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

Hengzhao Yang

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REPORT 19-03

A SUPERCAPACITOR-BASED ENERGY STORAGE SYSTEM FOR ROADWAY ENERGY HARVESTING APPLICATIONS

Hengzhao Yang

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The objective of this project is to develop a supercapacitor-based energy storage system for piezoelectric roadway energy harvesting applications. This report summarizes the author's work on supercapacitor modeling and characterization. It first discusses the applicability of Peukert's law to supercapacitors and its application in predicting the supercapacitor discharge time during a constant current discharge process. Then, it examines the dependence of the supercapacitor Peukert constant on its terminal voltage, aging condition, and operating temperature. Finally, it studies the supercapacitor energy delivery capability during a constant power discharge process. Based on the work on supercapacitor characteristics, a supercapacitor-based energy storage system is being developed.

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Mineta Transportation Institute
College of Business
San José State University
San José, CA 95192-0219

Tel: (408) 924-7560
Fax: (408) 924-7565
Email: mineta-institute@sjsu.edu

transweb.sjsu.edu

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EXECUTIVE SUMMARY

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I. INTRODUCTION

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 piezoelectric technology.[1] In both projects, the generators rely on the piezoelectric effect to harvest energy, which is the ability of certain materials to generate electric charge in response to an applied mechanical stress. In terms of technologies used, the two projects are similar, although their power conditioning modules and end users are different: road traffic as power source and piezoelectric generators as energy transducers. 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. This report summarizes the author's work at the device level, which will facilitate developing the supercapacitor-based energy storage system.

II. SUPERCAPACITOR CHARACTERISTICS

Several published studies investigate various aspects of the supercapacitor behavior.[2] This section summarizes the main results.

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.[3] Originally developed for lead-acid batteries, Peukert's law states that the delivered charge increases when the discharge current decreases.[4] This work reveals that this law also applies to supercapacitors when the discharge current is above a certain threshold. The applicability study of Peukert's law is conducted using the three supercapacitor samples with different rated capacitances from different manufacturers listed in Figure 1. The samples are tested using an automated Maccor Model 4304 tester at room temperature. For each sample, a set of constant current discharge experiments is performed when the initial voltage of the discharge process is fixed at a particular value (e.g., the rated voltage of 2.7 V) and the cutoff voltage is fixed at 0.01 V. The rated voltage is the same for the three samples and the initial voltage is approximately linearly swept: 2.7, 2, 1.35, and 0.7 V. The experiments and results are summarized as follows.

Sample	1	2	3
Manufacturer	Eaton	AVX	Maxwell
Model	HV1030-2R7106-R	SCCV60B107MRB	BCAP0350
Capacitance (F)	10	100	350
Voltage (V)	2.7	2.7	2.7

Figure 1. Supercapacitor Samples

When the initial voltage of the discharge process is 2.7 V, the relationship between the delivered charge and the discharge current for sample 2 is plotted in Figure 2, which is partitioned into two pieces: Peukert's law applies when the discharge current is above a certain threshold and does not apply anymore when the discharge current is below the threshold. Specifically, when the discharge current decreases from 10 to 0.01 A, the delivered charge increases from 250.55 to 299.41 C and Peukert's law applies. On the other hand, the delivered charge decreases from 299.41 to 292.62 C when the discharge current decreases from 0.01 to 0.0025 A and Peukert's law does not apply anymore. Similar observations hold for the other three initial voltages: 2, 1.35, and 0.7 V.

