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# Design Verification Plan for electrified Powertrains

**MASTER'S THESIS**

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AVL List GmbH.

Graz, January 31, 2019

## Statutory Declaration

I declare that I have authored this thesis independently, that I have not used other than the declared sources/resources, and that I have explicitly marked all material which has been quoted either literally or by content from the used sources.

Graz, ________________________________ ____________________________________

Date Signature

## Abstract

AVL is expanding its knowledge and expertise in eAxle development and therefor this thesis was triggered.

Due to increasing numbers in BEVs and P4-hybrid architectures new questions for validating those systems emerge. This thesis elaborates the basic steps for a generic DVP for eAxles that later on can be adjusted and modified to the requirements of the customer. In addition to that, the thesis shall also focus on the factor reliability and cost, which are interconnected.

Especially durability tests for eAxles are standardized by e.g. VDA, FCA etc. Their failure mechanisms, procedures and damage calculations are described in this thesis as well. Moreover, it shall offer a bridge between the mentioned above and the factor reliability. Coming back to the factor cost, the number of samples shall be reduced to save costs and total testing time, while keeping the reliability on the same level as with the original planned number of samples.

White spots of the elaborated DVP can also be seen, together with where failures of specific machine components occur and how to intercept them as early as possible in the development process.

Finally, in the last chapter an outlook for future steps is given.


Graz, January 31, 2019

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Thank you all!


*"Success is never owned, it is rented and the rent is due every day!"*

Graz, January 31, 2019

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## Abbreviations

AC Alternating Current

DUT Device under test

E/E electrical and electronic

eAC electric Air Condition

DC Direct Current

EM Electric Motor

EMC Electromagnetic Compatibility

FMEA Failure Mode and Effects Analysis

FCA Fiat Chrysler Automobiles

FP-Sheet Failure Parameter Sheet

HCF High Cycle Fatigue

HV High Voltage

ICE Internal Combustion Engine

LCF Low Cycle Fatigue

NVH Noise Vibration Harshness

PE Power Electronics

RAD Relative Accumulated Damage

RPN Risk Priority Number

UUT Unit Under Test

VDA Verband der Automobilindustrie

WSC Wet Starting Clutch

# 1 Introduction

The following thesis is prepared in collaboration with Graz University of Technology's "Institute of Machine Components and Methods of Development" and AVL LIST GmbH.

## 1.1 Scope

During the development of ICEs, transmissions or powertrains manufacturers use standardized procedures for endurance and functional test conditions both in vehicle and on test beds, to evaluate the state of development on system, subsystem and component level. Especially for this generic DVP durability considerations are emphasized. In the last years AVL was expanding its knowhow in the field of electrified powertrains and therefore a standardized test program for electrified powertrains to verify and validate their design needs to be developed. To systematically derive and evaluate test procedures AVL is using the AVL – Load Matrix $^{TM}$ method. This thesis will focus on deriving the DVP on eAxle level from partly existing test cases on subsystem level (transmission, eMotor, and inverter) and the differentiation between different development phases. In addition to that the thesis will also focus on reliability evaluation.

AVL has come up with three different scenarios in March 2018 for the distribution of ICEs, BEVs & HEVs and hydrogen fuel cell powered vehicles. Figure 1 shows the medium version of the mentioned scenarios with is the average assumption. The estimations say that in 2030 the pure ICE vehicles will become less and the number electrified powertrains is increasing.

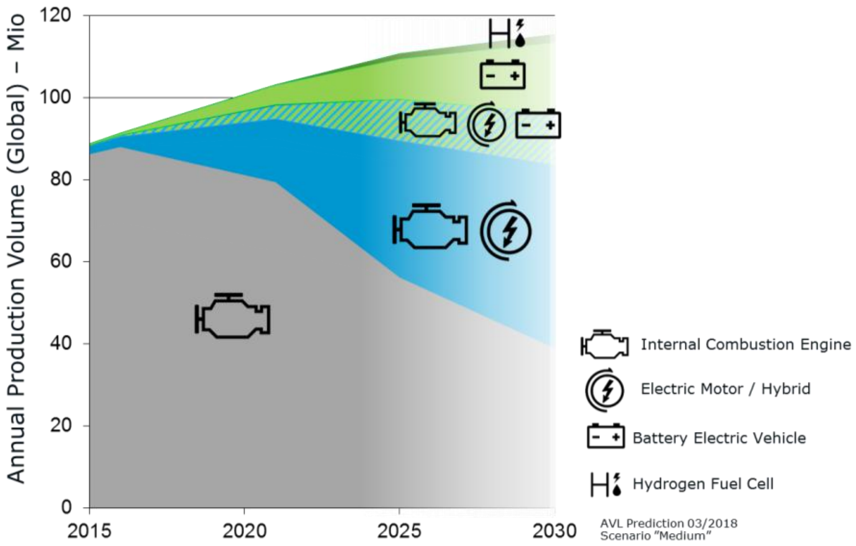



*Figure 1: AVL's prediction for the future distribution of powertrains for light vehicles*

## 1.2 Objective

The aim of this master's thesis is to derive a generic DVP for electrified powertrains.

## 1.3 Schedule

The following schedule was consistently and constantly modified during the progress of this master's thesis. It includes the most important milestones, the parallel approaches and initiated actions that are necessary to perform the master's thesis.

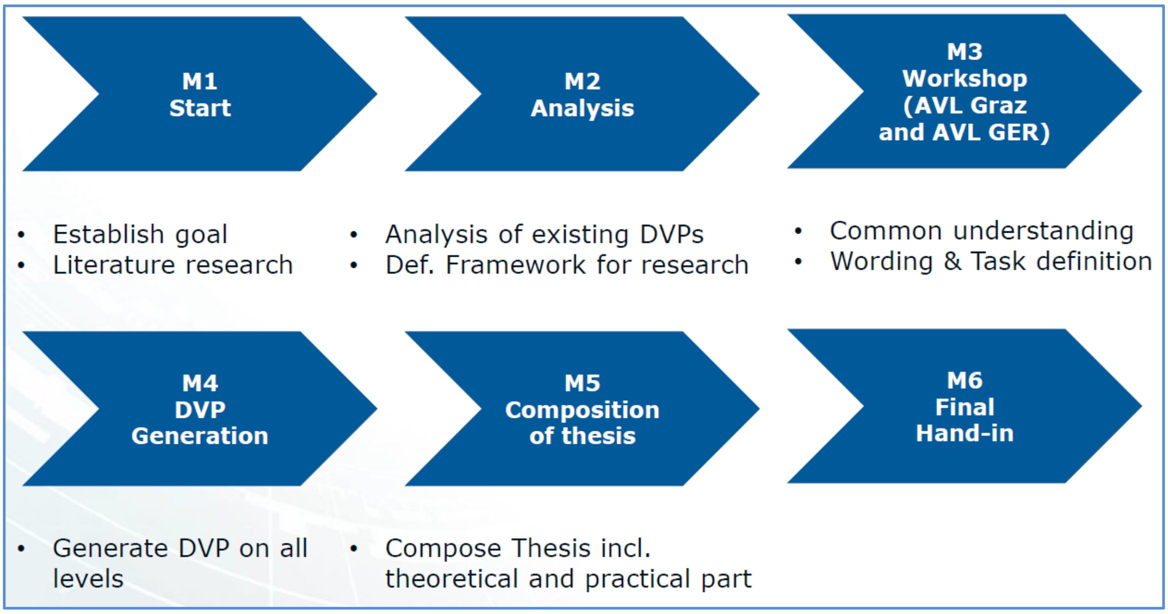



*Figure 2: Milestone plan*

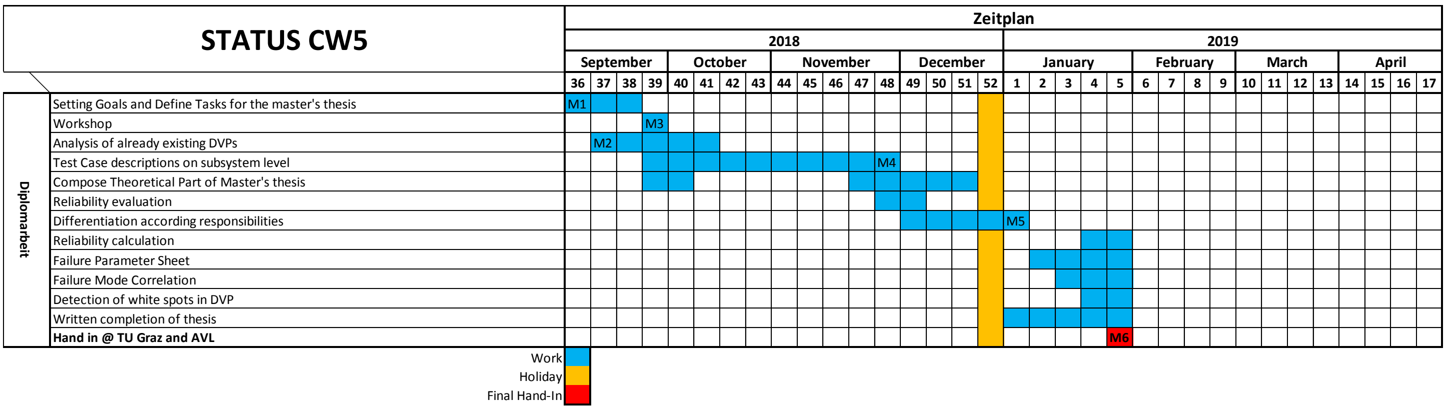



*Figure 3: Time schedule for Masters' Thesis*

# 2 The fundamentals for developing a DVP

In this chapter all the necessary theoretical contexts for e-drive systems and for developing a generic DVP will be illustrated and described separately.

## 2.1 Electric Vehicles

Due to high energy efficiency, diversification of energy resources, load equalization of their power systems, no local exhaust emissions and political will and therefor laws, regulations and fundings, electric vehicles are an uptrend on the global market. In addition to that they can also be operated very quietly. The main obstacles to overcome are shorter driving ranges, high upfront costs and especially recharding topics compared to cars powered by ICEs. The possible solution approaches range from better battery technology, fuel cells, and capacitors to flywheels. To overcome those shortcomings HEVs have been introduced to the market as interim solution, which incorporate electric motors with ICEs. HEVs combine the strengths of both power supplies and therefore extend the range and reduce recharging / refueling times drastically. [1] The benefits and shortcomings of ICE and battery electric vehicles are shown in the following figure:

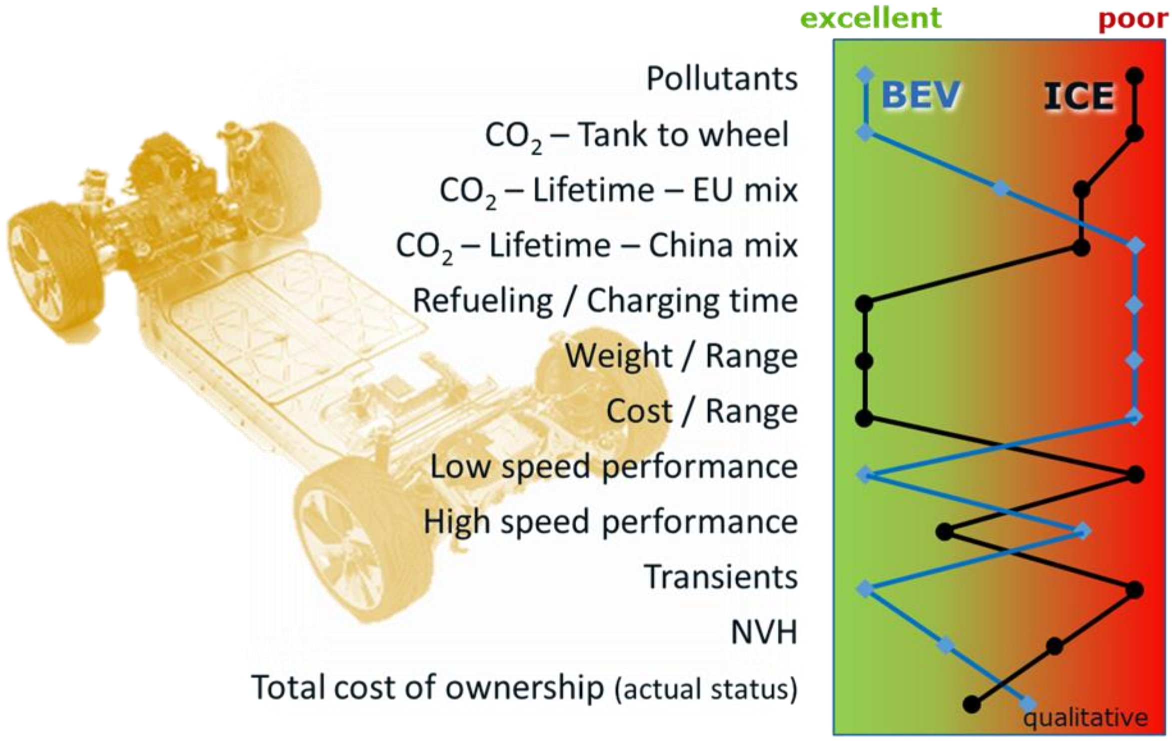



*Figure 4: Electrification and ICE offer quite complementary characteristics [2]*

Additionally, from a development perspective it is necessary to state that the complexity for hybrid powertrains is higher than for BEVs or ICE-powered vehicles on their own.

### 2.1.1 Hybrid Electric Vehicles

Referring to Art. 3 Par. 14 of the EU-Directive 2007/46/EC a hybrid motor vehicle is defined as a vehicle which uses at least two different energy converters and two different energy storage systems (on-vehicle) with the purpose of vehicle propulsion. [3] Chemical, electrical or mechanical energy storage systems number among them, with applicable energy converters that may convert stored energy into mechanical energy for propulsion of the vehicle. [4] [5] If the conventional propulsion system is combined with a rechargeable storage system, additional degrees of freedom derive that enable more efficient operating strategies. [4] In addition to that energy from braking may be recovered by using recuperative braking systems during adequate driving conditions (downhill, accelerator pedal position = 0, etc.). Therefor rechargeable systems like eMotors together with capacitor or batteries or mechanical storage systems like flywheels and pressure reservoir may be used. In the automotive sector most of the hybrid cars combine conventional combustion systems with eMotors and save the electric energy in a battery. Those batteries have a higher energy density, but lower power density compared to mechanical storage systems or capacitors. [6]

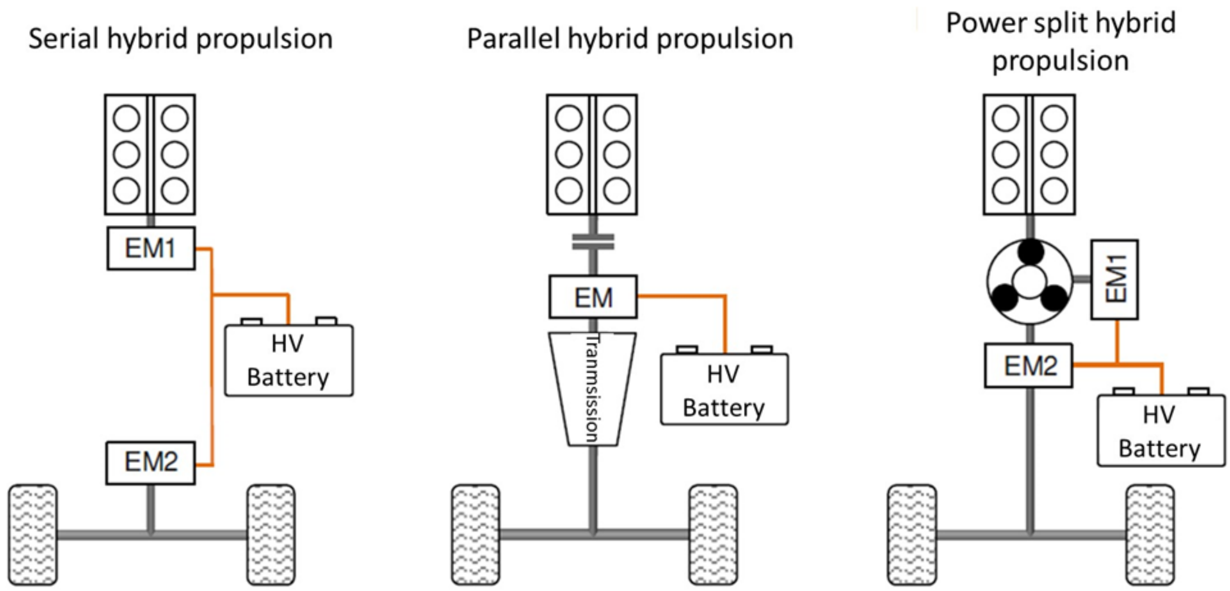



*Figure 5: Schematic overview of the three base structures for hybrid electric powertrains (serial, parallel, power split) [7]*

#### 2.1.1.1 Parallel hybrid propulsion systems

One of the main benefits of the parallel hybrid system is that only one eMotor is necessary for simultaneous propulsion of ICE and eMotor and that it may also be used pure mechanically driven. This leads to the so-called boost modes, where the eMotor supports the ICE during maximum load situations with additional propulsion power. Due to this fact the ICE's dimensions may also be smaller and therefor the fuel consumption decreases. [7]

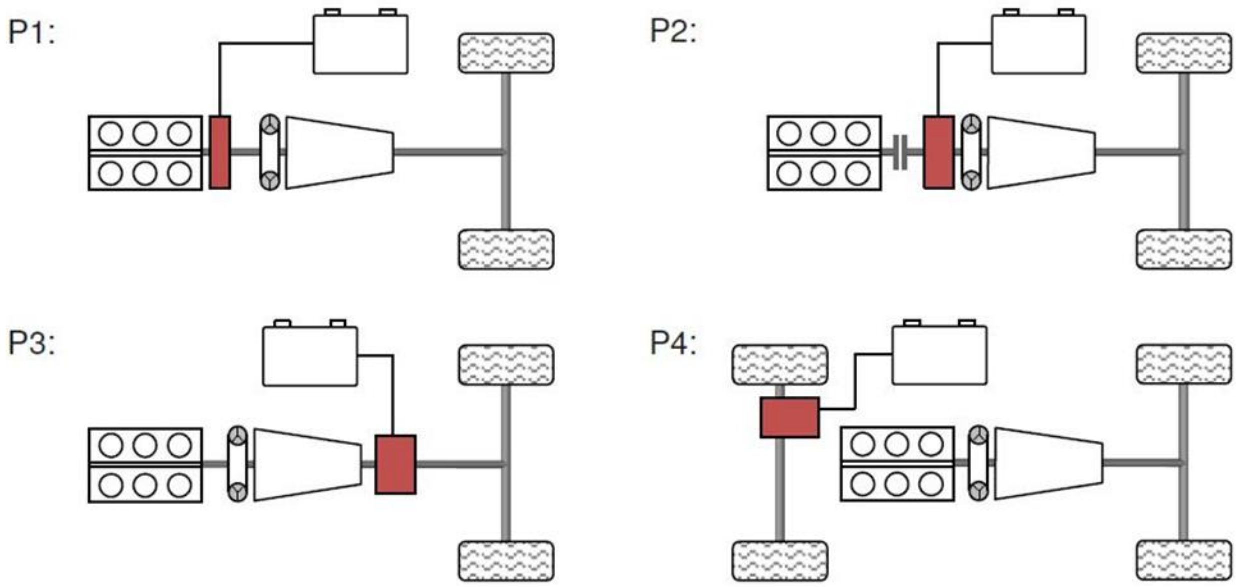



*Figure 6: Differentiation of parallel hybrid powertrains concerning the location of the eMotor (P1 -P4) [7]*

| | |
|---|---|
| P1 | The EM is mounted directly to the crank shaft, therefor it may not be decoupled from the ICE. The ICE has to be dragged during electric driving and recuperation phases. |
| P2 | The EM is separated from the ICE by a clutch and so the ICE and EM can be used independently. P2 systems may be used with DCTs and automatic transmissions with or without torque converters. |
| P3 | EM is sitting at the output shaft of the transmission and the power doesn't have to be routed through the transmission. The EM can use a broader rev range. |
| P4 | EM and ICE power different axles. Due to that fact all-wheel drive systems can be realized. P4 hybrids are also often combined with P1 systems, in which the second EM is located directly at the crank shaft. |

*Table 1: Differentiation of parallel hybrid powertrain systems [7]*

### 2.1.2 Battery Electric Vehicle

BEVs can achieve zero emissions (tank to wheel), due to only using batteries or other electric energy storage bases power sources. Nevertheless, high initial costs, the earlier mentioned lower driving range and long periods for recharging cause limitations.

Additionally, fuel cell vehicles may also be considered as BEVs, regarding architectural point of view. They can be equipped with batteries or supercapacitors. They generate electrical energy from hydrogen, which is later on stored in batteries or used to propel the eMotor. [1]

## 2.2 eMotor

For passenger car powertrains different types of EMs, provided by different manufacturers, are used. Those different types have their own advantages and disadvantages, which will be illustrated in the following chapters. Generally speaking the main types are

- Permanent magnet synchronous motors (Tesla Model 3, Chevy Bolt, BMW i3, VW e-Golf)
- Series wound DC motors (used in early applications)
- 3 phase AC motors (Mercedes EQC, Audi eTron, Tesla Model S)

which are quite similar structure wise but have different operation modes. [8]

The following table gives a brief overview for different eMotor designs:

**Rating criteria:** (+) advantage, (0) neutral rating, and (-) disadvantage

| Machine type / Criteria | PMSM | DCM | 3 phase AC IM |
|---|---|---|---|
| Cost | - | 0 | ++ |
| Torque/power density | ++ | - | 0 |
| Efficiency | ++ | - | + |
| Manufacturability | 0 | ++ | ++ |
| Reliability | + | - | ++ |
| Size/weight/ volume | ++ | - | + |
| Overload capability | + | - | + |
| Robustness | + | 0 | ++ |
| Field weakening | + | ++ | ++ |
| Thermal limitations | - | 0 | + |
| Noise/torque ripple | ++ | - | ++ |
| Lifetime | + | - | ++ |
| Future potential | ++ | - | ++ |

*Table 2- Overview of different eMotor designs [9]*

e.g.: Field weakening as seen in Table 2 is used to adjust an emotors rotational speed through reducing the magnetic flux of the excitation winding. The point from where the voltage is kept at a specific level (e.g. 400V @ 50Hz), the output torque and magnetic flux a start to decrease.

### 2.2.1 Permanent magnet synchronous motor

PM synchronous motors are used for high powers or special applications. The excitation is generated by DC-fed windings, especially for large motors. For smaller applications of synchronous machines the providing of DC is more complex, particularly with small motors. As a result of that the field winding is less efficient compared to the bigger ones. For those small application permanent magnets, reluctance variations or usage of a ring shaped hysteretic material are used in the rotors. Through the excitation of the permanent magnets the speed of the motor is similar to induction machines but without joule losses. PM synchronous motors have a high efficiency, can be controlled accurately, are compact and have good dynamic characteristics. One of the main cons is the high price for acquisition.

Figure 7 shows a half section of an excited synchronous motor: [8]

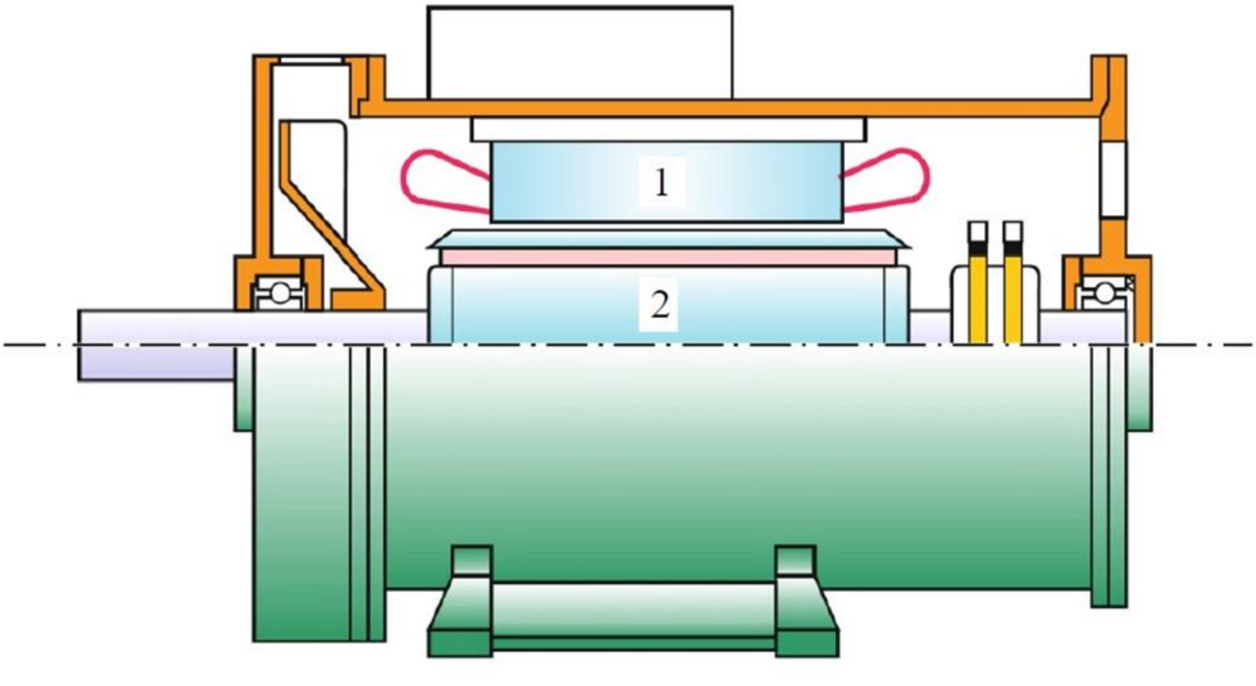



*Figure 7: Half section of a PM synchronous motor [8]*

The main parts of a PM synchronous motor are: [8]

- Winding in the stator (1)
- PM or DC excitation on the rotor (2)

### 2.2.2 DC motors

DC machines had a leading position for a long period in time due to the simple use of direct current. Although AC machines were introduced DC machines remained in favor for some applications, due to their good controllability and startup behavior. As soon as power electronics appeared on the market, induction and synchronous machines took the lead over due to their higher reliability and lower costs for maintenance. DC machines are sometimes still used for low power applications. They consist of two main parts: the rotating armature and the standstill excitation system. Figure 8 shows a half section of a DC motor. [8]

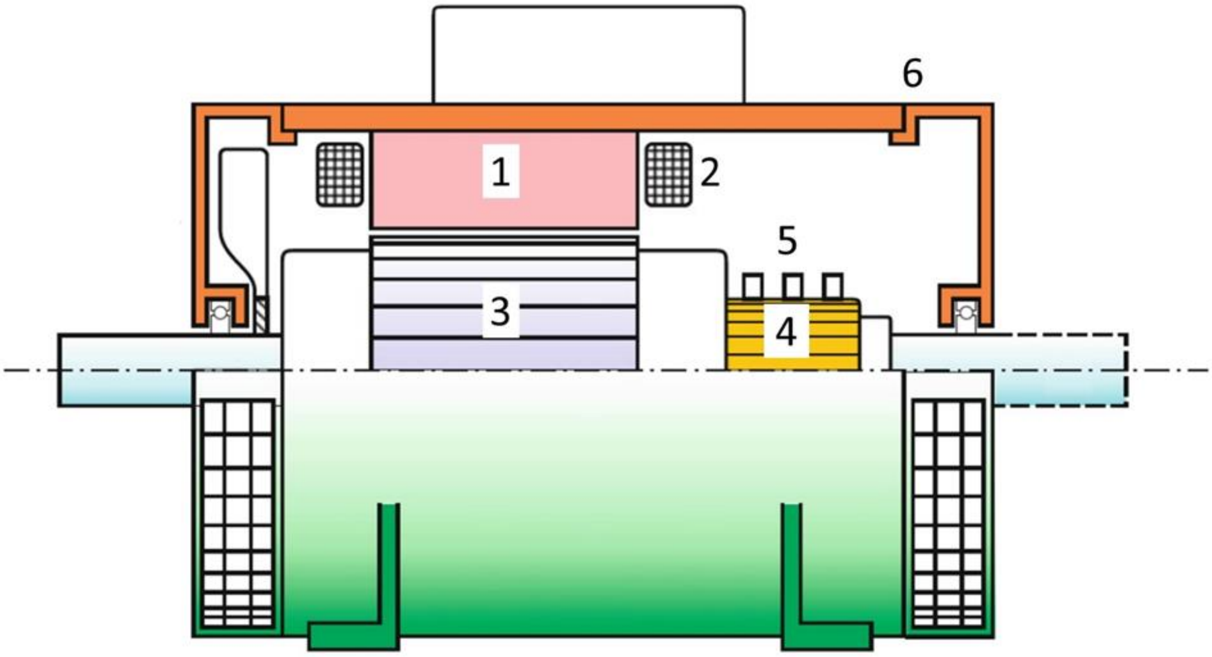



*Figure 8: Half section of a DC motor [8]*

The main parts of a DC motor are:

- Main poles (1)
- Excitation winding / permanent magnets (2)
- Core – iron sheets (3)
- Commutator segments (4)
- Segments and brushes (5)
- Closing Yoke (6)

The main benefits of those DC motors are fast rev up and down, simple and good controllability and high starting torque.

### 2.2.3 3 phase AC Induction Motors

Induction motors characteristics show a robust design combined with a high efficient energy conversion. Due to those facts they are the most common in electric powertrains. Moreover, the induction motors together with power electronic converters drove DC commutator motors off the market, regarding variable speed applications.

Figure 9 shows the half section of a 3 phase AC induction machine:

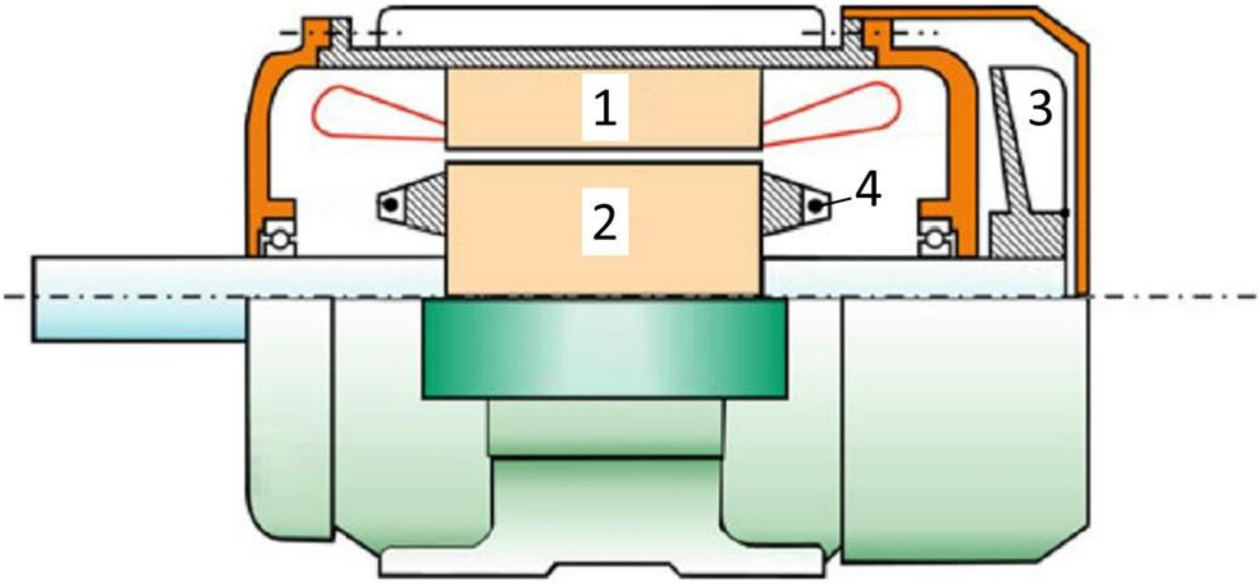



*Figure 9: Half section of a 3 phase AC induction motor [8]*

The main parts of a 3 phase AC induction motor are:

- Laminated stator core with 3 phase winding in slots (1)
- Laminated rotor core with bars in slots (2)
- ventilator (3)
- short circuit end-rings with cooling blades (4)

## 2.3 Inverter / Power electronic

AC may be converted to DC via rectifiers in generator mode. Controlled rectifiers can do this but are not capable of converting it with a variable frequency. Therefor inverters are necessary to convert DC to AC efficiently. Rectifiers only convert AC to DC, but inverters are capable of doing it both ways, even though their primarily used function is converting DC to AC. They are very often used to do that with variable amplitude and variable frequency. Variable frequency currents determine rotational speed. Therefore, frequency may be allocated to rotational speed and amplitude determines the resulting torque. A combination of frequency and amplitude then creates an operation point for the e-motor. 3 phase voltage source inverters are most commonly used in automotive. In Figure 10 the location of the inverter (PE) is shown in a schematic parallel hybrid system. Figure 10 also shows the structure of a P2 hybrid powertrain including the inverter / power electronic.

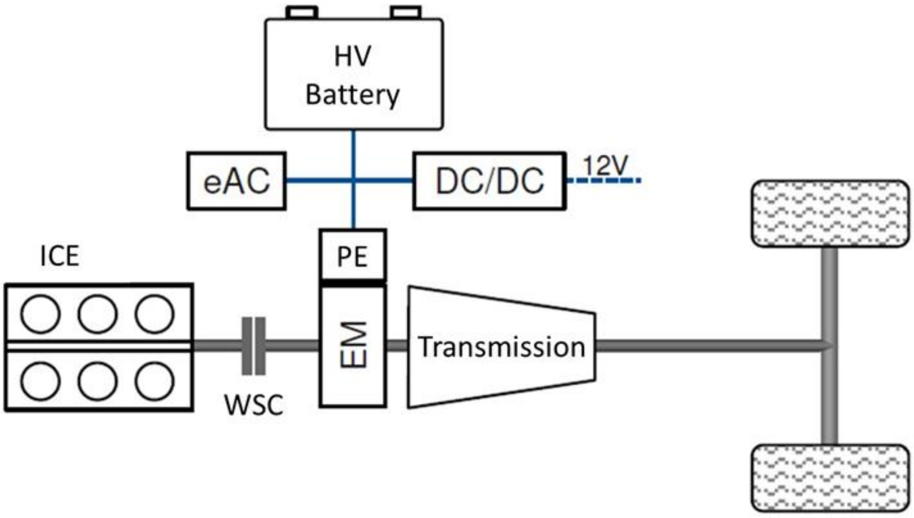



*Figure 10: Structure of a P2 powertrain system [7]*

Legend:

eAC - electric Air Conditioning

HV Batter – High Voltage Battery

DC - Direct Current

EM – eMotor

WSC – Wett Slip Clutch

PE – Power Electronics

## 2.4 Transmissions for electrified powertrains

In contrast to conventional transmissions, transmissions for purely electric propelled cars (also for P4 hybrid axles) multi-speed gearboxes are not given, only single or double speed transmissions. Due to the properties and characteristics of EMs only a limited number, if even necessary, is needed for the application. Small EM applications may be used, because of their high maximal revolution speeds, to achieve the desired vehicle speed. The high low-end torque of those motors is necessary for low vehicle speeds. Usually gear ratios for passenger cars range from 9 to 16, which make the Ems perform well. Generally spoken four designs of gearboxes are used for purely electrified powertrains:

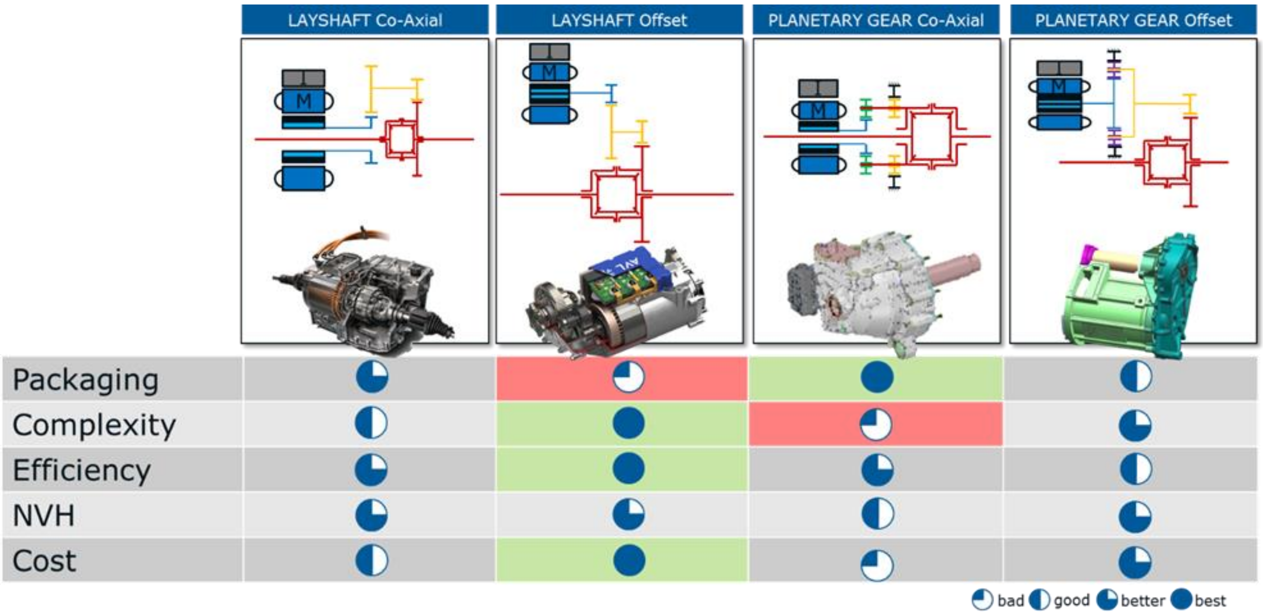



*Figure 11: Overview of typical e-Drive architectures [2]*

As seen in Figure 11 the benefits and downsides of different transmission architectures are listed.

The layshaft Co-Axial layout has its benefits especially in regard to packaging, NVH and efficiency. The high efficiency and NVH are interconnected due to the gear design.

The layshaft Offset layout’s major downside is the high consumption in space caused by less favorible packaging. In contrast to that the complexity and therefore cost as well as efficiency is very desirable.

The planetary Gear Co-Axial layout’s main advantage is packaging due to its compact design, which leads to the high complexity in the gear stages.

The planetary gear offset layout is very similar to the the planetary Co-Axial layout with the downside of higher space distribution, but the benefit of less costs.

For hybrid systems that combine ICE and EM in their power flow, automated transmissions are used. Those can be:

- Double Clutch Transmissions
- Automated Manual Transmissions
- Automatic torque converter transmissions

## 2.5 Design Verification Plan

From recent experience it may be stated that many customers don't know how to verify and validate their electrified powertrains efficiently and reliably, due to the high level of innovation. According to "Verification, Validation and Testing of Engineered Systems " [10] 50 to 60 % of all system development costs can be assigned to verification, validation and testing activities or to correcting system defects during the lifetime of the product or its development process. Those processes need to be carried out in all development processes or manufacturing projects. [10] Therefor a DVP is like a compendium of verification, validation and testing (VVT) activities with corresponding methods that need to be executed over the entire lifecycle of a product. It also tries to answer the questions: How and when should a test be performed and when is it time to stop testing? With this elaborated AVL model of the DVP, costs, time or both shall be further reduced in the future.

### 2.5.1 What is the DVP&R?

This tool is used to approve if products, systems, subsystems or components meet their design specifications and performance requirements. Design specifications and performance requirements are documented in the DVP&R together with the test cases that are performed to check whether they have been met or not. This thesis focuses on the DVP part of the DVP&R and therefor the reporting part will be kept short. The DVP is connected closely to the Failure Mode and Effects Analysis (FMEA), but both have different purposes during the development of a product. The FMEA's purpose is to answer the question "What" and the DVP the question "How" to assess the product.

The "Whats" are answered by lists of the analysis and verification tests during the FMEA

The "Hows" are describe how the test has to be performed, or rather the testing methods and conduct of the tests, including acceptance criteria.

### 2.5.2 Why should a DVP&R be implemented?

The DVP&R includes thorough and complete documentation of all analysis and verification procedures during the product development phase, design changes or later on product recertifications. The goal is to have one single document that includes the status of the analysis and the verification procedures understandably, for the whole team, all stakeholders and customers. Furthermore, it is beneficial for quality investigations during the whole lifespan of a product.

### 2.5.3 When should a DVP&R be implemented?

These DVP&R tools are very frequently used in combination with FMEA during the development of a new product or design changes to a product. Additionally, it may also be used for any other verification analysis or testing. The DVP&R methodology is used for

| |
|---|
| Performing tests for root cause analysis |
| Planning and documenting test information to validate a product's performance after a design change |
| Recertification of a product for new regulatory requirements. |

The DVP&R method can also be used to document the history of a product. This information may then be used if a new iteration step is outstanding, or a new but similar design is developed.

### 2.5.4 How should a DVP&R be implemented?

Different DVP layouts differ greatly from company to company, according to the preferences and own requirements. The quintessence is though the same, independently from the used format. The DVP is not a static document, due to adjustments during the design verification process. It derives from the following:

| |
|---|
| FMEA activities |
| Product improvement processes |
| Product certification / recertification |
| Root Cause Analysis |

The “R” of DVP&”R” stands for the reporting section. It documents all results after each test performed and completed. This may be the trigger for design changes or further testing. The whole DVP&R process is finished, when all tests and analysis have verified that the design meets its requirements and specs.

### 2.5.5 Definition of Verification, Validation and Testing

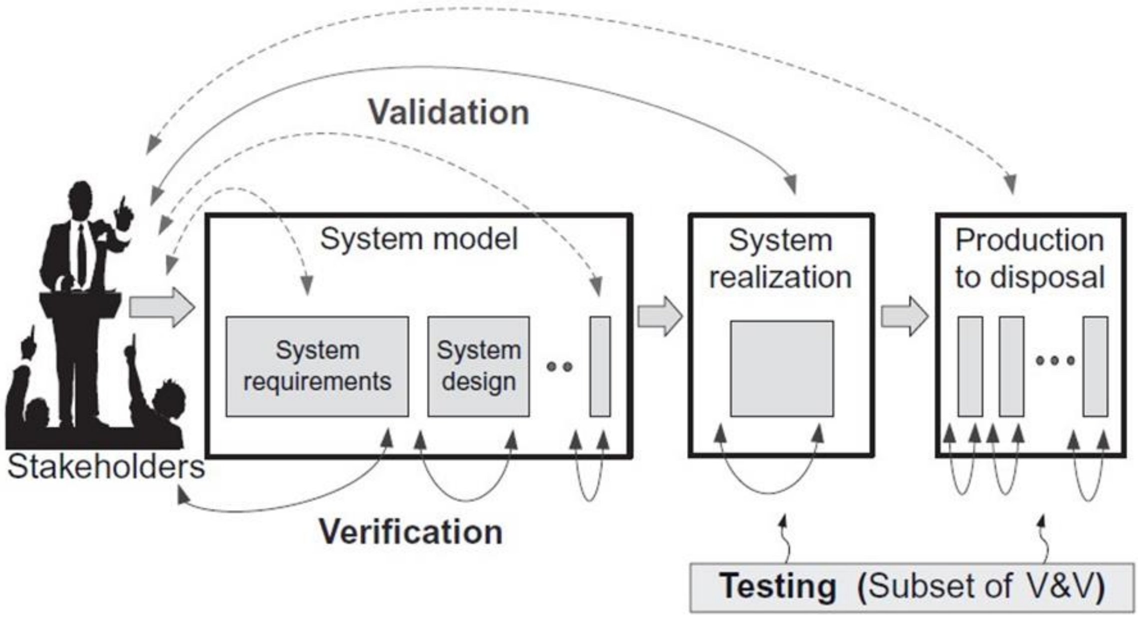



*Figure 12: Verification and validation in SE perception [10]*

General differentiation between verification and validation:

- **Verification** is the process of evaluating a system to determine whether the products of a given development phase satisfy the conditions imposed at the start of that phase. [10]
- **Validation** is the process of evaluating a system to determine whether it satisfies the stakeholders of that system. [10]

#### *2.5.5.1 Verification*

A verified system is one that has been finished and evaluated against specified requirements, to find out whether it satisfies the requirements it was built for. Verification answer the question: *Was the product built correctly? [10]*

Therefore functional tests are defined as verification of a component's or system's function.

*ANSI/EIA-632 defines verification as "the confirmation by examination and provision of objective evidence that the specified requirements to which a product was built, coded or assembled has been fulfilled."* [10]

*In contrast to that IEEE-610 defines verification as "the process of evaluating a system or component to determine whether the products of a given development phase satisfy the conditions imposed at the start of that phase."* [10]

A failure in verification may derive from one or more of the following:

- Specified requirements (specifications, drawings, parts lists) have not been documented adequately.
- Developers/builders have not been following the specified requirements for the product.
- Procedures, workers, tools and equipment are improper or have been improperly used for building the product.
- Procedures and means have been improperly planned for verification.
- Verification procedures have been improperly implemented. [10]

If a failure occurs the DVP needs to be adjusted and an iterative loop has to be performed.

#### *2.5.5.2 Validation*

A validated system is one that has been realized and evaluated against specified requirements to identify if a product satisfies the stakeholders. Validation answers the questions: *Does the product do what it is supposed to do in its intended environment? Was the right product built?*

Therefore, durability tests are defined as validation of a component's or system's ability to withstand durability loads.

ANSI/EIA – 632 defines validation as *"the Confirmation by examination and provision of objective evidence that the specific intended use of a product (developed or purchased), or aggregation of products, is accomplished in an intended usage environment."* [10]

In contrast to that IEEE-610 defines validation as *"The process of evaluating a system or component during or at the end of the development process to determine whether it satisfies specified requirements"* [10]

To generate a duty cycle, which is an input for the DVP it is necessary to know specific input variables like:

- In which market shall the product be used?
- What are the lifetime targets?
- What does the road profile distribution look like?
- Does a reference customer load duty cycle exist?

From those variables the load data can then be derived via track profile selection, AVL CRUISE simulation, system analysis and damage calculation. The duty cycle is then defined by evaluating & balancing part specific damages, design duty cycle verification and the test program generation.

