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MINERVA PROJECT: A Novel Cooperation Platform for High-Performance Racing e-Powertrains[#]

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ABSTRACT

This paper outlines the key activities and outcomes of the MINERVA project. This project involves the cooperation of various academic, research, and industrial partners to develop and test hybrid storage architectures for use in high-performance racing vehicles. With this aim, simulation and experimental characterisation tests have been carried out by means of an advanced and interconnected laboratory network. In this case, a bottom-up approach is proposed, starting from a single battery cell up to the whole vehicle level.

Keywords: Hybrid Energy Storage Systems, Racing Electric Vehicles, Energy Management Systems

1. INTRODUCTION

Historically, the road transportation sector has relied heavily on fossil fuels, which continue to offer superior performance in terms of energy density and refuelling time. In recent decades, growing environmental concerns related to climate change and pollution have led to the adoption of stringent new regulations regarding exhaust emissions. The electrification of vehicle powertrains is poised to play a key role in achieving those ambitious goals through the increasing expected adoption of electric road vehicles (EVs).

As a matter of fact, supported by the availability on the market of high-performance lithium battery technologies, the new generations of electric vehicles are now able to satisfy most of the user needs in terms of vehicle autonomy and driving comfort, with acceptable charging times [1]. Nevertheless, EVs can still be considered a new vehicle technology, and therefore, different technical bottlenecks need to be properly addressed to support their wide adoption in the vehicle market. Most of these challenges are directly related to the durability and management of the on-board battery pack, which represents the core component of the entire vehicle [2]. In this regard, EV racing, following the well-known "*race-to-road*" paradigm previously established by traditional Internal Combustion Engine (ICE) vehicles, is now operating as an accelerated, high-intensity test bed. This directly boosts technological advancements on e-powertrains for transfer to the consumer market [3].

Unlike the power usage in typical urban driving, in racing operations, the power demand from e-powertrains is generally highly variable, due to many rapid acceleration and deceleration phases, which involve peak power operations for the on-board battery pack. Consequently, proper battery sizing and management have to simultaneously balance energy and power density, both to ensure an acceptable driving range and sustain high-stress operations. The above objectives can be conveniently achieved through the use of a Hybrid Energy Storage System (HESS), combining a high-energy battery (e.g. high-nickel-content NMC lithium batteries) with a high-power device (e.g. supercapacitors or high-power lithium batteries) to handle the transient power peaks, through the use of properly controlled bidirectional DC/DC converters [4].

In the above context, the MINERVA project aims to develop a scaled prototype at TRL 4 of an innovative braking energy recovery system (hereinafter referred to as BRB) for the next Italian sustainable high-performance car of the future. In this regard, two Italian laboratories are involved in the development activities, CNR-STEMS, based in Naples, and CARS at Politecnico di Torino. In particular, these laboratories are equipped with cutting-edge technology infrastructures to test innovative battery systems and develop small-scale prototypes to validate all BRB subsystems that will be used to set up the TRL7 vehicle demonstrator. MINERVA will therefore

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be an enabler for the development of future, more efficient electric cars.

2. CASE STUDY AND METHODOLOGY

2.1 Case Study

The reference application for the MINERVA project consists of a high-performance electric car, whose main architecture is composed of propulsion, energy management (EMS) and energy storage systems (ESS). About propulsion, the EV is equipped with four electric drives, one for each wheel. The EMS manages the electric power request of the propulsion system, controlling the electric power fluxes drawn/supplied to the ESS through a DC/DC Converter. In this regard, the ESS is divided into High Power (HPB) and High Energy (HEB) Batteries, as reported in Fig. 1.