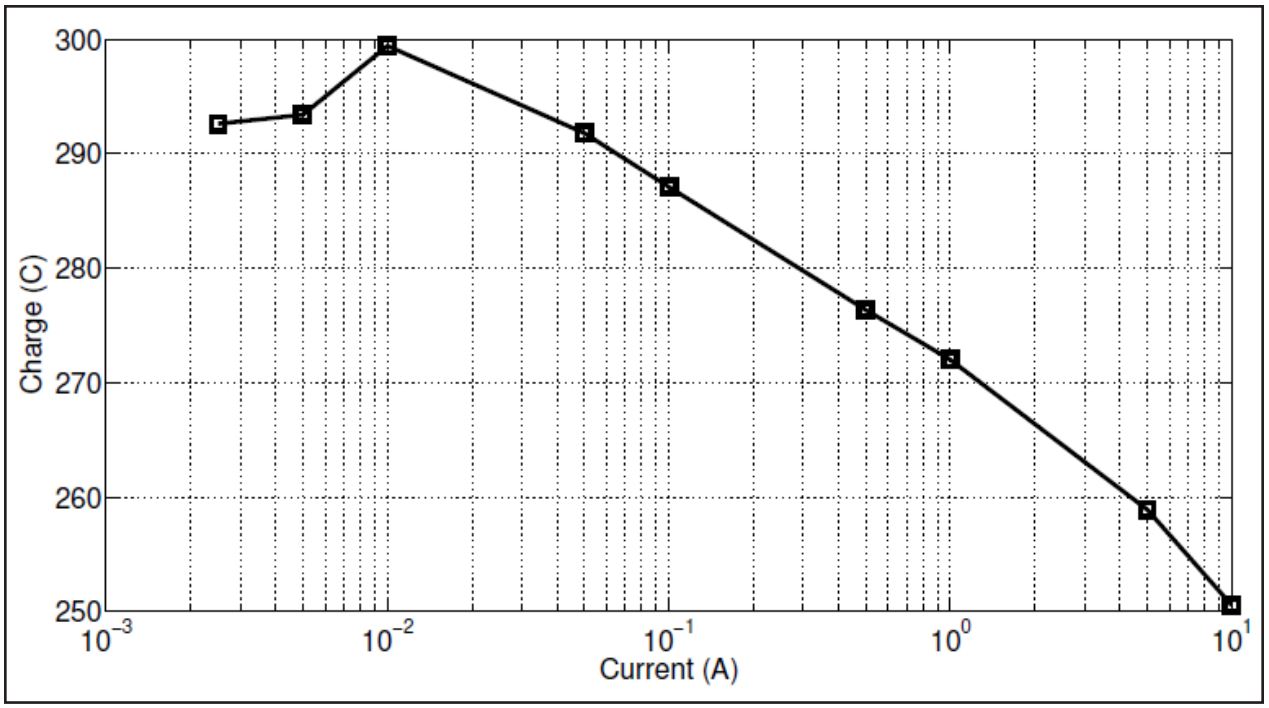

Figure 2. Relationship Between Delivered Charge and Discharge Current for Supercapacitor Sample 2 When Initial Voltage of Constant Current Discharge Process is 2.7 V

The delivered charge 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.

Based on the applicability study, this work examines two application scenarios in which Peukert's law is utilized to predict the supercapacitor discharge time during a constant current discharge process. Extensive experiments are performed using three supercapacitor samples with different rated capacitances from different manufacturers at various voltages. Experimental results show that the prediction error is significantly reduced when the supercapacitor nominal charge and the Peukert constant are properly determined and therefore demonstrate the effectiveness of Peukert's law in improving the prediction accuracy.

DEPENDENCE OF SUPERCAPACITOR PEUKERT CONSTANT

Motivated by three prior studies,[5] the dependence of the supercapacitor Peukert constant on its terminal voltage, aging condition, and operating temperature is investigated by the author in a fourth study.[6] 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. Specifically, Figure 3 plots the Peukert constant results for all the three samples when the initial voltage of the discharge process varies. Clearly, the Peukert constant increases when the voltage decreases. For sample 2, it increases from 1.023 to 1.036 when the voltage drops from 2.7 to 0.7 V. The effects of the aging condition are shown in Figure 4. The Peukert constant increases when the supercapacitor is more heavily aged. For sample 2, the Peukert constant increases from 1.023 to 1.031 because of the 3000 hours of use between S1 and S2. From S2 to S3, the Peukert constant remains unchanged because of the relatively short use time of 400 hours. Finally, the effects of the operating temperature on the Peukert constant are shown in Figure 5. In general, the Peukert constant increases when the temperature is lower although the change is moderate. For sample 2, it strictly increases from 1.029 to 1.039 when the temperature decreases from 60 to -18 ºC. For sample 1, the Peukert constant increases when the temperature decreases from 60 to -18 ºC although it flattens between 40 and 0 ºC. The temperature ranges between which the Peukert constant remains unchanged are 60–40 ºC and 23–0 ºC for sample 3.