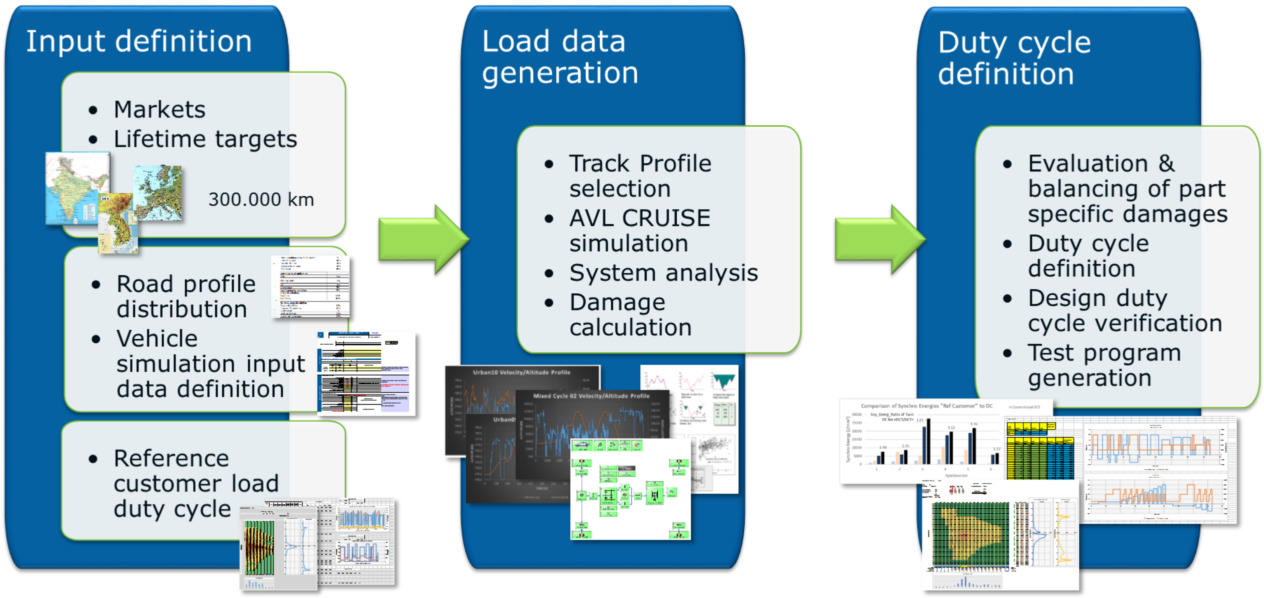



*Figure 13: Overview of the AVL Duty Cycle Generation [2]*

The AVL Load Matrix approach is used to identify how to activate certain failure modes within the duty cycle.

| SUBSYSTEM | FAILURE MODE | FAILURE LOCATION | CAUSE OF FAILURE | EFFECT ON SYSTEM | ACTIVATION |
|---|---|---|---|---|---|
| Input Shaft / Gear | Wear | Tooth flank | Mech. Load | NVH → Damage of transmission | High load operation |

*Table 3: Exemplary failure mode activation methodology [2]*

A failure in validation may derive from one or more of the following:

- Input requirements have not been identified adequately, e.g. target market or usage space of product not clear
- Design process has been executed incorrectly
- Input requirement changes have not been communicated
- Procedures have been improperly planned for validation
- Validation procedures have been improperly implemented [10]

#### 2.5.5.3 Testing of a system

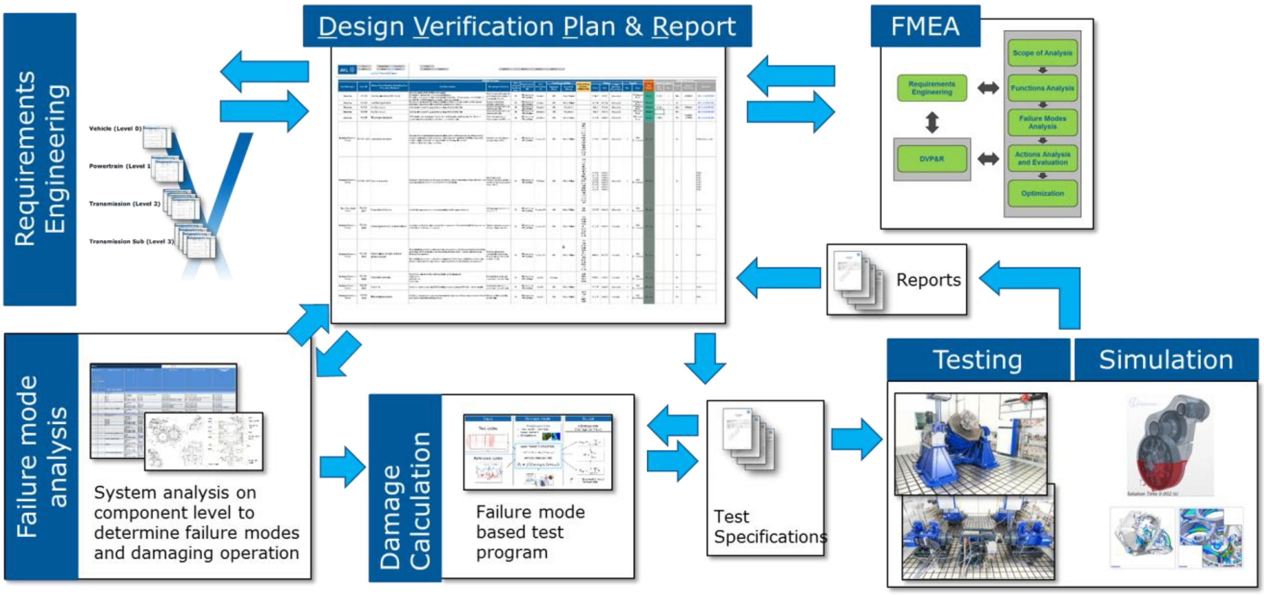



*Figure 14: AVL Validation Methodology DVP&R [2]*

Figure 14 shows the schematic overview of AVL's validation methodology DVP&R, which consists of the following main sections:

- Requirement engineering
- FMEA (Failure Mode and Effects Analysis)
- Failure Mode Analysis
- Damage Calculation
- Testing & Simulation

They all have a huge impact on the DVP due to both giving and receiving information from the above-mentioned main sections of the DVP&R.

This methodology covers all necessary tasks both to verify and validate a product and to monitor the ongoing progresses of the execution and the activities connected to it. On the one hand this methodology on the one hand aims at reducing the risk of missing tests in the validation and verification process and on the other hand to increase efficiency in regard to economical and technical aspects.

First of all, requirements need to be defined, second the system analysis has to be performed, where all components and their failure modes are identified. (See also chapter *2.10 - Failure Mode and Effects Analysis*)

This analysis includes the following topics:

1. Location of the component or subsystem e.g. housing, shaft, gear
2. Failure modes e.g. wear, HCF, LCF
3. Root cause of the failure e.g. thermal, electrical or mechanical load
4. Effect on the system e.g. leakage, short circuit, breakage
5. Damaging operation conditions e.g. transient-, high load operations
6. Damage model e.g. empirical, simulation based, simplified physical model

Generally speaking, the next step is to define all necessary verification and validation targets that need to be met in order to have a validated design. All failure modes from the system analysis need to be covered by the listed test cases in the DVP.

| DVP&R: Planning | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Test ID | Test Category | Test Case | Test Description | Test Environment | Test Environment additional in | Test Responsibility | | Test Duration (Execution Time) | Sample | | | | | Test status |
| | Functional Mechanical Testing | **Lubrication Oil Pump Suction Cold Test** | Check of sufficient oil supply to components which require lubrication (bearings, seal rings, gears,...) and cooling (solenoids, clutch packs) under all normal operating conditions. Also T low temperatures conditions (high viscosity of the fluid) particularly the oil pump will be tested - additional check lubrication under tilting | Test Bed | Tilt TB | Reinprecht | DTV | 4 | 4 | 1 | 1 | 1 | 1 | Done |

*Figure 15: Overview of the most important sections of the DVP [2]*

Figure 15 shows an exemplary overview of the DVP at transmission level. The main sections are shown in the following table:

| | |
|---|---|
| Test ID | Nomenclature for every test |
| Test Category | Every test may be differentiated into either functional or durability testing |
| Test Case | The smallest unit of a test procedure. It contains the name and minimal hints to the procedure (See also chapter *3.1.3.3*) |
| Test description | Brief description of the test case. How, what and why it is performed. |
| Test Environment | Test Bed, Simulation, In Vehicle |
| Test Environment Additional info | This column includes additional information about e.g. on which test bed the test has to be performed. E.g. Powertrain test bed, High load test bed etc. |
| Test Responsibility | Name of the responsible engineer and also whether AVL, the supplier or the customer is responsible. |
| Test Duration | Includes information about the test duration itself, without setup and commissioning time |
| Samples | Number of samples needed for every sample phase |
| Test status | Passed, Not Passed, Open, Done, Cancelled, Planned, Not Planned, e.g.: Passed (Not Passed) means that all requirements were (not) met. Those requirements are project specific. |

*Table 4 Overview of the components*

## 2.6 The theory of reliability

*"Reliability is the probability that a product does not fail during a defined period of time under given functional and surrounding conditions. [11]"* The following chapters were elaborated to better understand the impact of reliability on test duration and number of used samples.

### 2.6.1 The failure rate

To calculate the failure rate $\lambda(t)$ it is necessary to divide the failures at a point in time $t$ or in a class $i$ by the sum of units still intact:

$$\lambda(t) = \frac{Failures}{sum\ of\ units\ that\ are\ still\ intact}$$

*Equation 1 - Calculation of the failure rate*

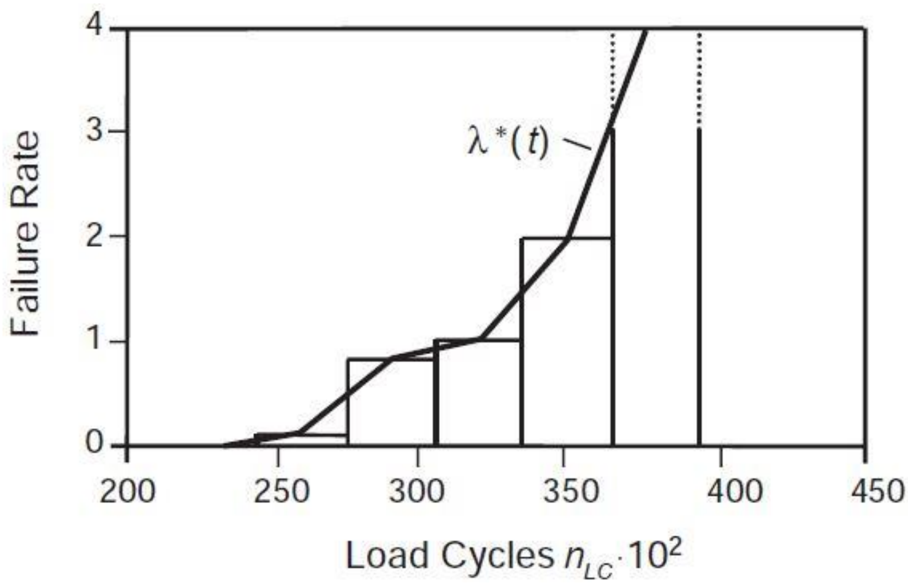



*Figure 16: Histogram of the failure rate and the empirical failure rate [11]*

Figure 16 shows the failure rate $\lambda(t)$ and the empirical failure rate $\lambda*(t)$ for a S-N curve trial run. The failure rate in the last class in Figure 16 is shooting towards infinity, because no intact samples are left any more. The equation's denominator approaches zero.[11]

## 2.6.2 The bathtub curve

The failure rate represents the measurement for the risk of a part to fail, under the condition that the sample has already survived up to this point in time. It defines how many of the still intact samples will break in the next time unit. To gain more statistical data the failure rate is not only used to describe wear out failures, but also early and random failures. The whole lifecycle of a sample can then be visualized in the so-called bathtub curve:

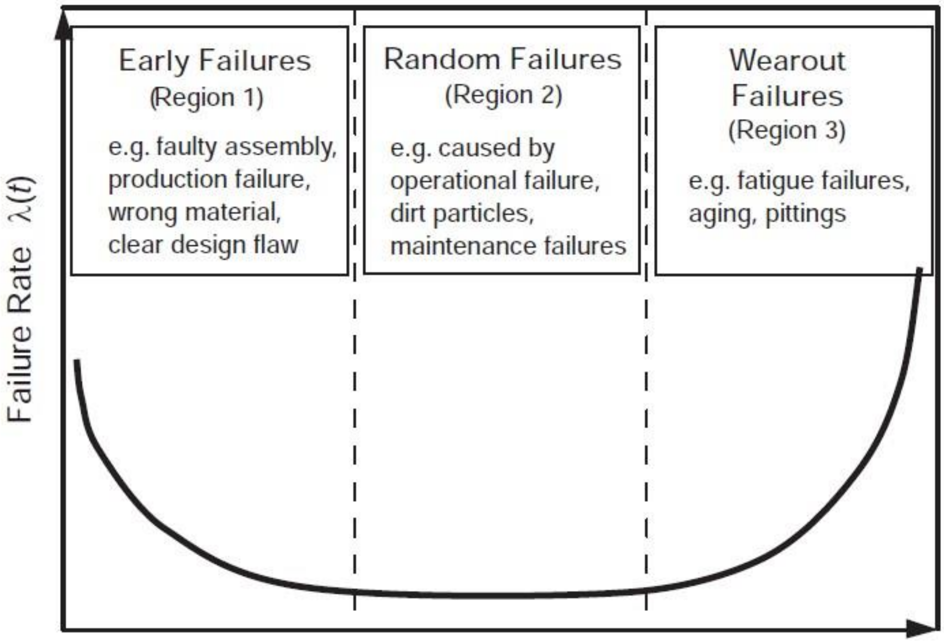



*Figure 17: Bathtub curve [11]*

The name bathtub curve derives from its shape. [12] [13] It describes the failure rate of the sample over time, but also takes its cause into account. For example, early failures may be caused by faulty assembly processes or production failures, random failures by operational failures by the customer or maintenance failures and wear out failures due to failure modes described at a later time in this thesis. To overcome those failures different counter measures can be set like pilot run series for early failures, correct operation and maintenance for random failures and practical trials for wear out failures. [11]

**Region 1:**

The likability for failure is decreasing over time, due to decreasing failure rate. Those failures are mostly caused by assembly-, production-, material problems or by design flaws. [11]

**Region 2:**

Due to the constant failure rate the risk for failure of the sample stays the same. In this region the risk can also be assumed as relatively low. Those failures are very hard to predict. Often they are caused by dirt particles or maintenance and operation failures. [11]

**Region 3:**

In the last region both the failure rate and the risk for failure increase drastically, due to wear out failures.

The counter measures for the failures in region 1 and 2 have to be taken early into account in the development process (design phase). Counter Measures for region 3 have to be implemented in the dimensioning phase, thus the design engineer has a huge impact on the results. Region 3 is the only region that may be calculated. In addition to that this region is also the most decisive one for reliability. [11]

### 2.6.3 Behavior of the bathtub curve

The bathtub curve is not always significant for all technical systems. A complex system’s failure behavior is not only characterized by the bathtub curve, but also by differing failure distribution, that show different behaviors in individual areas. Different behaviors are shown in the figure below:

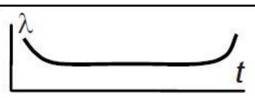
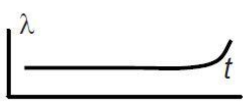
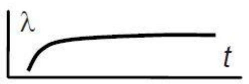
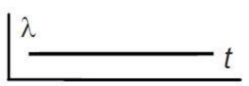
| | Failure behaviour | | General characteristics | Typical examples |
|---|---|---|---|---|
| wearout failures | A |  | • abnormal curve | • old steam engine (late 18th to early 19th century) |
| wearout failures | B |  | • simple devices<br>• complex machines with bad design (one single dominating type of failure) | • car water pump<br>• shoelace<br>• 1974 Vega engine |
| wearout failures | C |  | • structures<br>• wearout element | • car bodies<br>• airplane and automobile tires |
| random failures | D |  | • complex machines with high-stress trials after start of operation | • high pressure relief valves |
| random failures | E |  | • well designed complex machines | • gyro compass<br>• multiple sealing high pressure centrifugal pump |
| random failures | F |  | • electronic components<br>• complex components after corrective maintenance | • computer “mother boards”<br>• programmable controls |

*Figure 18: Various failure behaviors [14]*

*„Studies done by civil aviation (1968 UAL) show that only 4% of all failures have a trend as in example “A”, 2% have a trend as in example “B”, 5% as in example “C”, 7% as in example “D”, 14% as in example “E” and 68% as in example “F”. A constant failure behavior trend as in example “E” should be strived for in the design phase.“* [11]

### 2.6.4 Parameters of reliability

The following parameters are used to describe reliability data in the area of reliability engineering:

| | |
|---|---|
| MTTF | Mean Time To Failure |
| MTTFF | Mean Time To First Failure |
| MTBF | Mean Time Between Failure |
| $\lambda$ | Failure Rate |
| $q$ | Failure Quota |
| $B_q$ | Lifetime |

*Table 5 Parameters of reliability*

#### *2.6.4.1 MTTF*

The lifetime of a non-repairable system can be defined differently. The mean for the time without failures for an observed period of time is the expected value for the lifetime t, normally called (Mean Time To Failure). [11]

MTTF may be calculated as follows:

$$\mathrm{MTTF} = \mathrm{E}(\tau) = \int_0^\infty t * f(t)dt = \int_0^\infty R(t)dt$$

*Equation 2 - Calculation of MTTF*

Concerning MTTF it is not of importance, what happens to the components after the failure. [11] For MTTF the mathematical mean serves a good estimation, whereat $t_1$to $t_n$ are realizations of failure free time periods which are observed independently for identical time observation units.[15]

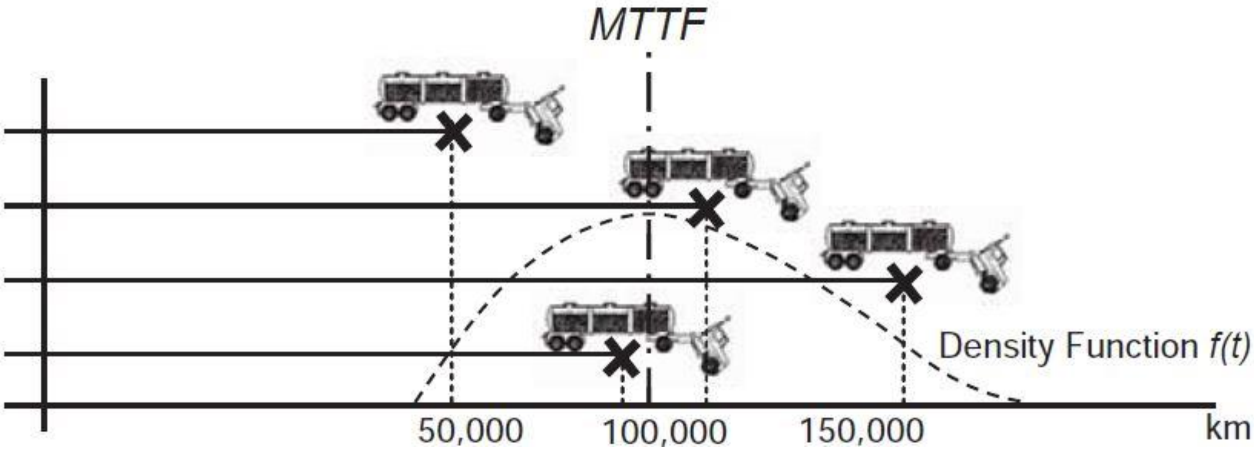



Figure 19: Schematic overview of MTTF function [11]

## 2.6.4.2 MTTFF

If a component may be repaired, the MTTFF should be used to describe the mean lifetime of a repairable component until its first failure. Therefore MTTFF correlates to MTTF of non-repairable components. [11]

## 2.6.4.3MTBF

In addition to that MTBF is used to describe the lifetime after the first failure of a component, until the next failure occurs and repair or maintenance is necessary. [11]

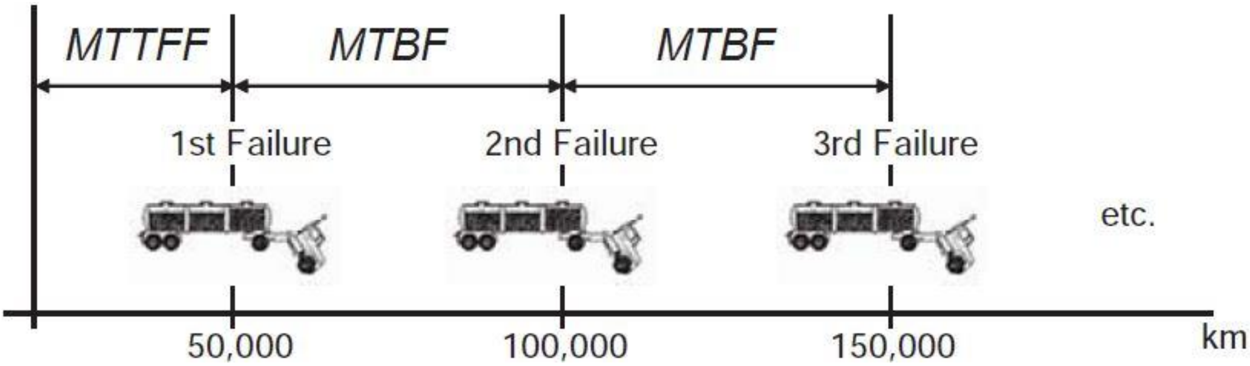



Figure 20: Schematic overview of MTTFF and MTBF [11]

### 2.6.4.4 Failure Rate and Failure Quota

The failure quota is defined as:

$$q = \frac{failures\ in\ a\ time\ interval}{initial\ quantity * interval\ size}$$

*Equation 3 - Calculation of the failure quota*

This failure quota may be used as an estimation for the failure rate $\lambda$. In contrast to that, the failure quota focusses on the relative change of an observed time interval.

If 10 Units out of a total number of 100 specimen fail within one day, the failure quota is:

$$q = \frac{10}{100}\left[\frac{1}{day}\right] \triangleq 10\%\ per\ day$$

*Equation 4 - Exemplary calculation of the failure quota*

The failure rate focusses on the risk of a component to fail if it has survived until now. For a more detailed description go to chapter *2.6.1 The failure rate*.

### 2.6.4.5 $B_x$ Lifetime

The x in $B_x$ stands for the point in time at which x% of all components have already failed. As a general rule $B_1$, $B_{10}$ and $B_{50}$ lifetime values are used to describe the reliability of a system. [11]

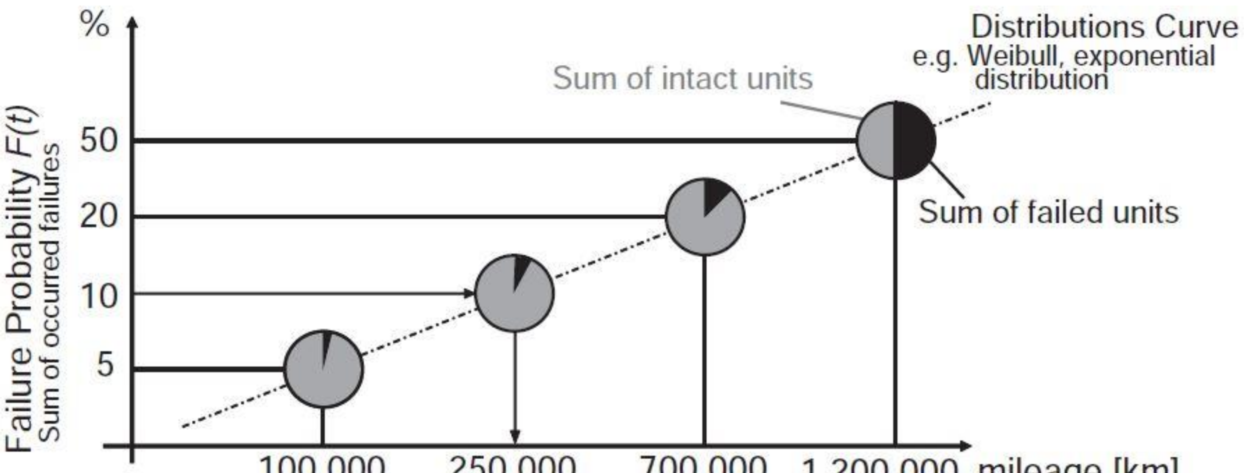



*Figure 21: $B_x$ Lifetime of a system [11]*

## 2.7 The meaning of probability

Von Mises defined the relative frequency in 1912 as:

$$h_{rel} = \frac{m}{n}$$

*Equation 5 - Calculation of the relative frequency*

Where $n$ is the size of a random test specimen, in that all entries are distributed equally in the trial and where $m$ is the number of elements which are recorded. The further $n$ is increased, the less $h_{rel,n}$ is scattered and strives against a constant value of $h_x$ as shown in the following figure: [11]

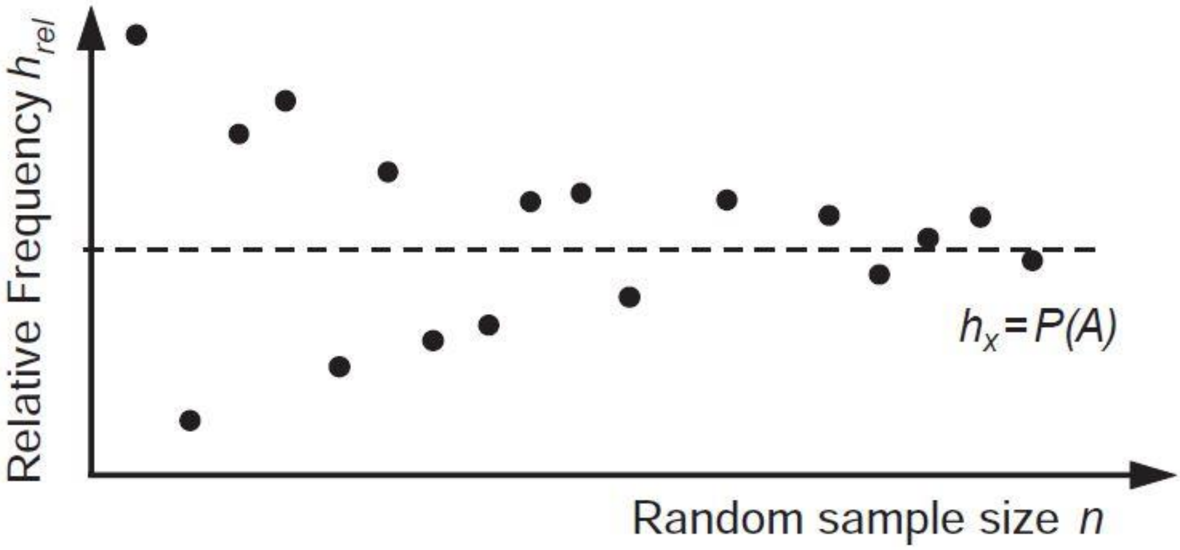



*Figure 22: Dependency of the relative frequency at random specimen sizes [11]*

Due to that fact, the limit of the relative frequencies can be approximated by the probability of failure.

$$\lim_{n \to \infty} \frac{m}{n} = P(A)$$

*Equation 6 - Calculation of the probability of failure*

*„The exact theoretical observations can be seen in the weak and strong law of large numbers as well as in the Bernoulli law of large numbers“ [16–18]*

This equation lacks reliability due to dealing with estimation and not with definition. Therefore, it is not universal. There have been attempts to develop an all-inclusive probability theory, which could not be solved. However for basic reliability judgments the equation is sufficient enough. [11]

## 2.8 Weibull Distribution

Many different failure behaviors can be described with the Weibull Distribution. Its density function illustrates this.

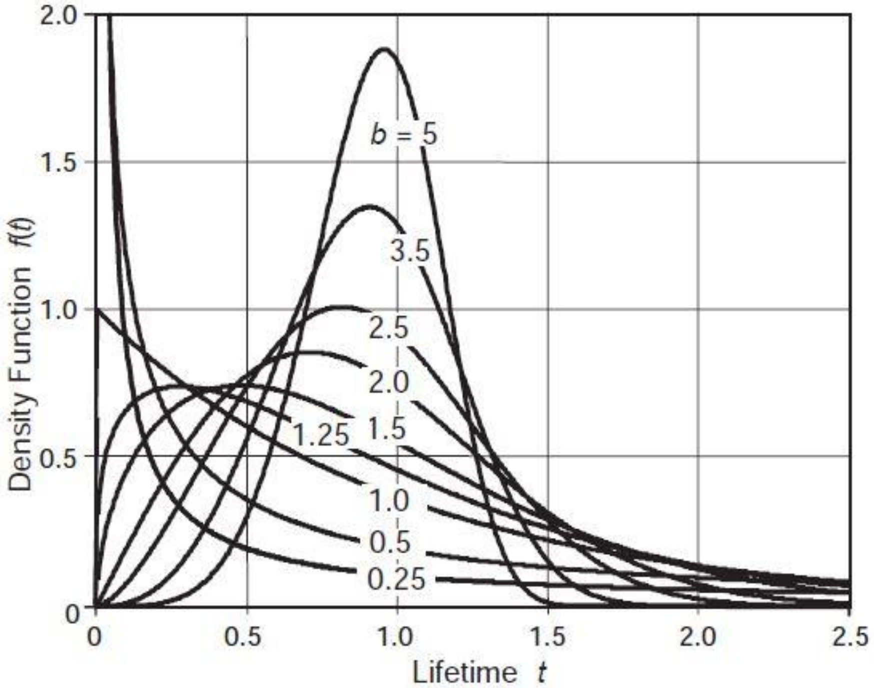



*Figure 23: Density function of the Weibull distribution [11]*

The density function is depending on the shape function $b$. The confidence intervals of statistical analysis are represented by the spread of the shape parameters. These are also dependent on the level of stress. Especially for gears and shafts the shape parameter $b$ has to be chosen in accordance to the level of stress. The higher the stress, the higher the shape parameter $b$ has to be. For low $b$-values the function behaves like an exponential distribution [11]

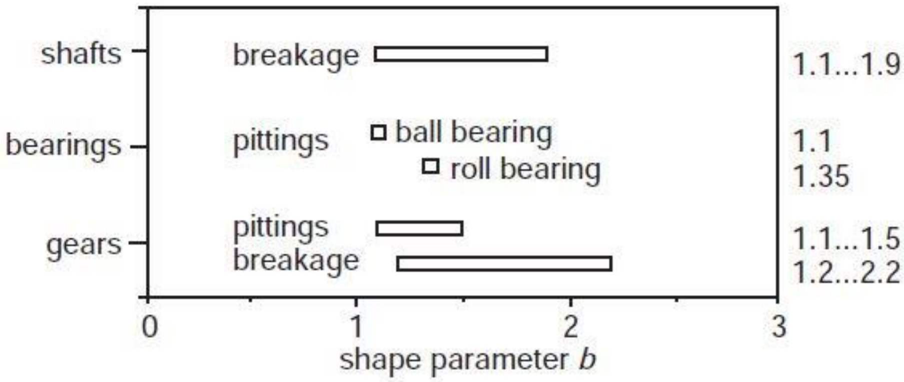



*Figure 24: Shape Parameter [11]*

Particularly bearings are the only machine components for which the failure behavior is documented in standards (ISO DIN 281 and DIN 622). [11]

In addition to that the three parametric Weibull distribution consists of the parameter's lifetime $T$, shape parameter $b$ and the failure free time $t_0$.

## 2.9 Calculation of System Reliability with the Boolean Theory

Based on the components' failure behavior it is possible to calculate the failure behavior of a complete system using Boolean system theory. [11, 19–23]

The parameters $b$, T and $T_0$ describe the failure behavior for each individual component.

For this calculation some assumptions have to be made:

- Either the system is non-repairable (lifetime until first failure), or a repairable system. Then it is only possible to calculate the reliability up to the first occurring failure.
- The state of condition is either "failed" or "functional"
- Failure behavior of one component does not influence the failure behavior of another component

Reliability schematic diagrams show effects and influences of one component to the complete system. A system starting with I (Input) and ending with O (Output) is functional as long as the connection between those two can be established. [11]

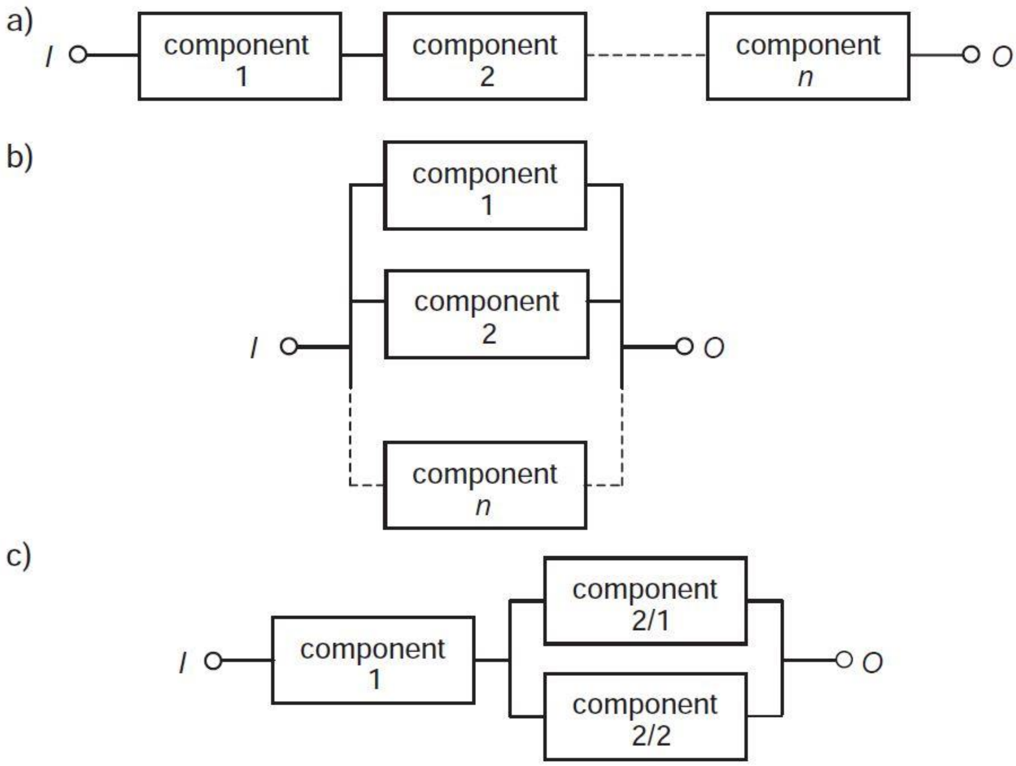



*Figure 25: Reliability Schematic Diagram [11]*

Figure 25.a shows that if one of the components fails, the whole system fails. (Serial structure)
Figure 25.*b means that* only if all components fail the system fails (Parallel Structure)
Figure 25.*c* is a combination of the two mentioned above. If component 1 fails, the whole system fails. Also, both components 2/1 and 2/2 have to fail, to make the system fail.

It is possible that the mechanical setup does not correlate with the reliability schematic diagram and that some components occur more than once.

The following example shows the process of creating a reliability schematic diagram from a drawing of a free wheel clutch to the complete reliability structure:

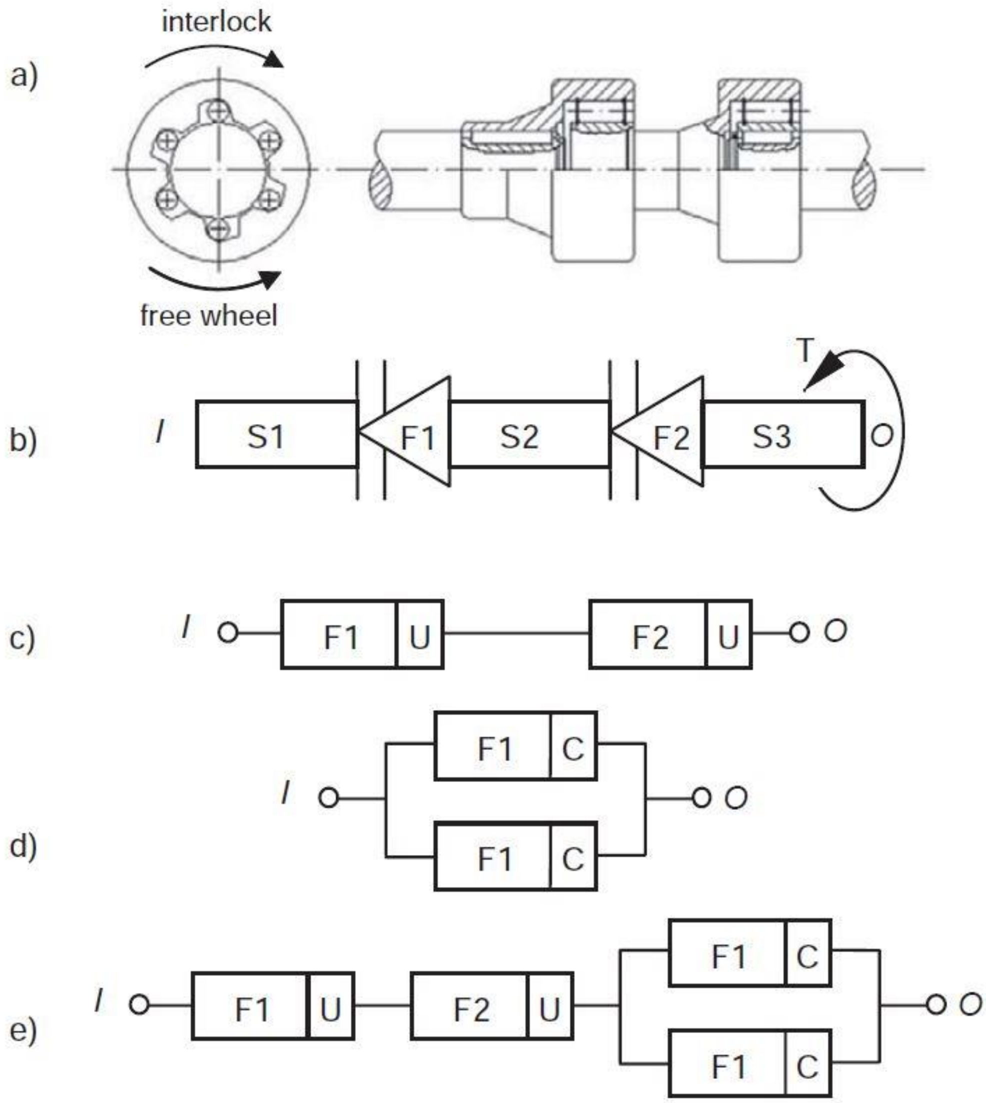



*Figure 26: From free Wheel Clutch drawing to Reliability Schematic Diagram [11]*

Figure 26 shows:

a) Drawing of the example system "free wheel clutch"

b) Principle sketch of the free wheel clutch system

c) Serial structure for the failure cause "interruption"

d) Parallel structure for the failure cause "clamping"

e) Complete reliability structure for the system free wheel clutch

The system's function in Figure 26 consists of transferring torque in one direction and interrupting it in the other direction. Then no torque transfer is possible any more. This method is used to break the single failure causes down on a structural level and then to evaluate them. The failure cause in this case is clamping on the one hand and interruption on the other. Clamping leads to rotational movement, whereas interruption disconnects the linked joints. *Figure 21.d* states a parallel system, due to further functionality of the system, even if one clutch clamps. Many systems therefore have a serial structure, due to elaborate evaluation of redundancies for high volume parts and repetition. To calculate the reliability for a serial system like this the following equation is used: [11]

$$R_s(t) = R_{C1}(t) * R_{C2}(t) * \dots * R_{CN}(t) \text{ or } R_s(t) = \prod_{i=1}^{n} R_{Ci}(t)$$

*Equation 7 - Calculation of the reliability of a serial system*

The definite reliability of each component is supposedly smaller than 1. Therefore, the reliability of the system is always less than the weakest component's reliability. With every additional component the reliability decreases. The failure behavior of the component may be described with a three-dimensional Weibull distribution: [11]

$$R_C(t) = e^{-\left(\frac{t-t_0}{T-t_0}\right)^b}$$

*Equation 8 - Calculation of the failure behavior*

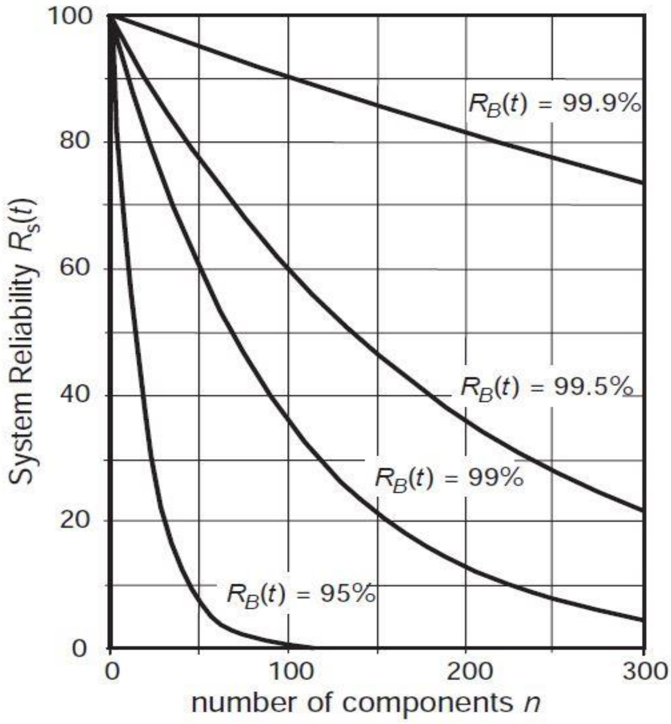



*Figure 27: System reliability over the number of components [11]*

The system's reliability may be calculated by the following equation:

$$R_S(t) = e^{-(\frac{t-t_{01}}{T_1-t_{01}})^{b_1}} * e^{-\left(\frac{t-t_{02}}{T_2-t_{02}}\right)^{b_2}} * e^{-(\frac{t-t_{03}}{T_3-t_{03}})^{b_3}}$$

*Equation 9 - Calculation of the system reliability*

To calculate the time $t$ for a specific system reliability $R_S(t)$ can only be done by iteration. An exception would be $R_S(t) = 0,9$, where the $B_{10s}$ lifetime may be used. For special occasions the function of $R_S(t)$ is represented by an exact Weibull distribution. [11]

For a parallel system the reliability may be calculated by:

$$R_s(t) = 1 - (1 - R_1(t)) * \left(1 - R_2(t)\right) * \ldots * \left(1 - R_N(t)\right) \; or \; R_s(t) = 1 - \prod_{i=1}^{n}(1 - R_i(t))$$

*Equation 10 - Calculation of the system reliability for a parallel system*

Here, $n$ represents the system's redundancy grade.

## 2.10 Failure Mode and Effects Analysis

*"FMEA can be understood as the most commonly used and well-known qualitative reliability method in the area of reliability methodology. It is a dynamic preventive reliability method used in the modification of systems and accompanies the design cycle for modification of components. The overall aim is to analyze and modify components in the light of experience to achieve an optimum criterion of reliability assessment." [11]*

FMEA was used and developed by NASA (National Aeronautics and Space Administration) in the sixties of the last century and is used since then. It is also used for quality assurance, due to increasing complexity of products, cost demands and the desire for shorter development periods. In the following the FMEA methodology according to VDA 4.2 will be elaborated, because it is the most commonly used and most extensive procedure in the automotive industry in Europe. [11]

Since 1980 the FMEA method is specified in DIN 25 448 and stands for "**F**ailure **M**ode and **E**ffects **A**nalysis". It is a systematically, preemptively and team-oriented used method, with its fundamental idea to find all possibly occurring failure modes for random systems, subsystems and components, in combination with their failure effects and causes. Additionally, risk assessments and specifications for optimization actions are performed. This methodology shall help to find weak spots and occurring risks of a product early in the development phase of a product, in order to still be able to eradicate problems.[11]

*Figure 28* shows different procedures of the FMEA that are used most often:

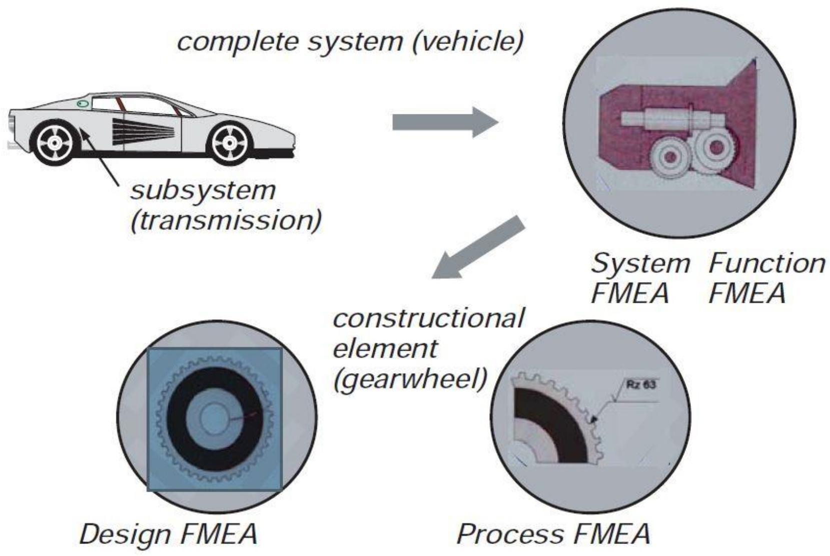



*Figure 28: Types of FMEA [11]*

An FMEA is carried out by interdisciplinary teams, to contain all areas of operation for the analysis.

FMEA is used due to the following:

- increasing quality demands from customers
- cost optimization for products
- compulsory liability required of the producer

The aims pursued by the system FMEA are:

- increase in the function security and reliability of products
- reduction in guarantee and warranty costs
- shorter development processes
- new production startups with fewer disturbances
- improved fulfilment of deadlines
- economical manufacturing
- improved services
- improved internal communication

### 2.10.1 FMEA improvements in VDA 4.2

The procedure has been improved to

- identify functional relationships between the system and its system elements
- to derive possible failure functions of a system element and all logical connections between failure functions of various system elements that belong together, to describe their effects, failure modes and cause for the system. [11]

Thus, a system is defined as an entity

- that excludes itself from surroundings via system boundaries. Interfaces are input and output variables.
- that can be separated into partial systems or system elements, with hierarchical levels
- that may be divided into different types according to its purpose (e.g. assembly, function groups, etc.) [11]

A function in terms of FMEA is the general specific connection between input and output variables for systems.

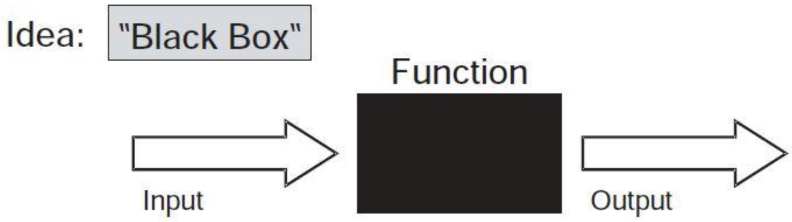



*Figure 29: A function modifies the Input to generate a desired output [11]*

Examples of functions would be:

| | |
|---|---|
| Transmission | Convert torque / speed |
| Electric motor | Convert electrical energy into mechanical energy |
| Pressure relief valve | Limit pressure |
| RAM (Read Access Memory) | Save signals |

*Table 6 – Gives examples of functions*

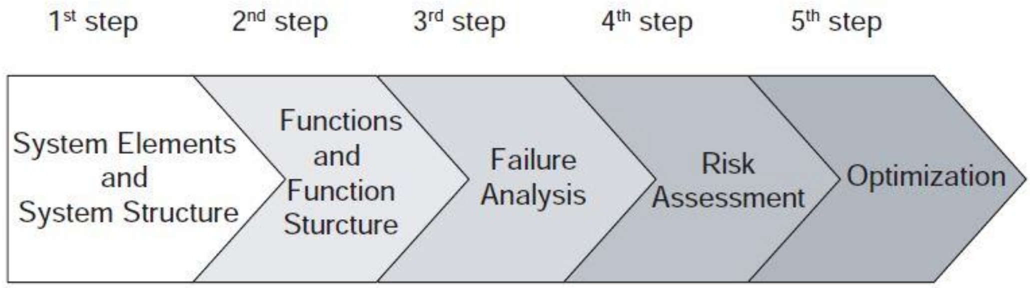



*Figure 30: The 5 steps of FMEA [11]*

### *2.10.1.1 System Elements and System Structure*

This step is further divided into the following subsections:

- Definition of level of complexity of the system that is investigated
- Separating the system into its system elements (assembly, function groups, components)
- Hierarchical order of those system elements

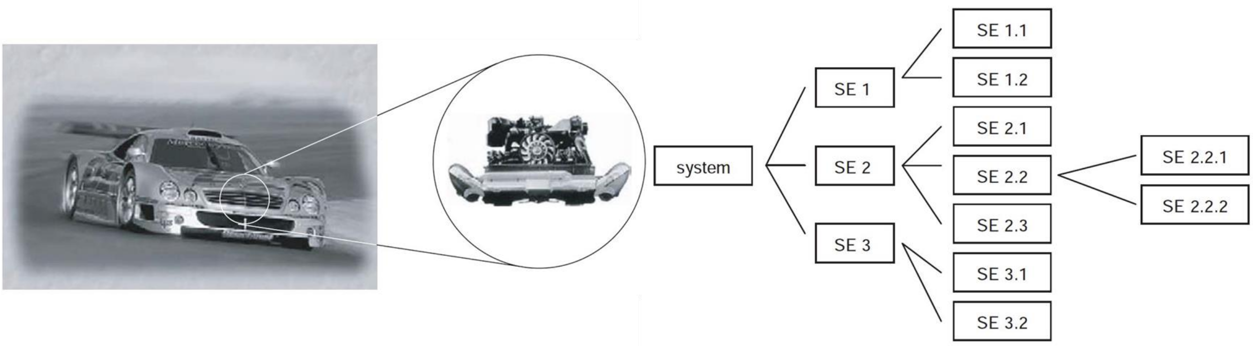



*Figure 31: Limitation of the observed system and its system structure [11]*

#### 2.10.1.2 Functions and Function Structure

For creating the functions of the system, the “top down” approach may be used, beginning with the function on the highest level.

