SIMULATING ELECTRIC VEHICLE DRIVING CYCLES WITH A HARDWARE-IN-LOOP (HIL) SYSTEM

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ABSTRACT

Electric vehicles (EVs) are gaining attention as a promising solution to reduce greenhouse gas emissions. This paper proposes system architecture of a Hardware-In-Loop (HIL) system to explore simulating the electric vehicle (EV) driving cycles using HIL testing approach. The HIL system uses an Arduino DUE as the controller, connecting MATLAB Simulink to an RC Car acting as the EV. It employs an L298N motor driver, B25, and ACS712 sensors to measure voltage and current behavior from an 11.1V 4200mAh Lithium-Ion battery. Simulink's GUI allows users to select desired driving cycles for simulation. Results show that the voltage decreases with speed, while the current increases as expected across various driving cycles (NEDC, WHVC, WLTP Class 1, UDDS, and SC03). This success confirms the HIL system's architecture capability to simulate and monitor battery discharging trends in terms of their voltage and current.

KEYWORDS

Hardware-In-Loop (HIL); Electric Vehicle (EV); voltage sensor; current sensor; battery discharging

INTRODUCTION

Electric vehicles (EVs) have been around for over 100 years and are now gaining popularity due to their environmental benefits and comparable performance to conventional vehicles. EVs operate by plugging into a charge point, storing electricity in rechargeable batteries that power an electric motor. The testing of EVs involves Hardware-In-Loop (HIL) integration of hardware and software to simulate real-world conditions, reducing costs and time associated with physical tests. The main objective of Hardware-In-Loop (HIL) systems is to replace expensive and time-consuming physical road tests and accommodate dangerous or impractical scenarios. This study focuses on developing the overall system architecture with Arduino DUE controller and communicating with MATLAB Simulink. The goal is to use MATLAB Simulink and Arduino DUE to control the motor speed based on different driving cycles. Observed parameters are battery discharge voltage and current trends when running based on NEDC, WHVC, WLTP Class 1, UDDS, and SC03.

Chmielewski *et al.* (2013) studied electric vehicle batteries under the NEDC cycle, creating a simulation model in MATLAB Simulink. It considered air drag, friction, inertia, and road slopes. The simulation utilizes the NEDC cycle as input to generate battery clamp voltage and discharge current. During acceleration, the battery discharges rapidly, decreasing the voltage. At constant velocity, the voltage decreases steadily. Regenerative braking charges the battery, increasing the voltage. Bao *et al.* (2012) found that the current is positive during battery charging, and it becomes negative during discharge. Similarly, Chmielewski A. (2015) discovered that as voltage increases, current also increases. The current is positive during charging, and it is negative during discharging. In their study, Almatrafi *et al.* (2023) modelled an EV in MATLAB Simulink and assessed power consumption and battery health under different driving cycles: UDDS, NYCC, and WLTP. They found that WLTP had the lowest power consumption (11.113 kWh) and SOC usage (87.62%). Ramaswamy *et al.* (2004) studied the development of an ECU for a HEV using HIL testing. They found that HIL systems enable the simulation of challenging scenarios, improving transparency. Additionally, HIL systems are easily reproducible, with recorded configurations for future use. (Bacic, 2005) also supports the importance of predicting various scenarios in HIL testing.

The development of a complete test rig for an EV is very costly. Hence, a scaled-down version that can reflect the conditions of the complete test rig is desired. This study developed a HIL system to measure the battery discharging trend of a small-scale electric vehicle.

METHODOLOGY

The primary goal of this paper is to create a Hardware-in-the-Loop (HIL) system for an Electric Vehicle (EV), enabling the monitoring of battery discharging patterns under various driving cycles. To achieve this, a small-scale EV is employed, resembling a remote control (RC) car, integrated with an L298N motor driver under the command of an Arduino DUE. Powering the system is an 11.1V 4800mAh Lithium-ion battery, with both voltage and current levels closely observed through implementing a B25 voltage sensor and an ACS712 current sensor.

The development of the HIL system begins with creating a Simulink model. This Simulink model development process involves three key parts: first, the configuration of Simulink to facilitate communication with the RC Car, utilizing a fixed step time of 0.1 seconds. Second, the focus is on the motor control signal, ensuring smooth operation and accuracy. Lastly, the calibration of voltage and current sensor signals is carried out.

The L298N motor driver offers the advantage of controlling the motor in clockwise and counterclockwise rotations. However, for this project, the specific direction of the motor is not a critical factor. Consequently, only two digital output blocks are used to set the motor's direction as clockwise, activated by a constant source signal.

