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DC-DC Converter Validation for Battery Electric Vehicle Using HILS

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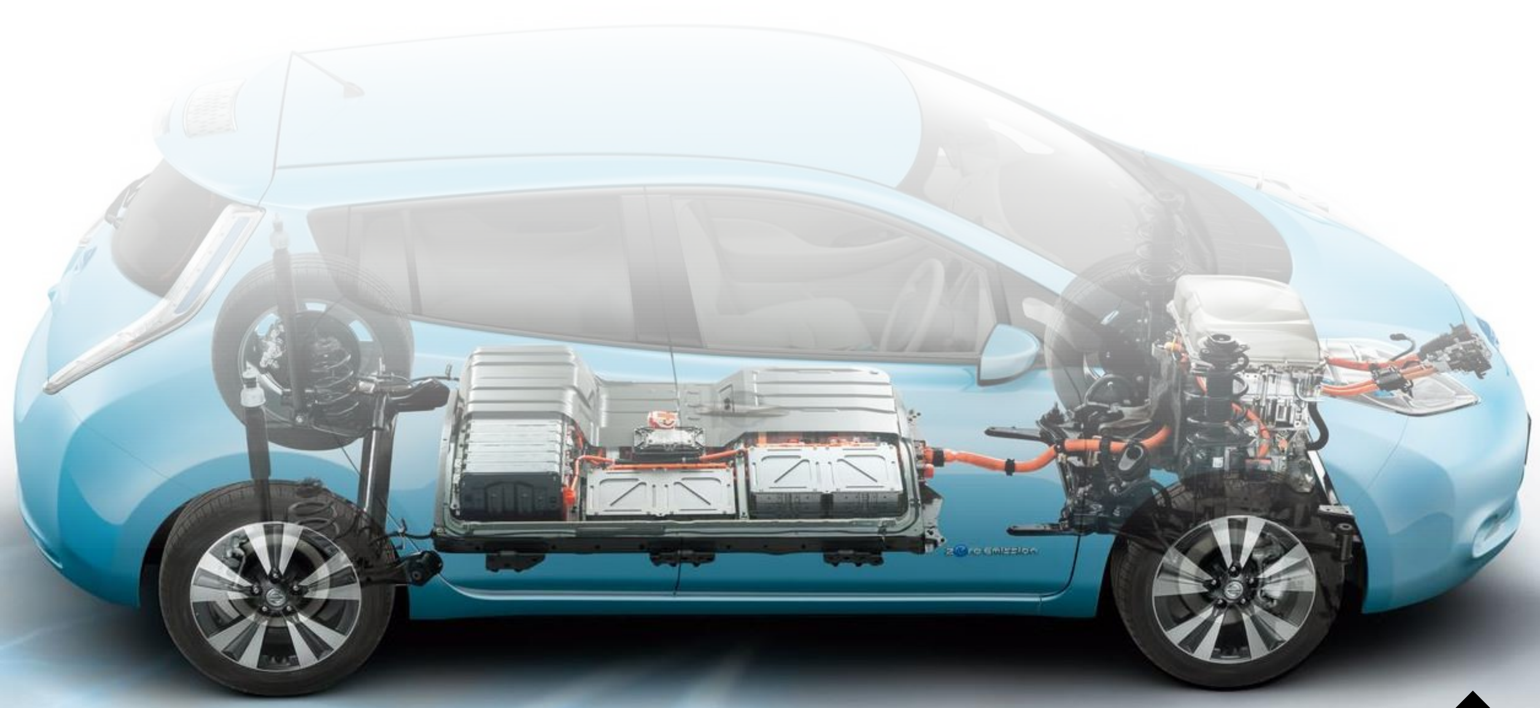

ABSTRACT

In this paper, we look at the viability and industrial relevance of Electric Vehicles (EVs) and discuss the scope of validating DC-DC convertors used in Battery Electric Vehicles (BEVs). We address the various challenges prevalent during validation of DC-DC convertors and provide a practical solution to carry out different validation levels.

The main advantage of this system over the existing solutions is that the test setup's hardware part is scalable according to the device under test. The software part is specifically built to handle automatic test execution. The solution includes the details of signal level and power level validation approach and the test automation framework used to execute test cases.

The proposed test system is developed to avoid high investment costs, minimize complexity, and facilitate easier maintenance. In addition, the emphasis is mostly being placed on finding simple solutions that are easy to integrate.

INTRODUCTION

The batteries of a Battery Electric Vehicle (BEV) typically output several hundred volts of Direct Current (DC). However, the electric components inside the vehicle vary in their voltage requirements, with most running on a much lower voltage. This includes the radio, dashboard readouts, air conditioning, and in-built computers and displays.

A DC-to-DC converter is a category of power converters, which converts a DC source from one voltage level to another. It can be unidirectional, which transfers power only in one direction, or bidirectional, which can transfer power in either direction. Moreover, a DC-DC converter is a critical component in the architecture of a BEV, where it is used to convert power from the high voltage (HV) bus to the 12V Low Voltage (LV) bus to charge the LV battery and power the onboard electric devices.

