Confirmation of diagnostic results provided by diagnostics based only on electrical quantities measurement.

Owner: BUT

ID: AI4CSM_WP1_SCD4.1_12

Name: Utilization of Finite-Control-Set Model Predictive Control

Description: FCS MPC algorithm shell be used for the control of two times three phase motor.

Rationale: FCS MPC algorithm minimizes defined criteria function. The stress on energy efficient control algorithm can be defined easily.

Metrics: Algorithm power efficiency will be compared to classical FOC control algorithm.

Owner: BUT

4.2 SCD4.2 – AI accelerated powertrain control

4.2.1 Introduction

With the development of the Aurix TC4x microcontrollers (MCUs) Infineon targets the next generation eMobility, ADAS, automotive E/E architectures and artificial intelligence (AI) applications. The MCU will include a parallel processing unit (PPU), a SIMD vector digital signal processor (DSP), which addresses the demands of various AI topologies. This may include use cases as diverse as powertrain engine and transmission control, powertrain for electric vehicles (xEV), chassis and safety applications for braking, steering, suspension, airbags, advanced driver assistance systems (ADAS) like sensor data fusion, or radar sensors and connectivity gateways for telematics host control, or gateway and domain control.

Targeting a wide range of automotive applications including the strong demand for functional integration in domain and zone-based E/E architectures, the MCU will support both eMobility and automated driving through safety systems. The microcontroller will offer enhanced connectivity including advanced safety and cybersecurity functionality supported by cybersecurity modules meeting the ISO 21434 standard. Software Over the Air (SOTA) features will cover demands for fast and secure car-to-cloud connection, enabling updates in the field, plus diagnosis and analysis during vehicle usage.

The planned MCU will support high-speed communication interfaces like 5 Gbit Ethernet and PCI Express (PCIe) along with interfaces such as CAN-XL and 10BASE T1S Ethernet. This increased network throughput and connectivity will provide performance and flexibility needed to implement new E/E architectures and will ensure safe and secure processing. The MCU architecture is based on smart accelerators that allow real-time performance and fast networking throughput. Given the growing vehicle complexity and the enablement of AI implementations, significant focus has been placed on the MCU ecosystem to ensure fast time-to-market and ease-of-use. Compilers, debuggers and libraries as well as a simulator to develop software for the PPU accelerate the development cycles.

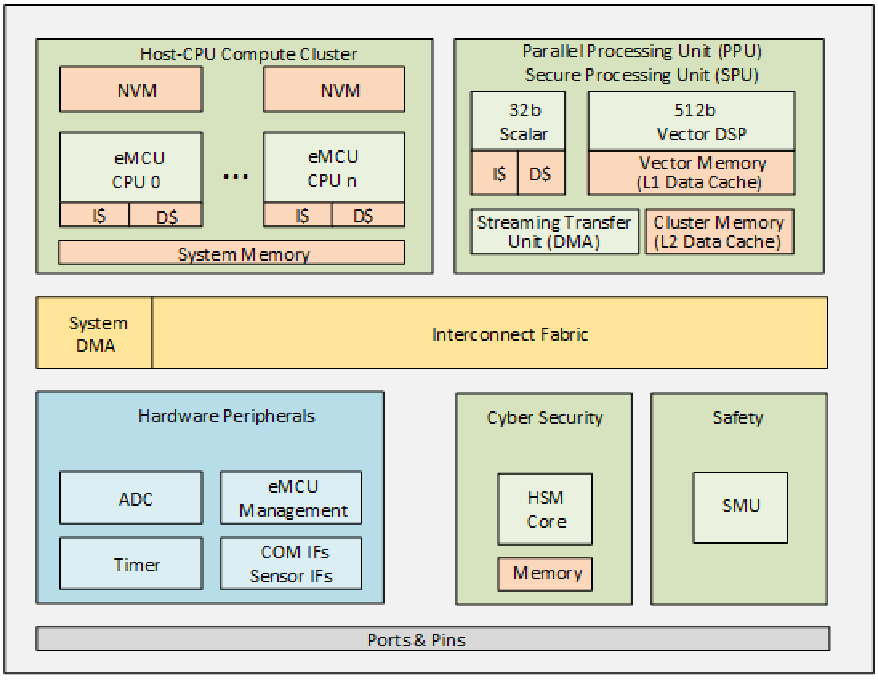


FIGURE 17 - POWERTRAIN EMCU ARCHITECTURE (SOURCE: IFAG)

The central task in this work package (WP) of the AI4CSM project was to evaluate the use of AI methods for optimized control of electric traction drives. The IFAG project team focused on requirements identification during this reporting period.

Identification of Requirements

Potential improvements in the areas of efficiency, torque accuracy, control, implementability, and user-friendliness of the current traction control system were evaluated. The state of the art to address these issues were explored. Applicability and gain of using AI with respect to these problems were researched. Furthermore, hardware (accelerator) requirements for AI were determined.

Results in the Reporting Period

According to the specifications, the project team defined use cases and areas of use for AI approaches. Other tasks included preliminary research on AI methods, followed by the definition of evaluation matrices. The WP description was default to consider criteria such as complexity, real-time capability, and accuracy. It also identified solutions to evaluate control methods that lead to improvements and cost reductions.

The IFAG research focus in the project is the use of AI-based methods for the optimal operation of electric powertrains in vehicles. AI-based modeling approaches to describe the physical domains of the e-drive will be explored in the project in combination with classical and AI-based control methods. The staff of the IFAG AI lab expects that the results achieved will contribute to increased efficiency and torque accuracy of the e-drive.

Efficiency improvements are highly relevant in terms of energy requirements and environmental footprint. The target is a loss saving of 10 percent in the e-drive. Another guideline was the reduction of cooling requirements. Precise knowledge of the thermal behavior of electric drivetrains allows the cooling to be optimally designed and the drive to be optimally utilized. Dynamic thermal modeling is aimed at increasing the short-term overload capacity of electric machines by 20 percent.

For automated driving, precise control of the electric traction machines is essential. This is important in multi-motor concepts, where it is used for torque vectoring. As soon as parameters deviate due to inaccuracies or parameter drift, the error of the controlled torque can exceed five percent. The IFAG project team has set itself the goal of achieving an error value in torque control of less than two percent over the relevant temperature range with the aid of newly developed control processes.

IFAG is addressing various points in the vehicle and in development to simplify the precise, efficient and intelligent control of electric drives. Time-intensive test bench investigations are to be reduced by AI-supported selection of operating points as well as automated measurement of the electric drive train. The newly developed AI methods help to optimize classic simulation models and reduce computing times. By optimally setting the controller gain for different operating ranges in terms of dynamics and efficiency, the vehicle's operating behavior can be optimized offline.

Another component of the investigation was the extent to which AI-based control can be used to dynamically optimize the operating behavior of a vehicle in terms of efficiency and precision. The tests showed that, for example, pulse patterns of the drive inverter can be optimally adjusted in terms of energy in real time to increase the range of the vehicle. Another result of the preliminary tests proved that AI-based models of nonlinear effects in the e-machine and inverter can be used to precisely determine e.g. dead times, sensor inaccuracies, useful effects and saturations in the drive control. Temperature and aging-related parameter variations can be tracked, increasing torque accuracy and helping to improve efficiency. Initial results have also shown that sensor data from the vehicle and route information can be used to adapt and optimally set the control system. The holistic approach to design and the modeling and control of the drive system offer high potential based on initial IFAG studies. Synergy effects can be expected in terms of efficiency, driving functionality and ride comfort.

