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Model-Based Development and Simulation of Operating Conditions in a Battery Electric Vehicle Using Simulink

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ABSTRACT

The objective of this thesis is the development of a model-based strategy for analyzing and simulating the operating conditions of a Battery Electric Vehicle (BEV), implemented in the Matlab/Simulink environment. Following a brief overview of BEVs, their societal importance and the challenges they face (e.g., energy efficiency, control strategies, battery management), the focus shifts to the role of Model-Based Design (MBD) as a systematic approach for simulation, testing and validation.

The project centers on the creation of a simulation model compliant with automotive standards, based on a Modular Technical Model (MTM) architecture. The system is organized into five main modules: “Environment and External Inputs”, “Plant”, “Control”, “HMI” and “Driver”. The physical model (Plant) includes key subsystems such as the battery, electric motor, transmission and vehicle body. Control logic is implemented using Simulink controllers and Stateflow state machines to manage four core operational phases: Start-up, Drive, Charge and Stop.

A custom interactive dashboard (HMI) was also developed to monitor vehicle behavior in real time during simulation. Additionally, an extensive regulatory and safety analysis was carried out to define system requirements and perform risk assessment through the Hazard Analysis and Risk Assessment (HARA) methodology. These requirements were then translated into test objectives to verify the system under various operating conditions.

Once the model was completed, it was validated through simulation scenarios designed to ensure logical and functional consistency. The project concludes with the validation of the system in a Model-in-the-Loop (MiL) environment, laying the groundwork for future expansion to Hardware-in-the-Loop (HiL) implementation.

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1 INTRODUCTION

1.1 Introduction to Battery Electric Vehicles

Battery Electric Vehicles (BEVs) operate by converting electrical energy stored in onboard batteries into mechanical energy through an electric motor, eliminating the need for combustion engines. As they do not rely on fuel combustion, BEVs produce no tailpipe emissions and are classified as zero-emission vehicles under current environmental standards. Each vehicle is equipped with a rechargeable battery that supplies energy and can be charged through private or public charging infrastructure.

The widespread adoption of BEVs plays a crucial role in reducing air pollution and mitigating climate change by lowering greenhouse gas emissions. Additionally, the shift toward electric mobility reduces dependence on fossil fuels, promoting energy security and facilitating the transition to renewable energy sources. BEVs also contribute to technological advancement, particularly in the development of batteries with greater capacity, efficiency and durability, thereby improving overall vehicle performance [1].

However, several challenges must be addressed to support the broader implementation of BEVs. One of the main limitations is their driving range, which remains shorter than that of conventional vehicles. Although battery technology is improving, range is still influenced by external temperature, terrain and driving behavior. Furthermore, charging times are significantly longer compared to the refueling process of internal combustion engine vehicles, despite the growing availability of fast-charging solutions. The current charging network, while expanding, is still not uniformly distributed, particularly in less urbanized areas.

Lithium-ion batteries, the most commonly used in BEVs due to their high energy density, are still less energy-dense than fossil fuels and degrade over time with use. Thermal conditions also affect battery performance: cold temperatures reduce available capacity, while high temperatures accelerate degradation. As a result, proper thermal management is essential for maintaining battery efficiency and ensuring vehicle safety.

The Battery Management System (BMS) is a key component that monitors and controls battery parameters, helping to preserve longevity, prevent malfunction and ensure optimal operation. Over time, battery capacity diminishes due to chemical aging and charge/discharge cycles, making effective battery management critical.

Finally, while BEVs offer clear environmental benefits during use, battery production and disposal pose ecological concerns.

The extraction of raw materials, such as lithium, cobalt and nickel, can have adverse environmental and social impacts. Moreover, recycling technologies for batteries are still developing and disposal remains a complex and costly issue. For these reasons, it is essential to carefully manage the operating conditions of BEVs to maximize battery lifespan and system efficiency, improve vehicle performance and support the broader adoption of electric mobility [2].

Table 1: Advantages and disadvantages of Battery Electric Vehicles

Advantages	Disadvantages
Absence of tailpipe emissions, contributing to urban air quality	Limited range
	Long charging times
Reduced reliance on petroleum-based energy sources	Insufficient charging infrastructure
	Weather conditions
Encouragement of advancements in vehicle and battery technology	Battery thermal management
	Battery degradation
Higher overall energy conversion efficiency compared to internal combustion engines	Environmental impact of battery production
	Battery recycling and disposal

1.2 The Use of Model-Based Design for the Simulation and Analysis of BEVs

Model-Based Design (MBD) employs mathematical abstractions to simulate and analyze the behavior of complex systems under various conditions, streamlining both development and testing [3]. In the context of BEVs, it enables the simulation of different operating phases, allowing analysis of system performance under varying factors such as temperature, terrain and driving conditions, and facilitates the testing of multiple scenarios, significantly reducing development time and cost.

This methodology enhances energy efficiency, battery management and other key parameters critical to vehicle operation. It enables the continuous optimization of BEV design during simulation, minimizing the cost of design errors and improving overall system performance.

By simulating the model in an integrated environment using Simulink and the Model-In-the-Loop (MiL) technique, the system's behavior can be validated against functional requirements before proceeding to physical prototyping.

Therefore, Model-Based Design makes it possible to model, simulate and optimize battery electric vehicles within a virtual environment, avoiding the need for physical prototypes and increasing the efficiency of the development process.

1.3 V- Model

In this thesis project, the V-Cycle model was adopted as the foundational framework for system development, allowing a structured and traceable workflow from requirements definition to final validation. This model is particularly suited to the development of complex systems such as Battery Electric Vehicles, as it clearly links each design phase to its corresponding verification and validation phase.
The V-Cycle model outlines a structured, phased approach to system and software development, visualized in a V-shaped diagram that maps the relationship between system design stages and corresponding validation steps. The left side of the "V" represents the design and development phases, while the right side corresponds to verification and validation [4].
The advantage of using this model lies in its ability to provide a clear and systematic structure for managing the system lifecycle, with particular focus on traceability and requirement compliance. Each development stage is directly linked to a specific test phase to ensure that the system behaves correctly in every aspect.

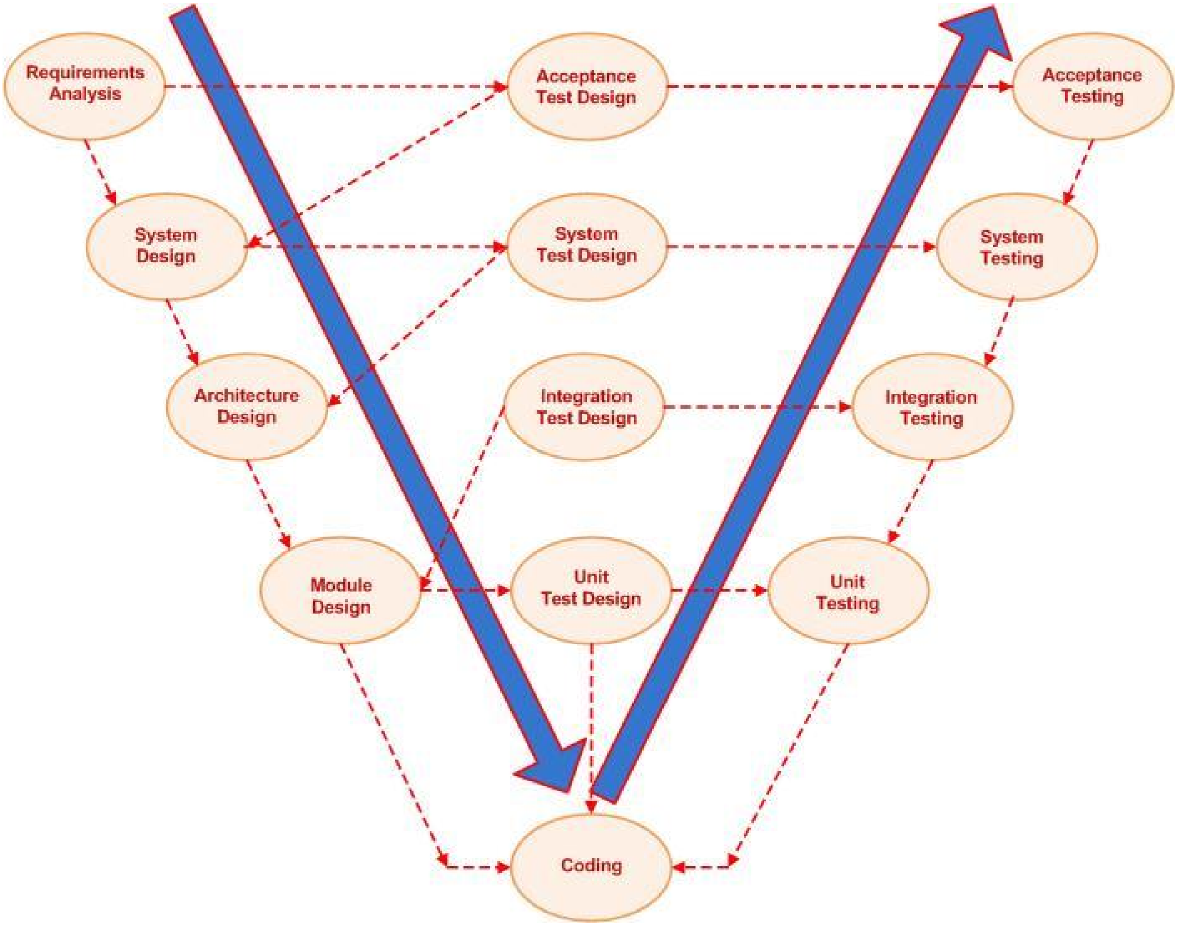

Figure 1: V-Model [4]

The main phases of the V-Cycle are:

1. Requirements Definition: the process begins with identifying and defining the system requirements (what the system is intended to do and which characteristics it must exhibit). This phase is essential for setting the design targets and the functional specifications of the model;

2. System Design and Architecture: in this phase, the system's overall architecture is outlined and its main components are defined;

3. Implementation and Development: the model is developed by implementing the different modules that constitute the system;

4. Verification and Testing: this phase marks the transition to the right side of the cycle, where each module is tested to ensure compliance with the corresponding requirements;

5. Validation: finally, the system is validated as a whole to ensure that it meets the initial requirements and performs as intended under realistic conditions, in accordance with applicable standards and safety guidelines.

2 REQUIREMENTS DEFINITION

2.1 Regulatory Framework

In order to ensure safety, reliability and compliance with automotive industry standards, a preliminary study of the most relevant regulations was conducted. This regulatory framework guided the definition of both functional and non-functional system requirements for the development of a model-based simulation environment for a Battery Electric Vehicle (BEV). Among the most significant standards is ISO 26262 [5], which governs the functional safety of electrical and electronic systems in road vehicles. It introduces the concept of Automotive Safety Integrity Level (ASIL), useful for classifying and mitigating risks, and provides recommendations for all phases of the system lifecycle, from design to validation.
Regarding battery behavior and performance, two key standards were considered: IEC 62660 [6], focused on testing lithium-ion cells and thermal behavior, and UN ECE R100 [7], which defines safety requirements for battery systems in electric vehicles. These standards guided the modeling of battery performance, degradation phenomena and thermal protection mechanisms. Additionally, the definition, classification and management of requirements were conducted following the guidelines of the ISO/IEC/IEEE 29148 standard [8], which describes recommended principles and practices for requirements engineering in complex systems. This standard provided a methodological reference for structuring requirements and ensuring traceability within the V-Cycle development process.
The following sections describe the process of translating these guidelines into concrete system requirements that were implemented, tested and validated within the Matlab/Simulink environment.

2.2 Methodology for Defining Functional Requirements

The definition of the functional requirements for the BEV model was based on a control logic design approach using a dynamic state machine, in line with the Model-Based Design methodology and the adopted requirements engineering standards (ISO/IEC/IEEE 29148 [8]). The system was decomposed into four main states: Start-up, Drive, Charge and Stop. They represent the fundamental operational phases of the electric vehicle. For each state, essential functional requirements were specified to describe the expected behavior of the simulated model, as well as the conditions governing the transitions between states.

For example, for safety and operational consistency reasons, some direct transitions between states are not allowed, such as the transition from ‘Drive’ to ‘Charge’, which requires an intermediate ‘Stop’ phase.

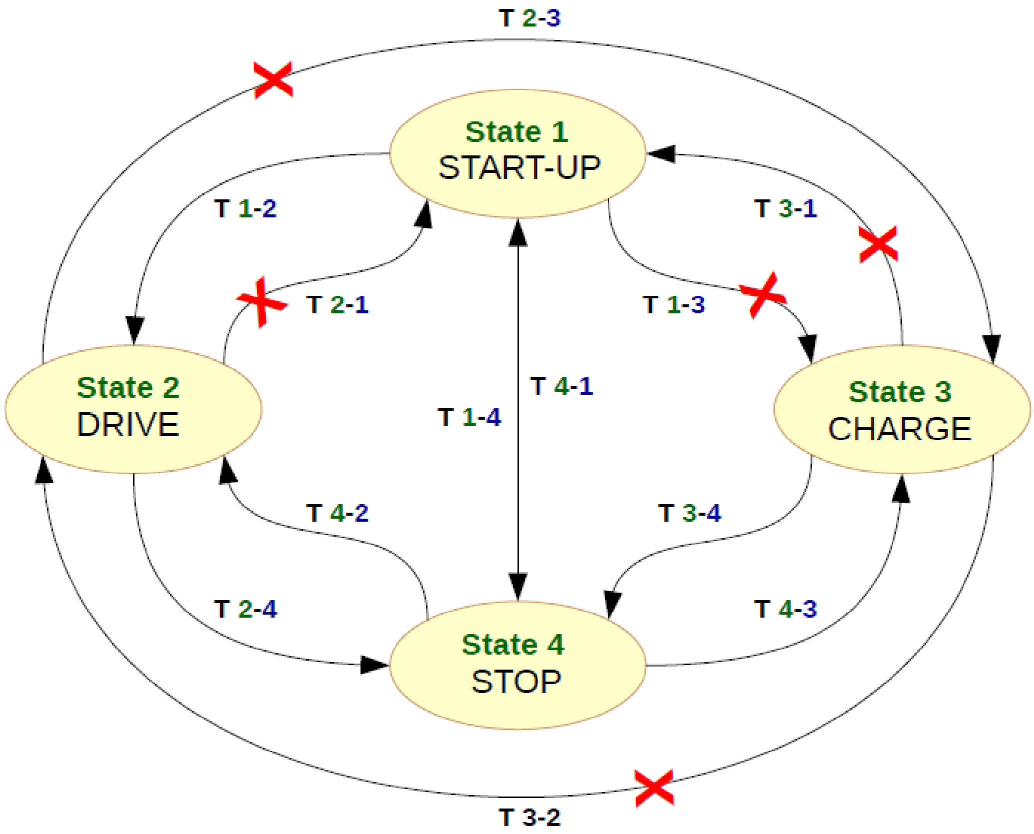

Figure 2: Control logic design

The four states are briefly described below to provide context for the subsequent detailed requirements:

1. Start-up: in this state, the vehicle’s power system is active but the electric motor remains stationary. This state occurs when the vehicle is turned on but has not yet started moving.
2. Drive: the vehicle is in motion with the electric motor engaged and providing propulsion. Power is supplied from the battery to the motor to enable driving.
3. Charge: the vehicle is connected to an external charging source and the battery is undergoing the charging process.
4. Stop: the vehicle is stationary, with the motor turned off and no movement occurring. This state can be triggered when the vehicle is turned off by the user, parked (for example, with the parking brake engaged or due to insufficient battery charge to continue driving), or if a system error necessitates stopping.

The following table lists the corresponding set of functional requirements for each state, highlighting the main functions the model must implement to ensure coherent and reliable behavior during simulation.

Table 2: Functional requirements overview

ID STATE	NAME	FUNCTIONAL REQUIREMENTS
S1	Start-up	**R1**. The model must correctly initialize the system, activating the motor, the battery and the auxiliary systems.
		R2. The system checks and monitors the battery status. The battery must have sufficient charge to start the vehicle and the anomalies must be reported. The battery management system (BMS) must verify the battery health condition, its charge level and its temperature.
		R3. The model must allow the communication between the modules of the vehicle.
S2	Drive	**R1**. The motor must ensure the correct power response in order to dynamically react to accelerator input signal and battery management.
		R2. The model must compute the remaining range in real-time and communicate it to the driver, taking into account the operational conditions and the driving parameters.
		R3. The regenerative braking must be active and adjustable, in order to optimize the range during the braking phase.
		R4. The model must simulate different road conditions and vehicle loads, in order to affect the power and the energy recovery.
S3	Charge	**R1**. The model must consider the interaction with a charging point, monitoring the battery charge state, the power received and the duration of the charge.
		R2. The temperature of the battery must be monitored to avoid overheating and improving efficiency.
S4	Stop	**R1**. The vehicle must ensure a correct shutdown cycle of the vehicle, gradually disabling the action of the motor.
		R2. The battery must be monitored to avoid anomalies and preserve the residual energy.
		R3. The system must collect and store the simulation data.

The following table summarizes the possible state transitions within the BEV model's control logic. It specifies the transition paths allowed between the main operational states, along with the corresponding conditions that enable or prohibit each transition. This clear definition of transitions ensures safe and consistent vehicle behavior during simulation.
It should be noted that the control logic enforces restrictions on certain state transitions to maintain safety and system integrity. Specifically, some transitions are disallowed to prevent inconsistent or unsafe vehicle behavior, as previously mentioned.

Table 3: State transition conditions

Transition	Name	Conditions
1-2	Start-up2Drive	When the brake pedal is released, the gear is set to "Drive" or "Reverse," the accelerator pedal is pressed and no errors are detected.
1-3	Start-up2Charge	This transition is not possible.
1-4	Start-up2Stop	If the shutdown button is pressed, or a critical error is detected, or the vehicle is not ready to drive.
2-1	Drive2Start-up	This transition is not possible.
2-3	Drive2Charge	This transition is not possible.
2-4	Drive2Stop	If the driver selects the "Park" mode, the vehicle is stationary and the accelerator pedal is not pressed. In case a fault is detected, the vehicle enters the fault state, and a message on the display will warn the user.
3-1	Charge2Start-up	This transition is not possible.
3-2	Charge2Drive	This transition is not possible.
3-4	Charge2Stop	If the charging station is disconnected, or the battery has reached full charge, but the user has not activated driving, the vehicle automatically enters the Stop state. This can also occur if errors occur during the charging phase.
4-1	Stop2Start-up	If the vehicle is off and the user turns the key, the systems power on and the vehicle moves to Start-up.
4-2	Stop2Drive	If the vehicle is on and parked, the user selects gear (“Drive” or “Reverse”), releases the parking brake and presses the accelerator with no errors.
4-3	Stop2Charge	The AC charging cable is connected to the vehicle and the parking brake is active.

2.3 Functional Requirements Specification

Below are the detailed functional requirements for the four operational phases of the BEV model. These requirements specify the key functions the system must implement to ensure correct and safe behavior during simulation.

Table 4: Functional requirements for BEV model

START-UP	
ID	**Requirements**
R1	When the start button is pressed, the vehicle must start.
R2	When the vehicle is started, the motor must not be rotating or delivering torque.
R3	When a vehicle is started, the lights must be tested to ensure they are functioning.
R4	To enter the 'Ready' mode, the parking brake must be active. If the parking brake is not active, the vehicle must not enter the 'Ready' mode and a notification must be sent to the driver.
R5	It is necessary to verify that all doors are closed to enter 'Ready' mode. If a door is not closed, the driver must be notified and 'Ready' mode must not be activated.
R6	The vehicle control system must be active.
R7	All safety devices and systems (e.g. sensors, brakes, airbags) must be active. Otherwise, an anomaly must be notified to the user.
R8	Access to the gearshift must be enabled only when all safety devices are ready.
R9	The BMS must actively monitor battery health, charge status and temperature to prevent overheating or malfunctions, display real-time data on the dashboard and ensure the motor activates only when the battery is healthy and charged; otherwise, motor start must be prevented and a warning shown to the user.
R10	If the motor fails to start due to a malfunction, the 'Ready' state will be suspended and the issue will be notified to the user.
R11	The 'Ready' mode must be displayed on the dashboard.
R12	If the vehicle does not enter 'Ready', a message must explain the reason (battery, motor, brake, error...).
DRIVE	
ID	**Requirements**
D1	The parking brake must be automatically disabled while driving to ensure normal vehicle operation.
D2	The motor must respond linearly to the accelerator input.
D3	If the motor does not respond consistently to the accelerator input, the vehicle must enter limp mode to allow for a safe stop, and a problem must be notified to the driver.
D4	The regenerative braking system must be active when the vehicle slows down and adjusted based on the vehicle's speed.
D5	The driver must be able to modify the usage of regenerative braking through the user interface.

D6	If the regenerative braking system is not functioning, a problem must be notified to the user.
D7	If the battery is fully charged, regenerative braking must be temporarily interrupted and automatically resume when the battery discharges a bit.
D8	The traction control system must maintain stability, especially during low-traction conditions.
D9	In case of loss of traction, the traction control and ABS systems must intervene.
D10	The BMS must manage the available power to optimize range.
D11	The motor temperature must be monitored and, in case of overheating, the vehicle must switch to limp mode and notify the user.
D12	The battery temperature must be monitored and, when cooled, the user must be notified to restart the vehicle.
D13	The driver must receive real-time information about the driving mode, speed and vehicle status through the dashboard.
D14	If a critical failure occurs in the motor, battery, transmission, critical sensors or ECU, the vehicle must enter reduced driving mode (limp mode) or immediate stop, and the driver must be alerted to the error.
D15	BMS parameters, such as charge level and health status, must be displayed in real-time on the dashboard.
D16	ADAS systems must be initialized and ready for use in ‘Drive’ mode. The driver must be informed of their operational status.
D17	The stop lights must be active when the vehicle is braking.
CHARGE	
ID	**Requirements**
C1	When the charger is connected to the vehicle, the charging phase must start.
C2	If the charger is not inserted, the charging phase must not start.
C3	The charging system must establish a stable and secure connection with the charger, correctly regulating incoming power in line with the battery capacity.
C4	During charging, the system must automatically lock the charging cable to prevent accidental disconnections.
C5	During charging, the vehicle must not move.
C6	If vehicle movement is detected, the charging state must be interrupted.
C7	The BMS must continuously verify the charge.
C8	The BMS must stop charging to prevent overcharging when the battery is fully charged or in case of overcharging.
C9	Charging time must be optimized to reduce downtime.
C10	Charging efficiency must be managed, especially during the transition from fast charging to maintenance charging.
C11	The battery must be cooled or maintained at a safe temperature during charging.
C12	The user must be constantly informed about the charging status.
C13	When the charger is disconnected from the vehicle, the charging phase must stop.
C14	If the charger is not disconnected from the vehicle, the charging phase must not stop.

STOP	
ID	**Requirements**
S1	The parking brake must be automatically activated.
S2	When parking mode is selected, the motor must be locked by interrupting the power transmission.
S3	In the event of a vehicle stop, the stability control systems must ensure the vehicle does not move or slide. The transmission lock system must be activated to prevent accidental movement.
S4	In case of malfunction, it must be ensured that the vehicle does not move unintentionally.
S5	If the vehicle is in parking mode, the driver must receive confirmation.
S6	When the vehicle enters 'STOP' mode, all high-voltage systems must be disconnected from the traction motor.
S7	The onboard electronic systems must remain powered at low voltage.
S8	When the power-off button is pressed, the vehicle must turn off, deactivating the motor and disconnecting all non-essential power sources.

2.4 Hazard Identification and Risk Assessment

At this stage, a preliminary risk analysis (HARA – Hazard Analysis and Risk Assessment) was carried out to identify potentially hazardous scenarios associated with the BEV system and to evaluate their consequences in worst-case conditions.

This assessment, conducted in accordance with the ISO 26262 guidelines [5] and based on the previously defined functional requirements,, represents a fundamental step in defining the safety goals and subsequently classifying the ASIL levels. The following table summarizes the identified hazards.

Table 5: List of hazards identified in the HARA process

START-UP		
ID	**HAZARD**	**DESCRIPTION**
HR1	**Unintended start**	The vehicle starts unintentionally when the start button is pressed accidentally or due to a malfunction.
HR2	**Motor activation during ‘Start-up’ phase**	The motor is active when the vehicle is started but not ‘Ready’, resulting in unintended acceleration.
HR3	**Lights test failure**	The vehicle starts without testing the lights, leading to unsafe driving conditions.
HR4	**Inactive parking brake**	The parking brake is not active and the vehicle enters the ‘Ready’ state.
HR5	**Open door**	The vehicle enters ‘Ready’ mode with an open door, which may lead to hazards for passengers.
HR6	**Control system failure**	The vehicle control system is not active and the vehicle is not under control.
HR7	**Safety Devices and Systems Malfunction**	Inactive or uncommunicated failure of critical safety systems increases the risk of injury to occupants.
HR8	**Gearshift access failure**	The access to gearshift is allowed even if safety devices are not active, causing potential accidents.
HR9	**BMS failure and motor activation issues**	BMS malfunction, battery issues and lack of information may lead to vehicle inoperability, damage or fire risks with no user notification.
HR10	**Motor startup failure**	The motor fails to start but the vehicle enters the ‘Ready’ state and/or the issue is not notified to the user.
HR11	**Display failure**	The ‘Ready’ state is not displayed, confusing the driver.
HR12	**Lack of Display explanation**	The driver is not informed about the reason why the vehicle fails to enter the ‘Ready’ phase.
DRIVE		
ID	**HAZARD**	**DESCRIPTION**
HD1	**Parking Brake Malfunction**	The brake fails to disengage, causing the vehicle to stall, overheat the brake system or impede normal vehicle operation, increasing the risk of an accident or damage to the vehicle.

HD2	**Unresponsive motor**	The motor does not respond linearly to the accelerator input, leading to unpredictable vehicle behavior.
HD3	**Lack of limp mode**	The limp mode is not activated even if the motor does not respond consistently to the inputs, exposing the passengers to dangerous conditions.
HD4	**Regenerative braking failure**	The regenerative braking system is not active, decreasing braking efficiency and reducing the range of the vehicle.
HD5	**Inadequate braking control**	The driver cannot manipulate regenerative braking intensity, reducing control over the vehicle.
HD6	**Lack of information about regenerative braking**	The regenerative braking malfunctions are not notified to the driver, causing a lack of information about the range of the vehicle.
HD7	**Overcharging**	The regenerative braking system overcharges the battery, leading to possible damages.
HD8	**Loss of stability**	The traction control system fails, leading to loss of vehicle stability in slippery conditions.
HD9	**Inactive safety systems**	Traction control and ABS fail during loss of traction, causing possible accidents.
HD10	**Power management failure**	The BMS fails to optimize available power, reducing the vehicle's driving range.
HD11	**Motor overheating without limp mode.**	Motor overheating without limp mode activation increases the risk of damage or fire and endangers passengers.
HD12	**Cooling system failure causing battery overheating**	Battery overheating and cooling system failure hinder safe reboot and increase the risk of damage or fire.
HD13	**Lack of information about the vehicle status**	The driver is not informed of critical vehicle status or driving mode.
HD14	**Failure to activate limp mode**	Critical system failures do not activate limp mode, potentially causing unsafe vehicle operation.
HD15	**Lack of battery information**	The driver does not receive information about the battery, like its state of charge or state of health, causing confusion or potential neglect.
HD16	**ADAS failure**	ADAS systems fail to initialize, leaving the vehicle without essential driver support.
HD17	**Stop indicators failure**	When the vehicle is braking, the stop indicators are not active, increasing the risk of collision with other vehicles.
CHARGE		
ID	**HAZARD**	**DESCRIPTION**
HC1	**Charging not started**	The vehicle does not begin charging when the charger is connected.
HC2	**Unintended start of the charging phase**	The system enters the charging phase even if the connector is not fully or correctly inserted.
HC3	**Charging system failure**	The charger does not establish a secure connection, leading to overheating or undercharging.

HC4	**Disconnection during charging**	The charging cable disconnects accidentally during charging, causing charging interruption or damage to the battery.
HC5	**Vehicle movement during charging**	The vehicle moves during charging, risking cable damage or safety issues.
HC6	**Charging state during vehicle movement**	The charging process continues despite vehicle movement, risking system damage.
HC7	**Charge monitoring failure**	The BMS fails to monitor charge, leading to overcharging or undercharging.
HC8	**Overcharging**	The BMS failure to stop charging when the battery is full or in case of overcharging leads to system damage, potential damage or fire risk.
HC9	**Inefficient charging**	Charging process takes too long, reducing vehicle availability.
HC10	**Inefficient charging transition**	The charging system fails to manage transitions between fast and maintenance charging, affecting efficiency.
HC11	**Battery overheating**	The battery overheats during charging, risking damage or fire.
HC12	**Lack of information about charging**	The driver is not informed of the charging status, causing confusion.
HC13	**Charging not stopped**	The system fails to detect disconnection of the charger, keeping the charging state active in software or showing misleading UI status.
HC14	**Unintended interruption of charging**	Charging is suddenly interrupted even though the charger is still connected and the battery level is not full.
STOP		
ID	**HAZARD**	**DESCRIPTION**
HS1	**Parking brake failure**	The parking brake does not activate and the vehicle may slip unintentionally.
HS2	**Power transmission failure**	The power transmission is not interrupted and the vehicle may move while in parking mode.
HS3	**Loss of stability**	The vehicle may move or slide because of a failure in the stability control systems.
HS4	**Vehicle movement during malfunction**	Malfunctions cause unintended vehicle movement, increasing the risk of accidents.
HS5	**Absence of confirmation**	The driver does not receive confirmation that the vehicle is in parking mode.
HS6	**High-voltage systems failure**	HV systems remain active after shutdown, creating risks for maintenance or in case of accident recovery.
HS7	**Power failure of critical electronic systems**	Loss of power to critical low-voltage systems affects telemetry, remote diagnostics or alarm systems.
HS8	**Incomplete shutdown**	The vehicle doesn’t turn off completely. The motor and/or non-essential power sources remain active.

For the risk analysis related to the hazards identified in the BEV system, the methodology defined by the ISO 26262 standard has been applied [5]. This methodology involves classifying risks based on four fundamental parameters: Severity (S), Exposure (E), Controllability (C) and the resulting Automotive Safety Integrity Level (ASIL).

- Severity (S): measures the extent of potential harm to the persons involved (drivers, passengers, pedestrians, cyclists). The classification takes into account the type of collision and the velocity difference (dV) between vehicles, with values ranging from 1 (low) to 3 (high). For example, S1 indicates a dV less than 20 km/h, while S3 indicates a dV greater than 40 km/h. Accidents involving pedestrians or cyclists are assigned at least S2 or S3, depending on the type of area (urban or rural).
- Exposure (E): indicates the probability that the vehicle is in an operational situation where the hazard can occur. It can be defined in terms of percentage of operating time or frequency of occurrence, ranging from E1 (very low) to E4 (very high).
- Controllability (C): represents the probability that the persons involved (mainly the driver) can avoid or mitigate harm through timely and appropriate actions. It ranges from C0 (generally controllable) to C3 (difficult or uncontrollable).

The combination of these parameters determines the ASIL (Automotive Safety Integrity Level), which classifies the risk into four levels (A, B, C, D) in increasing order of severity and safety requirements, with ASIL D being the most stringent. The QM classification (Quality Management) indicates that the hazard does not require specific functional safety measures under ISO 26262 and is managed through standard quality processes.

Table 6: ASIL levels

Sum of Parameters	ASIL
6 or less	QM
7	A
8	B
9	C
10	D

The following table reports, for each identified hazard, the worst-case scenario considered and the assigned values of S, E, C and ASIL, which will guide the definition of safety measures and design.

Table 7: ASIL classification of hazards in the BEV system

START-UP					
Hazard	**Worst Case Scenario**	**S**	**E**	**C**	**ASIL**
HR1	Accidental activation of the start button while a person is nearby the vehicle, potentially creating a hazardous situation.	3	2	3	ASIL B
HR2	Vehicle parked on an incline, with the motor still engaged, leading to unintended motion.	3	3	3	ASIL C
HR3	The vehicle is started at night without headlight activation, reducing visibility and road safety.	2	3	2	ASIL A
HR4	Transitioning to 'Ready' mode without proper brake engagement causes the vehicle to move, i.e. on a sloped terrain.	3	3	3	ASIL C
HR5	The system allows 'Ready' mode activation while a door remains open, creating passenger fall risk.	3	2	3	ASIL B
HR6	Control systems fail to initialize correctly during vehicle startup.	3	2	3	ASIL B
HR7	Inactive safety systems (e.g., airbags) combined with a lack of driver notification increase the risk of injury due to unawareness of system failures.	3	4	3	ASIL D
HR8	Gear shifting is allowed even when safety sensors are unresponsive.	3	3	2	ASIL B
HR9	The BMS fails to properly monitor the battery, causing operation with a damaged or discharged battery, lack of information to the driver and fire risk.	3	4	3	ASIL D
HR10	The driver is not alerted to a system fault during initialization of the motor.	2	3	2	ASIL A
HR11	The absence of clear 'Ready' mode indication misleads the driver.	2	3	2	ASIL A
HR12	Diagnostic feedback is missing, leaving users unaware of entry conditions not met.	1	4	1	ASIL QM
DRIVE					
Hazard	**Worst Case Scenario**	**S**	**E**	**C**	**ASIL**
HD1	The parking brake does not disengage while driving, the driver loses control of the vehicle and the risk of an accident is increased.	3	4	3	ASIL D
HD2	Driver experiences unstable power delivery while joining traffic.	3	2	3	ASIL B
HD3	No limp mode triggers after motor fault, causing dangerous stop.	3	3	3	ASIL C
HD4	Brake system cuts out unexpectedly during descent.	3	3	3	ASIL C
HD5	Regenerative braking kicks in too strongly, no driver control.	2	3	3	ASIL B
HD6	Vehicle doesn't charge during regenerative braking and no notification is given.	1	4	2	ASIL A
HD7	Regeneration braking continues despite battery being full, risking overcharge.	3	2	2	ASIL A
HD8	Traction control fails, resulting in oversteer on slippery turn.	3	2	3	ASIL B
HD9	ABS malfunction leads to wheel lock in emergency.	3	2	3	ASIL B

HD10	BMS underestimates needed power for overtaking and the vehicle discharge completely while driving.	3	3	2	ASIL B
HD11	The motor seizes, triggering a fire and battery explosion, resulting in burns or poisoning, total vehicle loss and serious danger to occupants and other road users.	3	3	3	ASIL C
HD12	Battery overheating combined with a cooling system failure leads to uncontrolled thermal escalation, causing a fire or explosion, potentially destroying the vehicle and putting occupants at severe risk of injury or death.	3	3	3	ASIL C
HD13	The vehicle enters reduced performance mode without notifying the driver, leading to confusion or improper reactions.	2	3	2	ASIL A
HD14	Despite a critical fault in the control unit, the vehicle continues operation as if fully functional.	3	2	3	ASIL B
HD15	The user is not informed of passive battery consumption, which can lead to unexpected inoperability.	2	3	2	ASIL A
HD16	Critical ADAS functions are inactive on the highway, creating a false sense of support and increasing risk.	3	3	3	ASIL C
HD17	While stopped at an intersection or during braking, the vehicle's signal indicators are inactive, making it less visible to approaching traffic.	2	3	3	ASIL B
CHARGE					
Hazard	**Worst Case Scenario**	**S**	**E**	**C**	**ASIL**
HC1	The connector is inserted but the charging is prevented and the vehicle cannot be used.	1	3	3	ASIL A
HC2	The system still energizes HV bus even if pin is not fully inserted.	3	2	2	ASIL A
HC3	No voltage regulation, the battery overcurrent.	3	2	2	ASIL A
HC4	User trips on cable, connector rips out causing discharging.	2	3	2	ASIL A
HC5	Vehicle moves slightly tearing cable (i.e. on a sloped terrain).	2	3	2	ASIL A
HC6	Charging continues after car is shifted into gear.	3	2	3	ASIL B
HC7	An error in battery, as overvoltage, is not detected, causing internal damage or fire.	3	2	3	ASIL B
HC8	Battery charging beyond safe limits can cause malfunctions, internal damage or fire.	3	2	3	ASIL B
HC9	Slow charge during emergency need.	2	4	1	ASIL A
HC10	Fast charge does not switch to maintenance charging and battery wears.	2	3	2	ASIL A
HC11	Thermal runaway during fast charge, causing internal damage or fire.	3	2	3	ASIL B
HC12	Dashboard does not show progress during charging and the driver is unaware.	2	3	2	ASIL A
HC13	Charger is unplugged but vehicle still shows active charging.	2	3	2	ASIL A
HC14	Charging stops suddenly even though charger is connected and battery is not fully charged, leaving the battery drained.	1	4	2	ASIL A

STOP					
Hazard	**Worst Case Scenario**	**S**	**E**	**C**	**ASIL**
HS1	Vehicle remains stationary on a slope without the parking brake engaged, increasing the risk of rolling.	3	3	3	ASIL C
HS2	In parking mode, the motor continues to deliver torque to the drivetrain, causing slow unintentional vehicle movement while a person is nearby the vehicle.	3	2	3	ASIL B
HS3	Loss of traction control on slippery surfaces (e.g., icy road) results in the vehicle sliding when stationary.	3	2	3	ASIL B
HS4	A failure in the electronic control system leads to unexpected vehicle movement in an urban environment.	3	2	3	ASIL B
HS5	Driver assumes the vehicle is securely parked, but no actual parking confirmation exists, leading to potential movement.	3	3	2	ASIL B
HS6	Maintenance staff may come into contact with live high-voltage components due to improper system shutdown.	3	2	3	ASIL B
HS7	During diagnostics, a sudden loss of power causes braking system functions to become unavailable.	3	2	3	ASIL B
HS8	Following shutdown, non-essential systems continue to draw power, risking battery depletion over time.	1	4	2	ASIL A

The subsequent phase involved the definition of Safety Goals, that represent the fundamental safety objectives aimed at mitigating identified risks and ensuring a level of safety commensurate with the associated hazards. Safety Goals were established for all hazards classified from ASIL A to D and served as primary references for the implementation of safety measures throughout the project. In some cases, a single Safety Goal addresses multiple hazards, or certain hazards were not mitigable through technical safety requirements. Although detailed Functional Safety Requirements are not explicitly enumerated in this document, the Safety Goals have guided the system modeling process to ensure adherence to the necessary safety standards and compliance with ISO 26262 [5].

