MAIT Journal of Science & Technology
Issue No. 1, Volume No. 2, December 2025, Page No.20-26
ISSN(Online)

Supercapacitor-Powered Urban Train: A Cost-Effective Alternative

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***Abstract**: This paper investigates the role of supercapacitor technology in enhancing traction efficiency and reducing infrastructure costs in metro rail systems by replacing conventional track-based electrification. Traditional metro systems rely heavily on continuous electrification through overhead lines or third-rail systems, leading to high capital expenditure, complex infrastructure requirements, and significant energy losses, especially in urban environments with frequent stops. Whereas, the quick charging, adequate regenerative braking, and longevity of supercapictor powered trains enables them preferred choice for local railroad lines.*

Keywords: Supercapacitor, Electrification, Third-Rail System, Regenerative Braking, Overhead catenary systems.

1. INTRODUCTION

The need for a sustainable and efficient public transport system is to deal with the problems that come up because of more people living in cities, less fossil fuel reserves, and the effects on the environment. Electric trains, trams and tram buses are the main types of sustainable transportation. The Delhi metro is the largest metro train system in the world [1]. The metro rail network system includes 25 kV AC overhead catenary systems and 750 V DC third-rail systems [2]. These systems contributes speedy transit, but with significant funds and operational expenditures. Moreover, the electrification infrastructure includes high installation cost, complex maintenance requirement, especially in densely populated areas are challenging.

The urban metro trains have frequent stops, thus, requires continuous acceleration and deceleration . Which leads to considerable energy consumption and wear on mechanical components. This results in increased maintenance costs and reduced system efficiency.

The alternative method to run the metro trains are required to improve efficiency, reduce costs, and mitigate environmental impact to cope up these challenges. Supercapacitor based technology is an emerging solution, known for its fast charging capability, high power density, and durability. This provides on-board energy storage, thus, reduces reliance on conventional electrification of track.

The electrification cost is reduced and efficiency is improved and train is powered through pre-charged supercapacitor.

2.LITERATURE REVIEW.

Delhi Metro operates primarily using a 25 kV AC overhead catenary system for electric supply. In this configuration, electrical energy is transmitted through overhead supply line commonly referred to as the Overhead Equipment (OHE), which is suspended above the tracks. The rolling stock (train) is equipped with pantographs—mechanical devices mounted on the roof of each train car—that maintain continuous contact with the overhead wire. The pantograph collects current and transfers it to the train's power systems, enabling propulsion and mobility, lighting, air conditioning, and control systems.

The cost of electrification infrastructure in metro rail systems forms a substantial portion of the overall capital expenditure. The component of the metro train systems are overhead catenary lines to feed electric powers to train through pantographs, traction substations to feed the catenary lines, and the related transmission equipment and accessories.

The electrification cost of metro rail systems at various part of the globe varies such as, Mexico City's Line B had a total US$970 million capital expenditure, US$50.4 million which is approximately 5.2% of total expenditure is for the power system. Whereas Caracas Metro's Line 3 budget is US$372 million, and it spent US$33.1 million, which is 8.9% of total budget on electrification infrastructure. Similarly, Santiago Metro's Line 5 extension, which is of 2.8 km in length, is given US$5.5 million to metro rail electrification components. Which is 2.8% of its total budget of US$197 million. These figures confirm that electrification regularly consumes between 2% to 9% of a metro system's capital budget, depending on the complexity, train, and system voltage **[3]**.

In the Indian context, metro electrification costs are even more pronounced due to the scale and engineering challenges in densely populated urban areas. According to the Sub-Committee on Traction System, Power Supply & Energy Efficiency under the Ministry of Urban Development, the estimated electrification costs are:

- For a 25 kV AC Overhead Catenary System:
    - Elevated corridors: ₹9.51 crore per km
    - Underground corridors: ₹11.26 crore per km
- For a 750 V DC Third Rail System:
    - Average cost: ₹13.36 crore per km
- For a 1500 V DC Overhead Catenary System:
    - Elevated corridors: ₹10.51 crore per km
    - Underground corridors: ₹12.26 crore per km

The above figures emphasises that the selection of traction system has a considerable impact on capital expenses **[4]**. The electrification cost depends on length of electrification network and the configurations used. The Delhi Metro, which is a large network of over 390 km length, the total electrification cost exceeds ₹4,000 Crore. This causes heavy financial burden on urban infrastructure projects, and raises long-term issues of operation and maintenance costs.

