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SCAPE
POWERING E-MOBILITY

D2.3 – Test Cases

SWITCHING-CELL-ARRAY-BASED POWER ELECTRONICS CONVERSION FOR FUTURE ELECTRIC VEHICLES

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Executive Summary

This deliverable introduces the system test cases for validation of Integrated Inverter On-Board Charger and auxiliary DC-DC converter developed as outcomes of SCAPE. It describes the test cases and how to interpret them according to the requirement engineering process described in D2.1. Test cases are used to validate the functional requirements by using their acceptance criteria as a precursor. System test cases of the IIOBC and DC-DC converter are explained in detail with their titles, descriptions, evaluation criteria and objectives based on SCAPE metrics and considered use cases. Furthermore, lower-level test cases are currently being developed in parallel with the lower-level requirements, which are to be derived from the top-level requirements. It is always possible to detect any discrepancies between the requirements and the test cases during the forthcoming development phases via the gap analysis process which is already defined in the collaboration methodology. It is also within the realm of possibility that the discrepancies may be redressed by making amendments according to the change management process which is also developed as a part of the collaboration methodology of SCAPE. The following documents are supplements to this document and make the information conveyed complete.

- D2.1 Collaboration Method Report.
- D2.2 Use cases and requirements.

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List of Tables

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List of Acronyms and Abbreviations

AC	Alternative Current
CAN	Controller Area Network
DC	Direct Current
EM	Electric Machine
EV	Electric Vehicle
HV	High Voltage
HV2LV	Operation mode where power is transferred from the traction-battery side (the HV side) to the service-battery side (LV side).
IIOBC	Integrated Inverter On-Board Charger
LV	Low Voltage
LV2HV	Operation mode where power is transferred from the service-battery side (the LV side) to the traction-battery side (HV side)
pu	Per Unit
rms	Root Mean Square
SoH	State of Health
Tamb	Ambient Temperature
WP	Work Package
VHV,min	Minimum expected voltage at the traction battery module in the HV side
VHV,max	Maximum expected voltage at the traction battery module in the HV side
Vin	Input Voltage
Vout	Output Voltage
VLV,min	Minimum expected voltage at the service battery pack in the LV side
VLV,max	Maximum expected voltage at the service battery pack in the LV side

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1. Introduction

WP2 tasks aim at contributing to the efficient system development of switching cell array based power converters for a wide range of EV applications. An effective collaboration method among partners to apply AVL-TR system development procedures has been initially established. After a comprehensive market, industry and literature survey, three use cases have been selected. The intention is to narrow the scope of SCAPE studies and efforts to a reasonable subset of use cases that enables illustrating the benefits of the approach. Then, for each these three use cases, and according to the project objectives, system requirements have been derived for two particular converters in the EV: an integrated inverter and on-board charger (IIOBC) and an auxiliary dc-dc converter to feed the service battery from the traction battery. These system requirements will lead to the definition of correlated subsystem requirements, and all the requirement tree with the corresponding connections among requirements needs to be clearly reflected in an appropriate documentation.

This document presents a list of defined test cases to validate if the system requirements reported in D2.2 are fulfilled. The test cases were developed with the support of IREC and UPC, and they were reviewed and approved by the partners. All details such as attributes, comments and test procedures can be found in the corresponding internal documentation.

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2. Short Description of the Considered Use Cases

The three considered use cases have already been selected in D2.2, and correspond to an e-motorcycle, a passenger car, and a truck. Table 1 and Table 2 show their main parameter values. Since SCAPE experimental validation focuses on the case of the passenger car, the tests in this document will be defined for this use case.