The selection of suitable methods for the use of embedded systems is challenging due to the limited resources in microcontrollers, which only allows the use of Tensorflow models for offline calculations to a limited extent. In embedded systems, real-time control requirements are also necessary and the available cycle times are limited. The IFAG strategy is therefore to define improvement potentials within the motor control and to identify and evaluate problematic solution approaches. This is done with regard to the required memory and computing power, drive efficiency and user-friendliness. Examples include the adaptive parameterization of PI controllers or the efficient storage of large conversion tables. These could be optimized in initial trials in offline operation using AI methods.

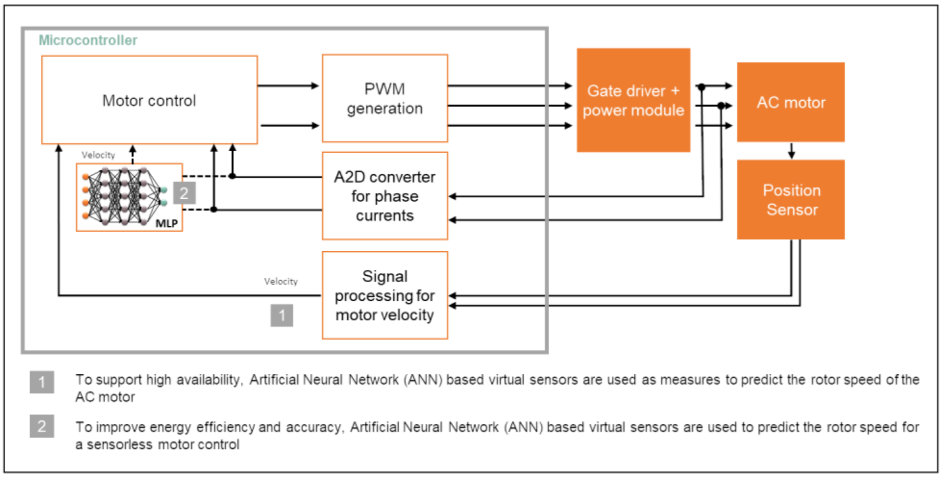


FIGURE 18 - AI METHODS FOR INCREASING SYSTEM AVAILABILITY AND ENERGY EFFICIENCY (SOURCE: IFAG)

Another project goal for the first reporting period was the use of AI methods for control. Neural networks, support vector machines or Gaussian processes offer good approaches for this. According to initial results, simulative validation of improved motor control with AI methods creates a good basis for further trials and analyses. For traction drives based on embedded systems, real-time capability is of key importance. The future generation of IFAG's microcontroller series AURIX creates the prerequisites for this with integrated function blocks and high-performance processing features (hardware accelerators).

In summary, the transformation of simulatively validated AI methods to real-time capable microcontrollers enables and optimizes applications in AI-based control of electric motor drives. In this context, hardware accelerators support cost- and time-efficient implementations. Software implementation of the optimized algorithms is currently not possible for embedded systems. The goal is to adapt the algorithms to the optimized hardware taking into account the results of the simulation validation. Here, the IFAG team will place special emphasis on ease of use and limited resources such as memory and computing time.

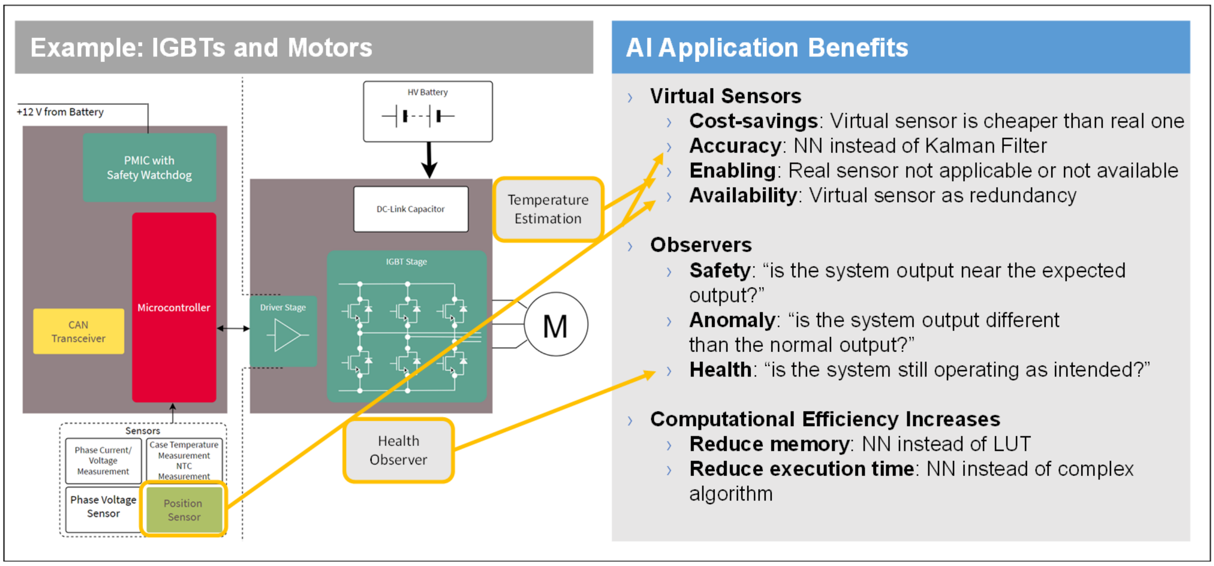


FIGURE 19 - ADDITIONAL COLLABORATION OPPORTUNITIES (SOURCE: IFAG)

4.2.2 List of requirements

ID: AI4CSM_WP1_SCD4.2_1

Name: Traction inverter application

Description: The MCU shall be able to support automotive traction inverter applications

Rationale: Needed to support automotive traction inverter applications

Metrics: verfiable support of traction inverter failures via discrete test cases

Owner: IFAG ATV MC

Reference UC: Automotive traction inverter applications

ID: AI4CSM_WP1_SCD4.2_2

Name: Battery management application

Description: The MCU shall be able to support automotive battery management applications

Rationale: Needed to support automotive battery management applications

Metrics: verfiable support of battery management failures via discrete test cases

Owner: IFAG ATV MC

Reference UC: Automotive battery management applications

ID: AI4CSM_WP1_SCD4.2_3

Name: PPU support for AI algorithms

Description: The MCU shall support a parallel processing unit for optimized execution of AI algorithms

Rationale: Needed to support PPU for execution of AI algorithms

Metrics: verifiable PPU support for executing AI algorithms

Owner: IFAG ATV MC

Reference UC: A parallel processing unit for optimized execution of AI algorithms

ID: AI4CSM_WP1_SCD4.2_4

Name: PPU support for NN (MLP, RNN, CNN)

Description: The AI parallel processing unit shall be able to execute neural networks from type MLP, RNN and CNN

Rationale: Needed to support AI PPU to execute NN

Metrics: verifiable support of AI parallel processing unit to execute neural networks from type MLP, RNN and CNN

Owner: IFAG ATV MC

Reference UC: Neural networks from type MLP, RNN and CNN

ID: AI4CSM_WP1_SCD4.2_5

Name: PPU support for ML framework

Description: The AI parallel processing unit shall be supported by a SW eco system which enables the use of machine learning frameworks like TensorFlow

Rationale: SW eco system needs support for ML framework use

Metrics: verfiable PPU support of ML frameworks by example of TensorFlow

Owner: IFAG ATV MC

Reference UC: The use of machine learning frameworks like TensorFlow

ID: AI4CSM_WP1_SCD4.2_6

Name: MATLAB/Simulink support

Description: The MCU shall be supported by a SW eco system which enables the use of MATLAB/Simulink based model-based development

Rationale: Needed to support by SW eco system for use of MATLAB/ Simulink

Metrics: verfiable support of SW eco system to use MATLAB/Simulink for model-based development

Owner: IFAG ATV MC

Reference UC: The use of MATLAB/Simulink based model-based development

4.3 SCD4.3 – Intelligent battery by AI

4.3.1 Demonstrator description

The intelligence in a battery system is provided by the battery management system (BMS), which is responsible for a safe and reliable operation of the battery cells within the manufacturer specification. The BMS monitors the battery cells and to keeps them balanced. The system is commonly monitored by measuring the battery current, the cell voltages, and the temperatures at several positions in the battery system. Based on these parameters the BMS provides e.g., temperature regulation of the system and state estimations, such as state of charge and state of health. Also, safety-relevant decisions e.g., like power derating or even the complete shutdown of the whole system are based on these three system parameters, which underlines the importance of measuring them accurately.

