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Research Article

Design and Optimization of a Super Capacitor-Based High-Speed Charging System for Electric Vehicles

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Abstract *–*In this study, the design and optimization of high-speed charging systems for supercapacitor banks are investigated to meet the fast charging needs of electric vehicles. The limitations of current energy storage technologies and the requirements for fast charging of electric vehicles are addressed. While examining the advantages and energy storage potentials of supercapacitors, appropriate capacity, and voltage levels are determined in the design process to increase the charging speed. Additionally, power electronic components and control strategies are discussed to enhance the efficiency of the charging system. These components and strategies aim to optimize the fast charging process by enabling supercapacitors to be charged with maximum efficiency. The effectiveness and optimization potential of the design are evaluated and discussed through simulations conducted using the Matlab/Simulink software program. This article emphasizes the significance of supercapacitor-based high-speed charging systems in meeting the fast charging needs of electric vehicles and provides a foundation for future advancements. With the progress of electric vehicle technologies, supercapacitor-based charging systems aim to enable faster and more efficient charging, thereby further popularizing the use of electric vehicles.

Keywords – Supercapacitor; Efficiency; Energy Storage; Electric Vehicles; Fast Charging; Design; Power Electronics; Modeling; Simulation

I. INTRODUCTION

The use of fossil fuels has become a serious problem for humanity. The exhaustion of fuel reserves is expected shortly. Therefore, the concept of fuel economy has become even more important, especially for automobiles. In recent years, there has been a significant focus on electric vehicle research. Batteries are used as the primary power source in electric vehicles. In the coming years, research on battery technologies will be one of the most crucial areas of investigation. Batteries are currently the most effective method of energy storage. Lead-acid, Ni-Cd, Ni-Zn, Ni-MH, and lithium-ion batteries can be counted among the most popular battery types. However, due to their low power density, batteries cannot deliver high instantaneous currents. Overcharging and deep discharging shorten the lifespan of batteries and cause damage. Therefore, extensive research is being conducted on supercapacitors as complementary power sources to overcome the limitations of batteries. [1]

Table 1: Parameters of Energy Storage Units

Battery Type	Cycle Count	Efficiency	Power Density (W/kg)	Energy Density (Wh/kg)
Lead-acid	500-800	50-92	150-400	30-40
Lithium-ion	400-1200	80-90	300-1500	150-250
Ni-MH	500-1000	66	250-1000	30-80
Supercapacitor	1000000	90	1000-9000	0.5-30

Supercapacitors are devices that store and release energy rapidly by storing energy in the electrolyte solution between the electrodes. Unlike other storage devices, supercapacitors store energy as static electricity. Supercapacitors consist of conductive electrodes and an electrolyte solution, which is an ionic solvent. When a voltage is applied to the nanoporous electrodes, positive ions move toward the negative electrode, and negative ions move toward the positive electrode. This creates an electric field between the electrodes and allows energy to be stored as static electricity. This storage method enables supercapacitors to achieve high capacitance values.

The energy density of supercapacitors is lower than that of most batteries and fuel cells, making them less efficient for long-term storage applications. Additionally, it should be noted that high-capacity supercapacitors can be expensive. Temperature variations can adversely affect the performance of supercapacitors, especially at low temperatures, where their capacitance may decrease, requiring larger-sized supercapacitors for certain applications.

Supercapacitors are ideal for energy storage and recovery applications due to their ability to be rapidly charged and discharged. Additionally, their high power density allows them to deliver high currents and energy in a short period. Supercapacitors are also long-lasting and can withstand a high number of charge-discharge cycles. With low internal resistance, their cycle efficiencies are above 90%. They are environmentally friendly as they do not contain toxic materials and do not pose a risk of generating hazardous waste.