No	Parameter	e-Motorcycle	Passenger Car	Truck
1	Nominal electrical motor power (kW)	50	100	300
2	Nominal total battery voltage (V)	400	800	1200
3	Inverter leg number of levels	2	3	4
4	Estimated nominal phase current (Arms) (for m = 0.75 and j = 30°)	80	80	160
5	Estimated number of SCs per leg	4	8	24
6	Power Flow Direction	Bi-Directional	Bi-Directional	Bi-Directional
7	Efficiency (%)	> 97.5%	> 97.5%	> 97.5%

Table 1: Main parameter values for the integrated inverter and on-board charger for the three selected use cases

No	**Parameter**	**e-Motorcycle**	**Passenger Car**	**Truck**
1	Nominal power (kW)	0.5	1	3
2	Input voltage (V)	400	400	400
3	Output voltages (V)	12	12/24	12/24/36
4	Type	Single Phase	Single Phase/Three Phase	Three Phase
5	HV-side: Converter-leg number of levels	2	2	2
6	LV-side: Converter-leg number of levels	2	3	4
7	HV-side: Estimated # of SCs per leg	2	2	4
8	LV-side: Estimated # of SCs per leg	4	8	18
9	Power Flow Direction	Bi-Directional	Bi-Directional	Bi-Directional
10	Efficiency (%)	> 90%	> 90%	> 90%

Table 2: Main parameter values for the auxiliary dc-dc converter for the three selected use cases

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3. System Test Cases

The main inputs for creating system test cases are the analysis of system requirements and use cases. However, only functional system requirements are verified with the test cases. In addition, it is necessary to consider different approaches for test case creation so that the outcome of the project can be fully validated. Test bench capability is also a significant factor in test case structure. The following approach has been considered for the creation of the test cases:

- **Analysis of requirements:** The test case is derived purely from the requirements as their acceptance criterion.
- **Analysis of use cases:** Test cases are derived based on an analysis of operational use cases to specifically capture properties of the field of applications.
- **Boundary condition analysis:** Most of the errors occur at the boundaries of input domain. Test cases are designed to check the edges and design limits.
- **Error guessing based on knowledge or experience:** In addition to formal testing procedures, the tester's expertise is utilized in the detection of potential bugs or defects, and it ends up with the creation of a new test case or the modification of an existing one.
- **Analysis of external and internal interface:** These test cases are derived from the interface specification and aim at the verification of the correct implementation of these interfaces.
- **Analysis of environmental conditions:** Test cases are derived from known relevant environmental conditions, focusing on the limits specified for the equipment under test.

3.1. System Test Cases for IIOBC

In the following, system test cases for the IIOBC are provided in tabular form.

3.1.1 TC_IIOBC_01_Continuous Power Test for IIOBC

Description & Procedure	For automotive applications, there is no power request because the vehicle control units calculate torque demand according to the status of the throttle which is controlled by the driver. This test case is defined to check the continuous power capability by applying different torque requests for all boundaries while IIOBC is in traction mode
Evaluation Criteria	The output torque of the EM behaves based on the torque request from the tester while IIOBC is in the traction mode.
ID(s): Validated Requirement(s)	• **Req #3:** The IIOBC output shall be rated for 100 kW of continuous power in traction mode. • **Req #25:** The EM shall be designed for a minimum nominal power of 100 kW.
Project Objectives Under Validation	TO2, TO3 - an increase in compactness of SCAPE - advanced board integration technology - reduced need of heat dissipation - higher switching frequency - advanced control strategies

Table 3: Continuous Power Test for IIOBC

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3.1.2 TC_IIOBC_02_Inverter Efficiency Test

Description & Procedure	Inverter efficiency test case is defined to check and ensure that the target efficiency metric of IIOBC (at least 97,5%) is fulfilled as planned. This test is to validate the overall DC-link to AC bus efficiency under normal highway driving operation. The test should be conducted via requesting different torque values while the IIOBC is in traction mode.
Evaluation Criteria	DC link to AC bus efficiency is at least 97,5%.
ID(s): Validated Requirement(s)	• **Req #2:** At normal highway cruising operating point, the IIOBC shall have an overall DC-link to AC bus efficiency of at least 97.5% at 20% of the nominal current.
Project Objectives Under Validation	TO3, TO4 - improvement of the EV powertrain performance and reliability - lifetime extension - development in advanced control strategies