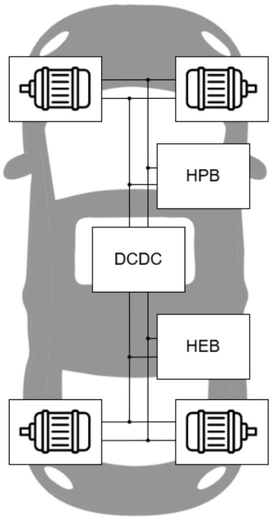

Fig. 1 High-performance electric car layout

As depicted in Figure 1, the HPB is positioned at the vehicle front, while the HEB is allocated at the rear. With this electrical framework, the DC/DC converter facilitates the routing of the electrical power to one of the two BP units, thereby enabling distinct voltage potentials across the two DC buses.

2.2 Modelling and Energy Management Strategy

For the effective utilisation of the powertrain layout, a real-time energy management strategy is implemented to calculate the projected partitioning of the electrical power demand across the two BPs. In particular, the real-time strategy is based on the Equivalent Consumption Minimisation Strategy (ECMS) described in [5], which is usually employed in hybrid powertrains. Specifically, the ECMS strategy is an online energy-management method based on the minimisation of ESS total energy consumption, from fuel and BP SoC perspectives. To achieve this objective, the optimisation strategy introduces an equivalence factor to directly compare the two different energy sources, fuel and battery energy. [6]. In the investigated case study, the methodology is adopted to manage the electrical energy fluxes between the two BPs, enabling the optimal electrical energy split. To mathematically formulate the optimisation problem, the following equations are used:

$$\min_{P_{b1},P_{b2}} P_{oc1} + \lambda P_{oc2}$$

$$s.t. P_{oci} = V_{oci}(SoC_i)I_{bi} \qquad i = 1,2$$

$$V_{bi} = V_{oci}(SoC_i) - R_{bi}I_{bi} \qquad i = 1,2$$

$$P_{bi} = V_{bi}I_{bi} \qquad i = 1,2$$

$$V_{mini} \leq V_{bi} \leq V_{maxi} \qquad i = 1,2$$

$$I_{mini} \leq I_{bi} \leq I_{maxi} \qquad i = 1,2$$

$$P_b = P_{bi} + P_{b2} \qquad i = 1,2$$

Where P_{OCV} is the open circuit power and λ is a tuning parameter. Referring to the proposed equations, the ECMS optimisation algorithm tries to minimise/maximise the ESS power consumption/regeneration while satisfying BPs and driver requests (P_b) constraints. For the λ parameter, the value calculated in [5] is used where Raddrizzani et Al. solve a Minimum Race Time (MRT) problem, leaving the power split between the battery systems as an optimisation variable. Consequently, the ratio between the powers is computed, obtaining an average value of 0.979. Interestingly, the two batteries are weighted almost equally.

Once λ is estimated, and knowing the driver request and the BPs' status, the problem can be solved online, obtaining the desired power for a battery, e.g the HPB one. Eventually, the DCDC voltage is regulated to obtain the desired behaviour.

3. EXPERIMENTAL SET-UP

3.1 CNR STEMS Battery Test Bench

A specific laboratory test bench has been developed to test the BRB system at the battery module level in the CNR STEMS laboratory in Naples. The operative scheme of the test bench is reported in Figure 2