3.PROBLEM STATEMENT

The conventional metro train system due to dependence on rail electrification depends on significant capital and operational expenditure. These systems are costly to install and maintain, particularly in densely populated areas,. This research aims to explore alternative propulsion strategies, specifically supercapacitor-based onboard energy systems, to substantially reduce the cost of electrification infrastructure and enhance overall system efficiency, reliability, and sustainability

4. PROPOSED SOLUTION

The metro train systems based on conventional electrification are characterized by frequent halts at stations located closely, usually every 1 to 2.5 kilometres **[5]**. Which causes the train to accelerate, cruise, brake, and decelerate frequently. Thus, most of the time train remains in transient states rather than in steady-state cruising **[6]**. This causes repeated high power demand for traction motors and hence, substantial electrical loading on the overhead catenary system. Additionally, shorter distance between the halting stations causes little opportunity for the energy generated due to regenerative braking to be efficiently absorbed or reused except adequate energy storage or grid susceptibility exists [**7**].

The problems of costly track electrification systems is overcome by the integration of supercapacitor-based on-board energy storage units in metro rolling stock **[8]**. Supercapacitors, which are also known as ultracapacitors, are high power density, quick charge-discharge characteristics, and minimal energy loss electrochemical energy storage devices. The supercapacitors due to extremely low equivalent series resistance (ESR) in contrast to batteries gains high levels of charge in seconds and delivers large bursts of current **[9]**.

In the proposed system, supercapacitor modules is integrated within the train cars and designed to recharge at every station stop. Since metro dwell times typically range from 20 to 40 seconds [**10**], this stationary window is sufficient for partial or full recharging of supercapacitors, especially when paired with high-efficiency power interfaces. Furthermore, regenerative braking energy—currently underutilized in many systems due to lack of on-board storage—can be captured and stored directly into the supercapacitor bank during deceleration.

Once charged, the supercapacitors feeds the traction system during acceleration phase, thereby reducing the instantaneous demand on the overhead line or third-rail system. through fully offloading peak power requirements from the main transmission infrastructure, the overall grid load decreases and more predictable, enabling reduced infrastructure ratings and improved system stability.

Additionally, the mechanical simplicity, long cycle life, and temperature tolerance of supercapacitors make them highly suitable for the stop-and-go operational profile of urban metros **[11]**. Their negligible ESR (equivalent series resistance) allows for efficient energy transfer with minimal heat generation, ensuring high performance even under frequent charge-discharge conditions. The super capacitors bridges the gap between conventional capacitors and batteries by storages energy electrostatically, thereby, significantly, higher power densities and larger cycle lives **[12].**

5. METHODOLOGY

The supercapacitor are considered as electric double-layer capacitance (EDLC). When a voltage is placed across the electrodes of an EDLC, charges develop on the surfaces within the electrode materials and in some instances along the region adjacent to electrolyte which is thought of forming Electrical double-layer at interface **[13]**. This mechanism is non-faradaic (redox) which enables fast charging and discharging cycles **[14].**

The material and structural advancements are reasons for supercapacitors to store large energy including reasons mentioned below as,

1. Porous electrodes include large surface area materials of activated carbon, graphene or carbon nanotubes. These materials have a large specific surface area (often > 2000 m²/g) which allows for a huge amount of charge storage due to ion adsorption on the surface **[15]**.
2. Electric Double Layer Effect EDLCs are different from the traditional capacitors, which utilizes physical polarization of current carriers enclosed within a dielectric layer to increase capacity. In this way a truly massive capacitance per unit volume is achieved.
3. Some supercapacitors uses metal oxide or conducting polymer based electrodes, these mechanisms offer additional capacitance on the surface through the reversible redox reactions of Faradaic charge The pseudocapacitance is quite similar to double-layer capacitance and may be easily integrated into a standard electrolytic capacitor. This is referred to as pseudocapacitance which serves in conjunction with the EDLC mechanism **[16]**.
4. Dielectric Engineering: The use of advance dielectrics material like GO, RGO and even layer materials such as MXene has triggered the higher energy densities because it enhances the conductivity and decreases ESR. Graphene, in particular, possesses high electrical conductivity and mechanical properties that are superior to any other state-of-the-art materials today which makes graphene a very promising candidate for next-generation supercapacitors **[17]**.