Table 4: Inverter Efficiency Test

3.1.3 TC_IIOBC_03_Performance Test

Description & Procedure	Performance test case is defined to check and ensure that the IIOBC operates without any performance reduction (no derating) within the pre-defined ambient temperature conditions. This test is to validate thermal resistance performance of IIOBC under rated operation conditions of EM in the traction mode. Test case should be applied for different ambient temperature values within the pre-defined interval (0°C - 40°C).
Evaluation Criteria	IIOBC has no performance reduction (no derating) for ambient temperatures between 0 °C and 40 °C.
ID(s): Validated Requirement(s)	• **Req #6:** The IIOBC should be able to operate without any derating in temperatures between 0 ℃ ≤ Tamb ≤ 40 ℃.
Project Objectives Under Validation	TO2 - achieving the junction-to heatsink thermal resistance decrease of at least 25% <0.75pu) - higher liquid/air cooling operational temperatures - optimum thermal performance

Table 5: Performance Test

3.1.4 TC_IIOBC_04_Inverter Leg Fault Tolerance Test

Description & Procedure	The inverter leg fault tolerance test case is defined to check whether the IIOBC can still operate in the case that its power output reduces due to the failure of at least one converter leg.
Evaluation Criteria	The power output of the IIOBC is reduced due to a number of failed legs but IIOBC is still operational
ID(s): Validated Requirement(s)	• **Req #9:** The IIOBC shall be able to tolerate at least one converter leg failure.
Project Objectives Under Validation	TO1, TO3 – taking full advantage of advanced integration technologies and scale economies – increased lifetime – fault tolerant objectives

Table 6: Inverter Leg Fault Tolerance Test

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3.1.5 TC_IIOBC_05_Zero Torque Insurance Test for Charging Mode

Description & Procedure	The zero-torque insurance test case is defined to check if the charge power value is same as the requested value when there is no torque and the IIOBC is in charging mode
Evaluation Criteria	The IIOBC is forced into charging mode and the charge power is equal to the requested power and EM torque is 0.
ID(s): Validated Requirement(s)	• **Req #10:** The IIOBC shall charge the HV battery with zero average torque induced on the e-machine rotor.
Project Objectives Under Validation	TO4 - higher safety standards - automotive quality level's objective of SCAPE

Table 7: Zero Torque Insurance Test for Charging Mode

3.1.6 TC_IIOBC_06_Charging Test for Single Phase AC Charging

Description & Procedure	This charging test case is defined to check if the charge power value is same as the requested value when there is no torque, the IIOBC is in charging mode and The AC grid supply is set to 230 Vrms at 50/60 Hz as planned. It aims higher charging standards, less power loss with higher efficiency.
Evaluation Criteria	The IIOBC is entered to charging mode and charge power is equal to requested power
ID(s): Validated Requirement(s)	• **Req #12:** The IIOBC shall be able to provide charging over a single-phase 50 Hz/60 Hz AC grid through eventually reconfiguration of motor windings. • **Req #14:** The IIOBC shall be able to charge the HV battery using the same power hardware used for traction mode. • **Req #15:** The IIOBC shall not require additional capacitors or inductors in addition to those used in traction. • **Req #16:** The IIOBC configuration shall be able to perform charging with a single motor.
Project Objectives Under Validation	TO1, TO4 - automotive quality level's objective of SCAPE - higher charging standards - higher efficiency and less power losses - modular and flexible design

Table 8: Charging Test for Single Phase AC Charging

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3.1.7 TC_IIOBC_07_Charging Test for Three Phase AC Charging

Description & Procedure	This charging test case is defined to check if the charge power value is same as the requested value when there is no torque, the IIOBC is in charging mode and the AC grid supply is set to 230 Vrms at 50/60 Hz as planned. It aims higher charging standards, less power loss with higher efficiency.
Evaluation Criteria	The IIOBC is forced to charging mode and the charge power is equal to requested power
ID(s): Validated Requirement(s)	• **Req #13:** The IIOBC should be able to provide charging over a three-phase 50 Hz/60 Hz AC grid through reconfiguration of motor windings. • **Req #14:** The IIOBC shall be able to charge the HV battery using the same power hardware used for traction mode. • **Req #15:** The IIOBC shall not require additional capacitors or inductors in addition to those used in traction. • **Req #16:** The IIOBC configuration shall be able to perform charging with a single motor.
Project Objectives Under Validation	TO1, TO4 - automotive quality level's objective of SCAPE - higher charging standards - higher efficiency and less power losses - modular and flexible design