To ensure the reliability of battery system monitoring, the validity of the measured system parameters must be verified, or reliable measurements must be ensured with a suitable technical solution. Commonly, in the BMS the system parameters are only checked for plausibility, i.e., whether they are in a predefined range or not. Hence, there are sensor failures that are undetectable with this kind of check and can therefore lead to inappropriate management of the battery system, resulting in a wrong state estimation, shortened battery lifetime or even an unnecessary shut down of the system. Known problems e.g., of temperature sensors in battery systems include the degradation of the thermal contact or a drift over time due to an adverse operating environment. These effects are hard to detect with commonly used built in self checks. Therefore, the proposed algorithm will focus on detecting anomalies in the temperature sensor signal. The demonstrator algorithm should be able to detect a temperature sensor drift and a temperature sensor interface degradation. The detection should be done only with the measured battery current, cell voltages and temperatures to make the algorithm suitable for a wide range of battery systems.

The algorithm will be demonstrated on a foxBMS 2 BMS Master unit connected to a module from the 1000kmPLUS project. The module consists of the battery cells, the cooling system, the sensors, and the casing. The sensors on the cells and the cooling system are connected via a BMS slave board with the BMS master board. The developed algorithm will be implemented onto the BMS master board, which is the main control unit of the battery system. A prototype of the foxBMS 2 master board is shown in Figure 20.

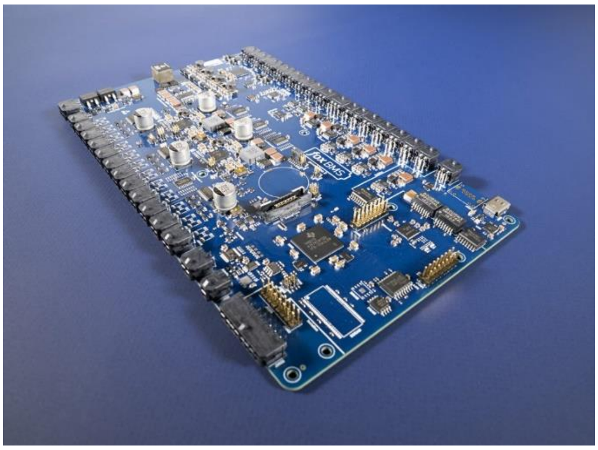


FIGURE 20 - FOXBMS GENERATION 2 MASTER UNIT

The cell arrangement in the module consists of 27 cells connected in parallel as a cell block and 7 cell blocks in series, as shown in Figure 21.

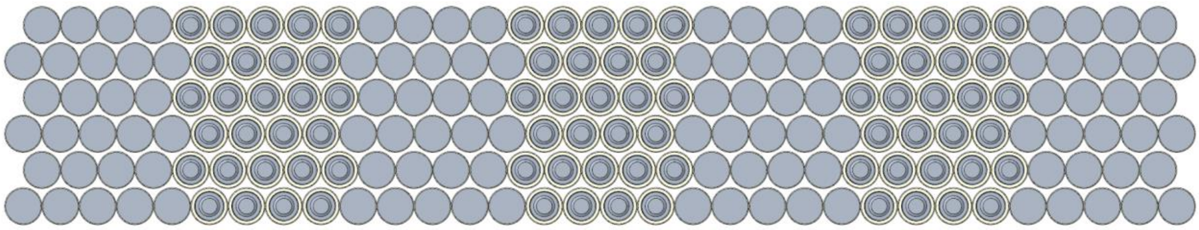


FIGURE 21 - 1000KMPLUS MODULE CELL ARRANGEMENT

For the module, cylindric battery cells (Molicel INR 21700 P42A) are used with a specified voltage range of 2.5-4.2 V. The module has a usable energy content of 79.4 kWh and voltage range of 29.5 - 17.5 V. The cooling system contains wave-shaped tubes with coolant that are in thermal contact with one side of the battery cells to regulate the temperature of the cells. The module provides a negative temperature coefficient thermistor (NTC-Thermistor) for each of the 7 cell blocks as seen in Figure 22.

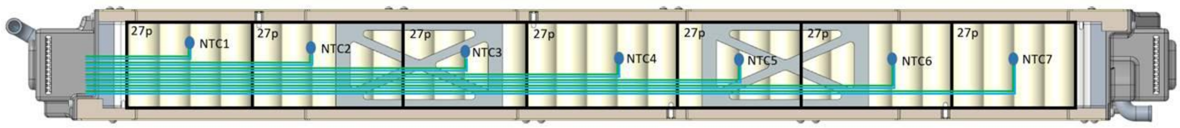


FIGURE 22 - POSITION OF THE TEMPERATURE SENSOR IN THE MODULE

An NTC-Thermistor is a temperature-dependent electrical resistance used by the BMS to determine the temperature at the sensor position. In the module, the temperature sensors are placed in the middle of each cell block using thermal adhesive. To demonstrate the functionality of the algorithm, a temperature sensor in the module is manipulated to create a synthetic anomaly in the measured signal. For the demonstration a temperature sensor on one cell block will be manipulated, causing the thermal contact to the cells to be compromitted and an incorrect temperature to be measured. The demonstration is considered successful if the manipulation is correctly detected by the algorithm.

4.3.2 List of Requirements

ID: AI4CSM_WP1_SCD4.3_1

Name: Temperature sensor anomaly detection with minimal input

Description: An anomaly of the temperature sensors shall be detected by the measured battery current, cell voltages and temperatures.

Rationale: The algorithm is intended to be applicable in a wide range of battery systems and only these three input parameters can be guaranteed in each system.

Metrics: The developed algorithm uses only these three input parameter.

Owner: FHG

ID: AI4CSM_WP1_SCD4.3_2

Name: Temperature sensor interface degradation

Description: A temperature sensor interface degradation shall be detected by the algorithm.

Rationale: To ensure safe operation of the battery system over a long period of time, reliable temperature measurements has to be fulfilled.

Metrics: In the demonstrator the sensor interface degradation is prevented or it is detected by the algorithm with a accuracy of more than 90 %.

Owner: FHG

ID: AI4CSM_WP1_SCD4.3_3

Name: Temperature sensor drift

Description: A temperature sensor drift shall be detected by the algorithm.

Rationale: To ensure safe operation of the battery system over a long period of time, reliable temperature measurements has to be fulfilled.

Metrics: In the demonstrator the sensor drift is prevented or it is detected by the algorithm with a accuracy of more than 90 %.

Owner: FHG

ID: AI4CSM_WP1_SCD4.3_4

Name: HV-safety

Description: The device shall fulfill the HV-safety requirements as described in UN R 100 / MBN20123

Rationale: Safe operation at high voltages requires components that fulfil state-of-the-art electrical safety requirements to avoid hazards for users and operators

Metrics: Validation of insulation resistance, discharging duration, withstand voltage, ground resistance, active safety measures (discharge, open connector detection)

Owner: MBAG

4.4 SCD4.4 – Safety Power Management IC

4.4.1 Demonstrator description

The Power Management IC - PMIC is aimed to provide all or at least most of the power supply rails needed for the control board of an application. It is strictly connected to the microcontroller unit that represents the main and usually more demanding user, but it is also enabling the communication infrastructure, that includes the standard low frequency interface (CAN bus) or the high-frequency interfaces, such as ethernet, emerging in the automotive scenario, and whenever possible also some sensor interfaces. The PMIC is therefore a medium complexity IC comprising many power supply rails (currently up to 8 voltages generated by the same integrated circuit) created by means of a mix of linear voltage regulators and switching DCDC converters.