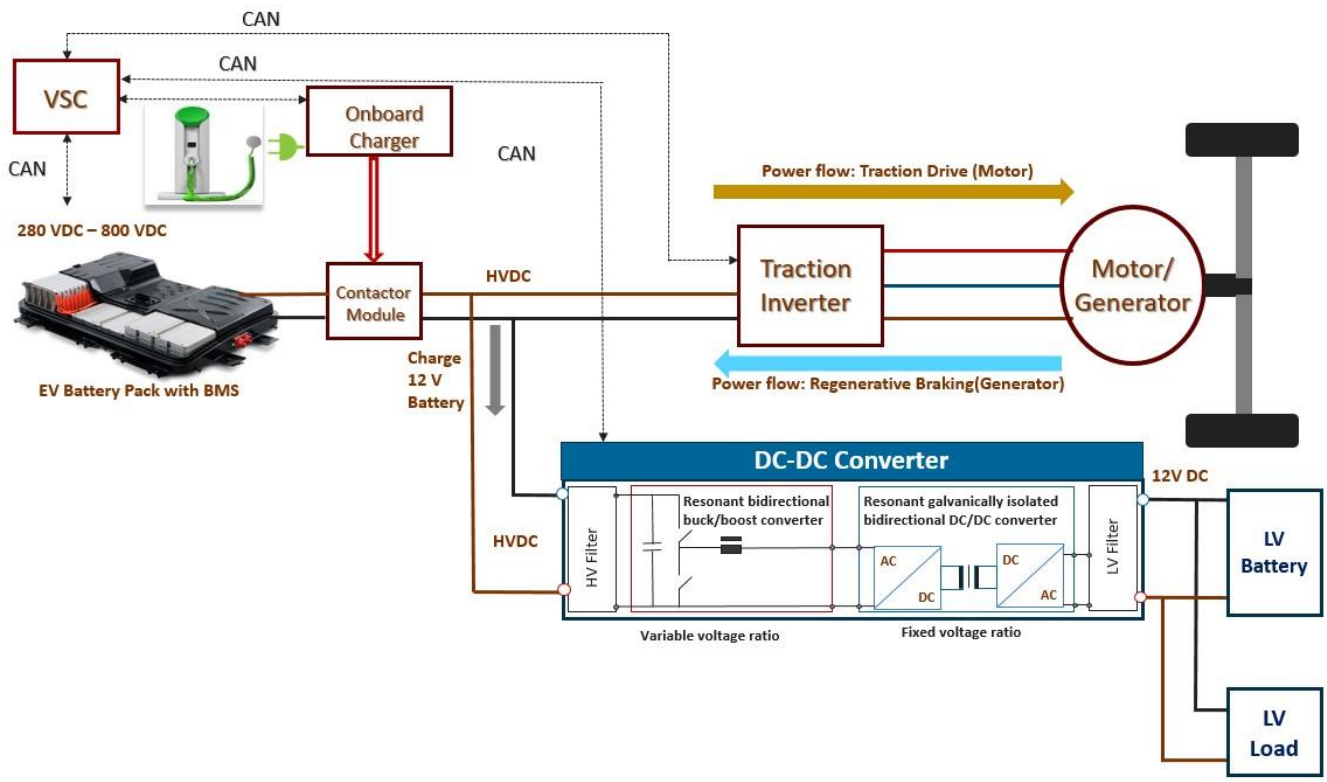

Figure 1: Typical architecture of BEV

Battery electric vehicles have multiple architectural variations, and figure 1 shows a simplified block diagram of one of this architecture. Here, an HV bus, supplied by the large battery, drives the electric powertrain. Most of the components are bidirectional, allowing power to go from the battery to the inverter, which rotates the motor and moves it (traction drive).

When decelerating, the vehicle's momentum turns the motor, which is now acting as a generator, drives power back through the inverter, and charges the battery (regenerative braking). Here, the DC-DC converter is the device that converts higher-voltage DC power from the traction battery pack to the lower-voltage DC power needed to run vehicle accessories and recharge the auxiliary battery.

The requirements for DC-DC converters are heavily dependent on the development of the EV sector. The need to design and test DC-DC converters is at its peak as the market for EVs is now exponentially expanding. According to the market studies available, the global automotive DC-DC converter market is expected to register a CAGR of over 10% during the forecast period, 2020-2025. The graphical representation of this data in the study period of 2019-2025 with the base year of 2019 is shown in Figure 2. [1]

Figure 2: Automotive DC-DC converter market snapshot.

Reference: https://www.mordorintelligence.com/industry-reports/automotive-dc-dc-converter-market

Figure 3 shows the expected growth rate level in the automotive DC-DC converter market for the interval of 2020 – 2025. It is readily visible that the Asia-Pacific region is about to take a giant leap forward in the upcoming years. Theoretically, this growth rate proves the need for advanced test setup for validating and ensuring the desired performance from the competent DC-DC converter models.

The prominent vendors in the DC-DC converter market include Denso Corporation, Toyota Industries Corporation, Robert Bosch GmbH, Continental AG, and Hella GmbH & Co. KGaA and according to the data available in 2019, Denso Corporation is accounted for the largest share [1].