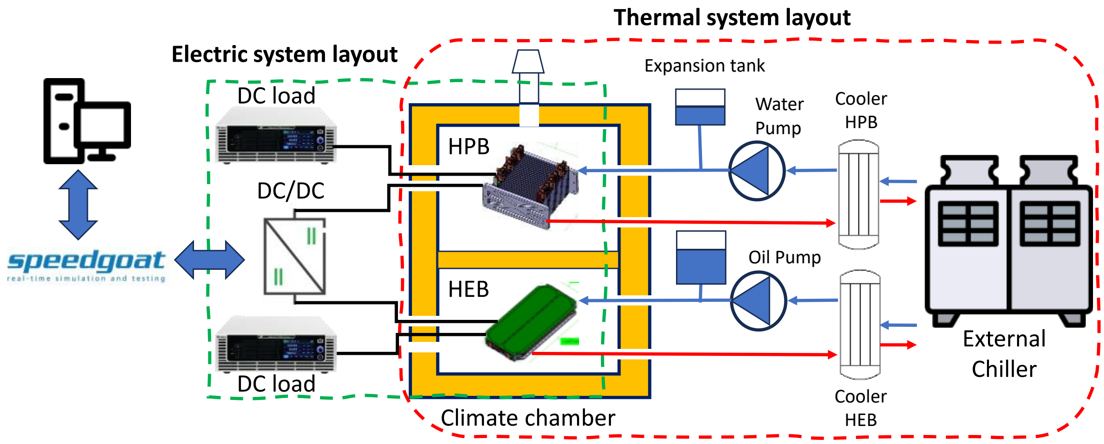

Fig. 2 CNR-STEMS Lab layout

The functional design of the lab is split into thermal and electrical schemes. In particular, the setup focuses on managing the temperatures of the HPB and HEB modules. Specifically, the HPB uses a water/glycol mixture for cooling, while the HEB employs a direct immersion, oil-based cooling system. An external chiller regulates and controls the temperature of both cooling systems according to the desired operating conditions. A 2 m^3 climate chamber is used to set the environmental temperature during the tests and to guarantee EUCAR 6 safety standards.

From the electrical point of view, a Speedgoat platform is used to control all the power flows of the test bench and to acquire the main operational electrical and thermal measures. The vehicle architecture described in Figure 1 is emulated on the test bench by simulating the scaled electric drive power profiles through the use of controlled bidirectional DC Loads, which can simulate the power demand during the discharging phases and the regenerative operations, through the recharge of the battery modules by using the power coming from the main grid.

3.2 Polito powertrain test bench

The Polito facilities consist of a Driver-in-the-loop test bench, as shown in Fig. 3. In particular, the setup is composed of a vehicle testbed, a driving simulator and a high-performance GPU server. This configuration allows for vehicle-level Advanced Driver Assistance System (ADAS) validation under reproducible settings with minimal vehicle modifications, as well as bridging simulation and physical testing to meet regulatory standards.

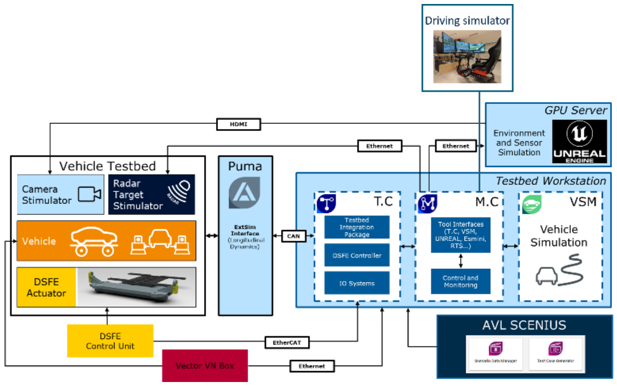

Fig. 3 Polito Complete test bench.

Starting from the first sub-system, the setup consists of the Powertrain Testbed designed and manufactured by *AVL GmBH*. This machine is the State-of-the-art test facility for the experimentation of automotive vehicles, being able to simulate conventional, hybrid and electric powertrains. The setup employs four separate hub-type dynamometers, called *AVL DynoULTRA PMM 2500*, to connect the front and rear axles of the unit being tested (UUT). Each dyno is designed to be attached to each of the four wheel hubs of the vehicle being evaluated, using specially made adapter flanges once the wheels have been taken off. In this framework, the vehicle is installed on a Powertrain Testbed and interfaced with road load emulators (four separate hub dynos). In addition, physical vehicle components, such as the ECU and actuators, are integrated into the testbench and implemented inside the virtual simulation environment thanks to the *AVL Driving Cube* for the ADAS. Furthermore, the vehicle's on-board sensors are tested by using camera and radar targets, Stimulators, which are hardware-based emulators that mimic perceptual inputs.