A drive cycle source block is utilized to determine the vehicle's speed trend, providing a time-independent representation of the speed. The signal from this block is then converted into PWM (Pulse Width Modulation) by dividing it with the maximum speed and multiplying it with the permissible PWM before being directed to the PWM output, which communicates with the RC Car.

Figure 1 below illustrates the Simulink model for motor speed control.

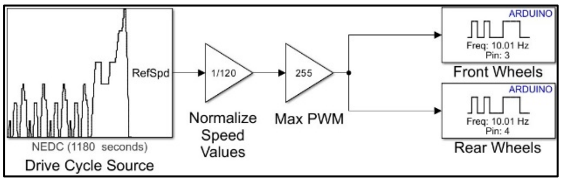

Figure 1: Motor speed control signal

Afterward, the sensors are calibrated to ensure the most accurate measurement values. The Arduino DUE receives analog signals from these sensors, which must be converted and calibrated into actual voltage readings. To adhere to the step time of the rest of the Simulink model, both sensors use a sampling frequency of 10 Hz. The Simulink model for the voltage sensor is developed based on the equation provided below.

$$Voltage\ (V) = AnalogValue \times \left(\frac{V_{cc} \times 5.128}{4095}\right) - V_{offset} \quad (1)$$

In equation (1), the analog signals are represented by *AnalogValue*. The V_{cc} supplied to the analog pins of the Arduino DUE is 3.3V, and 5.128 is a factor value for the B25 voltage sensor. V_{offset} represents the offset voltage, where it is essential to note that it may vary among different circuits. For this specific project, the offset voltage has been determined to be 0.4V.

$$Current\ (I) = AnalogValue \times \left(\left(\frac{V_{cc}}{4095}\right) - V_{offset}\right) \times \frac{1}{0.18} \quad (2)$$

Like the voltage sensor, the current sensor also transmits an analog signal to the Arduino DUE, which AnalogValue represents in equation (2). Similarly, the V_{cc} supplied to the analog pins of the Arduino DUE is 3.3V. The ACS712 employs a Hall effect principle, converting the magnetic field generated by the flowing current into voltage signals. As a result, the equation for the current sensor uses voltage values and converts them into corresponding current values by dividing by 0.18V/A. It is worth noting that the V_{offset} for the current sensor is 2.5V. Consequently, the Simulink model for the current sensor is built based on the provided equation.

The test rig development initiates with the Arduino DUE serving as the controller. The Arduino sends PWM and digital signals to the L298N motor driver, effectively regulating the RC Car's speed. An 11.1V battery is connected to the motor driver to provide power to the RC Car. Meanwhile, the voltage and current sensor draw power from the Arduino DUE and relay analog signals, measuring battery-related data back to the Arduino DUE.

Figure 2 illustrates the comprehensive system architecture of the test rig.

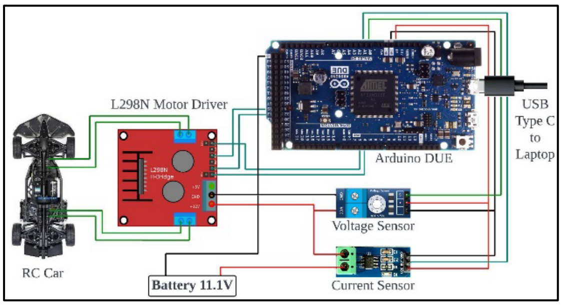

Figure 2: System architecture of test rig

RESULTS AND DISCUSSIONS

In the Simulink models of both the voltage and current sensors, moving average blocks are implemented to stabilize and minimize fluctuations in the data. However, it's important to note that the voltage values exhibit minimal fluctuations, rendering the moving average method unnecessary. On the contrary, the moving average method is crucial for current values due to a significant overlap in data caused by the PWM signals. This overlapping occurs as the sample time for the Simulink is set at 0.1 seconds, leading to the need for effective data smoothing techniques.

New European Drive Cycle (NEDC)