Table 9: Charging Test for Three Phase AC Charging

3.1.8 TC_IIOBC_08_Charging Test for Unity Displacement Factor

Description & Procedure	This charging test case is defined to check if the unity displacement factor of the IIOBC can be calculated. The charge power value is set to the same value as the requested value when there is no torque. The AC grid supply is set up as 230 Vrms at 50/60 Hz as planned. It aims higher charging standards, less power loss with higher efficiency.
Evaluation Criteria	Unity displacement factor is achieved.
ID(s): Validated Requirement(s)	• **Req #17:** The IIOBC shall perform with unity displacement factor during charging
Project Objectives Under Validation	TO1, TO4 - less power losses - higher efficiency - modular and flexible design - automotive quality level's objective of SCAPE

Table 10: Charging Test for Unity Displacement Factor

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3.1.9 TC_IIOBC_09_Temperature Interface Test

Description & Procedure	The temperature interface test case is defined to check whether the IIOBC can be driven with different load profiles in torque control mode by aiming to achieve maximum operational temperature.
Evaluation Criteria	The EM temperature is read by the software and observed that is changed according to the load profiles.
ID(s): Validated Requirement(s)	• **Req #31:** The designed EM shall have an interface for stator temperature measurement.
Project Objectives Under Validation	TO2 - achieving the increased maximum operational temperature - optimum thermal performance

Table 11: Temperature Interface Test

3.1.10 TC_IIOBC_10_Rotor Position Interface Test

Description & Procedure	The rotor position interface test case is defined to check whether the resolver interface behaves correctly at different speeds. The simulated speed and calculated speed should be the same while IIOBC is in torque control mode.
Evaluation Criteria	The simulated speed and the speed calculated in the software have the same value.
ID(s): Validated Requirement(s)	• **Req #32:** The designed EM shall have an interface for rotor position measurement.
Project Objectives Under Validation	TO2 - accurate calculation of rotor position - optimum operation - efficiency greater than 97.5% - cost less than €2.5/kW

Table 12: Rotor Position Interface Test

3.1.11 TC_IIOBC_11_DC Overvoltage Detection Test

Description & Procedure	The DC overvoltage test case is defined to check whether the used software detects the overvoltage error when DC voltage is increased above the overvoltage threshold via power supply.
Evaluation Criteria	Overvoltage error is detected by software
ID(s): Validated Requirement(s)	• **Req #33:** The IIOBC shall monitor each DC-link capacitor for overvoltage.
Project Objectives Under Validation	TO3, TO4 - achieve automotive quality level's objective of SCAPE - adapting the operation of the powertrain for each situation - detection potential hazards and failure

Table 13: DC Overvoltage Detection Test

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3.1.12 TC_IIOBC_12_Phase Overcurrent Detection Test

Description & Procedure	The phase overcurrent test case is defined to check whether the phase overcurrent error is detected when the overcurrent is increased above its upper limit by driving IIOBC.
Evaluation Criteria	Phase overcurrent error is detected
ID(s): Validated Requirement(s)	• **Req #34:** The IIOBC shall monitor every motor phase current.
Project Objectives Under Validation	TO3, TO4 - achieve automotive quality level's objective of SCAPE - adapting the operation of the powertrain for each situation - detection potential hazards and failure

