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# Modelling of supercapacitor by using parameter estimation method for energy storage system

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**Abstract**

Researches to increase efficiency in renewable energy systems are increasing the interest in high power density (HPD) energy storage units' day by day. HPD units form a hybrid energy storage system (HESS) when used together with a high energy density (HED) energy storage system. Supercapacitors are the most frequently used storage units among HPD with their features such as low cost, low self-discharge rate and high lifecycle. When systems need high power, supercapacitors which is used to support HED units to ensure that the transmitted power's stability, efficiency, and high quality. The use of supercapacitors in HESS with the exact timing has a significant impact on its performance. For this reason, supercapacitors must be modeled correctly and well-integrated with the system. In this study, parameter estimation was made by using the data obtained from the simulation study and the supercapacitor was modeled. The supercapacitor model has been tested for charging and discharging at different currents and successful results have been obtained.

## 1. Introduction

According to the National Energy Agency, if energy consumption habits continue as they are today, it is estimated that fossil fuel consumption will be up to 1.7 times in 40 years. Under these conditions, it is predicted that the carbon emission rate will increase by 1.3 times and the global temperature will increase by 6 degrees [1]. Renewable energy sources (RES's) are seen as the greatest alternative to fossil fuels' depletion and environmental impacts [2]. It is anticipated that RES's will play a major role in the energy world of the future, as they offer sustainable and environmentally friendly energy [3]. However, in addition to these advantages, it has disadvantages such as not being continuous and insufficient in terms of power quality. Photovoltaic systems, which are one of the most preferred types among RES types, can't produce energy at night times and cloudy days. In addition, being affected by atmospheric conditions negatively affects production. Similarly, wind energy systems operate directly depending on atmospheric conditions [3]. RES are used with energy storage systems to ensure continuity, power quality and load monitoring. In order to overcome this situation, RES's are used in integration with energy storage systems [4].

Energy storage systems are divided into two categories: high energy density and high-power density. High energy density storage units can provide continuous but low power. Pump hydro energy storage (PHES), compressed air energy storage (CAES), fuel cell (FC) and majority of batteries are in this category. High power density storage units, on the other hand, can provide short-term but high power. Superconducting magnetic energy storage (SMES), supercapacitor (SC), fywheel, and high power batteries can be count in this category [5-6]. The storage technologies in the literature, when used alone, cannot meet both power density and energy density due to the limitations of their chemical and physical structures [7]. By using the advantages of these two different types together, hybrid energy storage systems (HESS) are obtained [8].

SC are the most commonly used storage systems that provide high power density [9]. SC are used as secondary or backup storage on HESS, due to their higher power density and faster dynamic response. Also SC has very long life cycle and lower self-discharge rate [10]. A comparison of different ESS types is given in Table 1. As can be seen in the Table 1, SCs have obvious advantages in terms of power density and life cycle.

**Table 1.** Properties of different type of ESS [11-12]

| Storage Type | Power Density (W/l) | Energy Density (Wh/l) | Cycle Life | Efficiency (%) | Discharge Time | Self Discharge (%) | Power Rate (kW) |
|---|---|---|---|---|---|---|---|
| **Lead Acid Battery** | 90-700 | 3-15 | 250-1500 | 75-90 | s-h | 0.1-0.3 | 0-20000 |
| **Lithium Ion Battery** | 1300-10000 | 5-100 | 600-1200 | 65-75 | min-h | 0.1-0.3 | 0-100 |
| **Flywheel** | 5000 | 20-80 | 104-107 | 80-90 | s-h | 100 | 0-250 |
| **Fuel Cell** | 0.2-20 | 600 | 103-104 | 34-44 | s-h | 0 | 0-50000 |
| **SMES** | 2600 | 6 | - | 75-80 | ms-s | 10-15 | 0-300 |
| **Supercapacitor** | 40000-120000 | 10-20 | 500000 | 85-98 | ms-min | 20-40 | 100-10000 |

A model is needed to know in advance how the SC will behave in different operating conditions [13]. Also, while using in hybrid energy storage systems, the use of SC at the right time is of great importance in terms of system performance and efficiency. To decide the right time while designing the energy management system, the exact mathematical model of the SC must be known by designer. There are different SC modelling techniques in the literature.