The Autonomous Driving and Advanced Driver Assistance Systems are moreover moving the most of the applications to ASILB-ASILD compliance, requiring also the PMIC to support Functional Safety. Detection of faults in the device is therefore a must also for the PMIC and introduction of safety mechanism is required to properly react to failures.

The demonstrator SCD 4.4 will focus on the development of a novel architecture for Power Management IC (PMIC) to support the future generation of microcontrollers and in particular the needs of Infineon Aurix™ microcontroller embedding the novel Parallel Processing Unit.

The next generation of microcontrollers is introducing more computational capability to address also the possibility for Artificial Intelligence routines, thus demanding a much higher power capability to the related PMIC. The target power supply is increasing from the current 10W of state-of-the-art applications to approximately 50W to 60W for upcoming solutions. Meanwhile the trend of technology scaling will decrease the voltage supply for the microcontroller core from 1.2V-1.3V to 0.9V-1V.

The novel DCDC converters will therefore be challenged by a tremendous increase of load current demand and more strict requirements about regulated voltage precision affecting both in the static and dynamic domains.

In order to accommodate this trend, the current DCDC architectures used in the automotive PMIC devices cannot be longer used and new approaches need to be explored, such as multiphase topologies. The target activity in AI4CSM project is to develop such new PMIC device capable to provide a precise regulated voltage for the microcontroller core (1V) and high current capability (10A).

The second part of the activity will be related more strictly to the introduction of Artificial Intelligence in the PMIC.

Considering the future trend for car sharing and electric mobility, the demand for 24/7 availability and usage will increase. Prediction of failures and aging will become a mandatory feature to avoid unavailability, thus requiring predictive maintenance to avoid failure in the field. All electronic levels could be expected to contribute to the system surveillance and prognostic including the PMIC device that can support prediction of anomalies related to the PMIC itself, users (micro controllers, sensors, etc..) and infrastructure (communication interfaces).

Current monitoring approach is based mainly on a disaster check to ensure functional safety without impacting system availability. Big deviations of functionality are accepted in the operating region without any chance of warning as illustrated in Figure 23.

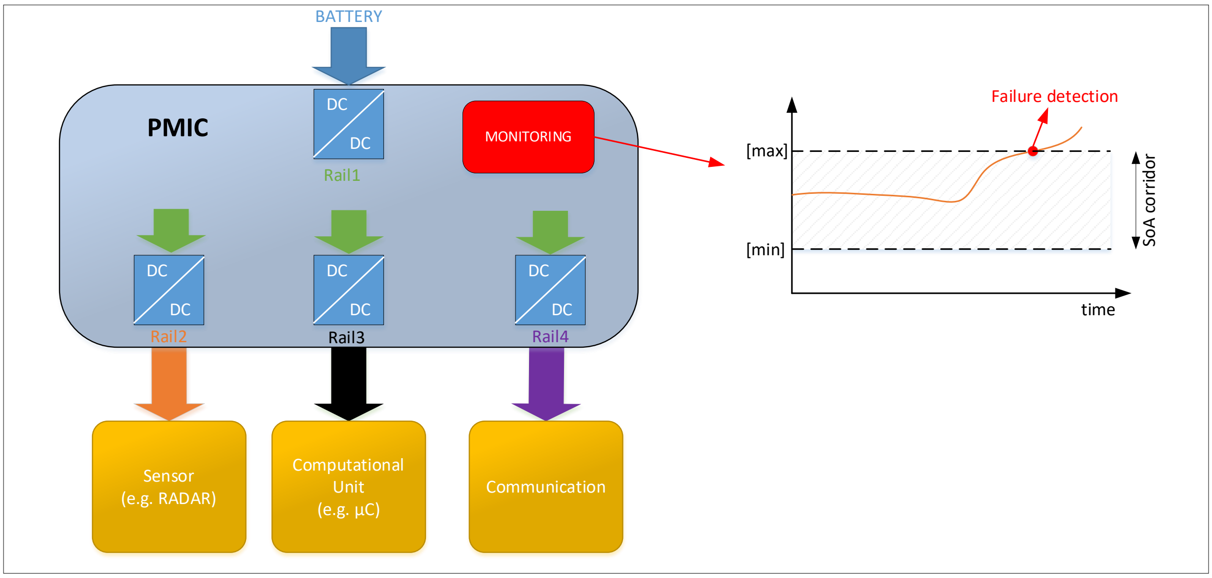


FIGURE 23 - MONITORING APPROACH CURRENTLY IN USE IN FUSA PMIC

Target in AI4CSM is to explore the possibility to introduce a fine detection of anomalies (PMIC related, micro controller related, BoM related, …) based on novel data analysis of the system through artificial intelligence algorithms embedded in the PMIC digital core.

The feature can allow to support aging detection and predictive maintenance, but also more sophisticated BIST of the micro controller in application.

The introduction of AI for user anomaly activity can moreover enable support to cybersecurity aspects even though not yet in scope and target in AI4CSM. The PMIC can indeed play a significant role in this context as supervisor system.

4.4.2 Validation concept

The demonstrator about high-power PMIC will be validated by means of a demo-board that will allow to test the functionalities in laboratory environment.

The tests will cover the full automotive range required by usual applications (e.g. ambient temperature variation from -40°C to 150°C) ensuring the capability to handle the maximum current statically and dynamically (load current steps) and the voltage fluctuations typical of the car environment.

The above-mentioned tests will be performed out of applications while in-applications tests will be possible exploiting the demonstrators developed in the other Supply Chains such as SCD 3.1 or SCD 6.5 that are going to make usage of the same PMIC.

The embedding of artificial intelligence in the PMIC will be conversely explored in a simulation environment (PC based) in order to investigate more algorithms and allow comparison with model-based simulator results. Synthetic data will be produced to test the machine learning capabilities. This approach will be necessary considering the relative short duration of AI4CSM project that would not allow for hardcoding and manufacturing of a PMIC with embedded AI in time.

4.4.3 List of requirements

ID: AI4CSM_WP1_SCD4.4_1

Name: PMIC Functionality

Description: The PMIC device shall support Aurix TC49x power demand, providing ISO26262 and AEC-Q100 compliance

Rationale: The PMIC is used in automotive environment for functional safety applications as a companion of next generation micro controller.

Metrics: 7A capability on 0.95V rail;

1A on 3.3V/5V rail;

additional capability for CAN and ethernet communication.

Owner: IFI

ID: AI4CSM_WP1_SCD4.4_2

Name: PMIC AI

Description: The PMIC shall detect anomalies in the device, board or user IC.

Rationale: The PMIC is contributing to prognostic of aging and predictive detection of failures and anomalies.

Metrics: Detection of failures/drifts in the PMIC BoM or warning about anomalous pattern in the user current absorption.

Owner: IFI

4.5 SCD4.5 – Foreign Object Detection for Wireless Charger

4.5.1 Introduction

The working principle of wireless power transfer applications, like e.g. high power automotive wireless chargers, is based on an alternating magnetic field, which bridges an air gap between a transmitting coil on the ground (part of the ground assembly, GA) and a receiving coil within the vehicle (part of the vehicle assembly, VA). As a consequence, electrically conductive or magnetic objects which are exposed to the alternating magnetic field interact with it and thus may heat up strongly. The SAE J2954 standard considers this a safety hazard if „a foreign object falls into the following three areas“:

- Metallic object becomes hot enough to damage the surface with which it is in contact and, as a result, creates an electrical thermal issue. For example, an object on the GA (Author's note: ground assembly) surface might get hot enough to damage the surface and expose components which could be dangerous.
- Metallic object is heated to a temperature that is dangerous to touch at the time that the object becomes accessible. Accessibility could happen after the vehicle leaves the charging spot or if someone reaches under the vehicle. The maximum temperature that an object reaches is not a sufficient test criterion; if the heat capacity of the object is small enough, by the time the object becomes accessible it may have cooled to a temperature below the touch threshold.
- Metallic object in contact with a flammable item becomes hot enough and contains enough thermal energy to cause ignition of the flammable item.

