Faculty of Health, Science & Technology
School of Engineering, Computing & Mathematics

OXFORD BROOKES UNIVERSITY

Assessment cover

STUDENTS, PLEASE COPY THIS PAGE AND USE AS THE COVER FOR YOUR SUBMISSION

Module No:	**ENGR7025**	Module title:	**Electric Vehicles**

Assessment weighting:	**70%**	Assessment title:	**Assignment 2 - Battery Management & Chargers**

Banner assignment identifier	**CWS2WEEK11**	Due date and time:	**13:00 on Friday, 11th April 2025**

Estimated total time to be spent on assignment:	**70 hours per student**

LEARNING OUTCOMES

On successful completion of this assignment, students will be able to achieve the following learning outcomes (LOs): *LO numbers and text to be copied and pasted from the module handbook*
3) Analyse and assess the performance of a range of energy storage systems, including associated safety and battery management systems.
4) Consider different controller and inverter types and evaluate their operation and suitability for automotive applications.
5) Assess different electronic sub-systems such as on-board communication and shutdown system required for safe operation of an electric vehicle.
6) Assess electrical energy provision, energy sources and electrical grid mix composition. Quantify different options using whole lifecycle assessment.

FOR ENGINEERING ONLY
Engineering Council AHEP4 LOs assessed (from S1 2024/25 Onwards)
LOs copied and pasted from the AHEP4 matrix (add rows as required)

LO number	**LO text**
M1	Apply a comprehensive knowledge of mathematics, statistics, natural science and engineering principles to the solution of complex problems. Much of the knowledge will be at the forefront of the particular subject of study and informed by a critical awareness of new developments and the wider context of engineering
M2	Formulate and analyse complex problems to reach substantiated conclusions. This will involve evaluating available data using first principles of mathematics, statistics, natural science and engineering principles, and using engineering judgment to work with information that may be uncertain or incomplete, discussing the limitations of the techniques employed
M3	Select and apply appropriate computational and analytical techniques to model complex problems, discussing the limitations of the techniques employed
M4	Select and critically evaluate technical literature and other sources of information to solve complex problems
M5	Design solutions for complex problems that evidence some originality and meet a combination of societal, user, business and customer needs as appropriate. This will involve consideration of applicable health & safety, diversity, inclusion, cultural, societal, environmental and commercial matters, codes of practice and industry standards
M7	Evaluate the environmental and societal impact of solutions to complex problems (to include the entire life-cycle of a product or process) and minimise adverse impacts
M17	Communicate effectively on complex engineering matters with technical and non-technical audiences, evaluating the effectiveness of the methods used

Statement of Compliance
By submitting this assessment I declare that the work submitted is my own and that the work I submit is fully in accordance with the University regulations regarding assessments. *(6. Assessment and progression - Oxford Brookes University and 4. Conduct and engagement - Oxford Brookes University)*

Use of AI Tools: You are required to use this form to declare which AI tools you have used and how you have used them. Please complete the form and attach it to your submission as an Appendix, if you have used such tools.

FORMATIVE FEEDBACK OPPORTUNITIES

Formative feedback will be provided during labs and seminar sessions. Individual feedback will be provided when marking your reports. Generic feedback will also be released with your individual feedback.

SUMMATIVE FEEDBACK DELIVERABLES

Deliverable content and standard description and criteria	**Weighting out of 100%**
Part A - Series Capacitors Behaving like Re-chargeable Batteries	**10%**
Part B - Design and Simulate a Battery Management System	**30%**
Part C: Constant Current Charger	**40%**
Introduction, Conclusion, Presentation, and References	**20%**

The marking grid is available on Moodle.

Introduction

The recent advancements in electric vehicles (EV) have seen significant improvements in battery management and charging systems. In order to improve battery life and minimize their environmental impact, efficient battery management systems (BMS) and power delivery systems are crucial. This report examines key aspects of battery management systems (BMS) and charging mechanisms, focusing on circuit simulation, design improvements and real-world application limitations.

- Part A explores the behaviour of series-connected capacitors behaving as rechargeable lithium-ion battery cells through circuit simulations, analysing voltage distribution and charge-discharge behaviour.

- Part B improves upon part A analysis by designing and simulating an improved BMS for lithium-ion cells, addressing key problems such as overcharging, undercharging, and cell balancing, while addressing environmental concerns of its application.

- Part C investigates a constant current charger, evaluating its performance, limitations, and potential enhancements to ensure efficient battery charging operations.

On this report, it will be shown how a well-rounded BMS is essential for managing battery cell performance, enhancing energy efficiency and preventing thermal-derived problems. Combined with optimized charging circuits, this contributes to faster, safer, and more reliable energy management. By integrating theoretical analysis with practical experimentation, this report aims to provide a comprehensive understanding of battery technologies, critical for EV applications.