One of the modeling types to improve the accuracy in SC modeling is the fractional order modeling method [14]. Fractional order models include non-integer differential equations and have proven to have higher accuracy compared to equivalent circuit models with integer orders. However, the cost is high due to the high mathematical computational load [15].

In intelligence-based SC modeling, artificial intelligence, fuzzy logic or learning methods are approached against complex and non-linear structures [16-17]. With the use of large amounts of data in training, very high accuracy modeling can be performed. Since it contains a much heavier mathematical load than the fractional order modeling method, its cost is much higher.

Equivalent circuit models consisting of capacitors and resistors are designed to imitate the behavior of supercapacitors exactly. Thanks to the capacitor it contains, it can be expressed with differential equations and has the feature of easy application in this way [18-19]. In against to intelligent based methods and fractional order methods, mathematical complexity is low. Simple equivalent circuit [20], classical equivalent circuit [21], debye polarization equivalent circuit [22], zubieta equivalent circuit [23], faranda equivalent circuit [24], ladder equivalent circuit [25], voltage dependent equivalent circuit [26] methods were used in the literature on the past decade.

In this study, debye polarization equivalent circuit model was used because of its simplicity and non-complicated mathematical theory. The estimation of the model parameters was determined in the MATLAB/Simulink parameter estimation toolbox. Validation of method was proved by working under different current conditions.

## 2. Material and Method

In the literature, many equivalent circuit models have been proposed for supercapacitors. The proposed circuits include the simplest models as well as models containing many parameters such as leakage current, adsorption capacity, pulse load and slow discharge. The supercapacitor equivalent circuit models proposed in the literature are shown in Figure 1.