Such hazardous situations can be avoided with the following two approaches:

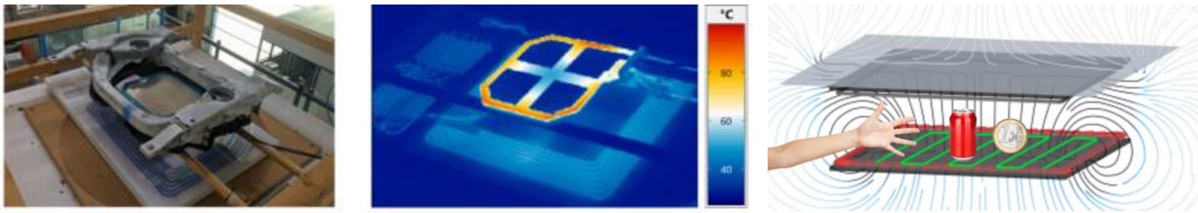
- The wireless power transfer system is per design not capable to heat any object up to dangerous temperature levels
- A foreign object detection (FOD) mechanism is implemented, which causes the system to either shut down if running or prevents the start of the power transfer in case of the detection of possibly hazardous object

Passive induction sensors are often proposed for use in wireless charging systems for vehicles. Corresponding designs can be found in [1] and [2]. The sensors are penetrated by the magnetic field of the charging system. By appropriate sensor design, the influence of metallic foreign objects can be detected, since these lead to gradients between neighboring sensors. Differences in the measurement signal can be detected very easily by means of subtraction - at the same time, the influence of the source of the magnetic field on the sensors cancels itself out. The detection of foreign objects that influence neighboring sensors in the same way, e.g. by completely covering several sensors or being located exactly between two sensors, is problematic. In both [1] and [2], it is proposed to use a second plane with similar sensors that is shifted in position relative to the first plane such that such foreign objects can be detected. However, this still leaves the detection in the edge area of the sensor field or the detection of foreign objects that symmetrically overhang the sensor field problematic. Moreover, twice the sensor material expenditure is required as the sensor coils need to be doubled.

The measurement method of electrical time domain reflectometry (TDR), which is well established in electrical engineering, enables spatially resolved measurement of the electrical properties of a transmission line based on propagation times and reflection characteristics of the electrical signals fed in at the beginning of the line. By modifying at least one of the components of the transmission line that serves as the sensing element, a physical quantity can be coupled to the electrical properties of the line (resistive coating, inductance coating, leakage coating, and capacitance coating).

In the TDR method, a high-frequency signal (pulse signal) is injected into a line. Reflections occur at inhomogeneities of the electrical line, which can be detected at the beginning of the line and displayed in a reflectogram in the time domain. Reflections occur as a result of discontinuities in the characteristic impedance along the line. The characteristic impedance at the point of discontinuity differs from the characteristic impedance of the line.

Within the project AI4CSM, both passive differential inductive sensors and active sensors based on electrical time domain reflectometry will be investigated for their characteristics and their suitability for the detection of metallic and non-metallic foreign objects in wireless charging systems.



a) b) c)

FIGURE 24 - A) GA AND VA OF THE 10 KW WIRELESS CHARGER B) INFRARED IMAGE OF THE WIRELESS CHARGER IN OPERATION C) PROPOSED TDR SENSOR LAYOUT LOCATION ABOVE GA COIL (GREEN LINE)

4.5.2 Requirements

Both methods, the conventional passive sensor layout as well as a novel TDR based sensor design require special considerations in the development process with a focus put on electromagnetic compatibility (EMC), used and applied software and algorithms, the validation concept and finally the project demonstrator.

Demonstrator

The AI4CSM demonstrator for foreign object detection is based on an existing 10 kW wireless charging system, as it is shown in Figure 24, in order to provide realistic operating conditions. The demonstrator is designed to represent the following scenarios:

1. Foreign objects placed on the surface of the GA in absence of the VA
2. Foreign objects placed on the surface of the GA in presence of the VA while power transfer is disabled
3. Foreign objects placed on the surface of the GA in presence of the VA while power transfer is enabled

The sensors of the FOD system are positioned directly above the GA coil on a carrier plate, as specified in the standard SAE J2954 (Figure 24c). This makes measurements with and without VA feasible.

Sensor

The FOD sensor shall be able to detect a catalogue of objects defined by SAE J2954 standard (ref. Table 3). The described procedure foresees, that all objects shall be positioned at and oriented along the location of their effectively strongest interaction with the magnetic field. The test is passed if the object does not exceed a certain temperature limit or the object is detected by the FOD system. However, from a hazard potential point of view, the objects actually need to be placed and checked at the location of its effectively weakest interaction with the magnetic field, which would still exceed a certain temperature limit. That is, basically, the sensor at least needs to cover certain areas of strong magnetic fields (which is expected to be right above the coil windings). Yet, a sensor layout covering the whole coil area is envisaged, as it is safer and more convenient to detect and remove any potential hazardous object on top of the GA in general. The sensor may also be able to detect non-metallic objects from a material according to the electromagnetic properties specification from Table 4. A suitable catalogue for additional test objects will be result of electromagnetic simulations performed in Task 2.4 - System Level Design.

TABLE 3 - CATALOGUE OF SAMPLE OBJECTS TO TEST FOR DETECTION ACCORDING TO SAE J2954

Item	Sample Objects	Notes
1	Paper stack with paper clip	Steel wire paper clip, approx. 1.25 inches long
2	Foil with paper backing	2 x 4 inches, similar to chocolate bar wrapper of cigarette foil material. Lying flat on the surface.
3	Coins	US standards forsees 5¢ coin, however, euro coins will be used in this project
4	Nail	10d common steel, oncoated
5	Aluminum foil	2 to 3 inch square or circular piece, 0.002 to 0.010 inch thick
6	Steel bar	4 x 2.75 x 0.4 inches lying flat on the surface

TABLE 4 - MATERIAL PROPERTIES CATALOGUE FOR NON-STANDARDIZED TEST OBJECTS

Item	Object Material Description	Conductivity*	Permeability*	Permittivity*
Ref.	Air, Reference Material (not detectable)	reference	reference	reference
1	E.g. Polymers, Paper	low	low	high
2	E.g. Ferrites	low	high	low / high
3		low	high	
4	Non magnetic metals, e.g. Copper, Aluminum	high	low	low
5	**	high	low	high
6	Magnetic Steel, Iron	high	high	low
7	**	high	high	high

* with regard to reference material

** combination high el. conductivity and high el. permittivity not physical, high el. conductivity case is also covered by standardized test objects

EMC

As the FOD system is intended to operate also under the influence of the electromagnetic field caused by the GA coil, the sensor's susceptibility shall be minimized. To reach this goal, two complementary approaches will be taken:

1. By topology: The minimization of the mutual magnetic coupling between the GA coil and the sensor coils respectively the sensor layout in order to minimize the total magnetic induction. This can be realized with topology optimization with the help of electromagnetic FEM simulations.
2. By electric design: Electric filtering (passive or active) of the sensor signals as well as protective ciruits. That is, the sensor signal can be processed by a suitable type of high-, low- or band-pass filters both in hardware and software. Furthermore, input protection circuits shall prevent damage from induced voltage peaks.