Table 8: Safety goals for the BEV system

ID	**ASIL**	**SAFETY GOALS**
START-UP		
HR1	**B**	Prevent unintended vehicle start when the start button is accidentally pressed or system fails.
HR2	**C**	Ensure the motor is inactive until all start-up conditions are safely met.
HR3	**A**	Ensure light system check is performed at startup.
HR4	**C**	Prevent transition to ‘Ready’ if parking brake is not active.
HR5	**B**	Prevent ‘Ready’ mode activation if any door is open.
HR6	**B**	Ensure control system is active and functioning before start-up.
HR7	**D**	All safety-critical systems shall be self-checked during start-up.

HR8	**B**	Gearshift access shall be inhibited if safety systems are not available.
HR9	**D**	BMS shall monitor battery conditions and inhibit motor activation if unsafe.
HR10	**A**	The driver shall be notified if the motor fails to initialize.
HR11	**A**	The 'Ready' mode status shall be clearly indicated to the driver.
DRIVE		
HD1	**D**	The parking brake shall disengage safely and completely during 'Drive' mode.
HD2	**B**	The motor response shall be consistent and proportional to driver input.
HD3	**C**	Limp mode shall be triggered in case of motor failure.
HD4	**C**	The regenerative braking system shall be available and functional.
HD5	**B**	The regenerative braking intensity shall remain within safe controllable limits.
HD6	**A**	The driver shall be informed of regenerative braking failure.
HD7	**A**	Regenerative braking shall be disabled when the battery is fully charged.
HD8	**B**	Traction control shall maintain vehicle stability in low-traction conditions.
HD9	**B**	The ABS shall prevent wheel lock under emergency braking.
HD10	**B**	The BMS shall provide sufficient power for safe driving conditions.
HD11	**C**	Motor overheating shall be detected and mitigated to prevent fire or damage.
HD12	**C**	Battery thermal events shall be detected and mitigated to prevent escalation.
HD13	**A**	The driver shall be notified of any reduced performance mode.
HD14	**B**	Critical faults shall trigger system degradation or shutdown.
HD15	**A**	Battery state of charge and health shall be displayed to the user.
HD16	**C**	ADAS systems shall be verified as available or unavailable before activation.
HD17	**B**	Stop indicators shall function while vehicle is braking.
CHARGE		
HC2	**A**	Charging shall only be enabled when a secure connection is confirmed.
HC3	**A**	The charging system shall regulate voltage and current within battery limits.
HC4	**A**	The charging connector shall be locked to prevent disconnection.
HC5	**A**	Vehicle movement shall be inhibited during charging.
HC6	**B**	Charging shall stop if gear is engaged or vehicle starts moving.
HC7	**B**	The BMS shall detect battery faults during charging.
HC8	**B**	Charging shall stop automatically when limits are exceeded.
HC11	**B**	Battery overheating during charging shall be detected and mitigated.
STOP		
HS1	**C**	The vehicle shall automatically activate the parking brake to prevent unintended movement during the 'Stop' phase.
HS2	**B**	In parking mode, torque transmission to the drivetrain shall be fully interrupted.
HS3	**B**	Stability control systems shall ensure the vehicle remains stationary when stopped.
HS4	**B**	In case of electronic control failure, the vehicle shall not be able to move.
HS5	**B**	The driver shall be promptly informed when the vehicle enters parking mode.
HS6	**B**	All high-voltage systems shall be automatically de-energized when entering 'Stop' mode.
HS7	**B**	Critical low-voltage electronic systems shall remain active after the vehicle shutdown.
HS8	**A**	In 'Stop' mode, all non-essential electrical loads shall be deactivated to prevent abnormal battery discharge.

3 SYSTEM DESIGN AND ARCHITECTURE

This chapter presents the functional and physical architecture of the developed model, focusing on the structure and behavior of the main subsystems within the simulation. The model is built in Simulink using a modular architecture composed of five main components: Environment, Plant, Control, HMI and Driver. This modular approach ensures a clear and organized system representation, facilitating readability, scalability and ease of modification during development, testing and validation phases.

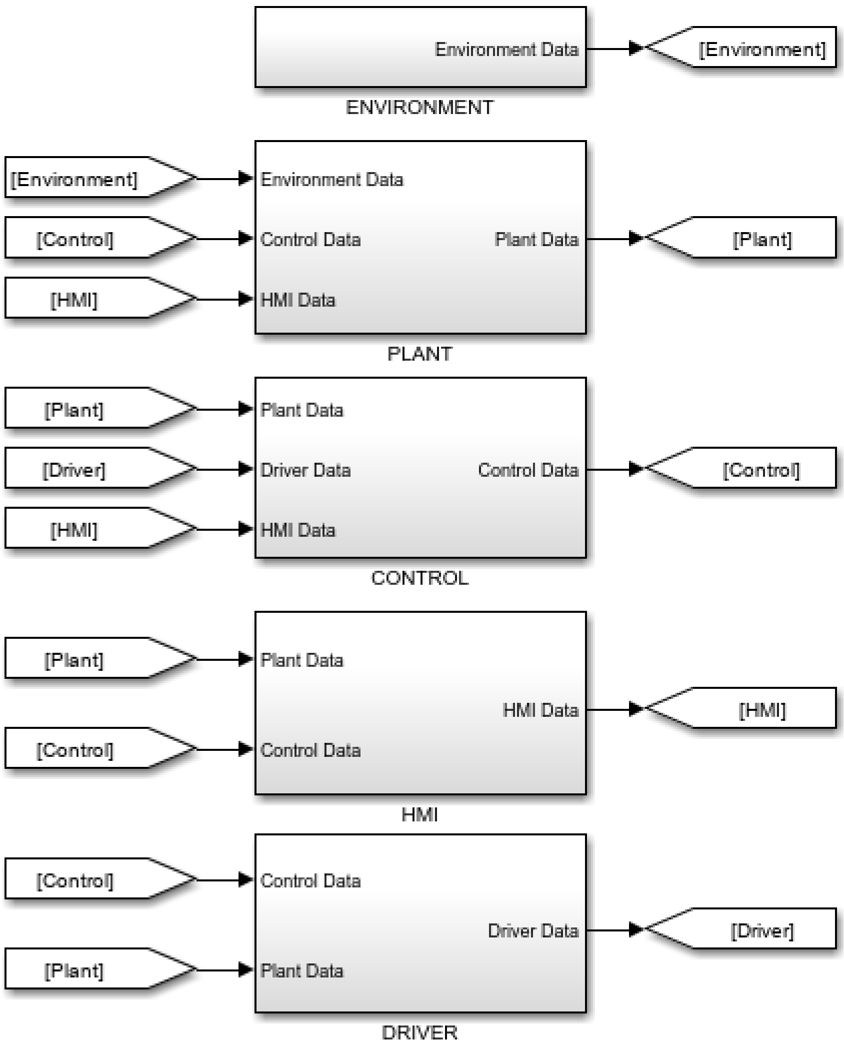

Figure 3: Block diagram of the Simulink model

This chapter focuses in particular on three key areas of the model:

- Environment: including external conditions that influence the vehicle's dynamic behavior;
- Plant: representing the physical vehicle system (battery, motor, transmission and vehicle dynamics);
- Driver: simulates the driver's behaviour.

3.1 Environment Model

The *Environment* block provides several essential parameters for the system modeling.

In particular, it includes the thermal model of the ambient temperature, allowing comparison between the thermal conditions of the motor and battery and the external temperature. For the thermal model, Simscape components have been used, such as *Environment Thermal Mass*, *Radiative Heat Transfer* and *Temperature Sensor*.

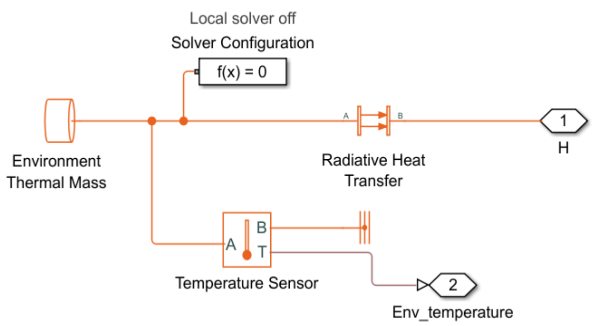

Figure 4: Thermal domain of the environment model

Additionally, it supplies configurable inputs within MATLAB for simulating driving scenarios, such as road slope, initial heat of the motor and battery, wind speed and braking force applied to the vehicle. These parameters are initially set to zero but can be modified to perform tests in critical scenarios.

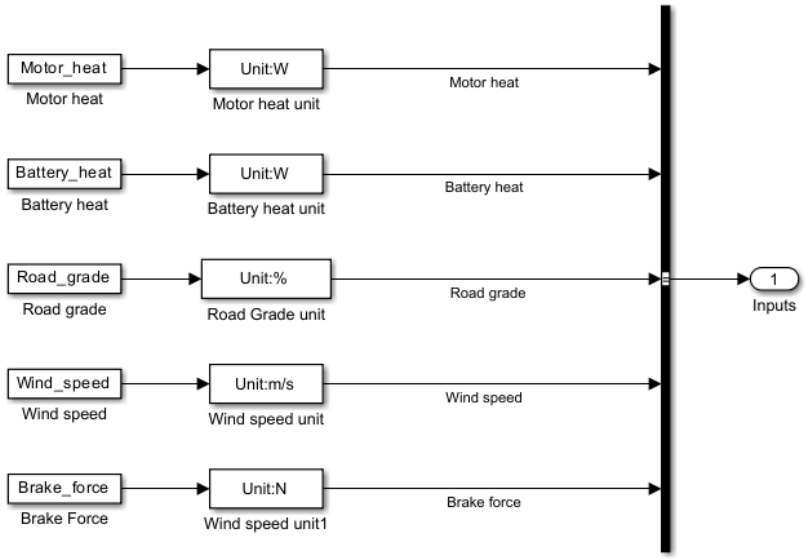

Figure 5: Input parameters of the environment block

3.2 Plant Model

In the context of this study, a BEV has been modeled into a block named *Plant*, which includes the main subsystems: battery (High Voltage and Low Voltage), electric motor, transmission and vehicle. The purpose of this chapter is to describe the subdivision of the system into subcomponents, illustrate their functional interaction and explain the connections among the main blocks within the model developed in the Simulink environment [9], [10]. This architectural structure will be used as the foundation for the subsequent implementation phase, in which the control logic and operational strategies will be developed.

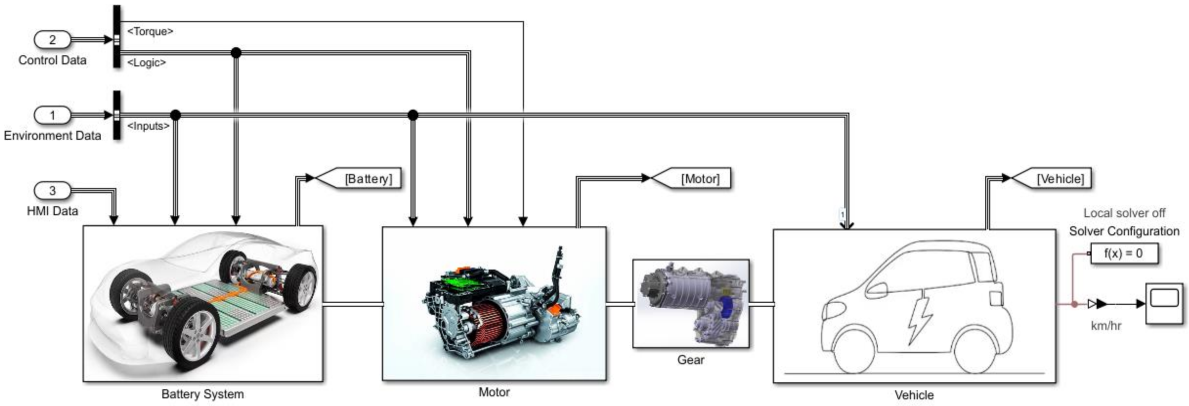

Figure 6: Simulink representation of the plant block [11],[12],[13],[14]

All the variables used within the Simulink blocks are defined in a dedicated MATLAB file, which allows for a centralized and easily modifiable management of system parameters. This organization facilitates adapting the model to different operating conditions and simulation scenarios, improving the maintainability and scalability of the entire model.

For the physical modeling of vehicle subsystems Simscape was used. Simscape is a Simulink environment dedicated to multi-domain physical simulation based on component modeling. This approach enables an accurate representation of interactions between electrical, mechanical and thermal domains, enhancing the model's precision and consistency. Furthermore, Simscape facilitates integration with control logic, ensuring a more realistic and modular simulation.

3.2.1 Battery Subsystem

The battery subsystem consists of two units: a high-voltage battery and a low-voltage battery. The high-voltage battery serves as the primary source of electrical energy for powering the electric motor and, consequently, enabling vehicle propulsion.

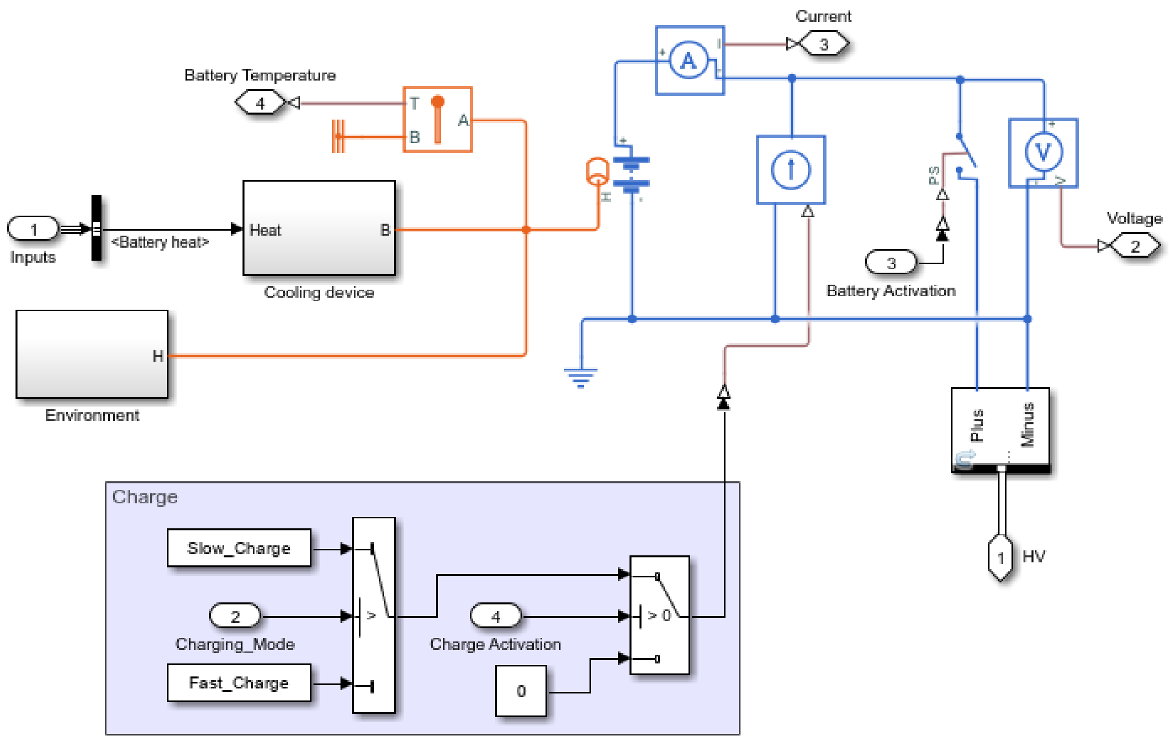

Figure 7: High-Voltage battery subsystem - Simulink model

The physical components were modeled using the Simscape environment, which allows for integrated simulation of both electrical and thermal domains. Specifically, the battery was represented using electrical elements (voltage, internal resistance and capacity) as well as thermal ones in order to implement thermal control. This thermal system ensures safe operating conditions and extends battery lifespan, particularly during prolonged charge or discharge phases. The high-voltage battery is characterized by a nominal voltage of 400 V, an energy capacity of 60 kWh (equivalent to 150 Ah) and an internal resistance of 0.5 mOhm [15]. To monitor key electrical quantities, a current sensor in series and a voltage sensor in parallel were integrated into the model, both compatible with the physical domain.
To manage battery activation, a Physical Signal Switch (*PS Switch*) was included, allowing disconnection from the motor when operating conditions require it (e.g. during charging or when the vehicle is stationary). The charging process was simulated using a *Controlled Current Source*, connected to a control signal that enables charging only when required.

The input current can assume two discrete values: 20 A (slow charging) or 80 A (fast charging), depending on the mode selected by the user via the HMI interface. In this context, the charging process has been deliberatly simplified, being treated as a functional interaction limited to receiving energy from a controlled external source, as the focus is on managing the operational phases of a BEV. This includes how the vehicle reacts to the charging process, but not the design of the external infrastructure.

The measured current and voltage values are used to compute, in real time, the delivered electric power, the electric power loss due to internal resistance, the remaining charge and the State of Charge (SoC) expressed as a percentage. These variables are essential for the Battery Management System (BMS), which uses them as reference inputs for control and protection functions.

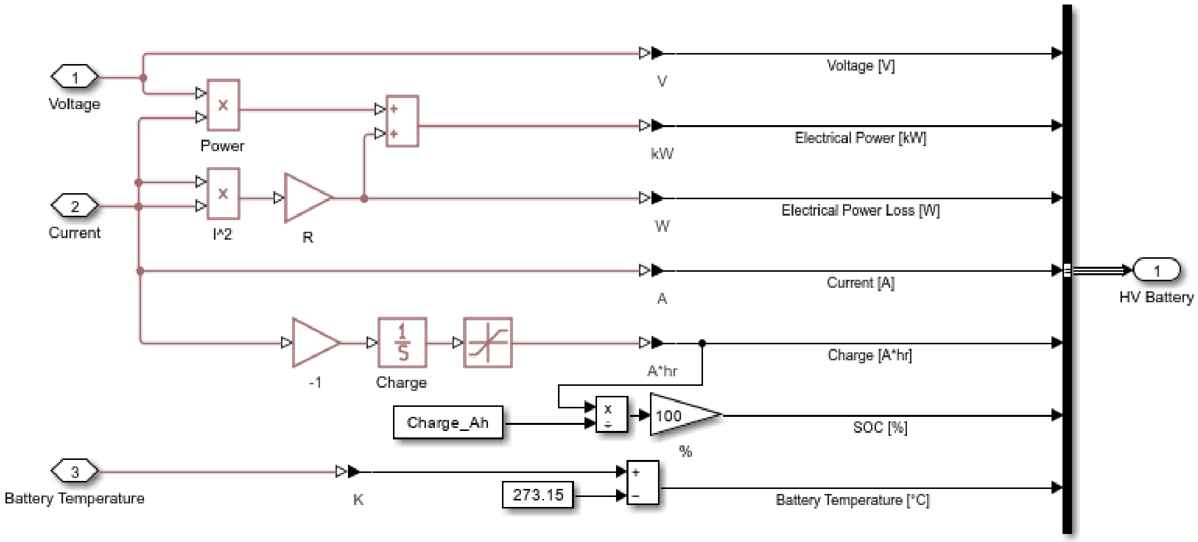

Figure 8: Subsystem for HV battery measurement and parameter estimation

The high-voltage (HV) battery cannot directly power the low-voltage circuits, as this would compromise vehicle safety, electrical isolation and operational continuity. Some essential safety systems, such as airbags, ABS, ESP, emergency lights and other critical devices, must remain operational even in the absence of HV power, for example, in the event of a fault or during the shutdown phases of the main system.

To ensure this functionality, a low-voltage (12 V) battery has been incorporated, with a nominal capacity of 0.72 kWh (60 Ah) and an internal resistance of 0.01 Ohm [16]. It is connected to an electrical load that represents the consumption of auxiliary devices, such as the air conditioning system and other vehicle electronics. Different resistance values can be assigned to the load depending on the expected consumption: in this case, three load levels were considered, corresponding to resistances of 28.8 Ω, 1.92 Ω and 0.72 Ω.

They simulate a minimum load of 5 W, an intermediate load of 75 W and a maximum load of 200 W, respectively.
The use of a separate 12 V battery allows powering the control logic and communication modules (VCU, BMS, gateway) even when the HV system is not active, ensuring the integrity of the supervision system and enabling safe management of operational transitions.
Sensors for current and voltage measurement have also been implemented for the 12 V battery and derived parameters such as electric power, losses, charge and state of charge, are calculated following the same logic used for the HV battery.

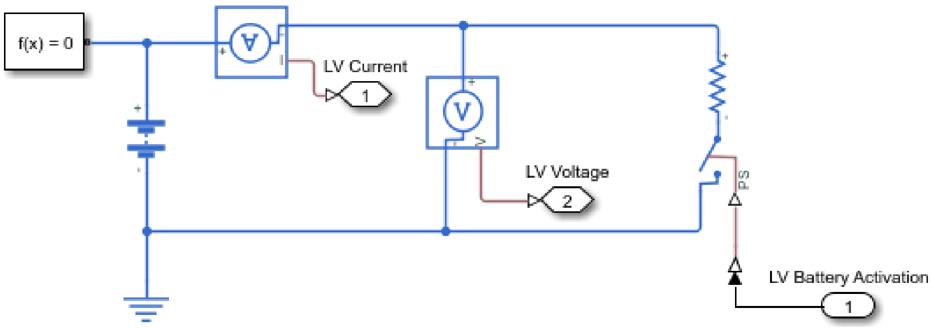

Figure 9: Low-Voltage battery subsystem - Simulink model

3.2.2 Electric Motor Subsystem

To represent the system's motor, the *Motor & Drive* block was used. It is responsible for converting the electrical energy supplied by the HV battery into mechanical energy required for vehicle propulsion. This block models the dynamic behavior of the motor-inverter system by receiving a desired torque profile as input and generating the corresponding electrical quantities needed to achieve it. The resulting mechanical torque is delivered to the motor shaft and serves as the input for the subsequent mechanical transmission. The motor is characterized by a maximum torque of 400 Nm, a peak power of 200 kW and a nominal efficiency set at 95% [17].

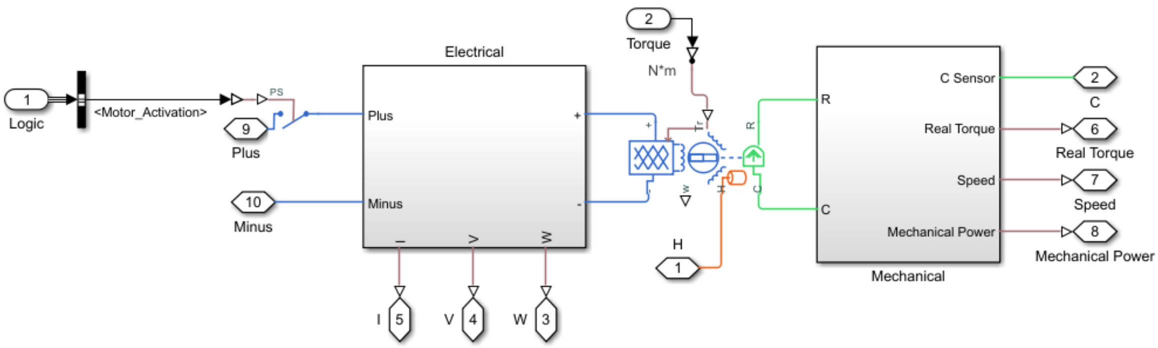

Figure 10: Motor subsystem - Simulink model

The *Motor & Drive* subsystem includes three primary domains: electrical, mechanical and thermal.

<u>Electrical Domain</u>

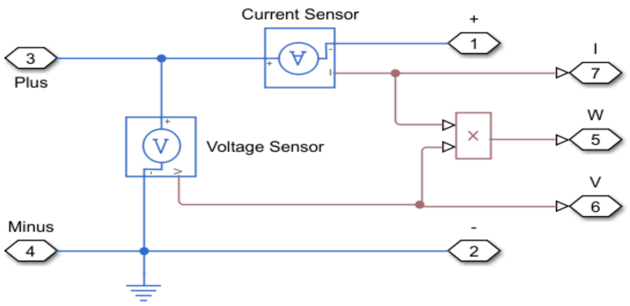

Figure 11: Electrical domain in motor subsystem

This domain refers to the electrical quantities that enter the motor, such as voltage and current. These inputs determine the electromagnetic behavior of the motor and are typically measured and monitored to ensure proper operation.

<u>Mechanical Domain</u>

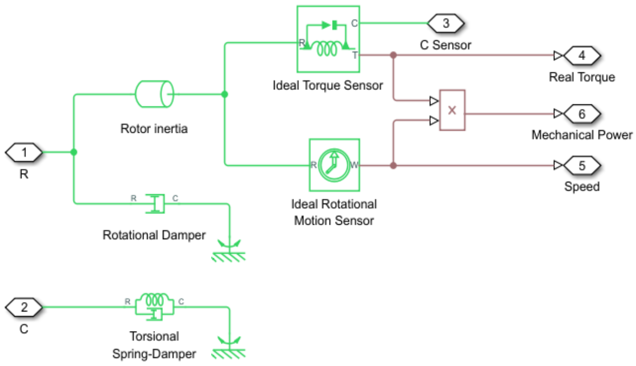

Figure 12: Mechanical domain in motor subsystem

This domain concerns the physical output generated by the motor. The internal electromagnetic interaction produces mechanical quantities such as torque, rotational speed and mechanical power, which are measured by dedicated rotation sensors and serve as inputs for the vehicle's drivetrain.

<u>Thermal Domain</u>

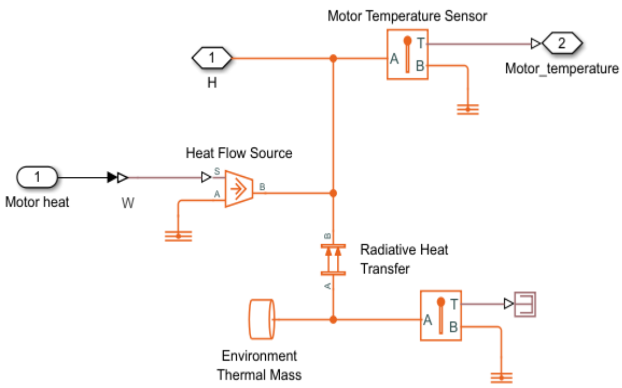

Figure 13: Thermal domain in motor subsystem

The thermal domain considers the heat generated inside the motor due to electrical and mechanical losses. Although simplified, the model includes heat exchange with the environment, represented by a thermal mass connected through a radiative heat transfer element. This allows evaluation of motor behavior under high load or prolonged operation.

Similarly to the battery, several control parameters are monitored for the motor. On the electrical side, current, voltage and actual electrical power supplied by the high-voltage battery (HV Battery) are tracked to ensure proper connection operation. The motor temperature (in degrees Celsius) is also measured for thermal monitoring. Additionally, rotational speed (rpm), torque and mechanical power output are acquired. By comparing the electrical power supplied with the rotational speed and torque, motor electrical losses are estimated. Finally, the Power Rate is calculated from the mechanical power, defined as the ratio between the mechanical power delivered and the maximum power available, expressed as a percentage.

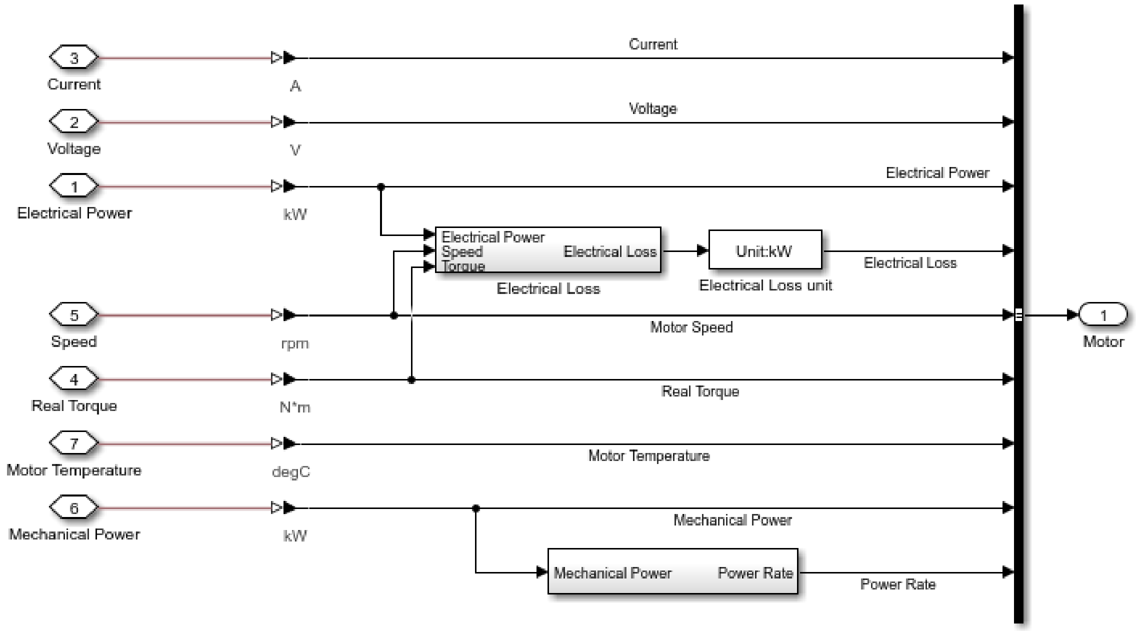

Figure 14: Subsystem for motor measurement and parameter estimation

3.2.3 Gearbox Subsystem

The transmission adapts the torque and angular speed coming from the electric motor to match the requirements of the vehicle. In this model, a fixed gear ratio of 9:1 is used, allowing the output torque to be nine times higher than the input torque, while the rotational speed is proportionally reduced. This behavior is modeled using the *Simple Gear* block from the Simscape library, which enables accurate physical modeling of mechanical components.

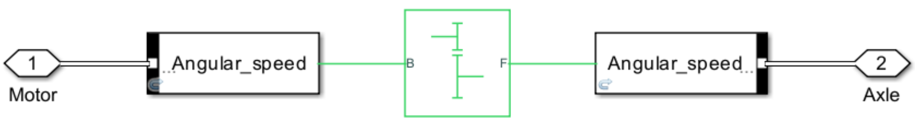

Figure 15: Gearbox subsystem - Simulink model

3.2.4 Vehicle Dynamics Subsystem

The vehicle behavior was modeled using the *Longitudinal Vehicle* block in Simulink. This block allows representing the vehicle as a system load by assigning parameters such as mass, tire radius, aerodynamic drag coefficient and others. It takes into account external inputs previously defined, including road slope, braking force and wind speed. The block outputs the vehicle speed and longitudinal acceleration (G), which can be positive, zero or negative depending on whether the vehicle is moving forward, stationary or decelerating.

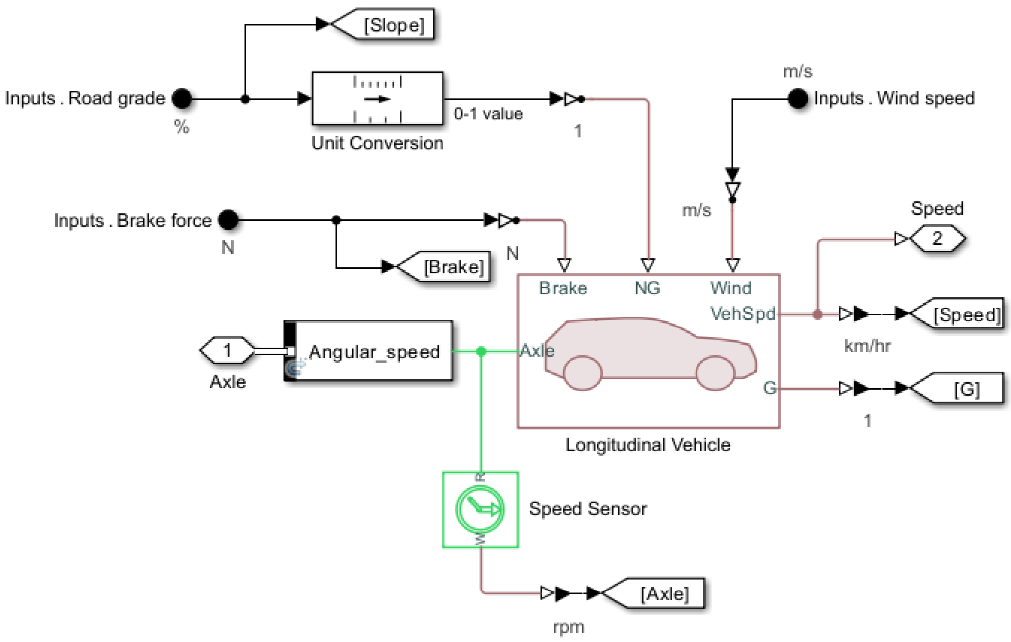

Figure 16: Vehicle subsystem - Simulink model

The control parameters of the vehicle subsystem include road slope, braking force, input axial speed, vehicle speed output from the block (expressed in both km/h and mph) and longitudinal acceleration.

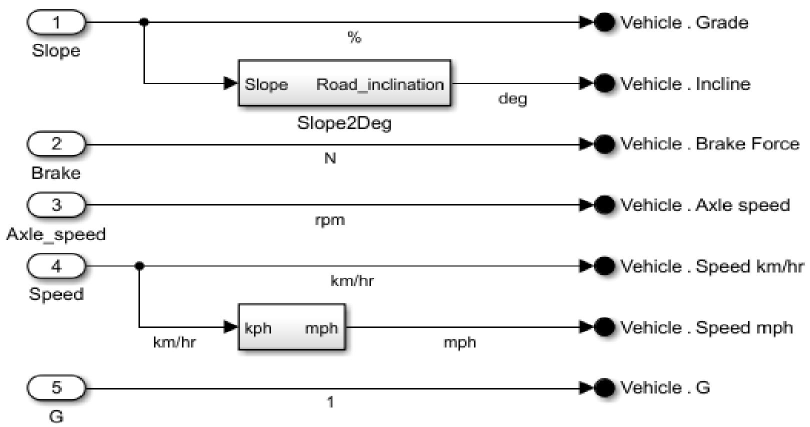

Figure 17: Subsystem for vehicle measurements and parameter estimation

3.3 Driver Model

To simulate the driver's behavior, the *Longitudinal Driver Model* block was used. It receives as input signals the reference speed, the measured speed from the output of the *Vehicle* block and the road slope. In return, it provides a simulation of the commands a driver would perform to achieve the given driving profile.

Specifically, the relevant outputs for this project are:

- the deceleration command: it represents when the driver presses the brake pedal and corresponds to a value between 0 and 1;
- the acceleration command: it corresponds to when the driver presses the accelerator pedal corresponds to a value between 0 and 1;
- the gear: it indicates the selected driving mode. It is defined by a numerical value corresponding to each phase. These values are summarized in the following table.

Table 9: Gear position corresponding to numerical value for driver block

Numerical value	Gear Position
-2	Park (P)
-1	Reverse (R)
0	Neutral (N)
1	Drive (D)

To convert these numerical values into strings, a MATLAB Function has been used.

All these signals will be particularly useful for describing the decision-making logic during the control development.