Part A - Series capacitors behaving like rechargeable batteries

The studied circuits are the following:

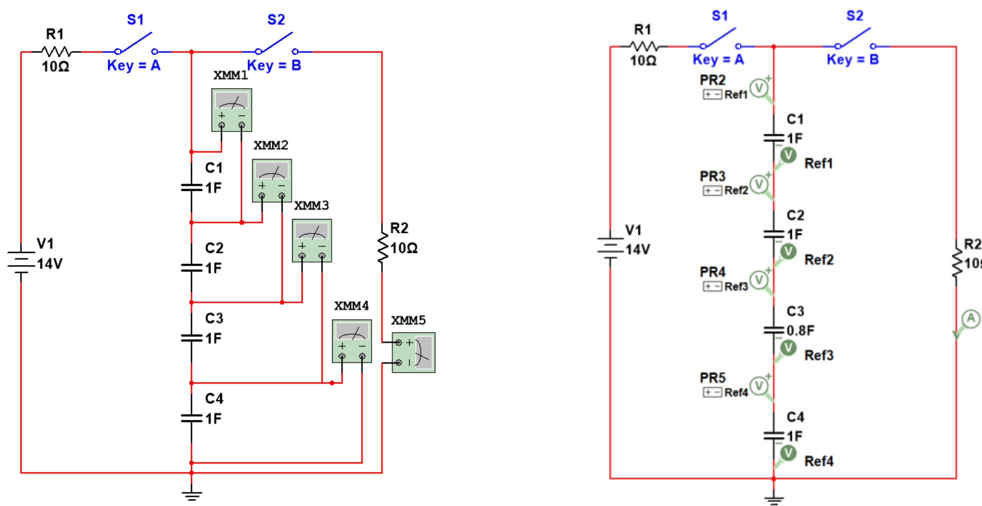


Figure 1. Balanced and unbalanced series capacitor's circuit

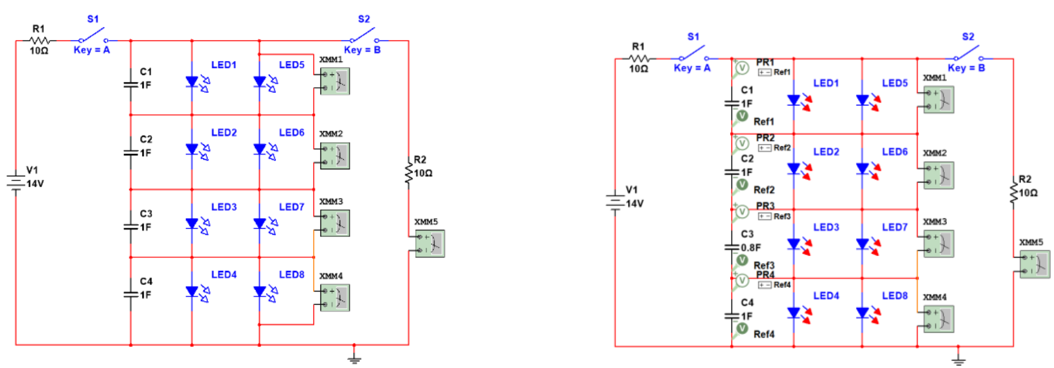


Figure 2. Balanced and unbalanced series capacitor's circuit with parallel LEDs

Applying Kirchhoff's voltage law (Bird, 2017), we obtain the maximum voltage across each capacitor [1]:

(1)

$$V_i = V_{source} * \frac{C_{eq}}{C_i}$$

Where:

- V_i: Voltage across capacitor i.
- C_{eq}: Equivalent capacitance.
- C_i: Capacitance of capacitor i.

In the first circuit [Figure 1], as voltage is divided between 4 equal capacitors, the maximum voltage across each capacitor is the same.

When an imbalance is introduced between the capacitors, changing C3 to 0.8F, C3's charge varies faster, due to the lower capacitance, achieving a higher voltage than the rest [Figure 3].

Additionally, the capacitor's charge rate is not constant, which can damage them.

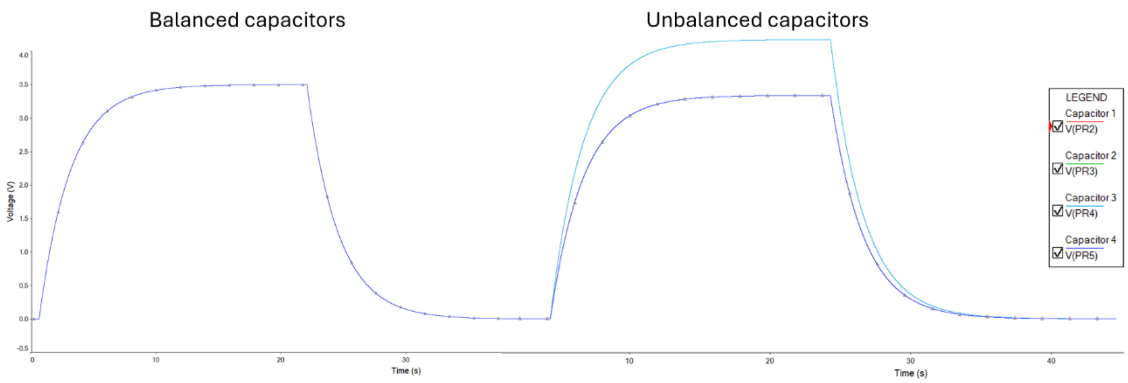


Figure 3. Series balanced vs unbalanced capacitors

In the second circuit [Figure 2], LEDs are used to prevent overcharging and assist in load balancing, conducting once their forward voltage is exceeded, becoming the less resistant path and limiting the voltage across the capacitors. The capacitor's charge rate becomes constant, avoiding possible damage.

When C3's imbalance is introduced, it charges faster, but is unable to exceed the LED's forward voltage, ensuring balanced voltages when charged [Figure 4]. However, when the switches are disconnected, the charge gradually dissipates due to the heat loss of the LEDs.