High power output due to low ES, This is because supercapacitors have an extremely lower equivalent series resistance (ESR) as compared with the batteries which allows fast delivery of energy. This is essential for use cases ranging from urban metro systems, which have low energy requirements in terms of the required bursts during frequent accelerations and deceleration cycles.

6. SIMULATED RESULTS

Fig. 6.1 depicts the implemented MATLAB Simulink model of supercapacitor powered metro train. The model replicates the energy flow from a supercapacitor to a Permanent Magnet DC (PMDC) motor, which acts as an approximate representation of an actual train traction system. Fig. 3.2 illustrates the performance of the developed prototype of the supercapacitor powered permanent magnet DC motor system.

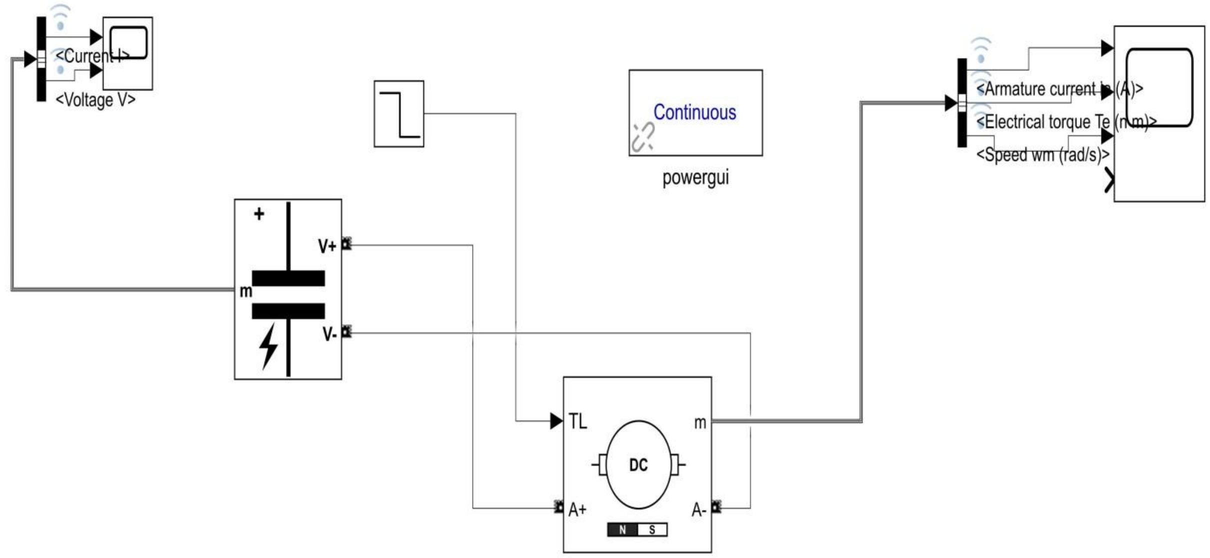

Fig 6.1 Supercapacitor powered metro train block diagram

6.1 **Supercapacitor Block**

This block models the behavior of an idealized supercapacitor with parameters corresponding to a typical high-capacitance, low-ESR energy storage device. In this model:

- The supercapacitor provides initial energy to drive the train.
- It mimics the quick discharge and rapid recharge capability inherent to Electric Double Layer Capacitors (EDLCs).

6.2 PMDC Motor Block

While real-world metro trains employ 3-phase induction or permanent magnet synchronous motor, a PMDC motor is used here for simulation due to its simplicity and ease of control. It serves as an effective approximation to demonstrate dynamic responses like torque generation, acceleration, and energy draw from the source.

6.3 Power Measurement Blocks

To track system performance, the following outputs are measured:

- Armature Current (ia): Shows the current drawn by the motor during acceleration.
- Electrical Torque (Te): Reflects the torque developed, which spikes during the initial phase.
- Speed (w_m): Indicates the angular speed rise over time as the vehicle accelerates and coasts.

6.4 Load Torque (TL)

This represents the mechanical load applied to the PMDC motor shaft, simulating the resistance of vehicle weight and friction forces.

It constitutes of two-state step function to depict the static and dynamic friction of the train wheel. Where dynamic friction < static friction.

