# Charge-Discharge behavior of series-connected printed supercapacitor modules – experimental and modelling results

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## Introduction

In this poster, Supercapacitors (SCs) or electric double layer capacitors (EDLCs) are modeled and analyzed. Typically, SCs have considerably larger capacitance than regular capacitors. SCs are a promising element in energy storage systems due to their large specific power density, high efficiency, fast charge and discharge time and long lifespan (in both charge/discharge and time cycles) compared to batteries. We modeled the charge and discharge behavior of three series connected printed SCs. The parameters needed for modeling were defined from SCs fabricated by printing methods [1]. Besides the capacitance, also equivalent series resistance (ESR) and non-linear self-discharge were considered. The non-linear element to model the self-discharge was connected in parallel with the capacitance element. The model can be used to define the charging and discharging behavior under various conditions. The results also offer insight into the effect of device-to-device variation on energy management and to the allowable device tolerances in multi-cell modules.

## Results

In this work, we connected three printed SCs in series in order to obtain an energy module and then charged them with a three-volt battery. After the SCs were fully charged, we disconnected them from the battery and analyzed their self-discharge behavior and voltage delivered to different small and large loads. In order to study how power is delivered to different loads, we modeled and simulated the discharge behavior of the fabricated energy module for different loads. Figure 1 shows the equivalent circuit of the energy module when discharging and delivering power to the load. The voltage across the two ends of the SCs at the beginning of the discharge phase is the same as the voltage stored in the SCs at the end of the charging phase.

As shown in Figure 1, for each SC, a series resistor is used to model the ESR, and an exponential element is used to model the leakage current and self- discharge. The parameters required for modeling ESR and leakage current are obtained from the characterization of SCs fabricated by printing methods [1]. The exponential parameters of each SC are unique to each SC and are obtained separately. These parameters are derived from the extraction of the exponential relationship of the actual I-V values of each SC during self-discharging. For example, how to obtain the exponential relationship of SC1 in the energy module is shown in Figure 2.

Figure 3 and 4 show the amount of voltage delivered to different loads by the modeled module. In addition, the simulation and actual results of the module discharge behavior can be seen in Figure 3. As shown in Figures 3 and 4, for self-discharge and loads larger than 1 MΩ, the simulation is performed for 30 days and for loads smaller than 500 kΩ, the simulation is performed for 120 seconds.

## Conclusion

In this work, an energy module was modeled by printed SCs and the amount of power delivered to different large and small loads by this module was simulated. By more detailed study and analysis of this energy module, it is possible to obtain optimal values for determining the parameters of SC fabrication. This energy module can be used in energy storage system applications.

## Acknowledgement

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## References

[1] J. Keskinen, S. Lehtimäki, A. Dastpak, S. Tuukkanen, T. Flyktman, T. Kraft, A. Railanmaa, D. Lupo, Architectural Modifications for Flexible Supercapacitor Performance Optimization, Electronic Materials Letters 12 (2016), 795-803.