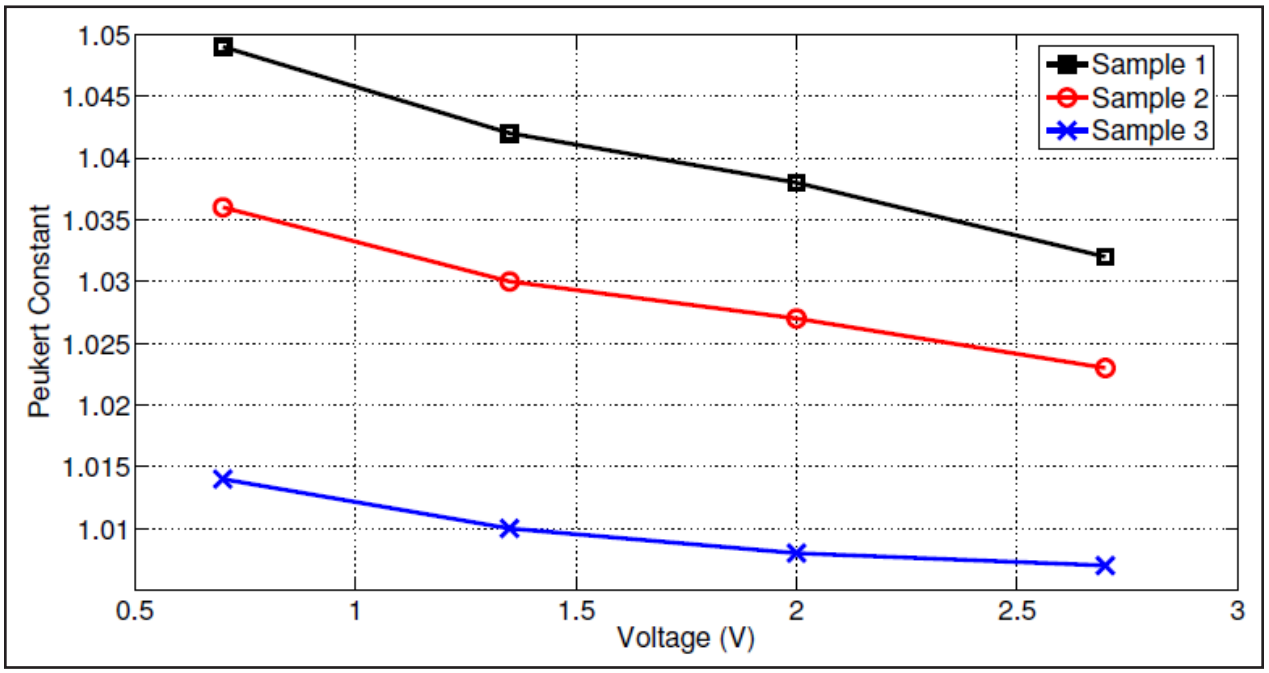

Figure 3. Dependence of Peukert Constant on Terminal Voltage for All Supercapacitor Samples