Table 14: Phase Overcurrent Detection Test

3.1.13 TC_IIOBC_13_Overtemperature Detection Test for Switching Cell

Description & Procedure	Overtemperature detection test case for switching cell is defined to check if at least a switching cell temperature is higher than the defined overtemperature threshold. An error signal should be set, and derating functions should not be active via software while IIBOC is in traction mode with maximum power.
Evaluation Criteria	Error signal for switching cell temperature is set when overtemperature threshold is reached.
ID(s): Validated Requirement(s)	• **Req #35:** The IIOBC shall monitor every switching cell temperature.
Project Objectives Under Validation	TO3,TO4 – achieve automotive quality level's objective of SCAPE – adapting the operation of the powertrain for each situation – detection potential hazards and failure

Table 15: Overtemperature Detection Test for Switching Cell

3.1.14 TC_IIOBC_14_State of Health (SoH)Test

Description & Procedure	The state of health test is defined to check the state of health variables of the IIOBC in case of manipulation. Input and output voltages should be set to their nominal values during this test case while IIOBC is in HV2LV mode. The goal of this test case is to see that the manipulated SoH variables start behaving normally after some time while the other variables are not significantly affected.
Evaluation Criteria	The manipulated SoH variables return to their expected value and the rest of the state of health is not significantly affected.
ID(s): Validated Requirement(s)	• **Req#36:** The IIOBC shall carry out SoH assessment of switching cells via Digital Twin. • **Req#37:** The IIOBC shall carry out SoH assessment of EM via Digital Twin. • **Req#38:** The IIOBC shall carry out SoH assessment of HV-Battery via Digital Twin.
Project Objectives Under Validation	TO3, TO4 – advanced switching, modulation and control strategies – increasing conversion efficiency – improved lifetime – implementing intelligent monitoring function

Table 16: State of Health Test

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3.1.15 TC_IIOBC_15_Configurable Electric Machine Winding Test

Description & Procedure	The configurable EM winding test is defined to check if EM output torque behaves normally in the case that the EM configuration changes. In order to observe this behavior, EM should be configurable for single, double and six phase operations. Maximum torque should be requested via the communication bus.
Evaluation Criteria	EM output torque behaves due to selected specification of the EM for all winding configurations.
ID(s): Validated Requirement(s)	• **Req#1:** The IIOBC shall be capable of driving a configurable (with open-end windings) symmetrical six-phase electrical machine. • **Req#11:** In case of vehicle configurations with multiple motors, all IIOBC shall be able to operate with same input AC and same output DC voltages for charging. • **Req#27:** The EM shall be designed as a symmetrical six phase motor with reconfigurable winding ends. • **Req#28:** The designed EM shall be able to operate with rated power as a six-phase machine. • **Req#29:** The designed EM shall operate with rated power as a double three-phase machine. • **Req#30:** The designed EM shall have a maximum fundamental electrical frequency of 1 kHz.
Project Objectives Under Validation	TO1, TO2, TO3, TO4 - modular and flexible design - automotive quality level's objective of SCAPE - highly integrable powertrains - functional modularity - extended fault tolerance

Table 17: Configurable Electric Machine Winding Test

3.1.16 TC_IIOBC_16_Phase to Ground Electric Machine Fault Tolerance Test

Description & Procedure	The phase to ground EM fault tolerance test is defined to check whether EM can be stabilized and enough torque is still provided by IIOBC after any triggered phase to ground fault. IIOBC should be in traction mode with nominal torque and speed.
Evaluation Criteria	The IIOBC is able to stabilize EM and provide (reduced/at least 50%) torque in case of a phase to ground.
ID(s): Validated Requirement(s)	• **Req#20:** The IIOBC modulation scheme shall be designed in a way that it tolerates phase-to-ground faults of the EM. • **Req#23:** The IIOBC modulation scheme shall be designed in a way that under a phase fault of the EM, at least 50% of the output is possible.
Project Objectives Under Validation	TO1, TO3 – taking full advantage of advanced integration technologies and scale economies – increased lifetime – fault tolerant objectives

Table 18: Phase to Ground Electric Machine Fault Tolerance Test

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3.1.17 TC_IIOBC_17_Phase to Phase Electric Machine Fault Tolerance Test