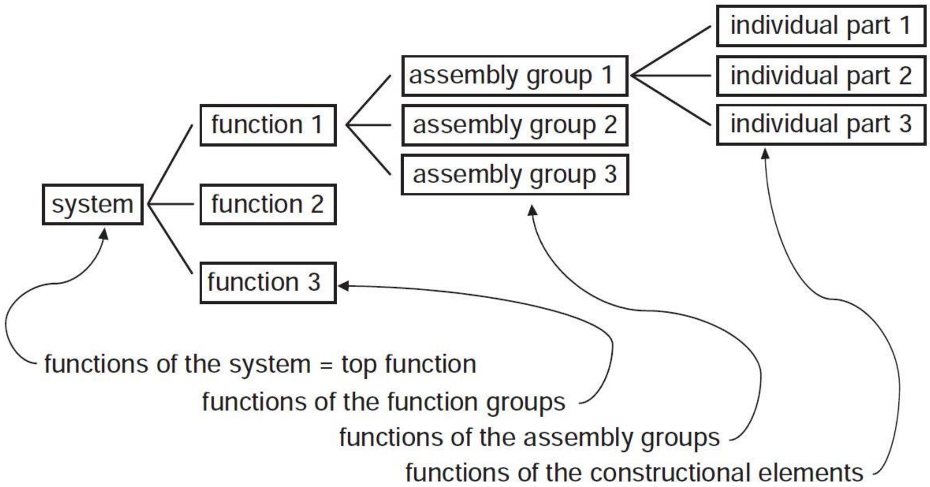



*Figure 32: Function analysis in FMEA [11]*

To fulfill the function at the top all functions below need to be functional as well. [11]

According to Pahl/Beitz the main categories for the functions are:

| | |
|---|---|
| Geometry | dimensions, height, width, length, diameter, required space, quantity, alignment, connection, extensions and expansion |
| Kinematics | extension and expansion |
| Forces | movement type, movement direction, speed, acceleration, size of force, direction of force, frequency of force, weight, load, strain, stiffness, spring, spring characteristics, stability, resonances |
| Energy | power, degree of efficiency, loss, friction, ventilation, state variables e.g. pressure, temperature, humidity, heating, cooling, connection energy, storage, work intake, transformation of energy |
| Material | physical and chemical characteristics of the input and output product, auxiliary materials, required materials (law of nourishment), material flow and transportation |
| Signal | input and output signals, display mode, operation and monitoring equipment, type of signal |
| Safety | direct safety technology, protective systems operation, work and environment safety |
| Ergonomics | Man-Machine relationship, operation, type of operation, lucidity, lighting, design |
| Manufacturing | confinement through production plants, largest producible dimensions, preferred production |
| Control | process, workshop facilities, possible quality and tolerances measuring and control options, specific regulations (TUV, ASME, DIN, ISO) |
| Assembly | specific assembly regulations, assembly, installation, construction site assembly,<br>foundation |
| Transportation | limitation through lifting gear, path profile, route of transport according to size and weight, type of dispatch |
| Usage | low noise level, wear rate, application / distribution area, place of installation |
| Maintenance | maintenance-free and/or amount and time required for maintenance, inspection, replacement and repair, painting, cleaning |
| Recycling | reuse, recycle, waste management, waste disposal, disposal |

| | |
|---|---|
| Costs | max. allowable production costs, tool costs, investment and amortization |
| Schedule | end of development, network plan for intermediate steps, time of delivery |

*Table 7- Guidelines for specification lists [24]*

Top functions are essential for the correct operation of the system to fulfill product goals. The top system function is separated into its partial system functions and subsystem functions until their components functions are established. [11]

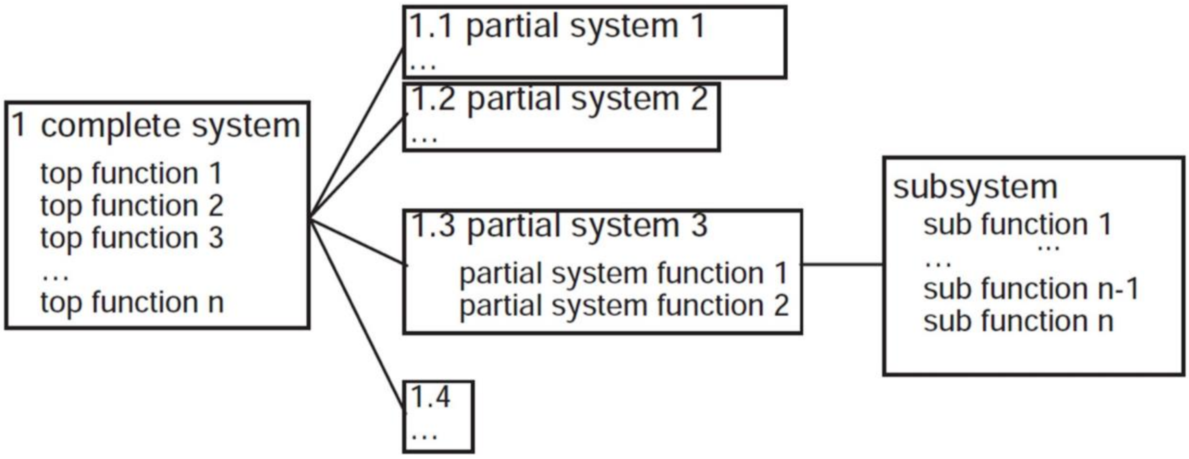



*Figure 33: Functions of the system elements [11]*

Figure 33 shows how the system's top functions may be further distributed until component level has been reached.

### 2.10.1.3 Failure Analysis

All possible failures that cause limitation or failure of the function have to be taken into account, during the failure analysis.

The following table shows typical failure modes that might occur during operation of the system:

| | | |
|---|---|---|
| • crack | • too loud | • overstretched |
| • abrasion | • congested | • bent, sagging |
| • rejected | • contaminated | • distorted, deformed, dented |
| • chips away | • leaky | • relaxed, loose, wobbles |
| • wear (also bedding-in, pittings,...) | • busted | • clamps, sluggish |
| • insufficient time characteristics | • depressurized | • friction is too high of too low |
| • rotted, decomposed (prematurely) | • false pressure | • too much expanded |
| • damaged, prematurely worn out | • corroded | • part is missing |
| • vibrates | • overheated | • wrong part (not a safely usable constr.) |
| • swings | • burnt | • wrong position (no constr. measurement) |
| • resonances | • charred | • too maintenance intensive |
| • unpleasant sound | • blocked | • poorly replaceable |
| • constr. inverted assembly possible | • false speed | • not further useable |
| • fracture | • false acceleration | • interchanged (no constr. measurement) |
| • location to reverse side is false | • false spring characteristics | |
| • false configuration | • false weight | |
| • entry of dirt and water | • poor degree of efficiency | |

*Table 8 - possible failure modes during operation [11]*

Those failure modes may be found and also supported by the following methods:

- damage statistics
- experience of the FMEA team members
- check lists
- creativity procedures (Brainstorming, 635, Delphi, etc.)
- systematically with the functions or failures functions / fault trees.

The relationships between failure- effects, modes and causes can be clarified with a failure network. This process is shown in the following figure:

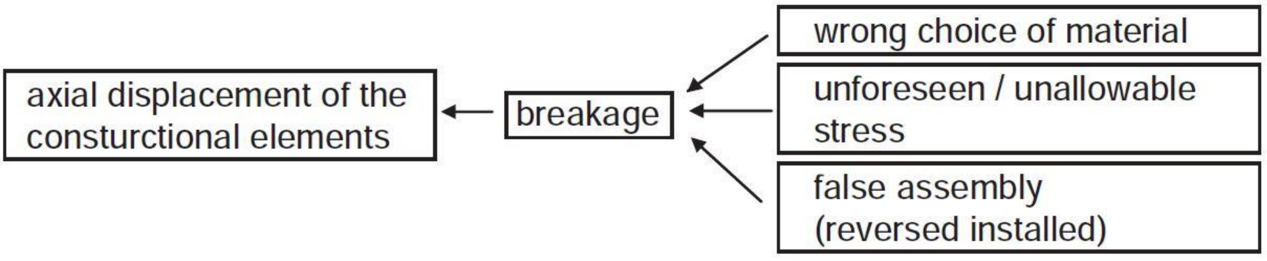



*Figure 34: Failure network for the fracture of a sleeve [11]*

Failure modes may be carried over to another level since there could be interdependencies or overlappings.

#### *2.10.1.4 Risk Assessment*

For assessing the risk three different criteria are used:

- **S**everity
- Probability of the **O**ccurrence
- Probability for **D**etection of the occurring failure cause

In regard to severity the investigation is performed from the standpoint of the customer. The range for the severity number $S$ ranges from 1 (very low severity) to 10 (extremely high severity – hazard for people) [11]

After considering all listed preventive actions the assessment for probability of occurrence $O$ is performed. Again, the value ranges from 1 (very improbable potential failure cause) to 10 (very likely that the failure cause will occur). Hence, this investigation states the quantity of defective components that remain in the whole batch of a product. [11]

To investigate the probability for detection $D$ all detection actions have to be assessed. Actions to detect resulting potential failure causes are taken into account. A value of 1 means that it is very likely to detect the failure cause before delivering the product to the customer, whereas a value of 10 is assigned if no detection actions are mentioned. [11]

Those three variables lead to the **R**isk **P**riority **N**umber. It is calculated by:

$$RPN = S \; x \; O \; x \; D$$

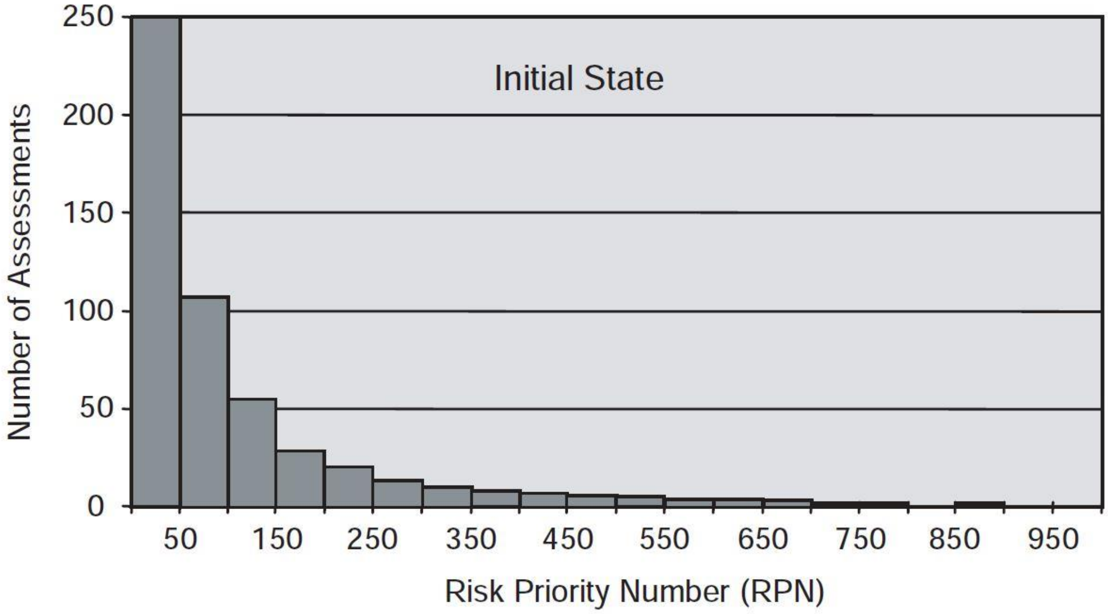



*Figure 35: Exemplary distribution of RPN [11]*

Therefore, it can range from 1 (very low) to 1000 (very high). The RPN represents the total risk for the system operator and is used as a base for decisions regarding optimization actions. For high RPNs it is important to lower the risk by design and quality assuring actions. This also goes for $S, O$ & $D$ values greater thatn 8. $O \; x \; D$ hints the probability for remaining defects that might get to the customers. [11]

### 2.10.1.5 Optimization

Optimization has to be performed for high RPNs or high individual assessment values. The process is started at the failure cause with the highest RPN. There are two commonly approaches used for how to proceed. Either the process is continued deceedingly until a certain limit is reached (e.g. RPN = 125) or following the Pareto principle, until the first 20-30 % of RPNs were processed.

Additionally, high individual assessment values have to be investigated. E.g. Occurrence > 8 leads to very frequently occurring failures. Severity > 8 points out that the risk has to be taken into account very seriously. Moreover detection values greater than 8 are very hard to detect. [11]

The following table gives a brief summary of the paragraph above:

- Ranking of failure causes according to their **RPN** values
- Concept optimization beginning with the failure causes with the
- greatest **RPN**
    - until a set RPN limit (e.g. RPN = 125) or
    - until a certain amount of failure causes (common according to the Pareto principle ca. 20 -30 %)
- Failure causes with
    - **> 8**
    - **S > 8**
    - **D > 8** observed separately
- **FMEA** result observed separately

*Table 9 - Concept Optimization Procedure*

Optimization measures would be new preventive or detection measures derived from the FMEA results. They can either prevent the potential failure cause, reduce its occurrence, reduce the severity, or increase the likability of detection by altering the design or process, conceptional changes for the product and changes in testing procedures. [11]

The taken measures shall be ranked according to their priority:

- Change of concept
- Increase concept reliability
- Effective detection actions

Then the RPN is recalculated for all the systems, subsystems and components and compared to the initial state as seen in the figure below:

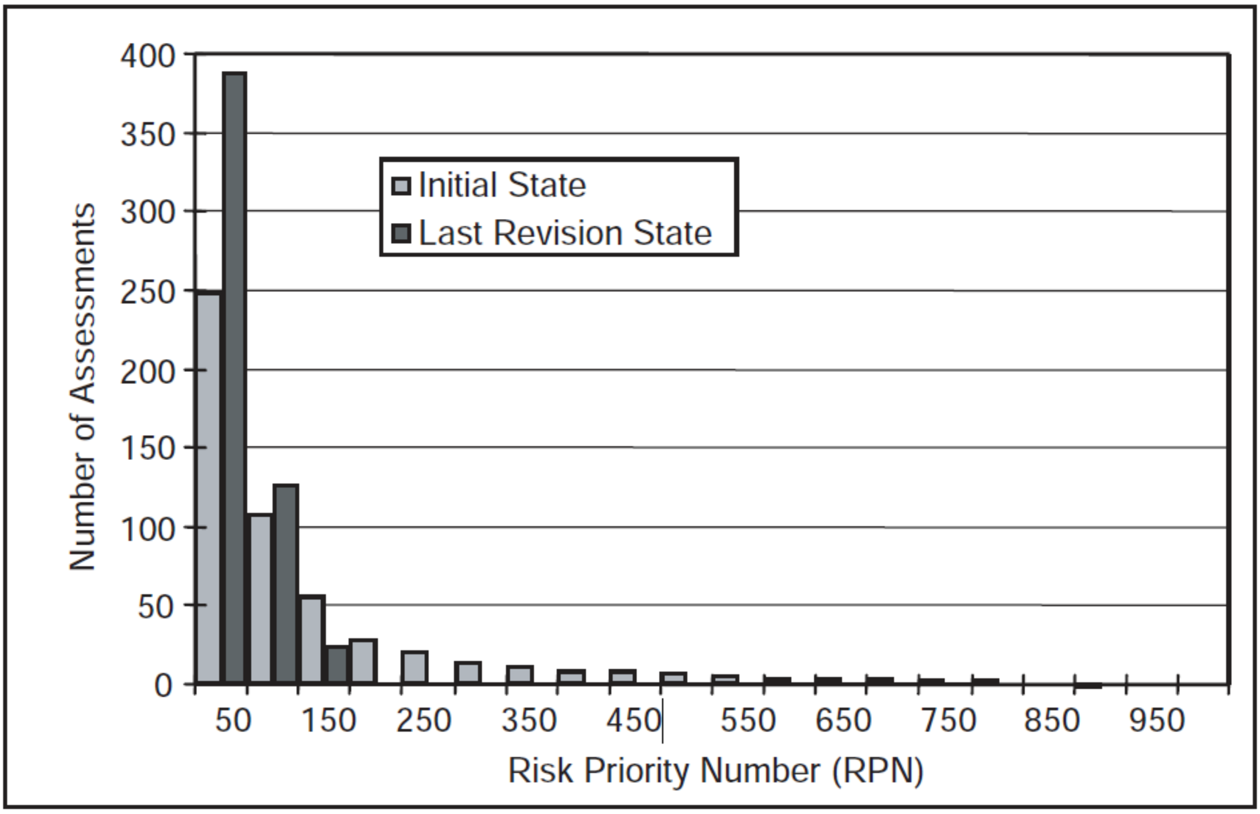



*Figure 36: Comparison of initial and revised RPNs [11]*

## 2.11 Failure Modes

### 2.11.1 Fatigue

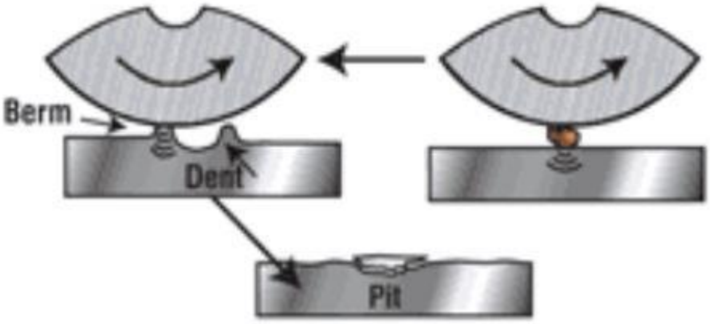



*Figure 37: Surface Fatigue [25]*

Fatigue may be divided into High Cycle Fatigue (HCF) and Low Cycle Fatigue (LCF) which are both parts of the dynamic strength of a material. All reoccurring load cycles lead to increasing material failure. They start to become visible by an initial crack and then further proceeding stress frequency lead to fatigue failure of the part. Even stresses that are significantly below the yield strength can cause fatigue failures. Due to that fact it is not enough to calculate the static proof of strength for the part. [26]

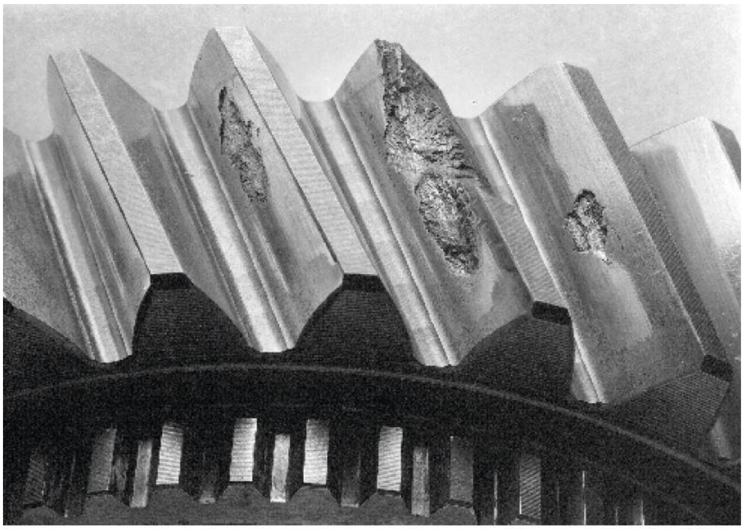


*Figure 38: Pitting and crack of the tooth tip due to fatigue of the tooth flank [27]*

### 2.11.2 Wear

Wear can be divided into abrasive- , adhesive-, tribochemical- and rubbing wear.

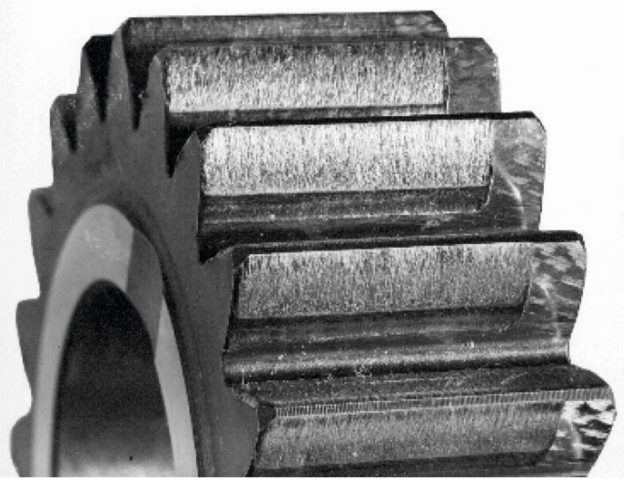


*Figure 39: Seizure over the total width of the gear contact pattern of a gear [27]*

### *2.11.2.1 Abrasive Wear*

Due to relative movement of surfaces, material separation processes occur. Abrasion may be further divided into micro-ploughing, micro-fatigue, micro-breakage and micro filing, whereby the three first listed play a subordinated role for gears. Chip formation may be a result of roughness peaks of hard tooth surfaces or hard particles within the lubricant rubbing against opposing bodies. [28]

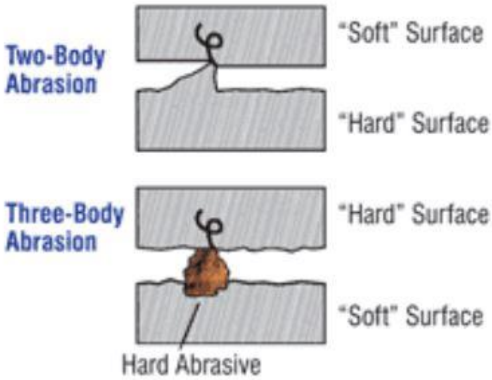



*Figure 40: Abrasive wear [25]*

### 2.11.2.2 Adhesive Wear

By reasons of boundary- and mixed friction roughness peaks are deformed, so that boundary layers which are adhesive to the surface, are broken through. The contact of metallic contact partners leads to molecular boundaries, which strength of material is higher than the surface material itself. Because of relative movement of the contact partners material separation occur. Thus, material is transferred from one surface to the other, or loosened wear particles are formed. This mechanism appears under too high load or lack or lubricant as seizure [28]

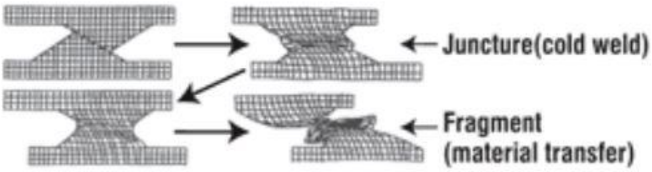



*Figure 41: Adhesive Wear [25]*

### 2.11.2.3 Tribochemical Wear

Herein chemical reactions between particles and intermediate- or ambient medium occur. They are activated by tribological stress. This chemical process leads to particles and reaction layers, which have different mechanical properties compared to the surface material. This process is deliberately used during gear production through using additives or cooling lubricants to generate wear reducing reaction layers at tooth flank surfaces. In contrast to that corrosion phenomena are undesirable, which may occur because of the condition of the ambient medium. [28]

### 2.11.2.4 Rubbing Wear

Rubbing wear occurs due to vibrational motion with small amplitude between two surfaces in contact which leads to loss of material.

### 2.11.3 Thermal and Chemical Aging

The term aging describes the chemical change that occurs because of high temperatures in combination with catalytic metals. During the aging process oil molecules are oxidized. Turbulences in the oil and contamination in it intensify aging. Through oxidation inhibiting additives in oils, it is possible to increase the resistance to oxidation.[27] Although high temperatures have a huge impact on the aging process, it is also necessary to take the ratio between total lubricant volume and lubricant throughput into account. Because only a relatively small part or the lubricant quantity is exposed to those high temperatures. [29]

### 2.11.4 Corrosion

DIN EN ISO 8044:2015 defines corrosion as the following:

„Physicochemical interaction between a metal and its environment that results in changes in the properties of the metal, and which may lead to significant impairment of the function of the metal, the environment, or the technical system, of which these form a part [30]“

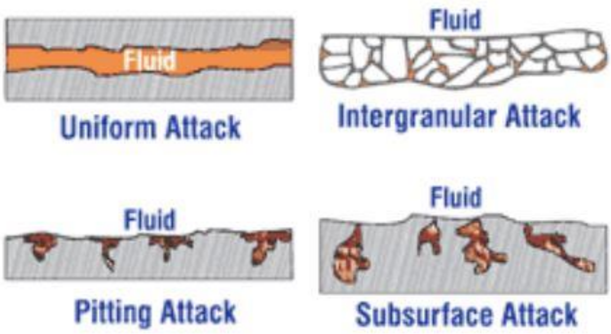



*Figure 42: Corrosive Wear [25]*

### 2.11.5 Cavitation

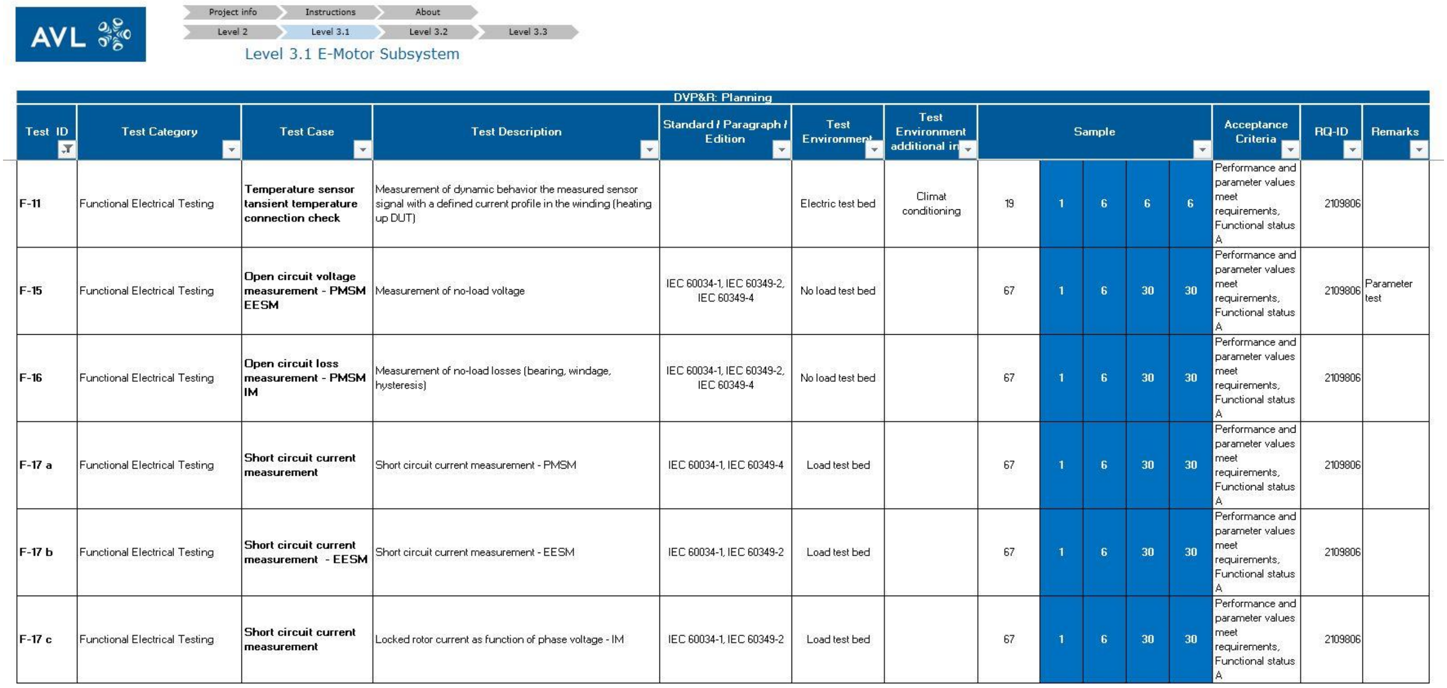
Cavitation is the formation of cavities in fluids due to local undershooting of the vapor pressure and is followed by an implosion. The undershooting of the vapor pressure may occur due to vibrations or turbulence flows. Hence micro jets with very high velocities emerge, that might hit the material's surface. [31]


*Figure 43: cavitation Wear [25]*

# 3 Developing the eAxle DVP

To stay competitive manufacturing companies need to improve their product and also introduce new ones to the market. Due to different reasons products may be rushed to the market, without concerning verification or validation procedures. Therefore, failures of the product are detected very often after the dispatch of those products. In addition to that, inappropriate testing or no testing leads to field failures, high warranty costs, loss of equity capital, product recalls and field campaigns. Those faults are very hard to endure for companies. To overcome those faults designers and manufacturers use design analysis tools and develop product testing procedures, which should be carried out very diligently. Especially with eAxles many manufacturers don’t know how to perform validation procedures. This is where AVL comes into play.

Overcoming those shortcomings is done in automotive, heavy equipment and aviation industry by organizing, describing, reporting and keeping documentation of the results with the Design Verification Plan and Report (DVP&R). AVL has DVPs on subsystem level (Transmission, eMotor and inverter). One of this master’s thesis’ goals was it to elaborate a DVP for eAxles that use synergies from their subsystems and enhance them in regards of reliability.




| DVP&R: Planning | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Test ID | Test Category | Test Case | Test Description | Standard / Paragraph / Edition | Test Environment | Test Environment additional in | Sample | | | | | Acceptance Criteria | RQ-ID | Remarks |
| F-11 | Functional Electrical Testing | **Temperature sensor tansient temperature connection check** | Measurement of dynamic behavior the measured sensor signal with a defined current profile in the winding (heating up DUT) | | Electric test bed | Climat conditioning | 19 | 1 | 6 | 6 | 6 | Performance and parameter values meet requirements, Functional status A | 2109806 | |
| F-15 | Functional Electrical Testing | **Open circuit voltage measurement - PMSM EESM** | Measurement of no-load voltage | IEC 60034-1, IEC 60349-2, IEC 60349-4 | No load test bed | | 67 | 1 | 6 | 30 | 30 | Performance and parameter values meet requirements, Functional status A | 2109806 | Parameter test |
| F-16 | Functional Electrical Testing | **Open circuit loss measurement - PMSM IM** | Measurement of no-load losses (bearing, windage, hysteresis) | IEC 60034-1, IEC 60349-2, IEC 60349-4 | No load test bed | | 67 | 1 | 6 | 30 | 30 | Performance and parameter values meet requirements, Functional status A | 2109806 | |
| F-17 a | Functional Electrical Testing | **Short circuit current measurement** | Short circuit current measurement - PMSM | IEC 60034-1, IEC 60349-4 | Load test bed | | 67 | 1 | 6 | 30 | 30 | Performance and parameter values meet requirements, Functional status A | 2109806 | |
| F-17 b | Functional Electrical Testing | **Short circuit current measurement - EESM** | Short circuit current measurement - EESM | IEC 60034-1, IEC 60349-2 | Load test bed | | 67 | 1 | 6 | 30 | 30 | Performance and parameter values meet requirements, Functional status A | 2109806 | |
| F-17 c | Functional Electrical Testing | **Short circuit current measurement** | Locked rotor current as function of phase voltage - IM | IEC 60034-1, IEC 60349-2 | Load test bed | | 67 | 1 | 6 | 30 | 30 | Performance and parameter values meet requirements, Functional status A | 2109806 | |

*Figure 44: Schematic overview of the E-Motor DVP [2]*

## 3.1 DVP Workshop

In September 2018 three different departments of AVL came together to hold a workshop on what the future DVP would look like. Representatives of the eMotor, Power Electronics, Design, Software and Testing fractions where attending. The initial obstacle was there removed jointly, to create a common understanding of the DVP that from now on is used for the above-mentioned fractions.

### 3.1.1 Naming

The first and most essential obstacle to overcome was the naming of different terms and definitions that are used in the DVP-document. For example, the term for the specimen was defined as UUT – Unit under Test and not as Design under Test, as many other fractions were used to use.

#### *3.1.1.1 The levels in the DVP*


*Figure 45: Overview of the DVP's header [2]*

As shown in Figure 45 the main sheet tabs of the DVP levels are mentioned together with project information, instructions and the about part.

The actual selected tab is highlighted in blue and all information according to the level is displayed below on the screen.

| | |
|---|---|
| Level 2 | eAxle level - consisting of generic test cases for eMotor, Inverter / Power Electronics and Transmission in conjunction |
| Level 2.1 | eDrive level – this level was additionally added at the very end of this master thesis, hence it is not shown in Figure 45 |
| Level 3.1 | eMotor level – here all generic test cases for verification of the eMotor are listed |
| Level 3.2 | Inverter / Power Electronics level – consists of all generic test cases for verification of an inverter |
| Level 3.3 | Transmission level – consists on all generic test cases for verification of a transmission, from which this thesis derived from partly, due to my former experience. |

*Table 10 - Brief description of the DVP levels*

Table 10 shows an overview including a short description for each level of AVL's DVP. In the further chapters more detailed explanations will be given.

#### 3.1.1.2 The definition of a test case

One of the main challenges was finding a word that would satisfy all fractions that were joining the workshop to describe one row or line in the DVP document.

Test case was the name that was agreed upon jointly. It describes the purpose of the test that shall be performed.

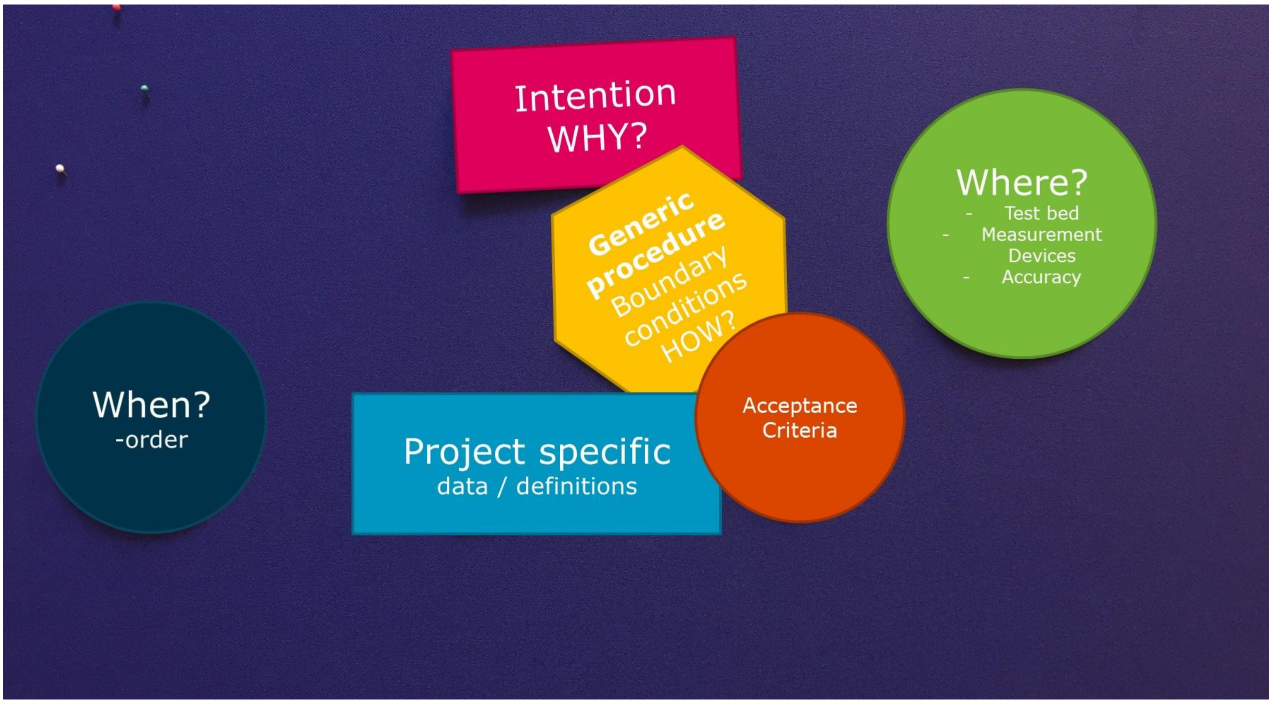



*Figure 46: Finding the building blocks of AVL's DVP [32]*

Therefore, a test case is one single line in the DVP that consists of the following main building blocks, that came up during the brainstorming process:

- Intention – Answers the "Why" the test is performed
- Generic Procedure – Answers the "How" the test is performed
- Acceptance Criteria
- Project specific data and definitions

Additionally, the questions "Where" and "When" are answered. E.g. "Where" would be on which test environment, with which measurement devices and which accuracy of those devices is necessary to perform the test. Furthermore "When" is used to come up with an order for the test cases to use synergies, to not always use a new specimen or UUT.

#### 3.1.1.3 The definition of a test specification

A test specification or test spec in short, consists of at least one test case. The worst-case scenario would be, if only one test case is covered. It can also consist of several test cases. Additionally, to that it also consists of more detailed information about the test environment.

$$Test\ Spec = Test\ Bed + AVL\ Puma + Periphery$$

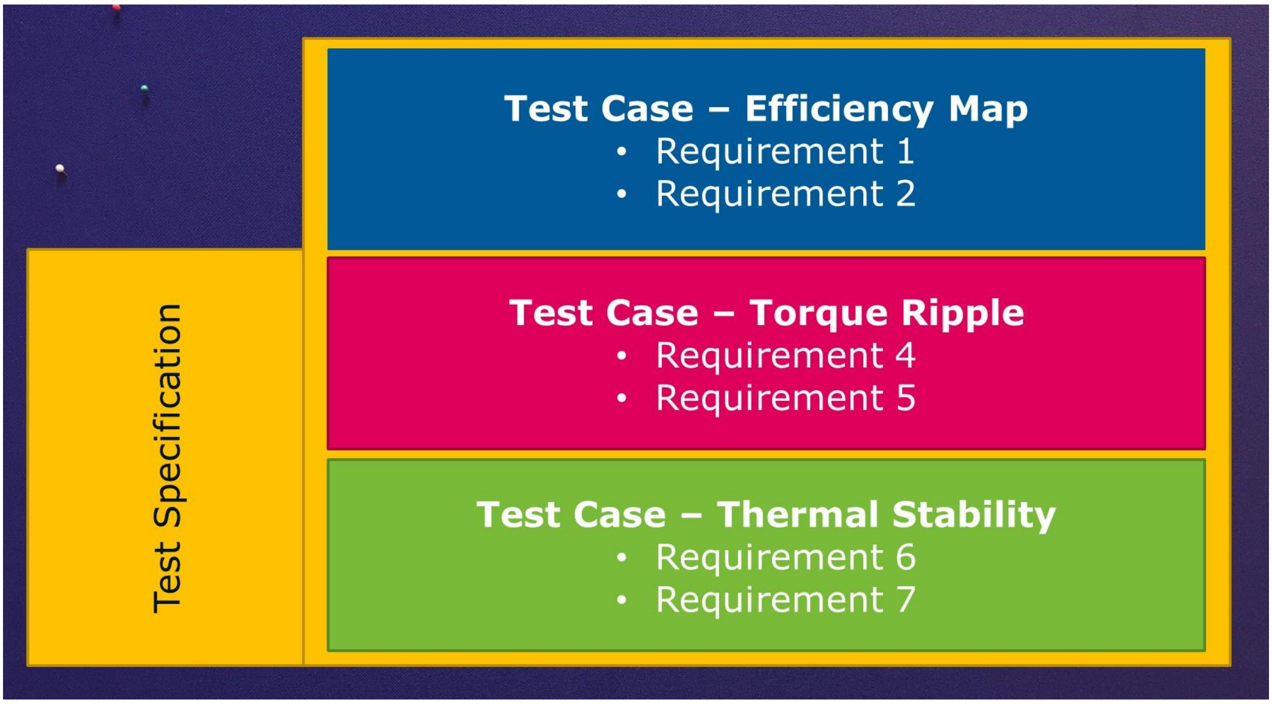



*Figure 47: Schematic example of a test specification [32]*

Figure 47 shows the structure of a test specification consisting of three exemplary test cases and their individual requirements.

### 3.1.1.4 *Sample Phases*

| Overview of the sample phases by AVL | |
|---|---|
| Generation 0 | Concept phase |
| Generation 1 | Functional development based on prototypes |
| Generation 2 | Durability behavior development based on prototype |
| Generation 3 | Production validation |

## 3.1.2 Test Categories

Every test case can be assigned to a specific test category, which is furthermore allocated to a main chapter.

Those chapters are either "Functional Testing" or "Durability Testing". This classification leads to the separation into two different types of tests that verify the function of a component, subsystem, system or product or check if lifetime targets were met.

Additional each of the main chapters can be further segmented as shown in Figure 48 and Figure 49.

Functional Testing aims at evaluating the component's, subsystem's or system's function by testing it.

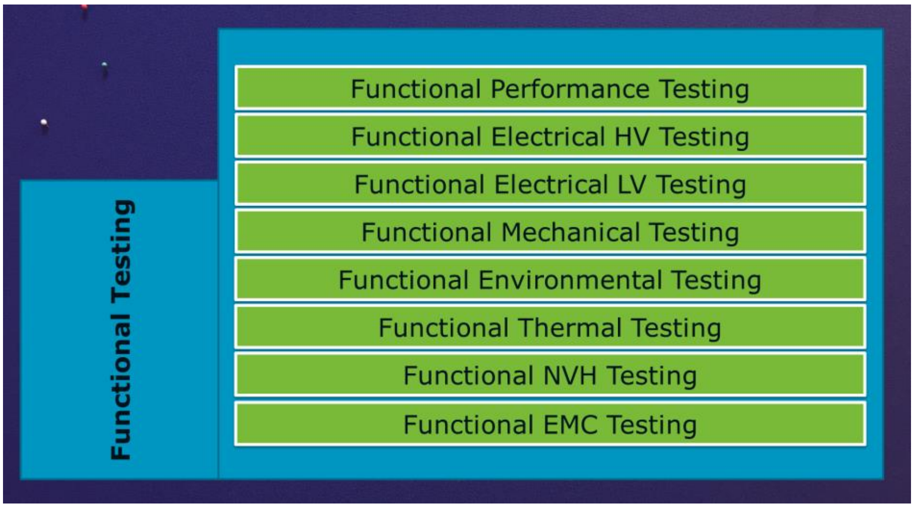



*Figure 48: Overview of the functional test categories [32]*

In contrast to that durability testing aims to cover the whole lifetime target of a component, subsystem or system.

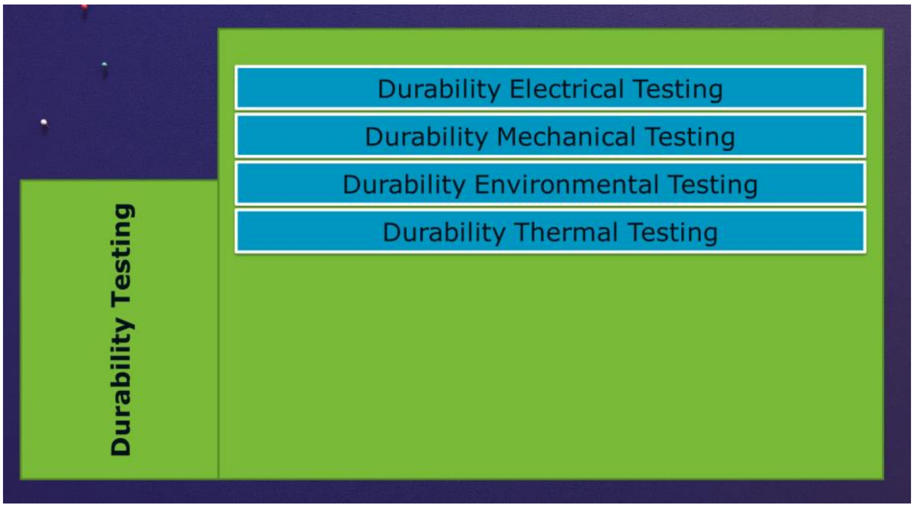



*Figure 49: Overview of the durability test categories [32]*

The following chapters explain the subcategories more detailed.

#### *3.1.2.1 Performance Testing*

Those tests aim at evaluating, verifying and assessing the products performance. The test cases for functional performance testing range from efficiency simulation with AVL simulation tools, to low temperature efficiency tests on transmission level, to maximum phase current tests on inverter level to check whether the operates correctly when maximum phase current is applied, to efficiency maps on eMotor level, to peak performance maps on eAxle level.

#### *3.1.2.2 Electrical Testing*

Functional electrical testing relates to power electronics, eMotor and eAxles. The distinction between high voltage (HV) and low voltage (LV) is necessary especially for assessing power electronics and eAxle test cases. Those tests range from simple insulation resistance measurements, to winding resistance measurements, to HV – pre – charge tests to verify the robustness of the system. Those tests have almost no impact on the mechanical components of a transmission.

### *3.1.2.3 Mechanical Testing*

Functional mechanical testing can be applied to all considered subsystem and system levels. Especially on transmission level a wide variety of mechanical test cases are part of the DVP. For transmission level many test cases are also simulation related. Due to frontloading money and time can be saved through simulation support, which is actively carried out for all mechanical parts. Housing or transmission shaft carrier FEA on transmission level, or demagnetization phenomena on eMotor level may be evaluated. In practice high load tests, pin perforation tests, maximum speed stop test by the eMotor or park lock actuation tests are performed.

### *3.1.2.4 Environmental Testing*

Functional environmental testing plays an important rule for all subsystems plus for the system level eAxle. More and more suppliers and manufactures have to ensure the resistance of their products or components to environmental influences like salt, high altitudes, humidity and water, sand and dust, radiation, as well as high pressure stream jets.

### *3.1.2.5 Thermal Testing*

Functional thermal testing considers tests that generally focus on high and low temperature impacts on the UUT. Those tests range from static temperature behaviors, where the unit under test is driven in the highest gear with maximum speed with the according torque to check for steady-state temperatures, to heat rejection tests, where cooling circuits are investigated, to locked rotor tests on eAxle levels, where the speed is 0 rpm and the current is increased in several steps until the limit of winding temperature in steady state is reached.

### 3.1.2.6 NVH Testing

NVH stands for Noise Vibration Harshness, which describes the sum of audible and perceptible vibrations of a vehicle or machine. Also, on simulation side multi body system dynamic analysis of housings, shafts, gears and bearings that are considering mounting stiffness are performed. On transmission and eAxle level NVH Rattle and Whine tests are carried out by assessing of structural weak parts by checking structure and air borne noise, but also general noise behavior tests for eMotor, Inverter and eAxles to verify that no noise pollution for the driver and pedestrians occurs.