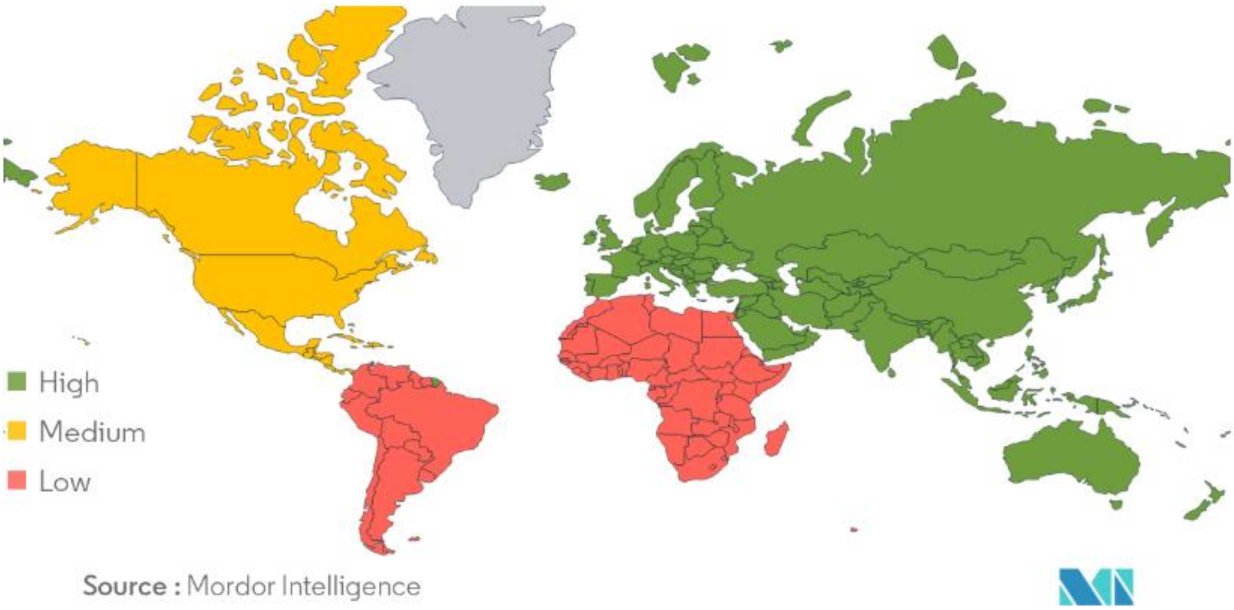

Figure 3: Automotive DC-DC converter market - Growth rate by region (2020-2025)

Reference: https://www.mordorintelligence.com/industry-reports/automotive-dc-dc-converter-market

Even though the trends point towards a growth in the DC-DC converter market, some facts need to be analyzed before developing a DC-DC converter test system. Some key findings particularly valid for DC-DC converter for EV are given below.

KEY FINDINGS ON DC-DC CONVERTER MARKET

- At present, 150+ BEVs are under development globally, which will be launched by 2021-2022, and OEMs are working out long-term supplier contracts for the DC-DC converter. This implies that the DC-DC converter is here to stay and needs a validation roadmap set up.
- In the passenger vehicle segment, Tesla vehicles have the most powerful DC-DC converter rating of 2.5kW. The compact Chinese BEVs have a low power converter, but their share has been gradually shrinking as of Q3-2019. This evidence supports that the demand and supply for high power DC-DC converters will increase in the upcoming market. In turn, this demands the test setup, which can validate high power automotive ECUs in safe lab conditions.
- In China, which accounts for 50% of global EV sales, the automotive DC-DC converter market is heavily skewed towards low powered compacts. Vehicles with <25kWh batteries and <2kW DC-DC converters comprised a significant share of EV sales in China in 2018. However, as of Q3-2019, the market structure has significantly changed. The need for low power and low-cost EV solutions may not be capable of providing satisfactory performance to the customer in terms of charging time and how far the EV can run on a full charge. In the era of fast charging, where the charging time of EV batteries is significantly reduced, customers will prefer high power battery and converters, which can be charged in a small interval of time and could run for a longer duration in a single charge.

DC-DC converter validation will continue to be a challenge as the DC-DC converters' functionality and other automotive ECUs evolves with the market requirements. The DC-DC converter is a mandatory part of the electric drive train to ensure high-efficiency energy conversion. The increase in demand for EVs, in turn, is expected to increase the demand for DC-DC converters.

While the demand for DC-DC converter in the market increases, the need for proper validation methodology gains strength. Even though real-world validation is cumbersome and nearly infeasible, a practical solution close to this should be implemented to ensure the device's proper validation. For delivering a quality solution, numerous challenges existing in the DC-DC converter's validation have to be identified and addressed.

CHALLENGES IN TESTING DC-DC CONVERTER

While designing a test system for DC-DC converter validation for BEV, several complexities exist. Some of them are listed below:

- Testing under actual operating conditions (e.g., potential surge current, frequency, voltage, etc.) is nearly impossible for high power devices. [3]
  - Replicating battery dynamics to match real-life scenarios and mimicking the actual loads in EV for testing various test conditions inside the lab is challenging.
  - The output of associated systems like Battery State of Charge (SOC), State of Health (SOH), and motor speed cannot be controlled and manipulated inside the EV to test the converter.
  - If the testing is carried out in the EV itself, it should be confined to the operating range of the components in it. It will not be feasible to force operate the whole DC-DC converter system as per the test requirements. It may affect the related subsystems and, in turn, the entire Electric Vehicle adversely. Therefore, tests like overcurrent, overvoltage, and short circuit simulation may become out of scope. [3]
- The challenges in developing a lab-based test set up for DC-DC converter validation include:
  - HEVs and EVs have multiple architectural configurations and different voltage operating ranges. Therefore, designing a generalized test system compatible with DC-DC converters used in both HEV and EV requires extra effort. [4]
  - As more and more DC-DC converters become bidirectional, testing both directions of power flow requires test equipment capable of sourcing and sinking power to the DC-DC converter. This is traditionally accomplished by

connecting a power supply and an electronic load in parallel. However, external circuitry (i.e., a diode to stop the current flow into the power supply) and cumbersome "two-instrument" programming typically do not allow smooth signal transitions between sourcing and sinking power, reflecting an inaccurate simulation of the operating conditions. [4][5]

- As power circuit components operate at high currents/voltages and high power densities, a rigorous effort is required to protect the DC-DC converter from faults. [3][4]
- Besides, a unique pre-charge circuit should be designed for DC-DC converters that require external pre-charge for protecting the circuit from sudden voltage build-up.
- Environmental conditions like extreme temperatures need to be simulated for testing automotive ECU as different countries have a wide variation in temperature.
- Simulation of different air and coolant water temperature is required to check the derating properties of the ECU.

OUR SOLUTION

A practical solution to address these challenges is to test and validate the DC-DC converter system in a simulated lab environment. HILS (Hardware-In-Loop Simulation) is the platform where the subsystem dynamics are tested, and the onboard software is validated in a real-time environment before the vehicle testing.

HILS testing helps to validate embedded software on automotive ECUs using simulation and modeling techniques. This method shortens test time and increases test coverage, especially for test cases that are hard to replicate reliably in physical lab/track/field testing. HILS testing can be used throughout the development of real-time embedded controllers to reduce development time and improve testing effectiveness.