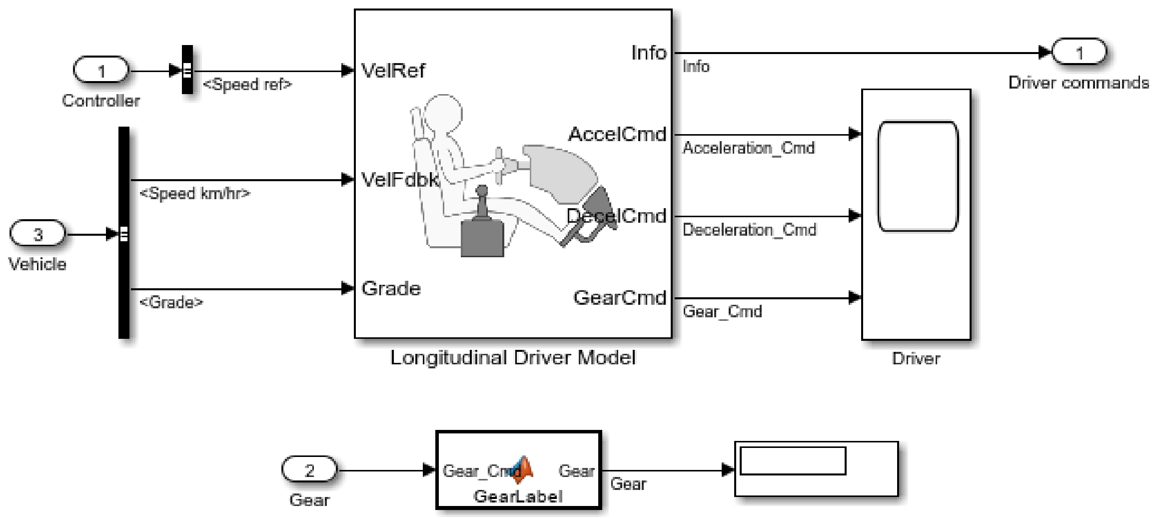

Figure 18: Driver subsystem - Simulink model

4 IMPLEMENTATION AND DEVELOPMENT

Phase 3 of the V-Cycle, “Implementation and Development”, involves the practical implementation of the control systems defined during the design phase. Control modules are developed and integrated with the physical vehicle model. This is a core phase where functional requirements are translated into operational logics ready for verification.
The *Control* block implements two key functionalities essential to system operation: torque control applied to the motor and the vehicle’s decision logic. The ABS and TCS blocks have also been included in an *Enabled* subsystem and are conceptually defined with internal logic, but they will not be analyzed in detail within the scope of this project. This is a core phase where functional requirements are translated into operational logics ready for verification.

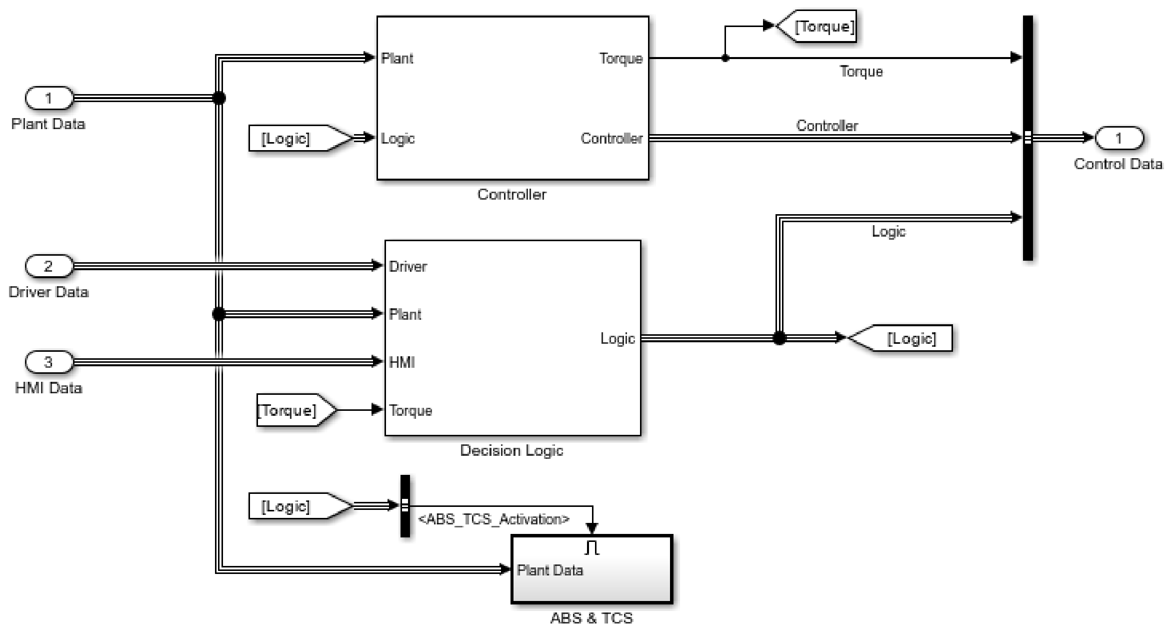

Figure 19: Control block - Simulink model

In this part of the project, the creation of an interactive dashboard (HMI) will be also presented. The HMI dashboard displays measured system parameters, as well as any messages, indicators and status lights, providing a real-time monitoring interface for the simulation.

4.1 Torque Control

In the model, a desired speed profile is used to compute the ideal torque to be applied to the motor, which is sent to the *Motor & Drive* block as a reference signal. However, there are two conditions in which this profile is overridden. The first is the activation of the *Zero Torque* signal, which forces the torque to zero in case of critical faults or when an immediate vehicle stop is required. The second is the activation of the limp mode, which limits the maximum torque to 30 Nm, for example when the battery is running low and the system switches to a degraded mode.

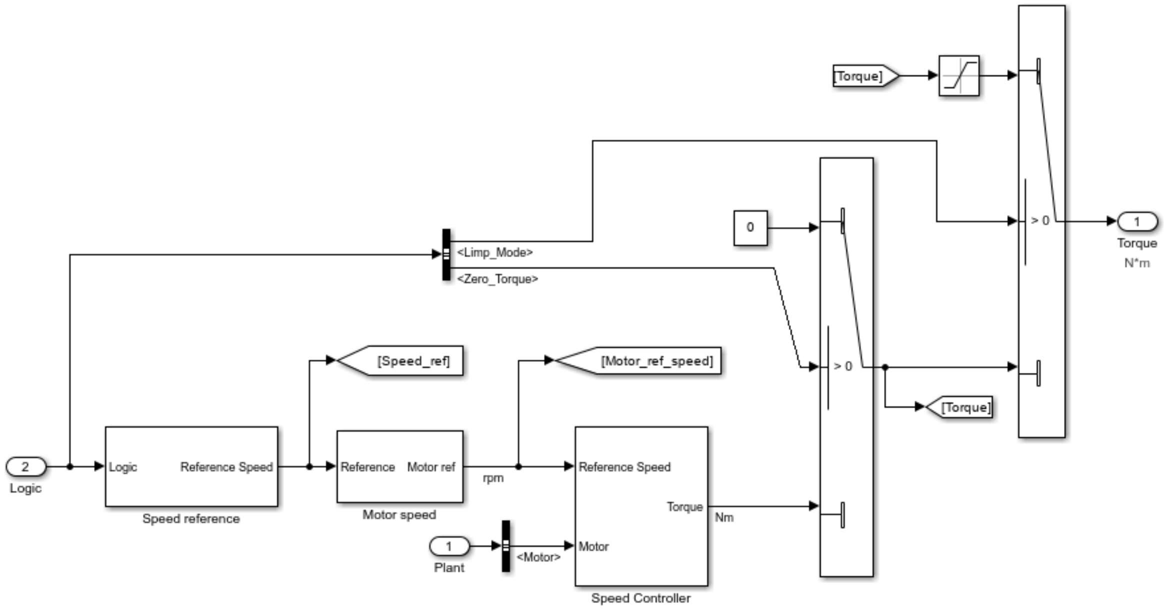

Figure 20: Torque control block - Simulink model

4.1.1 Speed Reference

The speed reference is defined through an input signal called *Simulation Case*, which is set within the control logic based on the operational phase to be simulated.

The first two speed profiles, *Simple Drive* and *High Speed Drive*, were generated in MATLAB and represent less dynamic driving cycles, suitable for testing under controlled conditions or at constant speeds.

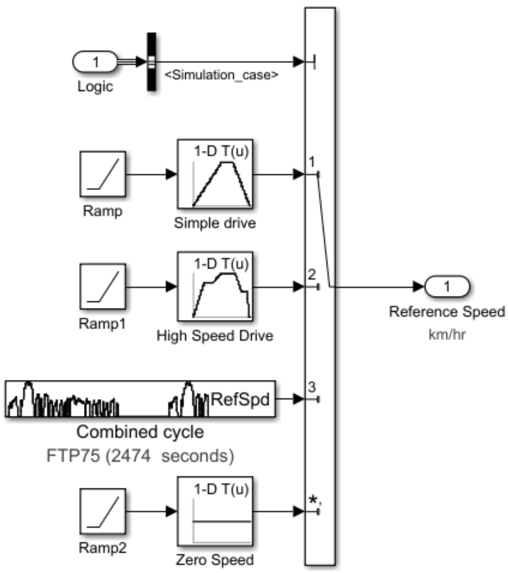

Figure 21: Speed reference model

The *Combined Cycle* profile is a block provided by Simulink and allows for the simulation of a realistic and variable driving cycle. This simulation case is used to assess the overall system behavior over longer time periods.
Finally, the *Zero Speed* profile is applied during operational phases where the vehicle remains stationary and no motion is expected, namely all modes except *Drive*.

The reference speed is then converted into the motor's rotational speed (in rpm) within the *Motor Speed* block.

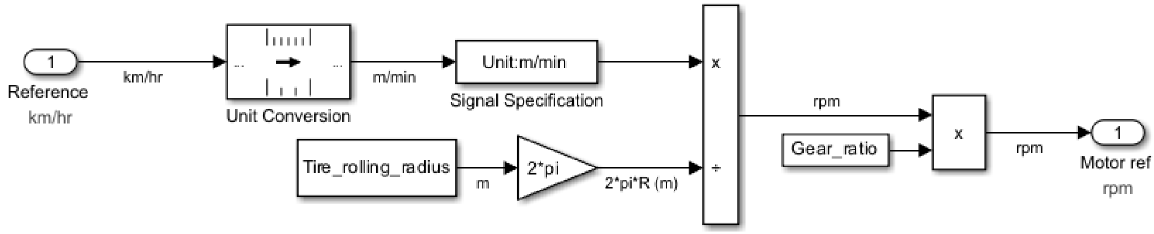

Figure 22: Conversion of the speed from km/hr to rpm

4.1.2 Speed Controller

A PI controller is then used to regulate the output based on the dynamic speed error, calculated as the difference between the reference speed and the actual motor speed.
The controller generates a torque signal, which is saturated at a maximum value of ±400 Nm. The actual motor speed is passed through a 20 Hz low-pass filter to attenuate high-frequency disturbances.
The PI (Proportional-Integral) controller combines a proportional response to the instantaneous error with an integral action on the accumulated error over time, enhancing system stability and reducing steady-state error.

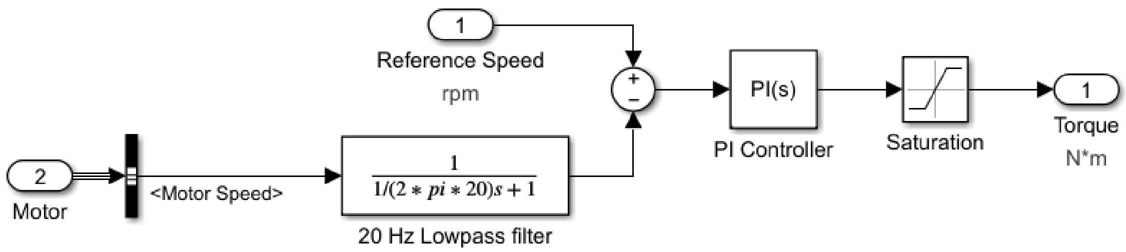

Figure 23: Speed controller model

4.2 Development of the System’s Decision Logic

To model and simulate the system's decision-making logic, Stateflow was used. It is a graphical environment within Simulink that enables the implementation of control logic based on finite state machines connected through transitions [18].

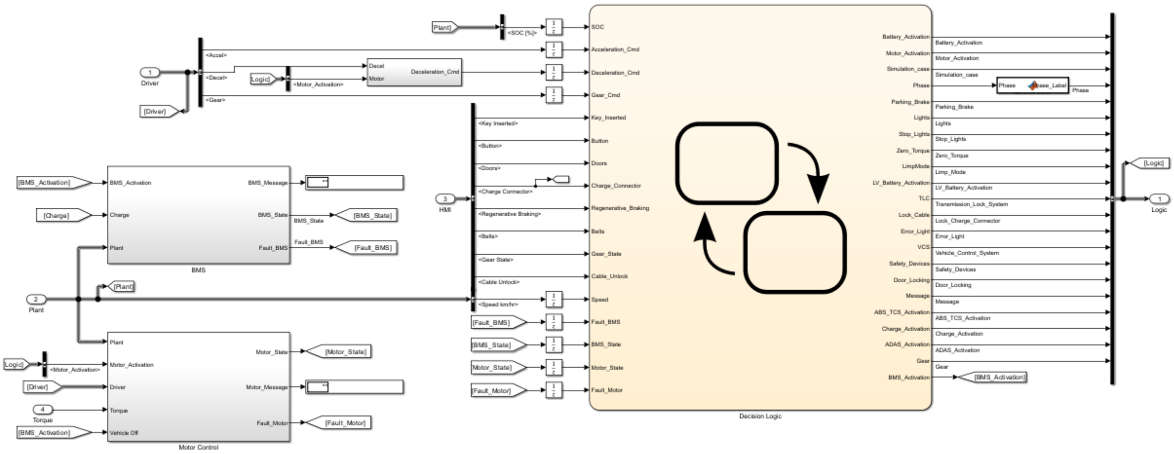

Figure 24: Decision Logic - Simulink model

In order to keep the overall system logic modular and readable, battery control and motor control were implemented in two separate subsystems, referred to as *BMS* and *Motor Control* respectively. These subsystems were properly interfaced with the main *Stateflow* chart, which manages the overall control logic.

For each Stateflow chart, specific inputs were configured to analyze system behavior and retrieve real-time information during the simulation. The inputs connected to the *Decision Logic* chart include:

- Commands received from the *Longitudinal Driver* (brake, throttle, gear position);
- The battery state of charge;
- HMI signals (key position, charge connector, start/stop button, cable unlock and all other user-defined inputs);
- Vehicle speed;
- Information received from the Battery Management (*BMS*) subsystem;
- Information received from the *Motor Control* subsystem.

Most of these inputs are connected through *Delay* blocks to prevent the creation of logical loops that would block execution.

The outputs from the *Decision Logic* chart are all the control signals used to manage system actions, such as battery and motor activation, parking brake control, dashboard warning lights and display messages. All other variables used within the chart are local variables, intended exclusivelly for communication between states and action executed internally by the chart.

4.2.1 Battery Management System (BMS)

The Battery Management System (BMS) is a fundamental component for the safety of a Battery Electric Vehicle (BEV), as it monitors and manages the vehicle's battery pack [19]. Its primary function is to continuously control the electrical and thermal parameters of the battery to ensure optimal operation and promptly detect any faults that could jeopardize passenger safety. In this context, only the high-voltage battery parameters are considered, since this component is more critical compared to the 12V battery, due to its requirement to supply significantly higher current.
As previously mentioned, a dedicated Stateflow chart was developed exclusively for battery monitoring. The input signals received by this chart include:

- The *BMS_Activation* signal, sent from the Decision Logic, which commands the BMS start-up;
- The Charge signal, a boolean indicating when the vehicle enters the charging phase, a critical phase during which the BMS must be active to monitor the battery status;
- The maximum and minimum reference values that define the limits for the control parameters;
- The electrical and thermal signals previously measured in the *Plant* model, namely vehicle speed, voltage, current, State of Charge (SOC) and vehicle temperature. Additionally, the estimated State of Health (SOH) of the battery has been included.

Since experimental data related to a real battery pack were not available, the SOH estimation was performed theoretically using a model dependent only on battery temperature [19], [20], [21]. The formula used for SOH estimation is as follows:

$$\mathrm{SOH} = \left(1 - \frac{\Delta \mathrm{C}}{\mathrm{C_{initial}}}\right) \cdot 100 \;\rightarrow\; \Delta \mathrm{C} = \mathrm{a_{SOH}} \cdot \mathrm{e}^{\left(\frac{\mathrm{b_{SOH}}}{\mathrm{T} - 273.15 + 293.15}\right)} \cdot \mathrm{Q_{charged}}$$

where $\mathrm{a_{SOH}}$ and $\mathrm{b_{SOH}}$ are empirical parameters used for illustrative purposes.

These parameters represent an approximation adopted for preliminary simulations in the absence of real data and will need to be properly calibrated with experimental data in future development phases.

As outputs, the Stateflow chart communicates the error string *Fault_BMS* and the status string *BMS_State*. The *BMS_Message* combines both strings and is displayed exclusively for BMS monitoring. Additionally, the activation and deactivation of the battery-related dashboard indicators are managed using the specific signals *BMS_Light* and *BMS_Temp_Light*.

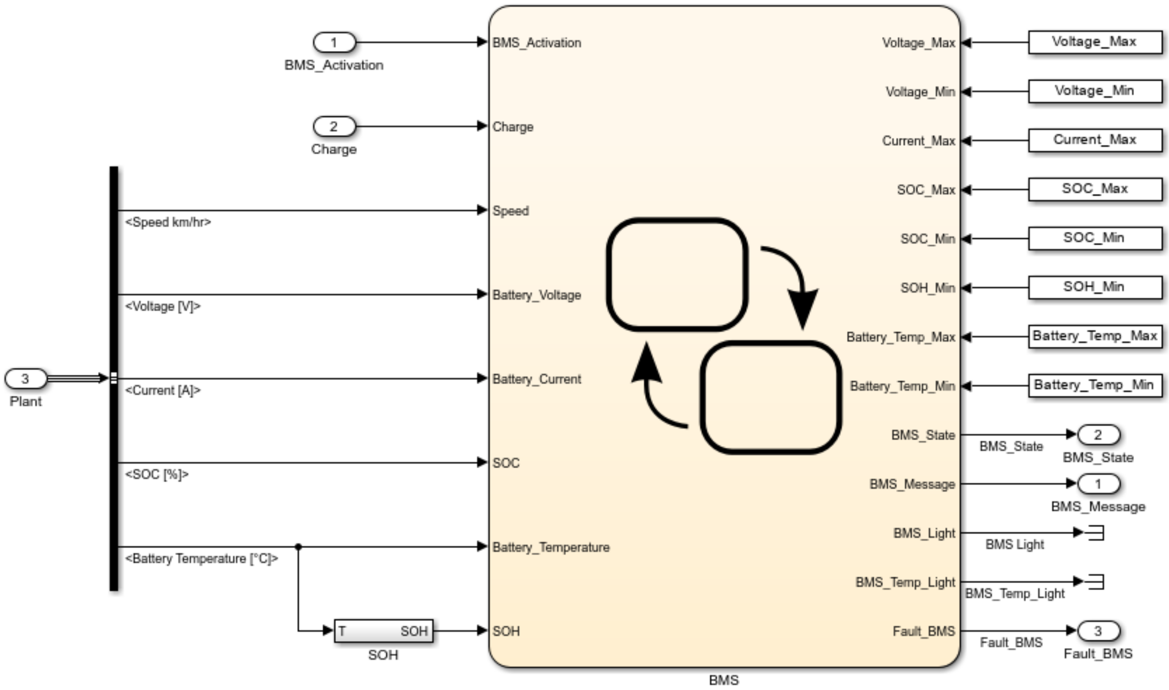

Figure 25: BMS - Simulink model

The initial state within the Stateflow block is a default state used to initialize messages and variables. When the BMS is activated, the BMS state is updated to "BMS Activation". After 20 seconds, the state changes to "BMS Activated Correctly" and, after an additional 30 seconds, it resets. The use of these timers is uniquely for simulation purposes, as during the Start-up phase, which includes BMS activation, it allows the BMS state to be displayed and messages to be properly read. During the charging phase, these steps are bypassed to allow immediate activation of the BMS as soon as the charging cable is connected. Once the activation messages have been displayed, the system transitions to the active BMS state, where all checks are performed. This state is exited only when the BMS is deactivated by the *Decision Logic*, returning to the default state.

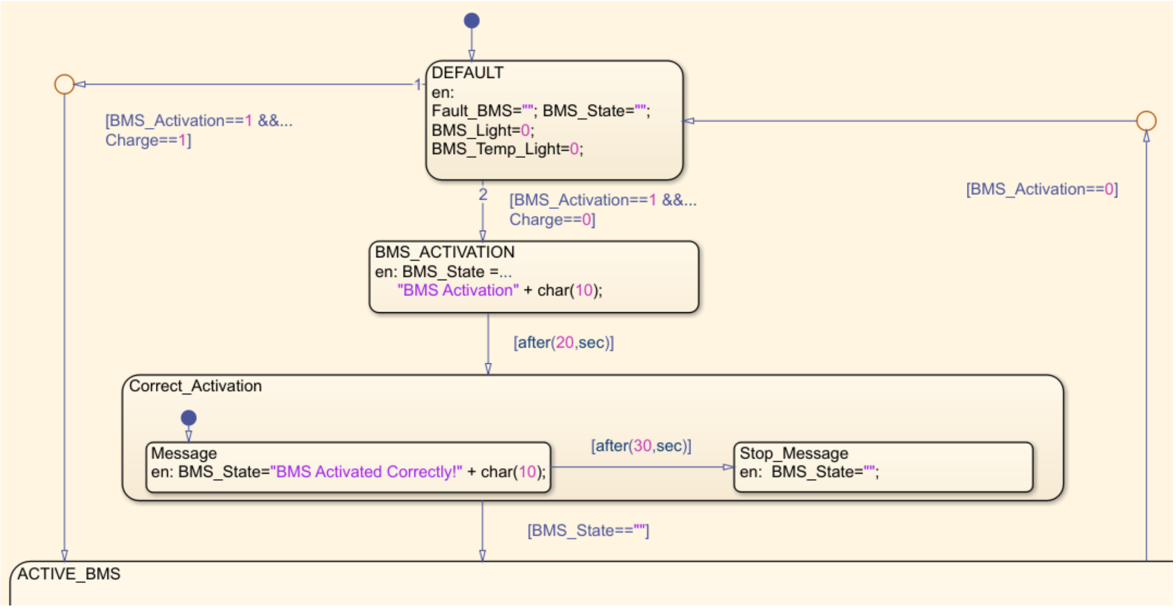

Figure 26: BMS - Stateflow model - Activation sequence

The monitoring of the main parameters is now carried out.

<u>Current monitoring</u>: The battery current is continuously monitored to ensure that its absolute value does not exceed the maximum allowed threshold of 500 A for more than 10 consecutive seconds. This interval allows short current peaks to be tolerated without immediate intervention, avoiding false alarms due to transient spikes. If the overcurrent condition persists beyond this interval, an error is generated to prevent potential thermal or structural damage.

<u>Voltage monitoring</u>: The battery voltage must remain within defined limits, not exceeding 117% of the nominal voltage (468 V) nor falling below 70% of the nominal voltage (280 V). If these thresholds are exceeded, overvoltage or undervoltage errors are notified accordingly.

<u>State of Health (SOH) monitoring</u>: The battery's health status is continuously checked. If the SOH falls below a critical threshold, here set at 50%, the error "BMS ERROR: Low SOH" is triggered.

For the above parameters, static diagnostics have been adopted, which means that once a fault is detected, it remains active throughout the phase even if the parameter later returns within limits. This approach is safer for critical components such as the battery. For the following parameters, a dynamic diagnostics approach is used, which involves continuous monitoring of the fault. If the abnormal condition ceases, the error flag can be cleared and the fault removed. This method applies to SOC and temperature, parameters that depend not only on the component's proper functioning but also on external factors.

SOC Monitoring: For the State of Charge (SOC), a maximum value (100%) and a minimum value (20%) have been set to maintain optimal operating conditions. In real vehicles, the 100% charge level shown to the user is actually slightly lower to prevent electrochemical stress and overheating. However, 100% represents the theoretical maximum charge. If this threshold is exceeded, an overcharging error is detected, considered critical because it can cause overheating and battery degradation. When the SOC reaches the maximum value during charging, the message “Battery Completely Charged” is displayed. The minimum SOC value is used to notify the user of the need to recharge. If it drops below 1%, an error is triggered and the vehicle must perform a controlled shutdown to ensure safety.

Temperature Monitoring: Temperature is a crucial parameter to monitor. Lithium-ion batteries generate heat during charge and discharge; excessive temperature increase can lead to degradation, capacity loss and serious risks such as fire or explosion. Therefore, a maximum temperature limit of 48°C is set, which the battery must not exceed. Low temperatures also cause damage; the minimum limit is 0°C. When the BMS detects temperatures approaching these limits (≥44°C or ≤5°C), it alerts the user. If the temperature exceeds critical limits, an error is flagged and the vehicle must be stopped. The battery temperature warning light on the dashboard turns on to provide a clear visual alert. If the temperature returns to a safe range, the light turns off, the message “Battery Temperature is OK” is displayed and the vehicle can restart.

Messages: During operation, all error and status messages are detected and aggregated, so the system can notify the user of multiple simultaneous faults or conditions. This message is sent directly to the *Decision Logic* to be processed together with all other information.

BMS Lights: In case of an error, besides displaying it on the screen, the battery fault indicator light on the dashboard is turned on, providing an additional clear visual warning to the user.

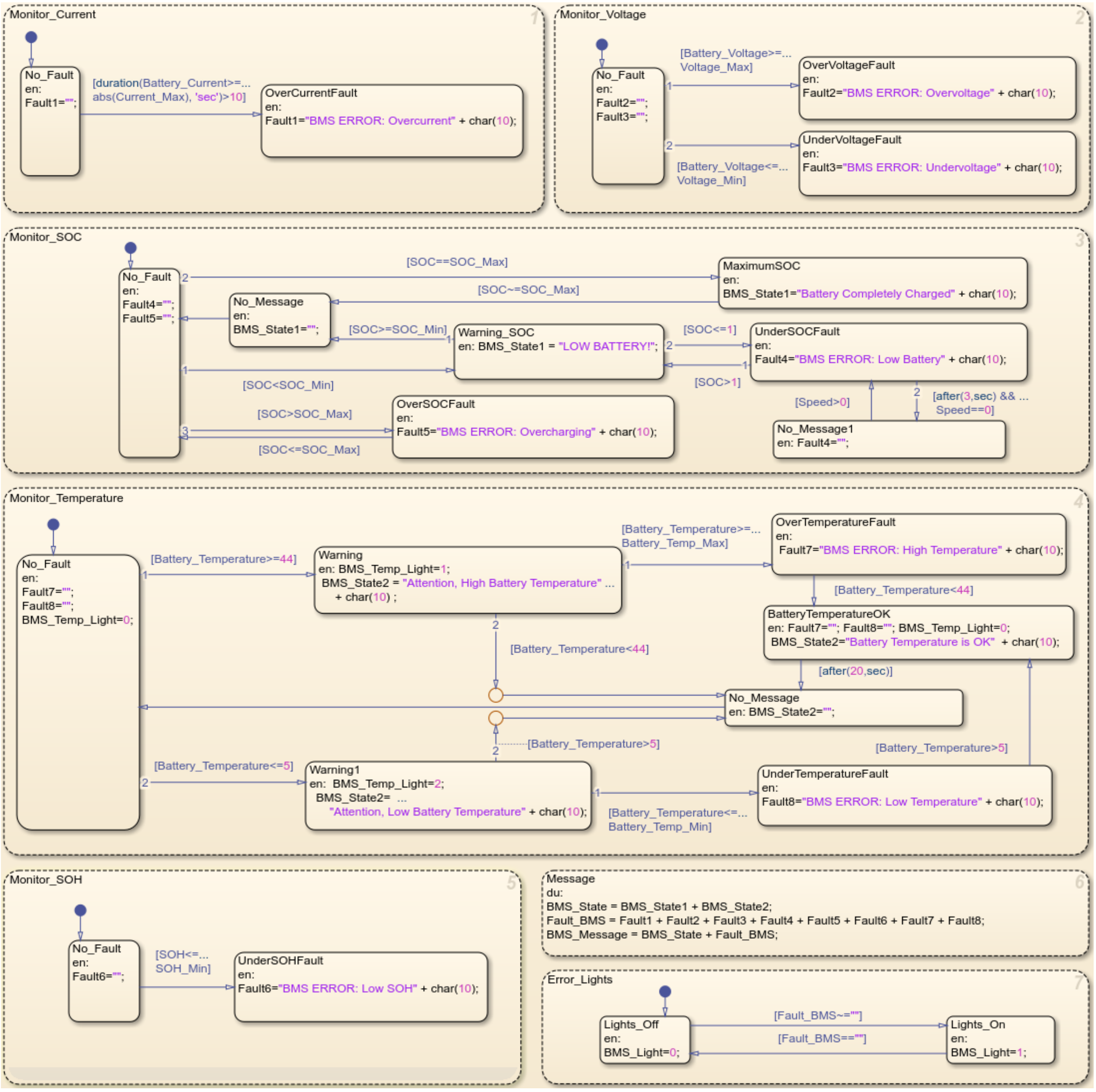

Figure 27: BMS - Stateflow model - Active BMS

4.2.2 Motor Control

Motor control is another fundamental aspect to ensure vehicle efficiency and reliability. It protects the motor from faults and guarantees appropriate and stable behavior during driving. The motor control block receives the following inputs:

- The *Motor_Activation* signal, used to turn the motor on or off;
- Motor temperature and imposed temperature limits;
- Information received from the *Driver* (acceleration and deceleration commands, gear position);
- The torque signal output from the *Controller* subsystem;
- Vehicle shutdown signal.

On the output side, it provides state and error messages as well as the activation signal for dashboard warning lights.

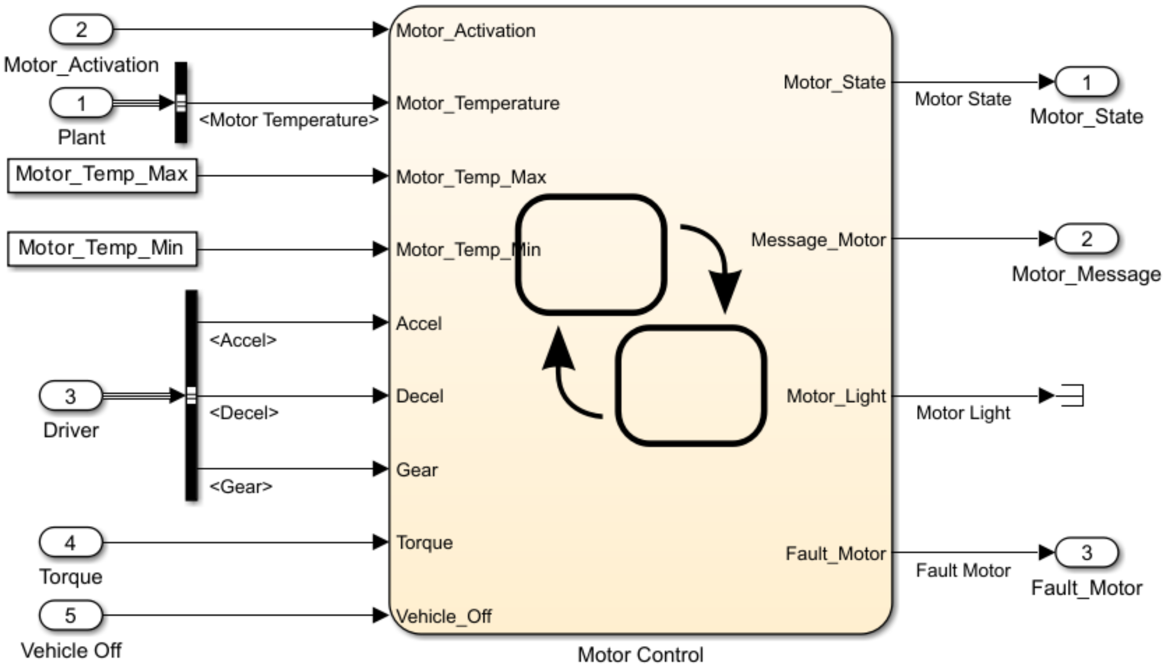

Figure 28: Motor Control - Simulink model

As in the BMS, the initial state within the Stateflow block of the *Motor Control* is a default state, used to initialize messages and variables. When the motor is activated, the state is updated to "Motor Activated Correctly". After 30 seconds, once the message has been displayed, the state is reset and motor control becomes fully active. When the vehicle is turned off, the motor control returns to the default state until it is reactivated.

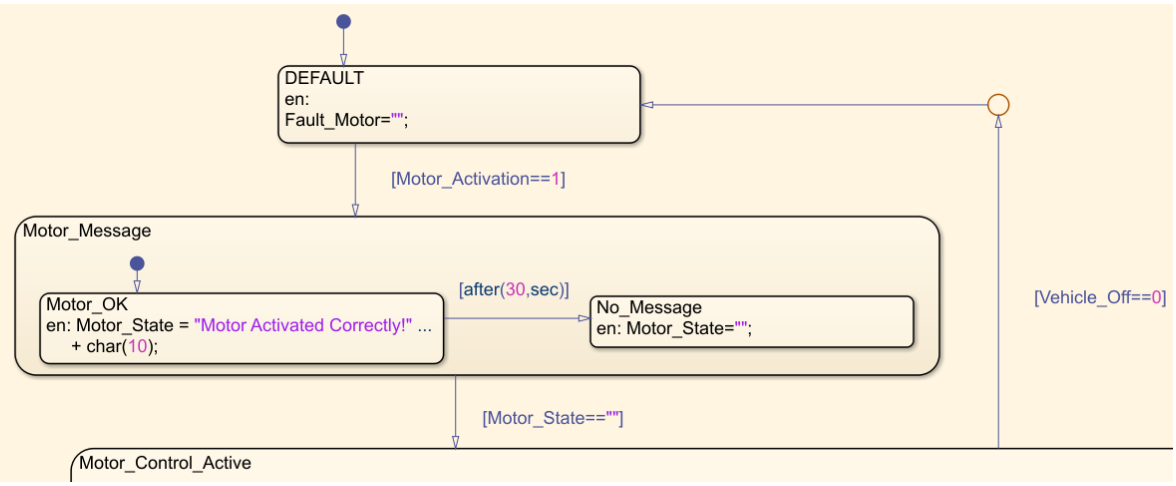

Figure 29: Motor Control - Stateflow model - Activation sequence

The active control block includes the following functions:

Motor temperature monitoring: This feature is essential to prevent overheating, which can damage internal components and cause premature failures. Therefore, as for the battery, a maximum temperature limit of 48 °C is set, which must not be exceeded. Extremely low temperatures are also harmful; the minimum acceptable value is 0 °C. When the temperature approaches the critical limits (≥ 44 °C or ≤ 5 °C), a warning is issued. If the limits are exceeded, an error is flagged and the vehicle must be stopped. Once the temperature returns to a safe range, the following message is displayed: "Motor Temperature is OK: vehicle can restart!".

Operational consistency monitoring: The system must ensure that the motor behaves consistently with the commands received from the *Driver*. A positive acceleration command must result in positive torque. Conversely, a deceleration command (greater than zero) must result in negative torque. If this consistency is not maintained for more than one minute during the driving phase, an error is triggered and the vehicle must be forcibly stopped.

Messages: The *Motor Control* sends its state and error messages to the *Decision Logic*. These messages are stored cumulatively in the variables *Motor_State* and *Fault_Motor*, which are then combined into *Message_Motor* for centralized handling.

Motor Light: The *Motor_Light* signal controls the activation of the motor warning indicator on the dashboard when an error is detected.