This study focuses on the design of using supercapacitors in small electric vehicles for urban environments, specifically studying fast-charging circuits. With the increasing use of electric vehicles in recent years, practical and affordable vehicles with low ranges have been developed for urban use. Some battery specifications of these vehicles have been investigated, and the researched battery specifications are provided in the table below. [2]

Table 2:The battery specifications of various electric cars

Parameter	Renault Twizy	Citroen Ami	RKS M5
Power(kW)	13	6	2,5
Capacity(kWh)	6,1	5,5	4,2
Charging time (hour)	3,5	3	6
Range (km)	80	75	90

The battery parameters of various electric vehicles are provided in Table 2. Based on these parameters, the characteristics of the bank to be constructed using supercapacitors would be approximately 72V and 58Ah. If 2.7V, 3000F capacitors are used, calculations show that achieving these levels would require 23 capacitors connected in series and 62 capacitors connected in parallel. Additionally, the designed battery aims to be charged much faster compared to other storage devices.

The rest of the paper is organized as follows: Section II covers the methods used in the design of a fast charger for supercapacitor banks. Section III demonstrates the simulation performance of the proposed fast charger. Section IV discusses the results of the study and provides concluding remarks and future work.

II. Materials and Method

A. *Supercapacitor Modeling*

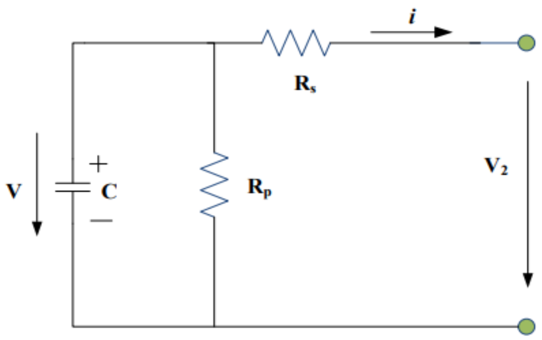

Figure 1: The basic equivalent circuit of a supercapacitor, (Feyyaz ALPSALAZ master thesis,2018)

The mathematical modeling of the supercapacitor to be used in the simulation is represented by the equivalent circuit model shown in Figure-1. Here, R_s represents the series resistance, which accounts for the charging and discharging resistance. R_s represents the parallel resistance, which represents the self-discharge losses. The equations that govern the electrical behavior of the supercapacitor is written as

$$V(t) = V_0 * e^{-\frac{t}{\tau}} \tag{1}$$

$$Q = Q_0 - \int_0^t i(t)\ dt \tag{2}$$

where $V(t)$, C, V_0, V_2, Q_0, Q are the instantaneous voltage across the supercapacitor during discharge, the capacitance of the supercapacitor, the initial voltage, the terminal voltage, the total charge, and is the remaining charge after discharge, respectively.

The total resistance and capacitance of the supercapacitor bank can be modeled by connecting individual supercapacitors in parallel and series. The total resistance and capacitance of the supercapacitor bank can be determined by combining individual supercapacitors in parallel and series.

$$R_{SK\_bank} = \frac{n_1}{n_2} * R_s \tag{3}$$

$$R_{SK\_bank} = \frac{n_2}{n_1} * C \tag{4}$$

In this equation, n_1 represents the number of capacitors connected in series, and n_2 represents the number of capacitors connected in parallel.

The test where a supercapacitor is charged or discharged with a constant current is called the Peukert test, while the test where a supercapacitor is charged or discharged with a constant power is called the Ragone test. In the Peukert discharge test, the discharge current (i) is constant, hence the terminal voltage of the supercapacitor.;

$$V_{2_{desarj}}(t) = V(t) - i.R_s = \frac{Q_0 - i.t}{C} - i.R_s \tag{5}$$

Similarly, for the constant current charging scenario, it is expressed as the terminal voltage;

$$V_{2_{sarj}}(t) = V(t) + i.R_s = \frac{i.t}{C} + i.R_s \tag{6}$$

The total energy obtained and the total energy to charge the supercapacitor are,

$$E_{discharge}(t) = \int_0^{t_d} V_{2discharge}(t) * \ i\ dt \tag{7}$$

$$E_{charge}(t) = \int_0^{t_d} V_{2charge}\ (t) * \ i\ dt \tag{8}$$

When the initial electric charge Q_0 is equal to the terminal voltage in the discharge state (V_{2od}) ;

$$V_{20d} = \frac{1}{2}\frac{Q_0}{C} + \sqrt{\frac{1}{4}\left(\frac{Q_0}{C}\right)^2 - P_2.R_s} \tag{9}$$