Once the discharge switch is connected, charge redistribution occurs, where C3's voltage polarity will invert, as it discharges earlier and aids distributing charge between capacitors.

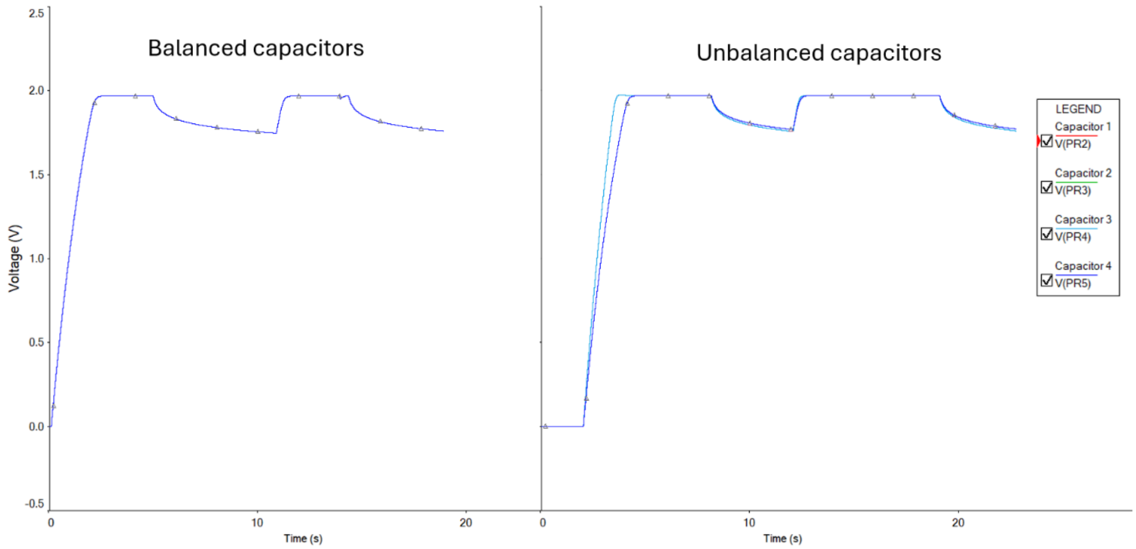


Figure 4. Series unbalanced capacitors with parallel LEDs

Both circuits present problems with undercharging, as voltage drops below 2.5v, where lithium-ion batteries are considered uncharged (Bird, 2017).

Part B - Design and simulate a battery management system

Following findings in Part A, key problems identified where voltage drops due to heat loss in the diodes, capacitor undercharging and overcharging, variable charge rate and inability to charge/discharge the cells automatically.

The cell balancing was investigated first, with an initial design [Figure 5] utilizing an OP AMP comparator (Elektronik, 2021).

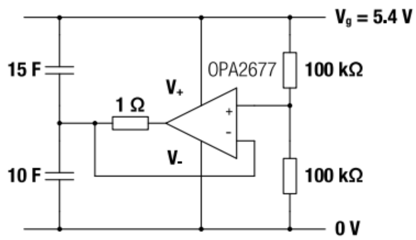


Figure 5. Active balancing circuit (Elektronik, 2021)

This comparator design makes use of voltage dividers to set the threshold voltage, and operational amplifiers to compare it to the voltage between capacitors via a negative feedback loop, successfully balancing the pair.

In order to improve the output of the design [Figure 6], hysteresis can be introduced to the operational amplifier, adding a resistance to the feedback loop (Texas Instruments, 2014). High resistance values (10kΩ to 100kΩ) are encouraged to achieve highly accurate output switching.

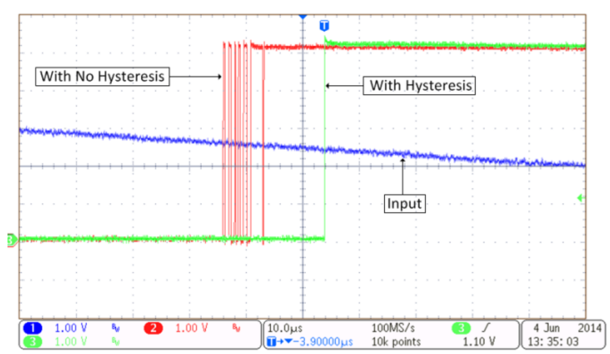


Figure 6. Output for a comparator with and without hysteresis

For lithium-ion cells, while they can be charged up to 4.2V, the recommended operating voltage range to prevent damage and thermal runaway is typically between 2.5V and 3.65V (Väyrynen & Salminen, 2012).

As previously mentioned in Part A, the design allows the cells to discharge completely, rendering them inoperative. To prevent this, Undervoltage-Lockout (UVLO) circuits can be implemented.

The simplest design [Figure 7] implements a Zener diode in a voltage divider to obtain a voltage reference to compare against the reference capacitor's voltage. An op-amp is used as a comparator, outputting to the base of a PNP BJT transistor. When the capacitor's voltage drops below the reference, it stops the BJT from transmitting current to the load, effectively stopping the discharge (Horowit & Hill, 2015).