### 3.1.2.7 EMC Testing

EMC stands for Electro-Magnetic Compatibility and describes a device's electro-magnetic isolation from other devices. This is the ability to not influence other devices by electric or electromagnetic effects or vice versa. No such tests are carried out on transmission level. Especially for power electronics, eMotor, E-Drive and eAxle level tests range from high voltage ripple immunity on HV DC supply lines, to immunity tests to magnetic fields against external narrow bands, to the radiated emissions of an eMotor below 30 MHz by using a loop antenna, to immunity against electrostatic discharge of the unit under test.

## 3.1.3 Structuring the DVP

AVL's DVP needed adjustments to the already existing design regarding its look and appearance. Therefor the following columns were added, moved or converted:

- Test ID
- Test Category
- Test Case
- Test Description
- Standard / Paragraph / Edition
- Test Environment
- Test Environment – Additional Info
- Number of Samples
- Acceptance Criteria
- RQ-ID (Requirement Identification)
- Remarks
-

AVL

Project info | Instructions | About

Level 2 | Level 3.1 | Level 3.2 | Level 3.3

Level 3.1 E-Motor Subsystem

DVP&R: Planning

| Test ID | Test Category | Test Case | Test Description | Standard / Paragraph / Edition | Test Environment | Test Environment additional in | Sample | | | | | Acceptance Criteria | RQ-ID | Remarks |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| F-11 | Functional Electrical Testing | **Temperature sensor tansient temperature connection check** | Measurement of dynamic behavior the measured sensor signal with a defined current profile in the winding (heating up DUT) | | Electric test bed | Climat conditioning | 19 | 1 | 6 | 6 | 6 | Performance and parameter values meet requirements, Functional status A | 2109806 | |
| F-15 | Functional Electrical Testing | **Open circuit voltage measurement - PMSM EESM** | Measurement of no-load voltage | IEC 60034-1, IEC 60349-2, IEC 60349-4 | No load test bed | | 67 | 1 | 6 | 30 | 30 | Performance and parameter values meet requirements, Functional status A | 2109806 | Parameter test |
| F-16 | Functional Electrical Testing | **Open circuit loss measurement - PMSM IM** | Measurement of no-load losses (bearing, windage, hysteresis) | IEC 60034-1, IEC 60349-2, IEC 60349-4 | No load test bed | | 67 | 1 | 6 | 30 | 30 | Performance and parameter values meet requirements, Functional status A | 2109806 | |
| F-17 a | Functional Electrical Testing | **Short circuit current measurement** | Short circuit current measurement - PMSM | IEC 60034-1, IEC 60349-4 | Load test bed | | 67 | 1 | 6 | 30 | 30 | Performance and parameter values meet requirements, Functional status A | 2109806 | |
| F-17 b | Functional Electrical Testing | **Short circuit current measurement - EESM** | Short circuit current measurement - EESM | IEC 60034-1, IEC 60349-2 | Load test bed | | 67 | 1 | 6 | 30 | 30 | Performance and parameter values meet requirements, Functional status A | 2109806 | |
| F-17 c | Functional Electrical Testing | **Short circuit current measurement** | Locked rotor current as function of phase voltage - IM | IEC 60034-1, IEC 60349-2 | Load test bed | | 67 | 1 | 6 | 30 | 30 | Performance and parameter values meet requirements, Functional status A | 2109806 | |

*Figure 50: Schematic overview of the eMotor DVP [2]*

### 3.1.3.1 Test ID

This column is used to allocate an identification number or code for each test case. They can either be AVL specific or derived from standards like IEC 60034-1.

### 3.1.3.2 Test Categories

See chapter *3.1.2* and its subchapters for further information

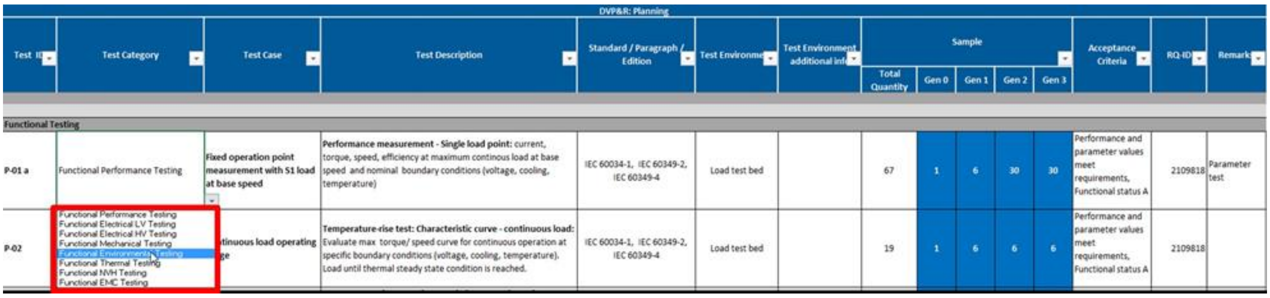



*Figure 51: Available test categories for functional testing [2]*

### 3.1.3.3 Test Case

In this column the names for each test are listed in a way that the basic idea – the intention of the test – is clear to all parties involved in the development process.

### 3.1.3.4 Test Description

This column contains brief descriptions for every test case. They shall be kept simple and short to not blow the extent of the DVP.

### 3.1.3.5 Standard / Paragraph / Edition

This section contains listing of the standards, norms, etc. where the test case was derived from.

### 3.1.3.6 Test Environment & Additional Info

The test environment was agreed upon to be either: Simulation, Test Bed or in Vehicle. The additional info contains further instructions about the test bed type. For instance, it can be:

- High load test bed
- Climatic chamber
- Inverter load test bed
- EMC chamber
- NVH test bed
- 3M test bed
- Workbench
- FEA
- Vehicle

### 3.1.3.7 Number of Samples

The number of total samples is calculated by summing up the number for every generation of samples according to chapter *3.1.1.4*. Those numbers either derive from standards, norms mentioned in the chapter *3.1.3.5 Standard / Paragraph / Edition*, from statistical probability or empirical values from the past. Figure 52 shows a schematic overview of the sample section in the DVP.

DVP&R: Planning

| Test ID | Test Category | Test Case | Test Description | Standard / Paragraph / Edition | Test Environme | Test Environment additional inf | Sample: Total Quantity | Sample: Gen 0 | Sample: Gen 1 | Sample: Gen 2 | Sample: Gen 3 | Acceptance Criteria | RQ-ID | Remark |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Functional Testing** | | | | | | | | | | | | | | |
| P-01 a | Functional Performance Testing | **Fixed operation point measurement with S1 load at base speed** | **Performance measurement - Single load point:** current, torque, speed, efficiency at maximum continous load at base speed and nominal boundary conditions (voltage, cooling, temperature) | IEC 60034-1, IEC 60349-2, IEC 60349-4 | Load test bed | | 67 | 1 | 6 | 30 | 30 | erformance and arameter values heet equirements, unctional status A | 2109818 | Parameter test |
| P-02 | Functional Performance Testing | **Continuous load operating range** | **Temperature-rise test: Characteristic curve - continuous load:** Evaluate max torque/ speed curve for continuous operation at specific boundary conditions (voltage, cooling, temperature). Load until thermal steady state condition is reached. | IEC 60034-1, IEC 60349-2, IEC 60349-4 | Load test bed | | 19 | 1 | 6 | 6 | 6 | erformance and arameter values heet equirements, unctional status A | 2109818 | |
| P-03 a | Functional Performance Testing | **Short time overload operating range** | **Temperature-rise test: Characteristic curve - short-time overload** Evaluate max torque/ speed curve for short time overload operation at specific boundary conditions (voltage, cooling, temperature) Specify start temperature and either time or temperature limit. Load until limits are reached | IEC 60034-1, (IEC 60034-4-1), IEC 60349-2, IEC 60349-4 | Load test bed | | 19 | 1 | 6 | 6 | 6 | erformance and arameter values heet equirements, unctional status A | 2109818 | |
| P-04 a | Functional Performance Testing | **Efficiency map (characteristic maps)** | **Characteristic machine maps test - Torque, Power, Current, Loss, Efficiency, Torque ripple** Measurement of operating points: Torque (n),Power(n), I_d(M,n), I_q(M,n), Losses(M,n), Efficiency (M,n) Torque ripple (M,n): @Un, Umax, Umin @target temperatures (winding, magnet) | IEC 60034-1, (IEC 60034-4-1), IEC 60349-2, IEC 60349-3, IEC 60349-4 | Load test bed | | 67 | 1 | 6 | 30 | 30 | erformance and arameter values heet equirements, unctional status A | 2109818 | Parameter test |

*Figure 52: Overview of how the sample number is calculated [2]*

### *3.1.3.8 Acceptance Criteria*

The idea was, since this DVP is a generic version, to come up with the following very general definition: "*No visible damage on the specimen. UUT must be fully functional after test.*" Later adaptions for customer projects are then performed. These acceptance criteria are then derived and narrowed down from the customer's requirements.

### *3.1.3.9 RQ ID / Remarks*

The last two columns contain information regarding requirements that are linked to customer or R&D projects or additional information that is not listed in the columns mentioned before.

## 3.2 Exemplary calculation of reliability

Due to requests by customers to reduce sample costs for the testing, this chapter shall elaborate how the reliability changes if the number of samples is modified. The calculation is based on chapters *2.6-2.9*.

For this example, a reliability value as well as the confidence level are requested to be 90%. Furthermore, a lifetime target of 250 000 km has been defined by the customer.

| Failure distribution: Weibull-Approach | | |
|---|---|---|
| | | |
| **Example: Reliability 90%, Confidence level 90%** | | |
| Max. significance level α | 0,1 | |
| Shape parameter b (Weibull distribution) | 2 | |
| Reliability goal R_target for target time | 0,9 | |
| target time t_Target | 250000 | [km] |
| RAD for all tests | 1 | |
| Time for equivalent test t_equivalent | 250000 | [km] |
| | | |
| Number of Samples n to reach R(t) | 21,9 | |
| | | |
| Numbers of samples (VDA) n_Plan | 27 | |
| Numbers of samples (suggested) n_suggested | 10 | |
| Reliability R_Plan | 91,8% | 91,8% |
| Reliability R_suggested | 79,4% | 79,4% |

*Figure 53: Calculating the reliabilities for 27 and 10 samples [2]*

The significance level is characterized as $\alpha = 1 - P_A$, where $P_A$ is the confidence level. Furthermore, the shape parameter $b$ of 2 was chosen. (AVL best practice $2 \leq b \leq 4$). $RAD$ stands for relative accumulated damage and is a value that compares the test cycle's damage to the one from the reference cycle. A value of $RAD = 1$ means that the test cycle's damage is equal to the reference cycle's.

To calculate the required number of samples needed to reach the reliability goal of 90% Equation 11 needs to be solved.

$$n_R = \frac{\ln(\alpha)}{\ln(R_{target})} * \left(\frac{t_{Target}}{t_{equivalent}}\right)^b$$

*Equation 11 – Calculating the number of samples*

For the requirements mentioned above, a total number of 22 samples need to be tested, for $RAD = 1$.

After that Equation 12 and Equation 13 need to be solved for the planned number of samples from the VDA document (27 samples) and the suggested number of samples.

$$R_{Plan} = e^{\left(\frac{\ln(\alpha)}{n_{Plan}} * \left(\frac{t_{Target}}{t_{equivalent}}\right)^{b}\right)}$$

*Equation 12 – Calculating the reliability for the planned number of samples from VDA*

$$R_{Suggested} = e^{\left(\frac{\ln(\alpha)}{n_{suggested}} * \left(\frac{t_{Target}}{t_{equivalent}}\right)^{b}\right)}$$

*Equation 13 - Calculating the reliability for the suggested number of samples*

The reliability for 27 samples is 91,8%, whereas for 10 sample it is only 79,4%, as seen in Figure 53. To increase the reliability although, only 10 samples are tested, the value for $RAD$ needs to be increased. MS Excels solver function was used to calculate the $RAD$ and the equivalent test range. Hence a $RAD$ value of 1,64 is the result of the calculation, which means that the test cycle is 64% more damaging than the reference cycle. This also leads to an equivalent test range of 409701 km for the same reliability (91,8%), as shown in Figure 54. Due to that fact it may be stated that through over testing the number of samples may be reduced.

| Failure distribution: Weibull-Approach | | |
|---|---|---|
| | | |
| **Example: Reliability 90%, Confidence level 90%** | | |
| Max. significance level α | 0,1 | |
| Shape parameter b (Weibull distribution) | 2 | |
| Reliability goal R_target for target time | 0,9 | |
| target time t_Target | 250000 | [km] |
| RAD for all tests | 1,6388026 | |
| Time for equivalent test t_equivalent | 409701 | [km] |
| | | |
| | | |
| | | |
| Numbers of samples (VDA) n_Plan | 27 | |
| Numbers of samples (suggested) n_suggested | 10 | |
| Reliability R_Plan | 91,8% | |
| Reliability R_suggested | 91,8% | 79,4% |

*Figure 54: Calculating the RAD value and test range [2]*

## 3.3 Case Study

In the following chapter a better understanding of the case study shall be given to the reader.

| | Case 1 | Case 2 | Case 3 | Case 4 |
|---|---|---|---|---|
| **eAxle** | X | B | | X |
| **eMotor** | X | B | A | |
| **Inverter** | X | | | |
| **Transmission** | X | | | X |

*Table 11 - Overview of the case studies*

*Legend:*

*X – All sample phases*

*B – B sample phase*

*A – A sample phase*

Case 1 shall be a DVP where the responsibility for all four levels lies with AVL to verify eAxle, eMotor, inverter and transmission.

Case 2 focuses on only verifying the eAxle and eMotor.

Case 3's responsibility aims at eMotor and inverter.

In contrast to that Case 4 assesses the DVP for an eAxle and its transmission.

### 3.3.1 Case 1 – The overall responsibility

This generic approach covers all test cases listed in the DVP for each level. To verify all functions and to meet all requirements the whole lot of test cases has to be handled, processed and conducted. The summary and tabular listing can be found in chapter *6.1.1 eAxle DVP*. This scenario can be seen as the total amount of possible test cases that are necessary to perform. Since it is a generic DVP with a black box approach some tests will be removed or adjusted in the customer project, due to interdependencies respectively to the system's or subsystem's architectures.

For example, in relation to transmissions, test cases that assess shift elements, electric oil pumps, park locks, differential tests, over speed capability or towing may be left out if not applicable to the system. In this case the architecture describes a P4 module / eAxle that is further explained in chapter *2.1.1.1 Parallel hybrid propulsion systems*.

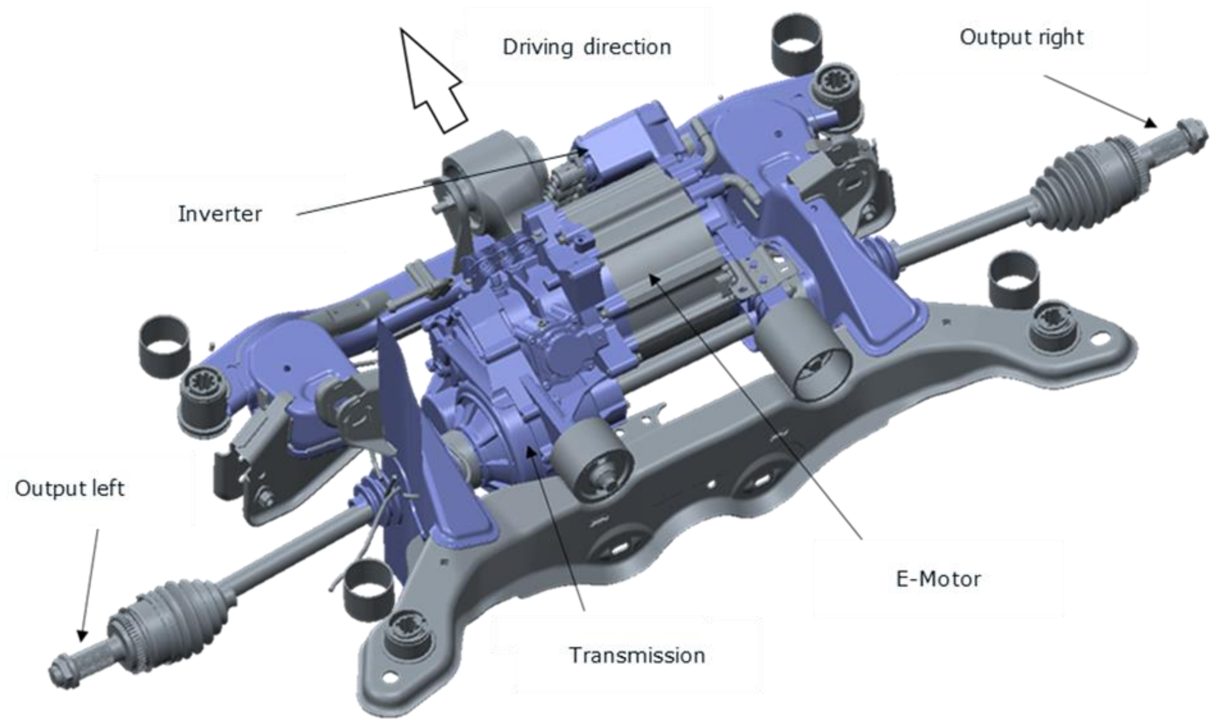



*Figure 55: Overview of the considered eAxle [2]*

If the responsibility lies with all levels of system and subsystems the following points have to be taken into account:

For large scale production series the number of validated samples and therefore depth of testing has to be high, to ensure a high reliability of the product. From experience German OEMs demand higher levels of reliability compared to Chinese ones. This results from the higher prices for the vehicle as well as the reputation from the past. A Reliability of 0% could be put into practice but is a high-risk approach, because no statement about how many samples will fail may be made. In Contrast to that a reliability of 100% is not possible to obtain, due to not justifiably cost-utilization ratio.

### 3.3.2 Case 2 – The eAxle and eMotor DVP

When the eAxle-only DVP is considered, suppliers or tier ones deliver the subsystems transmission, inverter and eMotor. They can either be delivered by one supplier or several independently working ones. Additionally, it can be assumed, that the suppliers already validated their designs sufficiently. Often suppliers, especially in the new emerging market of e-drive, are not sure how, to validate their subsystems. Therefor it is often necessary to support them with their testing and validation activity.

Those tests do not cover the whole generic test procedure for e.g. gearboxes. As mentioned above, it is assumed that the transmission and inverter have already been validated and therefore just the basic performance tests like efficiency test, torque and speed sweeps and initial run in procedures are performed. To validate the eAxle and eMotor without the final transmission or inverter a front-loading approach consisting of a HiL and SiL procedures are necessary. Instead of transmission and inverter dummy-systems which represent the physical attributes may be used for hardware test procedures.

For transmission the following parameters need to correlate with the real system:

- Mass
- Inertia
- Gear ratio
- Interface
- Stiffness
- Clearance

In regard to inverters, programmable controllers are necessary to perform similar current and amplitude ramps, plus the interface has to correlate with the original one.

Parameter tests are test procedures that are combined into one test. Therefor they are a collection of functional tests for characterization of eAxle functions.

Especially for eAxles specific durability tests are defined by norms, which are elaborated in the following chapters *3.4*.

### 3.3.3 Case 3 – The eMotor responsibility

To successfully test an eMotor an operational Inverter is necessary. Due to the fact that only the eMotor shall be investigated in the A phase / Gen 0, a special testing inverter, which will be replaced by the real inverter in later sample phases, shall be used. Especially in the A phase / Gen 0 it is important to verify basic functions of the component, subsystem or system considered, although some material or design changes are likely to occur after this phase. The resulting DVP can be found in chapter ***Fehler! Verweisquelle konnte nicht gefunden werden. Fehler! Verweisquelle konnte nicht gefunden werden.***. For later phases of the eMotor the number of samples is also added in chapter ***Fehler! Verweisquelle konnte nicht gefunden werden. Fehler! Verweisquelle konnte nicht gefunden werden.***. During A phase / Gen 0 only one sample for each test case was considered.

### 3.3.4 Case 4 – Validation of an eAxle and Transmission

In this case the responsibility for the validation of the transmission and eAxle. Firstly the transmission, which is considered as a subsystem, has to be tested. Secondly the whole eAxle is tested. The procedure is later on also performed in parallel for eAxle and transmission.

During A phase / Gen 0 only basic functionality tests, ultimate strength tests for the differential of the transmission plus durability test runs for the transmission as well shall be executed.

During B phase / Gen 1 contact pattern tests, to analyses the macro and micro geometry of the tooth flanks, durability and emergency shifting tests, no oil test, to analyze the behavior of the transmission without oil, lubrication tests, over speed and load tests together with torsional stiffness and NVH fingerprint tests need to be performed.

During C phase / Gen 2 the first environmental tests need to be implemented like altitude tests. In addition to that and the tests from the previous phase, bolt tests that check the bolt connection after a durability runs need to be added as well. The number of durability runs need to be increased also and extended by durability shifting and high-speed tests to cover the lifetime of the product. Emergency tests for the park lock, limp home and shift elements are also included in this phase.

During D phase / Gen 3 the number of samples has to be increased to result in a better statistical statement. Low and high temperature tests, emergency sealing tests and drag torque / efficiency tests at different oil temperatures have to be conducted, plus referencing tests for the shift actuation (if applicable).

## 3.4 High Temperature & High Humidity Endurance - HTHE

HTHE stands for High Temperature & High Humidity Endurance and is therefore assigned to durability testing. HTHE as well as HTOE and PTCE durability tests are mandatory tests for all modules, sensors that send CAN or LIN messages and for all ignition on/off related operations. This test shall simulate all possible failure modes and conditions that might occur during a vehicle's service life time, when electronic devices and modules are exposed to high temperature and humidity.

Failure modes include electrical short circuits resulting from oxidation and galvanic corrosion of metals and absorption of water by those materials. Further failures are potting, seal, adhesive and conformal coating compound failures that cause metals and materials to lose their strength and swell.

To describe all occurring effects of temperature and humidity on the failure life of a vehicle's electronic components the Lawson Model shall be used. This model is used to accelerate the HTHE test cycle. [33]

The test procedure goes as follows:

1. *Place component in a test chamber maintained at 85 °C.*
2. *Introduce humidity to the chamber and maintain the relative humidity inside the chamber at 85% RH.*
3. *Accumulate test time when both temperature and humidity are at 85 °C and 85% RH.*
4. *Functionally test the component every 47 hours or as specified in the Component Specific Performance Standard (may involve few minutes to 1-hour maximum operational time). If the component needs to be removed from the chamber for functional testing, then steps 1 and 2 must be repeated when resuming testing prior to accumulating additional test time.*
5. *Any parametric or functions checks at different thermal conditions (-40 °C, RT, +85 °C) can be performed with humidity uncontrolled. [33]*

Graz, January 31, 2019

To define the acceleration factor the following equation is used:

$$AF_T = e^{\left[-\frac{E_a}{k}\left(\frac{1}{T_a}-\frac{1}{T_f}\right)\right]}$$

*Equation 14- Calculating the temperature acceleration factor [33]*

- $AF_T: Temperature\ acceleration\ factor$
- $E_a: Activity\ energy$
- $k: Boltzmann\ constant$
- $T_a: Temperatur\ of\ accelerated\ test$
- $T_f: Field\ temperature\ condition$
- $T\ Absolute\ temperatur\ in\ Kelvin$

$$AF_{RH} = e^{b\left[RH_a^2 - RH_f^2\right]}$$

*Equation 15- Calculating the humidity acceleration factor [33]*

- $AF_{RH}: Humidity\ acceleration\ factor$
- $b: Constant\ (\ b = 5.57\ x\ 10^{-4})$
- $RH: Relative\ Humidity\ [\%]$
- $RH_a: Humidity\ during\ accelerated\ test$
- $RH_f: Field\ humidity\ condition$

Both equations *Equation 14* and *Equation 15* can be combined to one single equation:

$$AF_{T,RH} = AF_T * AF_{RH} = e^{\left[-\frac{E_a}{k}\left(\frac{1}{T_a}-\frac{1}{T_f}\right)\right]+b\left[RH_a^2 - RH_f^2\right]}$$

*Equation 16- The Lawson model equation [33]*

- $AF_{T,RH}: Combined\ acceleration\ factor\ of\ the\ Lawson\ model$

It has to be stated that Lawson and Arrhenius models use different Activation Energy models, since both describe two different failure mechanisms.

Hence the total HTHE testing time may be calculated by:

$$t_{HTHE} = \frac{t_{non-op.time}}{AF_{T,RH}}$$

*Equation 17 - Calculation of the total HTHE testing time [33]*

- $t_{HTHE}: Total\ testing\ time\ for\ HTHE\ test$
- $t_{non-op.time}: Non - Operatint\ time\ during\ service\ life\ in\ field$
- $AF_{T,RH}: Combined\ acceleration\ factor\ of\ the\ Lawson\ model$

Exemplary calculation of the HTHE test duration:

An ECU located under-hood compartment shall be considered. The target service life time in the field shall be 15 years / 150 000 miles. The average temperature during non-operating times is $T_f = 23\ °C\ or\ 296\ K$and the average humidity is supposedly$RH_f = 65\ \%$.

Further details:

- $T_a = 85°C\ or\ 358\ K \rightarrow Temperatur\ of\ accelerated\ test$
- $RH_a = 85\ \% \rightarrow Humidity\ during\ accelerated\ test$

From that the combined acceleration factor of the Lawson Model is calculated as:

- $AF_T = e^{\left[-\frac{E_a}{k}\left(\frac{1}{T_a}-\frac{1}{T_f}\right)\right]} = 23{,}32$
- $AF_{RH} = e^{b\left[RH_a^2 - RH_f^2\right]} = 5{,}32$
- $AF_{T,RH} = AF_T * AF_{RH} = 129{,}3$

The non-operating time in in the field for 15 years / 150 000 miles shall be 129 000 h.

- $t_{HTHE} = \frac{129\ 000}{129{,}3} = 998\ h$

For sake of simplicity the HTHE duration shall be 1000 h for powertrain or safety applications and 700 h for other applications.

The following table shows HTHE durations under different temperature and humidity conditions:

| Temperature & Relative Humidity | PT-Emission / Passive Safety* or Other Applications ** | All Other Applications (Inside Cabin) |
|---|---|---|
| 85 C & 85% RH | 1 000 Hours | 700 Hours |
| 80 C & 90% RH | 760 Hours | 530 Hours |
| 75 C & 95% RH | 570 Hours | 395 Hours |
| 70 C & 95% RH | 715 Hours | 500 Hours |
| 65 C & 95% RH | 905 Hours | 630 Hours |
| *either Outside or Inside Cabin<br>** only Outside Cabin | | |

*Table 12 - Overview for different boundary conditions [33]*

## 3.5 High Temperature Operating Endurance - HTOE

HTOE stands for High Temperature Operating Endurance test. An electronic component internally generated heat, packaging location and local environments have strong impacts on them regarding temperature. Therefor HTOE shall simulate all occurring cumulative damage resulting from bias operation and failure modes under different temperature conditions like solder plastic creep, crack propagation and drying of electrolytic capacitors. To reduce testing time and especially testing costs, accelerated tests at higher temperature levels with voltage are used to generate the damage corresponding to the real damage. To calculate the damage and to describe phenomena caused by kinetics of chemicals and molecules, the Arrhenius model is used. Which will be elaborated later on in this chapter. [33]

This test has to be performed for all electronic components / devices if certain features of the same module operate at different temperatures. E.g. a CD mechanism in a vehicle is not operable above 70°C, but the AM/FM/SAT function may still be above 85°C. Both features have to be split with agreed percentage ratios. (E.g. 50 % / 50 %) [33]

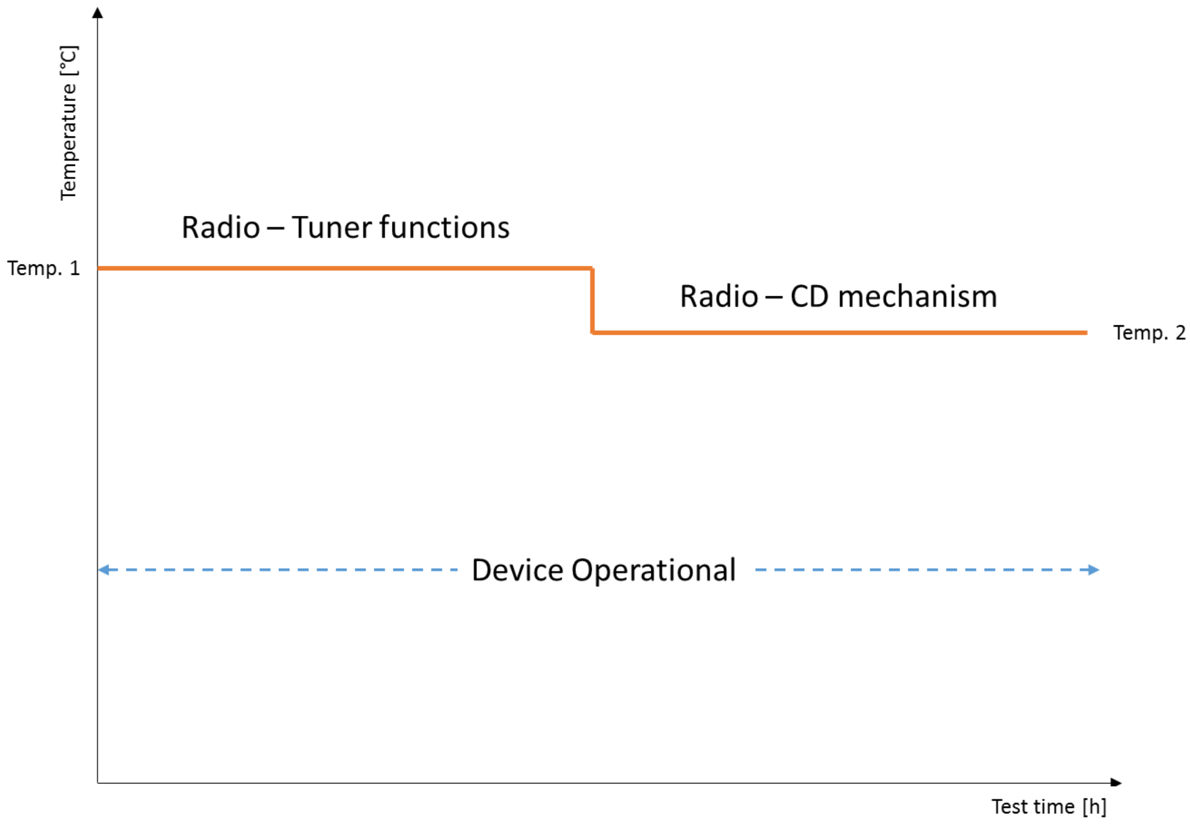



*Figure 56 - The HTOE test cycle*

*The Arrhenius model is used to describe the kinetics of many chemical and molecular phenomena. Many failure modes are caused by mechanisms that operate at the molecular level. These failure mechanisms include electro-migration, diffusion, oxidation, ionic contamination, dielectric breakdown, and surface charge accumulation in silicon oxides, electrolytic corrosion, chemical and galvanic corrosion, aluminum penetration in silicon, and others. Other failure mechanism operates at a macro level and includes solder plastic creep, crack propagation in many materials, drying of electrolytic capacitors, and others. [33]*

The mathematical relationship used for the HTOE test is:

$$R = C * e^{\frac{-E_a}{k*T}}$$

*Equation 18 - Calculation of the reaction rate[33]*

- $R: Reaction\ rate$
- $C: empherical\ constant$
- $k: Boltzmann\ constant$
- $E_a$: *empherical activation energy = 0.7 eV/K*
- $T\ Absolute\ temperatur\ in\ Kelvin$

For each failure mechanism a unique activation energy $E_a$ can be found like shown in the following table:

| Failure Mechanism | Ea [eV] |
|---|---|
| Dielectric breakdown | 0.3 to 0.6 |
| Diffusion failures | 0.5 |
| Corrosion - electrolysis | 0.3 to 0.6 |
| Corrosion - chemical and galvanic | 0.6 to 0.7 |
| Electro-migration | 0.5 to 1.2 |
| Charge loss (MOS/EPROM) | 0.8 |
| Ionic contamination | 1.0 |
| Surface charge accumulation in silicon oxide | 1.0 to 1.05 |
| Aluminum penetration into silicon | 1.4 to 1.6 |

*Table 13 - Failure mechanism and their activation energy constant [33]*

For HTOE tests $E_a$ is assumed to be 0,7 eV to calculate its test duration of E/E components. Thus, it appears that the testing time can be reduced by increasing the activation energy. Hence all activation energies greater or equal 0,7 eV and their failure mechanisms are covered by HTOE.

Furthermore, the Arrhenius model can be used to identify the lifetime of electronic components at constant temperatures, when failures are caused by the above mentioned molecular mechanisms. As with the Lawson Model also an acceleration factor, between ratio of field usage time and test time with equivalent damage, exists. [33]

$$AF_T = e^{\left[-\frac{E_a}{k}\left(\frac{1}{T_a}-\frac{1}{T_s}\right)\right]}$$

*Equation 19 - Calculation of the Test Acceleration Factor[33]*

- $AF_T: Test\ acceleration\ factor$
- $E_a: Activity\ energy$
- $k: Boltzmann\ constant$
- $T_a: Temperatur\ of\ accelerated\ test\ [K]$
- $T_s: Field\ service\ temperature\ [K]$

Since the temperature during component operation time is not the same as the field service life, different component temperature profiles are defined according to their mounting position. Each profile consists of various series of temperatures and their corresponding percentage distribution.

Hence the total testing time may be calculated by: [33]

$$t_{HTOE} = t_{op.time} \sum_i \frac{p_i}{A_{T,i}}$$

*Equation 20 - calculation of the HTOE test time[33]*

- $t_{HTOE}: Total\ testing\ time\ for\ HTOE\ test$
- $t_{op.time}: Operating\ time\ during\ service\ life\ in\ field$
- $A_{T,i}: Combined\ acceleration\ factor$

The test procedure may further be accelerated by using the maximum possible operating temperature, which is the maximum environmental temperature. $t_{op.time}$ has to be calculated and evaluated for every component. [33]

Exemplary calculation of the HTOE test duration:

The HTOE test time for a passive safety application like an ORC Module shall be calculated, with a service life time of 15 years / 150 000 miles. 95% of the customers operate the vehicle for 12 000 h and the HTOE test shall be conducted at 85°C.

1. *The temperatures are converted from Celsius to the Kelvin absolute temperature scale.*
2. *Using the distribution, the operating time at different temperatures is calculated.*
3. *For each temperature, an acceleration factor $AF_T$ is calculated using the Arrhenius equation.*
4. *The equivalent test time at $T_2$ is calculated by dividing the time at each temperature by the acceleration factor for each temperature.*
5. *The total test time required is the sum of the individual test times.*

| **Temperatures for Class TC1** | | **Distribution** | **Operating Time in 12 000 Hours** | **AFT** | **Equivalent Test Time @ 85°C** |
|---|---|---|---|---|---|
| -40°C | 233.15°K | 6% | 720 | 193 577 | 0,004 h |
| 23°C | 296.15°K | 65% | 7 800 | 115.9 | 67 h |
| 60°C | 333.15°K | 20% | 2 400 | 5.49 | 437 h |
| 80°C | 353.15°K | 8% | 960 | 1.38 | 696 h |
| 85°C | 358.15°K | 1% | 120 | 1 | 120 h |
| | | | | Total | 1320h |

To simplify the test procedure the test duration is reduced to 1300 h in total for powertrain / safety applications and to 950 h for all other applications. [33]

## 3.6 Power Thermal Cycle Endurance - PTCE

PTCE is an acronym for Power Thermal Cycle Endurance, which aims on assessing failure modes deriving from different coefficients of thermal expansion for different materials under temperatures that are not constant. Dynamic temperature changes cause mechanical stresses on adjoining materials during the lifetime of the vehicle. Hence cracked solder joints or similar mechanical failures may occur for electrical or electronic components. [33]

*The Coffin-Manson Model describes the fatigue life of materials under shear strain from thermal expansion & contraction.* [33]

The test procedure for the PTCE test consists of minimum and maximum temperatures and transitions between them in the test chamber.

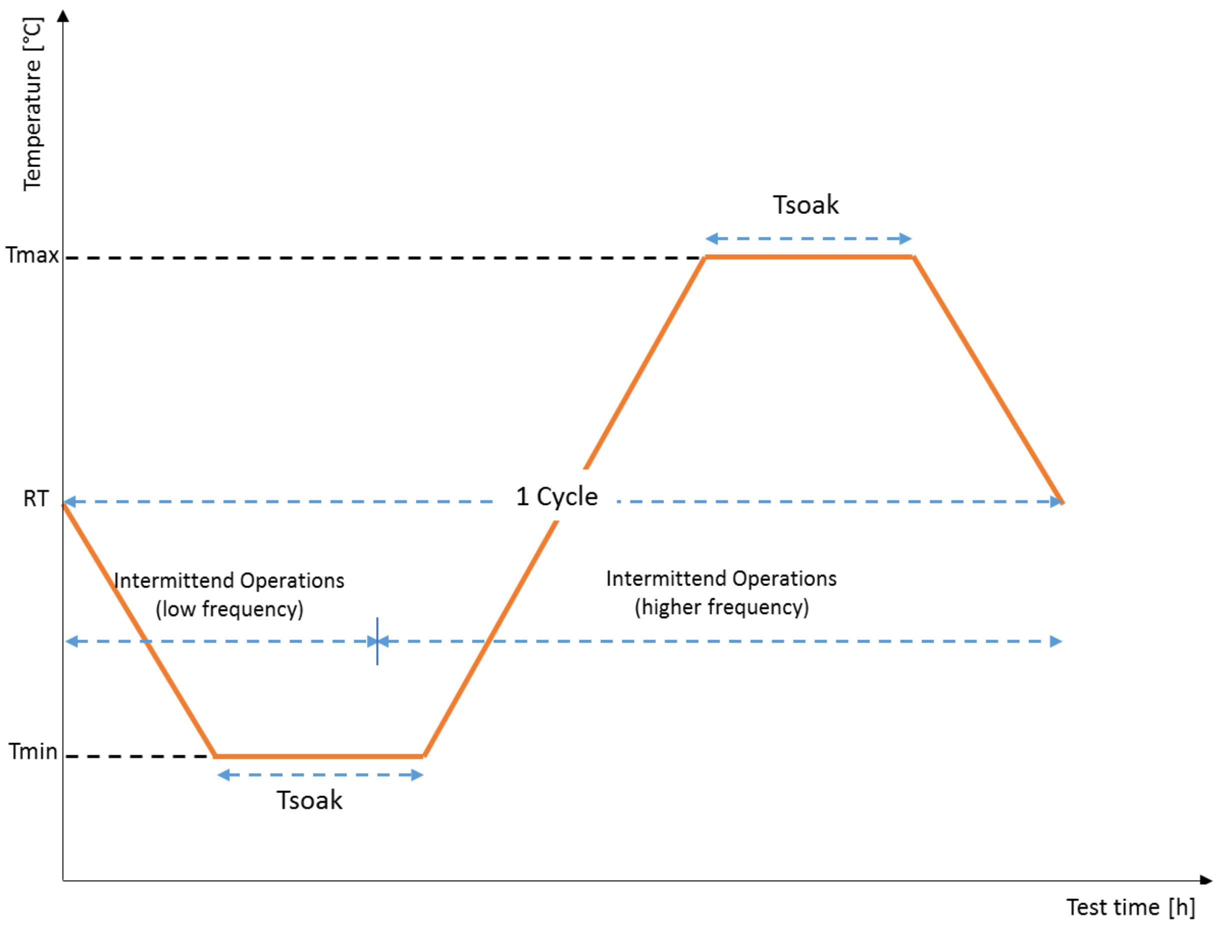



*Figure 57- Schematic overview of one PTCE cycle [33]*

Legend:

$T_{soak}$: *The dwell time required for the component to reach the same temperature as chamber ambient during thermal cycling.*

1. *Place component in a thermal chamber at RT.*
2. *Ramp down the chamber temperature to $T_{min}$ temperature in a non-operating or low power mode per the Component Specific Performance Standard*
3. *Maintain the chamber temperature for time duration $T_{soak}$. After the $T_{soak}$ time, start to operate the component before ramping the temperature. The time required should be specific to the component as specified in the Component Specific Performance Standard.*
4. *Ramp up the chamber temperature to $T_{max}$ temperature*
5. *Maintain the chamber temperature for time duration $T_{soak}$.*
6. *Ramp down the chamber to RT. Follow the operating mode, monitoring status and other test parameters.*
7. *Repeat steps 2 through 6 for the required number of cycles.*
8. *Perform the functional checks at start and end of the test cycles.* [33]

The Coffin-Manson Model describes the fatigue life of materials under shear strain and is therefore used fort the PTCE test.

$$N_f = A * \frac{1}{{\varepsilon_{ST}}^2}$$

*Equation 21 Calculating the number of shear cycles until failure [33]*

- $N_f: Number\ of\ shear\ cycles\ until\ failure$
- $\varepsilon_{ST}: Shear\ strain$
- $A: Empherical\ constant$

The exponent of 2 clearly shows that the damage caused by shear strain is non-linear. Hence the low-level shear events can be ignored and the focus shall lie on understanding the few high shear events occurring. The shear strain for different materials with different coefficients of thermal expansion are proportional to temperature change. Events with greater temperature differences have a greater impact for electronic components than smaller ones. They can be generalized as follows: [33]

$$N_f = \frac{1}{(\Delta T)^C}$$

*Equation 22 Calculating the number of shear cycles with ΔT [33]*

- $\Delta T: Difference\ in\ temperature$
- $C: approximately\ 2\ for\ solder\ materials$

To calculate accelerated cycles with procedure equivalent shear fatigue damage the relationship is:

$$A_f = \frac{N_a}{N_f} = \left(\frac{\Delta T_f}{\Delta T_a}\right)^C$$

*Equation 23 - Calculation of the test acceleration factor [33]*

- $A_f: Test\ acceleration\ factor$
- $N_a: Number\ of\ cycles\ required\ for\ an\ accelerated\ test\ temperature\ range$
- $N_f: Number\ of\ cyclesexperienced\ during\ the\ service\ life\ with\ the\ usage\ temperature\ ra$ ge

Typical $\Delta T_f$ values are defined in the FCA standard. Due to different values of the actual $\Delta T_f$ values may be different to the ones from the table. A responsible engineer has to validate the actual amount of thermal delta. [33]

The aim of PTCE test is a thermal cycle that is accelerated to the maximum.

Exemplary calculation of the PTCE test duration:

For an ECU (temp. class TC1 and a service life time in the field of 10 years) the number of cycles in the PTCE test shall be calculated.

1. The Number of Temperature Cycles during the Service Life is $\mathrm{N_f}$ = 8200 cycles

2. Since the component belongs to temperature class TC1, the Average Temperature difference in field is $\Delta \mathrm{T_{field}} = 34°\mathrm{C}$.

3. From $\mathrm{T_{max}}$ = 85°C and $\mathrm{T_{min}}$ = -40°C, the Temperature Delta during a test cycles is $\Delta \mathrm{T_f} = 125°\mathrm{C}$

To calculate the total test time the number of cycles has to be multiplied by the duration of every cycle: [33]

$$N_a = 8200 * \left(\frac{34}{125}\right)^2 = 607\ [cycles]$$

To simplify the procedure the number of PTCE test cycles shall be increased to 1000 for Powertrain and Passive Safety applications and reduced to 600 for other applications. [33]

## 3.7 Power Related Endurance Test - PRET

The term PRET stands for Power Related Endurance Test and is a method to verify the lifetime durability of different drivetrain components. In this exemplary calculation a test cycle is derived from a real driving cycle that has a life time target of 300 000 km. This is dependent on the vehicle category. Every operating point is defined with its own value of torque and speed. With this test all power related failure modes shall be assessed, to ensure high quality and reliability of the components. This test is to verify mechanical components to not show any signs of wear, cracks or similar failure modes after conducting the test. During this test parameter test inspections, trend measurements and visual inspections of oil samples are conducted.

The following components are investigated:

- E-machine
- Inverter
- Gears
- Solders
- Bondings
- Weldings
- Bonding and welding joints
- Seal rings
- Bearings
- Housing

Since this process is still in development phase the initial suggestion of the flow diagram goes as follows:

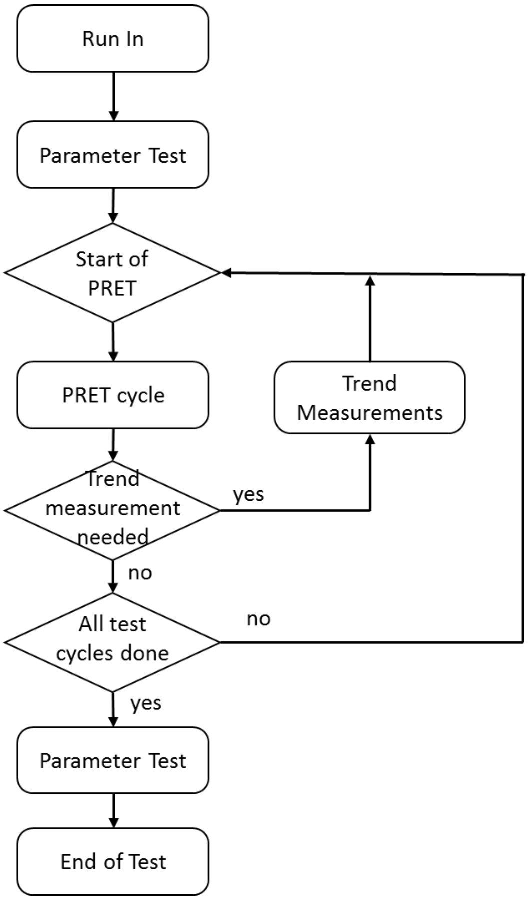



*Figure 58- Flow diagram of the PRET test procedure*

Parameter tests are performed to record and later on to evaluate specific parameters of the UUT like efficiency, drag torque etc. The evaluation can either be done on the fly via live evaluation or afterwards via post processing.

# 4 Further Steps

After the creation of the DVP an FP-Sheet was conducted, where possible occurring failures for typical machine components of an eAxle, transmission, eMotor and inverter are listed. Additionally, the location, where the failure might occur, its cause, effect on system level, the damaging operating condition and possible aggravating conditions are listed for every failure. The new approach was then to create a matrix, which shows by which functional or durability testing category a failure may be activated.

In chapter *6.1.5 FP-Sheet* the result is shown. Those failures were then put into the correlation sheet for functional and durability testing. In those sheets the brown cells show the need for condition monitoring that also shall be combined with new big data approaches. The red marked cells are the white spots were no test cases and therefor failures can be covered. This was only applicable for durability mechanical testing. Durability mechanical testing, as well as functional EMC and electrical testing is not applicable for transmissions.

# 5 Summary and Outlook

This master's thesis goal was to generate a generic DVP for eAxles based on the partly existing subsystem DVPs of eMotor, inverter and transmission. For better understanding and means of standardization a common wording within AVL was created, which will from now on used in the concerned departments in Regensburg, Stuttgart and in the headquarters in Graz.

In chapter 2 *The fundamentals for developing a DVP* the foundation for developing a DVP was elaborated, which was then intensified and implemented in chapter 3 *Developing the eAxle DVP*. Due to requests by suppliers the parameter of reliability had to be taken into consideration. Especially for sports cars and hyper sports cars a reduction of test samples was the desired goal. In these fields economy of scale regarding production is, due to very limited production numbers, not feasible. To reduce testing costs frontloading approaches and proper testing is necessary to intercept failures as early as possible in the development process. This is also shown in Figure 59. The aim is a shift to the left from the already established powertrain test beds and road testing to frontloading (simulation) and component test beds to reduce costs.