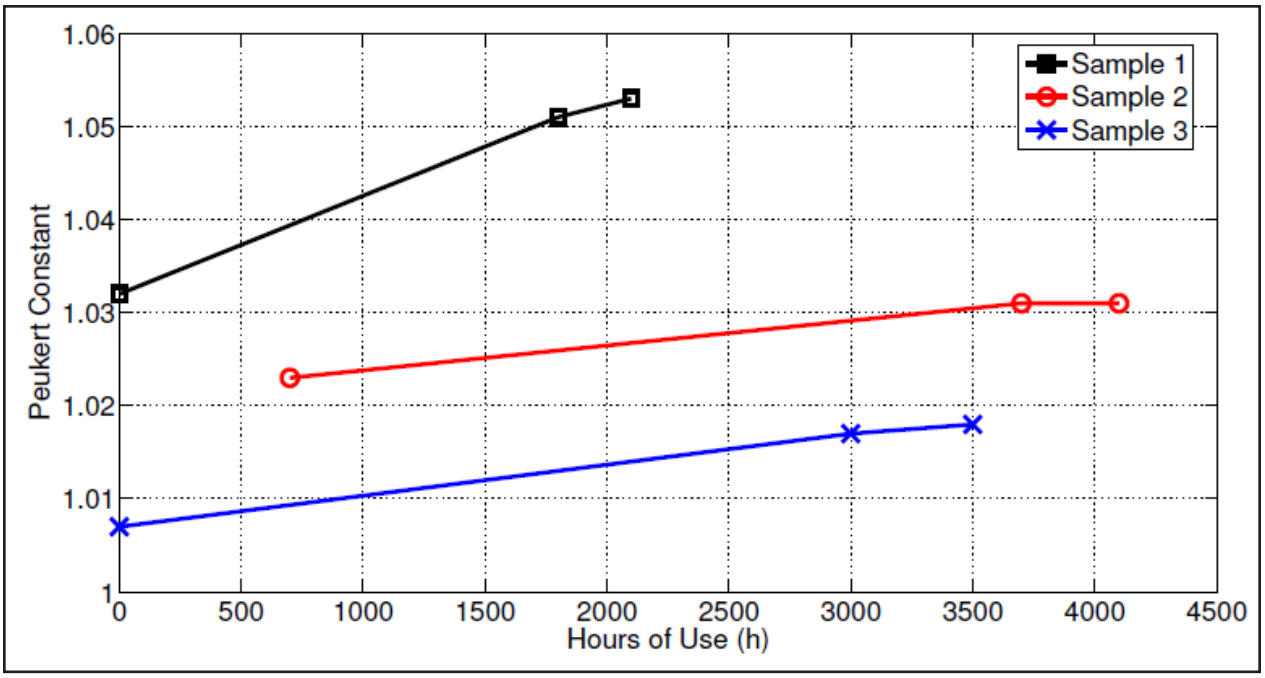

Figure 4. Dependence of Peukert Constant on Aging Condition for All Supercapacitor Samples

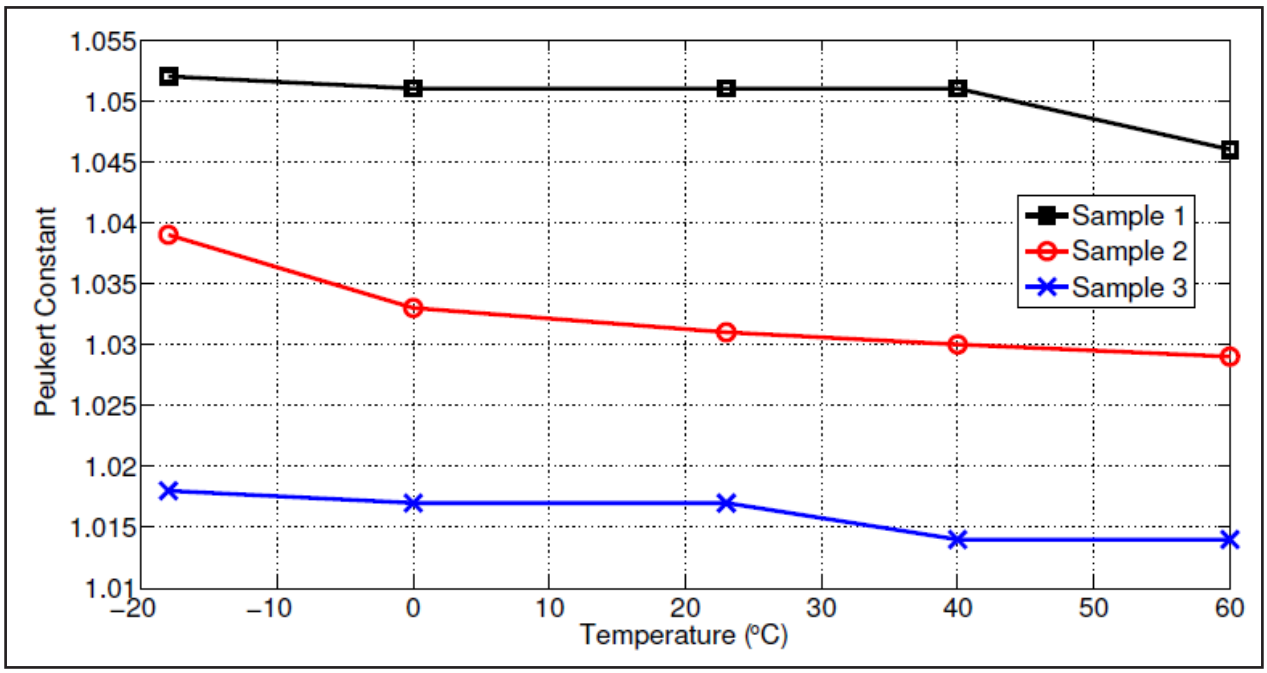

Figure 5. Dependence of Peukert Constant on Operating Temperature for All Supercapacitor Samples

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 behaves more like a single capacitor rather than a distributed capacitor network, which ultimately leads to a lower Peukert constant.