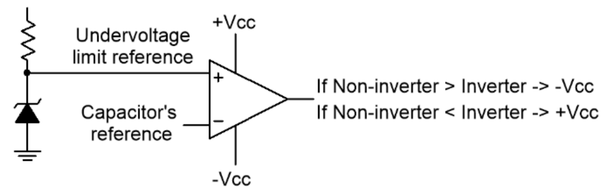


Figure 7. UVLO comparator diagram

As the cells will be damaged if held above the 3.65v threshold for too long, an Over Voltage Protector (OVP) is fitted, which protects the cells from overcharging in the event of a charger overvoltage. The simplest design [Figure 8] uses the comparator design explained previously, changing the inverting and non-inverting signals to only allow current to pass when the voltage is below the threshold (Horowit & Hill, 2015).

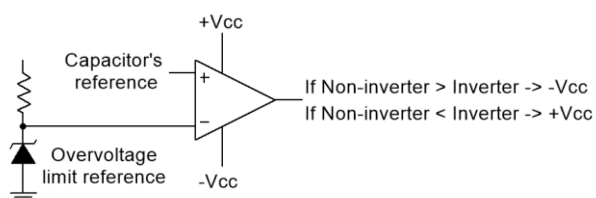


Figure 8. OVP comparator diagram

By combining the balancing and UVLO and OVP circuits, and applying them to multiple cells, we obtain a simple Battery Management System (BMS) [Figure 9].

This BMS allows us to control the battery pack voltage by taking a reference voltage from the positive terminal of the first capacitor to ground. To define our reference voltages, the overvoltage and undervoltage thresholds are multiplied by the number of capacitors (4) in our battery pack, giving an overvoltage threshold of 14.6v and an undervoltage threshold of 10v.

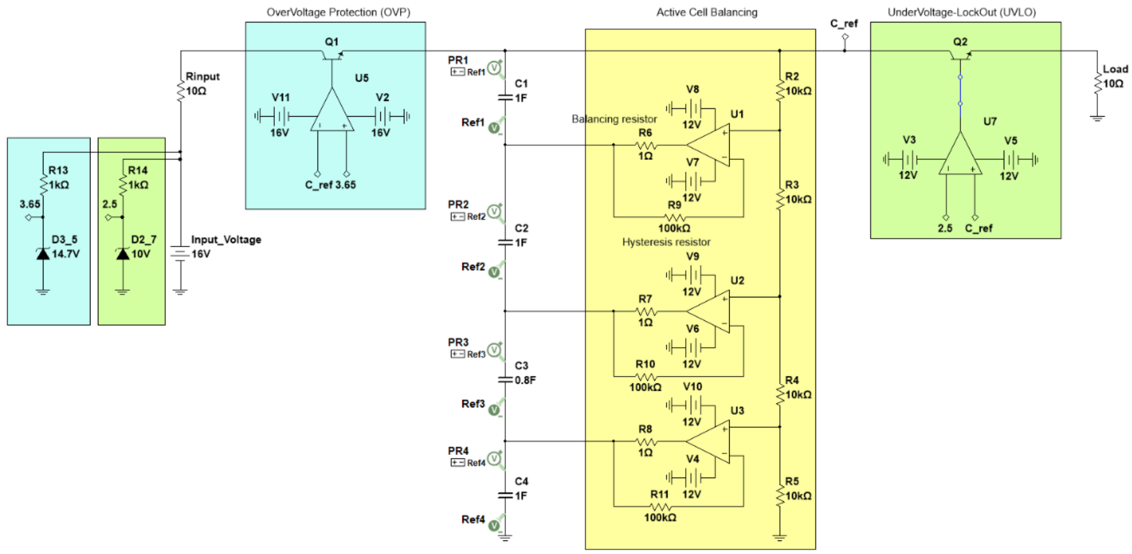


Figure 9. Proposed active balancing, UVLO and OVP circuit

In order to simulate a battery pack in need of charge, the capacitor's voltage was set at 2.7v. Additionally, the same imbalance as in Part A was introduced, changing C3 to 0.8F. Once simulated [Figure 10], we are able to see that the OVP prevents the capacitors from going over the 3.5v threshold and, once all the capacitors are balanced at 3.5v, discharge occurs. Once discharging, the UVLO prevents the capacitor's voltage from dropping below 2.5v.

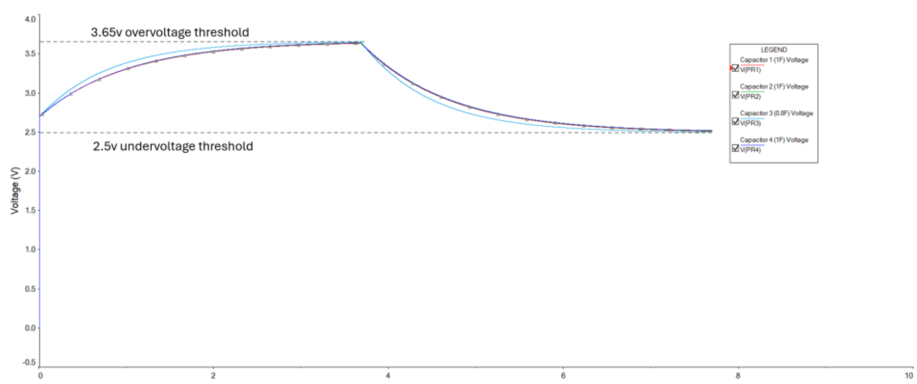


Figure 10. Proposed circuit charge/discharge cycle

The proposed circuit's sustainability and environmental impact are considered under Spanish regulations. It must comply with Royal Decree 110/2015, on Waste Electrical and Electronic Equipment (WEEE), establishing extended producer responsibility principles (Cutanda et al., 2015).