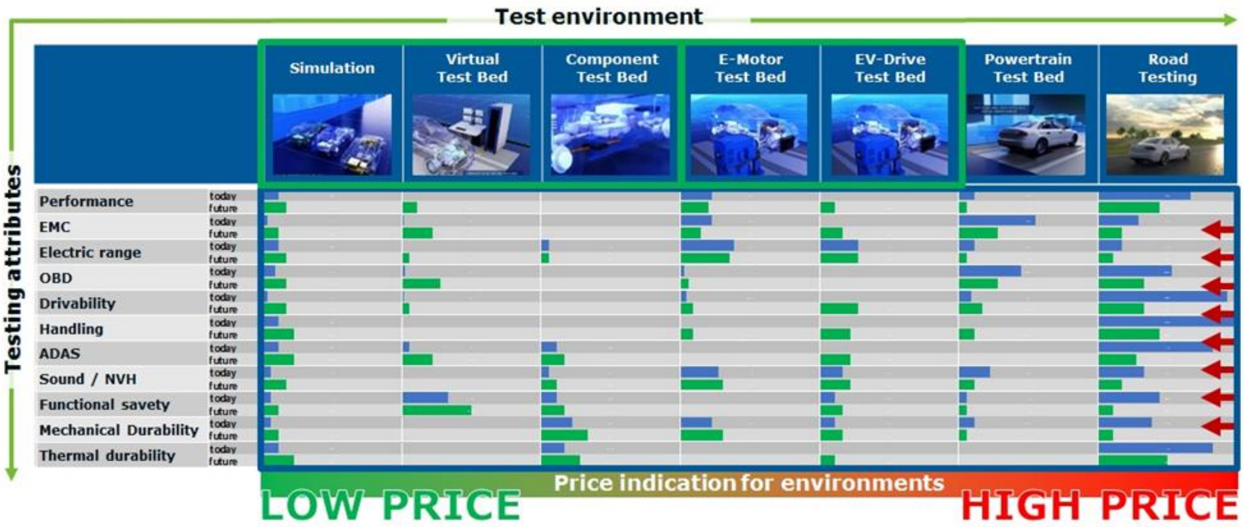



*Figure 59: Price indication for different test environments [2]*

To visualize failures and in order to track them through the development process the excel sheets shown in chapters *6.1.6* and *6.1.7* were used. The testing method used within AVL focuses on activating certain failures based on a FMEA and the AVL Load Matrix approach. One of the results is the FP-Sheet shown in chapter *6.1.5*. White spots could be found on inverter level, since no mechanical durability tests on subsystem level are implemented. In the future these white spots shall be eradicated and replaced by tests that activate the desired failures.

In chapter 3.2 *Exemplary calculation of reliability* the effects of reducing the number of test samples for durability testing was elaborated. This shows that a reduction of samples leads to reduction in reliability. To increase the reliability or achieve the same value as stated in the VDA the RAD and therefore testing time per sample needs to be increased.

Additionally, it is planned to elaborate a new test cycle that combines different temperature related and mechanical failure mechanisms, to reduce the number of samples and testing time.

# 6 Appendix

## 6.1.1 eAxle DVP

Project info | Instructions | About

Level 2 | Level 3.1 | Level 3.2 | Level 3.3

Level 2 e -Axle System

DVP&R: Planning

| Test ID | Test Category | Test Case | Test Description | Standard / Paragraph / Edition | Test Environment | Test Environment additional info | Test Responsibility: Responsible Person | Test Responsibility: Responsible Department | Test Duration (Execution Time) | Sample: Total Quantity | Sample: Gen 0 | Sample: Gen 1 | Sample: Gen 2 | Sample: Gen 3 | Test status | Test report ID / Path | Acceptance Criteria | RQ-ID | | Remarks |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Functional Testing** | | | | | | | | | | | | | | | | | | | | |
| | Functional Mechanical Testing | **Gearbox Test Run-In Test** | To run the gears of transmission. | | Test Bed | | | | | 2 | | | 1 | 1 | | | No visible demages after test, no water ingress in the DUT, no sealing demage. All functionalities remains as required after test. | 2067874 | | |
| x | Functional Mechanical Testing | **Gearbox Test Speed Sweep** | To execute the speed ramp for complete speed range. | | Test Bed | | | | | 2 | | | 1 | 1 | | | No visible demages after test, no water ingress in the DUT, no sealing demage. All functionalities remains as required after test. | 2067874 | | |
| x | Functional Mechanical Testing | **Gearbox Test Torque Sweep** | To execute the torque ramp for complete speed range. | | Test Bed | | | | | 2 | | | 1 | 1 | | | No visible demages after test, no water ingress in the DUT, no sealing demage. All functionalities remains as required after test. | 2067874 | | |
| | Functional Mechanical Testing | **Park Lock Actuation Test** | To check if the park lock engages and disengages. | | Test Bed | | | | | 6 | | | 3 | 3 | | | No visible demages after test, no water ingress in the DUT, no sealing demage. All functionalities remains as required after test. | 2067874 | | |
| | Functional Mechanical Testing | **Park Lock Dynamic Test** | To check when the park lock is engaged in speed relevant conditions. | | Test Bed | | | | | 6 | | | 3 | 3 | | | No visible demages after test, no water ingress in the DUT, no sealing demage. All functionalities remains as required after test. | 2067874 | | |
| | Functional Mechanical Testing | **Park Lock Static high load Test** | To evaluate the maximum static load that can be hold by park lock. | | Test Bed | | | | | 6 | | | 3 | 3 | | | No visible demages after test, no water ingress in the DUT, no sealing demage. All functionalities remains as required after test. | 2067874 | | |
| | Functional Electrical HV Testing | **Active Discharge** | To get the time of system active discharge. | | Test Bed | | | | | 0 | | | | | | | No visible demages after test, no water ingress in the DUT, no sealing demage. All functionalities remains as required after test. | 2067870 | | depending on eDrive variant (e.g. active discharge with motor winding) |
| | Functional Electrical HV Testing | **Pre-Parameter test** | To check i.g. CAN communication, interlock, HV connections, resolver, coolant, visual inspection, (for different ambient temperatures and voltages (LV & HV)) | | Test Bed | | | | | 0 | | | | | | | No visible demages after test, no water ingress in the DUT, no sealing demage. All functionalities remains as required after test. | | | parameter test |
| | Functional Electrical LV Testing | **Quiescent Current** | To get the value of quiescent current. | | Test Bed | | | | | 0 | | | | | | | No visible demages after test, no water ingress in the DUT, no sealing demage. All functionalities remains as required after test. | 2067868 | | |
| | Functional Electrical LV Testing | **Park Lock Actuation & Time** | To check if the park lock can engage and disengage & to check the time for engagement and disengagement. | | Test Bed | | | | | 0 | | | | | | | No visible demages after test, no water ingress in the DUT, no sealing demage. All functionalities remains as required after test. | | | parametertest |
| | Functional Electrical LV Testing | **Mass Evaluation** | To evaluate the mass of system. | | Test Bed | | | | | 0 | | | | | | | No visible demages after test, no water ingress in the DUT, no sealing demage. All functionalities remains as required after test. | 2067868 | | |
| | Functional Electrical LV Testing | **Geometrical Measurement** | To check if the system is deformed during the test. | | Test Bed | | | | | 0 | | | | | | | No visible demages after test, no water ingress in the DUT, no sealing demage. All functionalities remains as required after test. | | | |
| | Functional Mechanical Testing | **Park Lock Emergency Test** | To check if the park lock is able to engage and disengage. | | Test Bed | | | | | 6 | | | 3 | 3 | | | No visible demages after test, no water ingress in the DUT, no sealing demage. All functionalities remains as required after test. | 2067874 | | |
| | Functional Mechanical Testing | **Insertion Forces Side Shaft Test** | To get the needed force of side shaft assembly and disassembly . | | Test Bed | Workbench | | | | 6 | | | 3 | 3 | | | No visible demages after test, no water ingress in the DUT, no sealing demage. All functionalities remains as required after test. | 2067874 | | |
| | Functional EMC Testing | **LV - Conducted RF emission from components/modules on LV-power lines – Voltage method** | Measurement of RF disturbance voltages on Low voltage supply lines | CISPR 25 | Test Bed | EMC Chamber | | | | 4 | 1 | 1 | 1 | 1 | | | Emission does not exceed the limits according requirement | 2067876 | | |
| | Functional EMC Testing | **HV - Conducted RF emission from components/modules on HV power lines – Voltage method** | *Test methods for shielded power supply systems for high voltages in electric and hybrid vehicles:*<br><br>Measurement of RF disturbance voltages on shielded HV voltage supply lines | CISPR 25 | Test Bed | EMC Chamber | | | | 4 | 1 | 1 | 1 | 1 | | | Emission does not exceed the limits according requirement | 2067876 | | |
| | Functional EMC Testing | **LV - Conducted RF emission from components/modules other than supply lines and cable bunches – current probe method** | Measurement of RF disturbance cureents on low voltage wiring | CISPR 25 | Test Bed | EMC Chamber | | | | 4 | 1 | 1 | 1 | 1 | | | Emission does not exceed the limits according requirement | 2067876 | | |

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|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Functional EMC Testing | **HV - Conducted RF emission from components/modules on HV power lines and and three phase motor lines to the electric motor – current probe method** | *Test methods for shielded power supply systems for high voltages in electric and hybrid vehicles:*<br>Measurement of RF disturbances currents on shielded HV cables | CISPR 25 | Test Bed | EMC Chamber | | | | 4 | 1 | 1 | 1 | 1 | | | Emission does not exceed the limits according requirement | 2067876 | | |
| | Functional EMC Testing | **HV - Conducted Emissions from Currents on Shafts and Hoses** | Test methods for components with internal disturbance sources on Shafts and/or Hoses leading outside: | ( based on CISPR 25 ) | Test Bed | EMC Chamber | | | | 4 | 1 | 1 | 1 | 1 | | | Emission does not exceed the limits according requirement | 2067876 | | |
| | Functional EMC Testing | **LV - Conducted Pulse-Emissions - Voltages on LV Supply Lines** | Measurement of Pulse emissions at the LV Supply | ISO 7637-2 | Test Bed | EMC Chamber | | | | 4 | 1 | 1 | 1 | 1 | | | Emission does not exceed the limits according requirement | 2067876 | | |
| | Functional EMC Testing | **HV - Conducted Pulse Emissions on HV Supply Lines** | Voltage transient emissions test along high voltage supply lines<br>measured between HV+ and HV- (line-to-line) and between HV+ respectively HV- and ground (line- to-ground) | ISO DTS 7637-4 | Test Bed | EMC Chamber | | | | 4 | 1 | 1 | 1 | 1 | | | Emission does not exceed the limits according requirement | 2067876 | | |
| | Functional EMC Testing | **Max. voltage rise & fall slew rates of Power & Signals connections at connector pins** | Limitation of max. voltage rise and fall times for all extern available power and signal connections (power, I/O, Communication …) | - | Test Bed | laboratory | | | | 4 | 1 | 1 | 1 | 1 | | | rise and fall slew rates do not exceed limits of the requirement or exceptional approval is given by Vehicle manufacturer | 2100919 | | |
| | Functional EMC Testing | **Max. current rise & fall slew rates of Power & Signals connections at connector pins** | Limitation of max. current rise and fall times for all extern available power and signal connections (power, I/O, Communication …) | - | Test Bed | laboratory | | | | 4 | 1 | 1 | 1 | 1 | | | rise and fall slew rates do not exceed limits of the requirement or exceptional approval is given by Vehicle manufacturer | 2100919 | | |
| | Functional EMC Testing | **HV-Load Shedding** | To avoid voltage spikes in the case of HV-Relais switching<br>Countermeasures concept has to be delivered | based on ISO DTS 6737-4 | Test Bed | EMC Chamber | | | | 3 | | 1 | 1 | 1 | | | Spikes do not exceed requirement limits | 2067876 | | |
| | Functional EMC Testing | **Radiated electromagnetic emissions from components/modules - ALSE method** | Measurement of radiated RF disturbance with external antennas | CISPR 25 | Test bed | EMC Chamber | | | | 3 | | 1 | 1 | 1 | | | Emission does not exceed the limits according requirement | 2099323 | | |
| | Functional EMC Testing | **HV - Radiated electromagnetic emissions from components/modules - with shielded HV-wiring ALSE method** | *Test methods for shielded power supply systems for high voltages in electric and hybrid vehicles:*<br>Radiated emissions from components/modules – ALSE method | CISPR 25 | Test bed | EMC Chamber | | | | 3 | | 1 | 1 | 1 | | | Emission does not exceed the limits according requirement | 2099323 | | |
| | Functional EMC Testing | **HV - radiated emissions electrical field - < 30MHz** | Measurement of electrical fields in the frequency range below 30MHz using a monoploe (rod) antenna | CISPR 25 | Test bed | EMC Chamber | | | | 3 | | 1 | 1 | 1 | | | Emission does not exceed the limits according requirement | 2099323 | | |
| | Functional EMC Testing | **HV - Radiated Emissions magnetic field <30MHz** | Measurement of magnetic fields in the frequency range below 30MHz using a loop antenna | (GBT-18387 adopted for components) | Test bed | EMC Chamber | | | | 3 | | 1 | 1 | 1 | | | Emission does not exceed the limits according requirement | 2099323 | | |
| | Functional EMC Testing | **HV - radiated emissions electromagnetic field Stripline** | Measurement of radiated RF disturbance using the stripline methode | CISPR 25 | Test bed | EMC Chamber | | | | 3 | | 1 | 1 | 1 | | | Emission does not exceed the limits according requirement | 2099323 | | |
| | Functional EMC Testing | **Low frequency magnetic field emission <150kHz** | Measurement of magnetic fields in the frequency range below 150 kHz using a hand held loop antenna (MIL-STD-461 or similar) close to the component | | Test bed | EMC Chamber | | | | 4 | 1 | 1 | 1 | 1 | | | Emission does not exceed the limits according requirement | 2099323 | | |
| | Functional EMC Testing | **Magnetic field emission - protection of persons** | Measurement of magnetic fields to limit exposure of persons to variing magnetic fields | ICNIRP | Test bed | EMC Chamber | | | | 4 | 1 | 1 | 1 | 1 | | | Emission does not exceed the limits according requirement | 2100921 | | |
| | Functional EMC Testing | **LV - Conducted immunity against pulses on LV-supply lines** | Conducted immunuity against pulses on LV-supply lines | ISO 7637-2 | Test bed | EMC Chamber | | | | 4 | 1 | 1 | 1 | 1 | | | Functional status /stati at the requested severity level(s) are fulfilled according requirement | 2099325 | | |
| | Functional EMC Testing | **LV - Conducted Immunity Fast pulses coupled on other than supply lines** | Conducted Immunity against fast pulses capacitive coupled on other than supply lines | ISO 6737-3 | Test bed | EMC Chamber | | | | 4 | 1 | 1 | 1 | 1 | | | Functional status /stati at the requested severity level(s) are fulfilled according requirement | 2099325 | | |
| | Functional EMC Testing | **LV - Conducted Immunity Slow pulses coupled on other than supply lines** | Conducted Immunity against slow pulses inductive coupled on other than supply lines | ISO 7637-3 | Test bed | EMC Chamber | | | | 4 | 1 | 1 | 1 | 1 | | | Functional status /stati at the requested severity level(s) are fulfilled according requirement | 2099325 | | |
| | Functional EMC Testing | **Conducted Immunity - extended audio frequency range** | Immunity to conducted disturbances in the extended audio frequency range | ISO 11452-10 | Test bed | EMC Chamber | | | | 3 | | 1 | 1 | 1 | | | Functional status /stati at the requested severity level(s) are fulfilled according requirement | 2099325 | | |
| | Functional EMC Testing | **HV - Voltage Ripples on HV DC Supply Lines** | Immunity against pulses on the HV-DC Supply:<br>Voltage Ripple<br>coupling between HV+ HV-,<br>HV+ GND and HV- GND | ISO DTS 7637-4 | Test bed | EMC Chamber | | | | 3 | | 1 | 1 | 1 | | | Functional status /stati at the requested severity level(s) are fulfilled according requirement | 2099325 | | |
| | Functional EMC Testing | **HV - Pulsed Sinusoidal Disturbances on HV DC Supply Lines** | Immunity against pulses on the HV-DC Supply:<br>Pulsed Sinusoidal Disturbances coupling between HV+ HV-,<br>HV+ GND and HV- GND | ISO DTS 7637-4 | Test bed | EMC Chamber | | | | 3 | | 1 | 1 | 1 | | | Functional status /stati at the requested severity level(s) are fulfilled according requirement | 2099325 | | |
| | Functional EMC Testing | **HV - Low Frequency Sinusoidal Disturbances on HV Supply Lines** | Immunity against pulses on the HV-DC suply:<br>Low Frequency Sinusoidal Disturbances<br>coupling between HV+ HV-, HV+ GND and HV- GND | ISO DTS 7637-4 | Test bed | EMC Chamber | | | | 3 | | 1 | 1 | 1 | | | Functional status /stati at the requested severity level(s) are fulfilled according requirement | 2099325 | | |
| | Functional EMC Testing | **immunity to electrical fast transient/burst disturbances conducted along HV-DC power lines.** | Specifications concerning the immunity of ESAs to electrical fast transient/burst disturbances conducted along HV DC power lines. | (based on IEC 61000-4-4) | Test bed | EMC Chamber | | | | 4 | 1 | 1 | 1 | 1 | | | Functional status /stati at the requested severity level(s) are fulfilled according requirement | 2099325 | | |
| | Functional EMC Testing | **Immunity to surge conducted along HV DC power lines** | For components beeing HV-supplied during vehicle charging coupled to the power grid<br>'Specifications concerning the immunity of ESAs to surge on DC power lines - coupled throught chargers | (based on IEC 61000-4-5) | Test bed | EMC Chamber | | | | 3 | | 1 | 1 | 1 | | | Functional status /stati at the requested severity level(s) are fulfilled according requirement | 2099325 | | |
| | Functional EMC Testing | **Radiated Immunity LV - BCI** | *Radiated Immunity against external narrowband electromagnetic sources on LV-wiring* :<br>Harness Excitation (BCI) | ISO 11452-4 | Test bed | EMC Chamber | | | | 4 | 1 | 1 | 1 | 1 | | | Functional status /stati at the requested severity level(s) are fulfilled according requirement | 2099327 | | |
| | Functional EMC Testing | **Radiated Immunity HV - BCI** | *Radiated Immunity against external narrowband electromagnetic sources on HV-wiring (HV-DC, HV-inverter output to motor) - Shielded and also without shieding of HV - wiring:* Harness Excitation (BCI) | ISO 11452-4 | Test bed | EMC Chamber | | | | 3 | | 1 | 1 | 1 | | | Functional status /stati at the requested severity level(s) are fulfilled according requirement | 2099327 | | |
| | Functional EMC Testing | **Radiated Immunity external electromagnetic fields - Absorber-lined shielded enclosure** | *Radiated Immunity against external narrowband electromagnetic sources (without pulsed radar)* :<br>Test with external Antennas in the ALSE | ISO 11452-2 | Test bed | EMC Chamber | | | | 3 | | 1 | 1 | 1 | | | Functional status /stati at the requested severity level(s) are fulfilled according requirement | 2099327 | | |
| | Functional EMC Testing | **Radiated Immunity - Radar Pulses** | *Radiated Immunity against external radar pulses:*<br>Test with external Antennas in the ALSE | ISO 11452-2 | Test bed | EMC Chamber | | | | 3 | | 1 | 1 | 1 | | | Functional status /stati at the requested severity level(s) are fulfilled according requirement | 2099327 | | |
| | Functional EMC Testing | **Radiated Immunity on board transmitters** | *Radiated Immunity against narrowband electromagnetic sources of on board transmitters* :<br>Test with external Antennas in the ALSE | ISO 11452-9 | Test bed | EMC Chamber | | | | 3 | | 1 | 1 | 1 | | | Functional status /stati at the requested severity level(s) are fulfilled according requirement | 2099327 | | |
| | Functional EMC Testing | **Radiated Immunity - Direct power injection** | *Radiated Immunity against external narrowband electromagnetic sources* :<br>Direct radio frequency (RF) power injection | ISO 11452-7 | Test bed | EMC Chamber | | | | 3 | | 1 | 1 | 1 | | | Functional status /stati at the requested severity level(s) are fulfilled according requirement | 2099327 | | |
| | Functional EMC Testing | **Radiated Immunity - Stripline** | *Radiated Immunity against external narrowband electromagnetic sources* :<br>Stripline methode | ISO 11452-5 | Test bed | EMC Chamber | | | | 3 | | 1 | 1 | 1 | | | Functional status /stati at the requested severity level(s) are fulfilled according requirement | 2099327 | | |
| | Functional EMC Testing | **Immunity to magnetic fields** | *Radiated Immunity against external narrowband electromagnetic sources* :<br>Immunity against magnetic fields | ISO 11452-8 | Test bed | EMC Chamber | | | | 3 | | 1 | 1 | 1 | | | Functional status /stati at the requested severity level(s) are fulfilled according requirement | 2099327 | | |
| | Functional EMC Testing | **ESD - EUT unpowered - Packaging and Handling on PINs** | Immunity against electrostatic discharge - EUT unpowered and unconnected discharge on connector pins | ISO 10605 | Test bed | EMC Chamber | | | | 4 | 1 | 1 | 1 | 1 | | | Functional status /stati at the requested severity level(s) are fulfilled according requirement | 2099329 | | |
| | Functional EMC Testing | **ESD - EUT unpowered - Packaging and Handling on Housing** | Immunity against electrostatic discharge - EUT unpowered and unconnected discharge on housing | ISO 10605 | Test bed | EMC Chamber | | | | 4 | 1 | 1 | 1 | 1 | | | Functional status /stati at the requested severity level(s) are fulfilled according requirement | 2099329 | | |
| | Functional EMC Testing | **ESD - EUT operating** | Immunity against electrostatic discharge - EUT operating | ISO 10605 | Test bed | EMC Chamber | | | | 4 | 1 | 1 | 1 | 1 | | | Functional status /stati at the requested severity level(s) are fulfilled according requirement | 2099329 | | |

| | | | | | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Functional EMC Testing | **HV - LV -Coupling between HV and LV systems: Voltage method** | *For shielded HV systems:* *'Coupling between HV and LV systems:* Conducted emission with tests signal injection – Voltage method | CISPR 25 | Test bed | EMC Chamber | | | | 4 | 1 | 1 | 1 | 1 | | | Emission Limits of decoupling measurements according requirements are not exceeded | 2099331 | | |
| | Functional EMC Testing | **HV - LV - Coupling between HV and LV systems: Current probe method** | *For shielded HV systems:* *'Coupling between HV and LV systems:* Conducted emission with tests signal injection – Current probe method | CISPR 25 | Test bed | EMC Chamber | | | | 4 | 1 | 1 | 1 | 1 | | | Emission Limits of decoupling measurements according requirements are not exceeded | 2099331 | | |
| | Functional EMC Testing | **HV - LV - Coupling between HV and LV systems: Radiated Emission test** | *For shielded HV systems:* *'Coupling between HV and LV systems:* Conducted emission with tests signal injection – HV-specific radiated emission test | CISPR 25 | Test bed | EMC Chamber | | | | 3 | | 1 | 1 | 1 | | | Emission Limits of decoupling measurements according requirements are not exceeded | 2099331 | | |
| | Functional EMC Testing | **HV - LV -Coupling between HV and LV systems: Measurement of the HV-LV coupling attenuation** | *For shielded HV systems:* *'Coupling between HV and LV systems:* *Measurement of the HV-LV coupling attenuation with Network analyzer* | CISPR 25 | Test bed | EMC Chamber | | | | 4 | 1 | 1 | 1 | 1 | | | Decoupling factor is inot lower than requeseted in the requirement | 2099331 | | |
| | Functional EMC Testing | **shielding of housings** | Requirements regarding the shielding of HV-housings with its openeings | IEC 61000-5-7 | Test bed | EMC Chamber | | | | 3 | | 1 | 1 | 1 | | | Shielding factor is inot lower than requeseted in the requirement | 2099331 | | |
| | Functional EMC Testing | **HV wiring and connectors** | Requirements regarding the shielding/shield connection of HV-wiring and HV-connector housings | | Test bed | EMC Chamber | | | | 3 | | 1 | 1 | 1 | | | Shielding factor is inot lower than requeseted in the requirement and shielding impedance and shielding connection impedance are not higher than requested in the requirement | 2099331 | | |
| | Functional Electrical HV Testing | **Short circuit withstand** | parameter according requirement | | Test bed | | | | | 0 | | | | | | | parameter according requirement | 2067870 | | |
| | Functional Performance Testing | **Idle map** | parameter according requirement | | Test bed | | | | | 0 | | | | | | | parameter according requirement | 2067878 | | Part of efficiency map |
| | Functional Performance Testing | **Temperature Behaviour** | Hold each torque/speed set point for a period of time | | Test bed | | | | | 0 | | | | | | | parameter according requirement; repeat with different DC voltages; Cooling conditions, UUT starting temperatures to confirm design requirements | 2067878 | | |
| | Functional Performance Testing | **Efficiency Map** | Test is performed for (all four) operating area on the torque vs speed chart over the entire operating range of the motor | | Test bed | | | | | 0 | | | | | | | parameter according requirement | 2067878 | | |
| | Functional Performance Testing | **Continuous performance map** | At each speed level the load torque are raised slowly from zero to the specified continuous torque. Then it should be held for continuous load point | | Test bed | | | | | 0 | | | | | | | parameter according requirement | 1991273 | | |
| | Functional Performance Testing | **Peak performance map** | At the highest ramp up the load torque are raised quick from zero to the specified peak torque for defined time (~30sec). Then it should be held for the specific peak operating time. | | Test bed | | | | | 0 | | | | | | | parameter according requirement | 1991273 | | |
| | Functional Performance Testing | **Driving cycle test (Speed/Torque profile)** | Battery emulated Vehicle testing with non existing vehicle | | Test bed | | | | | 0 | | | | | | | parameter according requirement | 2067880 | | |
| | Functional Thermal Testing | **Locked Rotor test** | Rotor is blocked, speed is 0rpm. Increase current in several steps until limit of winding temperature in steady state is reached. | | Test bed | | | | | 0 | | | | | | | parameter according requirement | 2114274 | | e.g. standstill |
| | Functional NVH Testing | **NVH Test** | Idle mode, operating mode, accerlation etc.. Noise behaviour during nominal operating condition. (no noise pollution for the driver and for pedestrians) | | Test bed | | | | | 0 | | | | | | | | | | |
| | Functional Mechanical Testing | **Stone impact tests** | Harmfull impact test on surface due to stone impact. Faliure mode: deformation or crack | LV 124 | Test bed | | | | | 12 | | 6 | 6 | | | | No visible demages after test. All functionalities remains as required after test. | 2067874 | | |
| | Functional Mechanical Testing | **Vibration** | Test verify robustness of the DUT againts vibration load during "driving" operating situtation. Faliure mode: fatigue, cracks, subcomponent detachments, etc.. | LV 124 / ISO_16750-3 / ISO 19453-3:2018 | Test bed | | | | | 12 | | 6 | 6 | | | | No visible demages after testing. All functionality of the DUT remains the same, special care on NVH. | 2067874 | | e.g. loads from powertrain (e.g. 2,2 x 3,3g = 7,26g) |
| | Functional Mechanical Testing | **Free fall** | Test verify robustness of the DUT after free fall | LV 124 / ISO_16750-3 / ISO 19453-3:2018 | Test bed | | | | | 12 | | 6 | 6 | | | | No visible demages after test. All functionalities remains as required after test. | 2067874 | | e.g. eAxle falls from the pallet |
| | Functional Mechanical Testing | **Mechanical shock** | Test verify mechanical loads on the component, e.g., when driving over curbs or in the case of car accidents. Test also verify the resistance of the component to flaw patterns, such as cracks and subcomponent detachments /half sinus mechanical shocks in each direction/ | LV 124 / ISO_16750-3 / ISO 19453-3:2018 | Test bed | | | | | 12 | | 6 | 6 | | | | No visible demages after testing. All functionality of the DUT remains the same, special care on NVH. | 2067874 | | |
| | Functional Mechanical Testing | **Qualification of screw connection** | Verify the quality of the screw connection | AVL internal standard | Test bed | | | | | 12 | | 6 | 6 | | | | Control test (product related) | 2067874 | | Parameter test |
| | Functional Mechanical Testing | **Screwing after aging** | Verify the quality of the screw based fixation of the DUT | AVL internal standard | Test bed | | | | | 12 | | 6 | 6 | | | | Control test (product related) | 2067874 | | Parameter test |
| | Functional Mechanical Testing | **Tolerance (geometrical) evaluation on system level** | Tolerance evaluation (fit sizes) | AVL internal standard | Test bed | | | | | 12 | | 6 | 6 | | | | Control test (product related) | 2067874 | | |
| | Functional Environmental Testing | **Water protection test** | Intrusion Protection (IP) Test verify robustness of the DUT when exposed to water. e.g., when exposed to condensed water, rain, or splash water | LV 124 | Test bed | | | | | 12 | | 6 | 6 | | | | No visible demages after test, no water ingress in the DUT, no sealing demage. All functionalities remains as required after test. | 2067864 | | |
| | Functional Environmental Testing | **Dust protection test** | Intrusion Protection (IP) Test verify robustness of the DUT when exposed to dust. | LV 124 / ISO_16750-4 / ISO 19453-4 | Test bed | | | | | 12 | | 6 | 6 | | | | No visible demages after test, no sealing demage, only permitted amount of dust ingress in the DUT. All functionalities remains as required after test. | 2067864 | | |
| | Functional Environmental Testing | **High and Low Temperature storage** | Verifaction of rubustness of the DUT againts High and Low temperature storage. | LV 124 / ISO_16750-4 / ISO 19453-4 | Test bed | | | | | 12 | | 6 | 6 | | | | No visible demage on the speciement. DUT must be fully functional after test. | 2067864 | | |
| | Functional Environmental Testing | **Step temperature test / Incremental temperature test** | Test verify robustness of the DUT after temperature changes in small steps, during operation of the DUT | LV 124 / ISO_16750-4 | Test bed | | | | | 12 | | 6 | 6 | | | | All functionalities should remain as required in every temperature step | 2067864 | | |
| | Functional Environmental Testing | **Temperature shock** | Test verify robustness of the DUT againts fast temperature changes under different ambient temperatures | LV 124 / ISO_16750-4 | Test bed | | | | | 12 | | 6 | 6 | | | | No visible demage on the speciement. DUT must be fully functional after test. | 2067864 | | |
| | Functional Environmental Testing | **Thermal shock with submerge / Immerse** | Test verify the tightness and robustness of the DUT when the DUT is immeresed into cold water after heating it up. | LV 124 / ISO_16750-4 / ISO_19453-4 | Test bed | | | | | 12 | | 6 | 6 | | | | No visible demages after test. All functionalities remains as required after test. | 2067864 | | |
| | Functional Environmental Testing | **Thermal shock with splash water** | Test verify the tightness and robustness of the DUT when water splashes on the heated DUT. | LV 124 / ISO_19453-4 | Test bed | | | | | 12 | | 6 | 6 | | | | No visible demages after test, no water ingress in the DUT, no sealing demage. All functionalities remains as required after test. | 2067864 | | |
| | Functional Environmental Testing | **High-pressure cleaning / steam jet** | Test verify the tightness of the DUT againts steam jet. | LV 124 | Test bed | | | | | 12 | | 6 | 6 | | | | No visible demages after test, no water ingress in the DUT, no sealing demage. All functionalities remains as required after test. | 2067864 | | |
| | Functional Environmental Testing | **Corrosion test / Salt spray test** | Check the resistance of a system/component to salt mist and salt water on winter streets. Failure mode is electrical malfunction due to leakage currents caused by the ingress of salt water, or check the resistance of materials and surface-coating of a system/component to salt mist and salt water on streets in winter. Test generates corrosion similar to reality. | LV 124 / ISO_16750-4 / ISO 19453-4 | Test bed | | | | | 12 | | 6 | 6 | | | | No visible demages after test. All functionalities remains as required after test. No sealing damage. | 2067864 | | |
| | Functional Environmental Testing | **Damp heat, constant** | This test simulates the use of the system/component under steady high ambient humidity | LV 124 / ISO_16750-4 / ISO 19453-4 | Test bed | | | | | 12 | | 6 | 6 | | | | No visible demage on the speciement. DUT must be fully functional after test. | 2067864 | | |
| | Functional Environmental Testing | **Damp heat, cyclic** | Test verify robustness of the DUT by cyclic temperature changes with high humidity during vehicle operation. It is meant to verify the resistance of the component to damp heat. | LV 124 / ISO_16750-4 / ISO 19453-4 | Test bed | | | | | 12 | | 6 | 6 | | | | No visible demages after test. All functionalities remains as required after test. | 2067864 | | |
| | Functional Environmental Testing | **Damp heat, cyclic with frost** | Test verify robustness of the DUT by cyclic temperature changes and frost with high humidity during vehicle operation. It is meant to verify the resistance of the components to damp heat. | LV 124 | Test bed | | | | | 12 | | 6 | 6 | | | | No visible demages after test. All functionalities remains as required after test. | 2067864 | | |
| | Functional Environmental Testing | **Chemical resistance** | Resistance against the chemicals which can get in contact on/to the DUT. (Cemicals, should be defined by the project) | LV 124, ISO_16750-5 / ISO 19453-5 | Test bed | | | | | 12 | | 6 | 6 | | | | No visible demages after test, no ingress of cemicals in the DUT, no harm on componenets. All functionalities remains as required after test. | 2067864 | | |

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| | Functional Electrical HV Testing | **Equipotential bonding contact resistance** | Test verify the robustness of the equipotential bonding for all DUT parts that can be touched and are conductive. Faliure mode: The electrical contact between the equipotential bonding conductor and the DUT and to all the DUT's conductive parts that can be touched may deteriorate during environmental and service life tests. | LV 123 | Test bed | | | | | 0 | | | | | | | Required functional status should remain as specified. Required safety function should operate. | 2067870 | | control test/ parameter test |
| | Functional Mechanical Testing | **Protection against contact** | Verify the conctact protection of the DUT | AVL internal standard | Test bed | | | | | 0 | | | | | | | Control test (product related) | | | control test/ parameter test |
| | Functional Electrical HV Testing | **Insulation resistance** | The test gives an indication of the relative quality of the insulation system and material. This test ensures a minimum value of ohmic resistance required to avoid current between galvanically isolated circuits and conductive parts of the DUT. | AVL internal standard | Test bed | | | | | 0 | | | | | | | Required functional status should remain as specified. Required safety function should operate. | 2067870 | | control test/ parameter test |
| | Functional Electrical HV Testing | **Dielectric strength / Withstand voltage** | This test simulates the dielectric strength between components of the DUT that are galvanically isolated from each other, e.g., connector pins, relays, windings, or lines. The test must be performed on components that contain or control inductive subcomponents. | | Test bed | | | | | 0 | | | | | | | Required functional status should remain as specified. Required safety function should operate. | 2067870 | | control test/ parameter test |
| | | | | | | | | | | | | | | | | | | | | |
| **Durability Testing** | | | | | | | | | | | | | | | | | | | | |
| | Durability Thermal Testing | **PTCE Powered Thermal Cycle Endurance** | To check the effects of high temperatre and high humidity on durability | | Test Bed | B2B | | | | 18 | | 6 | 6 | 6 | | | | 2114399 | | |
| | Durability Mechanical Testing | **PRET Powertrain Related Endurance Test** | Check damage of electrical and mechanical components in shortened duty cycle | | Test Bed | Validation Rig | | | | 18 | | 6 | 6 | 6 | | | | 2114387 | | |
| | Durability Thermal Testing | **HTOE High Temperature Operating Endurance** | To check the effects of high temperatre and high humidity on durability | | Test Bed | Validation Rig - Climatic Chamber | | | | 18 | | 6 | 6 | 6 | | | | 2114399 | | |
| | Durability Thermal Testing | **HTHE High Temperature and Humidity Endurance** | To check the effects of high temperatre and high humidity on durability - damp heat steady state | | Test Bed | Validation Rig - Climatic Chamber | | | | 18 | | 6 | 6 | 6 | | | | 2114399 | | |

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## 6.1.2 eMotor DVP

Project info | Instructions | About

Level 2 | Level 3.1 | Level 3.2 | Level 3.3

Level 3.1 E-Motor Subsystem

**DVP&R: Planning**

| Test ID | Test Category | Test Case | Test Description | Standard / Paragraph / Edition | Test Environment | Test Environment additional info | Test Responsibility | | Test Duration (Execution Time) [h] | Sample | | | | | Test status | Test report ID / Path | Acceptance Criteria | RQ-ID | Remarks |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | Responsible Person | Responsible Department | | Total Quantity | Gen 0 | Gen 1 | Gen 2 | Gen 3 | | | | | |
| **Functional Testing** | | | | | | | | | | | | | | | | | | | |
| **P-01** | Functional Performance Testing | **Fixed operation point measurement** | **Performance measurement - Single load point:**<br>current, torque, speed, efficiency at a specific load point at specific boundary conditions (voltage, cooling, temperature) | IEC 60034-1, IEC 60349-2, IEC 60349-4 | Load test bed | | | DY-EM | | 1 | 1 | 6 | 6 | 6 | | | Performance and parameter values meet requirements, Functional status A | 2109818 | |
| **P-01 a** | Functional Performance Testing | **Fixed operation point measurement with S1 load at base speed** | **Performance measurement - Single load point:** current, torque, speed, efficiency at maximum continous load at base speed and nominal boundary conditions (voltage, cooling, temperature) | IEC 60034-1, IEC 60349-2, IEC 60349-4 | Load test bed | | | DY-EM | | 67 | 1 | 6 | 30 | 30 | | | Performance and parameter values meet requirements, Functional status A | 2109818 | Parameter test |
| **P-02** | Functional Performance Testing | **Continuous load operating range** | **Temperature-rise test: Characteristic curve - continuous load:**<br>Evaluate max torque/ speed curve for continuous operation at specific boundary conditions (voltage, cooling, temperature).<br>Load until thermal steady state condition is reached. | IEC 60034-1, IEC 60349-2, IEC 60349-4 | Load test bed | | | DY-EM | | 19 | 1 | 6 | 6 | 6 | | | Performance and parameter values meet requirements, Functional status A | 2109818 | |
| **P-03 a** | Functional Performance Testing | **Short time overload operating range** | **Temperature-rise test: Characteristic curve - short-time overload**<br>Evaluate max torque/ speed curve for short time overload operation at specific boundary conditions (voltage, cooling, temperature)<br>Specify start temperature and either time or temperature limit.<br>Load until limits are reached | IEC 60034-1, (IEC 60034-4-1), IEC 60349-2, IEC 60349-4 | Load test bed | | | DY-EM | | 19 | 1 | 6 | 6 | 6 | | | Performance and parameter values meet requirements, Functional status A | 2109818 | |
| **P-04 a** | Functional Performance Testing | **Efficiency map (characteristic maps)** | **Characteristic machine maps test - Torque, Power, Current, Loss, Efficiency, Torque ripple**<br>Measurement of operating points:<br>Torque (n),Power(n), I_d(M,n), I_q(M,n), Losses(M,n), Efficiency (M,n) Torque ripple (M,n): @Un, Umax, Umin @target temperatures (winding, magnet) | IEC 60034-1, (IEC 60034-4-1), IEC 60349-2, IEC 60349-3, IEC 60349-4 | Load test bed | | | DY-EM | | 67 | 1 | 6 | 30 | 30 | | | Performance and parameter values meet requirements, Functional status A | 2109818 | Parameter test |
| | Functional Performance Testing | **Step test continuous/peak** | **Temperature-rise test**<br>Verification of DUT capability to have a defined number of peak load events out of continuous operation in a specific time interval (e.g 5 peak load events of 2 sec in an interval of 5 min without reaching thermal limits) | DIN EN 60034-1 | Load test bed | | | | | 14 | 1 | 1 | 6 | 6 | | | Performance and parameter values meet requirements, Functional status A | 2109818 | |
| | | | | | | | | | | | | | | | | | | | |
| | Functional Electrical Testing | **No-load saturation** | Evaluate values of saturation in iron and magnets in no-load condition | | Simulation | FEM Evaluation | | | | 4 | 1 | 1 | 1 | 1 | | | Performance and parameter values meet requirements | 2109806 | |
| | Functional Electrical Testing | **Continuous load saturation** | Evaluate values of saturation in iron and magnets for previously defined critical continuous operating points | | Simulation | FEM Evaluation | | | | 4 | 1 | 1 | 1 | 1 | | | Performance and parameter values meet requirements | 2109806 | |
| | Functional Electrical Testing | **Peak load saturation** | Evaluate values of saturation in iron and magnets for previously defined peak load operating points | | Simulation | FEM Evaluation | | | | 4 | 1 | 1 | 1 | 1 | | | Performance and parameter values meet requirements | 2109806 | |
| | Functional Electrical Testing | **Torque current characteristic** | Evaluate values in constant speed range and impact of saturation | | Load test bed | | | | | 4 | 1 | 1 | 1 | 1 | | | Performance values meets requirement, Functional status A | 2109806 | |
| | Functional Electrical Testing | **Demagnetization** | Evaluate areas of demagnetization of permanent magnets - (Peak current times safety factor (e.g. 1.2) pure demagnetization filed in d-axis) | | Simulation | FEM Evaluation | | | | 4 | 1 | 1 | 1 | 1 | | | Performance and parameter values meet requirements | 2109806 | |
| | Functional Electrical Testing | **Current density** | Evaluate values of current density in slot (J) | | Simulation | | | | | 4 | 1 | 1 | 1 | 1 | | | Performance and parameter values meet requirements | 2109806 | |

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| | Functional Electrical Testing | **Thermal loading** | Evaluate values of thermal loading (~J*A) | | Simulation | | | | | 4 | 1 | 1 | 1 | 1 | | | Performance and parameter values meet requirements | 2109806 | |
| | Functional Electrical Testing | **Impulse voltage** | **Dielectric tests with impulse voltage (surge)**<br>Verify clearances will withstand specified transient overvoltages. Intented to simulate overvoltages of atmospheric origin and covers overvoltages<br>due to switching of low-voltage equipment | IEC 60664-1 (IEC60060-1) | Electric test bed | | | DY-EM | | 67 | 1 | 6 | 30 | 30 | | | Performance and parameter values meet requirements, Functional status A | 2109806 | |
| **F-07** | Functional Electrical Testing | **Withstand voltage** | **Dielectric tests with alternating voltage;**<br>dielectric tests with direct voltage;<br>demonstrate the adequacy of the protection measures to isolate live parts of voltage class B electric circuits | IEC 60034-1 (IEC 60060-1); IEC 60349-2, IEC 60349-4; ISO 6469-3 (IEC 60664-1, IEC 61180-1) | Electric test bed | | | DY-EM | | 67 | 1 | 6 | 30 | 30 | | | Performance and parameter values meet requirements, Functional status A | 2109806 | EOL |
| **F-08** | Functional Electrical Testing | **Insulation resistance** | Measurement of insulation resistance for voltage class B electric circuits | ISO 6469-3 | Electric test bed | | | DY-EM | | 67 | 1 | 6 | 30 | 30 | | | Performance and parameter values meet requirements, Functional status A | 2109806 | Parameter test |
| **F-09** | Functional Electrical Testing | **Winding resistance** | Measurement of phase resistance | IEC 60034-1, IEC 60349-2, IEC 60349-4 | Electric test bed | Climat conditioning | | DY-EM | | 67 | 1 | 6 | 30 | 30 | | | Performance and parameter values meet requirements, Functional status A | 2109806 | Parameter test |
| | Functional Electrical Testing | **Winding inductance** | Measurement of winding inductance | | Electric test bed | | | | | 4 | 1 | 1 | 1 | 1 | | | Performance and parameter values meet requirements, Functional status A | 2109806 | |
| **F-14** | Functional Electrical Testing | **Functional check of position / speed sensor** | Measurement of sensor signal over n rotations with a reference signal | | No load test bed | | | DY-EM | | 67 | 1 | 6 | 30 | 30 | | | Performance and parameter values meet requirements, Functional status A | 2109806 | Parameter test |
| **F-10** | Functional Electrical Testing | **Functional check of thermal sensors** | Measurement of thermal sensor at defined DUT temperatures | | Electric test bed | Climat conditioning | | DY-EM | | 67 | 1 | 6 | 30 | 30 | | | Performance and parameter values meet requirements, Functional status A | 2109806 | Parameter test |
| **F-11** | Functional Electrical Testing | **Connection check of thermal sensor** | Measurement of dynamic behavior the measured sensor signal with a defined current profile in the winding (heating up DUT) | | Electric test bed | Climat conditioning | | DY-EM | | 19 | 1 | 6 | 6 | 6 | | | Performance and parameter values meet requirements, Functional status A | 2109806 | |
| | Functional Electrical Testing | **Direction of rotation / Phase sequence** | Check direction of rotation / phase sequence in relationship to terminal markings and connection | IEC 60034-1, IEC 60034-8 | No load test bed | | | DY-EM | | 67 | 1 | 6 | 30 | 30 | | | Performance and parameter values meet requirements, Functional status A | 2109806 | EOL |
| **F-15** | Functional Electrical Testing | **Open circuit voltage measurement - PMSM EESM** | Measurement of no-load voltage | IEC 60034-1, IEC 60349-2, IEC 60349-4 | No load test bed | | | DY-EM | | 67 | 1 | 6 | 30 | 30 | | | Performance and parameter values meet requirements, Functional status A | 2109806 | Parameter test |
| **F-16** | Functional Electrical Testing | **Open circuit loss measurement - PMSM IM** | Measurement of no-load losses (bearing, windage, hysteresis) | IEC 60034-1, IEC 60349-2, IEC 60349-4 | No load test bed | | | DY-EM | | 67 | 1 | 6 | 30 | 30 | | | Performance and parameter values meet requirements, Functional status A | 2109806 | |
| | Functional Electrical Testing | **No-load losses and current - - EESM** | No-load condition, field current measurement for rated induced stator voltage, no-load losses | IEC 60034-1, IEC 60034-4-1, IEC 60349-2 | No load test bed | | | DY-EM | | 67 | 1 | 6 | 30 | 30 | | | Performance and parameter values meet requirements, Functional status A | 2109806 | |
| **F-17 a** | Functional Electrical Testing | **Short circuit current measurement** | Short circuit current measurement - PMSM | IEC 60034-1, IEC 60349-4 | Load test bed | | | DY-EM | | 67 | 1 | 6 | 30 | 30 | | | Performance and parameter values meet requirements, Functional status A | 2109806 | |
| **F-17 b** | Functional Electrical Testing | **Short circuit current measurement - EESM** | Short circuit current measurement - EESM | IEC 60034-1, IEC 60349-2 | Load test bed | | | DY-EM | | 67 | 1 | 6 | 30 | 30 | | | Performance and parameter values meet requirements, Functional status A | 2109806 | |