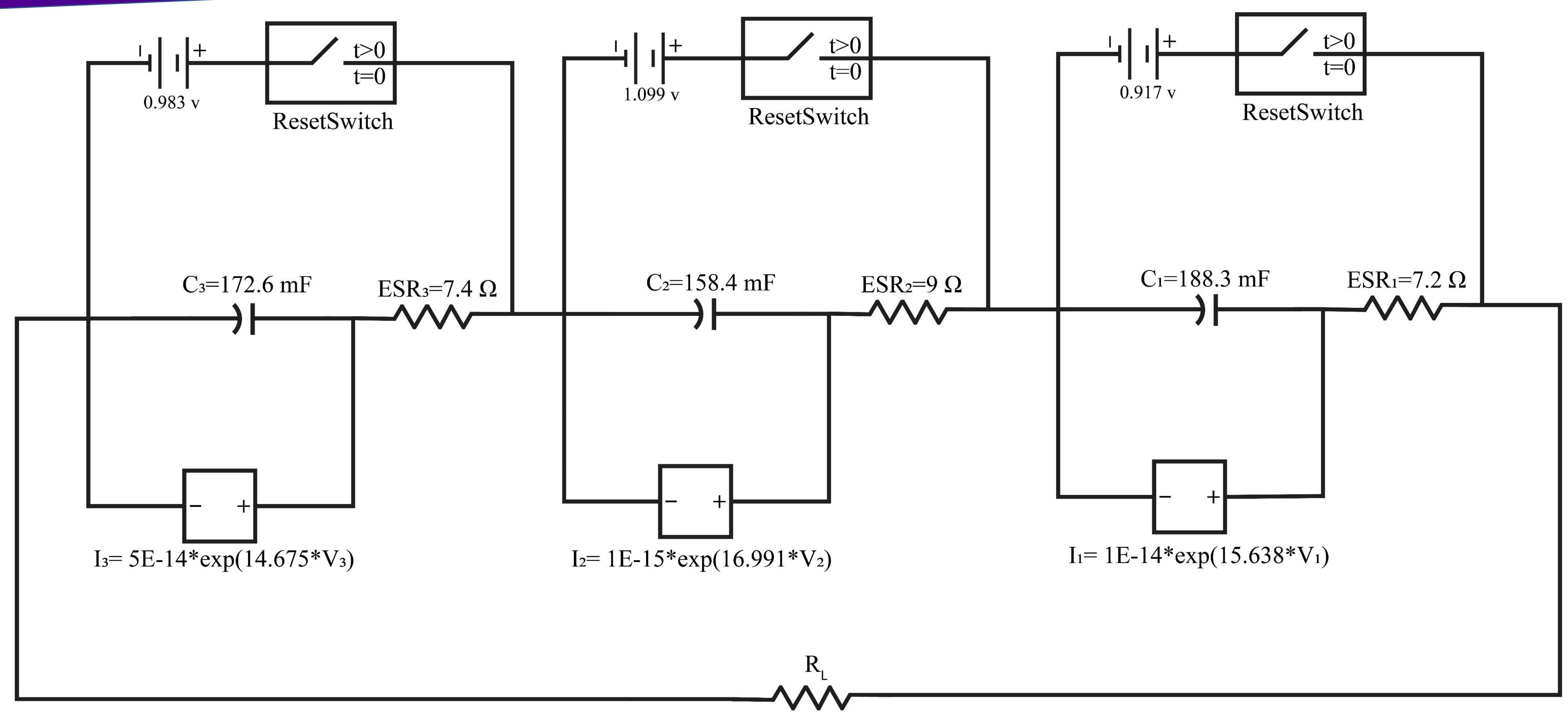


Figure 1. Discharge model of the energy module

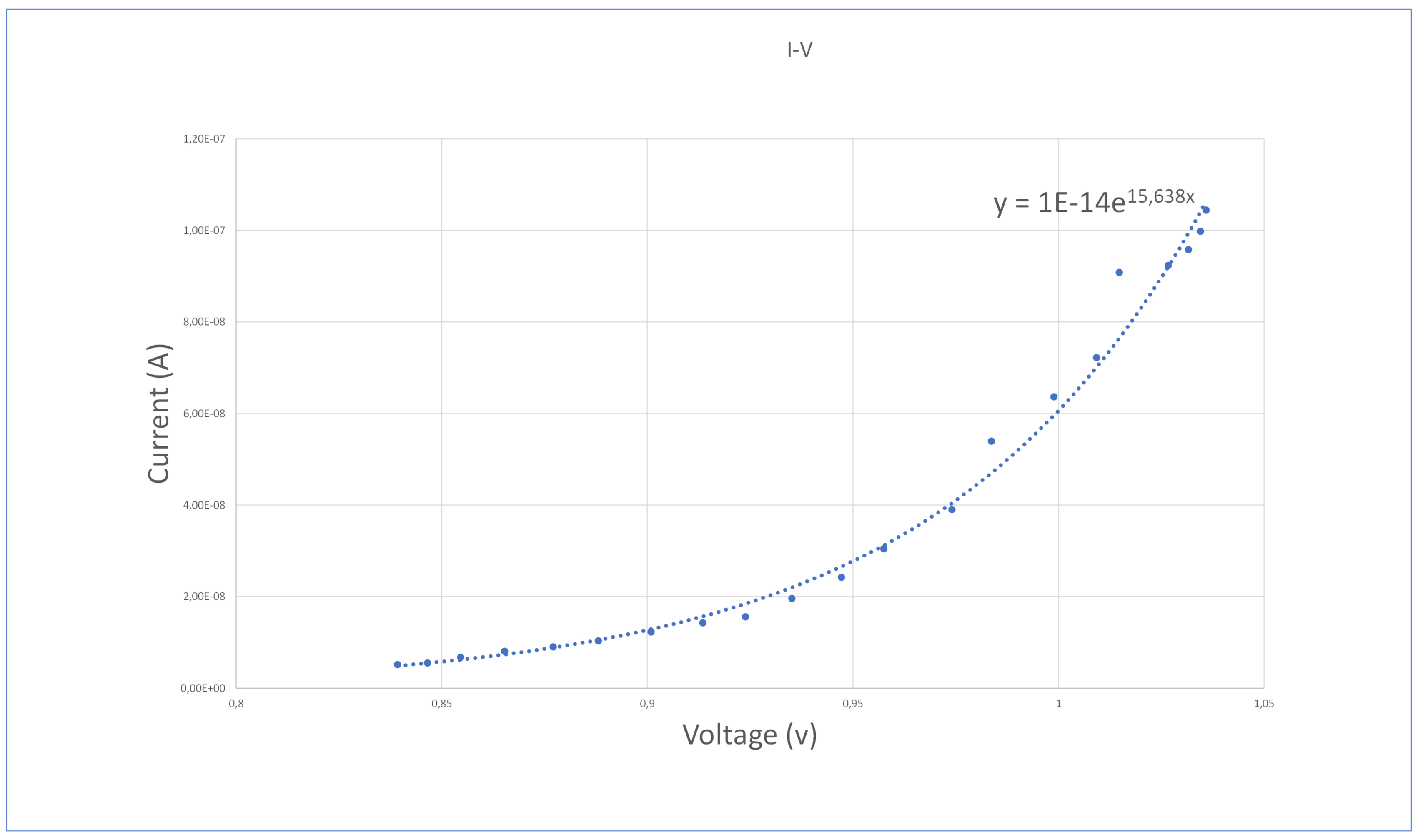


Figure 2. Method of obtaining exponential relationship