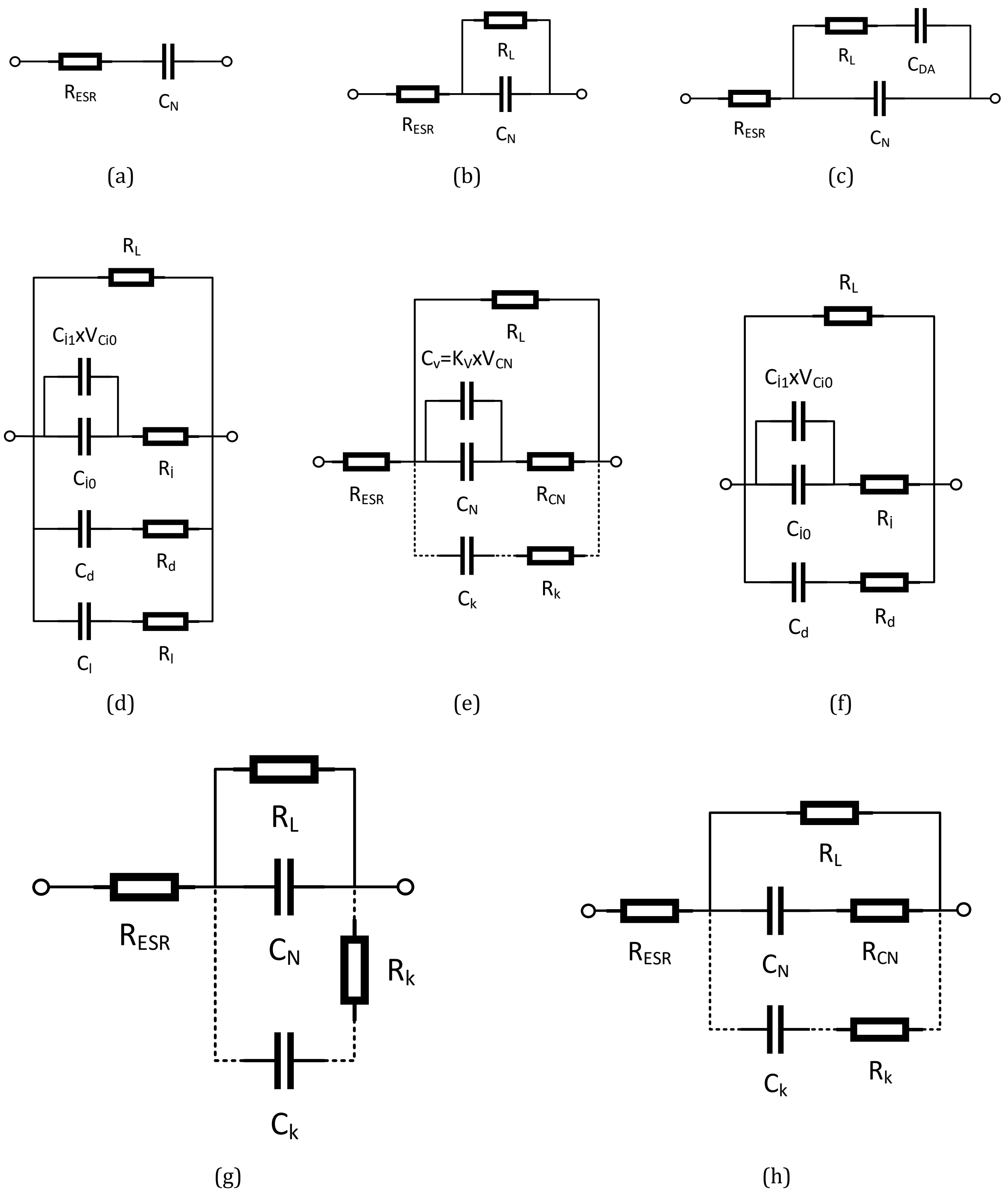


**Figure 1.** The supercapacitor equivalent circuit models. (a) Simple Equivalent Circuit, (b) Classical Equivalent Circuit, (c) Debye Polarization Equivalent Circuit, (d) Zubieta Equivalent Circuit, (e) Voltage Dependent Equivalent Circuit, (f) Faranda Equivalent Circuit, (g) Ladder Equivalent Circuit, (h) Voltage Independent Equivalent Circuit

### 2.1. Equivalent Circuit Model

In this study, supercapacitor model, given in Figure 1, is constructed using Debye polarization equivalent circuit. The Debye polarization equivalent circuit includes the leakage current and adsorption capacity parameters.

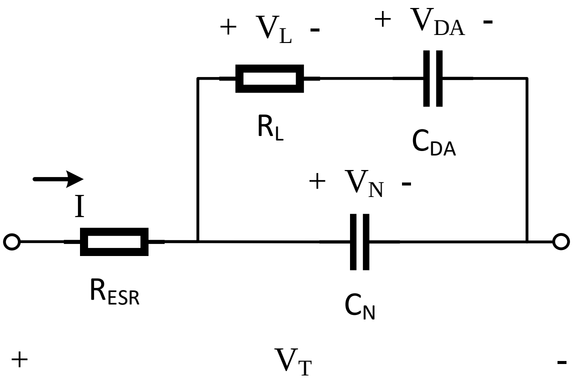


**Figure 2.** Debye polarization equivalent circuit model

where $R_{ESR}$ is the equivalent series resistor, $R_L$ is the leakage current resistance, $C_{DA}$ is the Debye adsorption capacitance, and $C_N$ is the nominal capacitance. The electrical behavior of the Debye polarization equivalent circuit model can be expressed as Equations 1-3:

$$\frac{dV_{DA}}{dt} = -\frac{1}{R_L C_{DA}} V_{DA} + \frac{1}{R_L C_{DA}} V_N \tag{1}$$

$$\frac{dV_N}{dt} = -\frac{1}{R_L C_N} V_{DA} + \frac{1}{R_L C_N} V_N - \frac{1}{C_N} I \tag{2}$$

$$V_T = V_N - IR_{ESR} \tag{3}$$

### 2.2. MATLAB/Simulink Model

The supercapacitor was modeled in MATLAB/Simulink using mathematical expressions of the Debye polarization equivalent circuit as seen in the Figure 3.