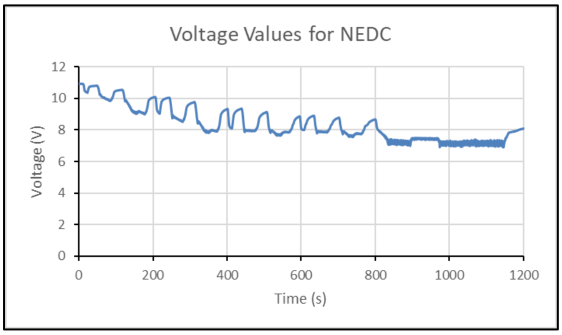

Figure 3: Actual voltage values for NEDC

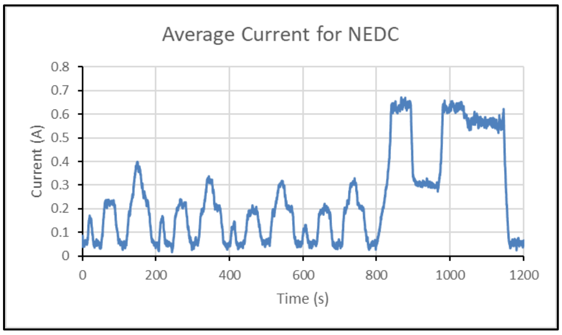

Figure 4: Average current for NEDC

The expected trends for voltage and current in relation to speed will refer to the paper by Chmielewski *et al.* (2013), where they found that as speed increases, voltage will decrease while the current increases. The measured voltage and current values during NEDC (New European Driving Cycle) exhibit the expected behaviour. However, it's important to consider a limitation in the voltage readings, where they reach 7V. This limitation arises from a depleted battery and the motor driver, preventing further voltage draw out. Consequently, the accuracy of the voltage and current values beyond the 7V mark is compromised.

World Harmonized Vehicle Cycle (WHVC)

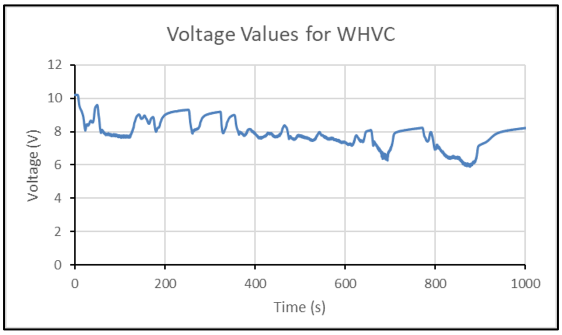

Figure 5: Actual voltage values for WHVC

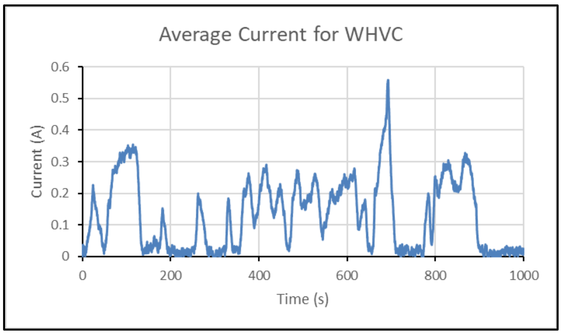

Figure 6: Average current for WHVC

Likewise, the voltage and current trends observed during WHVC (World Harmonized Vehicle Cycle) align with the expectations. The minimum voltage recorded for WHVC stands at 6V, while the peak PWM of 140 corresponds to a maximum current of 0.55A.

Worldwide Harmonized Light Vehicles Test Procedure (WLTP) Class 1

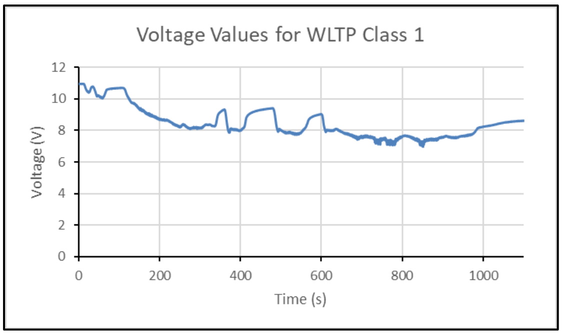

Figure 7: Actual voltage values for WLTP Class 1

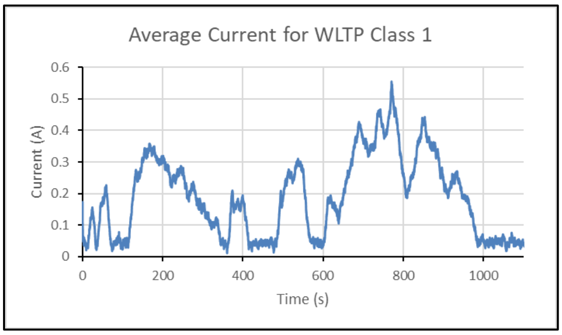

Figure 8: Average current for WLTP Class 1

The simulation results for WLTP Class 1 demonstrate that the voltage and current discharge trends align with the expectations where voltage decreases when speed increases, and current increases with speed. A minimum voltage of 7.2V and a maximum current of 0.55A at the peak PWM of 134 is observed throughout this drive cycle.