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| **F-17 c** | Functional Electrical Testing | **Short circuit current measurement** | Locked rotor current as function of phase voltage - IM | IEC 60034-1, IEC 60349-2 | Load test bed | | | DY-EM | | 67 | 1 | 6 | 30 | 30 | | | Performance and parameter values meet requirements, Functional status A | 2109806 | |
| **F-18 a** | Functional Electrical Testing | **Short circuit torque measurement - PMSM** | Short circuit torque measurement - PMSM | IEC 60034-1, IEC 60349-4 | Load test bed | | | DY-EM | | 67 | 1 | 6 | 30 | 30 | | | Performance and parameter values meet requirements, Functional status A | 2109806 | |
| **F-18 b** | Functional Electrical Testing | **Short circuit torque measurement - EESM** | Short circuit torque measurement - EESM | IEC 60034-1, IEC 60349-2 | Load test bed | | | DY-EM | | 67 | 1 | 6 | 30 | 30 | | | Performance and parameter values meet requirements, Functional status A | 2109806 | |
| | Functional Electrical Testing | **Short circuit dynamic test** | Transient current and torque measurement | IEC 60034-1, IEC 60349-2, IEC 60349-4 | Load test bed | | | DY-EM | | 4 | 1 | 1 | 1 | 1 | | | Performance and parameter values meet requirements, Functional status A | 2109806 | |
| **F-19** | Functional Electrical Testing | **Short circuit withstand test** | Check for temperature stability in continuous 3-pole short-circuit mode | IEC 60034-1, IEC 60349-2, IEC 60349-4 | Load test bed | | | DY-EM | | 67 | 1 | 6 | 30 | 30 | | | Performance and parameter values meet requirements, Functional status A | 2109806 | |
| | Functional Electrical Testing | **Pull up torque** | Starting torque measurement of DUT | IEC 60034-1, IEC 60349-2, IEC 60349-4 | Load test bed | | | DY-EM | | 67 | 1 | 6 | 30 | 30 | | | Performance and parameter values meet requirements, Functional status A | 2109806 | |
| | Functional Electrical Testing | **Idling - IM current** | No load current measurement - function of phase voltage - induction machine | IEC 60034-1, IEC 60034-2-3, IEC 60034-28 | Load test bed | | | DY-EM | | 67 | 1 | 6 | 30 | 30 | | | Performance and parameter values meet requirements, Functional status A | 2109806 | |
| | Functional Electrical Testing | **Idling - IM losses** | No load losses - induction machine | IEC 60034-1, IEC 60034-2-3, IEC 60034-28 | Load test bed | | | DY-EM | | 67 | 1 | 6 | 30 | 30 | | | Performance and parameter values meet requirements, Functional status A | 2109806 | |
| | Functional Electrical Testing | **Locked rotor torque - induction machine** | Measurement of locked rotor torque - IM | IEC 60034-1, IEC 60034-2-3, IEC 60034-28 | Load test bed | | | DY-EM | | 67 | 1 | 6 | 30 | 30 | | | Performance and parameter values meet requirements, Functional status A | 2109806 | |
| | Functional Electrical Testing | **No-load condition - PMSM** | No-load condition - Fundamental RMS voltage measurement | IEC 60034-1, IEC 60349-4 | Load test bed | | | DY-EM | | 67 | 1 | 6 | 30 | 30 | | | Performance and parameter values | 2109806 | EOL |
| | Functional Electrical Testing | **Current-load condition - PMSM** | Current-load condition - Fundamental RMS current measurement | IEC 60034-1, IEC 60349-4 | Load test bed | | | DY-EM | | 67 | 1 | 6 | 30 | 30 | | | Performance and parameter values meet requirements, Functional status A | 2109806 | EOL |
| | Functional Electrical Testing | **No-load excitation current at rated voltage by open-circuit test - EESM** | No-load condition, field current measurement for rated induced stator voltage, no-load losses | IEC 60034-1, IEC 60349-2 | Load test bed | | | DY-EM | | 67 | 1 | 6 | 30 | 30 | | | Performance and parameter values meet requirements, Functional status A | 2109806 | EOL |
| | Functional Electrical Testing | **No-load losses at unity power factor - EESM** | No-load condition, losses at unity power factor | IEC 60034-1 | Load test bed | | | DY-EM | | 67 | 1 | 6 | 30 | 30 | | | Performance and parameter values meet requirements, Functional status A | 2109806 | EOL |
| | Functional Electrical Testing | **Excitation current at rated armature voltage - EESM** | Field current measurement for rated stator current in short circuit condition | IEC 60034-1, IEC 60349-2 | Load test bed | | | DY-EM | | 67 | 1 | 6 | 30 | 30 | | | Performance and parameter values meet requirements, Functional status A | 2109806 | EOL |

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| | Functional Electrical Testing | **No Load current - induction machine** | No-load current measurement at specified phase voltage - IM | IEC 60034-1, IEC 60349-2 | Load test bed | | | DY-EM | | 67 | 1 | 6 | 30 | 30 | | | Performance and parameter values meet requirements, Functional status A | 2109806 | EOL |
| | Functional Electrical Testing | **Locked rotor current - induction machine** | Locked rotor current mesrurement at specified phase voltage - IM | IEC 60034-1, IEC 60349-2 | Load test bed | | | DY-EM | | 67 | 1 | 6 | 30 | 30 | | | Performance and parameter values meet requirements, Functional status A | 2109806 | EOL |
| | | | | | | | | | | 0 | | | | | | | | | |
| **F-02** | Functional Mechanical Testing | **Visual inspection** | Visual inspection of DUT, detect anomalies and faults, photo documentation, no disassembly | DIN EN 13018 | Workbench | | | DY-EM | | 67 | 1 | 6 | 30 | 30 | | | Anomalies shall be noted and documented by means of photos | 2109812 | Parameter test |
| **F-03** | Functional Mechanical Testing | **Visual inspection of stator and rotor** | Visual inspection of DUT, detect anomalies and faults, photo documentation | DIN EN 13018 | Workbench | | | DY-EM | | 67 | 1 | 6 | 30 | 30 | | | Anomalies shall be noted and documented by means of photos | 2109812 | Parameter test |
| **F-04** | Functional Mechanical Testing | **Dimensional check** | Dimensional check of DUT against drawing dimension and measurement of weight | | Workbench | | | DY-EM | | 67 | 1 | 6 | 30 | 30 | | | Performance and parameter values meet requirements, Functional status A | 2109812 | Parameter test |
| **F-05** | Functional Mechanical Testing | **Cooling duct tightness test** | Leak tightness test of the cooling duct DUT | | Workbench | Pressure | | DY-EM | | 67 | 1 | 6 | 30 | 30 | | | No leakage, Functional status A | 2109812 | Parameter test |
| | Functional Mechanical Testing | **Cooling duct pressure loss test** | Measurement of pressure loss in the cooling duct DUT, (Check max. permitted pressure drop) | | Workbench | Pressure measurement | | DY-EM | | 19 | 1 | 6 | 6 | 6 | | | Parameter values meet requirements, Functional status A | 2109812 | |
| | Functional Mechanical Testing | **Bolt test** | Losening torques compared to tightening torques, use digital torque wrench to measure residual torque of all bolt connection | | Workbench | | | DY-EM | | 67 | 1 | 6 | 30 | 30 | | | Parameter values meet requirements, Functional status A | 2109812 | |
| **M-06** | Functional Mechanical Testing | **Shaft extension run out** | Check of balancing quality of the rotor | ISO 21940-11 | No load test bed | | | DY-EM | | 67 | 1 | 6 | 30 | 30 | | | Performance and parameter values meet requirements, Functional status A | 2109812 | Parameter test |
| **F-12** | Functional Mechanical Testing | **Cogging torque - PMSM** | Cogging torque measurement for one rotation cycle of the rotor at different temperatures | IEC 60349-4 | No load test bed | | | DY-EM | | 67 | 1 | 6 | 30 | 30 | | | Performance and parameter values meet requirements, Functional status A | 2109812 | |
| | Functional Mechanical Testing | **Maximum speed run** | No load test at maximum speed | | No load test bed | | | DY-EM | | 19 | 1 | 6 | 6 | 6 | | | Performance and parameter values meet requirements, Functional status A | 2109812 | |
| | Functional Mechanical Testing | **Maximum speed stop test** | Break test at maximum speed | | No load test bed | Burst protection | | DY-EM | | 19 | 1 | 6 | 6 | 6 | | | Performance and parameter values meet requirements, Functional status A | 2109812 | |
| **M-03** | Functional Mechanical Testing | **Axial force test for validation of F_ax** | Check DUT for malfunction/breakage caused by axial forces to the shaft | | Load test bed | Vibration/external forces (Climat chamber) | | DY-EM | | 13 | | 1 | 6 | 6 | | | No plastification no functional impairment, no crack or fracture | 2109812 | |
| **M-04 a** | Functional Mechanical Testing | **Radial force test for validation of F_rad: Overspeed test** | Overspeed test at hot temperature | IEC 60034-1, IEC 60349-2, IEC 60349-4 | Load test bed | Climat chamber | | DY-EM | | 14 | 1 | 1 | 6 | 6 | | | Performance and parameter values meet requirements, Functional status C | 2109812 | |
| **M-04 b** | Functional Mechanical Testing | **Radial force test for validation of F_rad: Burst speed test** | Burst test at hot temperature at guranteed burst speed out of simulation | LV 147 | No load test bed | Climat chamber, Burst protection | | DY-EM | | 14 | 1 | 1 | 6 | 6 | | | No plastification no functional impairment, no crack or fracture | 2109812 | |
| | Functional Mechanical Testing | **Burst speed determination** | Burst test, rise of speed till distortion or burst | IEC 60034-1, IEC 60349-2, IEC 60349-4 | Special load test bed | Burst protection | | DY-EM | | 13 | | 1 | 6 | 6 | | | | 2109812 | |

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| **M-07** | Functional Mechanical Testing | **Resonant frequency analysis stator and rotor** | Identfy resonance frequency and determine amplitude of DUT | IEC 60068-2-6 | Vibration bed | Climat chamber | | DY-EM | | 13 | | 1 | 6 | 6 | | | Performance and parameter values meet requirements, Functional status A | 2109812 | |
| **M-08** | Functional Mechanical Testing | **Rotating bending test for validation of F_b** | Check DUT for malfunction/breakage caused by bending forces to the shaft | | Load test bed | Vibration/external forces (Climat chamber) | | DY-EM | | 13 | | 1 | 6 | 6 | | | No plastification no functional impairment, no crack or fracture | 2109812 | |
| **M-09** | Functional Mechanical Testing | **Torsion test for validation of M_T** | Check DUT for malfunction/breakage/plastification caused by torsional forces to the shaft | | Load test bed | Vibration/external forces (Climat chamber) | | | | 13 | | 1 | 6 | 6 | | | No plastification no functional impairment, no crack or fracture | 2109812 | |
| **M-11** | Functional Mechanical Testing | **Vibration test - imbalance** | Check for vibration associated with machine imbalance | IEC 60349-2, IEC 60349-4 | Load test bed | Vibration sensor | | DY-EM | | 14 | 1 | 1 | 6 | 6 | | | Performance and parameter values meet requirements, Functional status A | 2109812 | |
| **M-01** | Functional Mechanical Testing | **Mechanical Shock** | Check DUT for malfunction/breakage caused by shock to body and frame | ISO 19453-3 (IEC 6008-2-27) | Test bed | Shock | | DY-EM | | 37 | | 1 | 18 | 18 | | | No malfunction and/or breakage | 2109812 | |
| **M-02a** | Functional Mechanical Testing | **Vibration stress with temperature overlap** | Mixed mode vibriation test<br>a) Sine on random vibration<br>b) Random vibration | ISO 19453-3 (IEC 60068-2-80, IEC 60068-2-64) | Load test bed | Vibration/external forces (Climat chamber) | | DY-EM | | 12 | | | 6 | 6 | | | No malfunction and/or breakage | 2109812 | |
| | Functional Mechanical Testing | **Free fall** | Checks DUT for malfunctions / breakage caused by free fall | ISO 19453-3 (IEC 60068-2-31) | Test bed | Shock | | DY-EM | | 12 | | | 6 | 6 | | | No malfunction and/or breakage, Functional status C | 2109812 | |
| | Functional Mechanical Testing | **Surface strength/scratch and abrasion resistance** | Test and requirements to be agreed | ISO 19453-3 | Test bed | | | DY-EM | | 12 | | | 6 | 6 | | | Functional status C, Damage which influence fuction of DUT is not permissible | 2109812 | |
| **K-04** | Functional Mechanical Testing | **Gravel bombardment / Stone - chipping** | **Gravel bombardment**<br>Investigation of the robustness and corrosion behavior of the DUT as regards the effects of gravel and stone chipping plus prior damage for subsequent stresses | ISO 19453-3, ISO 20567-1 | Test bed | Gravel chaber | | DY-EM | | 12 | | | 6 | 6 | | | Functional status C, Damage which influence fuction of DUT is not permissible | 2109812 | |
| | | | | | | | | | | 0 | | | | | | | | | |
| **P-05** | Functional NVH Testing | **E-Motor Accoustic noise level** | Verify noise emission of equipment is below sound power level limits | IEC 60034-9, IEC 60349-2, IEC 60349-4 | Load test bed | Sound measurement | | DY-EM | | 62 | 1 | 1 | 30 | 30 | | | Performance and parameter values meet requirements, Functional status A | 2114178 | |
| **M-10** | Functional NVH Testing | **Vibration test - severity** | Quantitative mechanical vibration measurement bearing housing - no load condition | IEC 60034-14, IEC 60349-2, IEC 60349-4 | Load test bed | Vibration sensor | | DY-EM | | 61 | | 1 | 30 | 30 | | | Performance and parameter values meet requirements, Functional status A | 2109812 | |
| | | | | | | | | | | 0 | | | | | | | | | |
| | Functional Thermal Testing | **Heat rejection** | Evaluation of thermal coupling (cooling circuit) of the DUR [temperatur behaviour under heating condition eg. defined current for heating] | | Electric test bed | Climat chamber | | DY-EM | | 19 | 1 | 6 | 6 | 6 | | | Performance and parameter values meet requirements, Functional status A | 2114180 | |
| | Functional Thermal Testing | **Temperature rise in high speed with open terminals** | Temperature rise test - No load condition at high speed Temperature measurement (losses) | IEC 60349-4 | No load test bed | Climat chamber | | DY-EM | | 19 | 1 | 6 | 6 | 6 | | | Performance and parameter values meet requirements, Functional status A | 2114180 | |
| **F-15 a** | Functional Thermal Testing | **Temperature coefficient measurement of induced voltage - PMSM** | Confirmation of temperature coefficient of the induced voltage - no load measurement at hot condition | IEC 60349-4 | No load test bed | Climat chamber | | DY-EM | | 19 | 1 | 6 | 6 | 6 | | | Performance and parameter values meet requirements, Functional status A | 2114180 | |
| | Functional Thermal Testing | **E-Motor cooling behaviour test - Cool down** | Evaluation of cool down behaviour of DUT | | Load test bed | Climat chamber | | DY-EM | | 19 | 1 | 6 | 6 | 6 | | | Performance and parameter values meet requirements, Functional status A | 2114180 | |

| | | | | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **K-01** | Functional Thermal Testing | **Low temperature storage** | Exposure of DUT to low temperatures without electrical operation, e.g. during shipment of the system/component. | ISO 19453-4, IEC 60068-2-1: Test A | Load test bed | Climat chamber | | DY-EM | 24 | 13 | | 1 | 6 | 6 | | | No material changes that effect DUT function, Functional status A | 2114180 | |
| **K-09** | Functional Thermal Testing | **Hich tempeartur storage** | **Dry heat test storage**<br>Exposure of DUT to high temperatures without electrical operation, e.g. during the shipment of the system/component. | ISO 19453-4, IEC 60068-2-2: Test B | Load test bed | Climat chamber | | DY-EM | 48 | 13 | | 1 | 6 | 6 | | | No material changes that effect DUT function, Functional status A | 2114180 | |
| | Functional Thermal Testing | **High temperature operation test** | Simulates exposure of DUT to high temperature with electrical operation | ISO 19453-4, IEC 60068-2-2: Test B | Load test bed | Climat chamber | | DY-EM | 96 | 13 | | 1 | 6 | 6 | | | No material changes that effect DUT function, Functional status A | 2114180 | |
| | Functional Thermal Testing | **Temperature cycle with specific change rate** | Simulates varying temperatues with electrical operation of the DUT | ISO 19453-4, IEC 60068-2-14: Test Nb | Load test bed | Climat chamber | | DY-EM | | | | 1 | 6 | 6 | | | No material changes that effect DUT function, Functional status A | 2114180 | |
| | Functional Thermal Testing | **Rapid change of temperature with specified transition duration** | Accelerated test, simulates very high number of slow temperature cycles | ISO 19453-4, IEC 60068-2-14: Test Na | Load test bed | Climat chamber | | DY-EM | | | | 1 | 6 | 6 | | | No material changes that effect DUT function, Functional status A | 2114180 | |
| | | | | | | | | | | 0 | | | | | | | | | |
| **K-07** | Functional Environmental Testing | **IP protection class** | Test of the component's leak tightness requirements (ingress of water and solid foreign bodies) | ISO 20653 | Test bed | IP test environment | | DY-EM | | 13 | | 1 | 6 | 6 | | | Functional status A | 2109802 | |
| | Functional Environmental Testing | **Temperature shock with splash water** | **Cold water shock test - Splash test**<br>Simulates thermal shock induced by cold water for DUT in splash area | ISO 19453-4 | Test bed | Splash | | DY-EM | | | | 1 | 6 | 6 | | | Functional status A | 2109802 | |
| | Functional Environmental Testing | **Temperature shock with submersion** | **Cold water shock test - Submersion test**<br>Simulates thermal shock induced by cold water for DUT in splash area | ISO 19453-4 | Test bed | Water tub | | DY-EM | | | | 1 | 24 | 24 | | | Functional status A | 2109802 | |
| **K-05a** | Functional Environmental Testing | **Corrosion test - salt spray test** | **Salt spray test - corrosion test**<br>Simulates the exposure of the DUT to salt spray, failure mode corrosion | ISO 19453-4, IEC 60068-2-52, Test Kb | Load test bed | Salt spray, Climat conditioning | | DY-EM | | 13 | | 1 | 6 | 6 | | | Functional status A, DUTs corrosion and damage shall be documented with photos | 2109802 | |
| **K-05b** | Functional Environmental Testing | **Salt spray test - leakage and function test** | Simulates the exposure of the DUT to salt spray, failure mode leakage / malfunction | ISO 19453-4, ISO 60068-2-11 Ka | Load test bed | Salt spray, Climat conditioning | | DY-EM | | 13 | | 1 | 6 | 6 | | | Functional status A, no leakage | 2109802 | |
| **K-05c** | Functional Environmental Testing | **Salt spray test - combined cycle test** | The test simulates the exposure of the DUT to salt spray - accelerated corrosion test combination of corrosion and leakage and function tests | ISO 19453-4, IEC 60068-2-52, Test Kb ISO 60068-2-11 Ka | Load test bed | Salt spray, Climat conditioning | | DY-EM | | 13 | | 1 | 6 | 6 | | | Functional status A, DUTs corrosion and damage shall be documented with photos, no leakage | 2109802 | |
| **K-08** | Functional Environmental Testing | **Immersion test in salt water solution** | This test simulates sudden immersion of the DUT e.g. the situation when driving the vehicle through dirty water. | LV147 (IEC 60068-2-18) | Load test bed | Salt spray, Climat conditioning | | DY-EM | | 13 | | 1 | 6 | 6 | | | Performance and parameter values meet requirements, Functional status A | 2109802 | |
| | Functional Environmental Testing | **Damp heat , cyclic** | **Humid heat, cyclic test - dewing**<br>Simulates use of DUT under cyclic high ambient humidity | ISO 19453-4, IEC 60068-2-30, Test Db | Load test bed | Climat conditioning | | DY-EM | | | | 1 | 6 | 6 | | | Performance and parameter values meet requirements, Functional status A | 2109802 | |
| | Functional Environmental Testing | **Damp heat, constant** | **Damp heat test steady -state**<br>Simulates use of DUT under steady high ambient humidity | ISO 19453-4, IEC 60068-2-78 | Load test bed | Climat chamber | | DY-EM | | 13 | | 1 | 6 | 6 | | | Performance and parameter values meet requirements, Functional status A | 2109802 | |
| **C-02** | Functional Environmental Testing | **Corrosion test with flow of mixed gas** | simulates the use of the system/component in the presence of corrosive gases (e.g. in highly polluted atmospheres). | IEC 60068-2-60, Test Ke | Load test bed | Gas | | DY-EM | | 13 | | 1 | 6 | 6 | | | Performance and parameter values meet requirements, Functional status A | 2109802 | |
| | Functional Environmental Testing | **Solar radiation test** | Check resistance to solar radiation | ISO 19453-4 | Test bed | Solar chamber | | DY-EM | | | | 1 | 6 | 6 | | | Performance and parameter values meet requirements, Functional status A | 2109802 | |

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| **K-03** | Functional Environmental Testing | **Dust protection test** | **Dust test**<br>Resistance on ingress of dust into the DUT | ISO 20653, IEC 60068-2-68 | Test bed | Dust chamber | | DY-EM | | 13 | | 1 | 6 | 6 | | | Performance and parameter values meet requirements, Functional status A | 2109802 | |
| | Functional Environmental Testing | **Condensation test** | Simulates condensation by rapid chage of temperature and humidity | ISO 19453-4 | Load test bed | Climat chamber | | DY-EM | | | | 1 | 6 | 6 | | | Performance and parameter values meet requirements, Functional status A | 2109802 | |
| **K-06** | Functional Environmental Testing | **Damp heat ,cyclic with frost** | Behavior of the DUTs under condensation with frost overlap. | IEC 60068-2-38, Test Z/AD | Load test bed | Climat chamber | | | | 13 | | 1 | 6 | 6 | | | Performance and parameter values meet requirements, Functional status A | 2109802 | |
| | Functional Environmental Testing | **Atmospheric pressure test** | Test of partial discharge at low pressure | IEC 60664-1, 6.1.3.5 | Electric test bed | Pressure chamber | | DY-EM | | | | 1 | 6 | 6 | | | Performance and parameter values meet requirements, Functional status A | 2109802 | |
| **C-01** | Functional Environmental Testing | **Chemical resistance** | **Chemical Loads**<br>The purpose of the test is to determine whether UUT (e-machine) is unacceptably affected by temporary exposure to contaminating agents. | ISO 19453-5 | Test Bed | Chemical agents, Climat conditioning | | DY-EM | | 13 | | 1 | 6 | 6 | | | Performance and parameter values meet requirements, Functional status C, Markings and labelling shall remain visible | 2109802 | |
| | | | | | | | | | | 0 | | | | | | | | | |
| | Functional EMC Testing | **LV - Conducted RF emission from components/modules other than supply lines and cable bunches – current probe method** | Measurement of RF disturbance cureents on low voltage wiring | CISPR 25 | Test Bed | EMC Chamber | | | | 4 | 1 | 1 | 1 | 1 | | | Emission does not exceed the limits according requirement | 2100882 | |
| | Functional EMC Testing | **Max. voltage rise & fall slew rates of Power & Signals connections at connector pins** | Limitation of max. voltage rise and fall times for all extern available power and signal connections (power, I/O, Communication …) | - | Test Bed | laboratory | | | | 3 | | 1 | 1 | 1 | | | rise and fall slew rates do not exceed limits of the requirement or exceptional approval is given by Vehicle manufacturer | 2100944 | |
| | Functional EMC Testing | **Max. current rise & fall slew rates of Power & Signals connections at connector pins** | Limitation of max. current rise and fall times for all extern available power and signal connections (power, I/O, Communication …) | - | Test Bed | laboratory | | | | 3 | | 1 | 1 | 1 | | | rise and fall slew rates do not exceed limits of the requirement or exceptional approval is given by Vehicle manufacturer | 2100944 | |
| | Functional EMC Testing | **Radiated Emissions magnetic field <30MHz** | Measurement of magnetic fields in the frequency range below 30MHz using a loop antenna | (GBT-18387 adopted for components) | Test bed | EMC Chamber | | | | 3 | | 1 | 1 | 1 | | | Emission does not exceed the limits according requirement | 2100884 | |
| | Functional EMC Testing | **HV - radiated emissions electromagnetic field Stripline** | Measurement of radiated RF disturbance using the stripline methode | CISPR 25 | Test bed | EMC Chamber | | | | 3 | | 1 | 1 | 1 | | | Emission does not exceed the limits according requirement | 2100884 | |
| | Functional EMC Testing | **Low frequency magnetic field emission <150kHz** | Measurement of magnetic fields in the frequency range below 150 kHz using a hand held loop antenna (MIL-STD-461 or similar) close to the component | | Test bed | EMC Chamber | | | | 4 | 1 | 1 | 1 | 1 | | | Emission does not exceed the limits according requirement | 2100884 | |
| | Functional EMC Testing | **Magnetic field emission - protection of persons** | Measurement of magnetic fields to limit exposure of persons to variing magnetic fields | ICNIRP | Test bed | laboratory | | | | 4 | 1 | 1 | 1 | 1 | | | Emission does not exceed the limits according requirement | 2100946 | |
| | Functional EMC Testing | **LV - Conducted Immunity Fast pulses coupled on other than supply lines** | Conducted Immunity against fast pulses capacitive coupled on other than supply lines - e.g. resolver signal | ISO 6737-3 | Test bed | EMC Chamber | | | | 4 | 1 | 1 | 1 | 1 | | | Functional status /stati at the requested severity level(s) are fulfilled according requirement | 2100886 | |
| | Functional EMC Testing | **LV - Conducted Immunity Slow pulses coupled on other than supply lines** | Conducted Immunity against slow pulses inductive coupled on other than supply lines | ISO 7637-3 | Test bed | EMC Chamber | | | | 3 | | 1 | 1 | 1 | | | Functional status /stati at the requested severity level(s) are fulfilled according requirement | 2100886 | |

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|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Functional EMC Testing | **HV - Voltage Ripples on HV motor phase wiring** | Immunity against pulses on the HV-motor phase Voltage Ripple coupling between u-v-w and u-v-w against GND possibly affecting e.g. resolver signal | similar to ISO DTS 7637-4 | Test bed | EMC Chamber | | | | 3 | | 1 | 1 | 1 | | | Functional status /stati at the requested severity level(s) are fulfilled according requirement | 2100886 | |
| | Functional EMC Testing | **HV - Pulsed Sinusoidal Disturbances on HV motor phase wiring** | Immunity against pulses on the HV-DC Supply:<br>Pulsed Sinusoidal Disturbances coupling between u-v-w and u-v-w against GND possibly affecting e.g. resolver signal | similar to ISO DTS 7637-4 | Test bed | EMC Chamber | | | | 3 | | 1 | 1 | 1 | | | Functional status /stati at the requested severity level(s) are fulfilled according requirement | 2100886 | |
| | Functional EMC Testing | **HV - Low Frequency Sinusoidal Disturbances on HV motor phase wiring** | Immunity against pulses on the HV-DC suply:<br>Low Frequency Sinusoidal Disturbances<br>coupling between u-v-w and u-v-w against GND possibly affecting e.g. resolver signal | similar to ISO DTS 7637-4 | Test bed | EMC Chamber | | | | 3 | | 1 | 1 | 1 | | | Functional status /stati at the requested severity level(s) are fulfilled according requirement | 2100886 | |
| | Functional EMC Testing | **immunity to electrical fast transient/burst disturbances conducted on HV motor phase wiring** | Specifications concerning the immunity of ESAs to electrical fast transient/burst disturbances coupling between u-v-w and u-v-w against GND possibly affecting e.g. resolver signal | (based on IEC 61000-4-4) | Test bed | EMC Chamber | | | | 4 | 1 | 1 | 1 | 1 | | | Functional status /stati at the requested severity level(s) are fulfilled according requirement | 2100886 | |
| | Functional EMC Testing | **Radiated Immunity LV - BCI** | *Radiated Immunity against external narrowband electromagnetic sources on LV-wiring* :<br>Harness Excitation (BCI) | ISO 11452-4 | Test bed | EMC Chamber | | | | 4 | 1 | 1 | 1 | 1 | | | Functional status /stati at the requested severity level(s) are fulfilled according requirement | 2100888 | |
| | Functional EMC Testing | **Radiated Immunity external electromagnetic fields - Absorber-lined shielded enclosure** | *Radiated Immunity against external narrowband electromagnetic sources (without pulsed radar)* :<br>Test with external Antennas in the ALSE | ISO 11452-2 | Test bed | EMC Chamber | | | | 3 | | 1 | 1 | 1 | | | Functional status /stati at the requested severity level(s) are fulfilled according requirement | 2100888 | |
| | Functional EMC Testing | **Radiated Immunity - Radar Pulses** | *Radiated Immunity against external radar pulses:*<br>Test with external Antennas in the ALSE | ISO 11452-2 | Test bed | EMC Chamber | | | | 3 | | 1 | 1 | 1 | | | Functional status /stati at the requested severity level(s) are fulfilled according requirement | 2100888 | |
| | Functional EMC Testing | **Radiated Immunity on board transmitters** | *Radiated Immunity against narrowband electromagnetic sources of on board transmitters* :<br>Test with external Antennas in the ALSE | ISO 11452-9 | Test bed | EMC Chamber | | | | 3 | | 1 | 1 | 1 | | | Functional status /stati at the requested severity level(s) are fulfilled according requirement | 2100888 | |
| | Functional EMC Testing | **Radiated Immunity - Direct power injection** | *Radiated Immunity against external narrowband electromagnetic sources* :<br>Direct radio frequency (RF) power injection | ISO 11452-7 | Test bed | EMC Chamber | | | | 3 | | 1 | 1 | 1 | | | Functional status /stati at the requested severity level(s) are fulfilled according requirement | 2100888 | |
| | Functional EMC Testing | **Radiated Immunity - Stripline** | *Radiated Immunity against external narrowband electromagnetic sources* :<br>Stripline methode | ISO 11452-5 | Test bed | EMC Chamber | | | | 3 | | 1 | 1 | 1 | | | Functional status /stati at the requested severity level(s) are fulfilled according requirement | 2100888 | |
| | Functional EMC Testing | **ESD - EUT unpowered - Packaging and Handling on PINs** | Immunity against electrostatic discharge - EUT unpowered and unconnected discharge on connector pins | ISO 10605 | Test bed | EMC Chamber | | | | 3 | | 1 | 1 | 1 | | | Functional status /stati at the requested severity level(s) are fulfilled according requirement | 2100890 | |
| | Functional EMC Testing | **ESD - EUT unpowered - Packaging and Handling on Housing** | Immunity against electrostatic discharge - EUT unpowered and unconnected discharge on housing | ISO 10605 | Test bed | EMC Chamber | | | | 3 | | 1 | 1 | 1 | | | Functional status /stati at the requested severity level(s) are fulfilled according requirement | 2100890 | |
| | Functional EMC Testing | **ESD - EUT operating** | Immunity against electrostatic discharge - EUT operating | ISO 10605 | Test bed | EMC Chamber | | | | 3 | | 1 | 1 | 1 | | | Functional status /stati at the requested severity level(s) are fulfilled according requirement | 2100890 | |
| | Functional EMC Testing | **HV - LV -Coupling between HV and LV systems: Voltage method** | *For shielded HV systems:*<br>*'Coupling between HV motor phases and LV systems:*<br>Conducted emission with tests signal injection – Voltage method | based on CISPR 25 | Test bed | EMC Chamber | | | | 4 | 1 | 1 | 1 | 1 | | | Emission Limits of decoupling measurements according requirements are not exceeded | 2100892 | |

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| | Functional EMC Testing | **HV - LV - Coupling between HV and LV systems: Current probe method** | *For shielded HV systems:* *'Coupling between HV motor phases and LV systems:* Conducted emission with tests signal injection – Current probe method | based on CISPR 25 | Test bed | EMC Chamber | | | | 4 | 1 | 1 | 1 | 1 | | | Emission Limits of decoupling measurements according requirements are not exceeded | 2100892 | |
| | Functional EMC Testing | **HV - LV - Coupling between HV and LV systems: Radiated Emission test** | *For shielded HV systems:* *'Coupling between HV motor phases and LV systems:* Conducted emission with tests signal injection – HV-specific radiated emission test | based on CISPR 25 | Test bed | EMC Chamber | | | | 3 | | 1 | 1 | 1 | | | Emission Limits of decoupling measurements according requirements are not exceeded | 2100892 | |
| | Functional EMC Testing | **HV - LV -Coupling between HV and LV systems: Measurement of the HV-LV coupling attenuation** | *For shielded HV systems:* *'Coupling between HV motor phases and LV systems:* *Measurement of the HV-LV coupling attenuation with Network analyzer* | based on CISPR 25 | Test bed | EMC Chamber | | | | 4 | 1 | 1 | 1 | 1 | | | Decoupling factor is inot lower than requeseted in the requirement | 2100892 | |
| | Functional EMC Testing | **Shielding of housings** | Requirements regarding the shielding of HV-housings with its openeings | IEC 61000-5-7 | Test bed | EMC Chamber | | | | 3 | | 1 | 1 | 1 | | | Shielding factor is inot lower than requeseted in the requirement | 2100894 | |
| | Functional EMC Testing | **HV wiring and connectors** | Requirements regarding the shielding/shield connection of HV-wiring and HV-connector housings | | Test bed | EMC Chamber | | | | 3 | | 1 | 1 | 1 | | | Shielding factor is inot lower than requeseted in the requirement and shielding impedance and shielding connection impedance are not higher than requested in the requirement | 2100894 | |
| | | | | | | | | | | 0 | | | | | | | | | |
| | | | | | | | | | | 0 | | | | | | | | | |
| **Durability Testing** | | | | | | | | | | | | | | | | | | | |
| | Durability Electrical Testing | **Durability withstand voltage** | Voltage pulse pattern endurance test over defined cycle (e.g.also active discharge ) | | Load test bed | | | DY-EM | | 13 | | 1 | 6 | 6 | | | Performance and parameter values meet requirements | 2109810 | |
| | Durability Electrical Testing | **Partial discharge free insulation** | Impulse voltage test endurance (Impulse voltage insulation class test) | IEC 60034-18-41, IEC 60034-18-42 | Load test bed | | | DY-EM | | 13 | | 1 | 6 | 6 | | | Performance and parameter values meet requirements | 2109810 | |
| | | | | | | | | | | 0 | | | | | | | | | |
| | Durability Mechanical Testing | **High speed durability** | Endurance test, DUT is running at maximum continuous power and at maximum speed. | | Load test bed | | | DY-EM | | 13 | | 1 | 6 | 6 | | | Performance and parameter values meet requirements, Functional status A | 2114280 | |
| **M-05** | Durability Mechanical Testing | **Radial force test for validation of F_rad: Dynamic rpm test** | **Load cycle test** Accelration to max speed and breaking to stop with maximum torque | LV 147 | Load test bed | | | DY-EM | | 13 | | 1 | 6 | 6 | | | Performance and parameter values meet requirements, Functional status A | 2114280 | |
| | Durability Mechanical Testing | **Launch durability test** | Standstill, accleration under maximum load with maximum speed stop<br><br>(High speed on/off durability Endurance test, compare to PTCE test, DUT (e-machine) operating power toggle between maximum load and basic load at maximum speed ) | | Load test bed | | | DY-EM | | 13 | | 1 | 6 | 6 | | | Performance and parameter values meet requirements, Functional status A | 2114280 | |
| | Durability Mechanical Testing | **Driving cycle test** | Dynamical driving, hill driving and dynamical accleration to check the e-motor real driving condition | | Load test bed | | | DY-EM | | 13 | | 1 | 6 | 6 | | | Performance and parameter values meet requirements, Functional status A | 2114280 | |
| | Durability Mechanical Testing | **Constant load pattern test** | Durability test with constant load test profile (pattern durability) | | Load test bed | | | DY-EM | | 13 | | 1 | 6 | 6 | | | Performance and parameter values meet requirements, Functional status A | 2114280 | |
| | Durability Mechanical Testing | **Bearing test** | Durability test of bearing | | Load test bed | | | DY-EM | | 13 | | 1 | 6 | 6 | | | Performance and parameter values meet requirements, Functional status A | 2114280 | |

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|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Durability Thermal Testing | **High temperature endurance test** | Endurance test, the DUT (e-machine) is running at maximum continuous power and at at base speed (max speed before field weakening range). | | Load test bed | Climat chamber | | DY-EM | | 13 | | 1 | 6 | 6 | | | No material changes that effect DUT function, Functional status A, Discoloration shall be documented | 2109804 | |
| **K-02** | Durability Thermal Testing | **Thermal shock in air** | This is an accelerated test which simulates a very high number of slow temperature cycles in the vehicle. | IEC 60068-2-14, Test Na | Load test bed | Climat chamber | | DY-EM | | 13 | | 1 | 6 | 6 | | | No material changes that effect DUT function, Functional status A, Discoloration shall be documented | 2109804 | |
| **L-01** | Durability Thermal Testing | **HTOE High Temperature Operation Endurance** | **High Temperature Operation Endurance (HTOE)**<br>Calculation according to Arrhenius, lifetime of the component at high temperatures | IEC 60068-2-2: Dry Heat | Load test bed | Climat chamber | | DY-EM | | 13 | | 1 | 6 | 6 | | | Performance values meets requirement, Functional status A | 2109804 | |
| **L-02** | Durability Thermal Testing | **PTCE Power Thermal Cycle Endurance** | **Power Thermal Cycle Endurance (PTCE)**<br>Calculation according to Coffin - Manson, lifetime endurance load of the component for temperature change acc. to environment and operation. In addition the number of cold starts is to be ensured | IEC 60068-2-14 | Load test bed | Climat chamber | | DY-EM | | 13 | | 1 | 6 | 6 | | | Performance and parameter values meet requirements, Functional status A | 2109804 | |
| **L-03** | Durability Enviromental Testing | **HTHE High Temperature and Humidity Endurance** | **High Temperature and Humidity Endurance (HTHE)**<br>Calculation according to Lawson, lifetime load of the component at high temperatures and high air humidity. Different effects may occur as material bulging due to humidity absorption, failure of seals and sealing, coating agent failures, electrical short circuits due to condensation, oxidation and/or galvanic corrosion of metals etc | IEC 60068-2-38,<br>IEC 60068-2-30 | Load test bed | Climat chamber | | DY-EM | | 13 | | 1 | 6 | 6 | | | Performance and parameter values meet requirements, Functional status A | 2109804 | |

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## 6.1.3 Inverter DVP

AVL

Project info | Instructions | About

Level 2 | Level 3.1 | Level 3.2 | Level 3.3

Level 3.2 Power Electronics Subsystem

DVP&R: Planning

| Test ID | Test Category | Test Case | Test Description | Standard / Paragraph / Edition | Test Environment | Test Environment additional info | Test Responsibility | | Test Duration (Execution Time) | Sample | | | | | Test status | Test report ID / Path | Acceptance Criteria | RQ-ID | Remarks |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | Responsible Person | Responsible Department | | Total Quantity | Gen 0 | Gen 1 | Gen 2 | Gen 3 | | | | | |
| **Functional Testing** | | | | | | | | | | | | | | | | | | | |
| | Functional Thermal Testing | **High and Low Temperature storage** | Verifaction of rubustness of the DUT againts High and Low temperature storage. | LV 124 / ISO_16750-4 / ISO 19453-4 | Test bed | Climatic chamber | | | | 6 | | 6 | 6 | | Planned | | No visible demage on the speciement.<br>DUT must be fully functional after test. | 2067731 | Faliure mode: Componenet wear out (electonics, housing, sealing, wire, harness, corrosion etc..) cracks, componenet demages, dislocation of componenets, or deformation. |
| | Functional Thermal Testing | **Temperature shock** | Test verify robustness of the DUT againts fast temperature changes under different temperatures in between -40°C up to 150°C | LV 124 / ISO_16750-4 | Test bed | Climatic chamber | | | | 6 | | 6 | 6 | | Planned | | No visible demage on the speciement.<br>DUT must be fully functional after test. | 2067731 | Faliure mode: Componenet wear out (electonics, housing, sealing, wire, harness, corrosion etc..) cracks, componenet demages, dislocation of componenets, or deformation. |
| | Functional Thermal Testing | **Temperature cycle** | Test verify robustness of the DUT againts long run temperature changes cycle in between -40°C up to 140°C | LV 124 / ISO_16750-4 / ISO 19453-4 | Test bed | Climatic chamber | | | | 6 | | 6 | 6 | | Planned | | No visible demage on the speciement.<br>DUT must be fully functional after test. | 2067731 | Faliure mode: Componenet wear out (electonics, housing, sealing, wire, harness, corrosion etc..) cracks, componenet demages, dislocation of componenets, or deformation. |
| | Functional Thermal Testing | **Step temperature test / Incremental temperature test** | Test verify robustness of the DUT after temperature changes in small steps, during operation of the DUT | LV 124 / ISO_16750-4 | Test bed | Climate chamber + inverter test pad | | | | 12 | | 6 | 6 | | | | All functionalities should remain as required in every temperature step | 2067731 | Faliure mode: Functional status faliure occures in temperature steps |
| | Functional Thermal Testing | **Low Temperature operation** | Test verify robustness of the DUT and the right functional status requirement, after operatin under low temperatures. | LV 124 | Test bed | Climatic chamber | | | | 12 | | 6 | 6 | | | | All functionalities should remain as required after low temperature operation | 2067731 | Faliure mode: Functional status faliure occures after low temperature operation |
| | Functional Environmental Testing | **Noxious gas test** | Conditioning of the DUT under a special gas concentration over a temperature and humidity conditions | LV 124 / ISO_1650-4 / ISO 19453-4 | Test bed | Noxious Gas Test Chamber | | | | 6 | | 6 | 6 | | Planned | | No visible demage on the speciement. | 2067731 | Faliure mode: It is meant to verify the resistance of the component to flaw patterns, such as corrosion and component damage. |
| | Functional Environmental Testing | **Corrosion test / Salt spray test** | Check the resistance of a system/component to salt mist and salt water on winter streets. Failure mode is electrical malfunction due to leakage currents caused by the ingress of salt water, or check the resistance of materials and surface-coating of a system/component to salt mist and salt water on streets in winter. Test generates corrosion similar to reality. | LV 124 / ISO_16750-4 / ISO 19453-4 | Test bed | Salt spray chamber/ tub | | | | 6 | | 6 | 6 | | | | No visible demages after test. All functionalities remains as required after test. No sealing damage. | 2067731 | Faliure mode: Corrosion on componenet, elecrical faliure due to corrosion, dislocation of componenets. Functional status faliure occures after testing. |
| | Functional Environmental Testing | **Damp heat, cyclic** | Test verify robustness of the DUT by cyclic temperature changes with high humidity during vehicle operation. It is meant to verify the resistance of the component to damp heat. | LV 124 / ISO_16750-4 / ISO 19453-4 | Test bed | Climatic chamber | | | | 6 | | 6 | 6 | | | | No visible demages after test. All functionalities remains as required after test. | 2067731 | Faliure mode: Corrosion on componenets, sealing damage, electrical malfunction caused by moisture |
| | Functional Environmental Testing | **Damp heat, cyclic with frost** | Test verify robustness of the DUT by cyclic temperature changes and frost with high humidity during vehicle operation. It is meant to verify the resistance of the components to damp heat. | LV 124 | Test bed | Climatic chamber | | | | 6 | | 6 | 6 | | | | No visible demages after test. All functionalities remains as required after test. | 2067731 | Faliure mode: Corrosion on componenets, sealing damage, electrical malfunction caused by moisture |
| | Functional Environmental Testing | **Water protection test** | Intrusion Protection (IP)<br>Test verify robustness of the DUT when exposed to water.<br>e.g., when exposed to condensed water, rain, or splash water | LV 124 | Test bed | IP test environment | | | | 6 | | 6 | 6 | | | | No visible demages after test, no water ingress in the DUT, no sealing demage. All functionalities remains as required after test. | 2067731 | Faliure mode: leak tightness check, verification of the sealings, corrosion on components |
| | Functional Environmental Testing | **Dust test** | Intrusion Protection (IP)<br>Test verify robustness of the DUT when exposed to dust. | LV 124 / ISO_16750-4 / ISO 19453-4 | Test bed | Dust chamber | | | | 6 | | 6 | 6 | | | | No visible demages after test, no sealing demage,only permitted amount of dust ingress in the DUT. All functionalities remains as required after test. | 2067731 | Faliure mode: Dut is not tight againts dust, electrical or mechanical faliure |
| | Functional Environmental Testing | **Solar radiation test** | If required, resistance to solar radiation shall be ensured by the choice of a suitable material. | LV 124 / ISO_16750-4 / ISO 19453-4 | Test bed | Solar radiation chamber | | | | 6 | | 6 | 6 | | | | No visible demages after test, no sealing demage, no deformation of the componenets (mainly housing). | 2067731 | Faliure mode: DUT components (mainly housing) will deformate, cracks occure, other deformation on componenets |
| | Functional Environmental Testing | **Chemical resistance** | Resistance against the chemicals which can get in contact on/to the DUT. (Cemicals, should be defined by the project) | LV 124, ISO_16750-5 / ISO 19453-5 | Test bed | Climat chamber | | | | 6 | | 6 | 6 | | | | No visible demages after test, no ingress of cemicals in the DUT, no harm on componenets. All functionalities remains as required after test. | 2067731 | Faliure mode: Corrosion, component damage |
| | Functional Environmental Testing | **Thermal shock with splash water** | Test verify the tightness and robustness of the DUT when water splashes on the heated DUT. | LV 124 / ISO_19453-4 | Test bed | Climat chamber / water dispenser | | | | 6 | | 6 | 6 | | | | No visible demages after test, no water ingress in the DUT, no sealing demage. All functionalities remains as required after test. | 2067731 | Faliure mode: componenet damage, sealing damage, untightness |
| | Functional Environmental Testing | **High-pressure cleaning / steam jet** | Test verify the tightness of the DUT againts steam jet. | LV 124 | Test bed | Chamber with steam jet | | | | 6 | | 6 | 6 | | | | No visible demages after test, no water ingress in the DUT, no sealing demage. All functionalities remains as required after test. | 2067731 | Faliure mode: componenet damage, sealing damage, untightness |
| | Functional Environmental Testing | **Thermal shock with submerge / Immerse** | Test verify the tightness and robustness of the DUT when the DUT is immeresed into cold water after heating it up. | LV 124 / ISO_16750-4 / ISO_19453-4 | Test bed | Climat chamber / Water tub | | | | 6 | | 6 | 6 | | | | | 2067731 | Faliure mode: componenet damage, sealing damage, untightness |
| | Functional NVH Testing | **NVH testing / acoustic design** | Test checks the noise emmision of the DUT during operation | AVL internal standard | Test bed | Acoustic test bed | | | | 6 | | 6 | 6 | | | | Measured noise emmission is under limit | 2067731 | Faliure mode: The noise emmission exceeds the required limit. |
| | Functional Environmental Testing | **Atmospheric pressure test** | The partial discharge inception voltage is affected by atmospheric pressure. When distance is close enaugh that partial discharge can occure. | ISO 19453-4 | Test bed | Partial discharge testr + climat chamber | | | | 6 | | 6 | 6 | | | | No partial discharge occure during testing | 2067731 | Faliure mode: Partial discharge measurable |
| | Functional Mechanical Testing | **Connector Test I** | Insertion force / mounting force / locking force | AVL internal standard | Test Bed | Traction Machine | | | 3 | 12 | | 6 | 6 | | | | No demage on componenet, all functions remains the same after test.<br>As required after Test . | 2067764 | Faliure mode: componenet damage<br>according specification and offer drawing |
| | Functional Mechanical Testing | **Connector Test II** | Extraction force / dissasambly force | AVL internal standard | Test Bed | Traction Machine | | | 3 | 12 | | 6 | 6 | | | | No demage on componenet, all functions remains the same after test.<br>As required after Test . | 2067764 | Faliure mode: componenet damage<br>according specification and offer drawing |
| | Functional Mechanical Testing | **Connector Test III** | Pin torsion test | AVL internal standard | Test Bed | Traction Machine | | | 3 | 12 | | 6 | 6 | | | | No demage on componenet, all functions remains the same after test.<br>As required after Test . | 2067764 | Faliure mode: componenet damage<br>according specification and offer drawing |
| | Functional Mechanical Testing | **Tensile strength** | Verifying test for componets what should recieve higher tensile force durfing life time. | AVL internal standard | Test bed | Tensile tester | | | | 6 | | 6 | 6 | | | | No demage on componenet, all functions remains the same after test.<br>As required after Test . | 2067764 | Faliure mode: componenet damage<br>according specification and offer drawing |
| | Functional Mechanical Testing | **Pin perforation test** | Test verify pin push in and pull out forces with tensile tester. | AVL internal standard | Test bed | Tensile tester | | | | 6 | | 6 | 6 | | | | No demage on componenet, all functions remains the same after test.<br>As required after Test . | 2067764 | Faliure mode: componenet damage<br>according specification and offer drawing |
| | Functional Mechanical Testing | **Connector force perpendicular to the assembly direction** | Test verify connector's perpendicular push in and pull out forces with tensile tester. | AVL internal standard | Test bed | Tensile tester | | | | 6 | | 6 | 6 | | | | No demage on componenet, all functions remains the same after test.<br>As required after Test . | 2067764 | Faliure mode: componenet damage<br>according specification and offer drawing |