SUPERCAPACITOR ENERGY DELIVERY CAPABILITY

While prior research[7] studies the supercapacitor charge capacity, 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. For example, Figure 6 shows the relationship between the delivered energy and the discharge power for sample 2 when the initial voltage of the constant power discharge process is 2.7 V.

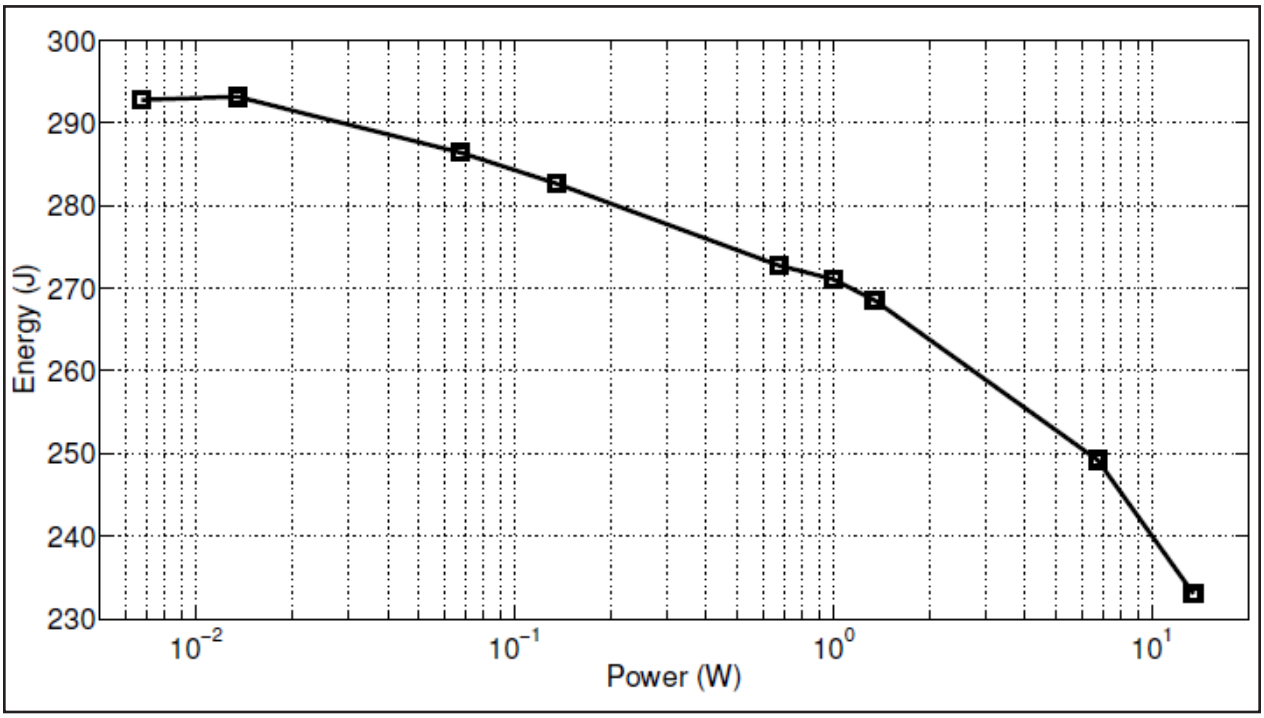

Figure 6. Upper Bound Case: Relationship Between Delivered Energy and Discharge Power for Supercapacitor Sample 2 When Initial Voltage of Constant Power Discharge Process is 2.7 V

In the lower bound case corresponding to a partially charged supercapacitor, the delivered energy peaks at a particular discharge power. For sample 2, the peaking power is 1.35 W, as shown in Figure 7. This work also compares the bounds of the delivered energy and shows that the difference is significant.