The main environmental concern of the circuit is electronic components containing potentially hazardous materials. To prevent improper disposal of electronics, the op-amps, transistors and capacitors require responsible end-of-life management (Cutanda et al., 2015). To reduce environmental impacts, the circuit should implement modular components facilitating repairs and recycling, following

Spanish waste framework, Law 7/2022 (Spanish Government, 2022). Additionally, the balancing and limitation of the capacitor's voltage, extends the capacitor's lifespan, reducing waste and aligning with Spanish WEEE legislation (Cutanda et al., 2015).

From an ethical perspective, component sourcing must address fair labor practices throughout the supply chain (Mancini et al., 2021).

The proposed circuit limitations include the inability to actuate based on the specific capacitor's voltage, inability to begin discharging without intervention and assumes that components behave ideally, not accounting for efficiency and response times.

Future improvements to this design should substitute the UVLO design with a Schmitt trigger design [Figure 11] (Cho et al., 2016).

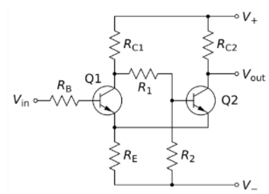


Figure 11. Schmitt trigger design

Additional improvements should include overcurrent and short-circuit protection circuits, and improve onto the OVP design [Figure 12] (Sharad Bhowmick, 2022).

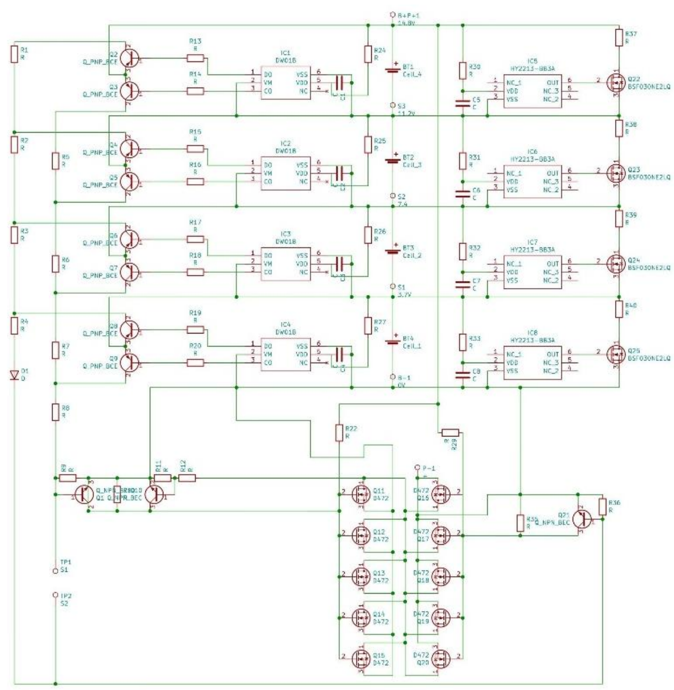


Figure 12. Proposed BMS circuit diagram

Part C – Constant current charger

In this part, we will do a real-world experimentation with a constant current charger [Figure 13], compare the obtained results with the circuit's simulation [Figure 14] and discuss limitations and improvements.