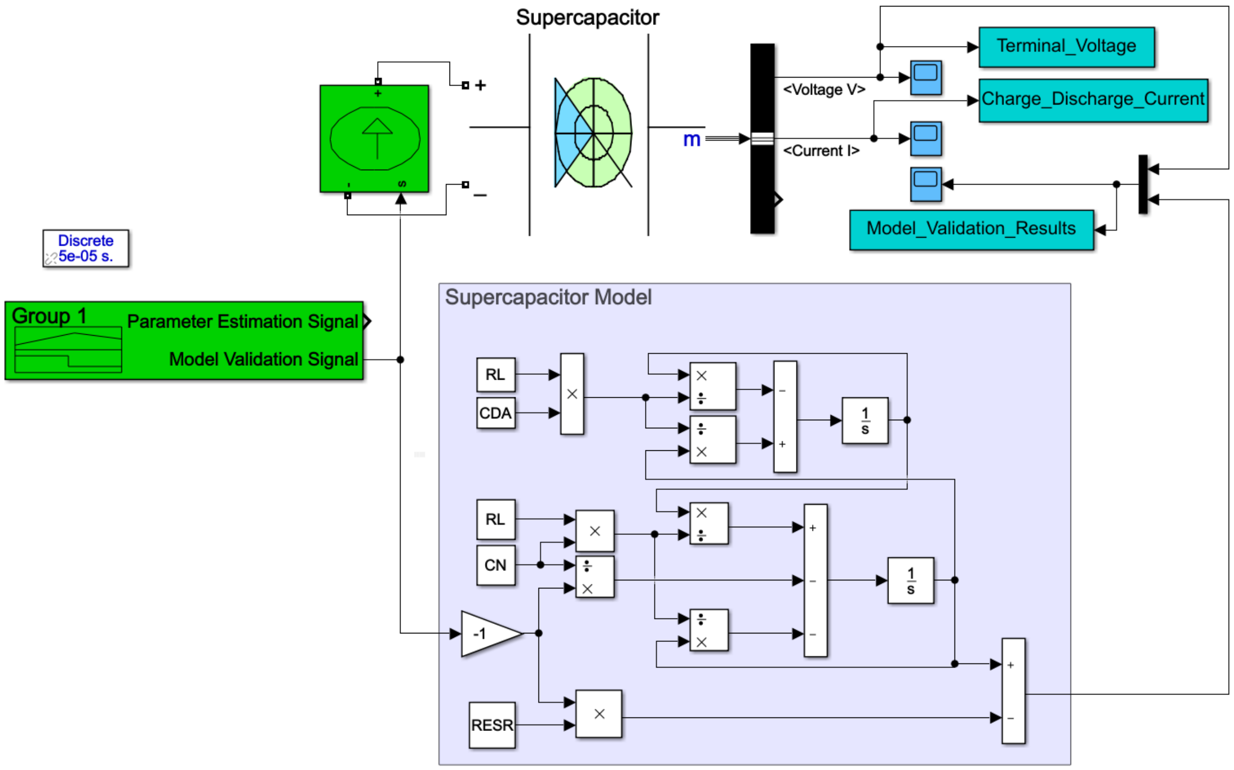


**Figure 3.** Validation of Debye polarization equivalent circuit model in MATLAB/Simulink

The Simulink model includes a real supercapacitor and a Debye polarization equivalent circuit model. The same input signal is applied to the model and the terminal voltages are observed for comparison. The model performance is verified by calculating the comparison errors of the terminal voltages.