These approaches shall ensure both the protection of the sensor electronics against the destruction from overvoltage and the suppression of interfering signals.

Algorithms

Although the sensor's susceptibility to electromagnetic interference shall be minimized and filtered, it is expected that residual interferences remain in the sensor signal. In combination with the random placement of the foreign objects, the signal evaluating algorithm needs to be robust with respect to noise and random object placement and orientation.

Depending on the measurement results in the upcoming work packages, both conventional (e.g. threshold based) algorithms as well as machine-learning based approaches shall be pursued. Especially, the sophisticated characteristics of the TDR based sensor signals may require such AI-based methods, like recurrent neural networks (RNN). According to their principle of operation, much training data will be required to teach the differences between the 3 testable scenarios described in the demonstrator description. This training data will be acquired using an automated XYZ-position table, which positions the objects randomly on the sensor area and thus generates training and validation data. The algorithms may also identify the location and the type of the object on the sensor, if the sensor signal is sufficiently distinctive.

Validation & Verification

The validation and verification of the FOD sensor system is a development accompanying process, which includes and builds up over all the prior development steps. The most important part is the correct electromagnetic modelling of the sensor coils as well as the wireless charger, as this is the base for both the design and topology optimization of the FOD sensor, with respect to EMC and object detectability. Accordingly, the simple laboratory-scale sensor layouts shall be modelled, simulated, manufactured and measured in order to validate the simulation model. Moreover, system level magnetic field measurements on the demonstrator shall confirm the correct implementation of the magnetic model, correctly predicting local magnetic field strengths.

This process culminates in the successful validation and verification of the foreign object detection system, by proofing the detectability of the listed foreign objects above the sensor area. That is, several metrics can be applied to measure the successful and correct realization of the FOD sensor system:

1. **Detection of the standardized test objects**: How many and which test objects of the official SAE J2954 standardization are detectable at the position of maximum interaction.

2. **Functional appropriateness:** For each test object: At how many of the tested positions is the object detectable.
3. **Influence of environmental conditions:** Is the sensor still working, if the wireless charger is operating.

The metrics can be divided in functional (FR) and non-functional requirements (NFR), as shown in Table 5, Table 6, Table 7 and Table 8.

TABLE 5 – FRS, NFRS AND MEASURES FOR SC-DEMONSTRATOR 4.5 – DETECTION OF THE STANDARDIZED TEST OBJECTS

FR	Detection of the standardized test objects
FR definition	Detection of metallic objects described as test objects in the standard SAE J2954 at positions with maximum magnetic flow
Description	How well does the selected sensor detect the standardized test objects?
Measure	Detectability of standardized test objects
Type of measure	Quantitative (signal amplitude ratio)
Method of collection and measurement	Measurement $$X = \frac{A}{B}$$ A … Number of detected objects B … Number of tested objects
KPI for Verification and validation	Comparison between different sensor types

TABLE 6 – FRS, NFRS AND MEASURES FOR SC-DEMONSTRATOR 4.5 – FUNCTIONAL APPROPRIATENESS

FR	Functional appropriateness
FR definition	Functional appropriateness of the sensor
Description	At which positions relative to the GA coil can standardized test objects be detected?
Measure	Detectability at different positions
Type of measure	Quantitative (ratio)
Method of collection and measurement	Measurement $$X = \frac{A}{B}$$ A … Number of measurement points where the foreign object can be detected B … Number of all measurement points
KPI for Verification and validation	Comparison between different sensor types

TABLE 7 – FRS, NFRS AND MEASURES FOR SC-DEMONSTRATOR 4.5 – INFLUENCE OF ENVIRONMENTAL CONDITIONS

FR	Influence of environmental conditions
FR definition	Detection of metallic objects described as test objects in the standard SAE J2954 in combination with typical environmental conditions at positions with maximum magnetic flow
Description	How well does the selected sensor detect the standardized test objects in combination with typical environmental conditions?
Measure	Detectability of standardized test objects
Type of measure	Quantitative (ratio)

Method of collection and measurement	Measurement $$X = \frac{A}{B}$$ A … Number of detected objects while wireless charger operating B … Number of detected objects while wireless charger not operating
KPI for Verification and validation	Comparison between different sensor types

TABLE 8 – FRS, NFRS AND MEASURES FOR SC-DEMONSTRATOR 4.5 – DETECTION OF NON STANDARDIZED TEST OBJECTS

NFR	Detection of the standardized test objects
FR definition	Detection of non-standardized test objects
Description	How well does the selected sensor detect the non-standardized test objects?
Measure	Detectability of non-standardized test objects
Type of measure	Quantitative (signal amplitude ratio)
Method of collection and measurement	Measurement $$X = \frac{A}{B}$$ A … Number of detected non-standardized objects B … Number of tested non-standardized objects
KPI for Verification and validation	Comparison between different sensor types

4.5.3 List of Requirements

ID: AI4CSM_WP1_SCD4.5_1

Name: Detectability

Description: The sensor shall detect a specified test catalogue of magnetically heatable or inflamable objects.

Rationale: The FOD sensor system's purpose is to prevent damage to property or persons due to heatable or inflamable objects in the airgap. Thus, the sensor must detect these objects.

Metrics: Standardized test object catalogue

Owner: TUD

ID: AI4CSM_WP1_SCD4.5_2

Name: Interference Immunity

Description: The sensor shall be functional under external magnetic field exposition due to inductive power transfer.

Rationale: As the sensor system is part of the ground assembly, it shall be operational and functional under the influence of the inductive charging system's magnetic field.

Metrics: Detectability test while active power transfer.

Owner: TUD

ID: AI4CSM_WP1_SCD4.5_3

Name: Positional Invariance

Description: The sensor design shall be free of blind spots with respect to object detectability.

Rationale: The FOD sensor system shall detect foreign test objects reliable regardless of the foreign object location or orientation on the sensor surface.

Metrics: 2D detectability map of the FOD sensor

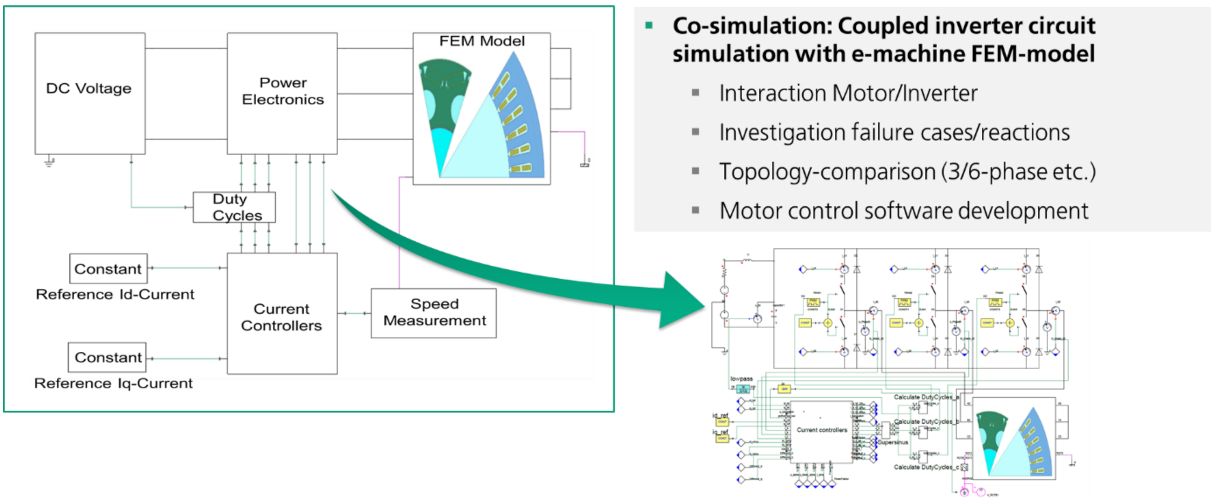
Owner: TUD

4.6 Cognitive Diagnostic System

4.6.1 Introduction

Fraunhofer IISB is focusing on the early detection of insulation and stator winding faults in the electric traction machine. Higher switching speeds (dU/dt) and higher winding temperatures lead to additional stress for the stator insulation system which could lead to short-circuits and complete drive failure if the system fails. The investigation and algorithm development focus on the detection of such deteriorations before complete system failures using existing sensor and inverter signals (phase-current, derived motor control parameters, etc.). Object of the investigation is an automotive 800 V traction PMSM with fast switching SiC or GaN inverter.

