A Supercapacitor-Based Energy Storage System for Roadway Energy Harvesting Applications

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On April 12, 2017, the California Energy Commission (CEC) approved two projects totaling $2.3 million to demonstrate the feasibility, effectiveness, and economic benefits of scavenging energy from the passing of vehicles on the road using the piezoelectric technology. In both projects, the generators rely on the piezoelectric effect to harvest energy. In terms of technologies used, the two projects are similar although their power conditioning modules and end users are different. In particular, both projects use batteries in the energy storage block. While it is obvious that the piezoelectric transducers are vital components of the energy harvesting system, the impact of energy storage on various aspects of the system performance should also be carefully investigated. Supercapacitors are well-suited for piezoelectric roadway energy harvesting systems because of their long cycle life. Therefore, the objective of this project is to develop a supercapacitor-based energy storage system for piezoelectric roadway energy harvesting applications.

Study Methods

To study the charge, energy, and power characteristics of supercapacitors, three samples with different rated capacitances from different manufacturers are tested using an automated Maccor Model 4304 tester. Extensive experiments are conducted. To reveal the physical mechanisms leading to the observed charge and energy patterns, a five-branch RC ladder circuit model for supercapacitors is analyzed.

Findings

1. Peukert's Law for Supercapacitors

This work examines the applicability of Peukert's law to supercapacitors and its application in predicting the supercapacitor discharge time during a constant current discharge process. Originally developed for lead-acid batteries, Peukert's law states that the delivered charge increases when the discharge current decreases. This work reveals that this law also applies to supercapacitors when the discharge current is above a certain threshold. This pattern is due to the combined effects of the three aspects of supercapacitor physics: porous electrode structure, charge redistribution, and self-discharge. Specifically, because of the porous electrode structure, or equivalently, the distributed nature of the supercapacitor capacitance and resistance, slow branch capacitors with large time constants are accessed during the extended discharge process when a lower discharge current is applied, which results in an increase in the delivered charge. In the meantime, the unidirectional charge redistribution from slow branches to fast branches decelerates the voltage drop in the main branch with the smallest time constant and prolongs the discharge time, which also contributes to the increase in the delivered charge. The impact of self-discharge on the delivered charge is negligible when the discharge current is relatively large. If the discharge current is sufficiently low, the energy loss due to self-discharge is significant, which results in a drop in the delivered charge.

2. Dependence of Supercapacitor Peukert Constant

This work investigates the dependence of the supercapacitor Peukert constant on its terminal voltage, aging condition, and operating temperature. By conducting extensive experiments, this work reveals that the Peukert constant increases when the initial voltage of the constant current discharge process is lower, the supercapacitor is more heavily aged, or the operating temperature is lower. The physical mechanisms accounting for the Peukert constant dependence are illustrated by analyzing an RC ladder circuit model. When the supercapacitor terminal voltage is higher, the aging condition is lighter, or the operating temperature is higher, more charge is stored in the supercapacitor. Consequently, when the same discharge current is applied, the discharge time is longer and the branch capacitors are more deeply discharged. Therefore, the relaxation effects of the slow branches are reduced and the supercapacitor be-haves more like a single capacitor rather than a distributed capacitor network, which ultimately leads to a lower Peukert constant.

Supercapacitor charge, energy, and power characteristics are studied.

3. *Supercapacitor Energy Delivery Capability*

This work examines the supercapacitor energy delivery capability during a constant power discharge process, which refers to the amount of energy delivered by a supercapacitor when a constant power load is applied. Extensive constant power discharge experiments are conducted. The relationship between the delivered energy and the discharge power is examined. In the upper bound case corresponding to a fully charged supercapacitor, the delivered energy increases when the discharge power decreases if the discharge power is above a certain threshold, i.e., Peukert's law applies. When the discharge power is below the threshold, this law does not apply anymore. In the lower bound case corresponding to a partially charged supercapacitor, the delivered energy peaks at a particular discharge power.

Policy Recommendations

To exploit the supercapacitor technology, the design and implementation of power converters need to take into account the supercapacitor characteristics.

About the Author

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