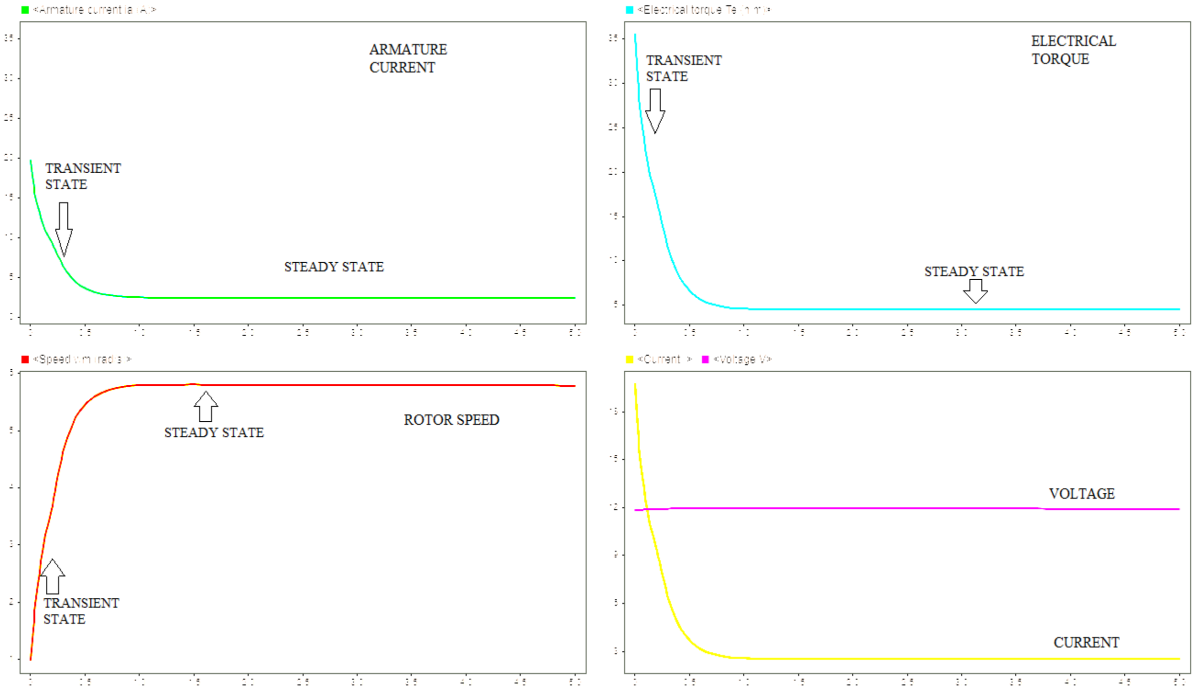

Fig 6.2 armature current (a), electrical torque (b)speed (c), capacitor voltage and (d) current

Key observations from the results are:

- The Armature Current and Electrical Torque exhibit a sharp initial spike within the first second (0–1 s), indicating high current and torque demand during the start-up and acceleration phase — a characteristic behavior in urban metro operations where frequent stops and rapid accelerations are typical.
- The speed of the motor (in rad/s) shows a smooth and rapid increase, reaching steady-state conditions shortly after 1.5 seconds, demonstrating the supercapacitor's ability to deliver fast-response power delivery and efficient motor startup.
- The voltage across the supercapacitor remains relatively stable throughout the simulation, with a minor drop, validating the low Equivalent Series Resistance (ESR) and minimal energy loss characteristics of supercapacitors.

7. REALIZED PROTOTYPE PERFORMANCE

Fig. 7.1 illustrates the block diagram of proto type developed in the laboratory. A scaled-down prototype of a supercapacitor-powered metro train is successfully developed to experimentally validate the feasibility of supercapacitors as the primary energy source for rail-based transportation. The working prototype emulates the actual traction system behavior using components selected for their functional similarity to real-world systems.

The traction drive of the prototype uses a 775 V DC motor as an equivalent substitute for a full-scale traction motor. Power delivery is managed via a BTS7960 high-current H-bridge driver module, which is capable of bi-directional motor control. The energy storage system consists of five 2.7 V, 500 F supercapacitors connected in series to achieve a combined voltage rating of 13.5 V. Two such series banks are connected in parallel, resulting in an effective capacitance of approximately 200 F at 13.5 V.