TEST SYSTEM ARCHITECTURE

Tata Elxsi's e-Mobility framework and test setup for power level validation are shown in figure 4. The test system consists of a 2-quadrant power supply, which can either source or sink current as per the requirement. The programmability of this power supply is utilized in such a way that it can mimic the performance of the battery to a larger extend.

The output of the DC-DC converter is connected to a programmable DC electronic load. The EV's actual loads are replicated using this load by configuring it to different modes like CV, CC, CP, CZ, CR, etc. or using User Defined Waveforms (UDW).

Both power supply and load are controlled using HILS (National Instruments RT and controller PXIe 8880, in this case) so that the desired performance is obtained. A 12V battery can be included in the LV side to check the boost functionalities, and the 2-quadrant power supply will act as the current sink during this.

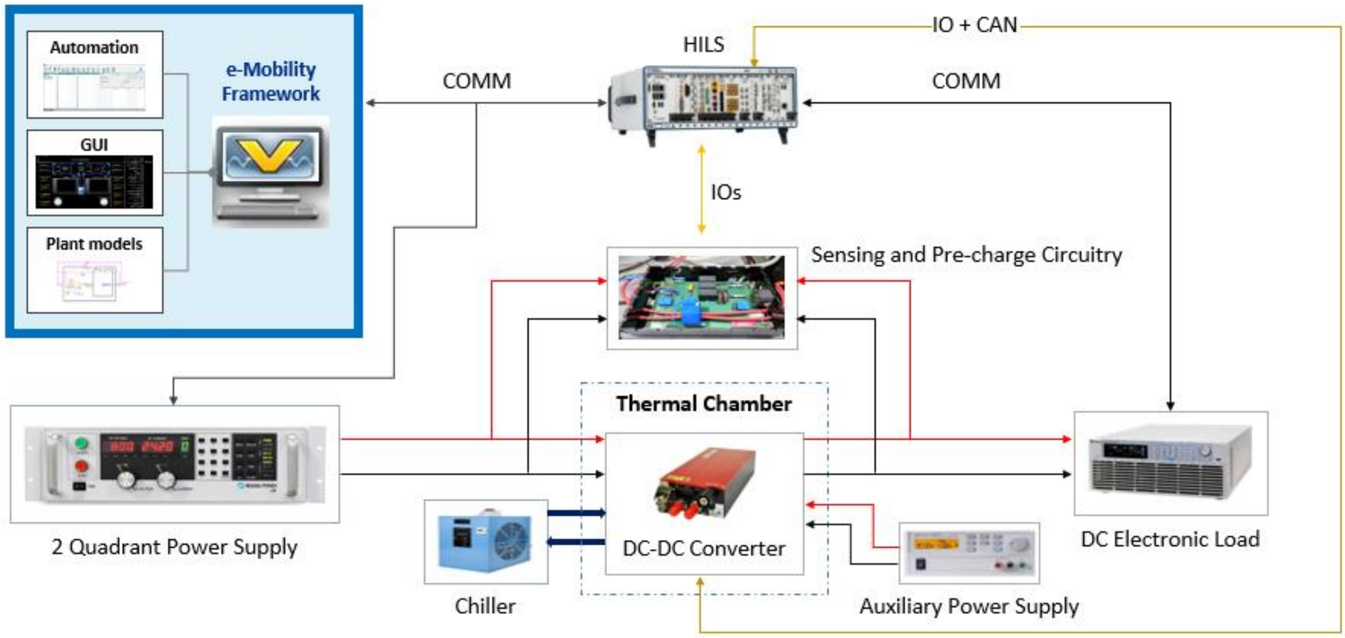

Figure 4: Tata Elxsi's e-Mobility framework for power level validation of the DC-DC converter

The test system also consists of a sensing and pre-charge circuitry created explicitly for the device under test (DUT). Both HV and LV side cables pass through this circuit with proper isolation, and the voltage and current can be measured accurately. This setup includes the relays and fuses so that the operation after and before pre-charge is adequately controlled.

All the input signals for operating relays and readings of the voltage and current sensors are controlled and monitored by NI RT HILS. The V, I values can be processed and used for further calculations, plotting the graphs, analyzing the response, etc., as per the test case requirement.

For ensuring normal operating conditions, a liquid cooling system is also incorporated in the test set up. This helps in controlling the temperature and flow rate based on the test requirements. A thermal chamber is used to ensure the validation of the DUT in extreme temperatures. For a power level device like a DC-DC converter, one important property is the derating capability. Both the temperature chamber and the controllable liquid cooling system help validate the device's thermal derating characteristic under test.

TYPES OF VALIDATION

Scalable and modular test solution from Tata Elxsi can be used to validate a wide range of DCDC converters of all types and ratings. It assures good value for money business models like validation as a service (VaaS), where customers neither need to invest heavily in EV test equipment nor wait for long lead time for the components it has. Instead, they can use Tata Elxsi's readymade solution. And the solution is not just a collection of EV test equipment, but it comes with a bundle of software counterparts like test cases, plant models, real-time test automation framework, drive cycle data, and GUI. Our DC-DC Converter HIL solution makes it viable to validate the system at two different levels:

- **Signal Level:** In this level, the controller board (which contains the process control) is tested, and the other parts (power electronics, machine, and mechanical load) are simulated in real-time. This method is called "signal level HIL simulation" because only signals are used at the interface between the system under test and the simulation environment.
- **Power Level:** Here, the controller board and the power electronics converter are tested, and the other parts are simulated in real-time. This method is called "power level HIL simulation" because the interface between the system under test and the simulation environment requires signal and power variables.

SIGNAL LEVEL VALIDATION

The HIL systems designed here has included several fully integrated software packages that allow controller software to be validated using an automated method. Even though the DC-DC converter is a power level device, power level components such as battery pack, loads, etc., are not used in this setup. The signal level test system can be represented as in figure 5.