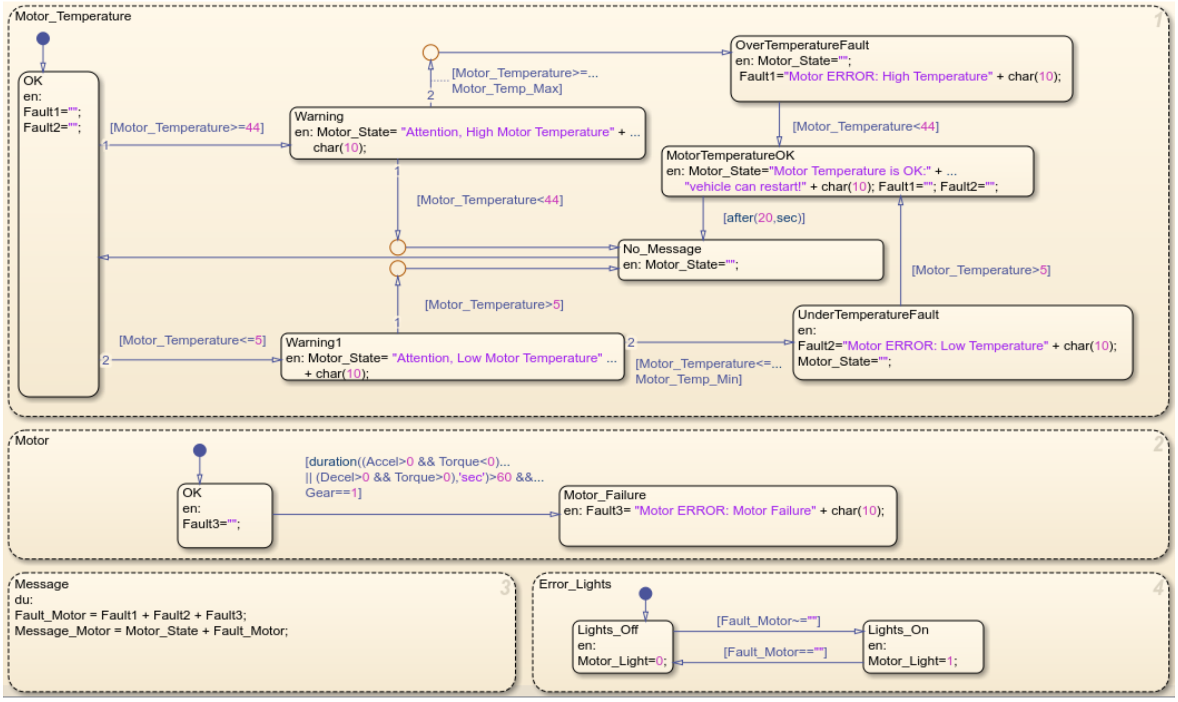

Figure 30: Motor Control - Stateflow model - Active control

4.2.3 Decision Logic - Start-up Phase

The structure of the *Decision Logic* is now presented, consisting of four main states corresponding to the four operational phases of the vehicle.

The initial block from which execution starts is *Power-off*. In order to start the vehicle, the key must be inserted, the charging cable must be disconnected and no active errors must be present. If all transition conditions are satisfied, the system enters the *Start-up* phase.

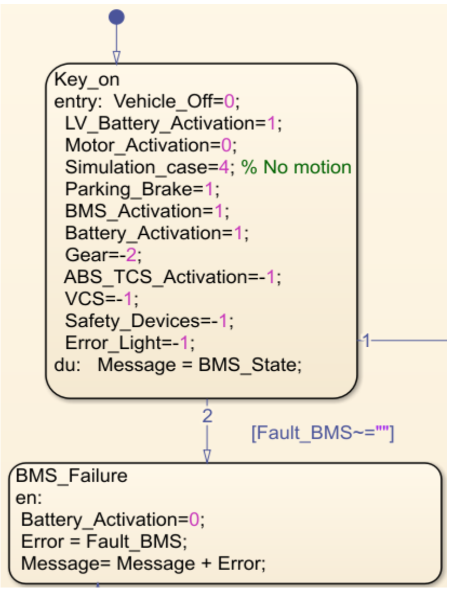

Figure 31: Start-up - Stateflow model - Key_on state

As soon as the *Key_on* state is activated, the vehicle powers on, enabling the high-voltage battery and the BMS. In this state, the *Simulation_case* signal, which defines the reference speed profile, is set to 4, corresponding to zero speed. The *gear* is set to -2, representing the *Park* state, and the *Parking Brake* is engaged. While this state is being executed, the message corresponding to BMS activation is displayed. If an error is reported by the BMS, the system transitions to the *BMS_Failure* state, which deactivates the battery. Otherwise, the initial vehicle diagnostics are performed during the *Initialization* phase.

During the *Initialization* phase, the following preliminary tests are performed:

Parking Brake Failure: This test analyzes the behavior of the parking brake. If the parking brake is not properly engaged during this phase, it constitutes an error that prevents the vehicle from starting. In case of failure, this error can be deliberately overridden by physically pressing and holding the brake pedal until the vehicle starts.

Safety Devices Failure: A fault in the safety systems detected during the *Start-up* phase is considered a critical error, as it compromises the necessary conditions to ensure safe vehicle operation. Therefore, it is essential to verify that all safety devices are active and, if not, to signal the error.

Vehicle Control System Failure: The VCS refers to the management of bidirectional communication among all vehicle subsystems. During this phase, it is ideally tested to ensure proper operation of decision logic and coordination among all vehicle components.

Light Test: A light test is performed where all lights are turned on for three seconds. Their proper function is confirmed during this time; if a fault is detected, it is notified to the user to prepare them accordingly.

Door Closure and Seat Belts: At start-up, all doors of the BEV must be properly closed and all passenger seat belts fastened. If open doors or unfastened seat belts are detected, the vehicle will not start until these conditions are met.

Messages: All diagnostic results are collected into messages. Successful tests return an empty string, while failed tests notify either an error or a warning, depending on the case. These messages are continuously updated throughout the diagnostic phase and communicated sequentially.

If the diagnostics detect no critical errors, all doors are closed and seat belts are properly fastened, pressing the start button will start the vehicle and transition it to *Ready* mode, notifying the user. At this point, the motor and Motor Control are also activated. If either the *Motor Control* or the *BMS* detect an error, *Ready* mode is suspended. Otherwise, if no errors are detected, after 40 seconds the message is reset and the vehicle can enter the driving phase. The timer allows setting the duration of the message display.

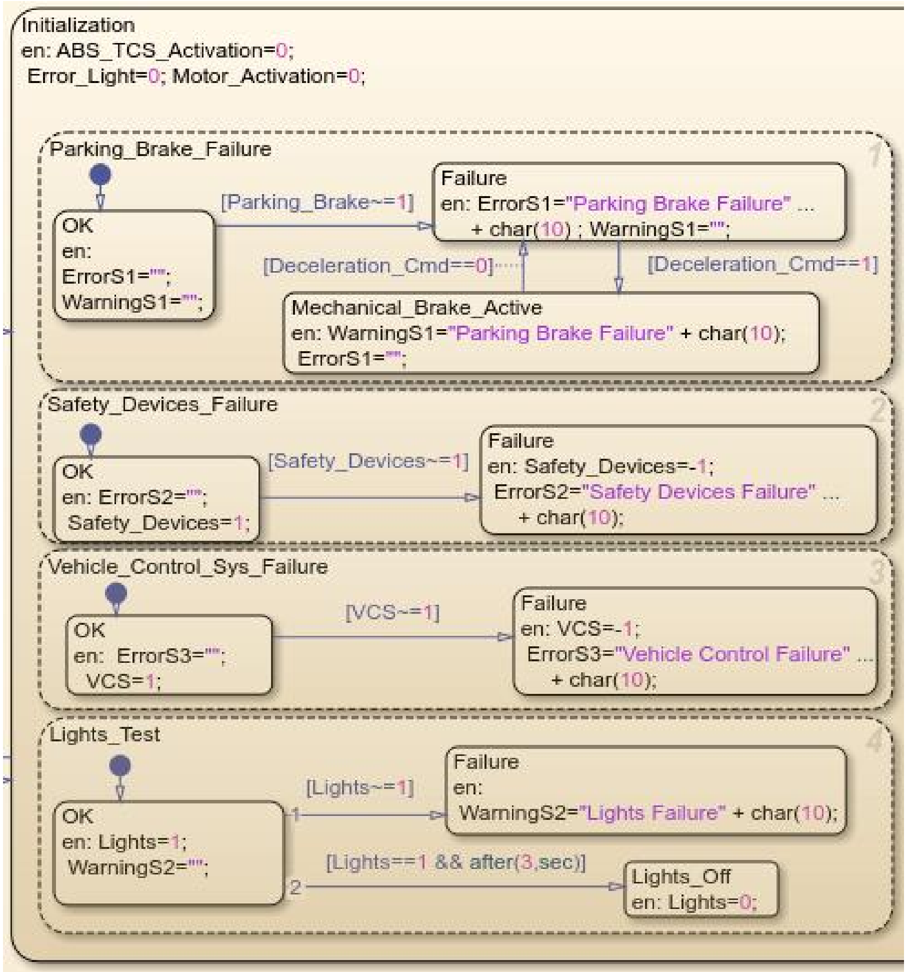

Figure 32: Start-up - Stateflow model - Initialization, states 1,2,3 and 4

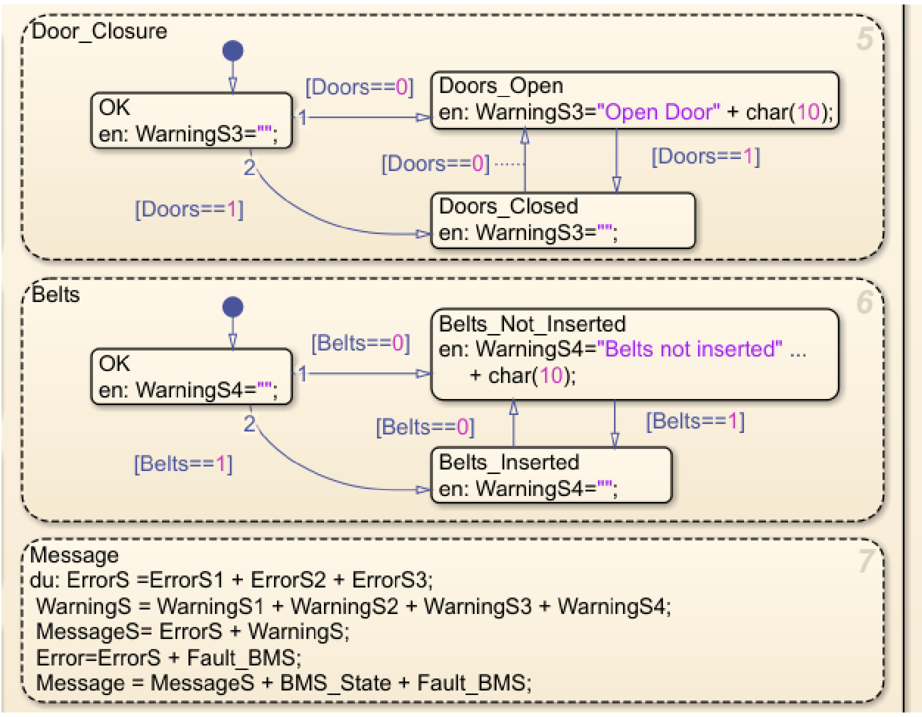

Figure 33: Start-up - Stateflow model - Initialization, states 5,6 and 7

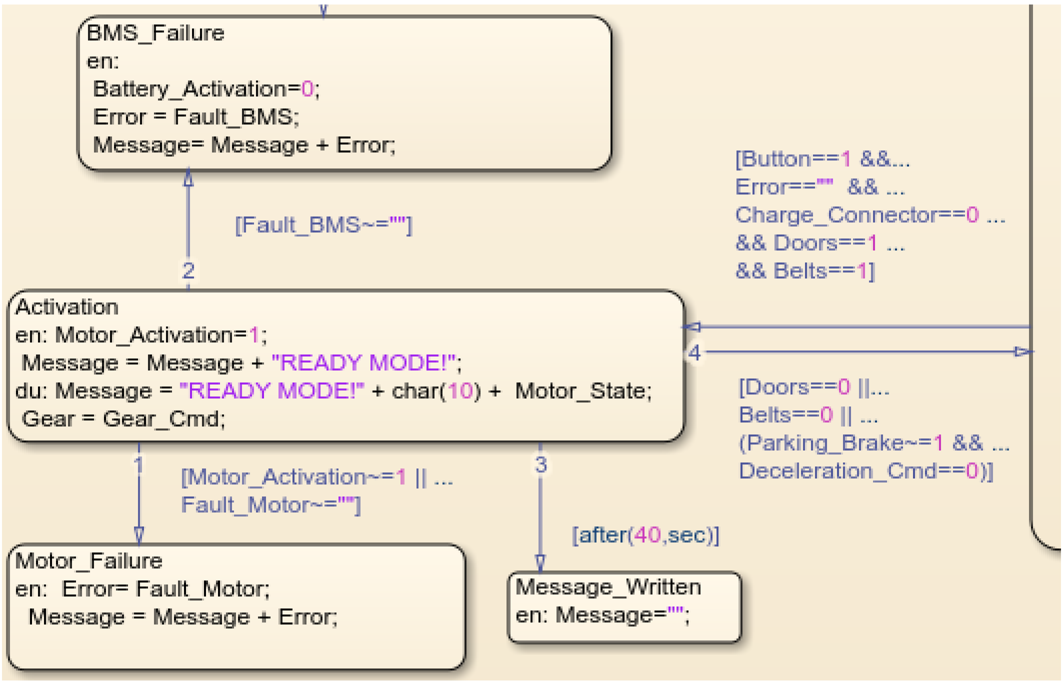

Figure 34: Start-up - Stateflow model - Ready mode

4.2.4 Decision Logic – Drive Phase

To transition to the *Drive* phase, the brake pedal must be pressed, the gear position must be set to 1 or -1 (for *Drive* or *Reverse*) and no errors should be present.
Upon entering the *Drive* phase, the parking brake is disengaged to allow the vehicle to enter the driving state. In this phase, the vehicle is actively moving under the driver's control. It therefore represents the most significant stage of the operating cycle. In this context, it corresponds to the phase when the controller calculates the torque required to follow the desired speed profile, which in this case is defined by the *Combined Cycle* (*Simulation_case* = 3). The following functions are managed during this phase:

<u>Regenerative Braking Management</u>: Regenerative braking is crucial in BEVs as it recovers energy during deceleration, increasing efficiency and range. However, when the battery's state of charge (SOC) is near full (>99%), regeneration can cause overcharging or stress, so it is important to disable it to protect the battery. This function can also be manually disabled by the user via a dashboard checkbox. To disable regenerative braking, since it is included in the torque generation logic of the controller, the *Zero_Torque* command is applied during braking to prevent the motor from rotating. Furthermore, the system monitors the correct activation of regenerative braking and notifies an error in case of malfunction.

Door Locking: Doors automatically lock once the vehicle speed exceeds 10 km/h, ensuring passenger safety and preventing accidental opening while driving.

BMS and Motor Monitoring: As previously mentioned, the *BMS* and *Motor Control* are directly connected to the *Decision Logic*, so any detected error triggers a system response.

Seatbelt Control: The seatbelt check performed during start-up is repeated during driving. If a seatbelt is unbuckled, the dashboard warning light turns on and the user is notified.

ABS, TCS and ADAS Systems: ABS (Anti-lock Braking System), TCS (Traction Control System) and ADAS (Advanced Driver Assistance Systems) must be active while driving.

- ABS prevents wheel lock-up during braking, enhancing stability and emergency steering capability.
- TCS prevents wheel slip during acceleration, ensuring traction and control, especially on slippery surfaces.
- ADAS includes technologies like lane keeping, automatic braking and adaptive cruise control to assist the driver and reduce accident risk.

In case of malfunction, the driver is alerted, but these faults do not prevent vehicle operation. They are treated as warnings that reduce safety but allow continued driving.

Stop Lights Control: Brake lights signal to other vehicles when braking is applied, indicating that the vehicle is slowing down or stopping.

Limp Mode: During the *Drive* phase, the battery state of charge is monitored. If it falls below 20%, the driver is alerted and limp mode is activated. This emergency mode limits vehicle performance to protect components, restricting torque to a maximum of 30 Nm and allowing the vehicle to move at reduced speed.

Message: All warnings and errors detected during this phase are collected, added to previous messages and communicated sequentially to the user.

In the event of a critical fault, the system exits the *Drive* state and transitions to the *Stop* phase.

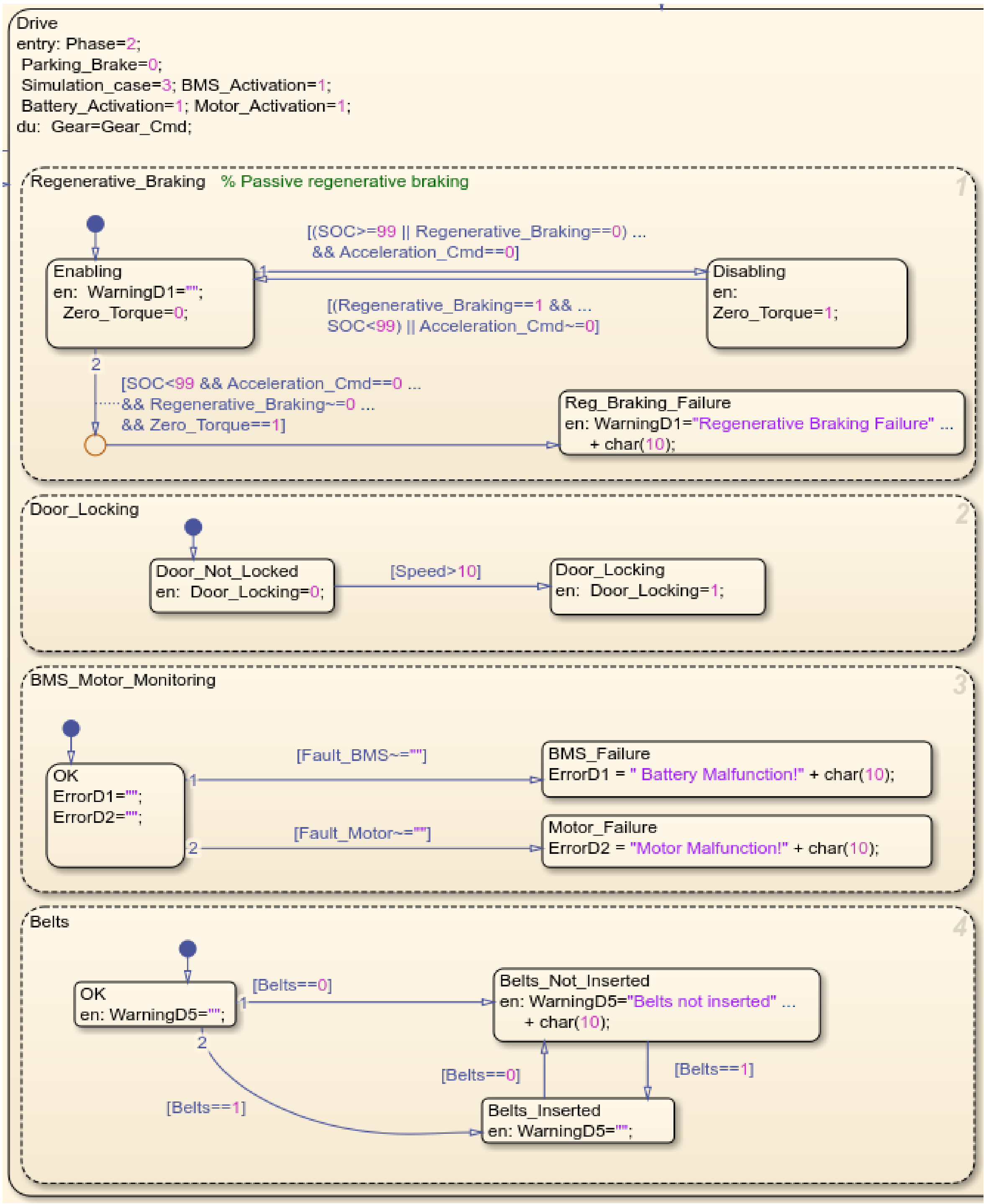

Figure 35: Drive phase - Stateflow model - States 1,2,3 and 4

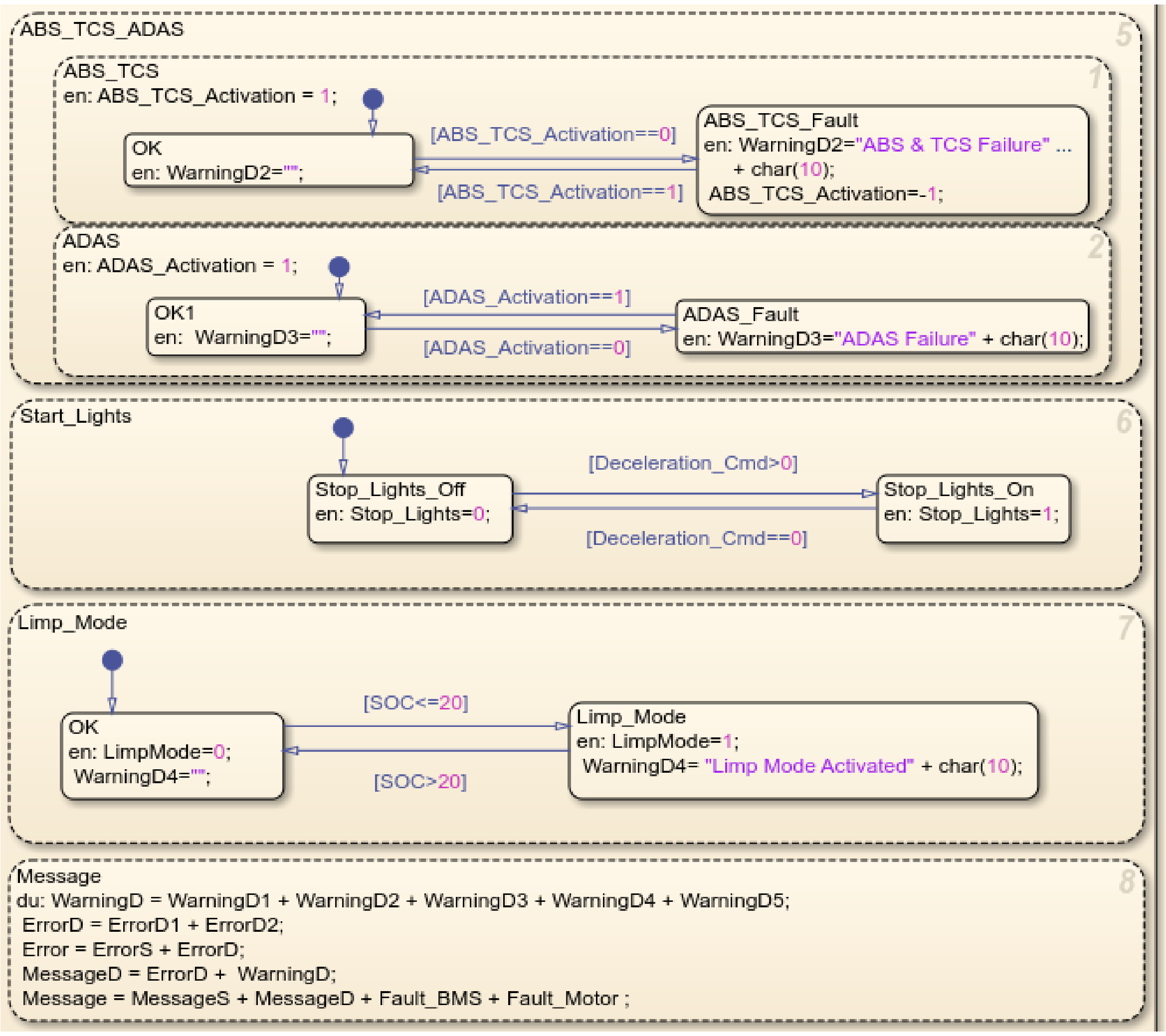

Figure 36: Drive phase - Stateflow model - States 5,6,7 and 8

4.2.5 *Decision Logic – Charge Phase*

The *Charge* phase can only be entered from the *Stop* phase. It is activated when the charging cable is connected, but only if the parking brake is engaged, the battery is not fully charged and no critical faults are present. Since charging directly involves the battery, it is essential for the BMS to be active. Once the charging phase is activated, the message "Battery is charging!" is displayed and current begins to flow into the battery. Two charging modes, slow (20A) and fast (80A), are available and can be selected via a combo box in the HMI. The following functions are managed during this phase:

<u>Cable Locking</u>: Once inserted, the charging cable is mechanically locked to prevent accidental disconnection. It can be manually unlocked via a dedicated dashboard button, or the lock is automatically released when charging stops due to an error or full charge.

The unlock button starts a 30-second timer. If the charging cable is not disconnected within this time, the locking mechanism is automatically reactivated. To unlock the cable again, the button must be pressed once more.

Detection of Undesired Movement: It is crucial that the vehicle remains stationary during the charging phase to avoid stress on the cable, which could become disconnected or damaged, potentially leading to hazardous battery faults. If any movement is detected, charging is immediately stopped and the error “Undesired Movement” is triggered.

Charging Interruption at SOC = 100%: When the battery reaches 100% SOC, charging is halted to prevent overcharging and its possible consequences. Continuing to charge a fully charged battery can cause thermal buildup and accelerate electrochemical aging. Disabling charging at this point is an essential safety measure to ensure system durability. As previously noted, 100% SOC is a theoretical maximum and not a real value, as in practical applications the maximum SOC is intentionally kept below this threshold to reduce risks.

BMS Monitoring: During the charging process, the BMS continuously monitors battery conditions to ensure safe and efficient charging. The charging phase is indeed the most critical for the battery, as it involves the flow of high currents. An anomaly in parameters such as overcurrent, overtemperature or overvoltage can lead to dangerous overheating, compromising vehicle safety. Moreover, monitoring allows the charging process to be optimized according to the battery’s condition, reducing energy waste. In the event of a fault, charging must be interrupted to prevent irreversible damage to the system.

Messages: Any notifications and errors are processed and communicated to the user.

The charging phase can be exited due to several events:

1. When charging is manually stopped by pressing the unlock button and disconnecting the cable;
2. When charging is complete and the SOC reaches 100%;
3. When an error is detected that requires charging to be deactivated.

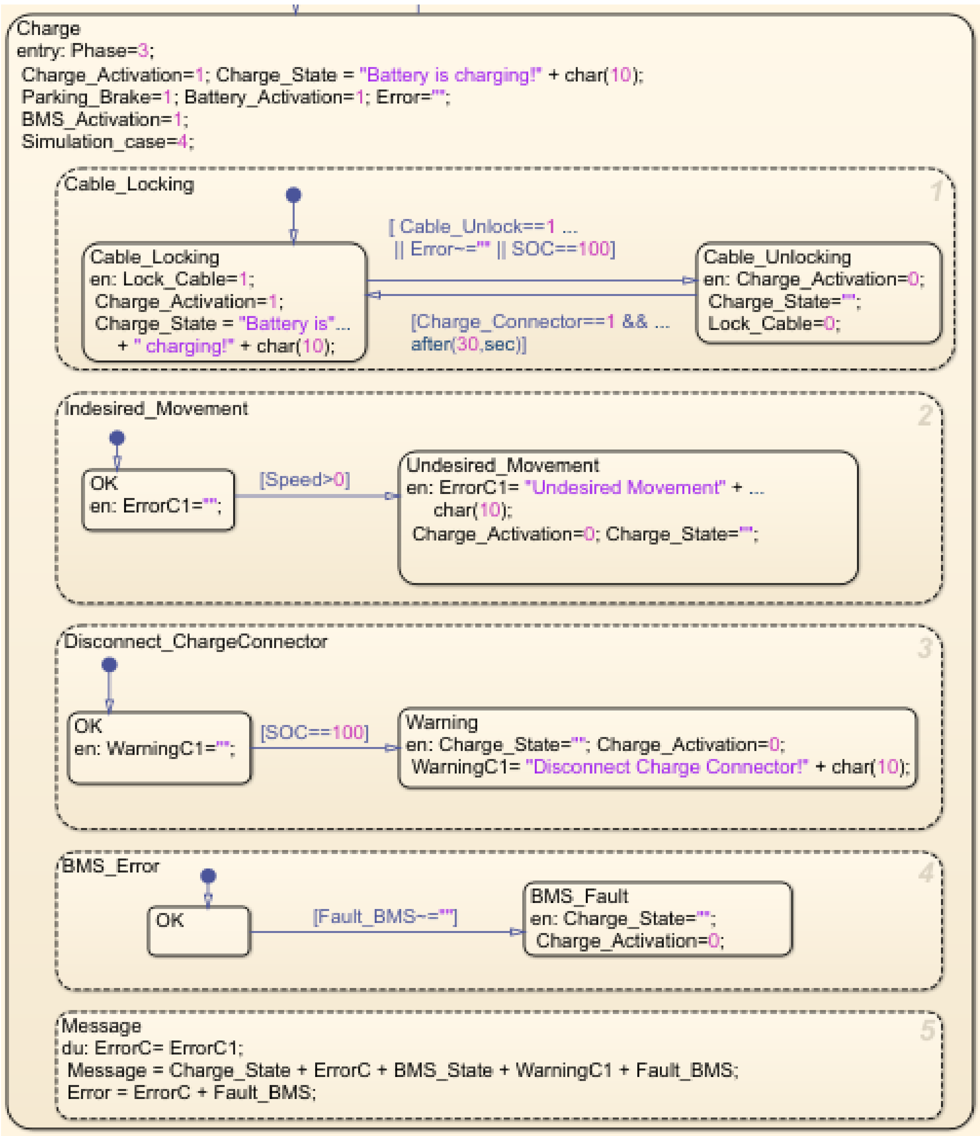

Figure 37: Charge phase - Stateflow model

4.2.6 Decision Logic – Stop Phase

Within the *Decision Logic* implemented in Stateflow, the transition to the *Stop* phase occurs under four main scenarios, which represent the conditions requiring the vehicle to stop or shut down:

1. When, during the *Start-up* or *Drive* phases, the vehicle is stationary and the park mode is selected on the gear;
2. When, during the *Start-up* or *Drive* phases, the vehicle is stationary and a shutdown is requested via the Start/Stop button or by removing the key;
3. When a critical error is detected during any operational phase;
4. When the *Charge* phase is interrupted, either manually, upon completion of charging or as a result of a fault.

Since the Stop phase includes both the condition in which the vehicle is on but stationary and the condition in which it is completely turned off, an initial OFF/ON state is defined to detect the presence of the key:

- If the key is inserted, the system enters the *Stop* state.
- If the key is removed, the system transitions to the *Power-off* state.

From this OFF/ON state, the four scenarios described above determine the specific behavior within the *Stop* phase.

Park Mode Selected.

If the vehicle is on, with the key inserted, and Park mode is selected while the vehicle is stationary, the system transitions to the *Stop* state, where the battery remains active. Subsequently, it proceeds to the *Park* state, in which the high-voltage battery is deactivated while only the low-voltage battery remains active. Motor deactivation is also essential to prevent torque transmission to the wheels. The velocity profile is set to Simulation Case 4 (*Zero Speed*). The parking brake and stop lights are activated and the doors are unlocked. In this state, the Traction and Launch Control (TLC) system is activated; it integrates traction control (TCS) and launch control to improve grip during acceleration. Any status or error messages are notified to the driver.

From this phase, it is possible to either restart or turn off the vehicle. To restart, the brake pedal must be pressed and *Drive* or *Reverse* selected on the gear. If the SOC is above 20%, the charging cable is disconnected and no errors are present, the vehicle returns to the *Drive* phase and resumes movement.

If the vehicle is to be turned off from the *Park* phase, pressing the Start/Stop button switches to the *Power-off* state. This state is also automatically activated when the key is removed, causing the vehicle to shut down.

Vehicle Shutdown.

From the *Park* phase, it is possible to access the vehicle shutdown phase. Activating the Power-off state triggers a sequence that deactivates the motor control, BMS and various subsystems (ABS, TCS, ADAS, HMI, etc.). The low-voltage battery remains connected to supply essential systems such as the Electronic Control Unit (ECU) in standby and the Body Control Module (BCM) for anti-theft and door management. The 12V battery is also crucial for restarting the vehicle. During this phase, error messages are reset and dashboard warning lights are turned off. Once the key is removed, the vehicle is considered turned off.

A door locking operation was also simulated by setting the *Door_Locking* variable to 1. From this state, it is possible to enter the *Charge* phase by connecting the charging cable or the *Start-up* phase by inserting the key.

<u>End of Charging</u>.

When entering the *Stop* phase after exiting the charging phase due to an error or completion, a different logical path is followed. If the charging cable connection is detected in the OFF/ON state, the vehicle does not immediately transition to Park or Power-off but displays the message “Charge has been stopped” to the user. Charging is interrupted, but the BMS remains active to monitor the battery until the cable is disconnected. Maintaining the BMS active even during charging interruption, without disconnecting the cable, is essential to ensure continuous monitoring of the battery conditions. This management allows for the timely detection of any anomalies or variations in critical parameters such as temperature, voltage and current, reducing the risk of irreversible damage. Consequently, keeping the BMS active helps preserve the safety of the vehicle. Once the charging cable is disconnected, the system returns to the initial charging phase, which can be either Power-off or Park.

<u>Error Detection during Start-up or Drive</u>.

The *Stop* phase also serves as an emergency phase in case of a critical error. If, during driving or *Ready* mode, an error preventing vehicle operation is detected, the *Stop* phase is activated and the error state is set. Upon entering Stop, the battery remains active. When an error occurs, the hazard lights activate and the message “The vehicle cannot move!” is displayed to the user. If the vehicle is moving (speed greater than zero), the stop is not immediate but preceded by a limp mode, which reduces performance and allows the driver to safely pull over. Once the vehicle stops, it can transition to Park; otherwise, limp mode lasts for 180 seconds, after which a zero torque command is issued to force a complete stop.

The *Stop* phase, specifically the *Power-off* state, also constitutes the initial phase considered for the system’s simulation and validation. Starting from the vehicle turned off was deemed the most suitable choice for simulating a real operational cycle.

Figure 39 shows the overall diagram of the *Decision Logic* block, where the four operational phases just described are connected through the transitions analyzed in *Table 3* of this document.