About the virtual environment, the GPU server runs a scenario engine, which connects the vehicle and sensor models to the simulated environment. This approach allows for real-time interaction between the vehicle and simulated scenarios, integrating environmental dynamics while testing. In this regard, the software suite AVL SCENIUS manages the tested virtual environment, providing a collection of standardised scenarios for regulatory testing. During the testing, the AVL VSM hosts the vehicle model, which couples physical powertrain responses to virtual vehicle dynamics and displacement.

In the framework, the testbed automation system AVL PUMA is responsible for overseeing the whole operation of the testbed, including creating the appropriate references for the dynos actuators and implementing a high-level hierarchical control system to ensure safety and operational limit compliance. Additionally, AVL testbed CONNECT (TBC) is responsible for the real-time interaction management between physical and virtual systems, such as data transmission, torque setpoints, and so on. The continuous data interchange between the simulation environment, the vehicle, and sensor stimulators is also guaranteed by the Model CONNECT (MC) environment. The integration of the real human drivers is obtained by the driver simulation, which is better described in the next section.

As reported above, the complete toolchain is very complex and extensive, but only a strict subsystem is employed in the virtual remote lab setup.

3.3 Polito Driver Simulation System

The Driving simulator serves an important role in integrating real human drivers during testing, resulting in genuine driver reactions to testing scenarios. In Fig. 4, the complete driver simulator setup is illustrated.

Fig. 4 Polito Driver Simulator Station

In particular, the setup consists of a vehicle cockpit, a simulation platform composed of SCANeR Studio and a vehicle MATLAB/Simulink model. This integrated approach is especially useful for conducting research, development, and validation of electric vehicle technologies in a controlled but life-like environment.

About the cockpit, the Logitech G290 force feedback steering wheel is used to recreate the tactile feel of actual vehicle physics during the driving experience. In particular, the steering wheel reproduces the vehicle's physical feedback, emulating the steering resistance and vibration during vehicle operations. In addition, the cockpit is equipped with three pedals: clutch, accelerator, and brake, as well as a manual gear lever that replicates a manual transmission and increases driver engagement. The cockpit also contains a racing bucket seat that provides ergonomic comfort and immersive feedback, further improving the driving experience.

Concerning the virtual simulation platform, the driver inputs are constantly tracked by the SCANeR™ Studio simulation platform, acquiring the steering angle, pedal pressure, braking force, and gear shifts. This software functions as a core for a real-time simulation framework, combining driver actions with dynamic road conditions, traffic scenarios, and environmental interactions. All the acquired driver inputs are provided to the vehicle MATLAB/Simulink model in real-time. In particular, the vehicle under test (VUT) is modelled as a pure electric vehicle, and it simulates the vehicle's interaction with traffic and road environments in real time, ensuring that responses such as torque delivery, regenerative braking, and energy consumption are accurately reflected under different driving conditions.

3.4 Virtual remote labs

One of the main innovative aspects of the MINERVA project proposals consists of the development of a virtual remote laboratory, connecting the facilities of CNR-STEMS and PoliTo. The idea behind this activity is to experimentally evaluate the direct effects of different driving operations on the vehicle energy storage system. In addition, the Remote Laboratory configuration allows institutions to share resources and exploit specialised equipment and experience that may not be available locally, maximising the use of existing resources while avoiding the duplication of costly hardware.

With this aim, a specific VPN-network architecture has been set up to interconnect the driving cockpit located in PoliTo lab with the battery testing system located in the laboratories of the CNR-STEMS. The main scheme of the X-in-the-Loop (XIL) testing environments developed during the MINERVA project is reported in Fig 5.

On the PoliTO side, the user tests the vehicle in a real driving scenario through SCANeR Studio and the Driving Cockpit. In the background, the MATLAB/Simulink VUT model calculates the propulsion system power request in real-time and transfers the BP target current load to the CNR-STEMS workstation.