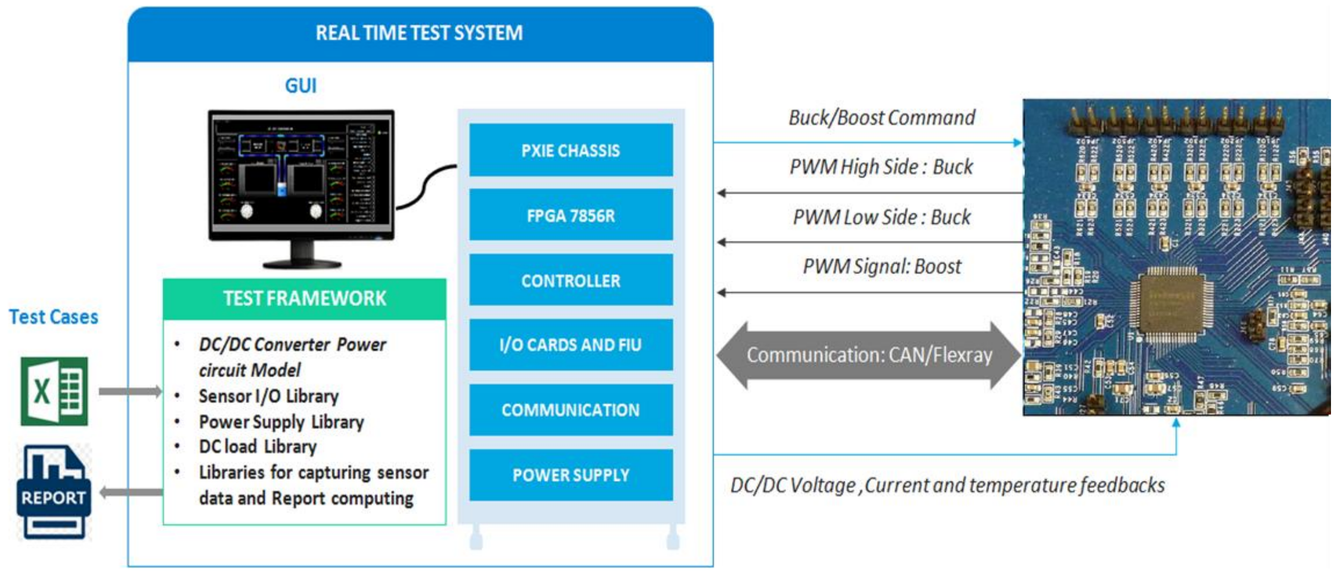

Figure 5: Signal level validation architecture

Image reference – PCB: https://www.renesas.com/eu/en/products/automotive/power-management/half-full-bridge-three-phase-drivers/device/ISL78424.html

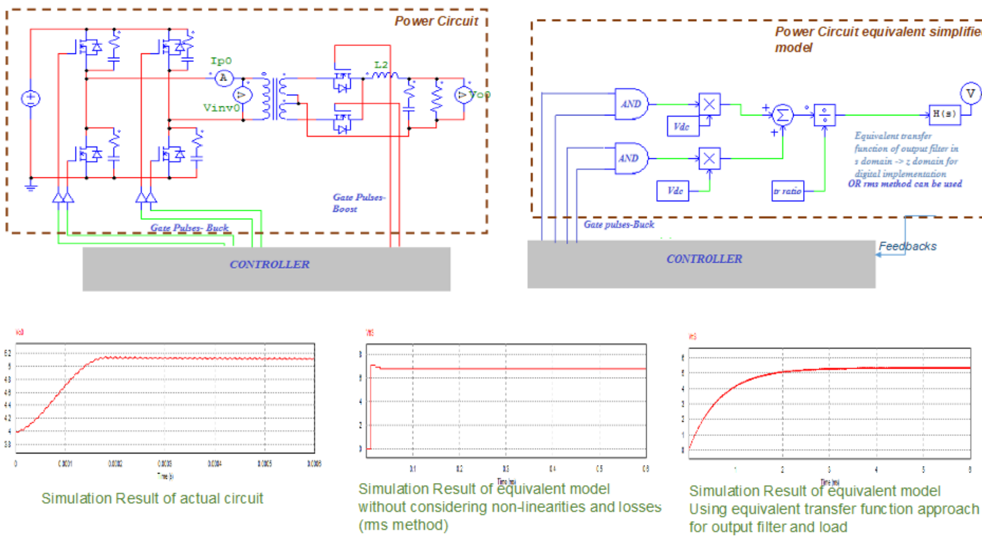

Figure 6: Simulation circuits and results of signal level models

In the signal level solution, the 100-150 kHz PWM signal is captured by the NI FPGA card and is fed to the buck/boost power conversion model created using LabVIEW. The higher-level control algorithm that depends on the drive cycle and other external parameters can also be validated.

The test system's functionality is based on the integrated platform of LabVIEW simulation software and the real-time computing system using NI hardware.

Figure 6 shows a sample power circuit and the simulation results created in PSIM. The test system's software model, which is implemented in LabVIEW and PSIM, includes a mathematical model of the vehicle dynamics together with descriptions of the actuators, the driver, and the environment.

POWER LEVEL VALIDATION

Power level testing of the DC-DC converter includes the verification of all modes of the BEV DC-DC converter. This consists of the pre-charge scenario, buck operation, boost operation, etc. In the power level test solution, all the key performance indicators of the DC-DC converter are validated with NI RT HILS system's aid, the custom board of sensors, high voltage power supply/battery, and DC electronic load.

NI I/O cards' scalability and the power of LabVIEW made the system design much flexible. A simplified representation of the system-testing setup is shown in figure 7.