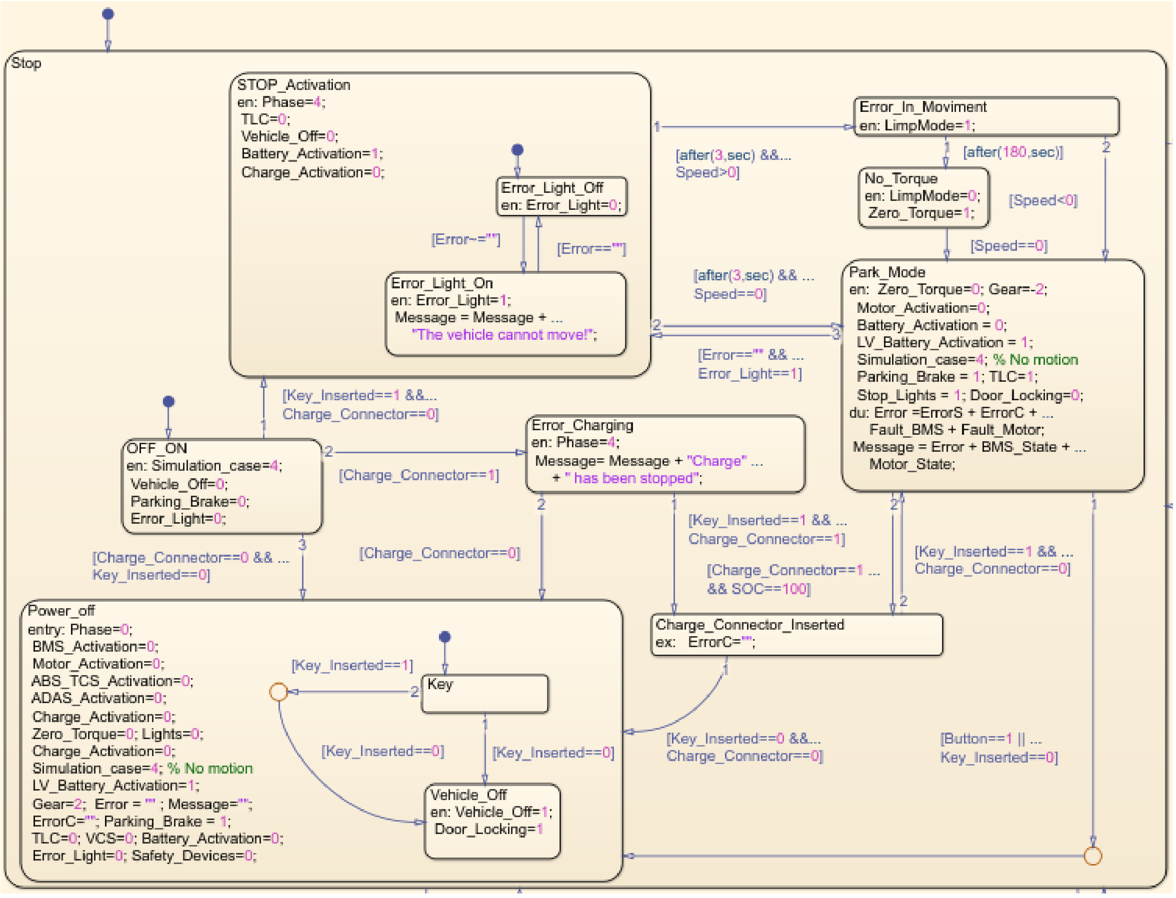

Figure 38: Stop phase - Stateflow model

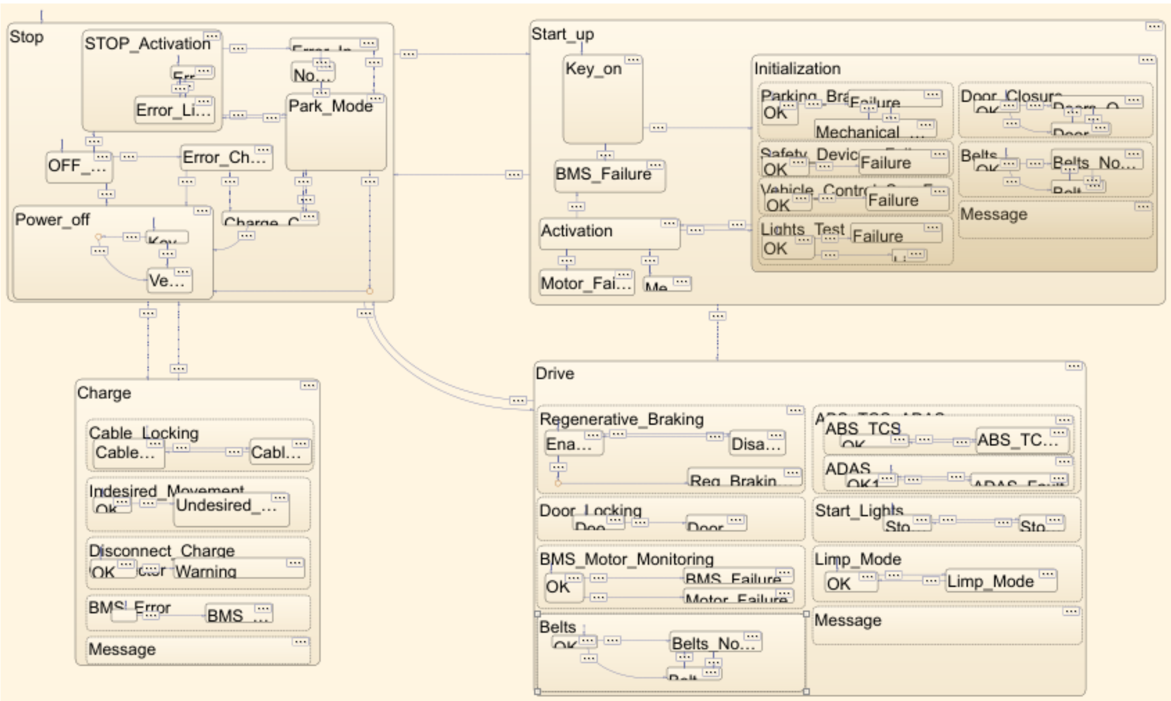

Figure 39: Decisional Logic - Stateflow model

4.3 HMI Dashboard

Within the context of this thesis project, an HMI (Human-Machine Interface) dashboard was implemented with the objective of providing an effective interface for real-time monitoring of the electric vehicle's control parameters. This system plays a crucial role in ensuring bi-directional communication between the driver and the vehicle, enabling continuous visualization of essential operational data and timely transmission of status messages, errors and relevant user information. The use of this interface significantly improves safety by assisting the driver in interpreting the operating conditions of the BEV and enhancing the overall system reliability. In summary, the HMI system constitutes an essential component for managing human-machine communication to ensure the safe and efficient operation of the vehicle. The following figure shows the HMI interface created using the *Dashboard* library in Simulink, which contains the blocks necessary for building the interactive interface.

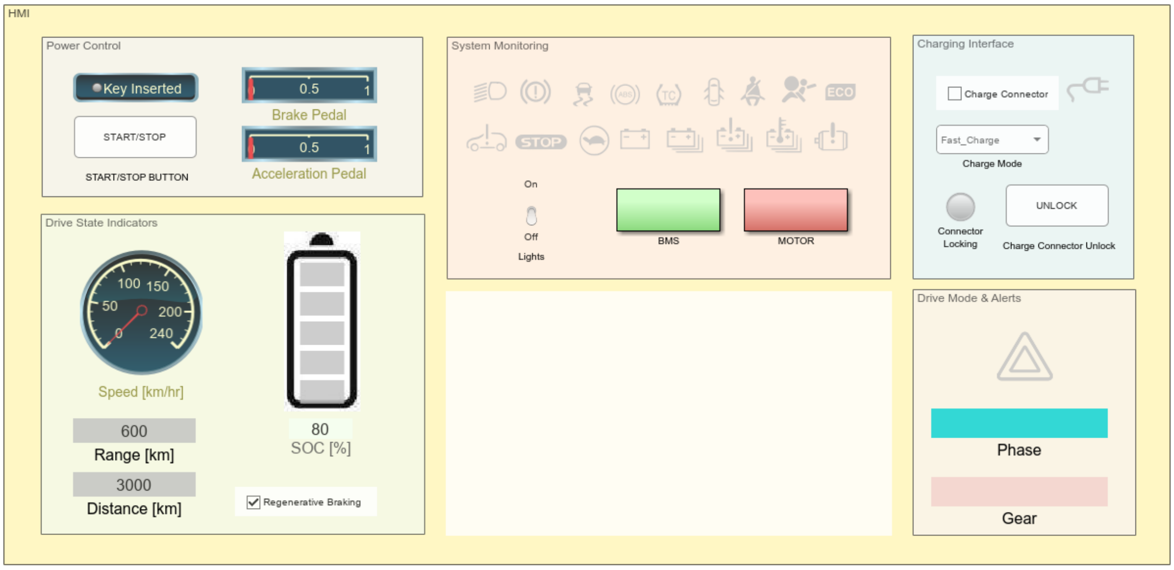

Figure 40: HMI - Simulink model

The interface has been divided into six sections to enhance clarity and communication efficiency. Each module groups related functions, facilitating targeted and intuitive management by the operator. The individual modules composing this subdivision are described below.

<u>Power Control</u>

This module manages the vehicle start and stop functions and the simulation of pedal inputs, controlling the activation of the vehicle's power state.

The key insertion is represented by a latch button, while the Start/Stop button is momentary and activates the signal only while pressed. To simulate pedal pressure, two horizontal gauges have been used, one for the brake and one for the accelerator, connected to the output signals from the *Longitudinal Driver* block. These gauges are not manually controlled but represent the actual pressure that a driver would apply to the pedals to execute the desired speed cycle set in the *Controller* subsystem.

Drive State Indicators

This section groups signals directly related to vehicle dynamics and provides real-time information to the driver, useful during the driving phase.
It includes a circular gauge that displays the vehicle speed in km/h in real time. Two displays are used to show the remaining range in kilometers and the total distance traveled by the vehicle. The "Regenerative Braking" checkbox allows the driver to disable regenerative braking while driving. Finally, the State of Charge (SOC) indicator was created by combining five different LEDs. It informs the user of the battery charge status, divided into five ranges. The following image shows the indicator visualization for the five possible cases: 0%-20%, 21%-40%, 41%-60%, 61%-80%, 81%-100% (rounding to the nearest integer).

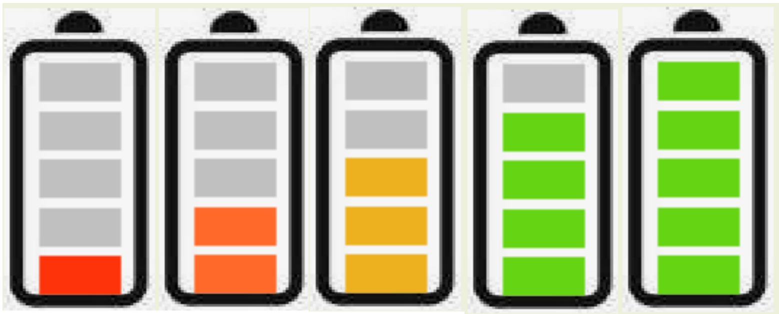

Figure 41: HMI - SOC indicator

System Monitoring

This section manages the monitoring and display of the vehicle systems' status, including warning indicators and in-depth supervision of the *BMS* and *Motor Control*. This ensures continuous diagnostics of the main components, enhancing reliability and safety.
Additionally, a switch is included to turn the headlights on and off. This control is symbolic, as it can also apply to other types of lights, such as high beams or interior vehicle lights. Below, the meanings of the various indicators are listed [22].

Figure 42: Indicators - HMI [22]

Starting from the top row, from left to right, the indicators represent:

- *Low beam headlights indicator*: controlled by the switch in this section, it is activated for three seconds during the vehicle's initial diagnostic;
- *Parking brake indicator*: lights up when the parking brake is engaged and turns off when released;
- *Vehicle stability control system indicator*: lights up when the system is active and turns off after a few seconds;
- *Anti-lock Braking System (ABS) indicator*: lights up at start-up and turns off after a few seconds. If it lights up during driving, it indicates an ABS fault;
- *Traction Control System (TCS) indicator*: lights up at start-up and turns off after a few seconds. If it lights up during driving, it indicates a traction control fault;
- *Door open indicators*: indicate one or more doors are open;
- *Seat belt indicator*: signals unfastened seat belts;
- *Airbag indicator*: lights up at start-up and turns off after a few seconds. If it lights up during driving, it indicates an airbag fault (in this project it represents a generic safety device fault);
- *ECO mode indicator*: lights up when ECO mode is active, i.e., when the battery SOC$\leq$ 20%, indicating reduced energy consumption to extend the remaining range.

Moving to the bottom row, again from left to right:

- *Electrotechnical system fault indicator*: signals an electrotechnical fault within the vehicle, potentially related to the battery or motor;
- *Immediate stop indicator*: lights up at startup and turns off after a few seconds. It indicates the need for an immediate vehicle stop;
- *Limp Mode indicator*: lights up when limp mode is active, meaning vehicle performance is limited;
- *12V battery indicator*: lights up at startup and turns off after a few seconds. If it lights during driving, it signals the low voltage battery is overcharged or discharged;

- *High Voltage (HV) battery level indicator*: lights up when the battery charge drops below 20%, reaching the reserve threshold;
- *Traction battery fault indicator*: signals a fault in the HV battery;
- *HV battery temperature warning indicator*: lights up when the temperature is too high. It is also used to indicate low temperature by illuminating blue instead of red;
- *Electric motor fault indicator*: signals a malfunction of the electric motor.

Below is the BMS monitoring interface. This section displays in real time the values of current, voltage, temperature, state of health and state of charge of the battery. The two displays at the top show the BMS status messages (*BMS State*) and any error messages (*Error*), respectively.

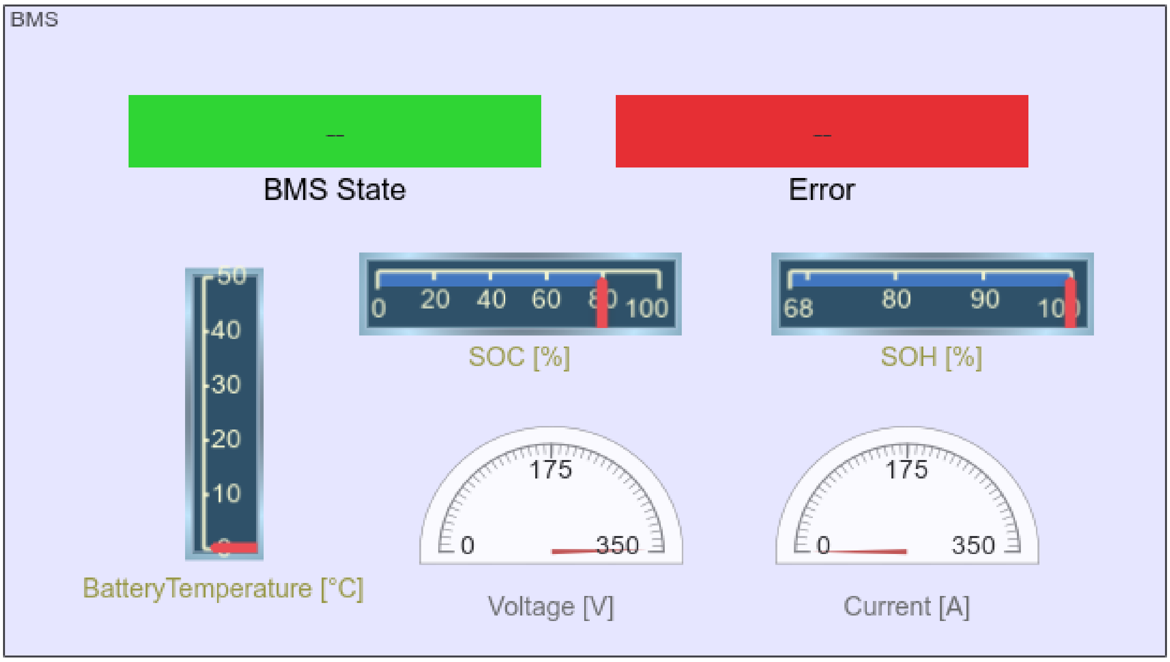

Figure 43: BMS - HMI

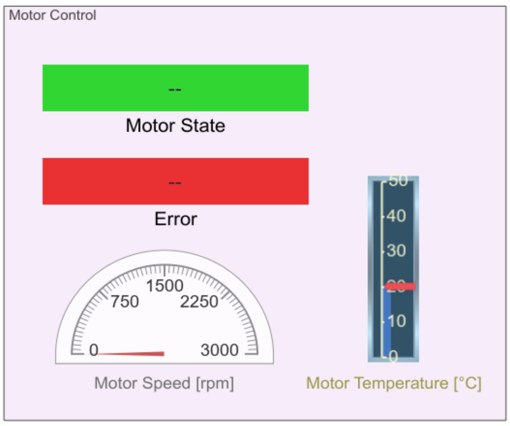

Figure 44: Motor Control - HMI

In the block dedicated to the motor, the temperature and speed values related to this component are displayed. Status messages and any errors concerning the motor are also shown on the respective displays.

Display

The central display is used to show communication messages and error notifications, serving as a direct textual interface between the system and the user for information delivery.

Charging Interface

The charging interface manages the interaction related to the battery charging process. A checkbox simulates the connection of the charging cable, activating the corresponding connection indicator located to its right. The type of charging, either *Slow Charge* or *Fast Charge*, can be selected using a combo box. Additionally, a LED indicates the mechanical locking of the cable, which can be released using the corresponding *UNLOCK* push button.

Drive Mode & Alert

This section includes the visualization of the current operational phase of the vehicle and the selected gear mode, through two dedicated displays directly connected to the system's *Decision Logic*. Additionally, a warning indicator is activated in the event of a fault or malfunction, lighting up in red to notify the user of the error.

In the context of the human-machine interface, additional functional blocks were also employed, although they were not included in the main HMI screen, as they are not essential for system analysis. Specifically, three combo boxes were used to simulate: fastening/unfastening of seat belts, opening/closing of doors and manual gear selection. Furthermore, two LEDs were used to indicate the locking/unlocking status of the doors and the activation/deactivation of the Advanced Driver Assistance System (ADAS).

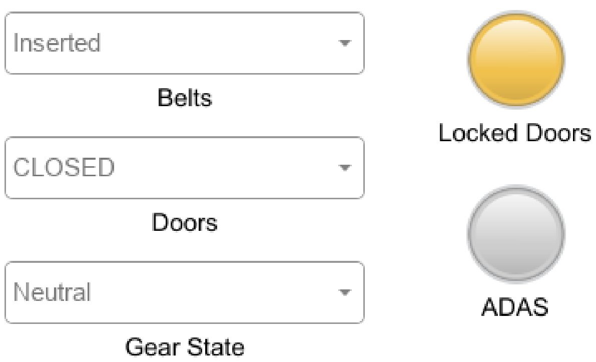

Figure 45: Additional functional blocks - HMI

5 VERIFICATION AND TESTING

The *Verification and Testing* phase represents a critical part of the project, as it ensures that the generated model correctly meets the requirements defined during the initial phase. The tests were designed to include two different levels: unit testing and integration testing. Specifically, unit testing involves verifying the operation of each component in isolation, ensuring its correct behavior. Integration testing, on the other hand, focuses on the interaction between various subsystems, in order to detect any issues arising from their integration. Together, these two levels of testing form the basis for ensuring that the system has been correctly implemented.

To describe and summarize the tests performed, a test table provided by the company was used as the main reference. The entries in these tables cover various aspects of functional verification, including:

- Requirement ID: identifies the functional requirement to which the test refers;
- Status: indicates the outcome of the test, showing whether it was successfully passed or not;
- Test Purpose: describes the objective of the test, i.e., which behavior is being verified;
- Initial Conditions: defines the initial conditions required to execute the test correctly and consistently;
- Test Inputs: lists the inputs applied during the test;
- Test Outputs: specifies the output signals observed as a result of the test;
- Test Result: reports the observed outcome during test execution, defining the *Status* and whether the requirement was satisfied or not;
- Test Procedure: outlines the steps performed during the test, including the actions taken and the corresponding results.

The tests are organized into four main groups, each corresponding to an operational phase of the BEV, with a fifth separate group dedicated to the verification of the BMS subsystem. Given the high number of test cases executed, for each group the test case considered most critical in terms of control logic and functional relevance has been selected and reported. The complete tables containing the full set of test cases are provided in Appendix A.

5.1 Start-up Phase Testing

For the *Start-up* phase, the most critical test was chosen to be one of the two requirements with ASIL D, namely TR7 or TR9. Since the Battery Management System (*BMS*) is addressed separately during the testing phase, the requirement considered is TR7. This requirement ensures that all safety devices are active before start-up, preventing hazardous conditions. It is directly accompanied by test TR8, which verifies that access to the gearbox is allowed only if the safety devices are active.

Table 10: Test case TR7-TR8 for Start-up phase

Requirement ID	**TR7-TR8**		**Status**	Passed ✓
Test Purpose	Verify that all safety devices are active at start-up and that, in case they are not, an anomaly is notified. Verify that access to the gearbox is enabled only if all safety devices are operational.			
Initial Conditions	Vehicle on, Start-up phase, Initialization state, no errors detected.			
Test Inputs	Safety_Devices, Start Button.			
Test Outputs	Entry into Ready state, Safety Devices indicator light, Error, Message.			
Test Result	Safety devices activate at system start-up. Otherwise, the anomaly is notified and access to the gearbox is disabled.			
Test Procedure	**Action**	**Result**		
	Safety_Devices = 1.	The indicator light is off, no error detected, Ready mode can be entered.		
	Safety_Devices = 0 (failure).	The Safety Devices indicator light turns red, error “Safety Devices Failure” is detected and sent as message to the user.		
	Start Button = Pressed.	The Ready mode is not activated.		

If the *safety devices* are correctly activated, the dashboard indicator remains off and no error is reported on the display. If, instead, the safety devices fail to activate for any reason, an error is displayed and the dashboard warning light turns on. In this case, even pressing the start button, the vehicle cannot enter *Ready* mode. In the following images, the two cases of the test are shown: in the first image, the safety devices are correctly activated, while in the second the devices are not active, resulting in an error notification.

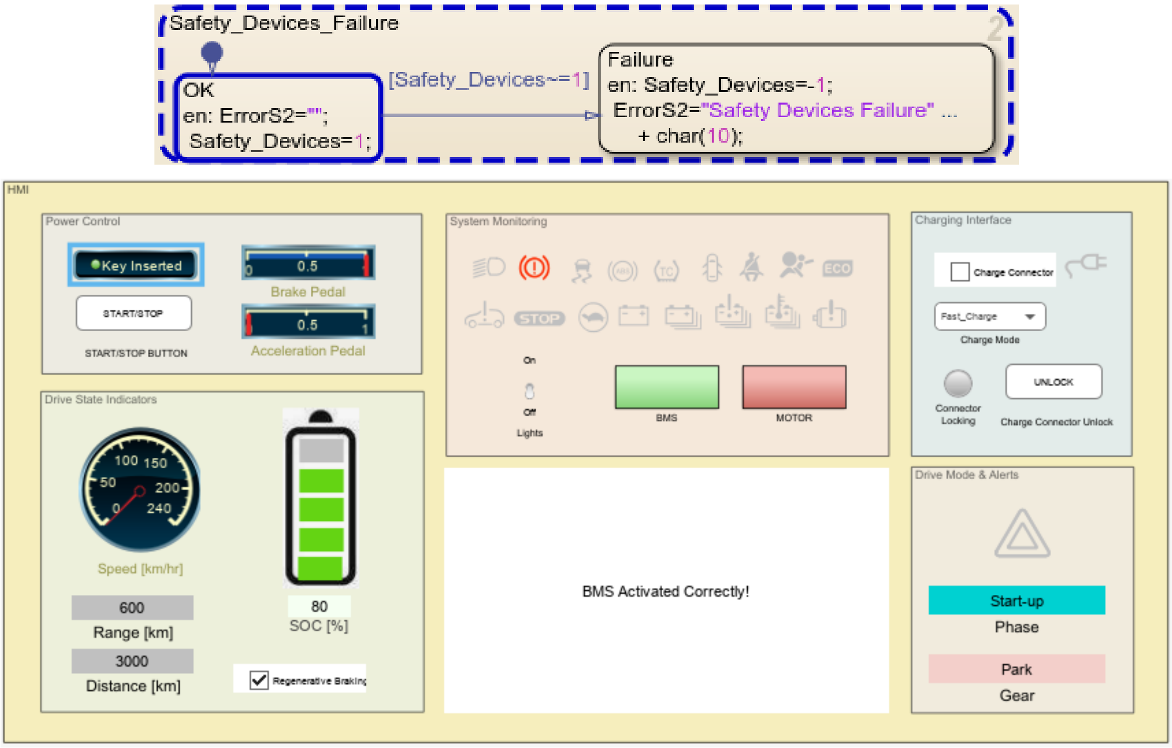

Figure 46: Test case TR7/TR8 - Safety devices correctly activated

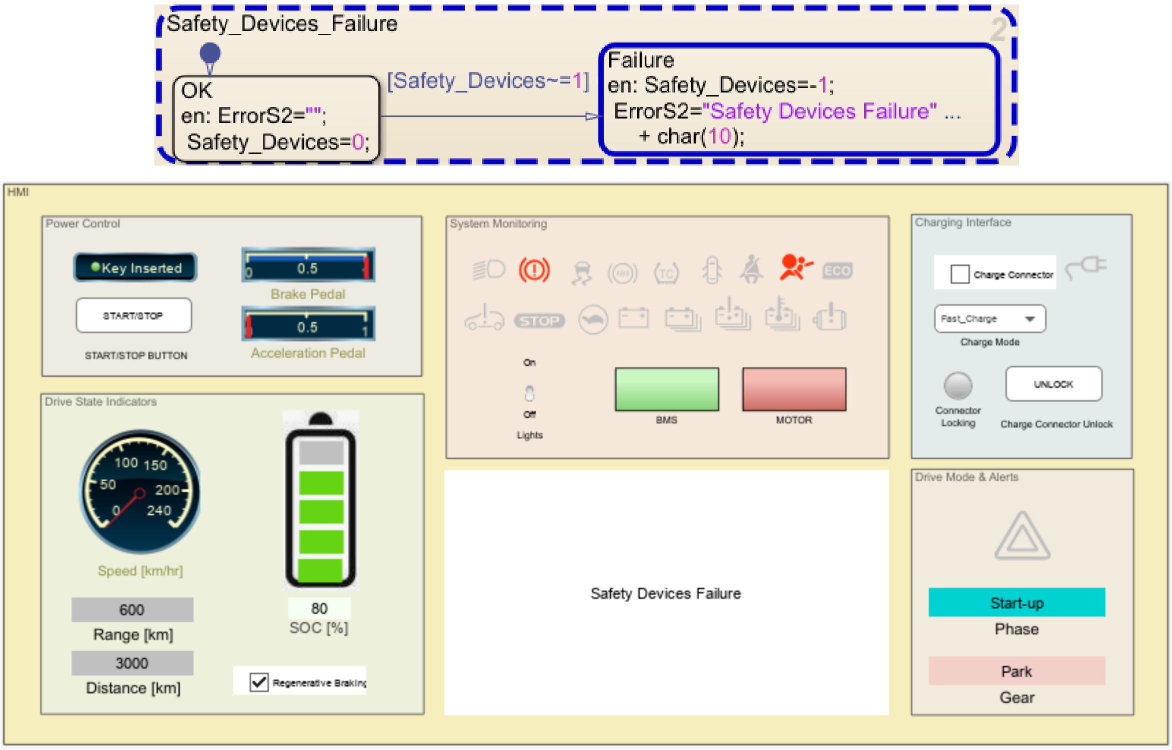

Figure 47: Test case TR7/TR8 - Safety devices not active

5.2 Drive Phase Testing

For the *Drive* phase, requirement TD1 was the only one classified as ASIL D during the HARA and is therefore considered the most critical case. This test ensures that the *Parking Brake* is disengaged during the *Drive* phase.

Table 11: Test case TD1 for Drive phase

Requirement ID	**TD1**	**Status**	Passed ✓
Test Purpose	Verify that the parking brake is automatically deactivated at the beginning of driving.		
Initial Conditions	Vehicle on, Start-up phase, Ready Mode, no error detected.		
Test Inputs	Drive Mode Selection, Deceleration Command.		
Test Outputs	Phase change, Parking Brake, Parking Brake indicator.		
Test Result	The parking brake is correctly deactivated upon entering the Drive State.		
Test Procedure	**Action**	**Result**	
	The Drive Mode position is selected on the gear, the brake pedal is released.	The system switches from Start-up phase to Drive, the Parking_Brake signal switches from 0 to 1 and the Parking Brake indicator turns off.	

The initial conditions of the test assume the vehicle is turned on, in the *Start-up* phase and in *Ready* mode, with no errors detected. Entering the *Drive* mode causes the parking brake to be disengaged, which is indicated by the parking brake warning light turning off on the dashboard.

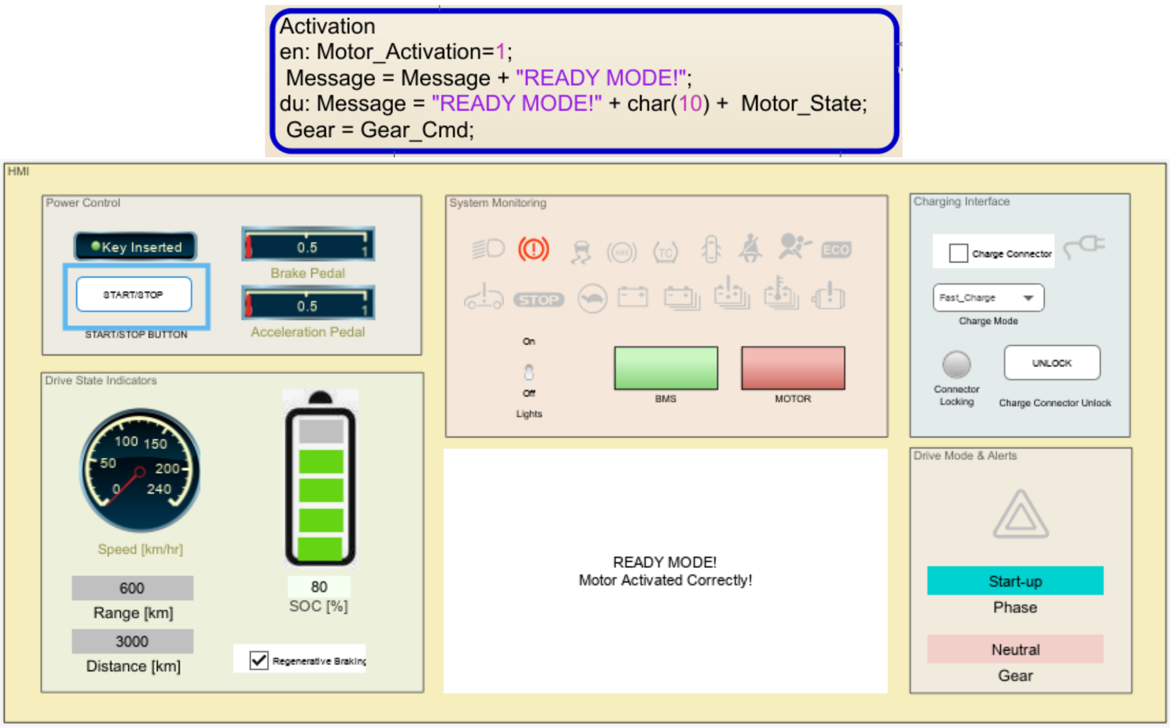

Figure 48: Test case TD1 - Initial conditions

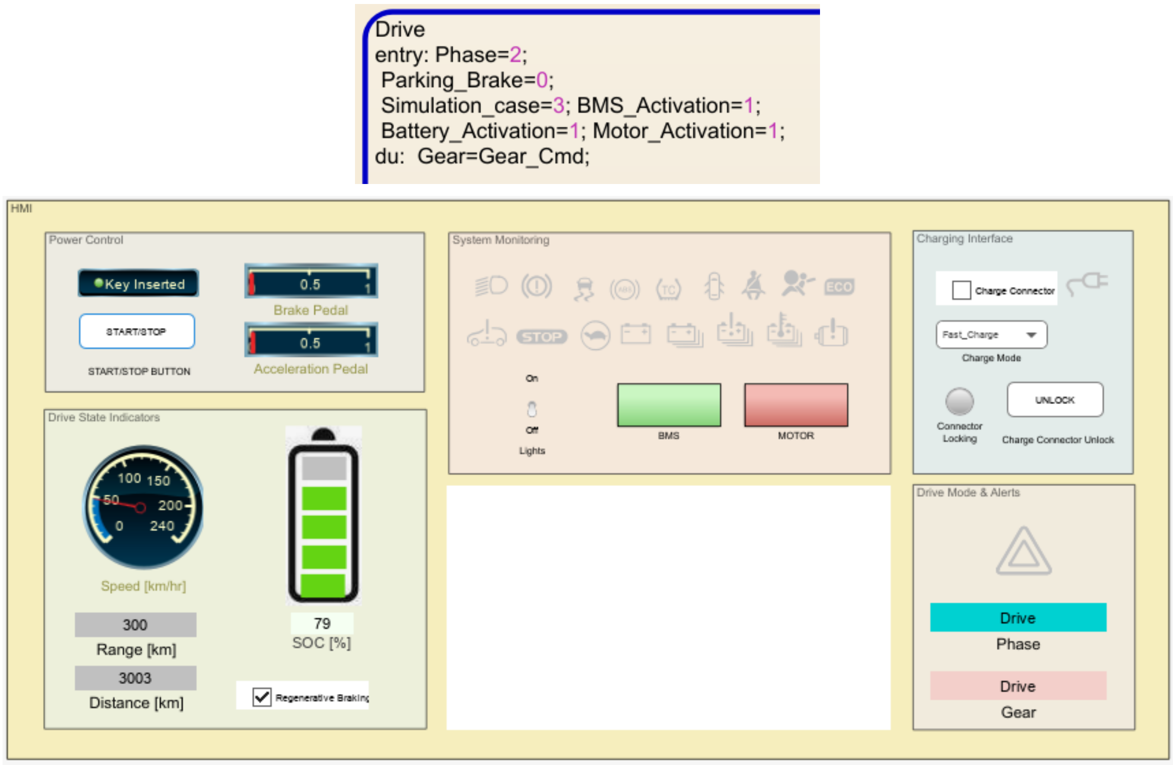

Figure 49: Test case TD1 - Parking brake deactivated

5.3 Charge Phase Testing

For the charging process, the most critical test chosen is TC6. This test specifically addresses the case in which movement is detected during the charging phase. In such a case, the system must stop the charging, unlock the charging cable and notify the user of the issue.

Table 12: Test case TC6 for Charge phase

Requirement ID	**TC6**	**Status**	Passed ✓
Test Purpose	Verify that if vehicle movement is detected during charging, the charging phase is immediately stopped.		
Initial Conditions	Vehicle in Charge phase, no errors detected, SOC < 99%.		
Test Inputs	Charge_Connector, Vehicle Speed.		
Test Outputs	Exit from charging phase, Lock_Cable, Error, Message.		
Test Result	If vehicle movement is detected during charging, the system exits charging phase and switches to Stop, notifying the error on the dashboard.		
Test Procedure	**Action**	**Result**	
	Apply Speed = 0.	Charge phase active.	
	Apply Speed = 20 km/hr.	Error detected and the system switches from charging to Stop phase. Lock_Cable = 0: cable unlocked. User is notified with the message: “Undesired Movement. Charge has been stopped”.	
	Charge_Connector = 0 (Charging cable disconnected).	Disconnecting the charging cable clears the message. Error is cleared. Vehicle in Park/Power-off mode.	

Initially, the system is in the charging phase. When a speed signal is applied, the system transitions from the *Charge* phase to *Stop*, either in Park or Power-off mode, depending on the initial state before charging began. The error is reported to the user and the charging process is interrupted. If the charging cable is disconnected, the error is no longer notified.

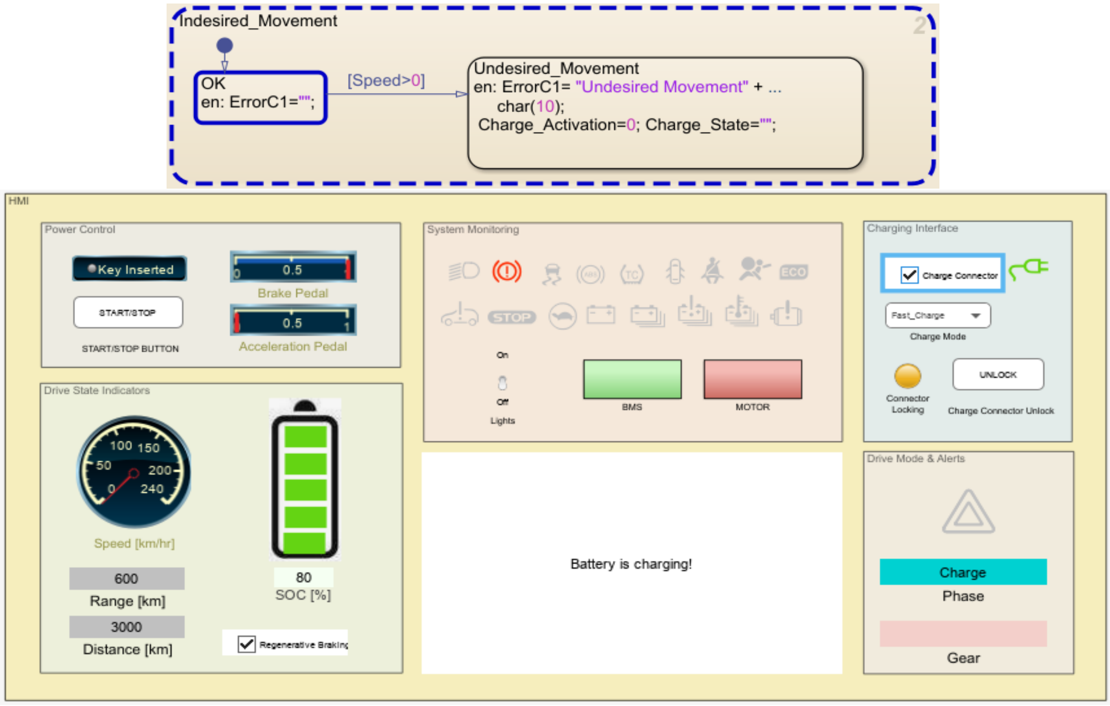

Figure 50: Test case TC6 - No errors detected

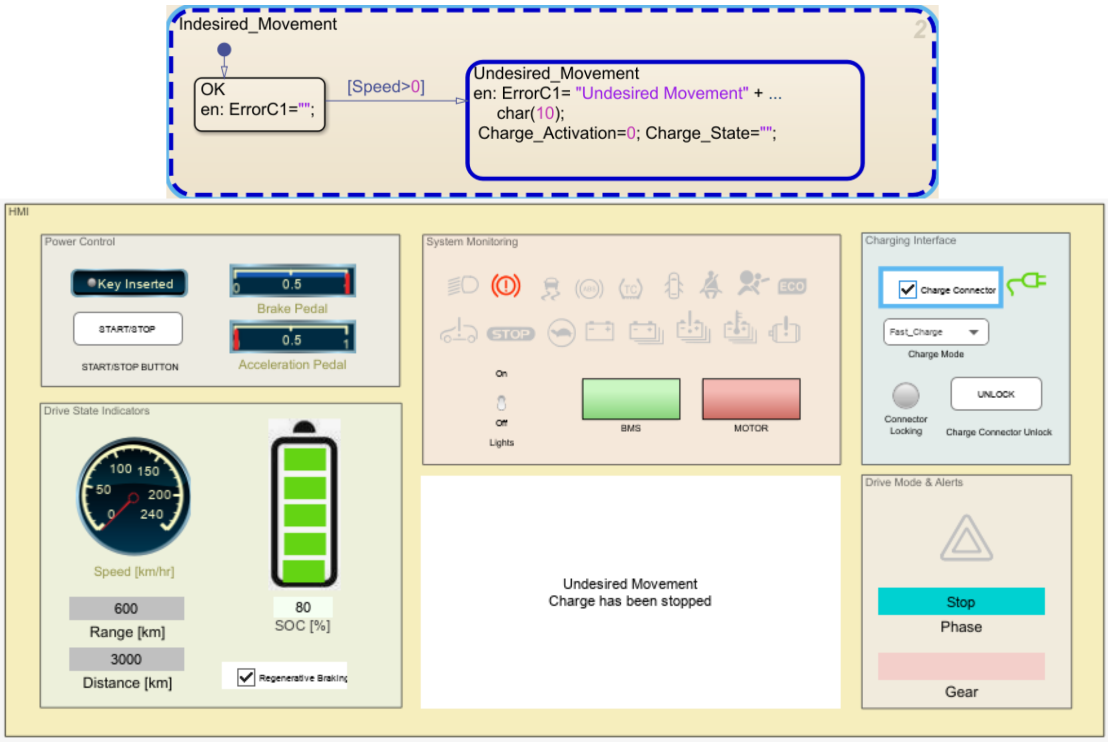

Figure 51: Test case TC6 - Undesired movement error detected

5.4 Stop Phase Testing

For the Stop phase, the critical requirement selected is TS1, as it ensures that the parking brake is automatically activated upon entering Park mode, guaranteeing that the vehicle remains stationary.