Similarly, when the electric charge (Q_0 is reached in the charging state, thus the terminal voltage is achieved.) ;

$$V_{20c} = \frac{1}{2}\frac{Q_0}{C} + \sqrt{\frac{1}{4}\left(\frac{Q_0}{C}\right)^2 + P_2.R_s} \tag{10}$$

When we simplify the equations, the electric charge accumulated in the capacitor can be found as

$$Q = C\ .\ V. \tag{11}$$

The energy of a capacitor is given by

$$E = \frac{1}{2}\ .\ C\ .\ V^2. \tag{12}$$

B. *Super Capacitor Fast Charging Circuit*

A fast charging circuit for a supercapacitor is simulated in MATLAB simulation environment, consisting of a 220VAC/72VAC voltage step-down transformer, a bridge rectifier, an IGBT module, capacitors, and supercapacitor banks.

a. 220Vac/72Vac Transformer

Figure 2: Voltage Step-down Transformer

The 220VAC/72VAC transformer shown in Figure-2 takes in 220-volt alternating current as input and provides 72-volt alternating current as output. By reducing the mains voltage, a more cost-effective and safer design can be achieved.

b. Bridge Rectifier

Figure 3: Bridge rectifier module

The bridge rectifier model shown in Figure-3 is a rectification bridge used to convert alternating current (AC) into direct current (DC). It has a current carrying capacity of 150 amperes and can withstand a maximum reverse voltage of 1600 volts. It consists of four diodes in a bridge configuration, which forms a complete bridge rectification circuit. This rectifier model is designed for high-power applications and industrial systems.

c. 330mF, 80V capacitor

Figure 4: Capacitor

The capacitor shown in Figure-4 can be used for energy storage and as a transient power source. After rectification, the capacitor is used to reduce fluctuations, provide a smooth DC output, and meet instantaneous power demands. The capacitor is connected in parallel in the circuit after rectification and is utilized to reduce fluctuations in the DC output voltage.

d. IGBT module

Figure 5: 1200V/200A IGBT module

The IGBT module mentioned is used in high-power and high-voltage applications. It is commonly employed in industrial motor drives, power conversion systems, alternative energy sources, and other high-performance demanding applications. This IGBT module typically has a current carrying capacity of around 200 Amperes and can withstand high voltages of up to 1200 Volts. It is often used with a heatsink for effective heat dissipation. It offers advantages such as high efficiency, fast switching characteristics, and reduced power losses.

e. 3000F, 2.7V Supercapacitor

Figure 6: Supercapacitor

The supercapacitor shown in Figure-6 is a high-capacity capacitor that excels in energy storage capacity. Supercapacitors offer advantages such as higher energy density, faster charge/discharge rates, and longer lifespan compared to traditional electrolytic capacitors. Due to these benefits, supercapacitors have been used in the depicted circuit.

C. *Cost Analysis*

Table 3: Costs of materials used

The used materials	Unit Price	Quantity used	Total Price
220V/72V transformer	15$	1	15$
Bridge Rectifier	15$	1	15$
Capacitor	275$	1	275$
IGBT module	110$	1	110$
Total:			**415$**

The total cost for the fast-charging circuit with supercapacitors has been calculated as $415. A detailed breakdown of costs is provided in Table-3.

D. *The block diagram of the circuit and simulation results*

The system shown in Figure-7 consists of an AC power source, a voltage step-down transformer, a bridge rectifier with PWM signal-controlled IGBT, an RL resistor, and a PID controller. This circuit is used to charge the supercapacitor with a constant current.