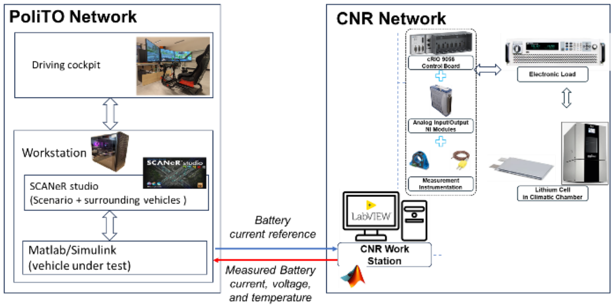

Fig. 5 PoliTO – CNR Remote lab network Framework

To enable encrypted and low-latency communication between the PoliTO and CNR-STEMS workstations, a WireGuard VPN tunnel is deployed. This tunnel allows the PoliTO PC to send control commands and receive telemetry from CNR PC while maintaining the responsiveness required for real-time systems.

On the CNR-STEMS side, the workstation receives the data and locally transfers the current request to the compact RIO. In this framework, the Compact RIO performs the critical function of controlling the IT6018C physical current drawn/supplied to the battery system. At the same time, the battery module’s real-current load, voltage and temperature are measured by the control board and sent to the CNR-STEMS workstation. At this point, the data are transferred to the PoliTo workstation through VPN, which updates the MATLAB/Simulink model.

The architecture is designed to prioritise performance and security, with VPN achieving a lightweight and reliable transport layer. This setup is well-suited for distributed testing scenarios where deterministic behaviour, secure communication, and integration with embedded hardware are essential.

4. RESULTS AND DISCUSSION

Preliminary experimental results have focused on the experimental characterisation tests of the HPB. In particular, the first set of tests has been carried out in order to evaluate the discharging efficiency of the cell under test for different values of temperature and C-rates. The cell under test is an HPB cell with a rated capacity of 2.5 Ah, with a maximum discharging rate of 250 C. The main results of the capacity test are reported in Figure 4.

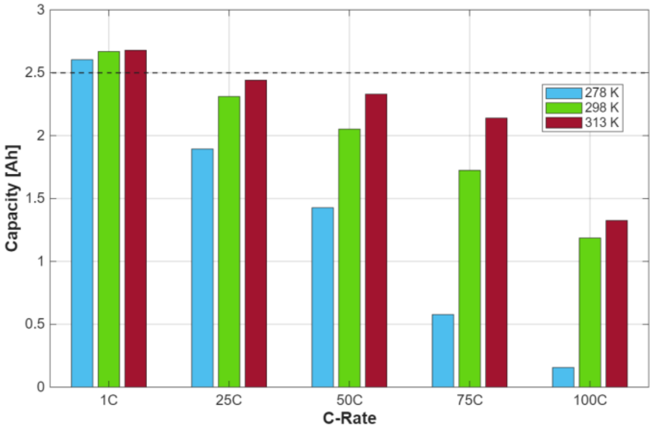

Fig. 6 Experimental results of the capacity tests for the HPB.

In particular, the cell has been tested for discharging rate values up to 100 C, which corresponds to a discharging current of about 250 A. As clearly visible from the results, a relevant decrease in the actual capacity values of the HPB has been observed for high values of discharging rates and lower values of temperature. This behavior needs to be properly taken into account in the energy management strategies of the BRB system.

The experimental activities have involved an investigation into the battery cell's thermal properties, specifically aiming to evaluate its specific heat and thermal conductivity across all spatial directions. Two thermal tests have been conducted to achieve this. The first, termed the overheating test, has assessed the temperature variation rate resulting from an increase in cell temperature. This has been performed by applying a 1C impulsive charge/discharge current to the lithium-ion cell, which has been thermally insulated using a double polystyrene panel covered with fibreglass (as shown in Fig. 5).

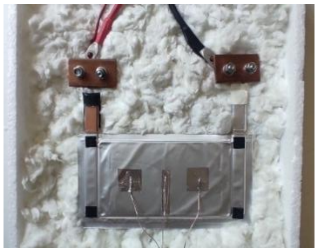

Fig. 7 Lithium cell experimental setup during Overheating test

The battery cell surface temperature has been measured in different spots by using three K-type thermocouples for acquisition redundancy. In particular, the temperature sensors have been placed only on one surface and positioned in the center, and in proximity of the electrodes, at the left and right of the center. With the thermal insulation, the overall thermal power has become equal to Joule losses during the current profile and has not been dissipated to the environment; instead, it has increased the battery cell temperature. In this condition, the temperature rise trend has been found to be mostly linear, as shown in Fig. 6.