First step of the investigation is the extension of a co-simulation tool of the overall electric powertrain to induce winding failures of different type and position. The model includes FEM-based electric machine simulation, B6-inverter and a field-oriented-control algorithm.



The effects, e.g. torque fluctuations, changes in phase currents, or the influence on motor-control-stability, are analysed. The induced failures were classified according to:

- Phase-to-Phase, Within-One-Phase
- Position within one phase (close to phase connection, star-point, etc.)
- Low impedance ⬄ High impedance (breakthrough depending on voltage difference)

The results of the finalized co-simulation will be first input for the detection algorithm development and the planning of the experimental verification.

4.6.2 List of requirements

ID: AI4CSM_WP1_SCD4.6_1

Name: Use of internal inverter sensors

Description: The detection method and algorithm should be able to work with the available sensors in typical automotive inverters , e.g. current, temperature, DC-voltage sensors

Rationale: Required for cost-effective integration of the detection method in automotive inverters

Metrics: Available sensors and their bandwith, measurement range is sufficient for the detection algorithm

Owner: IISB

ID: AI4CSM_WP1_SCD4.6_2

Name: Detection accuracy

Description: The fault is detected with an accuracy suitable for applicability in an automotive environment. The detection time ahead of failure occurency is subject of the R&D performed here.

Rationale: Required for user acceptance of the detection algorithm

Metrics: > 90%

Owner: IISB

4.7 Phase-based control algorithms

State of the art methods try to identify the electric motor parameters such as stator inductances and permanent magnet magnetic flux by offline parameter identification methods. This means that for the whole quantity of produced electric motors only a few if not only one motor is used to derive the parameters which are used as generic lookup tables. Due to production tolerances this already leads to mistakes regarding the control of the motor and therefor reduced efficiency. Further this kind of parameter identification does not include any detection of altering effects resulting in the need of additional sensors and algorithms to check for e.g. aging and faults.

A novel approach to these known problems of offline identification methods are the phase-based control algorithms. The key is the use of the current slopes caused by the switching of the inverter to determine the unknowns (inductances) of the motor within each PWM-cycle. This allows not only the online parameter identification and thus the identification of every electric motor but also the detection of altering effects during operation.

4.7.1 Specification & Requirements

The data acquisition and the data processing are the main challenge due to the amount of data (six phase motor equals six currents and voltages) and the short period of time available to compute the algorithms. To ensure the functionality of the phase-based control algorithms there can be defined following requirements regarding the computing processor and the sensors:

Computing Processor:

- Use of a FPGA with a sample-rate of 100 MHz

Sensors:

	Voltage sensor	Current sensor
Type	LEM Converter	Rogowski coil
Range of measurement	0… ±1500 V	0…±1200 A
Accuracy	±0.2%	±0.2%
Bandwidth	>800 kHz	> 20 MHz

The FPGA and phase-based algorithm should result in the following overall requirements:

ID: AI4CSM_WP1_SCD4.1_13

Name: Online machine parameter Identification

Description: The phase-based control algorithms should be able to derive motor parameter (inductances) during operation.

Rationale: The online parameter identification is needed to ensure a more efficient operation of the powertrain by the detection of altering effects.

Metrics: Derived Parameter will be verified in a simulation and on a testbench-run

Owner: HSO

ID: AI4CSM_WP1_SCD4.1_14

Name: phase-based control algorithm

Description: The phase-based controll algorithms should be able to generate optimized reference current (e.g. not sinusoidal) in normal operation as well as fail operation mode.

Rationale: Reference current generation should consider real world altering effects.

Metrics: The motor efficiency will be determined by simulations and on a testbench for the standard sinusoidal current shape as well as the optimized current shape

Owner: HSO

4.7.2 Validation and Demonstrator Concept

To develop and implement the phase-based control algorithm there will be used a model-based simulation. This model will include the power electronic, electric motor, the data acquisition and the motor control including real world effects like limited sensor bandwidth, measurement noise, realistic inverter switching pattern and nonlinearities in the parameters.

For further validation the demonstrator SCD4.1 will be used and equipped with the necessary components to test the phase-based control algorithm on a real world testbench at the facilities of HSO and/or MBAG.

4.8 Advanced Mission Profile Model

4.8.1 Description

Today, mission profiles are typically given as histograms of hours vs. temperatures, or number of cycles vs. temperature changes. We see that such information is very limited, and we need more detailed information about how a product is used.

In fact, a product's mission profile comprises of various parameters over time:

- temperature,
- temperature change,
- voltage,
- relative humidity,
- operating time,
- kind of load – this can also be a categorial variable,

Therefore, we see this as a multivariate description of mission profiles. We create a multidimensional space, where each dimension reflects the time a device is exposed to each stress parameter. In this case, the stress time is normalized to standard stress conditions according to the respective acceleration law. A path in this high-dimensional space reflects the usage of a single device. Such a path is strictly monotone.

A set of such paths reflects the various usages of cars in the field. Such a model contains all information about the mission profiles for a set of devices. Because such a model can be quite complex, we want to reduce it to a simplified model with a minimum loss of information. We are currently exploring methods which allow us to achieve the following goals:

- describe the set of paths,
- identify sets of the majority of the paths, similar like quantiles in probability distribution functions,
- and identify outlying paths.

Such a model will serve as a basis to describe mission profiles. Because this approach is new, we will align and strive for acceptance with OEMs and Tier1s.

The benefit of this model is that it gives the semiconductor manufacturer a complete picture about the devices' field usage. The semiconductor manufacturer can design, validate, and test a device much better to its real usage conditions. This improves reliability, optimizes functionality, and reduces costs.

4.8.2 Implementation

Currently, mission profile models are generally based on summary statistics of individual devices instead of considering the whole usage-paths. When we consider two parameters, e.g., temperature and humidity, aggregating those parameters for each observation to obtain new ones such as minimum, average, and maximum temperature/humidity vastly reduces the available information. While this might be preferable to obtain simpler, humanly interpretable results, using such simplified data for a mission profile model, does not consider important aspects of the data. For example, all the time-dependent information as well as the order of the stresses is lost.

To analyse all available information, we employ a data analysis method which is better suited for this task. This method allows us to consider the whole usage-paths, which is of special importance when we consider the parameters of a mission profile, e.g.:

- temperature,
- temperature change,
- voltage,
- relative humidity,
- operating time,
- kind of load – this can also be a categorial variable,

For each device the complete information about the usage is recorded in a multivariate path, which allows us to consider time-dependent information as well as the order of the stresses. With this model we can analyse field-usage data as well as laboratory data (e.g., expected lifetime tests). For some parameters, such as operating time or total kilometres, the paths should reflect the monotone behaviour in any case. Moreover, when we analyse laboratory data where the stress parameters are normalized to standard stress conditions according to the respective acceleration law, monotonicity constraints might apply to all parameters.

A set of those multivariate paths reflects the field-usage conditions of cars and contains all information about the mission profiles for a set of devices. With our newly developed method we can describe and analyse the usage-paths in more detail. Applying generalized concepts known from classical statistics such as quantiles and multivariate outlyingness scores allows us to distinguish between regular and outlying usage-paths. This information can in turn be used to determine the regular and most extreme usage conditions of devices for validation and testing purposes and to build robust models.