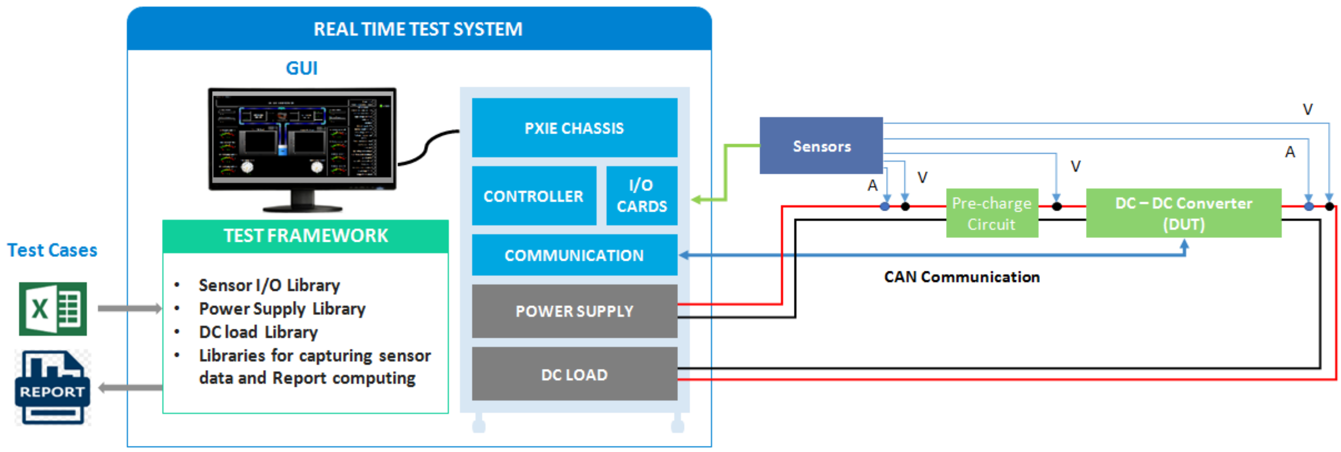

Figure 7: Power level validation architecture

Before connecting a voltage supply to the DC-DC converter (e.g., HV battery), the voltage must be pre-charged via a suitable pre-charging device. When DC input power is applied to a capacitive load, the voltage input's step response will cause the input capacitor to charge.

The capacitor charging starts with inrush current and ends with an exponential decay down to the steady-state condition. When the magnitude of the inrush peak is enormous compared to the components' maximum rating, then component stress is to be expected. The pre-charge set up avoids the formation of this stress.

TEST AUTOMATION FRAMEWORK AND TEST CASE EXECUTION

A test automation framework developed using LabVIEW is used to run the HIL real-time tests. Test cases are created in an excel sheet using a predefined template. The framework will read test cases developed in an excel sheet and convert it into the valuable NI Stimulus profile format once the build button is pressed.

Once the run button is pressed, the Real-Time Stimulus profile will be run inside the Veristand engine of RT PXI, and the data is stored in a TDMS file. Using Post-processing VIs, TDMS files will be analyzed, and a report can be generated in a PDF format with a timestamp and summary report in an Excel format. Figure 8 shows the software architecture used in the test setup. The flow of operation that executes inside the test PC and the RT PXI system is shown here.

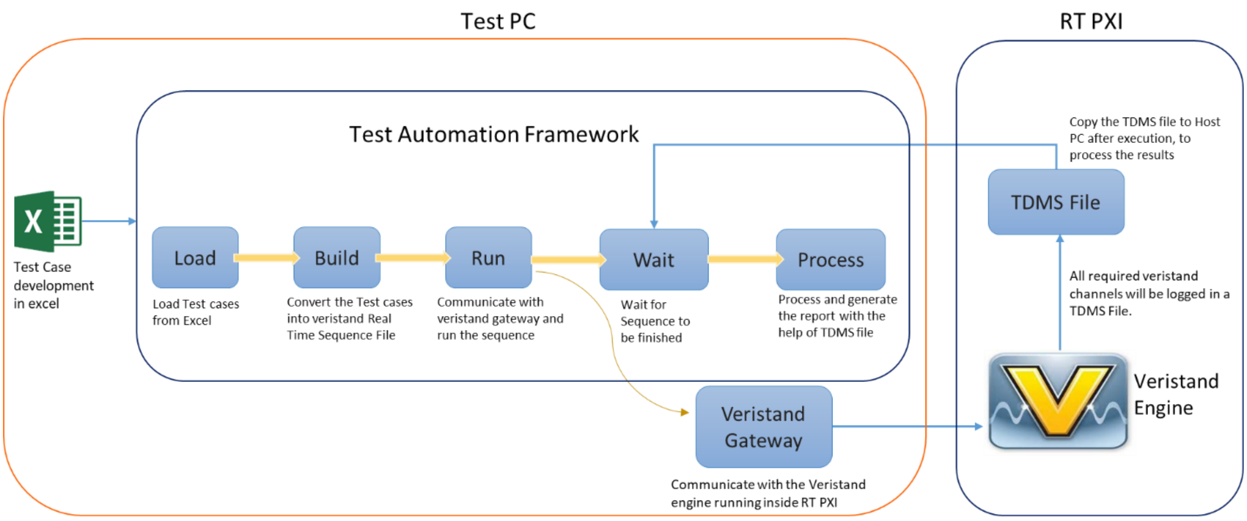

Figure 8: Software architecture

The test case created for calculating the efficiency of the DC-DC converter is shown in figure 9. The voltage and current of both LV and HV side are set to the predefined value, and the efficiency is determined as the ratio of output power to the input power. The LabVIEW VI carries out the calculation part.