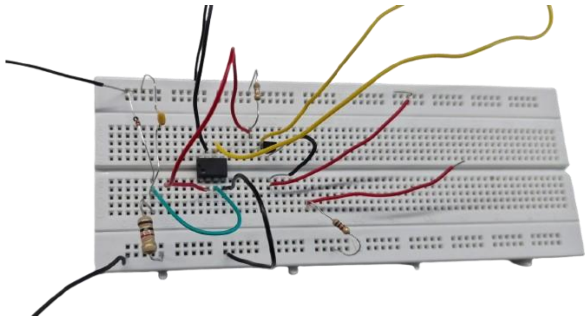


Figure 13. Constant current charger circuit measured

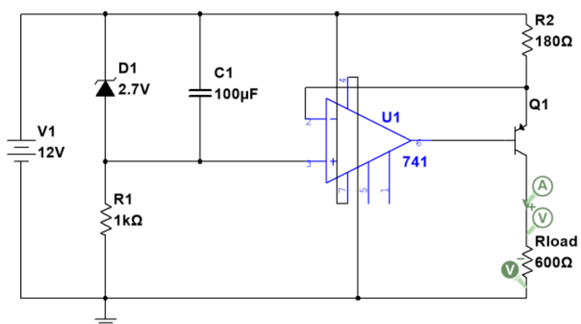


Figure 14. Constant current charger simulated circuit

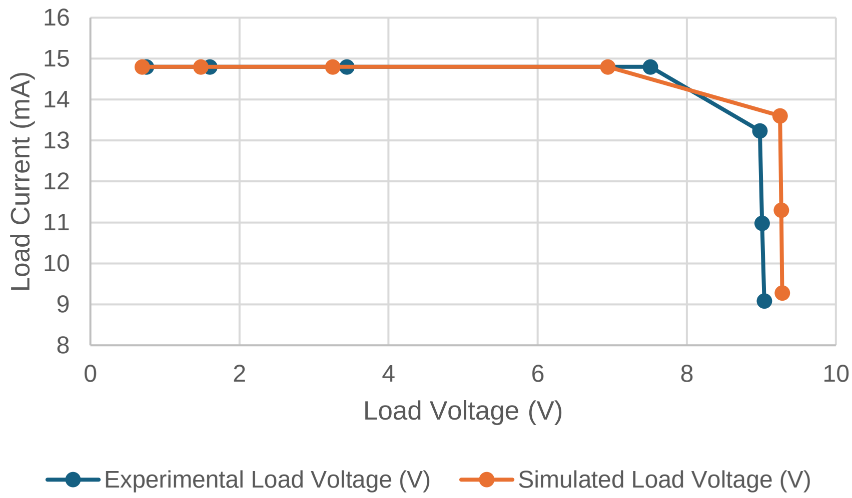
This circuit is designed to have a steady output current, despite varying load conditions, by means of a negative feedback operational amplifier.

The Zener diode provides the reference 2.7V difference required for the operational-amplifier, while the capacitor acts as a filter for the diode's voltage fluctuations and the 1KΩ resistor prevents current-derived damage to the diode.

The transistor allows the control of the load's current, as the operational amplifier compares the collector's voltage to the reference. When the transistor is not in saturation, the voltage in the negative feedback is set by the Zener, achieving a voltage difference of 2.7v at the collector's 180Ω resistor.

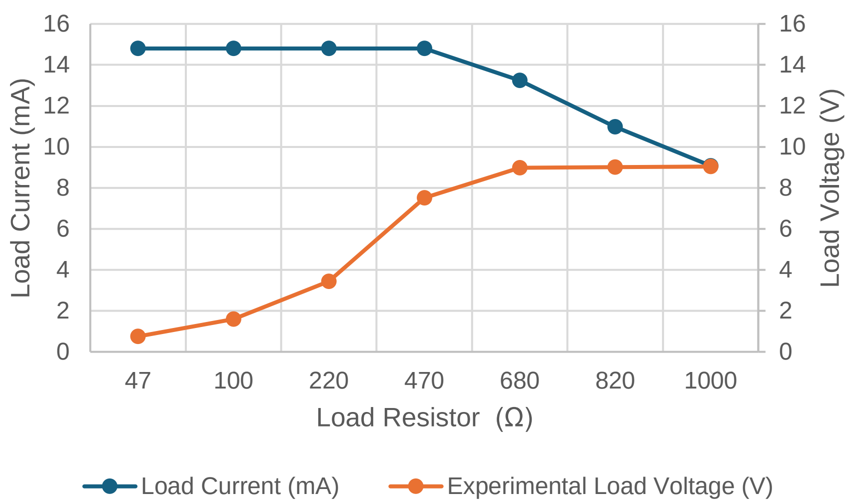
Applying Ohm's law, we find the current provided to the load, as in a PNP transistor, $I_E = I_C - I_B$ (Mora, 2012). In our application, $I_B \approx 0A$, thus, $I_E = I_C$, which gives us $I_{Load} = 15mA$.

Table 1. Load voltage against load current



By looking at the load voltage and current [Table 1], when the transistor enters saturation, we can see a clear drop in current and a stagnated voltage, this limits the performance of the charger. Additionally, we can validate the simulated results with the experimental ones.

Table 2. Experimental constant current charger



As seen on the experimental values [Table 2], current decreases after a load of 470Ω is applied and voltage stagnates past 680 Ω. We can find the maximum load (2) that allows the circuit to behave appropriately by utilizing Ohm's law (Bird, 2017) with the maximum voltage and current that we achieved experimentally:

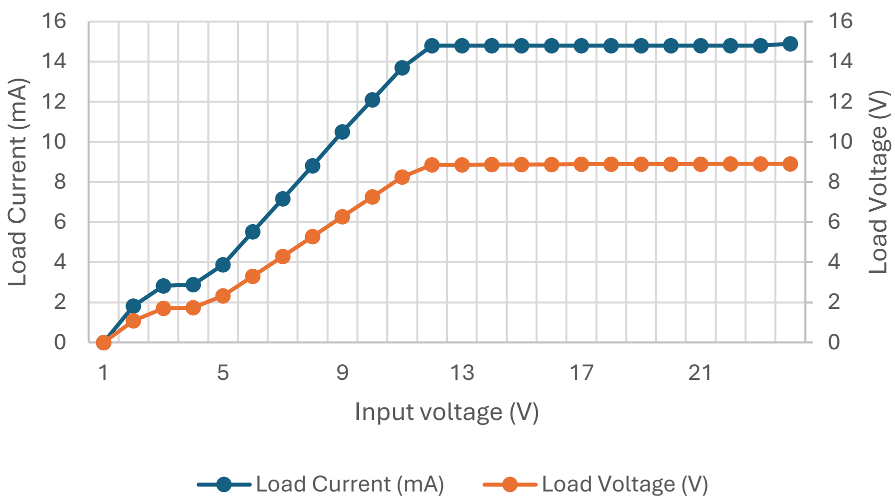
$$R_{load,max} = \frac{V_{load,max}}{I_{load,max}} = \frac{8.98V}{14.8mA} = 606\Omega \approx 600\Omega \tag{2}$$

In order to obtain the charger's output resistance (3), we make use of Thevenin's theorem, where we can see that the charger's equivalent circuit can be reduced to the behaviour of the transistor. We can approximate the charger's dynamic output resistance as (Bird, 2017):

$$R_{out} = \frac{\Delta V_{CE}}{\Delta I_C} = \frac{(7.51 - 0.75)V}{(14.8 - 14.8)mA} \approx Infinite\ \Omega \tag{3}$$

This high output resistance implies that the circuit will not allow significant variations in output current with changes in load voltage or resistance, as this is the objective of a constant current charger, we can confirm the effectiveness of the circuit.