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| | Functional Mechanical Testing | **Vibration** | Test verify robustness of the DUT againts vibration load during "driving" operating situtation. Faliure mode: fatigue, cracks, subcomponent detachments, etc.. | LV 124 / ISO_16750-3 / ISO 19453-3:2018 | Test bed | Vibration bed (climat chamber) | | | | 6 | | 6 | 6 | | | | No visible demages after testing. All functionality of the DUT remains the same, special care on NVH. | 2067764 | Faliure mode: Componenet wear out/damage (electonics, housing, sealing, wire, harness, corrosion etc..) cracks, dislocation of componenets, or deformation, subcomponeent detachment |
| | Functional Mechanical Testing | **Mechanical shock** | Test verify mechanical loads on the component, e.g., when driving over curbs or in the case of car accidents. Test also verify the resistance of the component to flaw patterns, such as cracks and subcomponent detachments /half sinus mechanical shocks in each direction/ | LV 124 / ISO_16750-3 / ISO 19453-3:2018 | Test bed | Shock bed | | | | 6 | | 6 | 6 | | | | No visible demages after testing. All functionality of the DUT remains the same, special care on NVH. | 2067764 | Faliure mode: Componenet wear out/damage (electonics, housing, sealing, wire, harness, corrosion etc..) cracks, dislocation of componenets, or deformation, subcomponeent detachment |
| | Functional Mechanical Testing | **Coolant Circuit pressure pulsation** | Verify pressure fluctuations in coolant circuit, as well during the post-heating phase and vacuum filling of the cooling system must be applied exclusively to components that are connected to a coolant circuit. | LV 124 | Test bed | Shock bed | | | | 6 | | 6 | 6 | | | | No component demage, all functionality remains as reqired after testing | 2067764 | Faliure mode: Due to pressure fluctuations in coolant circuit, componenet damage, subcomponeent detachment |
| | Functional Mechanical Testing | **Free fall** | Test verify robustness of the DUT after free fall, 1 meter on concrete or steel Generally: 3 direction - 3 parts at least. Simulates process chain faluire cases. | LV 124 / ISO_16750-3 / ISO 19453-3:2018 | Test bed | Free fall tester | | | | 6 | | 6 | 6 | | | | No visible demages after test. All functionalities remains as required after test. | 2067764 | Faliure mode: Componenet damage, subcomponeent detachment |
| | Functional Mechanical Testing | **Stone impact tests** | Harmfull impact test on surface due to stone impact. Faliure mode: deformation or crack | LV 124 | Test bed | stone impact test environment / chamber | | | | 6 | | 6 | 6 | | | | No visible demages after test. All functionalities remains as required after test. | 2067764 | Faliure mode: Componenet damage, subcomponeent detachment |
| | Functional Mechanical Testing | **Leakage** | Air/coolant leakage tightness of componenet/system. | AVL internal standard | Test bed | Container / tub /reductor | | | | 6 | | 6 | 6 | | | | No visible demages after test, no air leak above the specified air leak. | 2067764 | Faliure mode: sealing damage Parameter test |
| | Functional Mechanical Testing | **Visual inspection** | Naked eye inspection of component/system to evaluate the damage, cracks, changes, rupteres, flaking, discoloration, or deformation. | AVL internal standard | Test bed | natural eye | | | | 6 | | 6 | 6 | | | | Control test | 2067764 | Control test Begining, intermediate and end of the tests. |
| | Functional Mechanical Testing | **Residual torque** | Use digital torque wrench to measure residual torque | AVL internal standard | Test bed | torque wrench | | | | 6 | | 6 | 6 | | | | Control test | 2067764 | Control test, process description |
| | Functional Mechanical Testing | **Qualification of screw connection** | Verify the quality of the screw connection | AVL internal standard | Test bed | Tensile tester / torque wrench | | | | 6 | | 6 | 6 | | | | Control test (product related) | 2067764 | Qualification, process description according specification and offer drawing |
| | Functional Mechanical Testing | **Screwing after aging** | Verify the quality of the screw based fixation of the DUT | AVL internal standard | Test bed | torque wrench | | | | 6 | | 6 | 6 | | | | Control test (product related) | 2067764 | Control test, process description according specification and offer drawing |
| | Functional Mechanical Testing | **Protection against contact** | Verify the conctact protection of the DUT | AVL internal standard | Test bed | torque wrench | | | | 6 | | 6 | 6 | | | | Control test (product related) | 2067764 | Control test, process description according specification |
| | Functional Electrical LV Testing | **(LV) - Direct current supply voltage - Short / long term** | The purpose of this test is to verify equipment functionality at minimum and maximum supply voltage. | ISO 16750-2 | Test Bed | Inverter load test bed | | | 0,3 | 6 | | 6 | 6 | | | | Required functional status should remain as specified. Required safety function should operate. | 2067756 | Faliure mode: Required functional status failure after test-malfunction/dysfunction on the specified min and max supply voltage; required safty function not applicable |
| | Functional Electrical LV Testing | **LV - Long-term overvoltage** | Test examines componenet behavior and resistance in the event of long-term overvoltage. | LV 124 | Test bed | Inverter load test bed | | | | 12 | | 6 | 6 | | | | Required functional status should remain as specified. Required safety function should operate. | 2067756 | Faliure mode: Required functional status failure after test-malfunction/dysfunction on the specified min and max supply voltage; required safty function not applicable |
| | Functional Electrical LV Testing | **LV - Transient overvoltage** | Switching off loads when engine is operating, what may result transient overvoltages in the electric system. | LV 124 | Test bed | Inverter load test bed | | | | 12 | | 6 | 6 | | | | Required functional status should remain as specified. | 2067756 | Faliure mode: Required functional status failure after test |
| | Functional Electrical LV Testing | **LV - Tranisent undervoltage** | Switching on loads may result in transient undervoltages, depending on the state of the power electric system. | LV 124 | Test bed | Inverter load test bed | | | | 12 | | 6 | 6 | | | | Required functional status should remain as specified. | 2067756 | Faliure mode: Required functional status failure after test |
| | Functional Electrical LV Testing | **LV - Superimposed alternating voltage** | This test simulates a residual alternating current on the direct current supply. | LV 124 / ISO 16750-2 | Test Bed | Inverter load test bed | | | 0,3 | 12 | | 6 | 6 | | | | Required functional status should remain as specified. | 2067756 | Faliure mode: Required functional status failure after test |
| | Functional Electrical LV Testing | **LV - Variation of decrease and increase of supply votage (Slow decrease and increase of supply voltage)** | Test simulates the gradual discharge and recharge of the battery. | LV 124 / ISO 16750-2 | Test Bed | Inverter load test bed | | | 0,3 | 12 | | 6 | 6 | | | | 1.) Within the defined operating voltage: Required functional status should remain as specified. 2.) Outside of the defined operating: Required functional status can deviate from requirement, but deviation has to be specified. | 2067756 | Faliure mode: Required functional status failure after test |
| | Functional Electrical LV Testing | **LV - Momentary drop in supply voltage / Short interruprions** | This test simulates the effect when a conventional fuse element melts in another circuit. | LV 124 / ISO 16750-2 | Test Bed | Inverter load test bed | | | | 12 | | 6 | 6 | | | | Required functional status should remain as specified. | 2067756 | Faliure mode: Required functional status failure after test; required safty function not applicable |
| | Functional Electrical LV Testing | **LV - Reset behavior at voltage drop** | This test verify the reset behaviour of the DUT at different voltage drops. This test is applicable to equipment with reset function, e.g. equipment containing microcontroller(s). | LV 124 / ISO 16750-2 | Test Bed | Inverter load test bed | | | | 12 | | 6 | 6 | | | | Required functional status should remain as specified. | 2067756 | Faliure mode: Required functional status failure after test; required safty function not applicable |
| | Functional Electrical LV Testing | **LV - Starting profile / Start pulses** | This test verify the behaviour of a DUT during and after cranking. | LV 124 / ISO 16750-2 | Test Bed | Inverter load test bed | | | | 12 | | 6 | 6 | | | | Required functional status should remain as specified. Required safety function should operate. | 2067756 | Faliure mode: Required functional status failure after test; required safty function not applicable |
| | Functional Electrical LV Testing | **LV - Load dump** | This test is a simulation of load dump transient occurring in the event of a discharged battery being disconnected while the alternator is generating charging current with other loads remaining on the alternator circuit at this moment. | LV 124 / ISO 16750-2 | Test Bed | Inverter load test bed | | | | 12 | | 6 | 6 | | | | Required functional status should remain as specified. | 2067756 | Faliure mode: Required functional status failure after test |
| | Functional Electrical LV Testing | **LV - Reversed voltage** | This test checks the ability of a DUT to withstand against the connection of a reversed battery in case of using an auxiliary starting device. This test is not applicable to: | LV 124 / ISO 16750-2 | Test Bed | Inverter load test bed | | | 0,3 | 12 | | 6 | 6 | | | | Required functional status should remain as specified. Required safety function should operate. | 2067756 | Faliure mode: Required functional status failure after test-malfunction/dysfunction on the specified componenet; required safty function not applicable |
| | Functional Electrical LV Testing | **LV - Ground reference and supply offset** | This test shall be agreed between customer and supplier. This test serves to verify reliable operation of a component if two or more power supply paths exist. For instance, a component may have a power ground and a signal ground that are outputs on different circuits | LV 124 / ISO 16750-2 | Test Bed | Inverter load test bed | | | | 12 | | 6 | 6 | | | | Required functional status should remain as specified. | 2067756 | Faliure mode: Required functional status failure after test-malfunction/dysfunction on the specified componenet |
| | Functional Electrical LV Testing | **LV - Single line interruption / pin intteruption (Open circuit tests)** | This test simulates an open contact condition. | LV 124 / ISO 16750-2 | Test Bed | Inverter load test bed | | | | 12 | | 6 | 6 | | | | Required functional status should remain as specified. Required safety function should operate. | 2067756 | Faliure mode: Required functional status failure after test-malfunction/dysfunction on the specified componenet; required safty function not applicable |
| | Functional Electrical LV Testing | **LV - Multiple line interruption/ (Open circuit tests)** | The purpose of this test to ensure functional status as defined in the specification of the DUT when the DUT is subjected to a rapid multiple line interruption. | LV 124 / ISO 16750-2 | Test Bed | Inverter load test bed | | | | 12 | | 6 | 6 | | | | Required functional status should remain as specified. Required safety function should operate. | 2067756 | Faliure mode: Required functional status failure after test-malfunction/dysfunction on the specified componenet; required safty function not applicable |
| | Functional Electrical LV Testing | **LV - Connector interruption (Open circuit tests)** | The purpose of this test to ensure functional status as defined in the specification of the DUT when the DUT is subjected to a rapid connector interruption. | ISO 16750-2 | Test Bed | Inverter load test bed | | | | 12 | | 6 | 6 | | | | Required functional status should remain as specified. Required safety function should operate. | 2067756 | Faliure mode: Required functional status failure after test-malfunction/dysfunction on the specified componenet; required safty function not applicable |
| | Functional Electrical LV Testing | **LV - Short circuit protection: Signal circuits** | These tests simulate short circuits to the inputs and outputs of the DUT | LV 124 / ISO 16750-2 | Test Bed | Inverter load test bed | | | | 12 | | 6 | 6 | | | | Required functional status should remain as specified. Required safety function should operate. | 2067756 | Faliure mode: Required functional status failure after test-malfunction/dysfunction on the specified componenet; required safty function not applicable |
| | Functional Electrical LV Testing | **LV -Short circuit protection: Load circuits** | While the load circuits are under operation, the DUT is connected to the power supply. Short circuit should be performed. This test is applicable only for systems/components with load circuits. | LV 124 / ISO 16750-2 | Test Bed | Inverter load test bed | | | | 12 | | 6 | 6 | | | | Required functional status should remain as specified. Required safety function should operate. | 2067756 | Faliure mode: Required functional status failure after test-malfunction/dysfunction on the specified componenet; required safty function not applicable |

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| | Functional Electrical LV Testing | **LV -Short circuit protection: Load circuits** | This test stresses the insulation system and checks the ability of the dielectric material to withstand a higher voltage caused by switching off. This test ensures the dielectric withstand voltage capability of circuits with galvanic isolation. This test is required only for systems/components which contain inductive elements (e.g. relays, motors, coils) or are connected to circuits with inductive load. | LV 124 / ISO 16750-2 | Test Bed | Inverter load test bed | | | | 12 | | 6 | 6 | | | | Required functional status should remain as specified. Required safety function should operate. | 2067756 | Faliure mode: Required functional status failure after test-malfunction/dysfunction on the specified componenet; required safty function not applicable |
| | Functional Electrical LV Testing | **LV - Insulation resistance** | The test gives an indication of the relative quality of the insulation system and material. This test ensures a minimum value of ohmic resistance required to avoid current between galvanically isolated circuits and conductive parts of the DUT. | LV 124 / ISO 16750-2 | Test Bed | Inverter load test bed | | | | 12 | | 6 | 6 | | | | Required functional status should remain as specified. Required safety function should operate. | 2067756 | Faliure mode: Required functional status failure after test-malfunction/dysfunction on the specified componenet; required safty function not applicable |
| | Functional Electrical LV Testing | **LV - Dielectric strength / Withstand voltage** | This test simulates the dielectric strength between components of the DUT that are galvanically isolated from each other, e.g., connector pins, relays, windings, or lines. The test must be | LV 124 / ISO 16750-2 | Test Bed | Inverter load test bed | | | | 12 | | 6 | 6 | | | | Required functional status should remain as specified. Required safety function should operate. | 2067756 | Faliure mode: Required functional status failure after test-malfunction/dysfunction on the specified componenet; required safty function not applicable |
| | Functional Electrical LV Testing | **LV - Generated voltage slope** | This test evaluates the generated voltage slope and confirms that it is within the specified maximum rate. | ISO DIS 21498 | Test Bed | Inverter load test bed | | | | 12 | | 6 | 6 | | | | The DUT shall be connected to a load/source and shall provide the capability to change the power on request. The voltage shall be monitored and evaluated. | 2067756 | Faliure mode: Required functional status failure after test-malfunction/dysfunction on the specified componenet; required safty function not applicable |
| | Functional Electrical LV Testing | **LV -Low Voltage test 1** | Current compensation, standby- and pulsing mode shall be possible, LV voltage range shall be useable | AVL internal standard | Test bed | Inverter load test bed | | | | 12 | | 6 | 6 | | | | Required functional status should remain as specified. | 2067756 | Failure mode: Required functional status failure after test |
| | Functional Electrical LV Testing | **LV -Low Voltage test 2** | The level of the low voltage supply can vary, but full performance (@HV-side) shall be guaranteed in a nominal area. (HV working point is fixed, and the LV suppy vary) | AVL internal standard | Test bed | Inverter load test bed | | | | 12 | | 6 | 6 | | | | Required functional status should remain as specified. | 2067756 | Failure mode: Required functional status failure after test |
| | Functional Electrical LV Testing | **LV - Jump start** | Simulates an external power supply, with the maximum voltage from the commercial vehicles. | LV 124 | Test bed | Inverter load test bed | | | | 12 | | 6 | 6 | | | | Required functional status should remain as specified. Required safety function should operate. | 2067756 | Failure mode: Required functional status failure after test; required safty function not applicable |
| | Functional Electrical LV Testing | **LV - Voltage curve with electric system control** | Test simulates the behavior of the electric system with voltage controls. Testcase depands on the product, fluctuation of the voltage curves can be set, respected the load cases. | LV 124 | Test bed | Inverter load test bed | | | | 12 | | 6 | 6 | | | | Required functional status should remain as specified. | 2067756 | Failure mode: Required functional status failure after test |
| | Functional Electrical LV Testing | **LV - Quiescent current/closed circuit current** | Determination of the quiescent - current draw of the componenet on different environmental boundaries. | LV 124 | Test bed | Inverter load test bed | | | | 12 | | 6 | 6 | | | | Required functional status should remain as specified. | 2067756 | Failure mode: Required functional status failure after test |
| | Functional Electrical LV Testing | **LV - Backfeeds** | Test verify that the DUT is free of backfeeds to switched terminals | LV 124 | Test bed | Inverter load test bed | | | | 12 | | 6 | 6 | | | | Required functional status should remain as specified. Required safety function should operate. | 2067756 | Failure mode: Required functional status failure after test; required safty function not applicable |
| | Functional Electrical LV Testing | **LV - Overcurrent** | Test verify the robustness of the mechanical switches, electronic outputs, and contatcts againts overcurrent. Overcurrent protection | LV 124 | Test bed | Inverter load test bed | | | | 12 | | 6 | 6 | | | | Required functional status should remain as specified. Required safety function should operate. | 2067756 | Failure mode: Required functional status failure after test-malfunction/dysfunction on the specified componenet; required safty function not applicable |
| | Functional Electrical LV Testing | **LV - Wake-Up Test** | Wake-up signal shall be implemented within the specification | AVL internal standard | Test bed | Inverter load test bed | | | | 12 | | 6 | 6 | | | | Right signals for the wake up test. | 2067756 | Failure mode: No answer, or different behaviour for the signal |
| | Functional Electrical HV Testing | **HV - Operation within the regular HV operating voltage range** | Test verify the specified functional status, the max specified power under the specified working points. | LV123 / ISO DIS 21498 | Test bed | Inverter load test bed | | | | 12 | | 6 | 6 | | | | Required functional status should remain as specified. | 2067758 | Failure mode: Required functional status failure after test |
| | Functional Electrical HV Testing | **HV - Operation within the HV overvoltage range** | Test verify that the specified functional status and specified power is kept under various operating parameteres, in the HV overvoltage range. | LV123 / ISO DIS 21498 | Test bed | Inverter load test bed | | | | 12 | | 6 | 6 | | | | Required functional status should remain as specified. | 2067758 | Failure mode: Required functional status failure after test |
| | Functional Electrical HV Testing | **HV- Operation within the HV undervoltage range** | Test verify the specified functional status, the max specified power under the specified working points in the HV undervoltage range. | LV123 / ISO DIS 21498 | Test bed | Inverter load test bed | | | | 12 | | 6 | 6 | | | | Required functional status should remain as specified. | 2067758 | Failure mode: Required functional status failure after test |
| | Functional Electrical HV Testing | **HV - pre-charge** | Test verify the robustness of the HV energy storage and HV components when starting up during pre-chargig under operation. | LV123 | Test bed | Inverter load test bed | | | | 12 | | 6 | 6 | | | | Required functional status should remain as specified. | 2067758 | Failure mode: Required functional status failure after test |
| | Functional Electrical HV Testing | **HV - Generated HV voltage dynamics** | Test verify that the HV functional status does not change during the power jumps under the HV voltage dynamics generated by the componenet fall within the specified limits. | LV123 / ISO DIS 21498 | Test bed | Inverter load test bed | | | | 12 | | 6 | 6 | | | | Required functional status should remain as specified. | 2067758 | Failure mode: Required functional status failure after test |
| | Functional Electrical HV Testing | **HV - System HV voltage dynamics** | Test verify the HV componenets in the HV system when the HV voltage rate changes. | LV123 / ISO DIS 21498 | Test bed | Inverter load test bed | | | | 12 | | 6 | 6 | | | | Required functional status should remain as specified. | 2067758 | Failure mode: Required functional status failure after test |
| | Functional Electrical HV Testing | **HV- Voltage dynamics of energy storage devices** | Test has to verify the robustness of the HV energy storage device when the load jumps generate HV electric system dynamics in the energy storage. | LV123 | Test bed | Inverter load test bed | | | | 12 | | 6 | 6 | | | | Required functional status should remain as specified. Required safety function should operate. | 2067758 | Failure mode: Required functional status failure after test-malfunction/dysfunction on the specified componenet; required safty function not applicable |
| | Functional Electrical HV Testing | **HV - Generated HV voltage ripple** | Tests verify that the generated HV ripple will not cause any change in the HV functional status. | LV123 / ISO DIS 21498 | Test bed | Inverter load test bed | | | | 12 | | 6 | 6 | | | | Required functional status should remain as specified. | 2067758 | Failure mode: Required functional status failure after test |
| | Functional Electrical HV Testing | **HV - System HV voltage ripple** | Tests verify the robustness of the HV componenets when HV ripple produced in the HV system | LV123 / ISO DIS 21498 | Test bed | Inverter load test bed | | | | 12 | | 6 | 6 | | | | Required functional status should remain as specified. | 2067758 | Failure mode: Required functional status failure after test |
| | Functional Electrical HV Testing | **HV - Load dump** | Test verify the HV system in the event of a load dump. | LV123 / ISO DIS 21498 | Test bed | Inverter load test bed | | | | 12 | | 6 | 6 | | | | Required functional status should remain as specified. | 2067758 | Failure mode: Required functional status failure after test |
| | Functional Electrical HV Testing | **HV - Voltage offset** | Test verify the robustness HV componenets during and offset btw the HV potentials and GND | LV123 / ISO DIS 21498 | Test bed | Inverter load test bed | | | | 12 | | 6 | 6 | | | | Required functional status should remain as specified. | 2067758 | Failure mode: Required functional status failure after test |
| | Functional Electrical HV Testing | **HV - Overcurrent** | Test verify the robustness of the mechanical switches, electronic outputs, and contatcts againts overcurrent. Overcurrent protection. | LV123 | Test bed | Inverter load test bed | | | | 12 | | 6 | 6 | | | | Required functional status should remain as specified. Required safety function should operate. | 2067758 | Failure mode: Required functional status failure after test-malfunction/dysfunction on the specified componenet; required safty function not applicable |
| | Functional Electrical HV Testing | **HV - Service life** | Test verify the robustness of the DUT againts the occuring loads what has an influence on the required service life. | LV123 | Test bed | Inverter load test bed | | | | 12 | | 6 | 6 | | | | Required functional status should remain as specified. Required safety function should operate. | 2067758 | Failure mode: Required functional status failure after test-malfunction/dysfunction on the specified componenet; required safty function not applicable |
| | Functional Electrical HV Testing | **HV - Pulse** | The robustness of HV components must be tested in regard to switching edges with a high change rate | LV123 | Test bed | Inverter load test bed | | | | 12 | | 6 | 6 | | | | Required functional status should remain as specified. Required safety function should operate. | 2067758 | Failure mode: Required functional status failure after test-malfunction/dysfunction on the specified componenet; required safty function not applicable |
| | Functional Electrical HV Testing | **HV -Detection of open HV-lines** | Purpuse of the test is to detect the opened HV lines | LV123 | Test bed | Inverter load test bed | | | | 12 | | 6 | 6 | | | | Required functional status should remain as specified. Required safety function should operate. | 2067758 | Failure mode: Required functional status failure after test-malfunction/dysfunction on the specified componenet; required safty function not applicable |
| | Functional Electrical HV Testing | **HV - voltage cycle - Safety** | The purpose of this test is to check the component's HV-voltage-dependent serviceability and performance. | LV123 | Test bed | Inverter load test bed | | | | 12 | | 6 | 6 | | | | Required functional status should remain as specified. Required safety function should operate. | 2067758 | Failure mode: Required functional status failure after test-malfunction/dysfunction on the specified componenet; required safty function not applicable |
| | Functional Electrical HV Testing | **Passive Discharge** | The robustness of the DUT's passive discharge circuit must be verified | LV123 | Test bed | Inverter load test bed | | | | 12 | | 6 | 6 | | | | Required functional status should remain as specified. Required safety function should operate. | 2067758 | Failure mode: Required functional status failure after test-malfunction/dysfunction on the specified componenet; required safty function not applicable |
| | Functional Electrical HV Testing | **Active Discharge** | The robustness of the DUT's active discharge circuit must be verified | LV123 | Test bed | Inverter load test bed | | | | 12 | | 6 | 6 | | | | Required functional status should remain as specified. Required safety function should operate. | 2067758 | Failure mode: Required functional status failure after test-malfunction/dysfunction on the specified componenet; required safty function not applicable |
| | Functional Electrical HV Testing | **HV isolation resistance to LV** | Test verify that the insulation resistance is not lower than the value required in the Component Performance Specification. | LV 123 | Test bed | Inverter load test bed | | | | 12 | | 6 | 6 | | | | Required functional status should remain as specified. Required safety function should operate. | 2067758 | Failure mode: Required functional status failure after test-malfunction/dysfunction on the specified componenet; required safty function not applicable |
| | Functional Electrical HV Testing | **HV dielectric strength to LV** | Test verify that the component's dielectric strength is higher than the limits specified in the Performance Specification. Faliure mode: dielectric strength between HV and LV may deteriorate during electrical, environmental, and service life tests. | LV 123 | Test bed | Inverter load test bed | | | | 12 | | 6 | 6 | | | | Required functional status should remain as specified. Required safety function should operate. | 2067758 | Failure mode: Required functional status failure after test-malfunction/dysfunction on the specified componenet; required safty function not applicable |

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| | Functional Electrical HV Testing | **HV - Equipotential bonding contact resistance** | Test verify the robustness of the equipotential bonding for all DUT parts that can be touched and are conductive. Faliure mode: The electrical contact between the equipotential bonding conductor and the DUT and to all the DUT's conductive parts that can be touched may deteriorate during environmental and service life tests. | LV 123 | Test bed | Inverter load test bed | | | | 12 | | 6 | 6 | | | | Required functional status should remain as specified. Required safety function should operate. | 2067758 | <u>Faliure mode:</u> Required functional status failure after test-malfunction/dysfunction on the specified componenet; required safty function not applicable |
| | Functional Electrical HV Testing | **HV - shield contact resistance** | Test verify the robustness of the DUT's HV shield's electrical contact must be verified. Faliure mode: The electrical contact for the HV shield may deteriorate during environmental and service life tests. | LV 123 | Test bed | Inverter load test bed | | | | 12 | | 6 | 6 | | | | Required functional status should remain as specified. Required safety function should operate. | 2067758 | <u>Faliure mode:</u> Required functional status failure after test-malfunction/dysfunction on the specified componenet; required safty function not applicable |
| | Functional Electrical HV Testing | **HV - Protective earth and touch current** | Test verify that the requirements for the protective earth connection and for the DUT's touch current are being met. The test must be carried out for the on-board charger in the AC supply circuit. Fehlier mode: The properties of components, contacts, and insulation in an electric system charger may deteriorate as a result of aging or during electrical, environmental, and service life tests. | LV 123 | Test bed | Inverter load test bed | | | | 12 | | 6 | 6 | | | | Required functional status should remain as specified. Required safety function should operate. | 2067758 | <u>Faliure mode:</u> Required functional status failure after test-malfunction/dysfunction on the specified componenet; required safty function not applicable |
| | Functional Electrical HV Testing | **HV - Crash Signal Test** | Test simulates the behavior of the inverter in the event of a crash. | LV123 | Test bed | Inverter load test bed | | | | 12 | | 6 | 6 | | | | Required functional status should remain as specified. Required safety function should operate. | 2067758 | <u>Faliure mode:</u> Required functional status failure after test-malfunction/dysfunction on the specified componenet; required safty function not applicable |
| | Functional Performance Testing | **Continuous current test** | Confirmation of the correct thermal behaviour of the DUT during operating | AVL internal standard | Test bed | Inverter load test bed | | | | 12 | | 6 | 6 | | | | Required functional status should remain as specified. Required safety function should operate. | 2067773 | <u>Faliure mode:</u> Overheated wire, melted electronical componenets; required safty function not applicable |
| | Functional Performance Testing | **Maximum phase current test** | When maximum phase current is applied, DUT operates | AVL internal standard | Test bed | Inverter load test bed | | | | 12 | | 6 | 6 | | | | Required functional status should remain as specified. Required safety function should operate. | 2067773 | <u>Faliure mode:</u> Overheated wire, melted electronical componenets; required safty function not applicable |
| | Functional Performance Testing | **Maximum Power** | When maximum power applied, DUT operates | AVL internal standard | Test bed | Inverter load test bed | | | | 12 | | 6 | 6 | | | | Required functional status should remain as specified. Required safety function should operate. | 2067773 | <u>Faliure mode:</u> Overheated wire, melted electronical componenets; required safty function not applicable |
| | Functional Testing | **Basic Functionality** | Verify basic functions (coolant pressure, PWM control, torque setpoint) | AVL internal standard | Test bed | Inverter load test bed | | | | 6 | | 6 | 6 | | | | | 2067770 | Initially for each new sample/charge, test can be skipped at the end of the project. Important for desin changes and for A-sample (no serial production) |
| | Functional Testing | **Resolver Calibration** | Calibration of the right Resolver angle for commutation | AVL internal standard | Test bed | Inverter load test bed | | | | 12 | | 6 | 6 | | | | Required software routine should calibrate the offset angle of the resolver | 2067770 | Resolver calibration has to be done for each new resolver or each new e-machine |
| | Functional Testing | **Fault injection test** | Artificial made faliure on resolver, motor temperature, CAN, phase etc… (could be software [values are not correct or inactive] or mechanical failure) | AVL internal standard | Test bed | Inverter load test bed | | | | 12 | | 6 | 6 | | | | Required functional status should remain as specified. | 2067770 | |
| | Functional EMC Testing | **LV - Conducted RF emission from components/modules on LV-power lines – Voltage method** | Measurement of RF disturbance voltages on Low voltage supply lines | CISPR 25 | Test Bed | EMC Chamber | | | | 4 | 1 | 1 | 1 | 1 | | | Emission does not exceed the limits according requirement | 2067768 | |
| | Functional EMC Testing | **HV - Conducted RF emission from components/modules on HV power lines – Voltage method** | *Test methods for shielded power supply systems for high voltages in electric and hybrid vehicles:*<br><br>Measurement of RF disturbance voltages on shielded HV voltage supply lines | CISPR 25 | Test Bed | EMC Chamber | | | | 4 | 1 | 1 | 1 | 1 | | | Emission does not exceed the limits according requirement | 2067768 | |
| | Functional EMC Testing | **HV - Conducted common mode RF emission from components/modules on motor phases – Voltage methode** | *Test methods for 3 phase inverter output leading to the e-machine/motor*<br><br>Measurement of common mode RF disturbance voltages on 3 -phase Inverter output using motor motor simulation | CISPR 25 | Test Bed | EMC Chamber | | | | 4 | 1 | 1 | 1 | 1 | | | Emission does not exceed the limits according requirement | 2067768 | |
| | Functional EMC Testing | **LV - Conducted RF emission from components/modules other than supply lines and cable bunches – current probe method** | Measurement of RF disturbance cureents on low voltage wiring | CISPR 25 | Test Bed | EMC Chamber | | | | 4 | 1 | 1 | 1 | 1 | | | Emission does not exceed the limits according requirement | 2067768 | |
| | Functional EMC Testing | **HV - Conducted RF emission from components/modules on HV power lines and three phase motor lines to the electric motor – current probe method** | *Test methods for shielded power supply systems for high voltages in electric and hybrid vehicles:*<br><br>Measurement of RF disturbances currents on shielded HV cables | CISPR 25 | Test Bed | EMC Chamber | | | | 3 | | 1 | 1 | 1 | | | Emission does not exceed the limits according requirement | 2067768 | |
| | Functional EMC Testing | **HV - Conducted Emissions from Currents on Shafts and Hoses** | Current measurement for components with internal disturbances on hoses leading outside: and using a motor model (to simulated issues with potential shaft currents on later system level) | (based on CISPR 25 ) | Test Bed | EMC Chamber | | | | 4 | 1 | 1 | 1 | 1 | | | Emission does not exceed the limits according requirement | 2067768 | |
| | Functional EMC Testing | **LV - Conducted Pulse-Emissions - Voltages on LV Supply Lines** | Measurement of Pulse emissions at the LV Supply | ISO 7637-2 | Test Bed | EMC Chamber | | | | 4 | 1 | 1 | 1 | 1 | | | Emission does not exceed the limits according requirement | 2067768 | |
| | Functional EMC Testing | **HV - Conducted Pulse Emissions on HV Supply Lines** | Voltage transient emissions test along high voltage supply lines<br><br>measured between HV+ and HV- (line-to-line) and between HV+ respectively HV- and ground (line- to-ground) | ISO DTS 7637-4 | Test Bed | EMC Chamber | | | | 4 | 1 | 1 | 1 | 1 | | | Emission does not exceed the limits according requirement | 2067768 | |
| | Functional EMC Testing | **Max. voltage rise & fall slew rates of Power & Signals connections at connector pins** | Limitation of max. voltage rise and fall times for all extern available power and signal connections (power, I/O, Communication …) | - | Test Bed | laboratory | | | | 4 | 1 | 1 | 1 | 1 | | | rise and fall slew rates do not exceed limits of the requirement or exceptional approval is given by Vehicle manufacturer | 2100935 | |
| | Functional EMC Testing | **Max. current rise & fall slew rates of Power & Signals connections at connector pins** | Limitation of max. current rise and fall times for all extern available power and signal connections (power, I/O, Communication …) | - | Test Bed | laboratory | | | | 4 | 1 | 1 | 1 | 1 | | | rise and fall slew rates do not exceed limits of the requirement or exceptional approval is given by Vehicle manufacturer | 2100935 | |
| | Functional EMC Testing | **HV-Load Shedding** | To avoid voltage spikes in the case of HV-Relais switching<br>Countermeasures concept has to be delivered | based on ISO DTS 6737-4 | Test Bed | EMC Chamber | | | | 3 | | 1 | 1 | 1 | | | Spikes do not exceed requirement limits | 2067768 | |
| | Functional EMC Testing | **Radiated electromagnetic emissions from components/modules - ALSE method** | Measurement of radiated RF disturbance with external antennas | CISPR 25 | Test bed | EMC Chamber | | | | 3 | | 1 | 1 | 1 | | | Emission does not exceed the limits according requirement | 2099278 | |

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| | Functional EMC Testing | **HV - Radiated electromagnetic emissions from components/modules - with shielded HV-wiring ALSE method** | *Test methods for shielded power supply systems for high voltages in electric and hybrid vehicles:*<br><br>Radiated emissions from components/modules – ALSE method | CISPR 25 | Test bed | EMC Chamber | | | | 3 | | 1 | 1 | 1 | | | Emission does not exceed the limits according requirement | 2099278 | |
| | Functional EMC Testing | **HV - radiated emissions electrical field - < 30MHz** | Measurement of electrical fields in the frequency range below 30MHz using a monoploe (rod) antenna | CISPR 25 | Test bed | EMC Chamber | | | | 3 | | 1 | 1 | 1 | | | Emission does not exceed the limits according requirement | 2099278 | |
| | Functional EMC Testing | **HV - Radiated Emissions magnetic field <30MHz** | Measurement of magnetic fields in the frequency range below 30MHz using a loop antenna | (GBT-18387 adopted for components) | Test bed | EMC Chamber | | | | 3 | | 1 | 1 | 1 | | | Emission does not exceed the limits according requirement | 2099278 | |
| | Functional EMC Testing | **HV - radiated emissions electromagnetic field Stripline** | Measurement of radiated RF disturbance using the stripline methode | CISPR 25 | Test bed | EMC Chamber | | | | 3 | | 1 | 1 | 1 | | | Emission does not exceed the limits according requirement | 2099278 | |
| | Functional EMC Testing | **Low frequency magnetic field emission <150kHz** | Measurement of magnetic fields in the frequency range below 150 kHz using a hand held loop antenna (MIL-STD-461 or similar) close to the component | | Test bed | EMC Chamber | | | | 3 | | 1 | 1 | 1 | | | Emission does not exceed the limits according requirement | 2099278 | |
| | Functional EMC Testing | **Magnetic field emission - protection of persons** | Measurement of magnetic fields to limit exposure of persons to variing magnetic fields | ICNIRP | Test bed | EMC Chamber | | | | 3 | | 1 | 1 | 1 | | | Emission does not exceed the limits according requirement | 2100937 | |
| | Functional EMC Testing | **Radiated emissions from components/modules – Stripline method** | Measurement of radiated RF disturbance by using a stripline | CISPR 25 | Test bed | EMC Chamber | | | | 3 | | 1 | 1 | 1 | | | Emission does not exceed the limits according requirement | 2099278 | |
| | Functional EMC Testing | **LV - Conducted immunity against pulses on LV-supply lines** | Conducted immunuity against pulses on LV-supply lines | ISO 7637-2 | Test bed | EMC Chamber | | | | 3 | | 1 | 1 | 1 | | | Functional status /stati at the requested severity level(s) are fulfilled according requirement | 2099287 | |
| | Functional EMC Testing | **LV - Conducted Immunity Fast pulses coupled on other than supply lines** | Conducted Immunity against fast pulses capacitive coupled on other than supply lines | ISO 6737-3 | Test bed | EMC Chamber | | | | 4 | 1 | 1 | 1 | 1 | | | Functional status /stati at the requested severity level(s) are fulfilled according requirement | 2099287 | |
| | Functional EMC Testing | **LV - Conducted Immunity Slow pulses coupled on other than supply lines** | Conducted Immunity against slow pulses inductive coupled on other than supply lines | ISO 7637-3 | Test bed | EMC Chamber | | | | 4 | 1 | 1 | 1 | 1 | | | Functional status /stati at the requested severity level(s) are fulfilled according requirement | 2099287 | |
| | Functional EMC Testing | **Conducted Immunity - extended audio frequency range** | Immunity to conducted disturbances in the extended audio frequency range | ISO 11452-10 | Test bed | EMC Chamber | | | | 3 | | 1 | 1 | 1 | | | Functional status /stati at the requested severity level(s) are fulfilled according requirement | 2099287 | |
| | Functional EMC Testing | **HV - Voltage Ripples on HV DC Supply Lines** | Immunity against pulses on the HV-DC Supply:<br>Voltage Ripple<br>coupling between HV+ HV-,<br>HV+ GND and HV- GND | ISO DTS 7637-4 | Test bed | EMC Chamber | | | | 3 | | 1 | 1 | 1 | | | Functional status /stati at the requested severity level(s) are fulfilled according requirement | 2099287 | |
| | Functional EMC Testing | **HV - Pulsed Sinusoidal Disturbances on HV DC Supply Lines** | Immunity against pulses on the HV-DC Supply:<br>Pulsed Sinusoidal Disturbances coupling between HV+ HV-,<br>HV+ GND and HV- GND | ISO DTS 7637-4 | Test bed | EMC Chamber | | | | 3 | | 1 | 1 | 1 | | | Functional status /stati at the requested severity level(s) are fulfilled according requirement | 2099287 | |
| | Functional EMC Testing | **HV - Low Frequency Sinusoidal Disturbances on HV Supply Lines** | Immunity against pulses on the HV-DC suply:<br>Low Frequency Sinusoidal Disturbances<br>coupling between HV+ HV-, HV+ GND and HV- GND | ISO DTS 7637-4 | Test bed | EMC Chamber | | | | 3 | | 1 | 1 | 1 | | | Functional status /stati at the requested severity level(s) are fulfilled according requirement | 2099287 | |
| | Functional EMC Testing | **immunity to electrical fast transient/burst disturbances conducted along HV-DC power lines.** | Specifications concerning the immunity of ESAs to electrical fast transient/burst disturbances conducted along HV DC power lines. | (based on IEC 61000-4-4) | Test bed | EMC Chamber | | | | 4 | 1 | 1 | 1 | 1 | | | Functional status /stati at the requested severity level(s) are fulfilled according requirement | 2099287 | |
| | Functional EMC Testing | **Immunity to surge conducted along<br>HV DC power lines** | For components beeing HV-supplied during vehicle charging coupled to the power grid<br>'Specifications concerning the immunity of ESAs to surge on DC power lines - coupled throught chargers | (based on IEC 61000-4-5) | Test bed | EMC Chamber | | | | 3 | | 1 | 1 | 1 | | | Functional status /stati at the requested severity level(s) are fulfilled according requirement | 2099287 | |
| | Functional EMC Testing | **Radiated Immunity LV - BCI** | *Radiated Immunity against external narrowband electromagnetic sources on LV-wiring* :<br>Harness Excitation (BCI) | ISO 11452-4 | Test bed | EMC Chamber | | | | 4 | 1 | 1 | 1 | 1 | | | Functional status /stati at the requested severity level(s) are fulfilled according requirement | 2099303 | |
| | Functional EMC Testing | **Radiated Immunity HV - BCI** | *Radiated Immunity against external narrowband electromagnetic sources on HV-wiring (HV-DC, HV-inverter output to motor) - Shielded and also without shieding of HV - wiring:* Harness Excitation (BCI) | ISO 11452-4 | Test bed | EMC Chamber | | | | 3 | | 1 | 1 | 1 | | | Functional status /stati at the requested severity level(s) are fulfilled according requirement | 2099303 | |
| | Functional EMC Testing | **Radiated Immunity external electromagnetic fields - Absorber-lined shielded enclosure** | *Radiated Immunity against external narrowband electromagnetic sources (without pulsed radar)* :<br>Test with external Antennas in the ALSE | ISO 11452-2 | Test bed | EMC Chamber | | | | 3 | | 1 | 1 | 1 | | | Functional status /stati at the requested severity level(s) are fulfilled according requirement | 2099303 | |
| | Functional EMC Testing | **Radiated Immunity -<br>Radar Pulses** | *Radiated Immunity against external radar pulses:*<br>Test with external Antennas in the ALSE | ISO 11452-2 | Test bed | EMC Chamber | | | | 3 | | 1 | 1 | 1 | | | Functional status /stati at the requested severity level(s) are fulfilled according requirement | 2099303 | |
| | Functional EMC Testing | **Radiated Immunity on board transmitters** | *Radiated Immunity against narrowband electromagnetic sources of on board transmitters* :<br>Test with external Antennas in the ALSE | ISO 11452-9 | Test bed | EMC Chamber | | | | 3 | | 1 | 1 | 1 | | | Functional status /stati at the requested severity level(s) are fulfilled according requirement | 2099303 | |
| | Functional EMC Testing | **Radiated Immunity -<br>Direct power injection** | *Radiated Immunity against external narrowband electromagnetic sources* :<br>Direct radio frequency (RF) power injection | ISO 11452-7 | Test bed | EMC Chamber | | | | 3 | | 1 | 1 | 1 | | | Functional status /stati at the requested severity level(s) are fulfilled according requirement | 2099303 | |
| | Functional EMC Testing | **Radiated Immunity - Stripline** | *Radiated Immunity against external narrowband electromagnetic sources* :<br>Stripline methode | ISO 11452-5 | Test bed | EMC Chamber | | | | 3 | | 1 | 1 | 1 | | | Functional status /stati at the requested severity level(s) are fulfilled according requirement | 2099303 | |
| | Functional EMC Testing | **Immunity to magnetic fields** | *Radiated Immunity against external narrowband electromagnetic sources* :<br>Immunity against magnetic fields | ISO 11452-8 | Test bed | EMC Chamber | | | | 3 | | 1 | 1 | 1 | | | Functional status /stati at the requested severity level(s) are fulfilled according requirement | 2099303 | |
| | Functional EMC Testing | **ESD - EUT unpowered - Packaging and Handling on PINs** | Immunity against electrostatic discharge - EUT unpowered and unconnected discharge on connector pins | ISO 10605 | Test bed | EMC Chamber | | | | 4 | 1 | 1 | 1 | 1 | | | Functional status /stati at the requested severity level(s) are fulfilled according requirement | 2099305 | |
| | Functional EMC Testing | **ESD - EUT unpowered - Packaging and Handling on Housing** | Immunity against electrostatic discharge - EUT unpowered and unconnected discharge on housing | ISO 10605 | Test bed | EMC Chamber | | | | 4 | 1 | 1 | 1 | 1 | | | Functional status /stati at the requested severity level(s) are fulfilled according requirement | 2099305 | |
| | Functional EMC Testing | **ESD - EUT operating** | Immunity against electrostatic discharge - EUT operating | ISO 10605 | Test bed | EMC Chamber | | | | 4 | 1 | 1 | 1 | 1 | | | Functional status /stati at the requested severity level(s) are fulfilled according requirement | 2099305 | |
| | Functional EMC Testing | **HV - LV -Coupling between HV and LV systems:<br>Voltage method** | *For shielded HV systems:*<br>*'Coupling between HV and LV systems:*<br>Conducted emission with tests signal injection – Voltage method | CISPR 25 | Test bed | EMC Chamber | | | | 4 | 1 | 1 | 1 | 1 | | | Emission Limits of decoupling measurements according requirements are not exceeded | 2099307 | |
| | Functional EMC Testing | **HV - LV - Coupling between HV and LV systems:<br>Current probe method** | *For shielded HV systems:*<br>*'Coupling between HV and LV systems:*<br>Conducted emission with tests signal injection – Current probe method | CISPR 25 | Test bed | EMC Chamber | | | | 4 | 1 | 1 | 1 | 1 | | | Emission Limits of decoupling measurements according requirements are not exceeded | 2099307 | |
| | Functional EMC Testing | **HV - LV - Coupling between HV and LV systems:<br>Radiated Emission test** | *For shielded HV systems:*<br>*'Coupling between HV and LV systems:*<br>Conducted emission with tests signal injection – HV-specific radiated emission test | CISPR 25 | Test bed | EMC Chamber | | | | 3 | | 1 | 1 | 1 | | | Emission Limits of decoupling measurements according requirements are not exceeded | 2099307 | |

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| | Functional EMC Testing | **HV - LV -Coupling between HV and LV systems:<br>Measurement of the HV-LV coupling attenuation** | *For shielded HV systems:<br>'Coupling between HV and LV systems:<br>Measurement of the HV-LV coupling attenuation with Network analyzer* | CISPR 25 | Test bed | EMC Chamber | | | | 4 | 1 | 1 | 1 | 1 | | | Decoupling factor is inot lower than requeseted in the requirement | 2099307 | |
| | Functional EMC Testing | **shielding of housings** | Requirements regarding the shielding of HV-housings with its openeings | IEC 61000-5-7 | | | | | | 3 | | 1 | 1 | 1 | | | Shielding factor is inot lower than requeseted in the requirement | 2099309 | |
| | Functional EMC Testing | **HV wiring and connectors** | Requirements regarding the shielding/shield connection of HV-wiring and HV-connector housings | | | | | | | 3 | | 1 | 1 | 1 | | | Shielding factor is inot lower than requeseted in the requirement and shielding impedance and shielding connection impedance are not higher than requested in the requirement | 2099309 | |
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| **Durability Testing** | | | | | | | | | | | **a** | **b** | **c** | **d** | | | | | |
| | Durability Thermal Testing | **High temperature operation endurance (HTOE)** | Lifetime fullfillment under accelerated conditions with realistic loads under constant high temperature conditions | | Test Bed | Inverter load + Climat chamber | | | | 18 | | 6 | 6 | 6 | | | No visible demage on the speciement.<br>DUT must be fully functional after test. | 2067753 | Faliure: visual demages, wear outs, broken parts, broken side parts, sealing wear out, dislocation or deformation of componenets. |
| | Durability Thermal Testing | **Power temperature cycling endurance (PTCE)** | Lifetime fullfillment under accelerated conditions with realistic loads under thermal cycling conditions | | Test Bed | Inverter load + Climat chamber | | | | 18 | | 6 | 6 | 6 | | | No visible demage on the speciement.<br>DUT must be fully functional after test. | 2067753 | Faliure: visual demages, wear outs, broken parts, broken side parts, sealing wear out, dislocation or deformation of componenets. |
| | Durability Electrical Testing | **HV On/Off durability for HV components** | Test shall verify that the components initalization are reliable on all voltage levels. | | Test Bed | Inverter load test bed | | | | 18 | | 6 | 6 | 6 | | | All function requirements remains as specified. | 2067760 | Faliure: componenet faliure, required functional status failure after test, malfunction/dysfunction on the specified componenet; required safty function not applicable |
| | Durability Enviromental Testing | **High temperature humidity endurance (HTHE) / Damp heat steady state** | This test simulates the use of the system/component under steady high ambient humidity | | Test Bed | Climat chamber | | | | 18 | | 6 | 6 | 6 | | | No visible demage on the speciement.<br>DUT must be fully functional after test. | 2067753 | Faliure: visual demages, wear outs, broken parts, broken side parts, sealing wear out, dislocation or deformation of componenets, electrical malfunction caused by moisture. |