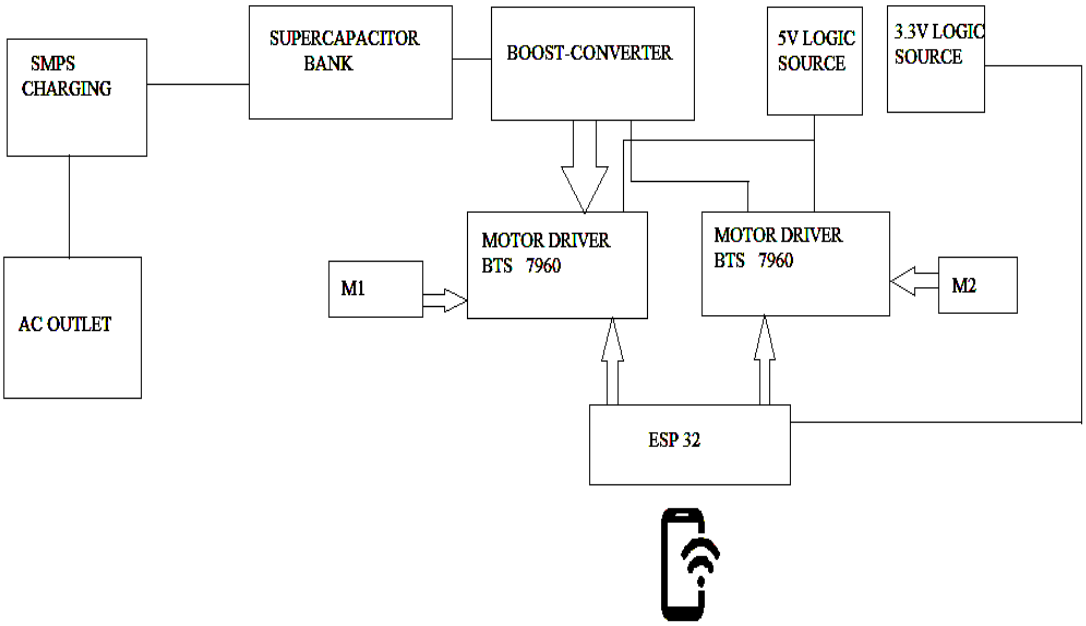

Fig 7.1 block diagram of prototype

The charging of the supercapacitors is done through a 1200W SMPS, and discharge is controlled through the boost converter which is connected to BTS7960, which in turn is governed by an ESP32 microcontroller. The ESP32 manages switching logic, speed control, and directional operation. During operation, the system demonstrates:

- High current discharge at start up, similar to real-world train acceleration conditions.
- Rapid attainment of peak motor speed, validating the high power density and low ESR (Equivalent Series Resistance) of the supercapacitor bank.

- Stable performance during low-load cruising and effective deceleration behavior during motor shutdown.

This prototype, while scaled for laboratory testing, successfully simulates the core behavior of a supercapacitor-driven metro rail, proving the concept and offering a low-cost and accessible platform for further research into regenerative braking, charge control algorithms, and energy efficiency optimization.

Table 7.1 backup time of motor at various speed

SNO	MOTOR SPEED	BACKUP TIME
1	70 %	205 SEC
2	30%	430 SEC

Table 7.2 chargin time of super capacitor for various range of voltage

SNO	VOLTAGE RANGE	CHARGING TIME
1	0-12 V	~40 SEC
2	6.5-12	~15 SEC

7.1 Limitations of Prototype

While the prototype successfully demonstrates the fundamental working of a supercapacitor-powered rail traction system, several limitations exist due to scaling and component constraints are as,

1 Scaled-Down Voltage and Power Levels:
The prototype operates at low voltage (12–13.5 V) and current levels, which do not fully represent the high-voltage environment (750 V to 25 kV) of actual metro systems. Thus, real-world power handling behavior is only approximated.

2 Use of PMDC Motor Instead of Traction Motor:
The 775 DC motor lacks the torque, speed range, and control complexity of AC traction motors (such as induction or permanent magnet synchronous motors) used in metro trains. This limits the dynamic fidelity of the prototype.

3. **Simplified Control Strategy**:
The ESP32 microcontroller operates the motor using basic control logic without advanced features such as regenerative braking, vector control, or real-time load adaptation, which are common in real systems.

4. **Limited Energy Storage**:
The supercapacitor bank (approx. 200 F at 13.5 V) provides only a brief energy window, insufficient for continuous or long-duration runs. This limits test durations and real-world applicability.

5. **Absence of Regenerative Braking Simulation**:
The prototype is not included mechanisms to recapture energy during braking or deceleration, a key advantage of supercapacitor-based systems in rail transport.