Table 3. Multiple input voltage study



Studying the effects of different input voltages on circuit performance [Table 3] for a 600Ω load, we observe that voltages below 12V do not meet the power requirements of the circuit, as the transistor remains in saturation.

When the input voltage is 12V or greater, we can observe that the power requirements of the circuit have been met, as the transistor behaves now in an active state, maintaining a constant output voltage and current.

Additionally, the maximum allowed load, although increasing with the input voltage, is severely restricted.

In order to optimize the circuit's operating range, we can calculate the optimal Zener forward voltage, first, we find the load current (4) is defined by the emitter resistor.

$$I_{load} = \frac{V_z}{R_{emitter}} \tag{4}$$

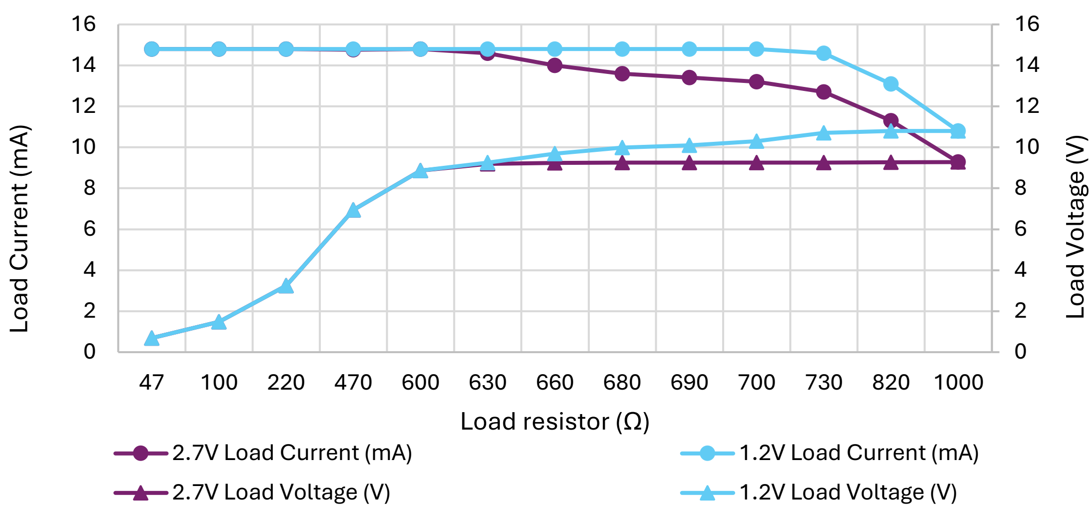
As the BJT's $V_{CE} > 0.3V$ to remain in the active state (Bird, 2017), we can obtain the maximum load voltage (5), and thus, the maximum load (6) dependence on the Zener's forward voltage.

$$V_{load} = V_{in} - V_{CE} - V_z \tag{5}$$

$$R_{load} = \frac{V_{load}}{I_{load}} = \frac{V_{in} - V_{CE} - V_z}{I_{load}} = \frac{(12 - 0.3 - V_z)}{14.8mA} \tag{6}$$

Maintaining the 12v input voltage, we can increase the load by utilizing a Zener's lower forward voltage. The lowest commercially available Zener's forward voltage is 1.2v (Rectron Semiconductor, 2025), this is implemented together with an 80Ω emitter resistor.

Table 4. Comparison between Zener's forward voltage for a 12v input



As seen in the simulation results [Table 4], decreasing the Zener's forward voltage resulted in an increase of 600Ω to 710Ω maximum allowable load.

In order to further increase the load, an increase in input voltage via a boost converter could be considered [Table 5].

Table 5. Input voltage effects on maximum load

Input voltage (V)	12	13	14	15	16	17	18	19	20	21	22	23	24
Maximum load (Ω)	710	778	845	913	980	1048	1115	1183	1250	1318	1386	1453	1521

Additionally, if the charger is connected to a battery, Multi-Stage Constant Current Chargers (Tahir et al., 2023) must be considered, as the circuit does not have any feedback element for the battery's State-of-Charge (SoC), it can lead to damaged battery cells, as current should decrease as SoC increases to prevent thermal damage [Figure 15].

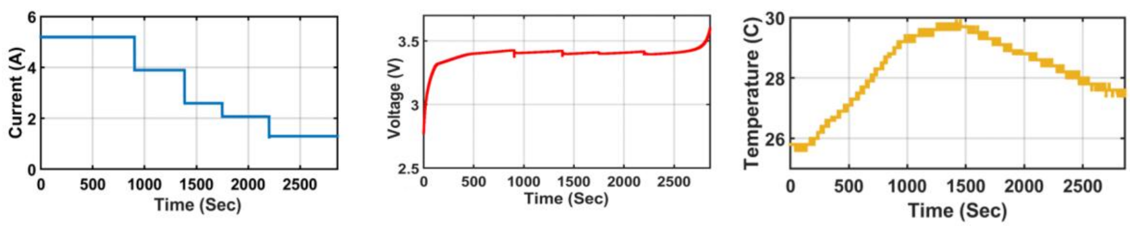


Figure 15. Effects of Multi-Stage Constant Current Charger on battery temperature

Thermal management must be considered, as both the Zener and operational amplifier dissipate heat, displaying an inefficient behaviour.