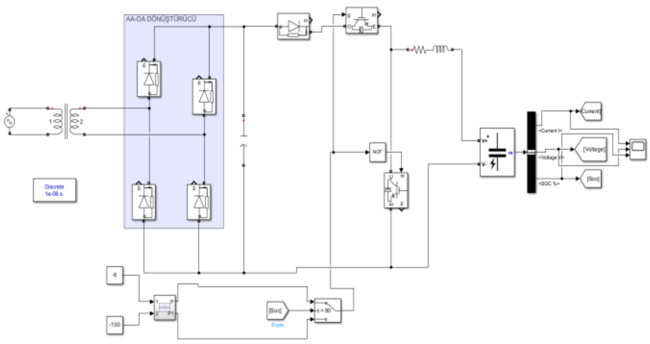

Figure 7: Fast Charging Circuit (MATLAB-Simulink)

The mains voltage is reduced to 72Vac using the voltage step-down transformer and then converted to 72Vdc by the full-wave rectification of the bridge diodes. The fluctuations in the DC voltage are mitigated using a capacitor at the output of the bridge diodes. The purpose of the diode at the capacitor output is to prevent any sudden current from flowing back from the supercapacitor to the power source.

By using voltage-controlled IGBTs and a PID controller, the current passing through the circuit is limited, and the charging process of the supercapacitor is initiated.

III. Results

The fast charging circuit in Figure 7 is tested using MATLAB-Simulink. The current limit is set to 130 amperes, and the voltage limit was adjusted to the maximum required voltage of the capacitor bank. Figure-8 shows the curves of charging a supercapacitor with a maximum charging current of 130 amperes. It can be observed that each parallel configuration of the designed supercapacitor reaches approximately 80% state of charge in about 148 seconds, starting from 0%.

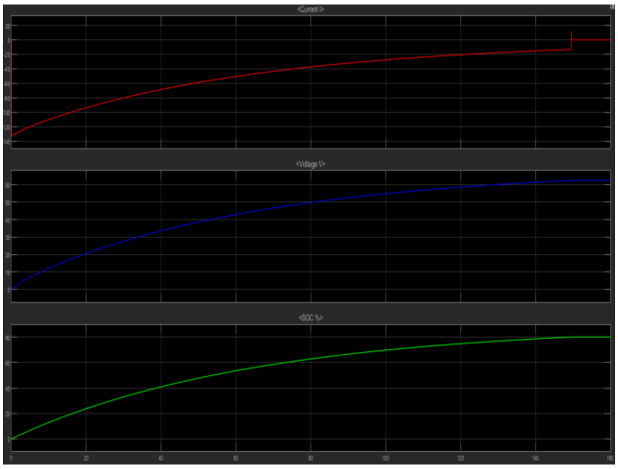

Figure 8: 0-80% charge state of super capacitor

IV. Discussion and Conclusion

This study focuses on the design and optimization of a supercapacitor-based high-speed charging system for electric vehicles. The results and findings of the study are summarized below:

Design and Optimization: Various parameters and components are considered for the design of the supercapacitor-based high-speed charging system, and an appropriate system architecture is created. Optimization techniques are also employed to maximize the system's performance.

High-Speed Charging Performance: The designed system offers high-speed charging performance to meet the fast charging needs of electric vehicles. Experiments and simulations have demonstrated that the supercapacitor-based charging system can store a large amount of energy in a short period and charge vehicles quickly. This makes the use of electric vehicles more practical and user-friendly.

Efficiency and Reliability: Analytical assessments have shown that the designed supercapacitor-based charging system provides high levels of efficiency and reliability. The system operates with low losses during energy conversion processes and ensures long-term usage. Additionally, safety measures and protection mechanisms are in place to ensure the secure and stable operation of the system.

Future Work: This study contributes significantly to the design and optimization of supercapacitor-based high-speed charging systems. Firstly, the circuit will be ensemble and tested in laboratory. Future research can focus on further improving the system's performance, grid integration, and energy management. Exploring the use of new materials and advanced control strategies also holds significant potential.

In conclusion, this study highlights the promising technology of supercapacitor-based high-speed charging systems for electric vehicles. With effective implementation of the design and optimization, the charging time and user convenience of electric vehicles can be significantly enhanced.

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