6. **Simplified Load Modeling**:
The mechanical load is idealized, without incorporating realistic parameters like , gradient, passenger mass variation, or environmental factors like wind resistance.

7. **Thermal Effects Ignored**:
Heating of the motor, capacitor bank, or driver circuitry under repeated cycles is not modeled, though it's a critical consideration in real-life systems.

8. **Inability to Include Certain Components in Simulation**:
MATLAB Simulink model has not included the real-world components like the BTS7960 motor driver and

ESP32 controller, which means hardware-specific behaviors are not present in simulation results.

8. CONCLUSIONS

This work explore different ways to improve the energy efficiency and cost-effectiveness of urban metro systems through the integration of supercapacitor-based propulsion system. The development of a scaled-down prototype using a 775V DC motor, BTS7960 motor driver, ESP32 controller, and a 13.5 V, 200 F supercapacitor bank successfully demonstrated the feasibility of capacitive energy storage for short, frequent transit operations characteristic of urban rail systems.

Simulation and prototype test results indicate that supercapacitors, due to their rapid charging, high cycle life, and low internal resistance efficiently deliver burst energy required during acceleration phases and recharge during station stoppages. However, the limitations of the system—such as reduced energy density, limited storage duration, and scaling constraints—suggest that it is currently more suited for short-distance urban applications rather than long-haul or high-speed rail systems.

9. REFERENCES

[1] Times of India. (2024, March 17). Delhi Metro’s Golden Line expansion to make it the world’s largest city metro system.
[2] DMRC's Environmental Impact Assessment (EIA) report for Phase IV Priority Corridors, the metro system utilizes a 25 kV AC overhead current collection system.
[3] Flyvbjerg, B., Bruzelius, N., & van Wee, B. (2008). Comparison of Capital Costs per Route-Kilometre in Urban Rail. European Journal of Transport and Infrastructure Research, 8(1), 17-30.
[4] .E Project09 Full – Sub-Committee on Traction System, Power Supply & Energy Efficiency, Ministry of Urban Development (India).
[5] Delhi Metro Rail Corporation (DMRC). (2020). EIA Phase IV Priority Corridors.
[6] Jiajia Feng, Xuan Li, Jungang Shi, Yang Shi, Joint optimization of metro train timetable and stopping plan for the first service period: An integrated energy-efficient and time-saving model,International Journal of Transportation Science and Technology, 2024.
[7] Tang, Y., et al. (2015). Improving Regenerative Energy Receptivity in Metro Transit Systems.
[8] Szeląg, A., et al. (2019). On-Board Energy Storage Devices with Supercapacitors for Metro Vehicles. Energies, 12(7), 1291.
[9] Adel, Mohamed & Mohammed, Omar & Younis, Ahmad. (2025). Estimation of Equivalent Series Resistance (ESR) of Supercapacitors Using Charging/Discharging Kinetics. ChemistryOpen. 10.1002/open.202400444.
[10] Kataria, J. (2019). Modelling Metro Ridership Pattern and Passenger Flow.
[11] Murray, Donal & Hayes, John. (2015). Cycle Testing of Supercapacitors for Long-Life Robust Applications. Power Electronics, IEEE Transactions on. 30. 2505-2516. 10.1109/TPEL.2014.2373368.
[12] Miller, J. R., & Simon, P. (2008). Electrochemical capacitors for energy management. Science, 321(5889), 651–652.
[13] Endo, M. & Takeda, T. & Kim, Yong & Koshiba, K. & Ishii, K.. (2001). High Power Electric Double Layer Capacitor (EDLC's); from Operating Principle to Pore Size Control in Advanced Activated Carbons. Carbon letters. 1.
[14] Aoki, Koichi. (2016). Frequency-dependence of electric double layer capacitance without Faradaic reactions. Journal of Electroanalytical Chemistry. 779. 10.1016/j.jelechem.2016.04.026.
[15] Simon, P., & Gogotsi, Y. (2008). Materials for electrochemical capacitors. Nature Materials, 7(11), 845–854.
[16] Conway, B. E. (1999). Electrochemical Supercapacitors: Scientific Fundamentals and Technological Applications.
[17] González, A., Goikolea, E., Barrena, J. A., & Mysyk, R. (2016). Review on supercapacitors: Technologies and materials. Renewable and Sustainable Energy Reviews, 58, 1189–1206.