Description & Procedure	The phase to phase EM fault tolerance test is defined to check whether EM can be stabilized and enough torque is still provided by IIOBC after any triggered phase to phase fault. IIOBC should be in traction mode with nominal torque and speed.
Evaluation Criteria	The IIOBC is able to stabilize EM and provide (reduced/at least 50%) torque in case of a phase to ground.
ID(s): Validated Requirement(s)	• **Req#21:** The IIOBC modulation scheme shall be designed in a way that it tolerates phase-to-phase faults of the EM. • **Req#23:** The IIOBC modulation scheme shall be designed in a way that under a phase fault of the EM, at least 50% of the output is possible.
Project Objectives Under Validation	TO1, TO3 – taking full advantage of advanced integration technologies and scale economies – increased lifetime – fault tolerant objectives

Table 19: Phase to Phase Electric Machine Fault Tolerance Test

3.1.18 TC_IIOBC_18_Inter-turn Electric Machine Fault Tolerance Test

Description & Procedure	The inter-turn EM fault tolerance test is defined to check whether EM can be stabilized and enough torque is still provided by IIOBC after any triggered inter-turn fault. IIOBC should be in traction mode with nominal torque and speed.
Evaluation Criteria	The IIOBC is able to stabilize EM and provide (reduced/at least 50%) torque in case of a phase to ground.
ID(s): Validated Requirement(s)	• **Req#22:** The IIOBC modulation scheme shall be designed in a way that it tolerates inter-turn faults of the EM. • **Req#23:** The IIOBC modulation scheme shall be designed in a way that under a phase fault of the EM, at least 50% of the output is possible.
Project Objectives Under Validation	TO1, TO3 – taking full advantage of advanced integration technologies and scale economies – increased lifetime – fault tolerant objectives

Table 20: Inter-turn Electric Machine Fault Tolerance Test

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3.1.19 TC_IIOBC_19_Switching Cell Failure Tolerance Test

Description & Procedure	The switching cell failure tolerance test case is defined to check whether the IIOBC continues its operation even if non-critical switching cells from the LV and HV side are disabled. IIOBC should be in traction mode with maximum power during this test case.
Evaluation Criteria	The IIOBC is able to operate even after all non-critical switching cells are disabled.
ID(s): Validated Requirement(s)	• **Req#8:** The IIOBC shall be able to tolerate multiple switching-cell failures.
Project Objectives Under Validation	TO1, TO3 – taking full advantage of advanced integration technologies and scale economies – increased lifetime – fault tolerant objectives

Table 21: Switching Cell Failure Tolerance Test

3.2. System Test Cases for Auxiliary DC-DC Converter

In the following, system test cases for the auxiliary dc-dc converter are provided in tabular form.

3.2.1 TC_DCDC_01_Continuous Power Test for the DC-DC Converter

Description & Procedure	The continuous power test case is defined to check whether the DC-DC continues its operation without any restrictions. Continuous power capability is verified by transferring the requested power. The input and output voltages of the DC-DC should be set accordingly to see the behavior of the power while the DC-DC is in HV2LV mode.
Evaluation Criteria	The DC-DC converter is able to transfer the requested power within the safe operating area.
ID(s): Validated Requirement(s)	• **Req#39:** The DC-DC Converter shall be designed for a continuous 100% nominal output power.
Project Objectives Under Validation	TO2, TO3 – increase in compactness of SCAPE – advanced board integration technology – reduced need of heat dissipation – higher switching frequency – advanced control strategies

Table 22: Continuous Power Test for the DC-DC Converter

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3.2.2 TC_DCDC_02_Input Voltage Test

Description & Procedure	The input voltage test case is defined to check whether the DC-DC continues its operation without any restrictions. The input voltage test is verified by increasing the input voltage and changing nominal power accordingly for different conditions. Output voltage of the DC-DC should be set accordingly to observe the input voltage behavior while DC-DC is in HV2LV mode.
Evaluation Criteria	The DC-DC converter is able to transfer the requested power within the SOA.
ID(s): Validated Requirement(s)	• **Req#42:** The DC-DC converter shall be able to operate at the nominal input voltage that is 400 V. • **Req#43:** The DC-DC converter shall be able to operate in the range of VHV,min < V_{in} < VHV,max.
Project Objectives Under Validation	TO2, TO3 – increase in compactness of SCAPE – advanced board integration technology – reduced need of heat dissipation – higher switching frequency – advanced control strategies – modular and scalable powertrain topology advanced control system