A more efficient op-amp should be considered, as the current draw from the 741 op-amp reduces the charger's efficiency significantly.

Individual reflection

During this assignment, the design, simulation, and evaluation of the behaviour of lithium-ion battery cells, designed as capacitors, battery management systems (BMS) and constant current chargers, provided a deeper understanding of their operation, performance, limitations, and possible applications to electric vehicles.

In part A, problems such as voltage imbalance due to damaged cells, undercharging, and overcharging were identified. Introducing LEDs to balance voltages demonstrated the importance of load balancing in preventing damage to components while revealing new problems like diode's heat dissipation and charge redistribution during discharge.

In Part B, the design of a simple BMS addressed the limitations observed in Part A, by incorporating an active cell balancing circuit, undervoltage lockout (UVLO), and overvoltage protection (OVP). Additionally, by using operational amplifiers, both the effects of comparators and hysteresis on precise voltage control were also studied. Afterwards, the environmental and sustainability effects were considered, investigating Spain's and EU laws on Waste Electrical and Electronic Equipment (WEEE). Further work proposed included more optimized and efficient UVLO and OVP integration, while implementing overcurrent and specific cell monitoring designs to the circuit.

Part C focused building on a breadboard and later analysing, simulating and optimizing a constant current charger. The original circuit design revealed severe limitations in load resistance. The experimental validation of the original design confirmed the simulated results, demonstrating how theoretical equations translate into the real world, while allowing the improvements and analysis to be made onto the simulated circuit. By replacing the Zener with a lower forward voltage alternative and recalculating emitter resistance, the maximum load resistance increased from 600Ω to 710Ω while maintaining a constant output current of 14.8mA. Investigating input voltage effects revealed that voltages below 12v caused the transistor to enter saturation, limiting circuit performance, while voltages above 12v greatly increased the maximum load. Further work proposed included integrating multi-stage constant current charging strategies or boost converters to further enhance efficiency and maximum load.

Through this work, a deeper understanding of BMS, operational amplifier operations and circuit design principles was developed. The coursework reinforced the importance of precise voltage and current control over power flow, robust safety features, and creating designs that ensure long-term reliability.

References

Bird, J. (2017). *Electrical Circuit Theory and Technology*. Routledge.

Cho, M.-H., Lee, W.-H., Kim, J.-S., Sa, Y.-H., Kim, H.-S., & Cha, H.-W. (2016). *Development ofundervoltage lockout (UVLO) circuit configurated Schmitt trigger*. https://doi.org/10.1109/ISOCC.2015.7401639

Cutanda, B. L., Poveda, P., & Muiña, A. L. (2015). *Royal Decree 110/2015 of 20 February on waste electrical and electronic equipment*. https://ga-p.com/wp-content/uploads/2018/07/royal-decree-110-2015-of-20-february-on-waste-electrical-and-electronic-equipment-key-changes.pdf

Elektronik, W. (2021). *Balancing of Supercapacitors*. Würth Elektronik; Würth Elektronik. https://www.we-online.com/catalog/media/o671684v410%20ANP090a_EN.pdf

Horowit, P., & Hill, W. (2015). *The Art Of Electronics* (3rd ed.). Cambridge University Press.

Mancini, L., Eslava, N. A., Traverso, M., & Mathieux, F. (2021). Assessing impacts of responsible sourcing initiatives for cobalt: Insights from a case study. *Resources Policy*, *71*. https://doi.org/10.1016/j.resourpol.2021.102015

Mora, J. F. (2012). *Circuitos Eléctricos*. Pearson.

Rectron Semiconductor. (2025). *1N5221B-B*. https://www.mouser.co.uk/datasheet/2/345/1n52xxb-24434.pdf

Sharad Bhowmick. (2022, May 9). *Lithium-Ion Battery Management and Protection Module (BMS)*. CircuitDigest. https://circuitdigest.com/electronic-circuits/lithium-ion-battery-management-and-protection-module-bms-teardown-schematics-parts-list-and-working

Spanish Government. (2022). *Spain: Legislative changes introduced by act 7/2022 on waste and contaminated soil for a circular economy* (Clifford Chance, Trans.). https://financialmarketstoolkit.cliffordchance.com/content/dam/cliffordchance/briefings/2022/10/Ley%207_22%20Residuos_ENG.pdf

Tahir, M. U., Sangwongwanich, A., Stroe, D. I., & Blaabjerg, F. (2023). The Effect of Multi-Stage Constant Current Charging on Lithium-ion Battery's Performance. *CPE-POWERENG 2023 - 17th IEEE International Conference on Compatibility, Power Electronics and Power Engineering*. https://doi.org/10.1109/CPE-POWERENG58103.2023.10227383

Texas Instruments. (2014, June). *Comparator with Hysteresis Reference Design*. https://www.ti.com/lit/ug/tidu020a/tidu020a.pdf?ts=1744093688026

Väyrynen, A., & Salminen, J. (2012). Lithium-ion battery production. *Journal of Chemical Thermodynamics*, *46*, 80–85. https://doi.org/10.1016/j.jct.2011.09.005