Table 13: Test case TS1 for Stop phase

Requirement ID	**TS1**	**Status**	Passed ✓
Test Purpose	Verify that the parking brake activates automatically upon entering Park mode.		
Initial Conditions	Vehicle on, Stop phase, Park Mode.		
Test Inputs	Initial conditions only.		
Test Outputs	Parking_Brake, Parking Brake indicator on dashboard.		
Test Result	The parking brake activates automatically upon entering Park mode.		
Test Procedure	**Action**	**Result**	
	Observe the behavior of the Parking Brake during Park mode.	Parking_Brake = 1: parking brake is active. The indicator on the dashboard is lit red.	

During the activation of Park mode, it can be observed that the parking brake is automatically engaged, causing the corresponding indicator on the dashboard to light up. This prevents the vehicle from making unintended movements during this phase, enabling a mandatory safety function for vehicles.

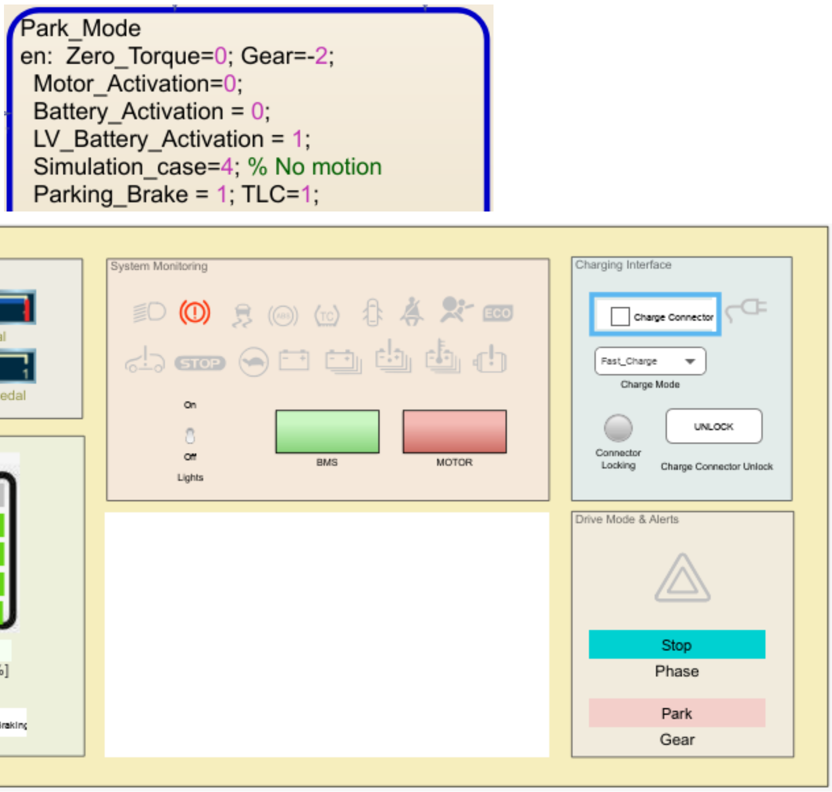

Figure 52: Test case TS1 - Parking brake activated

5.5 Battery Management System (BMS) Testing

Among the tests listed for the Battery Management System, the most critical is TBMS2, which verifies the detection and management of an overcurrent error. This error is one of the most dangerous faults in an electrical system, as it can cause overheating and irreversible damage to the battery.

Table 14: Test case TBMS2 for BMS subsystem

Requirement ID	**TBMS2**	**Status**	Passed ✓
Test Purpose	Verify that the BMS detects an overcurrent error and notifies it correctly.		
Initial Conditions	BMS active.		
Test Inputs	Battery current signal of 500 A (= maximum absolute value).		
Test Outputs	Fault_BMS, Battery Fault indicator on the dashboard.		
Test Result	The BMS behaves as expected, detecting the fault and notifying the user.		
Test Procedure	**Action**	**Result**	
	A current signal above the maximum threshold is sent for more than 10 consecutive seconds.	The BMS detects the fault and displays the message: "BMS ERROR: Overcurrent". The Battery Fault indicator light on the dashboard turns on.	

Considering the *Drive* phase, if an overcurrent error is detected, the BMS must immediately report it and block the driving, causing the system to enter the *Stop* phase and, specifically, the *Limp Mode* state (if the vehicle is in motion). This ensures a safe stop of the vehicle, which must be halted due to the error.

When the vehicle comes to a stop, it enters *Park* mode. Once the error is detected, the various warning indicators on the dashboard light up and the error message is displayed on the screen until the vehicle is turned off.

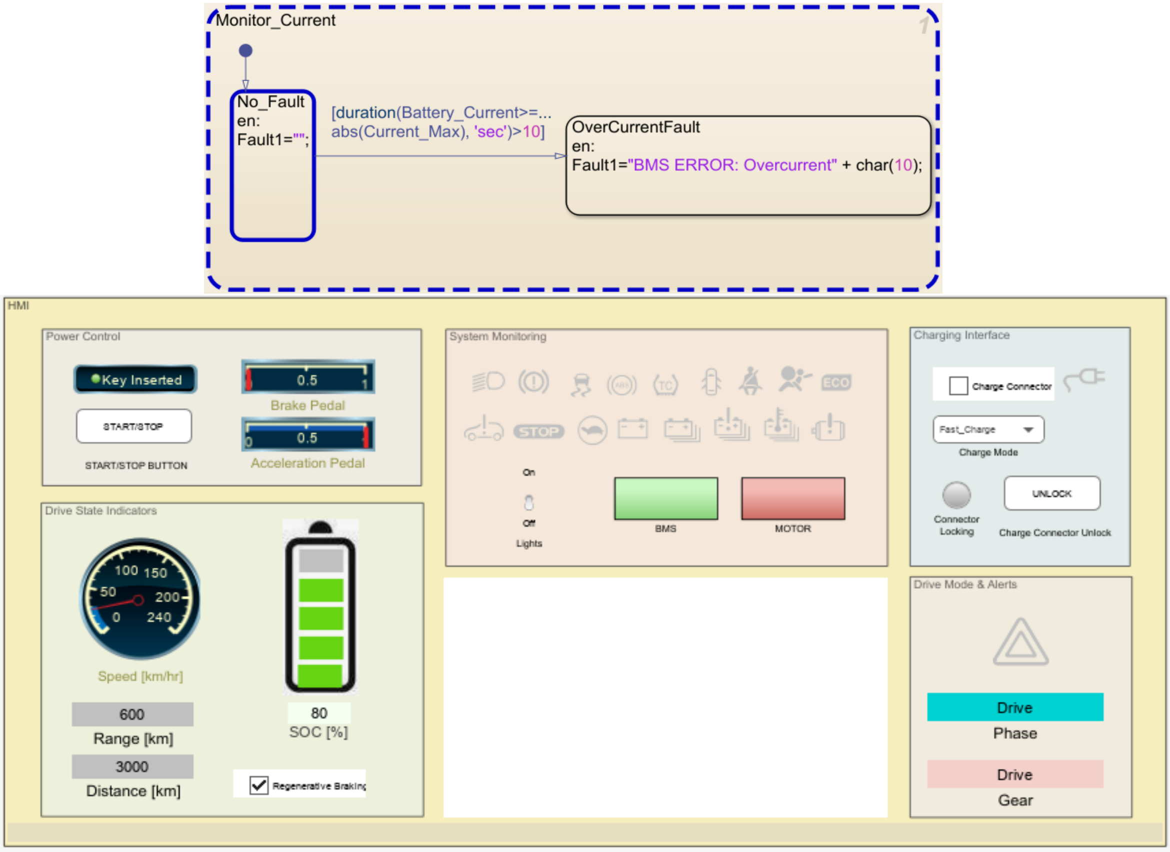

Figure 53: Test case TBMS2 - No overcurrent error detected

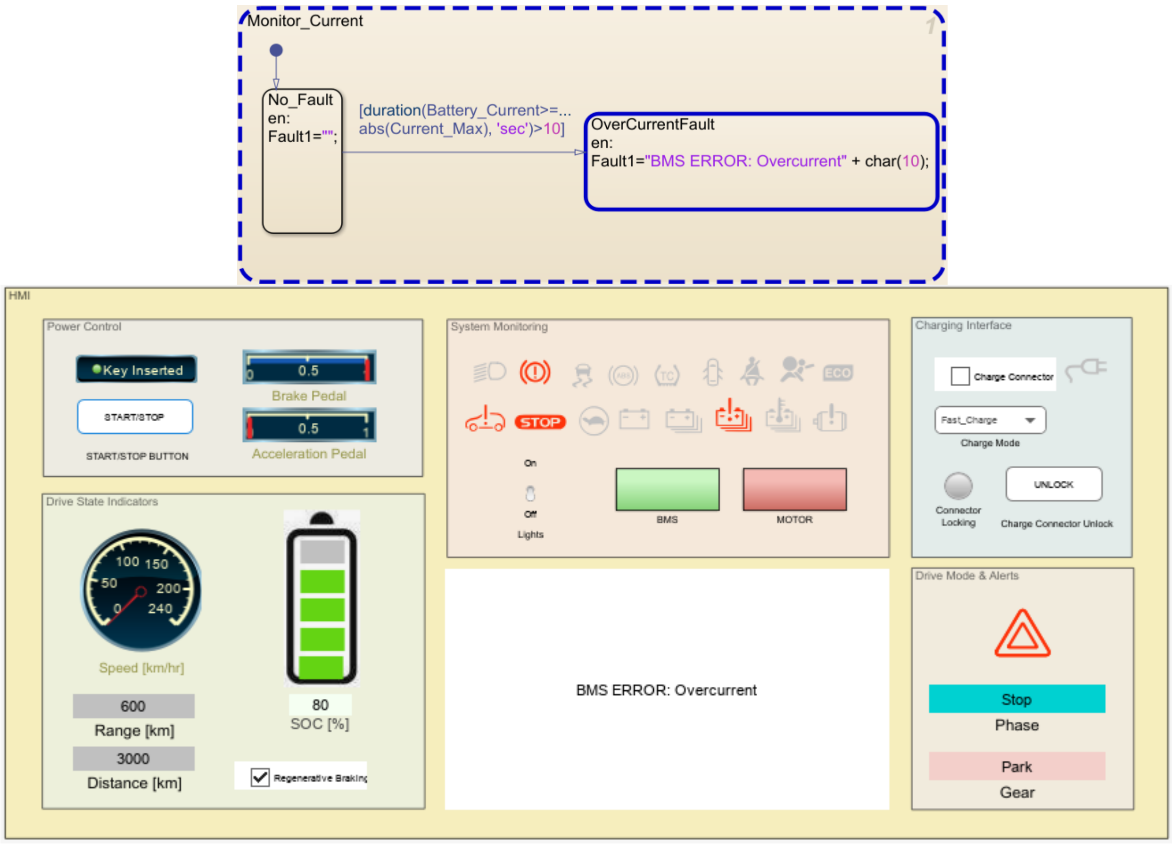

Figure 54: Test case TBMS2 - Overcurrent error detected

6 VALIDATION

In this final phase of model-based development, in accordance with the V-cycle approach, the complete BEV model was validated in order to verify its behavior during a realistic operational cycle. This phase involves analyzing the overall behavior of the model under plausible operating scenarios.
For this purpose, a Model-in-the-Loop (MiL) approach was employed, simulating the vehicle's entire operating cycle, which consists of:

- Start-up phase;
- Driving;
- Parking and Shutdown;
- Charging process with the vehicle turned off.

The Model-in-the-Loop (MiL) approach consists in testing and verifying the control system model developed in Simulink, by interacting with the numerical model of the physical system (*Plant*) within a simulation environment. At this stage, no hardware implementation is involved, as all operations are performed at the model level. The purpose of this procedure is to validate the logical and functional behavior of the controller and to identify any errors in the decision-making logic or in the interactions between the various subsystems.

Three distinct use-case scenarios were defined for the system simulation.

1. The first concerns the simulation of a complete vehicle life cycle, from start-up to shutdown, following a realistic speed profile.
2. The second scenario focuses on the simulation of the battery charging process.
3. The third scenario involves the simulation of a driving profile in reverse mode.

These integrated simulations allow for the evaluation of the system's reliability and logical correctness, including the transitions between the main subsystems and the control logic. Before presenting the simulation results for each case, the methodology used for monitoring and measuring the relevant control parameters is described.

6.1 Measurements

In the Simulink model, a dedicated subsystem was implemented to collect all the information related to the Plant components, in order to analyze their behavior during the simulation. For this purpose, a measurement subsystem was created for each main component, namely: Battery, Vehicle and Motor. Between the battery and motor blocks, a dedicated subsystem was implemented to compute the energy efficiency, expressed in kWh / (100 km). This parameter represents the amount of electrical energy required by the system to travel 100 kilometers and is commonly used to evaluate the energy performance of electric vehicles.

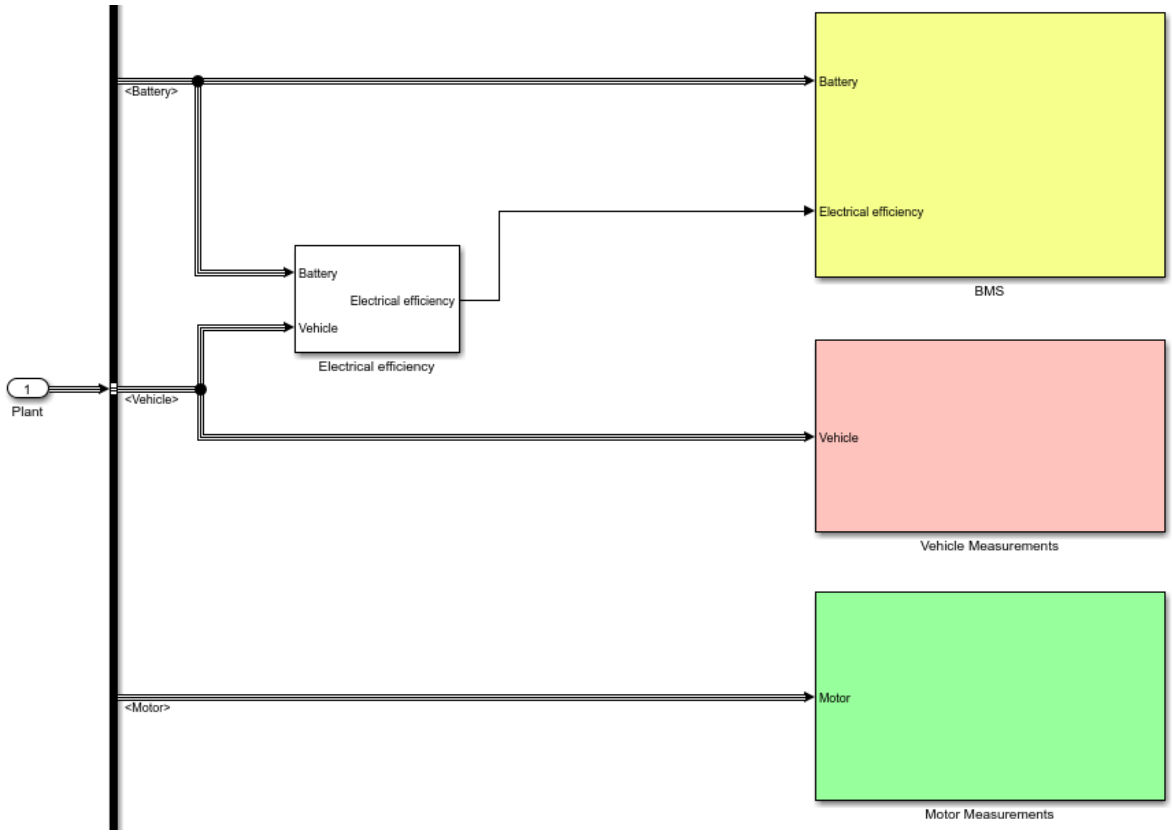

Figure 55: Measurements block - Simulink model

All the measurements collected within this subsystem are displayed through a *Scope* linked to the corresponding component. This approach enables real-time monitoring of key parameters during the simulation, facilitating the analysis of the system's dynamic behavior and the detection of any anomalies.

The following parameters are measured and plotted for the battery: voltage [V], charge [Ah], current [A], temperature [°C], state of charge [%], electric power loss [W], electrical power [kW] and energy efficiency [kWh / (100 km)]. Additionally, the vehicle's estimated driving range [km] is calculated as the ratio between the battery's nominal capacity and its energy efficiency. Finally, a percentage estimate of the battery's State of Health (SoH) [%] is computed as a function of its operating temperature.

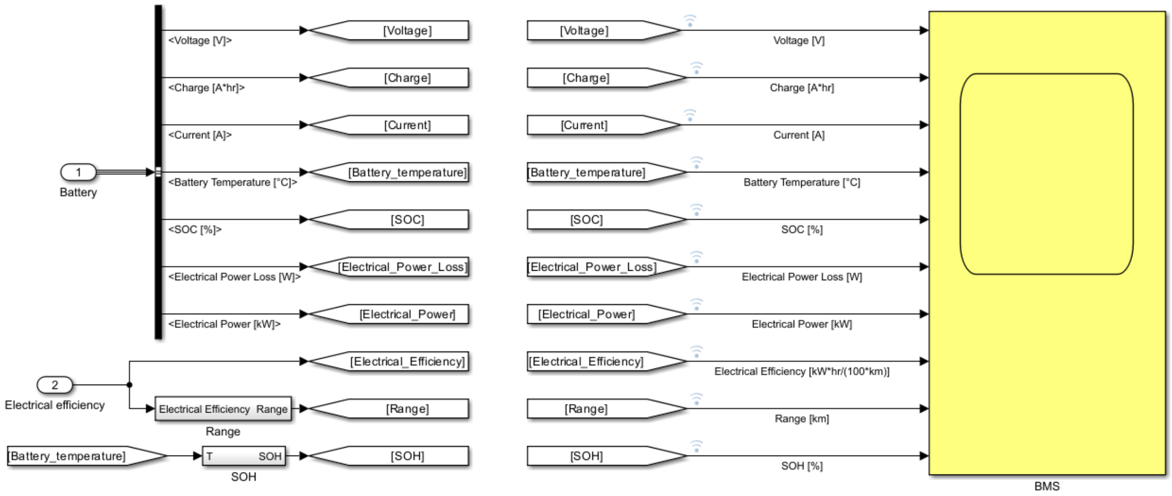

Figure 56: Battery measurements - Simulink model

The following parameters were considered for monitoring the vehicle's dynamic behavior: road gradient expressed in both percentage and degrees [% and °], braking force [N], axle speed received from the gear [rpm], vehicle speed [km/h and mph], normalized longitudinal acceleration [from -1 to 1] and total distance travelled [km].

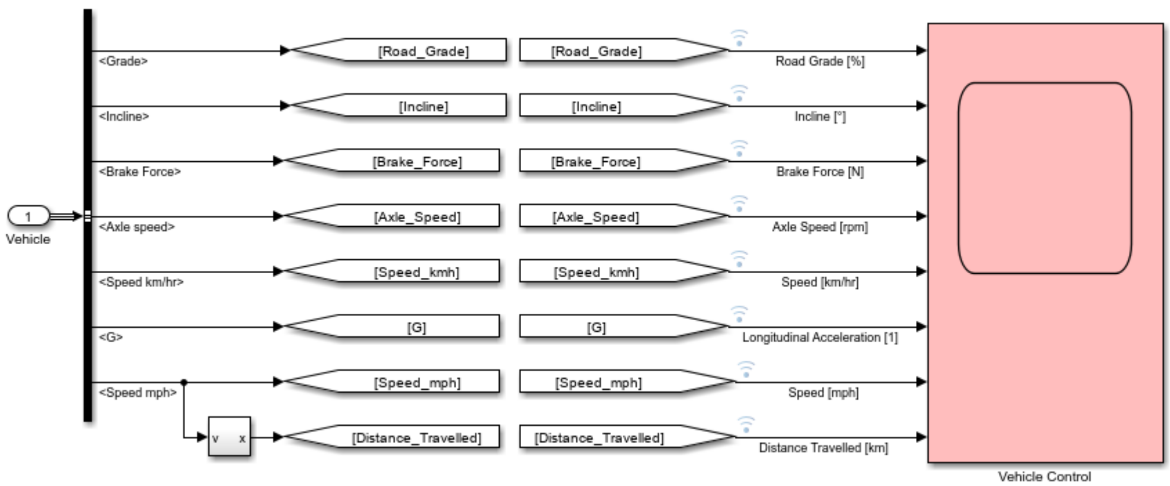

Figure 57: Vehicle measurements - Simulink model

Finally, for the motor, the following parameters were considered: electrical input values from the battery, namely current [A], voltage [V], electrical power [kW], electrical losses [W]; as well as rotational speed [rpm], torque [Nm], temperature [°C], mechanical power [kW], power rate [%] and finally efficiency [%], calculated as the ratio between mechanical power and electrical power.

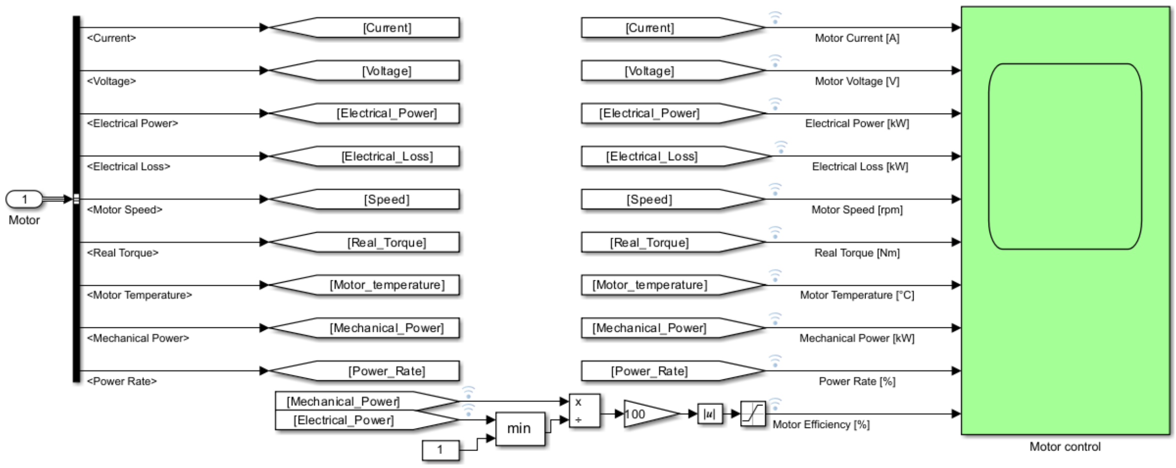

Figure 58: Motor measurements - Simulink model

Once all measurements related to the system components have been collected, the execution of the previously outlined test cases is carried out.

6.2 Simulation case – Realistic Driving Cycle

This scenario simulates a realistic usage cycle of the electric vehicle, encompassing the main operational phases: start-up, driving, parking and shutdown. After activating the system by inserting the key and pressing the start button, a predefined speed profile is applied, represented by the *Combined Driving Cycle* provided by Simulink. This profile enables the analysis of the vehicle's dynamic behavior during typical acceleration, braking and cruising phases. At the end of the cycle, the vehicle is stopped, switched to Park mode and finally shut down, completing the operational cycle. This simulation aims to verify the overall system behavior, including state transitions and the correct functioning of the main subsystems. The speed profile followed during the vehicle's driving phase is shown below, as well as the measurements of the control parameters recorded during the simulation. The simulation duration is set to one hour (3600 seconds).

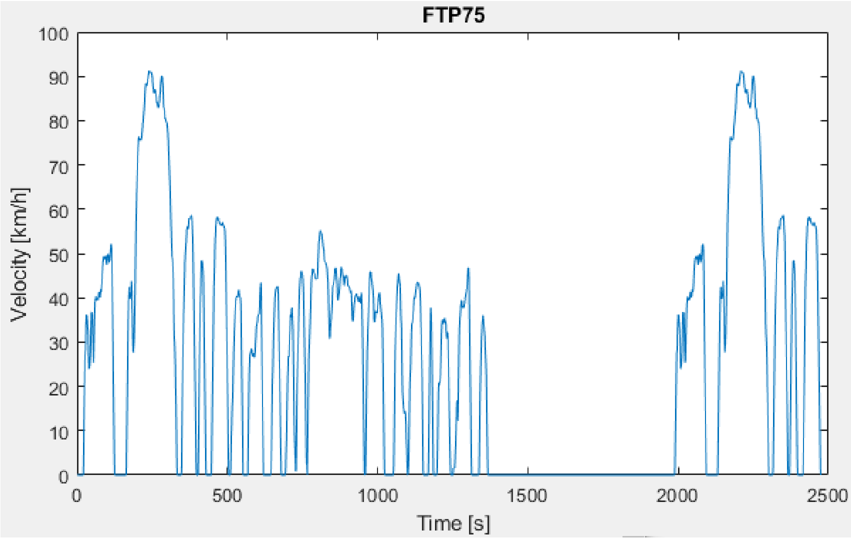

Figure 59: Simulation: Driving cycle for combined cycle

Below is the battery behavior during the simulation.

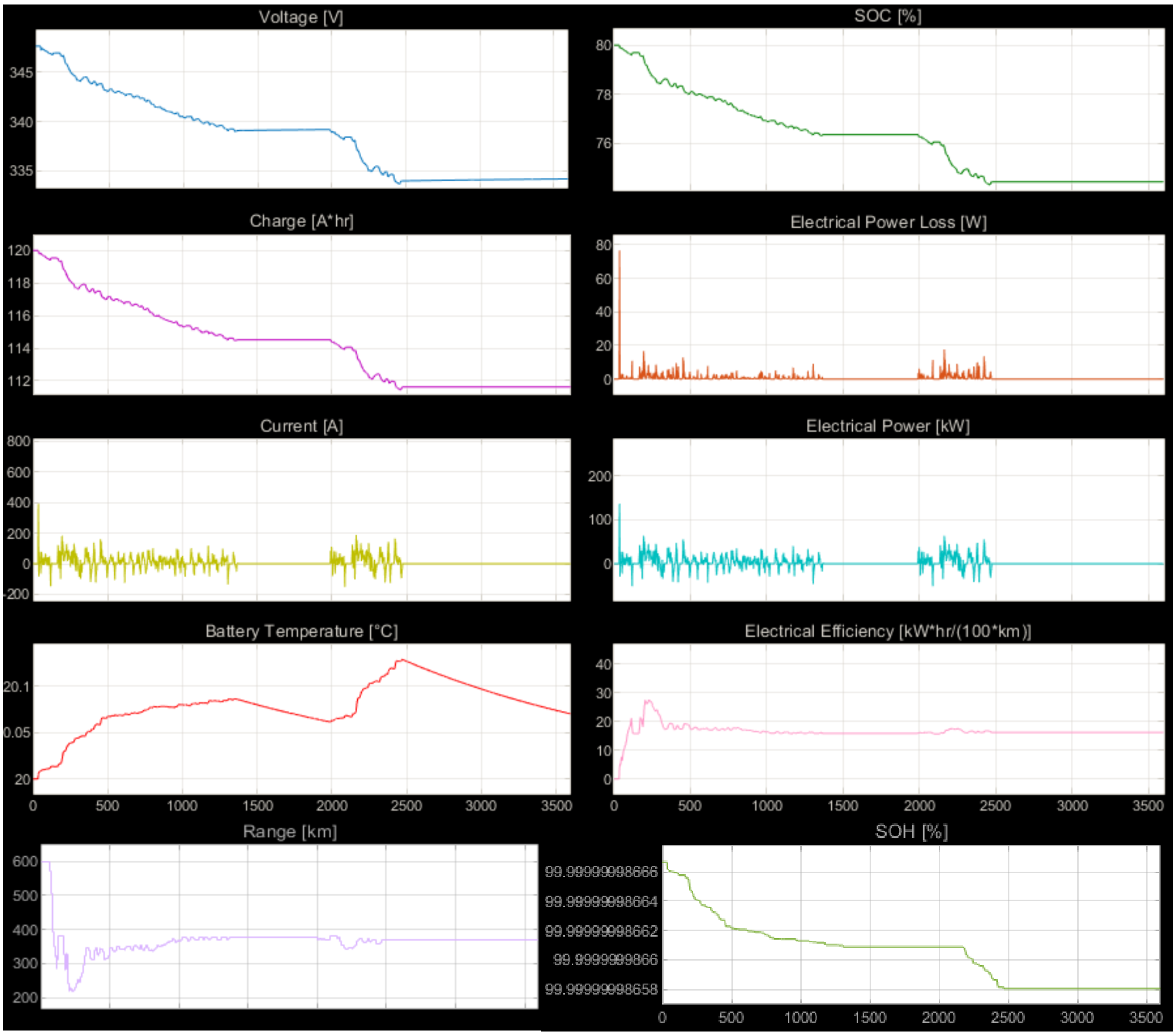

Figure 60: Driving cycle - Battery behavior

From the measurement plots, it is observed how the battery values vary according to the speed profile. The current increases when the vehicle accelerates or demands more power, while it decreases to become negative during regenerative braking. Along with the current, the delivered power also increases. Consequently, electrical losses increase as well. The voltage varies slightly depending on the load, while the temperature tends to rise slightly due to internal losses. The state of charge (initially 80%) and the state of health (initially 100%) progressively decrease during power delivery. Similarly to the SOC, the battery charge also decreases. However, it is noticeable that at certain points these two values increase due to regeneration during braking. Efficiency and range vary dynamically throughout the cycle, depending on the electrical power used.

Below are the graphs related to the vehicle parameters:

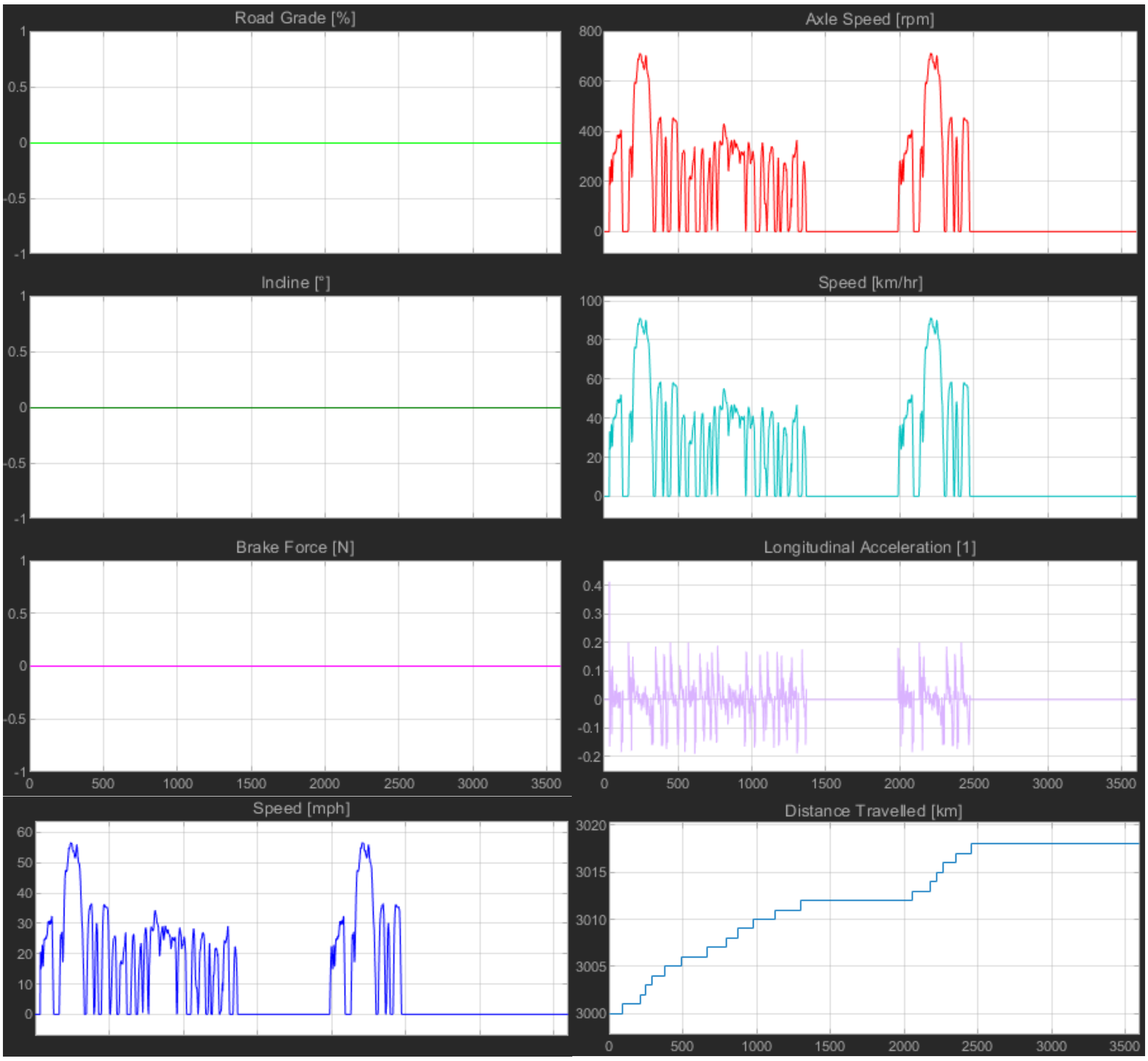

Figure 61: Driving cycle - Vehicle behavior

In this case, neither road slope nor brake forces were considered. However, these parameters can be easily adjusted to analyze the system's behavior under different scenarios. Observing the vehicle's behavior, it can be noted that the speed accurately follows the desired velocity profile, confirming the correct implementation of the control logic and the expected interactions between the various subsystems. The longitudinal acceleration reflects the acceleration and braking commands defined in the speed profile. The distance traveled increases over time, showing a stepped behavior due to the use of the rounding function in the measurements.