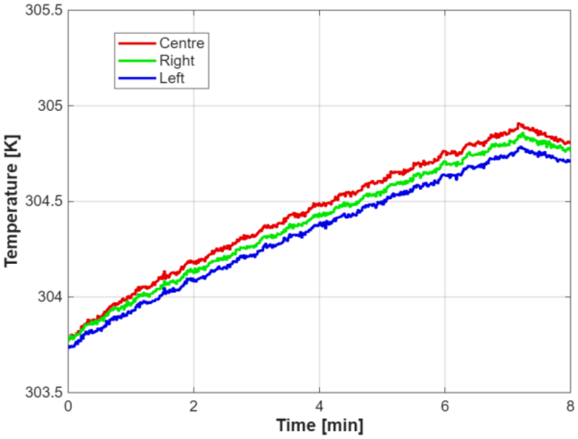

Fig. 8 Battery cell center, cathode and anode temperatures during overheating test

As shown in Fig.6, the Lithium cell temperature rise rate has increased linearly in the first step of the experimental test by 0.13 K/min in all the measured spots. Under this condition, the battery cell's specific heat can be calculated by following the simple relationship:

$$C_p = \frac{Q_{gen}}{mass} \cdot \frac{\Delta T}{\Delta t} \qquad (1)$$

Where the Qgen is the Joule losses, while ΔT is the temperature variation during a discrete time interval (Δt), chosen by the user. From the performed test, the lithium cell's specific heat is 1100 J/kg K.

Concerning the second test, the battery cell thermal conductivity has been evaluated, assuming that the lithium cell has an anisotropic thermal behaviour. In this test, the thermal load has been provided by an external 50W thermistor placed on the battery cell surface with thermal grease. The lithium cell temperature has been monitored in six spots, as shown in Fig 7. In particular, three thermocouples have been positioned on each side of the battery surfaces to acquire the temperature variations along cell width, length and thickness. About the allocation, the battery cell has been placed in a polystyrene box, filled with fibreglass on the bottom. In particular, the thermistor has been positioned between the fibreglass and lithium cell to transfer all the heat generated to the battery cell and avoid any heat dissipation to the environment. Regarding the thermal load, the thermistor has been supplied to generate 7.4W for only 5 minutes to avoid cell-hazardous temperature values.

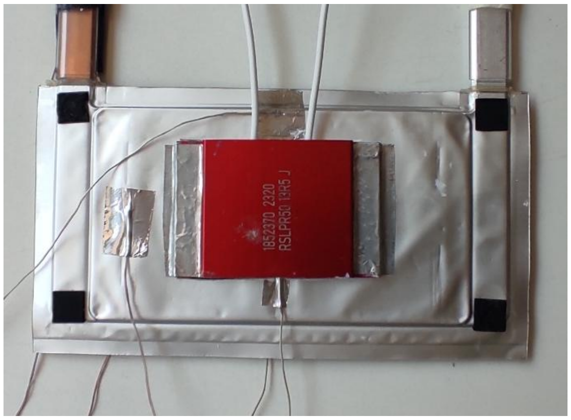

Fig. 9 Lithium cell setup during the Thermal Conductivity test

Before the test, the battery cell was rested for 30 minutes at an ambient temperature of 303 K. The results are shown in Fig 8.