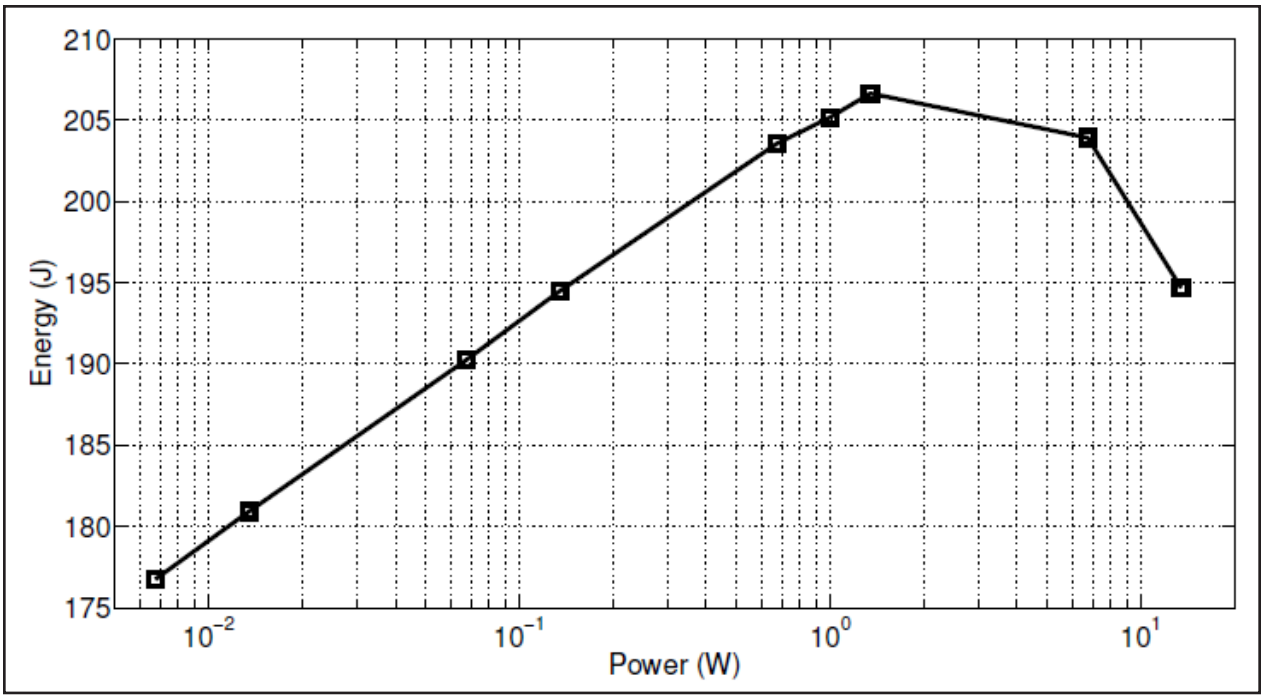

Figure 7. Lower Bound Case: Relationship Between Delivered Energy and Discharge Power for Supercapacitor Sample 2 When Initial Voltage of Constant Power Discharge Process is 2.7 V

III. CONCLUSION

Based on the device level work on the supercapacitor characteristics, the supercapacitor-based energy storage system is being prototyped using commercial off-the-shelf (COTS) components, which will be composed of five modules: power source, piezoelectric transducer, energy storage, power conditioning module, and energy consumer. In addition, this research has paved the way to develop a complete MATLAB/Simulink model that captures the characteristics of each module.

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ABOUT THE AUTHOR

HENGZHAO YANG

Hengzhao Yang received the B.S. degree in optoelectronics from Chongqing University, Chongqing, China, in 2005, the M.S. degree in microelectronics and solid-state electronics from the Shanghai Institute of Microsystem and Information Technology, Chinese Academy of Sciences, Shanghai, China, in 2008, and the Ph.D. degree in electrical and computer engineering from the Georgia Institute of Technology, Atlanta, GA, USA, in 2013.

Since 2016, he has been an Assistant Professor with the Department of Electrical Engineering at California State University, Long Beach. He was a Postdoctoral Fellow with the Georgia Institute of Technology from 2013 to 2015 and a Visiting Assistant Professor with Miami University from 2015 to 2016. His current research interests include supercapacitor modeling and characterization, design and control of energy storage systems, and power electronics for energy storage applications.

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