Finally, below are the graphs related to the motor parameters:

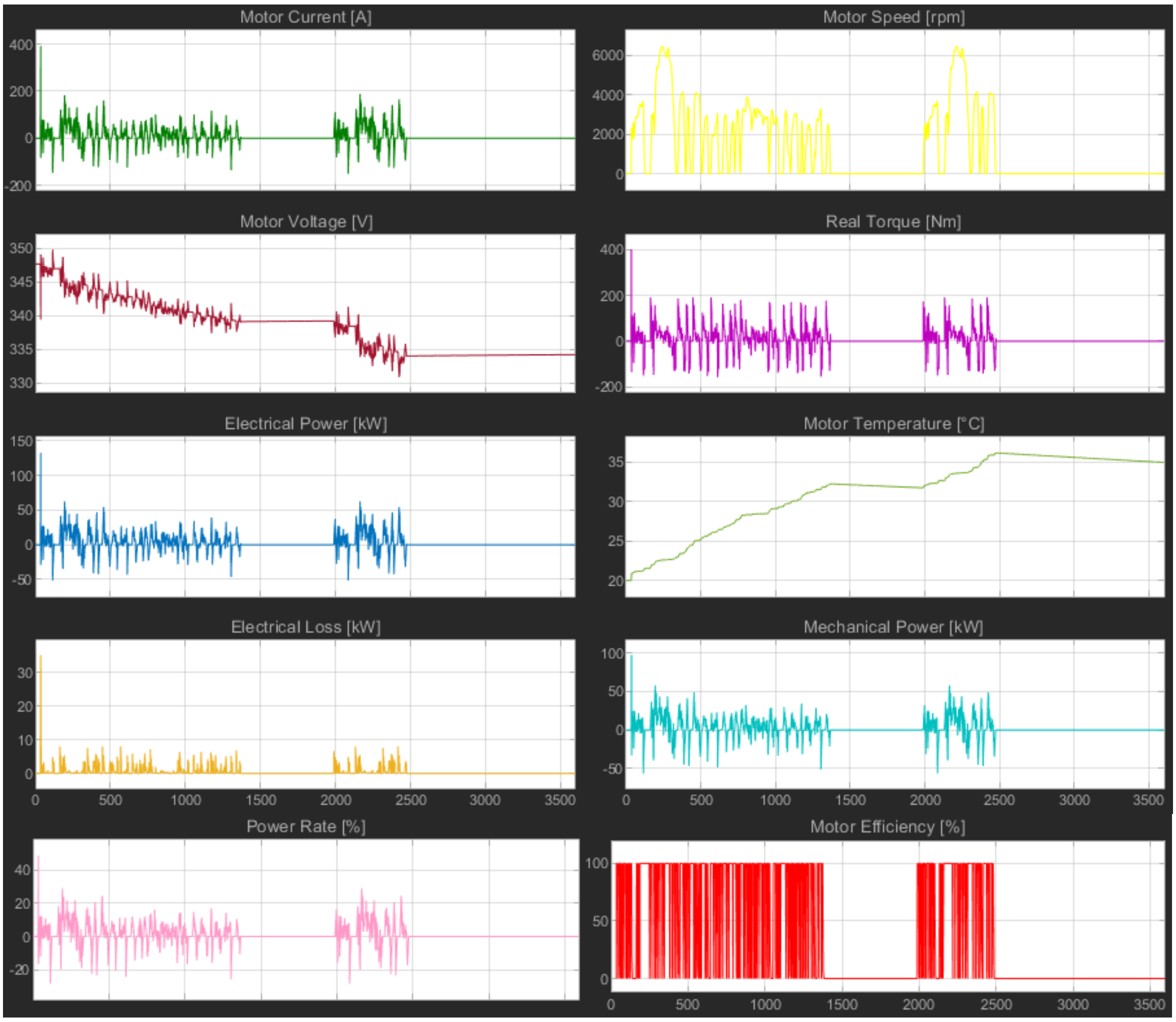

Figure 62: Driving cycle - Motor behavior

Analyzing the motor's behavior, it is observed that all electrical and mechanical parameters are consistent with those previously described for the battery and the vehicle. In particular, the motor temperature tends to increase during operation.

The efficiency, defined as the ratio between mechanical power output and electrical power input, varies dynamically depending on the load conditions and oscillates between 0% and 100%, with extreme values occurring during low-power phases.

The results obtained from the driving cycle simulation are consistent with the design expectations and confirm the correct behavior of the system. Based on these outcomes, the validation of the model for this operational phase is considered satisfactory.

6.3 Simulation Case – Charging Cycle

Continuing with the validation phase, a charging cycle simulation was performed. It is assumed that the battery initially has a residual state of charge of 20%. The charging cable is then connected. Initially, the Fast charging mode (80 A) is applied, followed by a transition to the Slow Charge mode (20 A). The total simulation time considered is one hour (3600 seconds). Since this phase focuses exclusively on the battery, only the behavior of this component is considered. The parameters related to the motor and vehicle remain at zero, as no torque is required and the vehicle is stationary. Below is the battery behavior during the simulation.

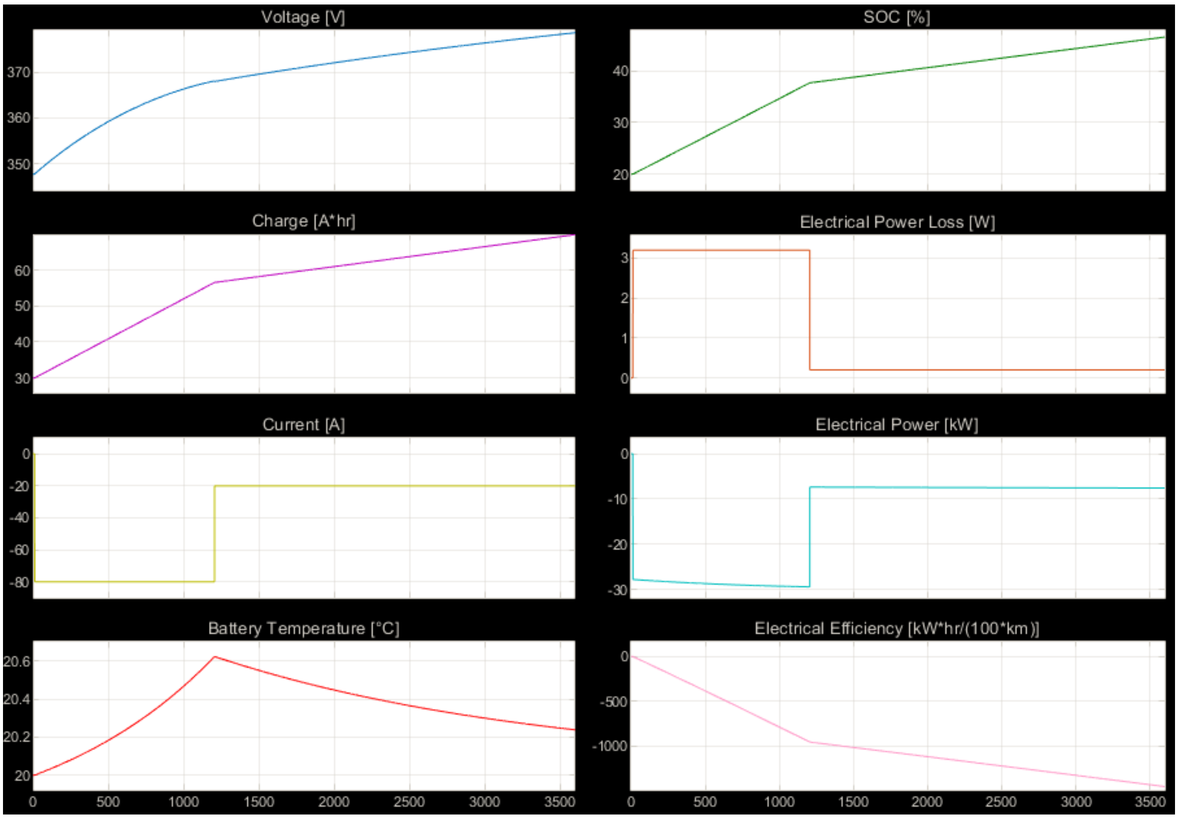

Figure 63: Charging cycle - Battery behavior

By observing the battery behavior, it is evident that during the initial fast-charging phase, the state of charge (SOC) increases rapidly, along with the voltage and the accumulated charge. Electrical power and losses follow the current trend, with slight variations also due to the increase in voltage. The battery temperature rises as a result of the high current intensity. The range value was excluded from the analysis, as it is related to the vehicle speed, which remains zero during the charging phase. The state of health (SOH), on the other hand, decreases extremely slowly, on the order of 10^{-8}. After approximately 20 minutes, the charging mode switches from fast to slow: the current, negative since it is being absorbed by the battery, decreases from 80 A to 20 A. All other parameters follow a similar trend to that observed during the fast charge, though with a more moderate progression.

From the overall analysis of the battery behavior, it can be concluded that the system operates correctly throughout the entire charging process.

6.4 Simulation Case – Reverse Driving

To verify the system behavior under *Reverse* mode and negative speed conditions, a specific speed profile was created in MATLAB and implemented using a *Lookup Table* block in Simulink. This profile was temporarily used in place of the *Combined Cycle* block to carry out the current simulation. The applied speed profile is shown in the following figure.

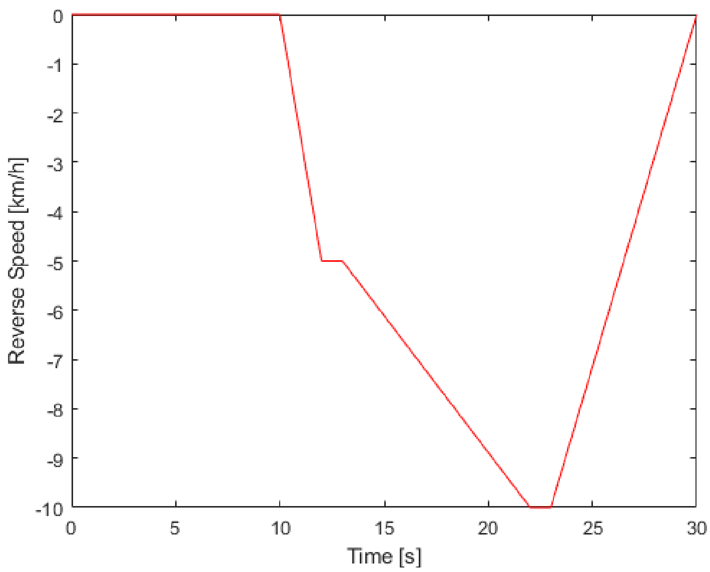

Figure 64: Simulation - Reverse driving, desired speed

A short simulation time of 30 seconds was considered, since reverse driving typically occurs over a brief duration, limited to maneuvers such as parking or turning around.

Furthermore, the vehicle behavior over longer simulation times has already been tested in previous scenarios. The maximum speed reached in the created profile is –7 km/h. This value is consistent with typical reverse driving conditions, as electric vehicles intentionally limit reverse speed for safety and control reasons, minimizing the risk of hazardous maneuvers. The behavior of the battery during the simulation is shown below.

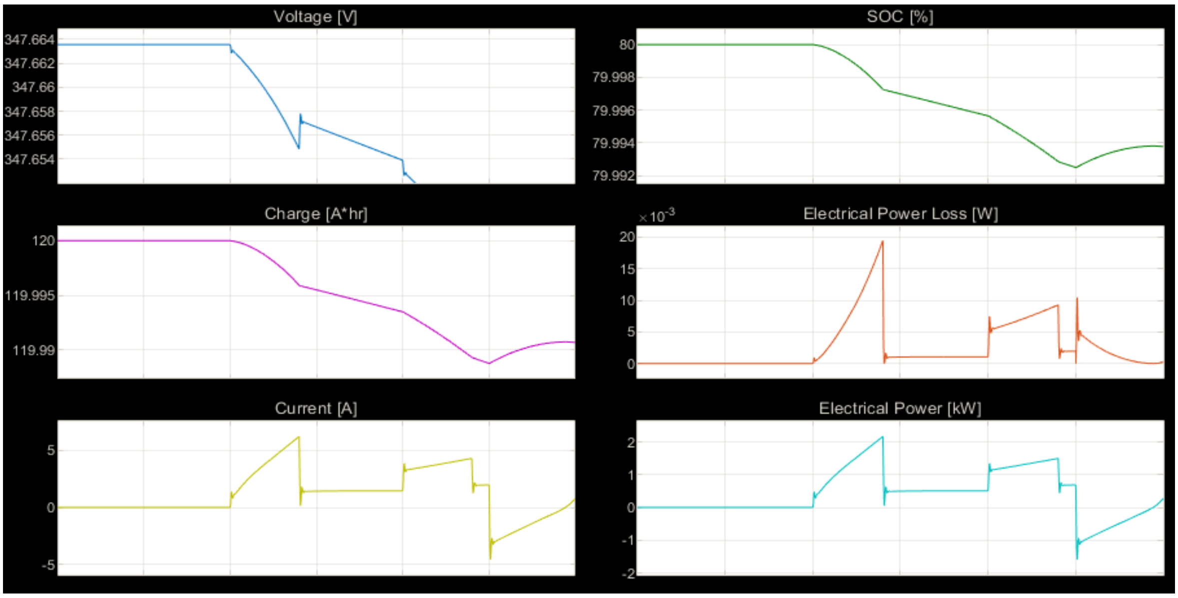

Figure 65: Reverse driving - Battery behavior

Given the short duration of the test, it is appropriate to focus the analysis on the most relevant parameters. It can be observed that the current trend, as well as the delivered and dissipated power, closely follows the velocity profile, with more pronounced variations during acceleration phases. As expected, the voltage, charge and, consequently, the State of Charge (SOC) progressively decrease over time.

As for the vehicle, it behaves exactly as expected, accurately reproducing the desired speed profile. Only the two most relevant trends in this context are presented below: the vehicle speed and the longitudinal acceleration.

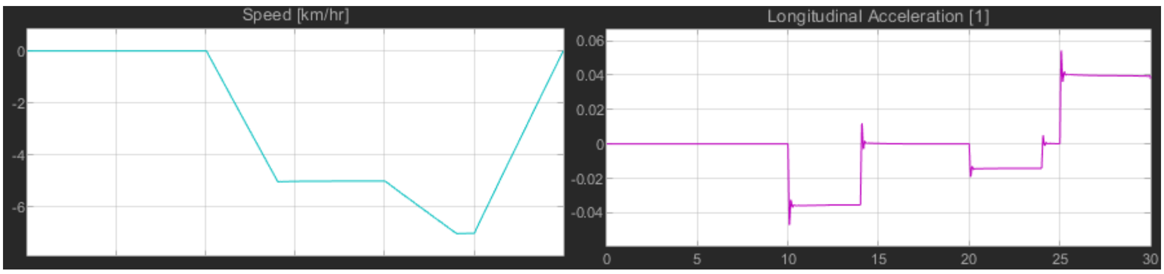

Figure 66: Reverse driving - Vehicle behavior

Finally, the behavior of the motor during the simulation is analyzed.

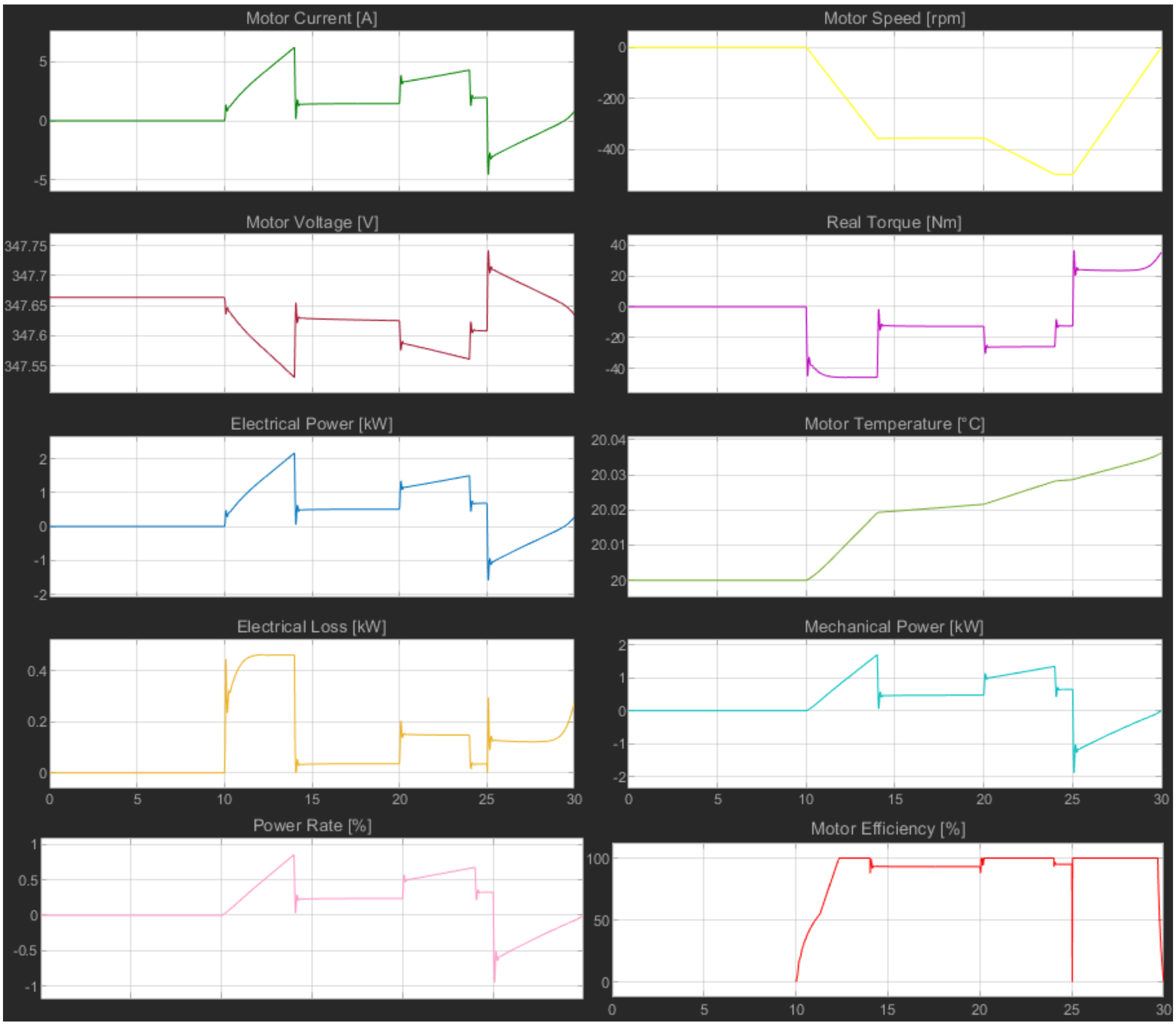

Figure 67: Reverse driving - Motor behavior

The electrical and mechanical parameters of the motor exhibit behavior consistent with the expected outcomes defined by the model, confirming the correct interaction between control signals and system dynamics.

The reverse driving scenario was successfully validated: all measured values were fully consistent with the expected results, demonstrating the reliability of the model under this specific operating condition.

7 CONCLUSIONS

This work addressed the development and validation of a model-based approach for a battery electric vehicle (BEV), aiming to reproduce in MATLAB/Simulink a realistic behavior consistent with the operational logic of a real system. Following the V-Cycle methodology, functional and safety requirements were defined, the system architecture was implemented, control logics were developed and, finally, testing and validation activities were performed through Model-in-the-Loop simulations.

The system modeling included the main physical components (battery, motor, vehicle, gear) and their related measurement and management subsystems. Particular attention was given to the HMI interface, designed to monitor vehicle parameters in real time and facilitate user-system interaction. The vehicle's operational phases (start-up, driving, charging and shut-down) were simulated through different scenarios, with the objective of testing the overall system behavior, including specific cases such as reverse driving and charging management. The obtained results confirmed the consistency and reliability of the developed model. Indeed, the measured signals were consistent with the initial expectations and requirements. In particular, the effectiveness of the control logic and the accuracy of the measurements demonstrate the validity of the adopted approach.

The model proved stable and suitable for future developments. Future work could extend the model by integrating Hardware-in-the-Loop validation, more advanced thermal and environmental models, and more sophisticated energy management systems, to further bring the model closer to real operational conditions.

In conclusion, the work carried out confirmed the effectiveness of the model-based approach in the development and validation of electric vehicle systems, demonstrating how integrated simulation is an essential tool for the design and optimization of electric vehicles.

Appendix A – Complete List of Functional Tests

This appendix contains the complete tables of the test cases performed in the *Verification and Testing* phase of the project, as described in Chapter 5. The tests are organized by functional blocks, each referring to a specific phase or subsystem.

Table 15: Test cases for the Start-up phase

<table>
<tr><th colspan="5">START-UP</th></tr>
<tr><td>Requirement ID</td><td colspan="2">TR1</td><td>Status</td><td>Passed ✓</td></tr>
<tr><td>Test Purpose</td><td colspan="4">Verify that when the key is inserted, the vehicle starts without activating the motor.</td></tr>
<tr><td>Initial Conditions</td><td colspan="4">Vehicle off, charging connector disconnected, key not inserted, no errors present.</td></tr>
<tr><td>Test Inputs</td><td colspan="4">Key Inserted.</td></tr>
<tr><td>Test Outputs</td><td colspan="4">State change, BMS_Activation and Motor_Activation.</td></tr>
<tr><td>Test Result</td><td colspan="4">The vehicle correctly switches to Start-up mode with battery activated and motor deactivated.</td></tr>
<tr><td rowspan="2">Test Procedure</td><td>Action</td><td colspan="3">Result</td></tr>
<tr><td>The variable Key_Inserted is changed from 0 to 1.</td><td colspan="3">The system switches from Stop state Power-off to Start-up, BMS_Activation=1.</td></tr>
<tr><td>Requirement ID</td><td colspan="2">TR2</td><td>Status</td><td>Passed ✓</td></tr>
<tr><td>Test Purpose</td><td colspan="4">Verify that the motor does not deliver torque to the transmission during the initial start-up phase if all start-up conditions are not satisfied.</td></tr>
<tr><td>Initial Conditions</td><td colspan="4">Vehicle on, Start-up phase, battery active, motor off, error detected, Initialization state.</td></tr>
<tr><td>Test Inputs</td><td colspan="4">Initial conditions only.</td></tr>
<tr><td>Test Outputs</td><td colspan="4">Motor_Activation.</td></tr>
<tr><td>Test Result</td><td colspan="4">The Ready mode is not enabled until all start-up conditions are satisfied.</td></tr>
<tr><td rowspan="2">Test Procedure</td><td>Action</td><td colspan="3">Result</td></tr>
<tr><td>Start Button = Pressed.</td><td colspan="3">Ready phase is not activated as ErrorS is not an empty string but contains the detected diagnostic error.</td></tr>
<tr><td>Requirement ID</td><td colspan="2">TR3</td><td>Status</td><td>Passed ✓</td></tr>
<tr><td>Test Purpose</td><td colspan="4">Verify that at start-up a light functionality test is automatically executed.</td></tr>
<tr><td>Initial Conditions</td><td colspan="4">Vehicle on, Start-up phase, Initialization state.</td></tr>
<tr><td>Test Inputs</td><td colspan="4">Initial conditions only.</td></tr>
<tr><td>Test Outputs</td><td colspan="4">Dashboard light indicator.</td></tr>
<tr><td>Test Result</td><td colspan="4">The light functionality test is correctly executed during start-up.</td></tr>
<tr><td rowspan="2">Test Procedure</td><td>Action</td><td colspan="3">Result</td></tr>
<tr><td>No explicit action. The system enters Initialization state.</td><td colspan="3">The dashboard light turns green for 3 seconds and then turns off.</td></tr>
</table>

Requirement ID	TR4	Status	Passed ✓
Test Purpose	Verify that the entry into Ready mode is allowed only with the parking brake active and that, if not active, a notification is issued.		
Initial Conditions	Vehicle on, Start-up phase, Initialization state, no errors detected.		
Test Inputs	Parking_Brake, Deceleration Command.		
Test Outputs	Entry into Ready state, Parking Brake indicator on dashboard, Error, Message.		
Test Result	Entry into 'Ready' is allowed only with parking brake active. If the brake is inactive, an error is detected and the message is correctly sent.		
Test Procedure	**Action**	**Result**	
	Parking Brake = 1 (correctly active).	No error is detected, the Parking Brake indicator on the dashboard turns red.	
	Parking Brake = 0 (failure), Deceleration Command = 0.	Error detected: "Parking Brake Failure". The error is correctly displayed on the dashboard.	
	Start Button = Pressed.	The string ErrorS is no longer empty and prevents entry into 'Ready'.	
	Parking Brake = 0, Deceleration Command = 1.	The error "Parking Brake Failure" becomes a Warning. The warning is correctly displayed on the dashboard.	
	Start Button = Pressed.	Entry into Ready mode.	
	Parking Brake = 0, Deceleration Command = 0, Start Button not pressed.	The Ready phase has not yet started. The brake is released, the warning "Parking Brake Failure" returns to being an error and prevents motor activation.	
Requirement ID	TR5	Status	Passed ✓
Test Purpose	Verify that the vehicle enters Ready only if all doors are closed and that, otherwise, a warning is given to the driver.		
Initial Conditions	Vehicle on, Start-up phase, Initialization state, no other errors.		
Test Inputs	Door signals (by a selector), Start Button.		
Test Outputs	Entry into Ready state, Message, dashboard Door indicator.		
Test Result	The vehicle enters Ready mode only if the doors are closed. Otherwise, the user is notified to close them. The same control was performed on seat belts.		
Test Procedure	**Action**	**Result**	
	Doors = Closed.	Door light off, no warning, no message sent to the user.	
	Doors = Open.	Door indicator lights up yellow. Warning detected: "Open Door" and displayed on the dashboard.	
	Start Button = Pressed.	No entry into Ready mode.	
	Doors = Closed.	Door indicator turns off, no warning detected, no message sent.	
	Start Button = Pressed.	Ready mode activated.	
	Doors = Open.	Exits Ready mode. To re-enter, doors must be closed and the Start button pressed again.	
Requirement ID	TR6	Status	Passed ✓
Test Purpose	Verify that, at start-up, the vehicle control system is active.		
Initial Conditions	Vehicle on, Start-up phase, Initialization state, no initial errors.		
Test Inputs	Vehicle_Control_System (VCS), Start Button.		
Test Outputs	Entry into Ready state, Error, Message, VCS indicator on dashboard.		
Test Result	At vehicle start-up, the control system is active and, if not, entry into Ready mode is not allowed.		

<table>
<tr><td rowspan="4">Test Procedure</td><td>Action</td><td colspan="3">Result</td></tr>
<tr><td>VCS = 1 (correctly active).</td><td colspan="3">Indicator is off, no error detected, Ready mode can be entered.</td></tr>
<tr><td>VCS = 0 (failure).</td><td colspan="3">VCS indicator lights up red, error “Vehicle Control Failure” is detected and sent as a message to the user.</td></tr>
<tr><td>Start Button = Pressed.</td><td colspan="3">Ready mode is not activated.</td></tr>
<tr><td>Requirement ID</td><td colspan="2">TR7-TR8</td><td>Status</td><td>Passed ✓</td></tr>
<tr><td>Test Purpose</td><td colspan="4">Verify that all safety devices are active at start-up and that, in case they are not, an anomaly is notified. Verify that access to the gearbox is enabled only if all safety devices are operational.</td></tr>
<tr><td>Initial Conditions</td><td colspan="4">Vehicle on, Start-up phase, Initialization state, no errors detected.</td></tr>
<tr><td>Test Inputs</td><td colspan="4">Safety_Devices, Start Button.</td></tr>
<tr><td>Test Outputs</td><td colspan="4">Entry into Ready state, Safety Devices indicator light, Error, Message.</td></tr>
<tr><td>Test Result</td><td colspan="4">Safety devices activate at system start-up. Otherwise, the anomaly is notified and access to the gearbox is disabled.</td></tr>
<tr><td rowspan="4">Test Procedure</td><td>Action</td><td colspan="3">Result</td></tr>
<tr><td>Safety_Devices = 1.</td><td colspan="3">The indicator light is off, no error detected, Ready mode can be entered.</td></tr>
<tr><td>Safety_Devices = 0 (failure).</td><td colspan="3">The Safety Devices indicator light turns red, error “Safety Devices Failure” is detected and sent as message to the user.</td></tr>
<tr><td>Start Button = Pressed.</td><td colspan="3">The Ready mode is not activated.</td></tr>
<tr><td>Requirement ID</td><td colspan="2">TR9</td><td>Status</td><td>Passed ✓</td></tr>
<tr><td>Test Purpose</td><td colspan="4">Verify that the BMS monitors the battery conditions and prevents motor start if it is not in optimal conditions, notifying the user of the error.</td></tr>
<tr><td>Initial Conditions</td><td colspan="4">Vehicle on, Start-up phase, Initialization state, no other error detected.</td></tr>
<tr><td>Test Inputs</td><td colspan="4">Fault_BMS, Start Button.</td></tr>
<tr><td>Test Outputs</td><td colspan="4">Entry into Ready state, Error, Message, BMS_State.</td></tr>
<tr><td>Test Result</td><td colspan="4">The BMS correctly monitors battery conditions and prevents motor start when an error is detected, notifying the user of the fault.</td></tr>
<tr><td rowspan="4">Test Procedure</td><td>Action</td><td colspan="3">Result</td></tr>
<tr><td>Vehicle start-up.</td><td colspan="3">BMS_State notifies the activation of the BMS, first sending the message “BMS Activation” for 20s and then “BMS Activated Correctly” for 30 seconds.</td></tr>
<tr><td>Fault_BMS = “Error” (error detected by the BMS).</td><td colspan="3">The error is detected and notified to the user.</td></tr>
<tr><td>Start Button = Pressed.</td><td colspan="3">Ready mode is not activated.</td></tr>
<tr><td>Requirement ID</td><td colspan="2">TR10</td><td>Status</td><td>Passed ✓</td></tr>
<tr><td>Test Purpose</td><td colspan="4">Verify that an anomaly in the motor leads to the suspension of the Ready mode with related notification.</td></tr>
<tr><td>Initial Conditions</td><td colspan="4">Vehicle on, Start-up phase, Ready state, no other error detected.</td></tr>
<tr><td>Test Inputs</td><td colspan="4">Fault_Motor.</td></tr>
<tr><td>Test Outputs</td><td colspan="4">Transition from Start-up to Stop, Motor_Activation = 0, Error, Message.</td></tr>
<tr><td>Test Result</td><td colspan="4">When a motor anomaly is detected in Ready mode, it is suspended, switching to Stop state, and the error is notified to the user.</td></tr>
</table>

Test Procedure	**Action**	**Result**		
	Fault_Motor = "Error" (error detected by the Motor Control System).	The phase switches from Start-up to Stop, interrupting the Ready mode. The error is correctly displayed and the motor is deactivated.		
Requirement ID	**TR11**		Status	Passed ✓
Test Purpose	Verify that the Ready state is correctly displayed on the dashboard.			
Initial Conditions	Vehicle on, Start-up phase, Initialization state, no error detected.			
Test Inputs	Start Button.			
Test Outputs	Entry into Ready state, Message.			
Test Result	When entering Ready mode, the driver receives a message informing them.			
Test Procedure	**Action**	**Result**		
	Start Button = Pressed.	When the Start Button is pressed and the vehicle enters Ready mode, the dashboard displays the message: "READY MODE!" followed by the motor status: "Motor Activated Correctly!".		
Requirement ID	**TR12**		Status	Passed ✓
Test Purpose	Verify that, in case of failure to enter Ready mode, the specific reason for the impediment is displayed.			
Initial Conditions	Vehicle on, Start-up phase, Initialization state, error detected.			
Test Inputs	Start Button, Error.			
Test Outputs	Message.			
Test Result	In case an error is detected in the initial diagnostics, Ready mode cannot be activated and the impediment is communicated to the user.			
Test Procedure	**Action**	**Result**		
	Start Button = Pressed.	Ready mode is not activated. The message communicates to the driver the content of the error.		

Table 16: Test cases for the Drive phase

DRIVE				
Requirement ID	**TD1**		**Status**	Passed ✓
Test Purpose	Verify that the parking brake is automatically deactivated at the beginning of driving.			
Initial Conditions	Vehicle on, Start-up phase, Ready Mode, no error detected.			
Test Inputs	Drive Mode Selection, Deceleration Command.			
Test Outputs	Phase change, Parking Brake, Parking Brake indicator.			
Test Result	The parking brake is correctly deactivated upon entering the Drive State.			
Test Procedure	**Action**	**Result**		
	The Drive Mode position is selected on the gear, the brake pedal is released.	The system switches from Start-up phase to Drive, the Parking_Brake signal switches from 0 to 1 and the Parking Brake indicator turns off.		
Requirement ID	**TD2**		**Status**	Passed ✓
Test Purpose	Verify that the motor response is linear with respect to the accelerator and brake pedal input.			
Initial Conditions	Vehicle on, Drive phase, motor active, no error detected.			
Test Inputs	Acceleration and Deceleration command, Torque.			
Test Outputs	Error, Message, motor indicator.			

Test Result	The motor response is linear with respect to the accelerator and brake pedal input.			
Test Procedure	**Action**	**Result**		
	Observe the motor response to the driving simulated by the Driver.	When the accelerator pedal is pressed, the torque applied to the motor increases, and viceversa when the brake pedal is pressed. No error is detected and no message is sent. The motor indicator is off.		
Requirement ID	**TD3**		**Status**	Passed ✓
Test Purpose	Verify that in case of inconsistent motor response to accelerator or brake, limp mode is activated and an error is notified.			
Initial Conditions	Vehicle on, Drive phase, motor active, no error detected.			
Test Inputs	Acceleration and Deceleration command, Torque.			
Test Outputs	Errore, Message, motor indicator.			
Test Result	If the motor response to the accelerator is inconsistent, an error is detected and the system switches from Drive mode to Stop, notifying the error to the user.			
Test Procedure	**Action**	**Result**		
	Changing the relationship between pedals and torque.	Requirements are not met, the error is detected: “Motor Malfunction! Motor ERROR: Motor Failure”, which is notified to the user. The system switches from Drive phase to Stop. If the vehicle is in motion, Limp Mode is activated to allow safe stopping. The motor indicator lights up red.		
Requirement ID	**TD4**		**Status**	Passed ✓
Test Purpose	Verify that regenerative braking is active during deceleration and adapts to vehicle speed.			
Initial Conditions	Vehicle on, Drive phase, no error detected.			
Test Inputs	Regenerative Braking activated by a check box.			
Test Outputs	Battery charge, SOC.			
Test Result	Regenerative braking is active during deceleration and adapts to vehicle speed.			
Test Procedure	**Action**	**Result**		
	Observe current, charge and SOC response during braking.	It is observed that, when the vehicle is braking, the battery charge increases, as does SOC and they vary according to speed.		
Requirement ID	**TD5**		**Status**	Passed ✓
Test Purpose	Verify that regenerative braking is modifiable via user interface.			
Initial Conditions	Vehicle on, Drive phase, no error detected.			
Test Inputs	Regenerative Braking activated by a check box.			
Test Outputs	Battery charge, SOC, Torque.			
Test Result	Regenerative braking activation is modifiable from the user interface.			
Test Procedure	**Action**	**Result**		
	Regenerative braking enabled.	When the vehicle is braking, the battery charge increases, as does the SOC, and they vary according to speed.		
	Regenerative braking disabled.	During braking, no torque is transmitted to the motor.		
	Regenerative braking re-enabled.	When the vehicle is braking, the battery charge increases, as does the SOC, and they vary according to speed.		

Requirement ID	**TD6**	**Status**	Passed ✓
Test Purpose	Verify that a malfunction in the regenerative system is notified to the user.		
Initial Conditions	Vehicle on, Drive phase, no error detected, regenerative braking active.		
Test Inputs	Regenerative Braking activated by a check box.		
Test Outputs	Message.		
Test Result	If regenerative braking malfunctions, a notification is sent to the user.		
Test Procedure	**Action**	**Result**	
	Force a malfunction in regenerative braking.	A warning is detected: "Regenerative Braking Failure" and notified to the user.	
Requirement ID	**TD7**	**Status**	Passed ✓
Test Purpose	Verify that, with fully charged battery, regeneration stops and automatically resumes after consumption.		
Initial Conditions	Vehicle on, Drive phase, no error detected, regenerative braking active.		
Test Inputs	Regenerative Braking activated by a check box, SOC.		
Test Outputs	Torque.		
Test Result	If the battery is fully charged, regenerative braking is disabled until SOC < 99%.		
Test Procedure	**Action**	**Result**	
	Apply SOC=100%.	During braking, no torque is applied to the motor.	
	When SOC<99%.	Regenerative braking is reactivated and torque is transmitted to the motor also during braking.	
	If SOC≥99% .	Regenerative braking is again disabled until SOC < 99%.	
Requirement ID	**TD8**	Status	Passed ✓
Test Purpose	Verify that the traction control system ensures stability in low grip conditions.		
Initial Conditions	Vehicle on, Drive phase, no error detected.		
Test Inputs	Initial conditions only.		
Test Outputs	ABS_TCS_Activation, Message, Traction Control System indicator on the dashboard.		
Test Result	The traction control system is active during driving. In case of malfunction, a message is notified to the user.		
Test Procedure	**Action**	**Result**	
	Enter Drive State.	ABS_TCS_Activation = 1. The Traction Control System indicator is off. No message is notified to the user.	
	Forcing ABS_TCS_Activation = 0 (failure).	The TCS indicator lights up yellow. The warning "ABS & TCS Failure" is notified to the user.	
Requirement ID	**TD9**	Status	Passed ✓
Test Purpose	Verify that in case of traction loss, TCS and ABS systems intervene.		
Initial Conditions	Vehicle on, Drive phase, no error detected.		
Test Inputs	Initial conditions only.		
Test Outputs	ABS_TCS_Activation, TCS and ABS indicators on the dashboard, Message.		
Test Result	TCS and ABS systems are active during driving and, in case of traction loss, are ready to intervene. If malfunctioning, a message is notified to the user.		
Test Procedure	**Action**	**Result**	
	Observe whether ABS and TC are correctly activated during driving.	ABS_TCS_Activation = 1. TCS and ABS malfunction indicators on the dashboard are off.	
	Forcing ABS_TCS_Activation = 0 (failure).	TCS and ABS indicators light up yellow. The warning "ABS & TCS Failure" is notified to the user.	