Urban Dynamometer Driving Schedule (UDDS)

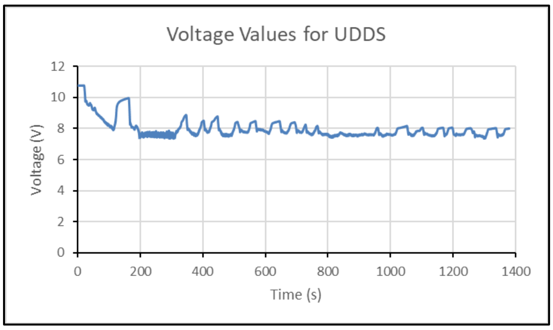

Figure 9: Actual voltage values for UDDS

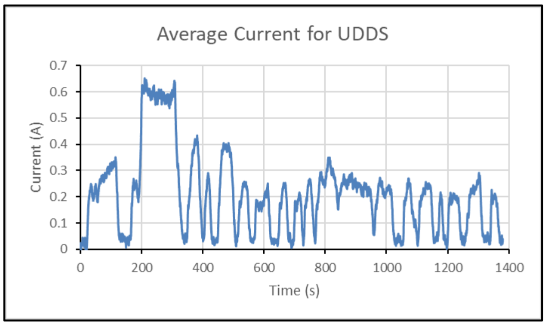

Figure 10: Average current for UDDS

During the simulation of UDDS (Urban Dynamometer Driving Schedule), a similar issue arises where the battery voltage is restricted to a minimum of 7.5V, accompanied by a maximum current of 0.6A. At this voltage level, the values are not entirely accurate because the motor driver reduces the speed of the RC car to prevent further voltage depletion from the battery. Nevertheless, the trends throughout the remaining cycle continue to align as expected, where voltage decreases when speed increases and current increases with speed.

SC03 Driving Cycle

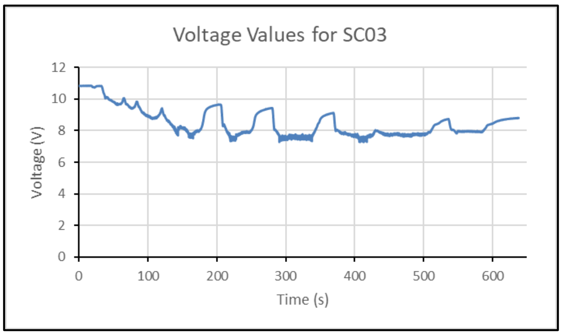

Figure 11: Actual voltage values for SC03

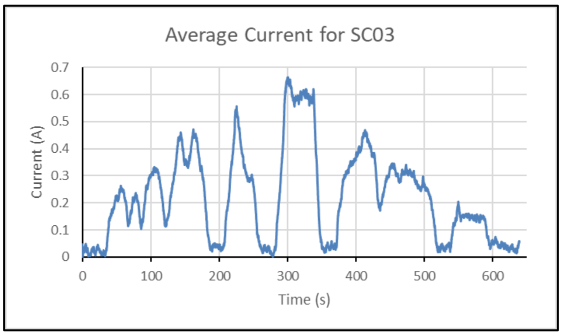

Figure 12: Average current for SC03

Finally, in the case of SC03, the voltage and current values behave as anticipated, with the voltage trend being inversely related to the speed and current trends. Throughout SC03, the minimum voltage is limited to 7.5V, and the maximum current reaches 0.61A.

Conclusion

In conclusion, the paper successfully achieves its objective of developing a Hardware-in-the-Loop (HIL) system to study the battery discharging trend of a small-scale EV under various driving cycles. Throughout all the driving cycles analysed, a consistent pattern emerges where the battery voltage trends show an inverse relationship with the speed. In other words, as the speed increases, the voltage decreases. Conversely, the current trends directly follow the speed trends. This observation provides valuable insights into the behaviour of the EV's battery during different driving conditions.

However, the integrated 11.1V Lithium-ion battery utilized in this project has experienced degradation over time due to multiple charge and discharge cycles. Consequently, this degradation causes data inaccuracies, especially at lower voltage levels. Two solutions can be considered to address this issue: opting for a larger capacity battery or using a completely new battery for data collection. This approach ensures that the battery's voltage does not fall into the critical range where inaccuracies become more pronounced.

Additionally, it's crucial to remember that the ACS712 current sensor exhibits inaccuracies for readings below 0.5A. Awareness of this limitation is vital when analysing data obtained from the sensor during low current scenarios. While calibrating the sensor, a deviation of 0.2A is observed when compared with a multimeter. However, for measurements above 0.5A, the deviation reduces to an acceptable range of 0.02A to 0.03A. To overcome this issue and ensure more accurate measurements, the INA219 current sensor can be considered better suited for measuring current below 0.5A. By utilizing the INA219, improved precision and reliability in current readings, particularly in the lower current range, can be achieved.

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