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## 6.1.4 Transmission DVP

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Level 2 | Level 3.1 | Level 3.2 | Level 3.3

Level 3.3 Tranmission Subsystem

DVP&R: Planning

| Test ID | Test Category | Test Case | Test Description | Standard / Paragraph / Edition | Test Environmen | Test Environmen additional info | Test Responsibility: Responsible Person | Test Responsibility: Responsible Department | Test Duration (Execution Time) | Sample: Total Quantity | Sample: Gen 0 | Sample: Gen 1 | Sample: Gen 2 | Sample: Gen 3 | Test status | Test repo ID / Path | Acceptance Criteri | RQ-ID | | Remarks |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Functional Testing** | | | | | | | | | | | | | | | | | | | | |
| | Functional Mechanical Testing | **Power unit modal analysis** | Natural frequencies assesment of the power unit using Finite Element Analysis (FEM). Evaluation of global eigenmodes (bending, torsion) of the engine block-transmission as well as complete power unit w/wo crank train and the local modes in the form of deformed structure and Strain-Energy-Plots. | AVL Guideline | Simulation | FEM | | DTV | | 4 | 1 | 1 | 1 | 1 | Open | | | 2110730 | | |
| | Functional Mechanical Testing | **Transmission shaft, carrier FEA** | A Finite Element Analysis (FEA) of load paths along transmission shafts incl. high cycle fatigue (HCF) strength evaluation is performed. Input data represented by gear parts along transmission shaft load path incl. gear wheels etc. and support regions like bearings as well as ultimate loads are taken into account. | | Simulation | | | DTV | | 4 | 1 | 1 | 1 | 1 | Open | | | 2110730 | | stresses, static and fatigue strength |
| | Functional Mechanical Testing | **Transmission housing FEA incl. Sealing** | Static Finite Element Analysis (FEA) of the transmission assembly is performed. Assembly and operating loads as well as various testing loads are considered. Evaluation and assessment of the global deformations, stress distribution and contact conditions is performed. Internal loads (from bearings loads) and external loads (accelerations global) are applied and housing is checked for static and HCF analysis<br>Flange connections are modelled in detail (considering the conatct and friction behavior) to understand the sealing and sliding beahvior under operating loads. | | Simulation | FEA | | DTV | | 4 | 1 | 1 | 1 | 1 | Open | | | 2110730 | | stresses, static and fatigue strength, contact opening |
| | Functional Mechanical Testing | **Housing stiffness matrix** | setup ABQ model for transmission housing and create stiff-matrix for bearing locations. --> need as input for quasistatic gear design | | Simulation | | | DTV | | 4 | 1 | 1 | 1 | 1 | Open | | | 2110730 | | bearing location stiffness check with benchmark |
| | Functional Mechanical Testing | **Bolt connections transmission** | bolt strength and contact conditions(EXCEL) --> pressure under bolt head and min safety factor. | | Simulation | Excel | | DTV | | 4 | 1 | 1 | 1 | 1 | Open | | | 2110730 | | tensile, shear |
| | Functional Mechanical Testing | **Validation of bolt connection (FEM)** | validation of bolt preload on contact surface (COPEN) | | Simulation | FEM | | DTV | | 4 | 1 | 1 | 1 | 1 | Open | | | 2110730 | | contact opening |
| | Functional Mechanical Testing | **gear design (macro/ micro geometry)** | A mating gear pair is designed that severeal requirements such as gear strength (pitting, tooth bending), noise excitation (quasistatic TE), and manufaturing are fulfilled. The gear micro-geometry is optimized with regards to optimum backlashes, where the deflection of the gear teeth, shafts and housing under load is considered. | | Simulation | | | DTV | | 4 | 1 | 1 | 1 | 1 | Open | | | 2110730 | | gear tooth strength (bending, pitting, spalling,..), robust macro geometry and pre optimized micro geometry. |
| | Functional Mechanical Testing | **bearing analysis (FVA WB)** | bearing lifetime calculation considering shaft stiffness, bearing preload, bearing ring deformation and lubrication based on provided load spectrum | | Simulation | | | DTV | | 4 | 1 | 1 | 1 | 1 | Open | | | 2110730 | | bearing lifetime acc. To load specturm, max. bearing pressure distribution |
| | Functional Performance Testing | **Efficiency simulation** | generation of transmission efficiency maps using AVL efficiency tool. Total loss maps and individual losses can be calculated | | Simulation | | | DTV | | 4 | 1 | 1 | 1 | 1 | Open | | | 2114363 | | total transmission losses (incl. Bearing, gears and bearings) and analytical churning losses |
| | Functional NVH Testing | **MBS (3D- NVH)** | Multi-body system dynamic analysis of transmission housing, shafts, gears and bearings considering mounting stiffness and simplified E- motor. | | Simulation | | | DTV | | 4 | 1 | 1 | 1 | 1 | Open | | | 2110618 | | torsional vibrations, gear and bearing forces, averaged surface velocity, gear specific results (dyn. TE, gear misalignment, contact pattern) |
| | Functional Mechanical Testing | **Gear micro geometry optimization** | Based on existing 3D- NVH, a design space will be defined for micro geometry variation. By the use of DOE optimized geometry will be calculated based on load spectrum. | | Simulation | | | DTV | | 4 | 1 | 1 | 1 | 1 | Open | | | 2110730 | | intersection plots to show individual influence of gear parameters, multidimensional optimization |
| | Functional Mechanical Testing | **Transmission parts FEA** | A Finite Element Analysis (FEA) of load paths in transmission parts incl. high cycle fatigue (HCF) strength evaluation is performed. Exclusive Transmission parts not covered under 'standard' transmissions are checked against strength. E.g. wheel hub for integrated transmissions. | AVL Guideline | Simulation | | | DTV | | 4 | 1 | 1 | 1 | 1 | Open | | | 2110730 | | |
| | Functional Mechanical Testing | **Transmission differential FEA** | A Finite Element Analysis (FEA) of load paths along transmission differential incl. static misuse and durability/damage strength evaluation is performed. Input data represented by transmission differential assembly and support regions like bearings as well as ultimate and durability loads are taken into account.<br><br>Results are represented by static safety for misuse load cases and accumulated damage distributions resp. strain or distortion levels of investigated regions. | AVL Guideline | Simulation | | | DTV | | 4 | 1 | 1 | 1 | 1 | Open | | | 2110730 | | |

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| | Functional NVH Testing | **Power unit vibrations analysis** | Power unit vibration analysis in low frequency range (up to 500-1000Hz) using multi-body dynamic simulation (MBS) by EXCITE in combination with Finite Element Method (FEM). Transient analysis in time domain of elastic vibrating, rotating and oscillating structure parts coupled by non-linear contact elements under operating conditions from inertia forces and gas forces. Vibration evaluation (engine mounts, auxiliaries,bearing caps), crankshaft vibration (torsion, bending), bearing loads (forces and moments) and normal liner forces under full operating speed range. | AVL Guideline | Simulation | | | DTV | | 4 | 1 | 1 | 1 | 1 | Open | | | 2110618 | | |
| | Functional Performance Testing | **Benchmark / Requirement definition** | Benchmark study to define requirements to define a base for testing and result evaluation. | | Test Bed | | | DTV | 5 | 4 | 1 | 1 | 1 | 1 | Open | | | 2114363 | | |
| | Functional Mechanical Testing | **Lubrication Oil Level Test** | The aim of the Oil Level Test is the verification of the correct oil volume in the transmission so that each operating function could be proceeded | | Test Bed | Tilt TB | | DTV | | 9 | 4 | 3 | 1 | 1 | Done | | | 2110730 | | |
| | Functional Mechanical Testing | **Lubrication Oil Pump Suction Cold Test** | Check of sufficient oil supply to components which require lubrication (bearings, seal rings, gears,...) and cooling (solenoids, clutch packs) under all normal operating conditions. Also T low temperatures conditions (high viscosity of the fluid) particularly the oil pump will be tested<br>- additional check lubrication under tilting | | Test Bed | Tilt TB | | DTV | 4 | 4 | 1 | 1 | 1 | 1 | Done | | | 2110730 | | |
| | Functional Mechanical Testing | **Transmission lubrication system development - Loaded Hot** | Check of sufficient oil supply to components which require lubrication (bearings, seal rings, gears,...) and cooling (solenoids, clutch packs) under all normal operating conditions. Defined load points (depending on UUT) | | Test Bed | Validation Rig | | DTV | 2 | 4 | 1 | 1 | 1 | 1 | Open | | | 2110730 | | |
| | Functional Mechanical Testing | **Transmission lubrication system development - Tilt Hot/Cold** | Check of sufficient oil supply to components which require lubrication (bearings, seal rings, gears,...) and cooling (solenoids, clutch packs) under tilting under all normal operating conditions and low temperatures conditions (high viscosity of the fluid). | | Test Bed | Tilt | | DTV | 2 | 4 | 1 | 1 | 1 | 1 | Open | | | 2110730 | | |
| | Functional Mechanical Testing | **Transmission basic parameter test** | Testing of all basic functions (shifting, speed variation, ...) of the transmission and base calibration. Test range depends on the further planned tests of each transmission | | Test Bed | Schlepppalette | | DTV | 0,5 | 4 | 1 | 1 | 1 | 1 | Open | | | 2110730 | | |
| | Functional Mechanical Testing | **Efficiency Strip Down Measurement** | The target is to receive the drag torque for each component or subsystem | | Test Bed | Schlepppalette | | DTV | | | | | | | Done | | | 2110730 | | |
| | Functional Mechanical Testing | **Efficiency Break Loose Torque Test** | During this test the needed break loose torque is measured for defined operating points of the UUT depending on the oil sump temperature and the engaged gear. | | Test Bed | Schlepppalette | | DTV | | | | | | | Done | | | 2110730 | | |
| | Functional Mechanical Testing | **Efficiency Run-In Procedure** | Stable operation and ready for further testing | | Test Bed | Schlepppalette | | DTV | | 0 | X | X | X | X | Done | | | 2110730 | | |
| | Functional Thermal Testing | **Transmission temperature behavior hot (static)** | check of the temperature behavior under maximal velocity, nmax, highest gear | | Test Bed | 2M Func. / Schlepppalette | | DTV | 0,5 | 4 | 1 | 1 | 1 | 1 | Open | | | 2110616 | | |
| | Functional Mechanical Testing | **Gear Contact Assessment** | Investigation to check the contact pattern in each gear under different load levels (Driving, coasting) on the tooth flank during very low speeds | | Test Bed | HLTB | | DTV | 1 | 4 | 1 | 1 | 1 | 1 | Done | | | 2110730 | | |
| | Functional Mechanical Testing | **Transmission static high load test (ultimate strength)** | Check of high torque resistance of torque transmitting components (ultimate strength). First test max. applied torque is the design torque and after passing this torque level --> max transmittable torque (Damage of transmission) | | Test Bed | HLTB | | DTV | 1,5 | 4 | 1 | 1 | 1 | 1 | Open | | | 2110730 | | |
| | Functional Mechanical Testing | **Park Lock Static High Load Test (ultimate strength)** | Check of high torque resistance of park lock components. First test max. applied torque is the design torque and after passing this torque level --> max transmittable torque (Damage of transmission) | | Test Bed | HLTB | | DTV | 0,5 | 2 | 1 | 1 | | | Done | | | 2110730 | | |
| | Functional Mechanical Testing | **Park Lock Functionality (dynamic)** | Check the functionality of the parking mechanismus (all components). | | Test Bed | HLTB | | DTV | 0,5 | 2 | 1 | 1 | | | Done | | | 2110730 | | |
| | Functional Mechanical Testing | **Seal ring run endurance test** | Check and Analsysis of all sealing parts during a test program with high rotating speeds and high oil temperatures in the transmission (high speed at highest gear) additional focus on bearings | | Test Bed | 2M Func. | | DTV | 3 | 4 | 1 | 1 | 1 | 1 | Open | | | 2110730 | | |
| | Functional Performance Testing | **Transmission efficiency test** | The Efficiency measurement test aims at assessing the transmission efficiency in each gear at different speed and load conditions and temperatures. | | Test Bed | 2M Func. / 3M | | DTV | 1 | 4 | 1 | 1 | 1 | 1 | Open | | | 2114363 | | |

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| | Functional Performance Testing | **Efficiency Normal Driving Condition Test** | The Normal Driving Condition Test simulates nominal driving conditions to determine the efficiency of every operating point depending on predefined loads, speeds and temperatures. | | Test Bed | 2M Func. / 3M | | | | | | | | | Done | | | 2114363 | | |
| | Functional Performance Testing | **Efficiency Low Temperature Test** | The Efficiency Low Temperature Test simulates low temperature driving conditions to determine the efficiency of the UUT depending on predefined loads and speeds in each gear. | | Test Bed | 2M Func. / 3M | | | | | | | | | Done | | | 2114363 | | |
| | Functional Mechanical Testing | **Transmission temperature behavior (dynamic)** | Validation of temperature behaviour of transmission at full load accelerations and decellerations | | Test Bed | 2M Func. /B2B / Validation rig | | DTV | 1 | 4 | 1 | 1 | 1 | 1 | Open | | | 2110730 | | |
| | Functional NVH Testing | **NVH Rattle Test** | Assessment of structural weak parts in terms of NVH by checking structure borne noise. | | Test Bed | NVH | | DTV | 2 | 4 | 1 | 1 | 1 | 1 | Done | | | 2110618 | | |
| | Functional NVH Testing | **NVH Whine Test** | Assessment of structural weak parts in terms of NVH by checking air borne noise. | | Test Bed | NVH | | DTV | 2 | 4 | 1 | 1 | 1 | 1 | Done | | | 2110618 | | |
| | Functional Performance Testing | **Efficiency Drag Loss Test** | The drag loss measurement test aims at assessing the drag losses in each gear at different speed and load conditions and temperatures. | | Test Bed | 2M Func. / 3M | | DTV | 1 | 4 | 1 | 1 | 1 | 1 | Done | | | 2114363 | | |
| | Functional Performance Testing | **Synchronizer Performance Test** | Shift force vs. Shift time | | Test Bed | Schlepppalette | | DTV | 0,5 | 4 | 1 | 1 | 1 | 1 | Done | | | 2114363 | | |
| | Functional Mechanical Testing | **Transmission overspeed capability** | | | Test Bed | | | DTV | | 4 | 1 | 1 | 1 | 1 | Open | | | 2110730 | | |
| | Functional Mechanical Testing | **Towing Test** | Check emergency oil lubrication behaviour of transmission during towing (emergency towing with low speed & | | Test Bed | Schlepppalette | | DTV | 0,5 | 4 | 1 | 1 | 1 | 1 | Done | | | 2110730 | | |
| | Functional NVH Testing | **Transmission NVH analysis (vibration)** | NVH behaviour in different driving manuevers | NTC | in Vehicle | Vehicle | | Customer | 2 | 2 | | | 1 | 1 | Open | | | 2110618 | | |
| | Functional NVH Testing | **Transmission NVH analysis (noise)** | NVH behaviour in different driving manuevers | NTC | in Vehicle | Vehicle | | Customer | 2 | 4 | | | 2 | 2 | Open | | | 2110618 | | |
| | Functional Mechanical Testing | **Park lock functionality (Dynamic)** | park lock different functions at vehicle testCheck the functionality of the parking mechanismus (all components) | NTC | in Vehicle | Vehicle | | Customer | 2 | 2 | | | | 2 | Open | | | 2110730 | | |
| | Functional Mechanical Testing | **Park lock function at max. gradient** | -reliability of park lock system at max gradient<br>- reliability of park lock system at 30% max gradient<br>-force of disanganging at hill (pull out force) | NTC | in Vehicle | Vehicle | | Customer | 1 | 2 | | | | 2 | Open | | | 2110730 | | |
| | Functional Mechanical Testing | **Park lock function at max. gradient** | -reliability of park lock system at max gradient<br>- reliability of park lock system at 30% max gradient<br>-force of disanganging at hill (pull out force) | | Test Bed | HLTB | | DTV | 1 | 4 | | | 2 | 2 | Open | | | 2110730 | | |
| | Functional Mechanical Testing | **Park lock functionality (Dynamic)** | Dynamic simualtion of park lock functionality (all mechanical components) | | Simulation | | | DTV | 2 | 4 | 1 | 1 | 1 | 1 | Open | | | 2110730 | | |

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| | Functional Mechanical Testing | **Vehicle lubrication testing** | Validation of max. tilting angle (high radial forces) | | in Vehicle | Vehicle | | Customer | 0,5 | 2 | | | 1 | 1 | Open | | | 2110730 | | |
| | Functional Thermal Testing | **Temperature behaviour - Cold climate** | Cold climate vehicle test | | in Vehicle | Vehicle | | Customer | 3 | 2 | | | 1 | 1 | Open | | | 2110616 | | |
| | Functional Thermal Testing | **Temperature behaviour - Hot climate** | Hot climate vehicle test | | in Vehicle | Vehicle | | Customer | 3 | 2 | | | 1 | 1 | Open | | | 2110616 | | |
| | Functional Environmental Testing | **High Altitude testing** | system behavior on high altitude | | in Vehicle | in Vehicle | | Customer | 3 | 2 | | | 1 | 1 | Open | | | 2110612 | | |
| | Functional Environmental Testing | **Corossion test** | Corossion (ISO) resistance (transmission parts in salt spray and climate chamber) | | in Vehicle | in Vehicle | | Customer | 0,5 | 4 | 1 | 1 | 1 | 1 | Open | | | 2110612 | | |
| | Functional EMC Testing | **EMC test** | EMC behavior of all transmission relevant electrical components | | in Vehicle | in Vehicle | | Customer | 0,5 | 2 | | | 1 | 1 | Open | | | | | |
| | Functional Environmental Testing | **Water wading** | Water resistance | | in Vehicle | in Vehicle | | Customer | 1 | 2 | | | 1 | 1 | Open | | | 2110612 | | |
| | Functional Mechanical Testing | **Vehicle rough road test** | Test on rough road (gravel, cobblestone, pot holes…) | | in Vehicle | in Vehicle | | Customer | 2 | 4 | 1 | 1 | 1 | 1 | Open | | | 2110730 | | |
| | Functional Mechanical Testing | **Transmission oil and hydraulic system simulation** | In transmissions with various gear ratios and mechanical continous variable transmissions, the gearbox oil has several functions. It transmits power hydrodynamically in the torque converter or retarder, affects the friction coefficient profiles of clutches, dissipates heat and lubricates the gears and bearings. It provides information and pressure energy for the actuation of valves and shifting elements. | AVL Guideline | Simulation | | | DTV | | 4 | 1 | 1 | 1 | 1 | Open | | | 2110730 | | |
| | Functional Mechanical Testing | **Park Lock Functionality (static)** | Check the functionality of the parking mechanismus (all components). | | Test Bed | HLTB | | DTV | 0,5 | 2 | 1 | 1 | | | Done | | | 2110730 | | |
| | Functional Mechanical Testing | **Stop and Go Test** | Acceleration with maximum load including coast phase. Focus on DMF and clutch functionality. | | Test Bed | 2M | | DTV | 1 | 3 | 1 | 1 | 1 | | Done | | | 2110730 | | |
| | Functional Mechanical Testing | **Big Parameter Test** | a collection of functional tests for characterization of RGS functions.<br>Test Rig Ping<br>Lubrication<br>Tn-Check<br>Static Shifting<br>Run In 2<br>Tn-Map / Efficiency<br>Torque Split Ratio<br>EOL (Dynamic All Functions Check) | | Test Bed | 2M | | DTV | 0,5 | 3 | | 1 | 1 | 1 | Open | | | 2110730 | | |
| | Functional Mechanical Testing | **Bolt Test** | Losening torques compared to tightening torques | | Test Bed | Workbench | | DTV | | 3 | 1 | 1 | 1 | | Open | | | 2110730 | | |
| | Functional Mechanical Testing | **Forbidden Shifting Test** | Shift conditions that are not allowed | | Test Bed | 2M | | DTV | | 1 | | | 1 | | Open | | | 2110730 | | |

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| | Functional Mechanical Testing | **Lubrication Static Tilting Test** | verification of the correct oil volume in the transmission so that each operating function could be proceeded | | Test Bed | Tilt TB | | DTV | | | | | | | Done | | | 2110730 | | |
| | Functional Mechanical Testing | **No Oil Test** | evaluation of steady state temperature without oil,Validation of the worst case lubrication of the Rear Gearbox System (RGS). By realizing an initial oiling only, extreme driving conditions | | Test Bed | 2M | | DTV | | 2 | | 1 | 1 | | Open | | | 2110730 | | |
| | Functional Mechanical Testing | **Temperature Cycle Test** | The aim of T cycle Low/High temperature Test is to check that all all material combinations and bolt connections do not loss function affected by temperature influences. | | Test Bed | Climatic Chamber | | DTV | | 2 | | 1 | 1 | | Open | | | 2110730 | | |
| | Functional Mechanical Testing | **Torsional Stiffness** | Validation according to backlash and elastic deformation Plastic deformations must not occur. | | Test Bed | HLTB | | DTV | | 2 | | 1 | 1 | | Open | | | 2110730 | | |
| | Functional Mechanical Testing | **Uncammanded Engangement** | FUSI: Validation of the Rear Gearbox System (RGS) in case that an uncommanded engagement in gear 1 (G1) and G2 at synchronization speeds higher 250 rpm is rejected.<br>RGS parts may fail but must not lead in a blocked gearbox. | | Test Bed | 2M | | DTV | | 2 | | 1 | 1 | | Open | | | 2110730 | | |
| | Functional Mechanical Testing | **FUSI Shifting Test** | Shifting under conditions where no shifts are intended | | Test Bed | 2M | | DTV | | 2 | | | 1 | 1 | Open | | | 2110730 | | |
| | Functional Mechanical Testing | **Limp Home Engagement** | Special vehicle conditions force the Rear Gearbox System (RGS) to start driving without being referenced. In this state (unknown position) the RGS shifts into Gear 2 (G2, most safety state). This is called "Limp Home Engagement" (LHE). The plausibility of G2 is checked via ratio | | Test Bed | 2M | | DTV | | 3 | | 1 | 1 | 1 | Open | | | 2110730 | | |
| | Functional Mechanical Testing | **Dynamic Shifting** | Validation of the shifting function of the Rear Gearbox System (RGS) at different vehicle speeds, de- and accelerations (±2 m/s² = ±50 rpm/s), at maximum operating temperature of 90 °C as well as -30 °C. | | Test Bed | 2M | | DTV | | 3 | | 1 | 1 | 1 | Open | | | 2110730 | | |
| | Functional Mechanical Testing | **Park lock function test** | park lock different functions at vehicle test<br>-drop in speed<br>-missuse | | in Vehicle | in Vehicle | | Customer | | 2 | | | 1 | 1 | Open | | | 2110730 | | |
| | Functional Thermal Testing | **Temperatur behaviour in vehicle** | Transmission cooling behaviour | | in Vehicle | in Vehicle | | Customer | | 3 | | 1 | 1 | 1 | Open | | | 2110616 | | |
| **Durability Testing** | | | | | | | | | | | | | | | | | | | | |
| | Durability Enviromental Testing | **Launch system durability** | Wide open throttle acceleration (WOT) including coast phase, durability of DMF and clutch | | Test Bed | 3M /2M TB Validation Rig | | DTV | 3 | 9 | 2 | 2 | 2 | 3 | Open | | | 2110614 | | |
| | Durability Mechanical Testing | **Shifting durability** | Shifting operation under real driving situations (torque, speed, ..) | | Test Bed | 3M TB | | DTV | 12 | 12 | 3 | 3 | 3 | 3 | Open | | | 2110732 | | |
| | Durability Mechanical Testing | **High Speed Endurance Test** | Durability run in each gear with 80% load and max. speed (reduction depending on gear dimensioning 1,2,R), highest speed duration to be checked. | | Test Bed | 3M/2M TB Validation, B2B | | DTV | 0,5 | 8 | 2 | 2 | 2 | 2 | Done | | | 2110732 | | |
| | Durability Mechanical Testing | **Transmission load cycle durability test (Load points)** | Accelerated durability run with max. loads (reduction depending on gear dimensioning 1,2,R) test run until transmission failure or 150% design lifetime damage to stop test | GWM | Test Bed | 3M/2M TB Validation, B2B | | DTV | 4 | 16 | 4 | 4 | 4 | 4 | Open | | | 2110732 | | |
| | Durability Mechanical Testing | **Transmission durability test (dynamic)** | Mixed cycle (dynamic) real life parts out of CRUISE) until transmission failure or 150% design lifetime damage to stop test | | Test Bed | 3M/2M TB Validation, B2B | | DTV | 18 | 4 | | | 2 | 2 | Open | | | 2110732 | | |
| | Durability Mechanical Testing | **Towing durability** | Durability towing with highway speed | | Test Bed | Schlepppalette | | DTV | 0,5 | 4 | 1 | 1 | 1 | 1 | Open | | | 2110732 | | |
| | Durability Mechanical Testing | **Park lock durability** | -ratcheting<br>-different loads (no load, pull out max gradient, pull out at 30% max gradient) | | Test Bed | HLTB | | DTV | | 2 | | 1 | 1 | | Open | | | 2110732 | | |
| | Durability Mechanical Testing | **Park Lock Mis-Engagement Wear Durability** | Test procedure is focused on Mis-Engagement of the parking mechanism pawl with tooth to tooth. | | Test Bed | | | DTV | | | | | | | Done | | | 2110732 | | |
| | Durability Mechanical Testing | **Vehicle durability** | Mixed cycle (dynamic) real life manuvers until transmission failure or 150% design lifetime damage to stop test | | in Vehicle | in Vehicle | | Customer | 6 | 4 | 1 | 1 | 1 | 1 | Open | | | 2110732 | | |
| | Durability Mechanical Testing | **Vehicle durability trailer towing** | Mixed cycle (dynamic) real life manuvers until transmission failure or 150% design lifetime damage to stop test. Max. gross vehicle weight (trailer) | | in Vehicle | in Vehicle | | Customer | 6 | 4 | 1 | 1 | 1 | 1 | Open | | | 2110732 | | |
| | Durability Mechanical Testing | **Park lock reliablity test** | -reliability of park lock system at max gradient<br>- reliability of park lock system at 30% max gradient<br>-force of disanganging at hill (pull out force) | | in Vehicle | in Vehicle | | Customer | | 3 | | 1 | 1 | 1 | Open | | | 2110732 | | |

## 6.1.5 FP-Sheet

| Subsystem / Component | Failure | Failure location | Cause of failure | Effect on system level | Damaging operating conditions | Aggravating conditions | Test Coverage | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | Functional Testing | | | | | | | | Durability Testing | | | |
| | | | | | | | Functional Performance Testing | Functional Electrical LV Testing | Functional Electrical HV Testing | Functional Mechanical Testing | Functional Environmental Testing | Functional Thermal Testing | Functional NVH Testing | Functional EMC Testing | Durability Electrical Testing | Durability Mechanical Testing | Durability Enviromental Testing | Durability Thermal Testing |
| Transmission | | | | | | | | | | | | | | | | | | |
| Housing | | | | | | | | | | | | | | | | | | |
| T-H1 | Fatigue | critical positions (differentia | mechanical load (vibration of Powertrain) | crack in housing -->oil escape -->transmission failure | Vibration at resonance point | | | | | x | | | | | | x | | |
| T-H2 | Low Cycle Fatigue (LCF) | housing "upper part" | mechanical load (high torque) -plastification | crack in housing -->oil escape -->transmission failure | Transient operation / High load | | | | | x | | | | | | x | | |
| T-H3 | Corrosion | housing surface | chemical load by water ingrees (winter activities) | Leakage --> Oil escape | | | | | | | x | | | | | | x | |
| Lubrication | | | | | | | | | | | | | | | | | | |
| T-L2 | Ageing (thermal) | lubricant | thermal load | malefucntion of lubrication -> tranmsission failure | High temperature impact | | | | | | | x | | | | | | x |
| T-L3 | Ageing (chemical) | lubricant | chemical load by water or foreign poarticles | malefucntion of lubrication -> tranmsission failure | humidity , abration from other parts | | | | | | x | | | | | | x | |
| Input shaft | | | | | | | | | | | | | | | | | | |
| T-IS1 | Fatigue (HCF) | notch area (area with geom | mechanical load | damage of transmission | High load operation | | | | | x | | | | | | x | | |
| T-IS2 | Fatigue (HCF) | critical area (shear stress c | mechanical load | damage of transmission | Transient operation | | | | | x | | | | | | x | | |
| T-IS3 | Wear | shaft (spline) | mechanical load and thermal load | damage of transmission | transient operation | | | | | x | | | | | | x | | |
| Ball bearing | | | | | | | | | | | | | | | | | | |
| T-BB1 | Fatigue (HCF) | ring | mechanical load | damage of transmission | High load operation | | | | | x | | | | | | x | | |
| T-BB2 | Wear | rolling body | mechanical load (low lubrication) - tribology | NVH degradation, damage of bearing | High load operation | High temperature operation | | | | x | | | | | | x | | x |
| T-BB3 | Wear (fracture fatigue) | rolling path | mechanical load | damage of transmission | High load operation | | | | | x | | | | | | x | | |
| Gear | | | | | | | | | | | | | | | | | | |
| T-G1 | Fatigue (HCF) | tooth root | mechanical load | damage of transmission | High load operation | | | | | x | | | | | | x | | |
| T-G2 | Low Cycle Fatigue (LCF) | tooth root | mechanical load (plastification) | damage of transmission | High load operation | | | | | x | | | | | | x | | |
| T-G3 | Wear | tooth flank | mechanical load | high backlash --> NVH degradation --> damage of transmission | High load operation | | | | | x | | | | | | x | | |
| EM | | | | | | | | | | | | | | | | | | |
| Housing | | | | | | | | | | | | | | | | | | |
| EM-H1 | Fatigue | critical positions (differentia | mechanical load (vibration of Powertrain) | crack in housing - > water intrution -> malefunciton of e-drive | Vibration at resonance point | | | | | x | | | | | | x | | |
| EM-H2 | Low Cycle Fatigue (LCF) | housing "upper part" | mechanical load (high torque) -plastification | crack in housing - > water intrution -> malefunciton of e-drive | Transient operation / High load | | | | | x | | | | | | x | | |
| EM-H3 | Corrosion | housing surface | chemical load by water ingrees (winter activities) | crack in housing - > water intrution -> malefunciton of e-drive | | | | | | | x | | | | | | x | |
| Rotor Shaft | | | | | | | | | | | | | | | | | | |
| EM-RS1 | Fatigue (HCF) | notch area (area with geom | mechanical load | Damage of eMotor | High load operation | | | | | x | | | | | | x | | |
| EM-RS2 | Fatigue (LCF) | Spline / press fit | mechanical load and thermal load | Damage of eMotor | High load operation | High temperature operation | | | | x | | x | | | | x | | x |
| EM-RS3 | Wear | shaft (spline) | mechanical load and thermal load | NVH degradation, damage of bearing | transient operation | High temperature operation | | | | x | | x | | | | x | | x |
| Ball bearing | | | | | | | | | | | | | | | | | | |
| EM-BB1 | Fatigue (HCF) | ring | mechanical load | Damage of eMotor | High load operation | | | | | x | | | | | | x | | |
| EM-BB2 | Wear | rolling body | mechanical load | NVH degradation, damage of bearing | High load operation | High temperature operation | | | | x | | | | | | x | | |
| EM-BB3 | Wear (fracture fatigue) | rolling path | mechanical load (Pitting) | Damage of eMotor | High load operation | | | | | x | | | | | | x | | |
| Cable | | | | | | | | | | | | | | | | | | |
| EM-C1 | Aging | Insulation | thermal load | Damage of eMotor | temperature impact | chemical load | | x | | | x | x | | | x | | x | x |
| EM-C2 | Wear | Insulation | mechanical load | Damage of eMotor | High load operation | High temperature operat | | x | | x | | | | | x | x | | |
| EM-C3 | Corrosion | Insulation | chemical load by water ingrees (winter activities) | Damage of eMotor | humidity | | | x | | | x | | | | x | | x | |
| Power Electronics | | | | | | | | | | | | | | | | | | |
| Housing | | | | | | | | | | | | | | | | | | |
| PE-H1 | Fatigue | critical positions (differentia | mechanical load (vibration of Powertrain) | crack in housing - > water intrution -> malefunciton of e-drive | Vibration at resonance point | | | | | x | | | | | | x | | |
| PE-H2 | Low Cycle Fatigue (LCF) | housing "upper part" | mechanical load (high torque) -plastification | crack in housing - > water intrution -> malefunciton of e-drive | Transient operation / High load | | | | | x | | | | | | x | | |
| PE-H3 | Corrosion | housing surface | chemical load by water ingrees (winter activities) | Leakage - > water intrution -> malefunciton of e-drive | humidity | | | | | | x | | | | | | x | |
| Sealing | | | | | | | | | | | | | | | | | | |
| PE-S1 | Wear | sealing | mechanical load | Leakage, undesired controled of elements, --> damage of e-drive | high speed operation | | | | | x | x | | | | | x | | |
| PE-S2 | Ageing (thermal) | sealing (rubber) | thermal load | Leakage, undesired controled of elements, --> damage of e-drive | temperature impact | | | | | | x | x | | | | | | x |
| Input Plug | | | | | | | | | | | | | | | | | | |
| PE-IP1 | Ageing (thermal) | Communication input | thermal load | accelerating or regenerative braking -> undesired motor torque | temperature impact | | | x | | | | x | | | x | | | x |
| PE-IP2 | Corrosion | Communication input | chemical load by water ingrees (winter activities) | No PDO (Process Data Object) timeout message -> undesired motor tc | humidity | | | | | | x | | | | x | | x | |
| PE-IP3 | Corrosion | Isolation | chemical load by water ingrees (winter activities) | Short Circuit or non operational / water or chemicals intrution | humidity | | | | | | x | | | | x | | x | |
| Circuit Board | | | | | | | | | | | | | | | | | | |
| PE-CB1 | Wear | Soldering | mechanical load | male function of the eDrive system -> undesired motor torque | Vibration at resonance poir | High temperature operat | | x | x | x | | x | | | | x | | x |
| PE-CB2 | Aging | Soldering | thermal load | male function of the eDrive system -> undesired motor torque | temperature impact | | | x | x | | | x | | | | | x | x |

## 6.1.6 Failure Correlation – Functional testing

| Functional Testing | | | | | | | |
|---|---|---|---|---|---|---|---|
| Functional Performance Testing | Functional Electrical LV Testing | Functional Electrical HV Testing | Functional Mechanical Testing | Functional Environmental Testing | Functional Thermal Testing | Functional NVH Testing | Functional EMC Testing |
| e-Axle | | | | | | | |
| Condition Monitoring | EM-C1 / EM-C2 / EM-C3 | EM-C1 / EM-C2 / EM-C3 / | T-H1 / T-H2 / T-H3 / T-IS1 / T-IS2 / T-IS3 / T-BB1/ T-BB2 / T-BB3 / T-G1 / T-G2 / T-G3 / EM-H1 / EM-H2 / EM-RS1 / EM-RS2 / EM-RS3 / EM-BB1 / EM-BB2 / EM-BB3 / EM-C2 / | | EM-RS3 / EM-RS2 / EM-C1 | Condition Monitoring | Condition Monitoring |
| Condition Monitoring | EM-C1 / EM-C2 / EM-C3 / PE - IP1 / PE - CB1/ PE-CB2 | EM-C1 / EM-C2 / EM-C3 / PE - CB1/ PE-CB2 | T-H1 / T-H2 / T-H3 / T-IS1 / T-IS2 / T-IS3 / T-BB1/ T-BB2 / T-BB3 / T-G1 / T-G2 / T-G3 / EM-H1 / EM-H2 / EM-RS1 / EM-RS2 / EM-RS3 / EM-BB1 / EM-BB2 / EM-BB3 / EM-C2 / PE-H1 / PE-H2 / PE - S1 / PE - CB1 | T-H3 / T-L3 / EM-H3 / EM-C1 / EM-C3 / PE-S2 / PE-IP1 / PE -CB1 / PE -CB2 | T-L2 / T-BB2 / PE-S2 / PE-IP1 / PE-CB1 / PE-CB2 | Condition Monitoring | Condition Monitoring |
| Condition Monitoring | EM-C1 / EM-C2 / EM-C3 / PE - IP1 / PE - CB1/ PE-CB2 | EM-C1 / EM-C2 / EM-C3 / PE - CB1/ PE-CB2 | T-H1 / T-H2 / T-H3 / T-IS1 / T-IS2 / T-IS3 / T-BB1/ T-BB2 / T-BB3 / T-G1 / T-G2 / T-G3 / EM-H1 / EM-H2 / EM-RS1 / EM-RS2 / EM-RS3 / EM-BB1 / EM-BB2 / EM-BB3 / EM-C2 / PE-H1 / PE-H2 / PE - S1 / PE - CB1 | T-H3 / T-L3 / EM-H3 / EM-C1 / EM-C3 / PE-S2 / PE-IP1 / PE -CB1 / PE -CB2 | T-L2 / T-BB2 / PE-S2 / PE-IP1 / PE-CB1 / PE-CB2 | Condition Monitoring | Condition Monitoring |
| Condition Monitoring | EM-C1 / EM-C2 / EM-C3 / PE - IP1 / PE - CB1/ PE-CB2 | EM-C1 / EM-C2 / EM-C3 / PE - CB1/ PE-CB2 | T-H1 / T-H2 / T-H3 / T-IS1 / T-IS2 / T-IS3 / T-BB1/ T-BB2 / T-BB3 / T-G1 / T-G2 / T-G3 / EM-H1 / EM-H2 / EM-RS1 / EM-RS2 / EM-RS3 / EM-BB1 / EM-BB2 / EM-BB3 / EM-C2 / PE-H1 / PE-H2 / PE - S1 / PE - CB1 | T-H3 / T-L3 / EM-H3 / EM-C1 / EM-C3 / PE-S2 / PE-IP1 / PE -CB1 / PE -CB2 | T-L2 / T-BB2 / PE-S2 / PE-IP1 / PE-CB1 / PE-CB2 | Condition Monitoring | Condition Monitoring |
| Transmission | | | | | | | |
| Condition Monitoring | | | T-H1 / T-H2 / T-H3 / T-IS1 / T-IS2 / T-IS3 / T-BB1/ T-BB2 / T-BB3 / T-G1 / T-G2 / T-G3 | | | | |
| Condition Monitoring | | | T-H1 / T-H2 / T-H3 / T-IS1 / T-IS2 / T-IS3 / T-BB1/ T-BB2 / T-BB3 / T-G1 / T-G2 / T-G4 | T-H3 / T-L3 | T-L2 / T-BB2 | Condition Monitoring | |
| Condition Monitoring | | | T-H1 / T-H2 / T-H3 / T-IS1 / T-IS2 / T-IS3 / T-BB1/ T-BB2 / T-BB3 / T-G1 / T-G2 / T-G5 | T-H3 / T-L3 | T-L2 / T-BB2 | Condition Monitoring | |
| Condition Monitoring | | | T-H1 / T-H2 / T-H3 / T-IS1 / T-IS2 / T-IS3 / T-BB1/ T-BB2 / T-BB3 / T-G1 / T-G2 / T-G6 | T-H3 / T-L3 | T-L2 / T-BB2 | Condition Monitoring | |
| EM | | | | | | | |
| Condition Monitoring | EM-C1 / EM-C2 / EM-C3 | | EM-H1 / EM-H2 / EM-RS1 / EM-RS2 / EM-RS3 / EM-BB1 / EM-BB2 / EM-BB3 / EM-C2 | | EM-RS3 / EM-RS2 / EM-C1 | Condition Monitoring | Condition Monitoring |
| Condition Monitoring | EM-C1 / EM-C2 / EM-C3 | | EM-H1 / EM-H2 / EM-RS1 / EM-RS2 / EM-RS3 / EM-BB1 / EM-BB2 / EM-BB3 / EM-C2 | EM-H3 / EM-C1 / EM-C3 | EM-RS3 / EM-RS2 / EM-C1 | Condition Monitoring | Condition Monitoring |
| Condition Monitoring | EM-C1 / EM-C2 / EM-C3 | | EM-H1 / EM-H2 / EM-RS1 / EM-RS2 / EM-RS3 / EM-BB1 / EM-BB2 / EM-BB3 / EM-C2 | EM-H3 / EM-C1 / EM-C3 | EM-RS3 / EM-RS2 / EM-C1 | Condition Monitoring | Condition Monitoring |
| Condition Monitoring | EM-C1 / EM-C2 / EM-C3 | | EM-H1 / EM-H2 / EM-RS1 / EM-RS2 / EM-RS3 / EM-BB1 / EM-BB2 / EM-BB3 / EM-C2 | EM-H3 / EM-C1 / EM-C3 | EM-RS3 / EM-RS2 / EM-C1 | Condition Monitoring | Condition Monitoring |
| Power Electronics | | | | | | | |
| | | | | | | | Condition Monitoring |
| Condition Monitoring | PE - IP1 / PE - CB1/ PE-CB2 | PE - CB1/ PE-CB2 | PE-H1 / PE-H2 / PE - S1 / PE - CB1 | PE-S2 / PE-IP1 / PE -CB1 / PE -CB2 | PE-S2 / PE-IP1 / PE-CB1 / PE-CB2 | Condition Monitoring | Condition Monitoring |
| Condition Monitoring | PE - IP1 / PE - CB1/ PE-CB3 | PE - CB1/ PE-CB3 | PE-H1 / PE-H2 / PE - S1 / PE - CB2 | PE-S2 / PE-IP1 / PE -CB1 / PE -CB3 | PE-S2 / PE-IP1 / PE-CB1 / PE-CB3 | Condition Monitoring | Condition Monitoring |
| | | | | | | | Condition Monitoring |

## 6.1.7 Failure Correlation – Durability testing

| Durability | | | |
|---|---|---|---|
| Durability Electrical Testing | Durability Mechanical Testing | Durability Enviromental Testing | Durability Thermal Testing |
| | | | T-L2 / T-BB2 / EM-RS3 / EM-RS2 / EM-C1 / PE -S2 / PE-IP1 / PE-CB1 / PE-CB2 |
| EM-C1 / EM-C2 / EM-C3 / PE-IP1 / PE-IP2 /PE-IP3 | T-H1 / T-H2 / T-H3 / T-IS1 / T-IS2 / T-IS3 / T-BB1/ T-BB2 / T-BB3 / T-G1 / T-G2 / T-G3 / EM-H1 / EM-H2 / EM-RS1 / EM-RS2 / EM-RS3 / EM-BB1 / EM-BB2 / EM-BB3 / EM-C2 / | T-H3 / T-L3 / EM-H3 / EM-C1 / EM-C3 / PE-H3 / PE-IP2 / PE-IP3 / PE-CB2 | T-L2 / T-BB2 / EM-RS3 / EM-RS2 / EM-C1 / PE -S2 / PE-IP1 / PE-CB1 / PE-CB2 |
| EM-C1 / EM-C2 / EM-C3 / PE-IP1 / PE-IP2 /PE-IP3 | T-H1 / T-H2 / T-H3 / T-IS1 / T-IS2 / T-IS3 / T-BB1/ T-BB2 / T-BB3 / T-G1 / T-G2 / T-G3 / EM-H1 / EM-H2 / EM-RS1 / EM-RS2 / EM-RS3 / EM-BB1 / EM-BB2 / EM-BB3 / EM-C2 / | T-H3 / T-L3 / EM-H3 / EM-C1 / EM-C3 / PE-H3 / PE-IP2 / PE-IP3 / PE-CB2 | T-L2 / T-BB2 / EM-RS3 / EM-RS2 / EM-C1 / PE -S2 / PE-IP1 / PE-CB1 / PE-CB2 |
| EM-C1 / EM-C2 / EM-C3 / PE-IP1 / PE-IP2 /PE-IP3 | T-H1 / T-H2 / T-H3 / T-IS1 / T-IS2 / T-IS3 / T-BB1/ T-BB2 / T-BB3 / T-G1 / T-G2 / T-G3 / EM-H1 / EM-H2 / EM-RS1 / EM-RS2 / EM-RS3 / EM-BB1 / EM-BB2 / EM-BB3 / EM-C2 / | T-H3 / T-L3 / EM-H3 / EM-C1 / EM-C3 / PE-H3 / PE-IP2 / PE-IP3 / PE-CB2 | T-L2 / T-BB2 / EM-RS3 / EM-RS2 / EM-C1 / PE -S2 / PE-IP1 / PE-CB1 / PE-CB2 |
| | T-H1 / T-H2 / T-H3 / T-IS1 / T-IS2 / T-IS3 / T-BB1/ T-BB2 / T-BB3 / T-G1 / T-G2 / T-G3 | T-H3 / T-L3 | T-L2 / T-BB2 |
| | T-H1 / T-H2 / T-H3 / T-IS1 / T-IS2 / T-IS3 / T-BB1/ T-BB2 / T-BB3 / T-G1 / T-G2 / T-G4 | T-H3 / T-L3 | T-L2 / T-BB2 |
| | T-H1 / T-H2 / T-H3 / T-IS1 / T-IS2 / T-IS3 / T-BB1/ T-BB2 / T-BB3 / T-G1 / T-G2 / T-G5 | T-H3 / T-L3 | T-L2 / T-BB2 |
| | | | EM-RS3 / EM-RS2 / EM-C1 |
| EM-C1 / EM-C2 / EM-C3 | EM-H1 / EM-H2 / EM-RS1 / EM-RS2 / EM-RS3 / EM-BB1 / EM-BB2 / EM-BB3 / EM-C2 | EM-H3 / EM-C1 / EM-C3 | EM-RS3 / EM-RS2 / EM-C1 |
| EM-C1 / EM-C2 / EM-C3 | EM-H1 / EM-H2 / EM-RS1 / EM-RS2 / EM-RS3 / EM-BB1 / EM-BB2 / EM-BB3 / EM-C2 | EM-H3 / EM-C1 / EM-C3 | EM-RS3 / EM-RS2 / EM-C1 |
| EM-C1 / EM-C2 / EM-C3 | EM-H1 / EM-H2 / EM-RS1 / EM-RS2 / EM-RS3 / EM-BB1 / EM-BB2 / EM-BB3 / EM-C2 | EM-H3 / EM-C1 / EM-C3 | EM-RS3 / EM-RS2 / EM-C1 |
| PE-IP1 / PE-IP2 /PE-IP3 | PE-H1 / PE-H2 / PE-S1 / PE- CB1 | PE-H3 / PE-IP2 / PE-IP3 / PE-CB2 | PE -S2 / PE-IP1 / PE-CB1 / PE-CB2 |
| PE-IP1 / PE-IP2 /PE-IP4 | PE-H1 / PE-H2 / PE-S1 / PE- CB2 | PE-H3 / PE-IP2 / PE-IP3 / PE-CB3 | PE -S2 / PE-IP1 / PE-CB1 / PE-CB3 |
| PE-IP1 / PE-IP2 /PE-IP5 | PE-H1 / PE-H2 / PE-S1 / PE- CB3 | PE-H3 / PE-IP2 / PE-IP3 / PE-CB4 | PE -S2 / PE-IP1 / PE-CB1 / PE-CB4 |

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# 9 List Of Formulas

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