<table>
<tr><td>Requirement ID</td><td colspan="2">TD10</td><td>Status</td><td>Passed ✓</td></tr>
<tr><td>Test Purpose</td><td colspan="4">Verify that the BMS manages power based on the available range.</td></tr>
<tr><td>Initial Conditions</td><td colspan="4">Vehicle on, Drive phase, no error detected.</td></tr>
<tr><td>Test Inputs</td><td colspan="4">SOC.</td></tr>
<tr><td>Test Outputs</td><td colspan="4">Limp Mode, Message, Limp Mode indicator on the dashboard.</td></tr>
<tr><td>Test Result</td><td colspan="4">Vehicle power is limited when SOC is equal to or below 20%.</td></tr>
<tr><td rowspan="4">Test Procedure</td><td>Action</td><td colspan="3">Result</td></tr>
<tr><td>Apply SOC=80%.</td><td colspan="3">Limp Mode = 0, no message notified to the user. Limp Mode indicator is off.</td></tr>
<tr><td>Apply SOC=15%.</td><td colspan="3">Limp Mode = 1, user is notified of the activation of Limp Mode with the warning: “Limp Mode Activated”. The Limp Mode indicator lights up red.</td></tr>
<tr><td>Apply SOC=25%.</td><td colspan="3">Limp Mode = 0, no message notified to the user. Limp Mode indicator is off.</td></tr>
<tr><td>Requirement ID</td><td colspan="2">TD11-TD12</td><td>Status</td><td>Passed ✓</td></tr>
<tr><td>Test Purpose</td><td colspan="4">Verify that in case of motor overheating the vehicle enters limp mode and notifies the anomaly. Verify that, after battery cooling, the system notifies readiness to drive.</td></tr>
<tr><td>Initial Conditions</td><td colspan="4">Vehicle on, Drive phase, no error detected.</td></tr>
<tr><td>Test Inputs</td><td colspan="4">Motor Temperature.</td></tr>
<tr><td>Test Outputs</td><td colspan="4">Phase, Limp Mode, Error, Message, motor indicator.</td></tr>
<tr><td>Test Result</td><td colspan="4">In case of motor overheating, the vehicle switches from Drive phase to Stop and the user is notified of the malfunction.</td></tr>
<tr><td rowspan="4">Test Procedure</td><td>Action</td><td colspan="3">Result</td></tr>
<tr><td>Apply Motor Temperature = 30°C.</td><td colspan="3">Limp Mode = 0, no error detected and no message notified to the user. Limp Mode and motor indicators are off.</td></tr>
<tr><td>Apply Motor Temperature = 70°C.</td><td colspan="3">The error “Motor Malfunction!” is detected, along with “Motor ERROR: High Temperature”. Both messages are notified to the user. The vehicle exits the Drive phase and enters Stop. The motor indicator lights up red. If the vehicle is in motion, it enters Limp Mode; otherwise, it goes directly into Park state.</td></tr>
<tr><td>Apply Motor Temperature = 30°C.</td><td colspan="3">The message: “Motor Temperature is OK: vehicle can restart!” appears for 20 seconds. No more errors are present. The motor indicator turns off. The vehicle can restart.</td></tr>
<tr><td>Requirement ID</td><td colspan="2">TD13</td><td>Status</td><td>Passed ✓</td></tr>
<tr><td>Test Purpose</td><td colspan="4">Verify that the dashboard provides real-time information on driving mode, speed and vehicle status.</td></tr>
<tr><td>Initial Conditions</td><td colspan="4">Vehicle on, Drive phase, no error detected.</td></tr>
<tr><td>Test Inputs</td><td colspan="4">Initial conditions only.</td></tr>
<tr><td>Test Outputs</td><td colspan="4">Information on dashboard.</td></tr>
<tr><td>Test Result</td><td colspan="4">All information related to driving is correctly displayed on the dashboard.</td></tr>
</table>

Test Procedure	**Action**	**Result**		
	Observe information on the dashboard.	During driving, the phase, gear, speed, range, distance traveled and all other information are correctly displayed.		
Requirement ID	**TD14**		Status	Passed ✓
Test Purpose	Verify that in case of critical fault, the vehicle enters reduced mode and notifies the error.			
Initial Conditions	Vehicle on, Drive phase.			
Test Inputs	Detected error.			
Test Outputs	Phase, Limp Mode, Error, Message, error indicator, Motor_Activation.			
Test Result	In case of critical fault, the vehicle switches from Drive phase to Stop and the user is notified of the malfunction. If the vehicle is moving, Limp Mode is activated, otherwise it goes directly into Park state.			
Test Procedure	**Action**	**Result**		
	Detected error.	The system switches from Drive phase to Stop phase. Error lights turn on and the detected error is notified to the user. The vehicle enters Limp Mode or Park, depending on whether it is moving or stationary. Once in Park mode, the motor is deactivated.		
Requirement ID	**TD15**		Status	Passed ✓
Test Purpose	Verify that BMS parameters (state of charge, state of health) are shown in real time on the dashboard.			
Initial Conditions	Vehicle on, Drive phase, no error detected.			
Test Inputs	Initial conditions only.			
Test Outputs	BMS information.			
Test Result	BMS parameters are shown in real time on the dashboard.			
Test Procedure	**Action**	**Result**		
	Observe BMS information on the dashboard.	Information related to the battery, such as SOC, SOH, temperature, etc., are correctly shown on the dashboard in real time.		
Requirement ID	**TD16**		Status	Passed ✓
Test Purpose	Verify that ADAS systems are initialized in Drive mode and that their status is indicated to the user.			
Initial Conditions	Vehicle on, Drive phase, no error detected.			
Test Inputs	Initial conditions only.			
Test Outputs	ADAS_Activation, Message.			
Test Result	ADAS systems are active during driving. In case of malfunction, a message is notified to the user.			
Test Procedure	**Action**	**Result**		
	Observe whether ADAS is correctly activated during driving.	ADAS_Activation = 1.		
	Forcing ADAS_Activation = 0 (failure).	The warning "ADAS Failure" is notified to the user.		
Requirement ID	**TD17**		Status	Passed ✓
Test Purpose	Verify that, when the vehicle brakes, the brake indicators are active.			
Initial Conditions	Vehicle on, Drive phase, no error detected.			
Test Inputs	Deceleration Command.			
Test Outputs	Stop_Lights.			
Test Result	When the vehicle brakes, the brake indicators are active.			

Test Procedure	**Action**	**Result**
	Apply Deceleration_Cmd>0.	Stop_Lights signal = 1.
	Apply Deceleration_Cmd=0.	Stop_Lights signal = 0.

Table 17: Test cases for the Charge phase

CHARGE			
Requirement ID	**TC1- TC2**	**Status**	Passed ✓
Test Purpose	Verify that the charging phase starts automatically when the cable is plugged into the vehicle. Verify that the charging phase does not start if the cable is not connected.		
Initial Conditions	Vehicle in Stop phase, no errors detected, SOC < 99%.		
Test Inputs	Charge_Connector.		
Test Outputs	Entry into charging phase, connector indicator and Parking_Brake indicator on the dashboard, Message.		
Test Result	The charging phase starts automatically when the cable is plugged into the vehicle. If the cable is not connected, the charging phase does not start.		
Test Procedure	**Action**	**Result**	
	Charge_Connector = 0 (Charging cable disconnected).	Vehicle remains in Stop phase. Connector indicator is off. No message.	
	Charge_Connector = 1 (Charging cable connected).	Vehicle switches from Stop to Charge. Connector indicator lights green, Parking Brake indicator lights red signaling the vehicle cannot move. The dashboard shows the message: "Battery is charging!".	
Requirement ID	**TC3**	**Status**	Passed ✓
Test Purpose	Verify that the charging system establishes a secure connection and regulates power according to battery capacity.		
Initial Conditions	Vehicle in Stop phase, no errors detected.		
Test Inputs	SOC.		
Test Outputs	Entry into charging phase.		
Test Result	The vehicle establishes a secure connection with the charger and regulates power based on battery capacity.		
Test Procedure	**Action**	**Result**	
	Apply SOC = 100%.	Applying a SOC signal at maximum charge level, even with the connector plugged in, the vehicle does not enter charging mode if SOC is higher than a certain threshold.	
Requirement ID	**TC4**	**Status**	Passed ✓
Test Purpose	Verify that during charging the cable is mechanically locked to avoid accidental disconnections.		
Initial Conditions	Vehicle in Charge phase, no errors detected, SOC < 99%.		
Test Inputs	Charge Connector Unlock Button on the dashboard, SOC.		
Test Outputs	Lock_Cable, Connector Locking indicator on the dashboard.		
Test Result	During charging, the cable is mechanically locked to avoid accidental disconnections.		

<table>
<tr><td rowspan="5">Test Procedure</td><td>Action</td><td colspan="3">Result</td></tr>
<tr><td>Charge_Connector = 0 (Charging cable disconnected).</td><td colspan="3">Connector Locking indicator off. Vehicle in Stop phase.</td></tr>
<tr><td>Charge_Connector = 1 (Charging cable connected).</td><td colspan="3">Switch from Stop to Charge. Cable locked: Lock_Cable = 1. Cable locking indicator lights yellow.</td></tr>
<tr><td>Apply SOC = 70%, Charge Connector Unlock Button = Pressed.</td><td colspan="3">Cable unlocked: Lock_Cable = 0. Cable locking indicator off. Vehicle can switch to Stop mode by removing cable.</td></tr>
<tr><td>Charge_Connector = 1 (Charging cable still connected).</td><td colspan="3">Cable locked again after 30 seconds:
Lock_Cable = 1. Cable locking indicator lights yellow.</td></tr>
<tr><td>Requirement ID</td><td colspan="2">TC5</td><td>Status</td><td>Passed ✓</td></tr>
<tr><td>Test Purpose</td><td colspan="4">Verify that the vehicle cannot be moved during charging.</td></tr>
<tr><td>Initial Conditions</td><td colspan="4">Vehicle in Charge phase, no errors detected, SOC < 99%.</td></tr>
<tr><td>Test Inputs</td><td colspan="4">Charge_Connector.</td></tr>
<tr><td>Test Outputs</td><td colspan="4">Parking_Brake, Parking Brake indicator on the dashboard.</td></tr>
<tr><td>Test Result</td><td colspan="4">During charging, the vehicle parking brake is activated to prevent movement.</td></tr>
<tr><td rowspan="2">Test Procedure</td><td>Action</td><td colspan="3">Result</td></tr>
<tr><td>Charge_Connector = 1 (Cable connected).</td><td colspan="3">Parking_Brake = 1, red indicator lit on dashboard.</td></tr>
<tr><td>Requirement ID</td><td colspan="2">TC6</td><td>Status</td><td>Passed ✓</td></tr>
<tr><td>Test Purpose</td><td colspan="4">Verify that if vehicle movement is detected during charging, the charging phase is immediately stopped.</td></tr>
<tr><td>Initial Conditions</td><td colspan="4">Vehicle in Charge phase, no errors detected, SOC < 99%.</td></tr>
<tr><td>Test Inputs</td><td colspan="4">Charge_Connector, Vehicle Speed.</td></tr>
<tr><td>Test Outputs</td><td colspan="4">Exit from charging phase, Lock_Cable, Error, Message.</td></tr>
<tr><td>Test Result</td><td colspan="4">If vehicle movement is detected during charging, the system exits charging phase and switches to Stop, notifying the error on the dashboard.</td></tr>
<tr><td rowspan="4">Test Procedure</td><td>Action</td><td colspan="3">Result</td></tr>
<tr><td>Apply Speed = 0.</td><td colspan="3">Charge phase active.</td></tr>
<tr><td>Apply Speed = 20 km/hr.</td><td colspan="3">Error detected and the system switches from charging to Stop phase. Lock_Cable = 0: cable unlocked. User is notified with the message: “Undesired Movement. Charge has been stopped”.</td></tr>
<tr><td>Charge_Connector = 0 (Charging cable disconnected).</td><td colspan="3">Disconnecting the charging cable clears the message. Error is cleared. Vehicle in Park/Power-off mode.</td></tr>
<tr><td>Requirement ID</td><td colspan="2">TC7</td><td>Status</td><td>Passed ✓</td></tr>
<tr><td>Test Purpose</td><td colspan="4">Verify that the BMS continuously monitors the charging process.</td></tr>
<tr><td>Initial Conditions</td><td colspan="4">Vehicle in Charge phase, no errors detected.</td></tr>
<tr><td>Test Inputs</td><td colspan="4">Initial conditions only.</td></tr>
<tr><td>Test Outputs</td><td colspan="4">BMS_Activation.</td></tr>
<tr><td>Test Result</td><td colspan="4">The BMS continuously monitors the charging process.</td></tr>
<tr><td rowspan="2">Test Procedure</td><td>Action</td><td colspan="3">Result</td></tr>
<tr><td>Observe that during charging the BMS is correctly active.</td><td colspan="3">BMS_Activation = 1, BMS is active and communicates in real-time with the system.</td></tr>
</table>

<table>
<tr><th>Requirement ID</th><th colspan="2">TC8</th><th>Status</th><th>Passed ✓</th></tr>
<tr><td>Test Purpose</td><td colspan="4">Verify that the BMS interrupts charging when the battery is fully charged, in case of overload or error.</td></tr>
<tr><td>Initial Conditions</td><td colspan="4">Vehicle in Charge phase, no errors detected.</td></tr>
<tr><td>Test Inputs</td><td colspan="4">SOC, Battery_Voltage.</td></tr>
<tr><td>Test Outputs</td><td colspan="4">Lock_Cable, Error, Message.</td></tr>
<tr><td>Test Result</td><td colspan="4">The BMS correctly interrupts charging when the battery is fully charged or in case of error.</td></tr>
<tr><td rowspan="5">Test Procedure</td><td>Action</td><td colspan="3">Result</td></tr>
<tr><td>Apply SOC=98%.</td><td colspan="3">When SOC reaches 100%, Lock_Cable = 0: cable unlocked. Charging phase stops and switches to Stop. User is notified with the message: “Battery Completely Charged. Disconnect Charge Connector! Charge has been stopped.”.</td></tr>
<tr><td>Charge_Connector = 0 (Charging cable disconnected).</td><td colspan="3">Returns to original phase (Park or Power-off). Error is cleared.</td></tr>
<tr><td>Apply SOC=70%, Charge_Connector =1 and Battery_Voltage = 500V (> maximum threshold).</td><td colspan="3">Error detected. Lock_Cable = 0: cable unlocked. Charging stops and switches to Stop. User is notified of Fault_BMS error (in this case: “BMS ERROR: Over Voltage”), followed by the message: “Charge has been stopped”.</td></tr>
<tr><td>Charge_Connector = 0 (Charging cable disconnected).</td><td colspan="3">Returns to original phase (Park or Power-off). In Park the error continues to be shown, while in Power-off the display is turned off.</td></tr>
<tr><th>Requirement ID</th><th colspan="2">TC9 - TC10</th><th>Status</th><th>Passed ✓</th></tr>
<tr><td>Test Purpose</td><td colspan="4">Verify that charging time is optimized to reduce idle time. Verify that charging efficiency is correctly managed during the transition from fast to maintenance charging.</td></tr>
<tr><td>Initial Conditions</td><td colspan="4">Vehicle in Charge phase, no errors detected.</td></tr>
<tr><td>Test Inputs</td><td colspan="4">Charge_Mode.</td></tr>
<tr><td>Test Outputs</td><td colspan="4">Charging profile.</td></tr>
<tr><td>Test Result</td><td colspan="4">Charging efficiency is correctly managed during the charging process and charging time is optimized according to the selected charging mode.</td></tr>
<tr><td rowspan="2">Test Procedure</td><td>Action</td><td colspan="3">Result</td></tr>
<tr><td>Observe battery charging profile, current and SOC during charging.</td><td colspan="3">It is observed that, varying the Charge_Mode input, current, SOC, charge, voltage profiles of the battery conform to expectations. Charging varies linearly in response to input current and time is correctly managed during the transition between Fast and Slow Charge.</td></tr>
<tr><th>Requirement ID</th><th colspan="2">TC11</th><th>Status</th><th>Passed ✓</th></tr>
<tr><td>Test Purpose</td><td colspan="4">Verify that the battery is kept at a safe temperature by cooling during charging.</td></tr>
<tr><td>Initial Conditions</td><td colspan="4">Vehicle in Charge phase, no errors detected.</td></tr>
<tr><td>Test Inputs</td><td colspan="4">Initial conditions only.</td></tr>
<tr><td>Test Outputs</td><td colspan="4">BMS_Activation.</td></tr>
<tr><td>Test Result</td><td colspan="4">The battery is kept at a safe temperature by cooling during charging.</td></tr>
<tr><td rowspan="2">Test Procedure</td><td>Action</td><td colspan="3">Result</td></tr>
<tr><td>Observe battery and BMS during charging.</td><td colspan="3">In the Plant, an always-active cooling system for the high-voltage battery is included. The BMS, as previously tested, is active and constantly monitors the battery temperature.</td></tr>
</table>

<table>
<tr><td></td><td></td><td colspan="3">If temperatures exceed the limits, an error is notified and the case addressed in tests TBMS5 and TC8 occurs.</td></tr>
<tr><td>Requirement ID</td><td colspan="2">TC12</td><td>Status</td><td>Passed ✓</td></tr>
<tr><td>Test Purpose</td><td colspan="4">Verify that the user receives continuous information on charging status.</td></tr>
<tr><td>Initial Conditions</td><td colspan="4">Vehicle in Charge phase, no errors detected.</td></tr>
<tr><td>Test Inputs</td><td colspan="4">Initial conditions only.</td></tr>
<tr><td>Test Outputs</td><td colspan="4">SOC indicator on dashboard, Message.</td></tr>
<tr><td>Test Result</td><td colspan="4">The user receives continuous information on charging status.</td></tr>
<tr><td rowspan="2">Test Procedure</td><td>Action</td><td colspan="3">Result</td></tr>
<tr><td>Observe dashboard during charging.</td><td colspan="3">During charging, the dashboard correctly notifies all necessary information for the user to monitor charging status, such as SOC level, phase activation messages, cable connected and/or locked, etc. Also, real-time information regarding the high-voltage battery such as current, voltage, temperature can be displayed in the BMS area. Error messages are notified to the user.</td></tr>
<tr><td>Requirement ID</td><td colspan="2">TC13</td><td>Status</td><td>Passed ✓</td></tr>
<tr><td>Test Purpose</td><td colspan="4">Verify that charging is interrupted when the cable is unplugged from the vehicle.</td></tr>
<tr><td>Initial Conditions</td><td colspan="4">Vehicle in Charge phase, no errors detected.</td></tr>
<tr><td>Test Inputs</td><td colspan="4">Charge Connector Unlock Button, Charge_Connector.</td></tr>
<tr><td>Test Outputs</td><td colspan="4">Exit from charging phase, Charge_Activation.</td></tr>
<tr><td>Test Result</td><td colspan="4">If the cable is unplugged from the vehicle, charging is interrupted.</td></tr>
<tr><td rowspan="4">Test Procedure</td><td>Action</td><td colspan="3">Result</td></tr>
<tr><td>Charge Connector Unlock Button = Not pressed, Charge_Connector = 0.</td><td colspan="3">It is not possible to disconnect the cable without unlocking it first. Charge_Activation = 1 and Charge phase continues.</td></tr>
<tr><td>Charge Connector Unlock Button = Pressed, then Charge_Connector = 0 after 30 seconds.</td><td colspan="3">The cable is relocked. Charge_Activation = 1 and remains in Charge phase.</td></tr>
<tr><td>Charge Connector Unlock Button = Pressed, then Charge_Connector = 0 within 30 seconds.</td><td colspan="3">Charge_Activation = 0. Phase switches from Charge to Stop.</td></tr>
<tr><td>Requirement ID</td><td colspan="2">TC14</td><td>Status</td><td>Passed ✓</td></tr>
<tr><td>Test Purpose</td><td colspan="4">Verify that charging is not interrupted as long as the cable remains plugged into the vehicle and no errors occur.</td></tr>
<tr><td>Initial Conditions</td><td colspan="4">Vehicle in Charge phase, no errors detected.</td></tr>
<tr><td>Test Inputs</td><td colspan="4">Charge Connector Unlock Button, Charge_Connector.</td></tr>
<tr><td>Test Outputs</td><td colspan="4">Charge_Activation.</td></tr>
<tr><td>Test Result</td><td colspan="4">Charging is not interrupted as long as the cable remains plugged into the vehicle and no errors occur.</td></tr>
<tr><td rowspan="2">Test Procedure</td><td>Action</td><td colspan="3">Result</td></tr>
<tr><td>Charge Connector Unlock Button = Not pressed, Charge_Connector = 1.</td><td colspan="3">Charge_Activation = 1. Battery charges correctly until full charge is reached, no errors are notified and the cable is not disconnected.</td></tr>
</table>

Table 18: Test cases for the Stop phase

STOP			
Requirement ID	**TS1**	**Status**	Passed ✓
Test Purpose	Verify that the parking brake activates automatically upon entering Park mode.		
Initial Conditions	Vehicle on, Stop phase, Park Mode.		
Test Inputs	Initial conditions only.		
Test Outputs	Parking_Brake, Parking Brake indicator on dashboard.		
Test Result	The parking brake activates automatically upon entering Park mode.		
Test Procedure	**Action**	**Result**	
	Observe the behavior of the Parking Brake during Park mode.	Parking_Brake = 1: parking brake is active. The indicator on the dashboard is lit red.	
Requirement ID	**TS2**	**Status**	Passed ✓
Test Purpose	Verify that, when selecting the Park mode, the motor is blocked by interrupting power transmission.		
Initial Conditions	Vehicle on, Stop phase, Park Mode.		
Test Inputs	Initial conditions only.		
Test Outputs	Motor_Activation.		
Test Result	In Park mode, the motor is blocked by interrupting power transmission.		
Test Procedure	**Action**	**Result**	
	Observe the behavior of Motor_Activation during Park mode.	Motor_Activation = 0: the motor is inactive.	
Requirement ID	**TS3**	**Status**	Passed ✓
Test Purpose	Verify that, with the vehicle stopped, the stability and transmission lock systems prevent any undesired movement.		
Initial Conditions	Vehicle on, Stop phase.		
Test Inputs	Initial conditions only.		
Test Outputs	Traction Loss Control.		
Test Result	With the vehicle stopped, the stability systems prevent any undesired movement.		
Test Procedure	**Action**	**Result**	
	Observe the behavior of TLC during Stop phase.	TLC = 1: Traction Loss Control active when the vehicle is on.	
Requirement ID	**TS4**	**Status**	Passed ✓
Test Purpose	Verify that in case of a fault the vehicle immobilization is still guaranteed.		
Initial Conditions	Vehicle on, Drive phase, no errors detected.		
Test Inputs	Fault_BMS (or Fault_Motor).		
Test Outputs	Parking_Brake, Traction Loss Control.		
Test Result	In case of fault, vehicle immobilization is guaranteed during Stop/Park phase.		
Test Procedure	**Action**	**Result**	
	Fault_BMS = No forced error input.	Parking Brake = 0: parking brake inactive. Vehicle is in driving phase. No errors detected.	
	Fault_BMS = Error detected.	An error is detected. If Speed > 0, vehicle enters Limp Mode.	An error is detected. If Speed = 0, vehicle enters Stop/Park mode and: TLC = 1, Parking_Brake = 1.

Requirement ID	TS5	Status	Passed ✓
Test Purpose	Verify that activation of Park mode is confirmed to the driver via visual or audible signal.		
Initial Conditions	Vehicle on, Stop phase, Park mode.		
Test Inputs	Initial conditions only.		
Test Outputs	Gear Position.		
Test Result	Activation of Park mode is correctly confirmed to the driver by visual indication.		
Test Procedure	**Action**	**Result**	
	Observe dashboard while vehicle is in Park mode.	When vehicle is in Park mode, Gear Position = Park is correctly displayed on the dashboard (also in case of forced Stop activation).	
Requirement ID	**TS6**	**Status**	Passed ✓
Test Purpose	Verify that entering Stop mode with the vehicle stopped disconnects high-voltage systems from the traction motor.		
Initial Conditions	Vehicle on, Stop phase, Park mode.		
Test Inputs	Initial conditions only.		
Test Outputs	Battery_Activation.		
Test Result	Entering Stop mode with the vehicle stopped disconnects high-voltage systems from the traction motor.		
Test Procedure	**Action**	**Result**	
	Observe Battery_Activation behavior during Stop phase.	When vehicle enters Park mode, Battery_Activation = 0: the high-voltage battery is disconnected from the motor.	
Requirement ID	**TS7**	**Status**	Passed ✓
Test Purpose	Verify that, in Park mode with the motor off, essential electronic systems remain powered at low voltage, while non-critical systems are turned off.		
Initial Conditions	Vehicle on, Stop phase, Park mode.		
Test Inputs	Initial conditions only.		
Test Outputs	Battery_Activation.		
Test Result	During Park mode with motor off, essential electronic systems remain powered at low voltage, while non-critical systems are turned off.		
Test Procedure	**Action**	**Result**	
	Observe LV_Battery_Activation behavior during Stop phase.	When vehicle enters Park mode, LV_Battery_Activation = 1: the low-voltage battery is connected to essential electronic systems.	
Requirement ID	**TS8**	Status	Passed ✓
Test Purpose	Verify that pressing the shutdown button completely turns off the vehicle, disabling the motor and non-essential loads.		
Initial Conditions	Vehicle on, Stop phase, Park mode.		
Test Inputs	Start/Stop Button.		
Test Outputs	Entry into Power-off state.		
Test Result	Pressing the shutdown button completely turns off the vehicle, disabling the motor and non-essential loads.		
Test Procedure	**Action**	**Result**	
	Start/Stop Button = Pressed.	The system correctly switches from Park mode to Power-off, disabling all non-essential loads.	

Table 19: Test cases for the BMS subsystem

<table>
<tr><th colspan="5">BMS</th></tr>
<tr><td>Requirement ID</td><td colspan="2">TBMS1</td><td>Status</td><td>Passed ✓</td></tr>
<tr><td>Test Purpose</td><td colspan="4">Verify that when the BMS is activated, parameter monitoring becomes active.</td></tr>
<tr><td>Initial Conditions</td><td colspan="4">BMS deactivated.</td></tr>
<tr><td>Test Inputs</td><td colspan="4">BMS_Activation changes from 0 to 1.</td></tr>
<tr><td>Test Outputs</td><td colspan="4">BMS_State.</td></tr>
<tr><td>Test Result</td><td colspan="4">Upon receiving BMS_Activation = 1, the BMS switches to the active state and outputs the expected messages.</td></tr>
<tr><td rowspan="2">Test Procedure</td><td>Action</td><td colspan="3">Result</td></tr>
<tr><td>The value of BMS_Activation is changed from 0 to 1.</td><td colspan="3">The BMS state changes to the activation phase, displaying the message “BMS Activation” for 20 seconds. Then the message “BMS Activated Correctly!” is displayed for 30 seconds. Finally, the control system becomes fully active.</td></tr>
<tr><td>Requirement ID</td><td colspan="2">TBMS2</td><td>Status</td><td>Passed ✓</td></tr>
<tr><td>Test Purpose</td><td colspan="4">Verify that the BMS detects an overcurrent error and notifies it correctly.</td></tr>
<tr><td>Initial Conditions</td><td colspan="4">BMS active.</td></tr>
<tr><td>Test Inputs</td><td colspan="4">Battery current signal of 500 A (= maximum absolute value).</td></tr>
<tr><td>Test Outputs</td><td colspan="4">Fault_BMS, Battery Fault indicator on the dashboard.</td></tr>
<tr><td>Test Result</td><td colspan="4">The BMS behaves as expected, detecting the fault and notifying the user.</td></tr>
<tr><td rowspan="2">Test Procedure</td><td>Action</td><td colspan="3">Result</td></tr>
<tr><td>A current signal above the maximum threshold is sent for more than 10 consecutive seconds.</td><td colspan="3">The BMS detects the fault and displays the message: “BMS ERROR: Overcurrent”. The Battery Fault indicator light on the dashboard turns on.</td></tr>
<tr><td>Requirement ID</td><td colspan="2">TBMS3</td><td>Status</td><td>Passed ✓</td></tr>
<tr><td>Test Purpose</td><td colspan="4">Verify that the BMS detects an overvoltage error and notifies it correctly.</td></tr>
<tr><td>Initial Conditions</td><td colspan="4">BMS active.</td></tr>
<tr><td>Test Inputs</td><td colspan="4">Battery voltage signal of 500 V (> maximum threshold).</td></tr>
<tr><td>Test Outputs</td><td colspan="4">Fault_BMS, Battery Fault indicator on the dashboard.</td></tr>
<tr><td>Test Result</td><td colspan="4">The BMS behaves as expected, detecting the error and notifying the user.</td></tr>
<tr><td rowspan="2">Test Procedure</td><td>Action</td><td colspan="3">Result</td></tr>
<tr><td>A voltage signal exceeding the maximum threshold is sent.</td><td colspan="3">The BMS detects the fault and displays the message: “BMS ERROR: Overvoltage”. The Battery Fault indicator light on the dashboard turns on.</td></tr>
<tr><td>Requirement ID</td><td colspan="2">TBMS4</td><td>Status</td><td>Passed ✓</td></tr>
<tr><td>Test Purpose</td><td colspan="4">Verify that the BMS detects an undervoltage error and notifies it correctly.</td></tr>
<tr><td>Initial Conditions</td><td colspan="4">BMS active.</td></tr>
<tr><td>Test Inputs</td><td colspan="4">Battery voltage signal of 100 V (< minimum threshold).</td></tr>
<tr><td>Test Outputs</td><td colspan="4">Fault_BMS, Battery Fault indicator on the dashboard.</td></tr>
<tr><td>Test Result</td><td colspan="4">The BMS behaves as expected, detecting the error and notifying the user.</td></tr>
<tr><td rowspan="2">Test Procedure</td><td>Action</td><td colspan="3">Result</td></tr>
<tr><td>A voltage signal below the minimum threshold is sent.</td><td colspan="3">The BMS detects the error and displays the message: “BMS ERROR: Under Voltage”. The Battery Fault indicator light on the dashboard turns on.</td></tr>
</table>

<table>
<tr><td>Requirement ID</td><td colspan="2">TBMS5</td><td>Status</td><td>Passed ✓</td></tr>
<tr><td>Test Purpose</td><td colspan="4">Verify that the BMS correctly monitors the temperature and notifies an error if the temperature is too high or too low.</td></tr>
<tr><td>Initial Conditions</td><td colspan="4">BMS active.</td></tr>
<tr><td>Test Inputs</td><td colspan="4">Battery Temperature signal controlled by a knob ranging from -10 to 60°C.</td></tr>
<tr><td>Test Outputs</td><td colspan="4">Fault_BMS, BMS_State, ‘Battery Fault’ and ‘Battery Temperature Fault’ indicators on the dashboard.</td></tr>
<tr><td>Test Result</td><td colspan="4">The BMS correctly monitors the temperature and notifies any faults.</td></tr>
<tr><td rowspan="8">Test Procedure</td><td>Action</td><td colspan="3">Result</td></tr>
<tr><td>Apply 20°C.</td><td colspan="3">BMS_State and Fault_BMS show no message. Battery Fault and Battery Temperature Fault indicators are OFF.</td></tr>
<tr><td>Apply 45°C.</td><td colspan="3">BMS_State displays: “Attention, High Battery Temperature”. The Battery Temperature Fault light turns red.</td></tr>
<tr><td>Apply 60°C.</td><td colspan="3">Fault_BMS displays: “BMS ERROR: High Temperature”. The Battery Fault light also turns red.</td></tr>
<tr><td>Apply 25°C.</td><td colspan="3">BMS_State displays: “Battery Temperature is OK” for 20 seconds. Fault_BMS shows no message. All indicators are OFF.</td></tr>
<tr><td>Apply 3°C.</td><td colspan="3">BMS_State displays: “Attention, Low Battery Temperature”. Battery Temperature Fault light turns blue.</td></tr>
<tr><td>Apply -10°C.</td><td colspan="3">Fault_BMS displays: “BMS ERROR: Low Temperature”. The Battery Fault light turns red.</td></tr>
<tr><td>Apply 30°C.</td><td colspan="3">BMS_State displays: “Battery Temperature is OK” for 20 seconds. Fault_BMS shows no message. All indicators are OFF.</td></tr>
<tr><td>Requirement ID</td><td colspan="2">TBMS6</td><td>Status</td><td>Passed ✓</td></tr>
<tr><td>Test Purpose</td><td colspan="4">Verify that the BMS monitors the battery SOH and correctly notifies the error in case of low SOH.</td></tr>
<tr><td>Initial Conditions</td><td colspan="4">BMS active.</td></tr>
<tr><td>Test Inputs</td><td colspan="4">SOH signal controlled by a knob ranging from 0 to 100%.</td></tr>
<tr><td>Test Outputs</td><td colspan="4">Fault_BMS, Battery Fault indicator.</td></tr>
<tr><td>Test Result</td><td colspan="4">The BMS correctly monitors the SOH and notifies the error when SOH is too low.</td></tr>
<tr><td rowspan="4">Test Procedure</td><td>Action</td><td colspan="3">Result</td></tr>
<tr><td>Apply SOH=100%.</td><td colspan="3">No error is notified. Battery Fault light is OFF.</td></tr>
<tr><td>Apply SOH=30%.</td><td colspan="3">Fault_BMS displays: “BMS ERROR: Low SOH”. Battery Fault light turns red.</td></tr>
<tr><td>Apply SOH=80%.</td><td colspan="3">No error is notified. Battery Fault light is OFF.</td></tr>
<tr><td>Requirement ID</td><td colspan="2">TBMS7</td><td>Status</td><td>Passed ✓</td></tr>
<tr><td>Test Purpose</td><td colspan="4">Verify that the BMS correctly monitors the SOC and notifies errors when the SOC is too high or too low.</td></tr>
<tr><td>Initial Conditions</td><td colspan="4">BMS active.</td></tr>
<tr><td>Test Inputs</td><td colspan="4">SOC signal controlled by a knob ranging from 0 to 120%.</td></tr>
<tr><td>Test Outputs</td><td colspan="4">Fault_BMS, BMS_State, ‘SOC [%]’ icon; Battery Fault, HV Battery and Eco Mode indicators on the dashboard.</td></tr>
<tr><td>Test Result</td><td colspan="4">The BMS correctly monitors the SOC and notifies the user of any errors.</td></tr>
</table>

Test Procedure	**Action**	**Result**	
	Apply SOC=70%.	No message from BMS_State or Fault_BMS. All indicators are OFF. SOC icon shows charge status.	
	Apply SOC=15%.	BMS_State displays: “LOW BATTERY”. HV Battery light turns yellow. Eco Mode light turns green. SOC icon updates.	
	Apply SOC=0%.	Fault_BMS displays: “BMS ERROR: Low Battery”. Battery Fault light turns red. SOC icon updates.	
	Apply SOC=50%.	No message. All indicators are OFF. SOC icon shows charge status.	
	Apply SOC=100%.	BMS_State displays: “Battery Completely Charged”. All indicators remain OFF. SOC icon updates.	
	Apply SOC=110%.	Fault_BMS displays: “BMS ERROR: Overcharging”. Battery Fault light turns red.	
	Apply SOC=60%.	No message. All indicators are OFF. SOC icon shows charge status.	
Requirement ID	**TBMS8**	Status	Passed ✓
Test Purpose	Verify that Fault_BMS includes all relevant messages when multiple errors occur simultaneously.		
Initial Conditions	BMS active.		
Test Inputs	Battery Temperature and SOH signals.		
Test Outputs	Fault_BMS, BMS_State; Battery Fault and Battery Temperature Fault indicators on the dashboard.		
Test Result	All errors detected by the BMS are correctly reported.		
Test Procedure	**Action**	**Result**	
	Temperature = 70°C and SOH = 30% are applied.	BMS_State displays: “Attention, High Battery Temperature”. Temperature Fault light turns red. Fault_BMS displays: “BMS ERROR: Low SOH \n BMS ERROR: High Temperature”. Battery Fault light turns red.	
Requirement ID	**TBMS9**	Status	Passed ✓
Test Purpose	Verify that when the BMS is deactivated, it shuts down completely.		
Initial Conditions	BMS active, errors detected, BMS_Fault and BMS_State not empty.		
Test Inputs	BMS_Activation signal.		
Test Outputs	BMS_State, BMS_Fault, and battery-related indicator lights.		
Test Result	The BMS shuts down correctly when BMS_Activation is set to 0.		
Test Procedure	**Action**	**Result**	
	BMS_Activation is set to 0.	The BMS deactivates, BMS_State and BMS_Fault strings are cleared, and all battery-related lights turn OFF.	

Appendix B – Industrial Collaboration

This Master's thesis was conducted at Brain Technologies, an engineering consulting company based in Turin. Founded in 2008, the company operates across multiple sectors, including mechatronics, embedded systems, industry 4.0 and advanced mobility.
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