for modeling leakage current and self-discharge.

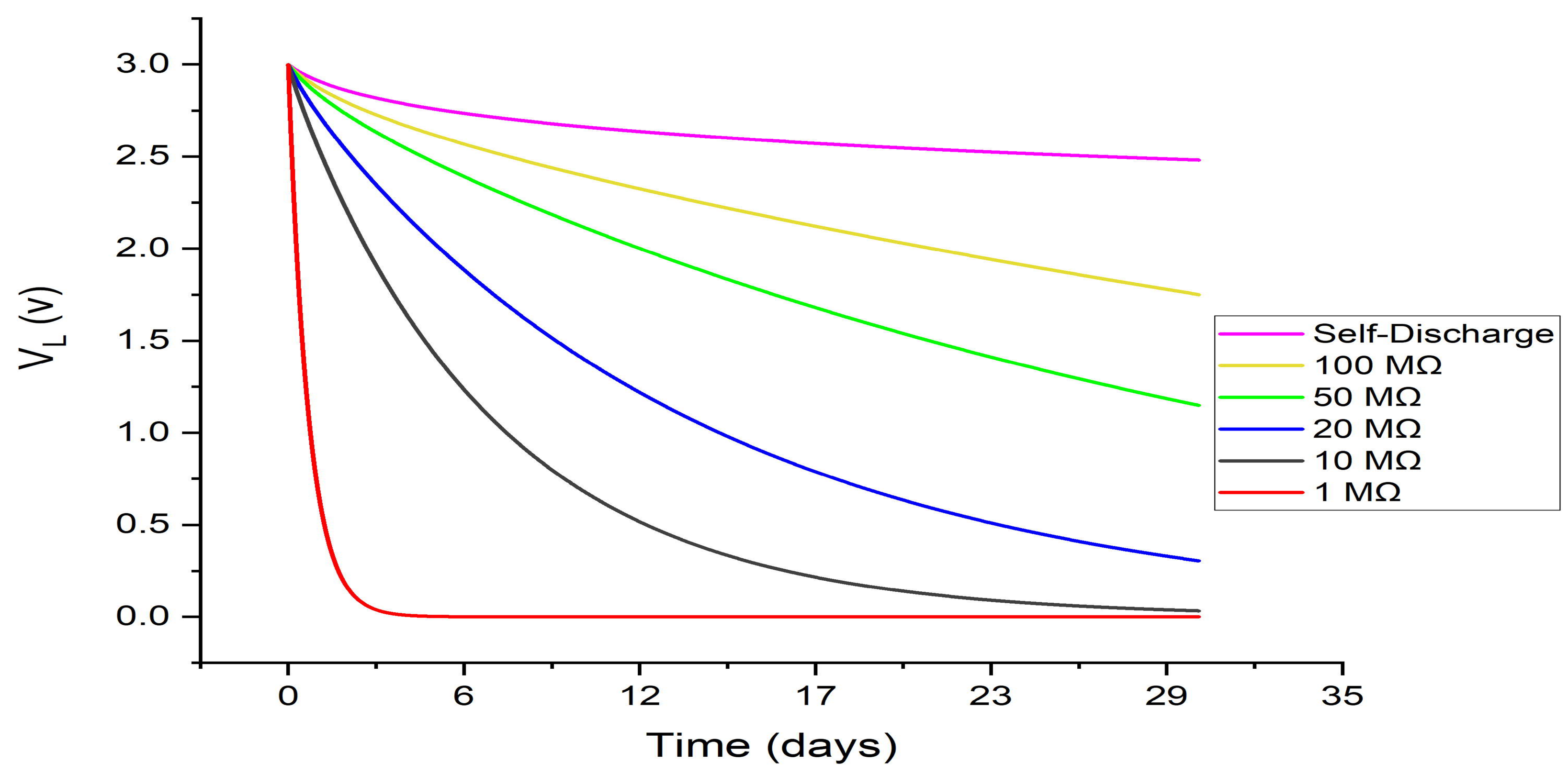


Figure 3. Simulation results of self-discharge and voltage delivered to different large loads.