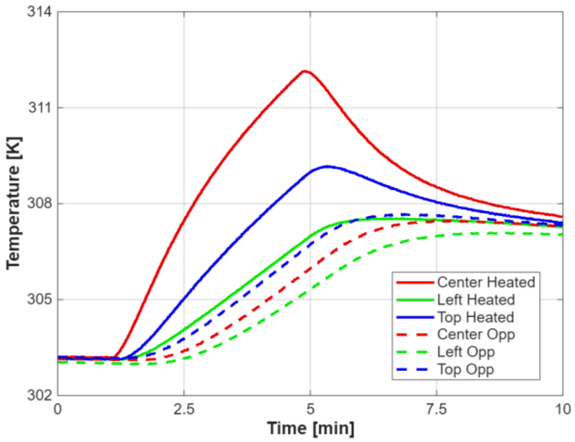

Fig. 10 Lithium cell spots temperature profiles during thermal conductivity test

As shown in Fig. 8, the temperature difference along the width, length and thickness directions is 2, 2 and 6K, respectively. Starting from the acquired experimental temperature, the COMSOL parameter estimation toolbox has been used to calculate the thermal conductivity along the monitored directions. This toolbox has employed an Nelder-Mead optimisation algorithm to calculate the local minimum of the difference between the battery cell experimental and simulated temperature of the measured spots by adjusting the thermal conductivity. In this regard, a 3D thermal model of the experimental setup has been developed to perform the parameterisation, obtaining a thermal conductivity of about 20 W/m K for the in-plane directions and 0.5 W/m K for the cell thickness direction.

These findings are in line with the thermal conductivity values reported in the literature [7].

4.1 Preliminary results on remote labs

At this stage, the actual configuration of the remote lab setup is able to evaluate only the HEB behaviour from a scaled perspective. In this regard, the BP is composed of the cylindrical-shaped lithium cell Molicel P45B, whose characteristics are reported in Table 1, arranged in the electrical configuration S108P14.

Table 1 – Molicel characteristics

Battery Cell	MOLICEL P45B
Mass	0.067 kg
Actual Capacity	4.5 Ah
Terminal Voltage	3.7
V_{min}/V_{max}	2.7V/4.2V
I_{min}/I_{max}	-18A/120A

Referring to the considered HEB, the tested setup consists of only one lithium cell (Fig. 11) whose target current load is scaled for one BP branch.

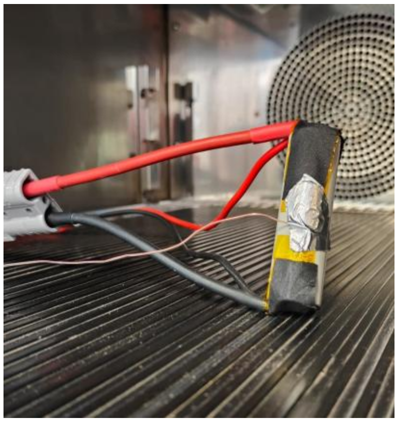

Fig. 11 Scaled HEB Remote Lab Experimental Setup

In particular, the BP target current is scaled inside the Compact RIO control board, as well as all the protection conditions. In addition, the measured battery cell voltage is multiplied by the number of cells in series of the electrical configuration and transferred to the Polito Workstation for the vehicle model feedback.

Furthermore, the actual remote lab setup is limited in the communication speed. In particular, the configuration achieves a round-trip time latency (RTTT) of about 20ms (50Hz). The findings suggest that the remote test bench is able to emulate sub-system dynamics lower than or equal to 25Hz.

5. CONCLUSIONS

The main goal of this manuscript is to report the primary deliverables and initial data derived from the research initiatives of the MINERVA Italian project. A key achievement within the project's mandate is the commissioning of the laboratory infrastructure, rendering it suitable for immediate testing of battery modules and the complete battery pack under representative operating conditions. Preliminary results have focused predominantly on HPC cell characterisation activities, alongside the successful configuration and validation of the virtual remote lab linking the PoliTo and CNR-STEMS Infrastructures.

Subsequent steps will involve enhancing the remote lab's communication speed to enable a rigorous assessment of vehicle dynamics during fast road trips. Furthermore, the CNR-STEMS setup will undergo an expansion from single-cell analysis to a module perspective, which will facilitate the investigation of the integrated electro-thermal BP behaviour.

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