4.8.3 Modelling mission profiles

Regarding the combination of mission profile models, we must map the data to a suitable space before we can analyse them in our model. Hence, we must transform the observations, which might be observed in a very fine grid, to a proper space, considering possible constraints such as the afore mentioned monotonicity. Once transformed, we can apply tools to investigate the structure of the multivariate paths. As in classical statistics, we can analyse the marginal paths using variants of a boxplot. However, due to the multivariate nature of the data, we should also employ multivariate tools for our data analysis proposes and not only investigate univariate structures. Therefore, using tools such as a generalization of statistical depth functions should allow us to distinguish between regular and outlying usage profiles. Since we are analysing usage-paths, we might want to distinguish between different types of outliers. For example, those paths can be outlying because of an unusual shape or magnitude, and they can also be outlying in only a subset of the variables. Moreover, they must not be outlying the entire time, but they can only be anomalous for fractions of the observational time.

For validation purposes, we will first use simulated data in this advanced mission profile model and depending on data availability, we can apply it to laboratory or field usage data.

4.8.4 Validation concept

In the beginning, we plan to use simulated data. Further on, we will use real data to the extent they will be available.

4.8.5 Demonstrator platform

We plan to use this advanced mission profile at the product validation and verification of the high-speed sensor interface from IFAT as well as at reliability tests.

4.8.6 List of requirements

In order to capture the needed features of the advanced mission profile model, we extracted specific requirements for this model:

ID: AI4CSM_WP1_SCD4.9_1

Name: Completeness of Mission Profile

Description: All relevant usage parameters should be included in the mission profile model, and the number of the parameters should be variable.

Rationale: Existing mission profile models typically cover each parameter individually. Dependencies between the parameters are not covered. A complete model enables a precise picture on use conditions and provides an accurate input to design, verification, and validation

Metrics: Nr. of parameters that can be used by the model.

Owner: IFAT

Reference UC: Advanced Mission Profile Model

ID: AI4CSM_WP1_SCD4.9_2

Name: Usage vs. Time

Description: Usage conditions over time should be reflected in the mission profile model.

Rationale: The performance of a device can depend on the sequence of stress factors.

Metrics: Stress parameters vs. time.

Owner: IFAT

Reference UC: Advanced Mission Profile Model

5 Conclusion

5.1 Contribution to overall picture

The presented work describes the characteristics and specification of the demonstrators and activities of Supply Chain 4. It contains the most significant functional and non-functional requirements for each device, algorithm or model and thus defines the objectives to be achieved by the following working steps in the project. The requirements will be further elaborated during the subsequent design phase and translated into a target specification. Finally, they will serve as guidelines and input for creating the different concepts of validation.

5.2 Relation to the state-of-the-art and progress beyond it

Partner/Topic	Description
BUT	Increasing demands on powertrain reliability requires utilization of redundancies. High level of redundancies is expensive and therefore the usual practice in high reliable applications is to use only limited number of redundancies supplemented with diagnostics. The selected powertrain structure composed from three level GaN inverter and six phase motor connected as two times three phase requires higher level of diagnostics compared to classical three phase case as e.g., in [3]. Combination of motor and inverter fault will be assumed during the development.
IFI	Power Management IC are currently supporting functional safety micro controller devices in the automotive environment having a current demand up to approximately 2A for core logic. The need for more computational logic is nevertheless showing a tremendous boost of power consumption that will bring the next generation micro controller already in the range of 7A (or more) current. Moreover, the advancement in technology scaling is moving the voltage set from current 1.25V to 0.9V-1V with consequent increase of needed precision (absolute value) for the regulated voltage that combined with larger load step dynamic response will further challenge the DCDC architecture and regulation scheme. Current monitoring approach is based mainly on a disaster check to detect short circuit failures. Target in AI4CSM is to explore the possibility to introduce a fine detection of anomalies (PMIC related, micro controller related, BoM related, …) based on novel data analysis of the system through artificial intelligence algorithms embedded in the PMIC digital core.
ZF	GaN for automotive applications is currently under research, but it still has not been used in 800V applications. Multi-level topologies, which themselves have not been used in automotive products, allow the use of 650V GaN in 800V systems. In addition, the selected ANPC topology offers full fail-operational capabilities, which may be desired for future autonomous vehicles.
HSO	Typically, offline parameter identifications are used to generate lookup-tables containing the machine parameters which are used in the control algorithms. However, these methods do not consider altering effect such as production tolerances or signs of aging. The online parameter identification realized by the FPGA and phase-based control algorithms take these altering effects into account and therefor allow for a more precise and efficient operation of the electric motor, as well as the detection of failure due to parameter change und thus allow to achieve a fail operational characteristic.
IFAT	Advanced mission profile model: Currently typical mission profiles are histograms of temperature and temperature changes. We develop a model that reflects the complete usage of a device, which includes all relevant stress parameters.

TUD	Foreign object detection (FOD) in automotive wireless charging is a sophisticated task, which, according to the current state of the art, is limited in the detectability of objects and materials per design. Furthermore, conventional designs are prone to blind spots, i.e. areas with reduced or zero detectability are formed. TUDs approach, the application of time domain reflectometry for FOD, shall mitigate these issues.

5.3 Impacts to other WPs, Tasks and SCs

Partner/Topic	Description
BUT	Specification will be used in T2.4 for the system level design of cognitive diagnostic system and FCS MPC control structure. Algorithms will be then developed in T4.3. In T5.4, they will be implemented in demonstrators. Cognitive diagnostic system and the controller will be tested and validated in T6.4. Some components developed in SC4 will be implemented and tested in a car in SC2.
IFI	The functional safety PMIC device developed in SC4 is going to be exploited also in SC3 and SC6 to support different demonstrators. The activities in task 1.3 are therefore synergic to the overall WP1 activities of IFI in the three SCs and represents the prerequisite for all following WPs (WP2, WP3, WP4, WP5 and WP6). The power management architecture definition will indeed benefit of this requirements identification and as well the PMIC device design. The identified requirements will also drive the subsequent validation of the PMIC in dedicated laboratory environment and in the integration in the demonstrator board.
ZF	Requirements will be directly used for the developments of task 2.4 (inverter system level design), task 3.2 (design of the GaN power stage) and task 4.3 (design of the control board).
HSO	The requirements and specification of the phase-based control algorithm will be used for further development and implementation in a simulation for task 2.4
IFAT	The work in task 1.4 is the foundation for the work in the subsequent tasks of SC4 in WP2 – WP7.

5.4 Contribution to demonstration

Partner/Topic	Description
BUT	This deliverable provides requirements and specification on the controller and the diagnostic system for three-level inverter with GaN transistors driving six-phase motor. At the end, they will be demonstrated on testbenches or directly in a car in SC2.
IFI	IFI will define the requirements for the PMIC device supporting the next generation microcontrollers and will set target for anomaly detection capability of the PMIC.
ZF	The inverter itself is demonstrator SCD4.1, which will combine as well contributions from BUT, HSO, IFAG and IFAT.
HSO	The FPGA and phase-based control algorithms will be tested and verified on a testbench by using demonstrator SCD4.1 and externally mounted sensors.
IFAT	Verification and validation of the high-speed sensor interface from IFAT.

5.5 Other conclusions and lessons learned

Partner/Topic	Description
TUWIEN	In the mission profile model, we do not only want to identify outlying paths but also explain why those are outlying. Hence, we want to measure, how much each variable contributes to the multivariate outlyingness. Before we approach this task in a multidimensional functional space, we first try to solve it in the multivariate context. To achieve this goal, we developed an outlier detection and interpretation method based on Mahalanobis distances and Shapley values.

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