## 3. Results

Nonlinear Least Square method based on Trust Region Reflective algorithm was used for estimation of equivalent parameters. The input current given in Figure 3(a) was applied to the circuit model for parameter estimation. Comparison of model and actual terminal voltages as a result of parameter estimation is given in Figure 3(b). The estimation result was confirmed with a mean squared error of 1.7520e-04.

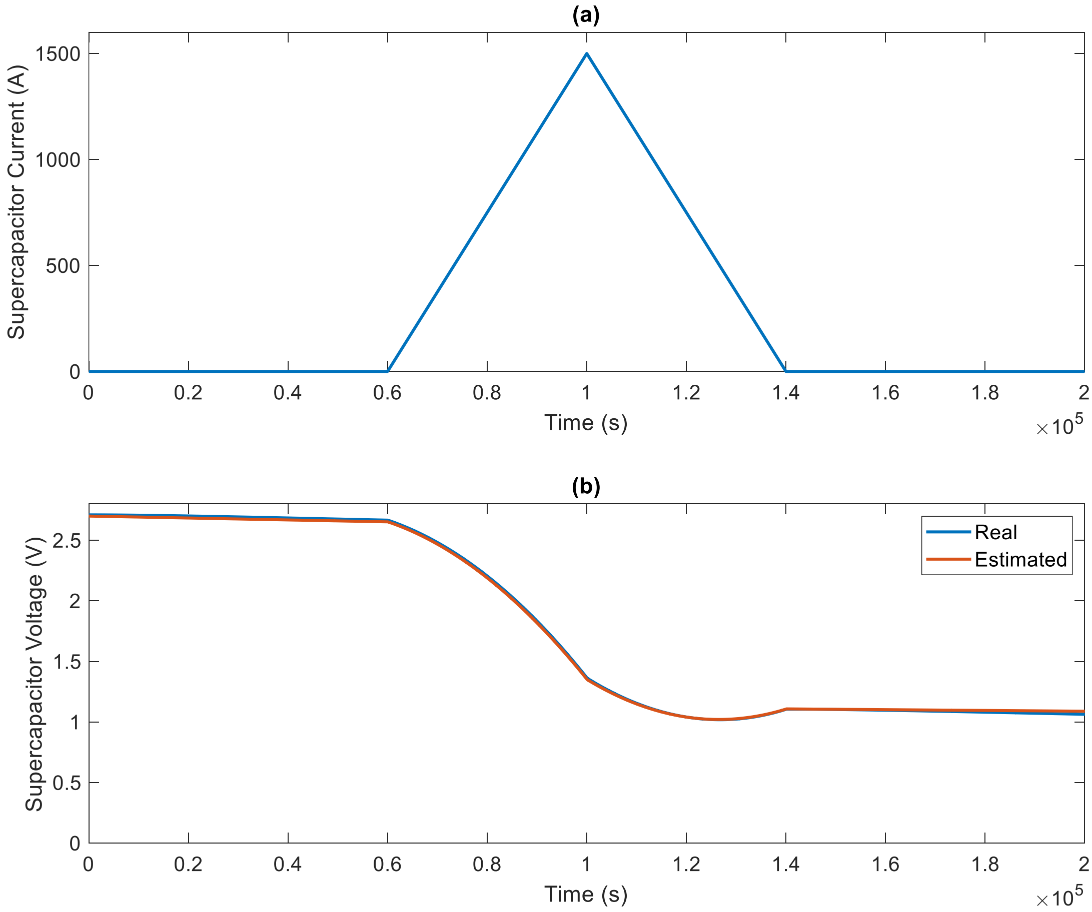


**Figure 4.** Parameter estimation results, (a) input current of Supercapacitor, (b) output voltage comparison

Different charge and discharge currents were used to validate the equivalent circuit model. The current values given as input to the model created in Figure 4(a) are given. Comparison of actual and model terminal voltage with respect to this given input matched as seen in Figure 4(b).