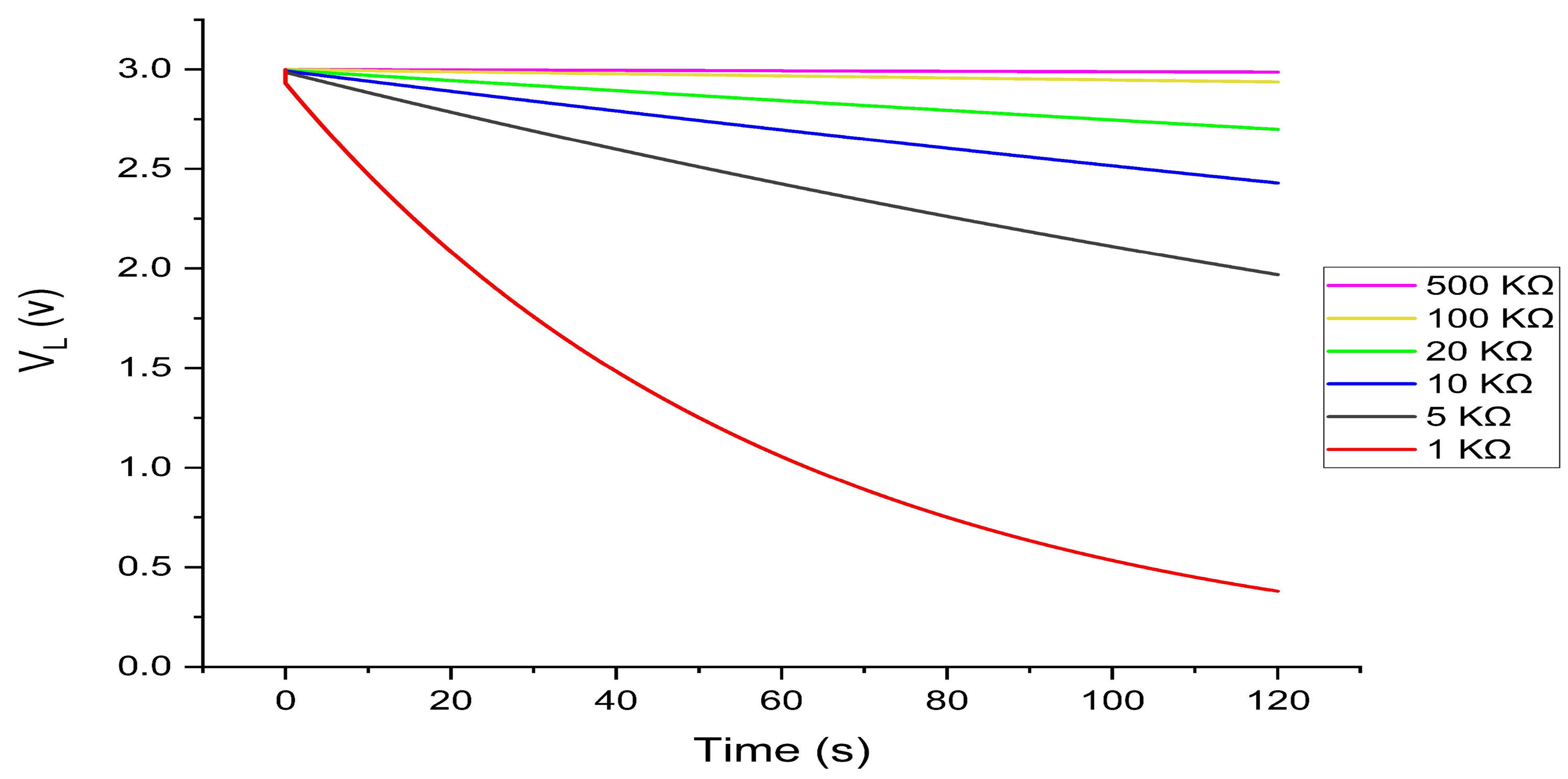


Figure 4. Simulation results of voltage delivered to different small loads.