Table 23: Input Voltage Test

3.2.3 TC_DCDC_03_DC-DC Converter Efficiency Test

Description & Procedure	The efficiency test case is defined to check whether the DC-DC continues its operation without any restrictions while its efficiency is at least 95%. This test case is verified by setting transferring power to 100% of the nominal value. Input and output voltages of the DC-DC should be set accordingly to observe efficiency while the DC-DC is in HV2LV mode.
Evaluation Criteria	Input-to-output transfer efficiency of the DC-DC converter is at least 95%.
ID(s): Validated Requirement(s)	• **Req#40:** The DC-DC converter shall be designed in a way that efficiency at the nominal operating point is at least 95%.
Project Objectives Under Validation	TO3, TO4 – improvement of the EV powertrain performance and reliability – lifetime extension – development in advanced control strategies

Table 24: DC-DC Converter Efficiency Test

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3.2.4 TC_DCDC_04_State-of-Charge (SoC) Equalize Function Test

Description & Procedure	The state-of-charge equalize function test is defined to check if the SoC of batteries are equal and has a value between 30-70%. The batteries can be substituted by voltage supplies via battery-emulation mode. This test must be verified in both HV2LV and LV2HV modes.
Evaluation Criteria	SoCs of each service battery module are equal (±tolerance) in both converter modes.
ID(s): Validated Requirement(s)	• **Req#41:** The DC-DC converter shall be able to equalize the state of charge of each battery module it is supplying.
Project Objectives Under Validation	TO3, TO4 - balanced state of charge (SoC) of the battery modules, - increased lifetime - early detection of failures

Table 25: State of Charge Equalize Function Test

3.2.5 TC_DCDC_05_Stress and Degradation Minimization Test

Description & Procedure	Stress and degradation test case is defined to check state of health variables of the DC-DC after any manipulation. Input and output voltages should be set to accordingly during this test case while the DC-DC is in HV2LV mode. The goal of this test case to see that the manipulated SoH variables start behaving normally after some time while the other variables are not affected greatly.
Evaluation Criteria	The manipulated state of health variables return to their normal value (±Tolerance) and the rest of state of health are not greatly affected.
ID(s): Validated Requirement(s)	• **Req#44:** The operation of the DC-DC converter shall be actively adapted to minimize the stress and degradation of its components and thus maximize its operating life.
Project Objectives Under Validation	TO3 - increased lifetime - fault tolerant operation by checking whether the state variables for online monitoring are appropriate

Table 26: Stress and Degradation Minimization Test

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3.2.6 TC_DCDC_06_Output Voltage Test

Description & Procedure	The output voltage test case is defined to check whether the DC-DC continues providing expected output voltage without any restrictions under different loads. The output voltage test is verified by increasing output voltage and changing nominal power accordingly for different conditions. The input voltage of the DC-DC should be set accordingly to see the behavior of the input voltage while DC-DC is in HV2LV mode.
Evaluation Criteria	The DC-DC converter is able to produce the requested voltage within the safe operating area.
ID(s): Validated Requirement(s)	• **Req#45:** The DC-DC converter shall be able to operate at the nominal output voltage of 24V.
Project Objectives Under Validation	TO2, TO3 - increase in compactness of SCAPE - advanced board integration technology - reduced need of heat dissipation - higher switching frequency - advanced control strategies