TestCase ID	Requirement IDs	Test case scope	Step Number	Test Condition	Timestamp	Input Aliases	Input Value	Input Condition	Output Aliases	Output Condition	Test Case Generation Method	ODC trigger	Remarks
DC_DC_EFFICIENCY_001	DCDC_Req_001	To check the efficiency of DC-DC converter in buck mode	1	PRECONDITION	1000	PS_CURRENT_LIMIT	2.50				Requirement Analysis	Test Coverage	NA
			2		1000	PS_VOLTAGE_SET	0.00						
			3		1000	PS_OUTPUT_ENABLE	1.00						
			4		1000	DC_CAN_DCDC_HVCUR_UPLIM_BUCK	6.5						
			5		1000	DC_CAN_DCDC_LVCUR_UPLIM_BUCK	52						
			6		1000	DC_CAN_DCDC_LVVOL_COMM	12.00						
			7		1000	DC_CAN_DCDC_HVVOL_COMM	250.00						
			8		1000	DC_CAN_DCDC_BOOST	0.00						
			9		2000	DC_CAN_DCDC_EN_DEBUG_ID	1						
			10		2500	DC_IO_HV_PLUS_RELAY	1						
			11		2500	DC_IO_HV_MINUS_RELAY	1						
			12		3000	DC_CAN_DCDC_RUNCOMM	0		DC_CAN_DCDC_INT_STATE	11,0,0,100			
			13	ACTION	5000	RAMP PS_VOLTAGE_SET	0,260,1,1,50						
			14		19000	DC_CAN_DCDC_RUNCOMM	1		DC_IO_LV_OUTPUT_VOLTAGE	12,0.5,0.5,800			
			15		20000	LOAD_LOAD_MODE_SET	2						
			16		21000	LOAD_LOAD_ENABLE	1						
			17		22000	RAMP LOAD_SET_LOAD_L1	0,40,1,1,500						
			18	CLEANUP	47000	DC_CAN_DCDC_RUNCOMM	0						
			19		47000	PS_VOLTAGE_SET	0						
			20		47000	LOAD_LOAD_ENABLE	0						
			21		48000	LOAD_SET_LOAD_L1	0						
			22		48000	PS_OUTPUT_ENABLE	0						
			23		48000	DC_IO_HV_PLUS_RELAY	0						
			24		48000	DC_IO_HV_MINUS_RELAY	0						
			25		48000	DC_CAN_DCDC_EN_DEBUG	0						
			26	PROCESS		CALCULATE	(((DC_IO_LV_OUTPUT_VOLTAGE*DC_IO_LV_SIDE_CURRENT)/(DC_IO_INPUT_HIGH_VOLTAGE_1*PS_CURRENT_SENSE))*100)	43500,46500,100,86-91					

Figure 9: Sample test case – Efficiency calculation

The test report corresponding to each test case will be generated in parallel with the test execution, and it is available once the test case is executed. This report consists of detailed information about the performance of the device under test during the test. The tester gets an opportunity to monitor every value so that the testing quality can be significantly improved.

PLANT MODELS

Plant models are used in the test system to control different systems and simulate real-world dynamics of devices. As the test system is developed in the NI platform, LabVIEW is used to create plant models/VI (Virtual Instrument).

LabVIEW models are also used for calculating the critical performance indicators such as efficiency, power loss, regulation, etc., and the value is calculated in real-time. These values are used in corresponding test cases where it is required.

Pre-charge model: This is a LabVIEW model created to control the DC-DC converter's HV side relays for enabling the pre-charging of the internal capacitor. Refer to the VI shown in figure 10. This VI is specifically designed to carry out the pre-charge operation. In this model, initially, the pre-charge relay and the negative main relay (HV-) is closed so that the current flows through the pre-charge resistor.

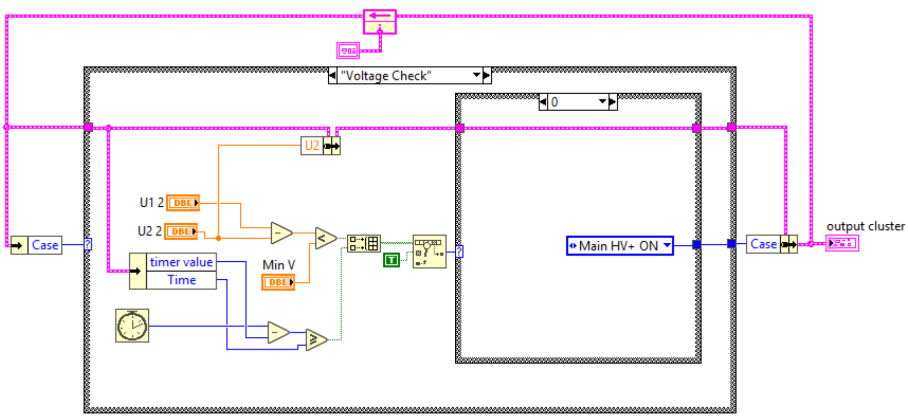

Figure 10: VI created for pre-charge operation

When the voltage difference between the power supply terminals and the DC-DC Converter HV terminals is less than 10V (|U1 - U2| < 10V), the positive main relay (HV+) is closed, and the pre-charge relay can be opened. Here, the VI controls the operation of the relays.

In addition, VI is designed in such a way that if the condition |U1 - U2| < 10V is not fulfilled after a specific maximum time (expected full pre-charge time can be provided as a user input variable); all the relays must be able to open simultaneously.

DC Load Custom device: The custom devices are extending the functionality of NI Veristand. A custom device can run either inline or in parallel with the Veristand engine's primary control loop. Figure 11 shows the custom device created for the programmable power supply. This custom device performs the mode changing operation, set parameters limit, enable and disable the load, and generates user-defined waveform in real-time.