The mean square error was calculated for the comparison of terminal voltages. The generated supercapacitor model accuracy was verified with a mean square error of 0.0028 in the comparison.

## 4. Conclusion

In this study, supercapacitor's mathematical model was determined by debye polarization equivalent circuit. The estimation of the model parameters was determined in the MATLAB/Simulink parameter estimation toolbox with a maximum error rate of 0.17‰. The accuracy of the model has been proven with a maximum error of 0.28% under different operating currents.

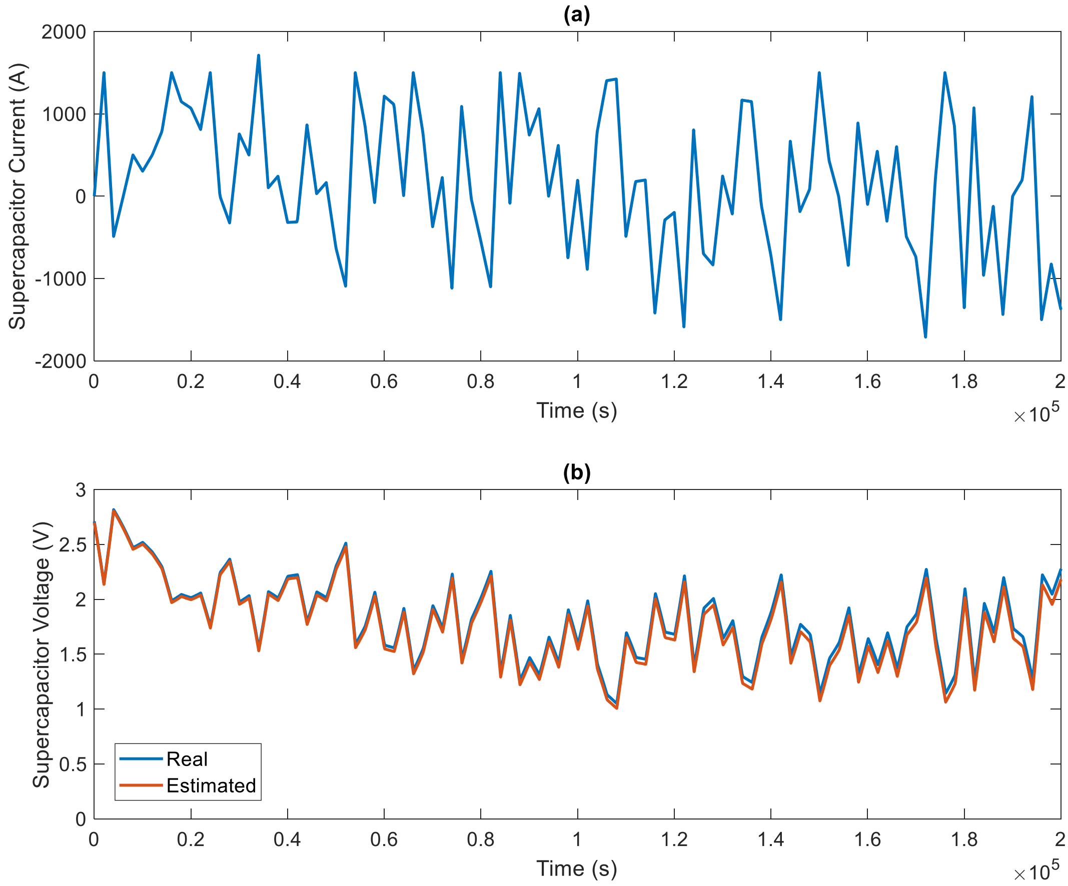


**Figure 5.** Model validation results, (a) input current of Supercapacitor, (b) output voltage comparison

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## Author contributions

**Gökhan Yüksek:** Writing-Original draft preparation, Methodology. **Yusuf Muratoğlu:** Software, Validation. **Alkan Alkaya:** Investigation, Reviewing and Editing.

## Conflicts of interest

The authors declare no conflicts of interest.

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