Table 27: Output Voltage Test

3.2.7 TC_DCDC_07_Output Current Test

Description & Procedure	The output current test case is defined to check whether the DC-DC continues providing expected output current without any restrictions under different loads. The output current test is verified by requesting nominal output current while the DC-DC is in both HV2LV and LV2HV mode. The test case is fulfilled if input and output voltage values are exchanged.
Evaluation Criteria	The output current of the DC-DC converter is equal to +/- nominal output current ± tolerance.
ID(s): Validated Requirement(s)	• **Req#46:** The DC-DC converter shall be capable of supplying/sinking a continuous current of 55 A at the output.
Project Objectives Under Validation	TO2, TO3 – advanced board integration technology – reduced need of heat dissipation – higher switching frequency – advanced control strategies

Table 28: Output Current Test

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3.2.8 TC_DCDC_08_Bidirectional Power Test

Description & Procedure	The bidirectional power transfer test case is defined to check whether the DC-DC continues its operation without any restrictions. The bidirectional power transfer test is verified by applying different percentages of nominal power while the DC-DC is in both HV2LV and LV2HV mode. The test case is fulfilled if input and output voltage values are exchanged.
Evaluation Criteria	The DC-DC converter is able to transfer the requested power within the safe operating area.
ID(s): Validated Requirement(s)	• **Req#47:** The DC-DC converter shall be able to provide bidirectional power flow between HV battery (input) and Service Battery (output). Two modes are defined: - HV2LV mode: Power is transferred from the traction battery to the service battery - LV2HV mode: Power is transferred from the service battery to the traction battery
Project Objectives Under Validation	TO2, TO3 - increase in compactness of SCAPE - advanced board integration technology - reduced need of heat dissipation - higher switching frequency - advanced control strategies

Table 29: Bidirectional Power Transfer Test

3.2.9 TC_DCDC_09_Continuous Power Test at Whole Ambient Temperature Range

Description & Procedure	The continuous power test case is defined to check if the DC-DC continues its operation under the ambient temperature range of 0 °C - 40 °C. In order to verify this test, the DC-DC should be in HV2LV mode while input and output voltages are set accordingly, and the ambient temperature should be increased from 0 °C to 40 °C with a gradient of 1 °C/min.
Evaluation Criteria	The DC-DC converter is able to operate in the safe operating area on all the tested operating points, and the converter has no performance reduction (no derating) for ambient temperatures between 0 °C and 40 °C.
ID(s): Validated Requirement(s)	• **Req#48:** The DC-DC converter should be able to operate without any derating in temperatures between 0℃ ≤ T_{amb} ≤ 40 ℃.
Project Objectives Under Validation	TO2 - achieving the junction-to heatsink thermal resistance decrease of at least 25% and less than 0.75pu - higher liquid/air cooling operational temperatures - optimum thermal performance

Table 30: Continuous Power Test at Whole Ambient Temperature Range

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3.2.10 TC_DCDC_10_Limp Home Mode Test

Description & Procedure	The limp home mode test case is defined to check the DC-DC is able to transfer the requested power even if the traction battery fails. This test case is verified by setting the transferred power to 100% of its nominal value and setting input and output voltages accordingly while DC-DC is in Limp home mode.
Evaluation Criteria	The output voltage of the DC-DC converter is equal to 400 V ± tolerance.
ID(s): Validated Requirement(s)	• **Req#49:** In Limp Home mode, the DCDC converter shall transfer power from the LV-side to the HV-side to enable (limited) vehicle motion when the traction battery fails.
Project Objectives Under Validation	TO1 - Optimum power transfer that is transferred by the auxiliary DC-DC converter for vehicle motion even though the battery is not useful - functional modularity and scalability

Table 31: Limp Home Mode Test

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4. Conclusion

This document has presented the relevant test cases conceived to validate the system requirements defined for the IIOBC and auxiliary dc-dc converter, especially tailored for the passenger car use case. While creating the test cases, bidirectional traceability with regard to the requirements was ensured, i.e. each functional requirement can be validated with at least one test case. In addition, the project objectives covered by the test cases are indicated.

All tests will be carried out experimentally in WP7 with the developed prototypes. It should be noted that requirements can only be fully validated if the tests are performed in an appropriate environment and positive results are obtained.

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