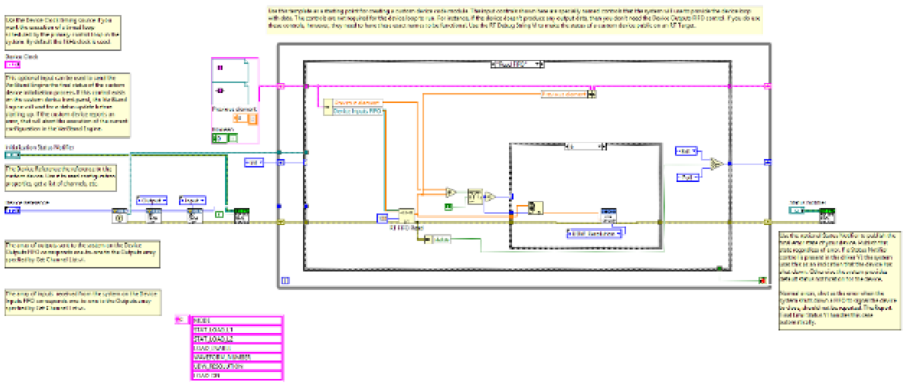

Figure 11: Custom device - User Interface

Figure 12 shows the Tata Elxsi's e-Mobility GUI created for the DC-DC Converter validation. The performance and response of the system are visualized here. This includes the details of input power supply voltage, temperature, HV side, and LV side voltage and current, the status of errors, and other DTCs.

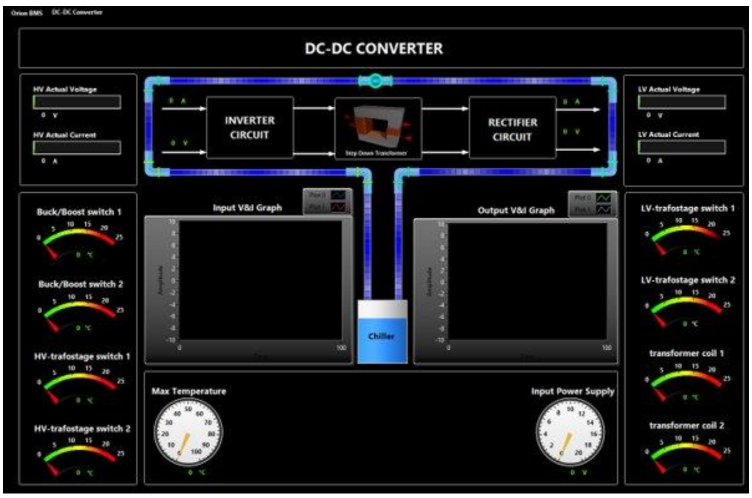

Figure 12: Tata Elxsi's e-Mobility GUI for DC-DC converter validation

This interface also has provisions to visualize the graphical representation of V, I of both input and output in real-time so that the response of output side with respect to the changes in input side. The performance of the system according to each test case can be easily assessed using this..

HIGHLIGHTS

- **Scalable:** The test system is designed so that the setup is scalable for DC-DC converters from multiple BEV vendors.
- **Multi-mode operations:** Even though the direction of power conversion reverses, the same setup can be used for testing the buck mode and boost mode operation. The use of a bidirectional power supply that can act as both load and power supply based on the direction of current flow on the one side with the DC electronic load and battery on the other side makes this possible.
- **Customizable:** The setup can be customized for validating DC-DC converter used in Mild Hybrid Electric Vehicles (MHEV).
- **Battery behavior simulation:** The DC power supply's programmability is utilized to the maximum extent for simulating different battery characteristics, which is impossible to be executed inside vehicle level testing. The waveforms can be simulated to mimic real-life battery behavior.
- **Real-life load characterization:** Simulation of various loading effects in different modes (CC, CV, CR, CZ, CP, etc.) and combining these, including the user-defined waveforms, are used for creating exact loading characteristics.
- **Test automation**: Usage of test automation framework makes test case implementation easy and efficient compared to manual execution. The test report will also be generated on its own, and details of the tests will be available as a document right after the execution.
- **Safety:** Automation ensures the safety of the tester, as manual intervention is avoided during test execution, so the risks that can be occurred while dealing with high power devices are reduced. Test execution requires a single engineer to operate the test PC alone.
- **Fault insertion:** Tests that are impossible to conduct inside a vehicle (like short circuit tests) can be performed in real-time using this test system. The test system is designed in such a way to withstand the current-voltage fluctuations due to faults so that the faults and failure situations can also be checked.

- **Test coverage:** For system-level testing, coverage is improved by a greater extend as HILS testing is implemented here. HILS supports real-time testing in a simulated environment, and the behavior of the DUT can be captured along with this.
- **Environmental testing:** Tests that are carried out in normal operating conditions will not be sufficient to ensure the DC-DC converter's proper operation. So, the temperature chamber's availability adds credibility to the test system by ensuring test execution in extreme temperature conditions.
- **Derating characteristics:** The temperature chamber and cooling system's presence helps validate the thermal derating characteristics of the DC-DC converter.

CONCLUSION

This paper brings to light the current trend in the automotive industry towards EVs and discusses the challenges in validating DC-DC convertors used in BEVs. As a solution to the challenges, this paper proposes a novel solution.

The DC-DC Converter HILS solution built by Tata Elxsi makes it viable to validate the system at signal level and power level. The DC-DC converter provided by the customer can be validated using the advanced equipment and facilities arranged in the Tata Elxsi's EV validation lab with the least effort. The system architecture can be customized for battery electric vehicles and hybrid vehicles with the least effort.

The system proposed in this paper is a customizable solution, which includes a programmable bidirectional DC power supply, programmable DC electronic load, sensing circuit, LV battery, cooling system, thermal chamber, and a dedicated HILS system for controlling the operations of each item, capturing and processing the necessary data. Also, a HILS based solution for validation has an advantage of real-time test execution and data logging. The test system is designed such that the tests in both buck and boost mode can be conducted. The system has taken care of the cooling requirement for the liquid-cooled model DC-DC converters. The thermal chamber availability makes it possible to validate the derating behavior of the DC-DC converter in different temperature conditions.

The test cases are executed using a test automation framework, reducing the efforts and test execution time vastly. Here, man-machine interference during test execution is limited to the minimum, and the test execution engineer can run the whole test using the test PC only. This test setup addresses almost all the challenges identified for validating a DC-DC converter.

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