ACTIVE CONTROL OF A HYBRID ENERGY STORAGE MODULE (HESM) DRIVING TRANSIENT LOADS

[1]David A. Wetz, [1]Isaac J. Cohen, and [2]John M. Heinzel

∗ [1]*The University of Texas at Arlington, Arlington, Texas, United States*
[2]*Naval Surface Warfare Center – Philadelphia Division, Philadelphia, Pennsylvania, United States*
∗ Corresponding Author. Email: – wetz@uta.edu

Abstract

As the US Navy transitions to a more electrical fleet, electrical load profiles will exhibit characteristics that have not been traditionally encountered. Conventional power generation devices are unable to meet the unique demands of these load profiles and so must be bolstered with energy storage devices to alleviate transient loading. Active hybrid energy storage modules offer both high-energy and high-power density when compared to traditional energy storage devices. Fuzzy logic control offers a method of controlling such a system to meet MIL-STD-1399 requirements on a shipboard system while requiring little knowledge of the system components. This paper evaluates a fuzzy logic controller's ability to maintain an energy storage module voltage while accommodating a bi-directional transient load that is representative of one that could be seen aboard a naval vessel.

Keywords: Hybrid Energy Storage Module, Fuzzy Logic Control, Energy Storage Device, Bi-Directional DC/DC Power Conversion

1. Introduction

As the US Navy transitions to a more electric fleet, it is expected that the electrical load profiles will drastically change from what has been traditionally encountered. With recent developments in electrical propulsion, energy-based weapons, and critical mission systems, the power systems of the past will no longer be able to provide critical energy with a high level of power quality. To alleviate the limitations of the current power generation systems, such as diesel generators or gas-turbine generators, it is proposed that more energy storage devices (ESD) could be utilized to bridge the gap (Cohen, Wetz, Storm, & Heinzel, 2014). It is generally understood that ESD's either possess a high-energy density or a high-power density, but not both. Key energy storage device technologies and their respective energy and power densities are shown below in Figure 1.

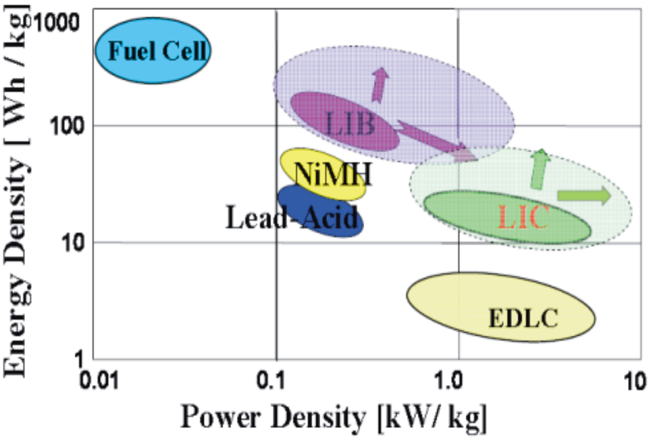

Figure 1 - Ragone Chart (JM Energy Corporation)

As is the case in most mobile power applications, volume and mass both come at a high premium and must be minimized as much as possible. One method of attempting to achieve both high-energy density and high-power density is to utilize a Hybrid Energy Storage Module (HESM) (Hoffman & Gur, 2012). HESM's combine energy dense devices such as batteries, fuel cells, or fossil fuel generators with power dense devices such as ultracapacitors to provide an optimized energy storage device that combines the best attributes of both devices.

Combining energy dense and power dense devices together is a non-trivial task that typically requires some form of power electronics for both interfacing the power onto a common bus and for managing the flow of energy both between the ESDs and into and out of the entire HESM. While implementing control over these power electronics devices is a relatively simple and well understood problem, understanding and implementing

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the overarching system level control is much more nuanced – especially when considering that a HESM would likely be inserted into a larger system where it would be expected to behave similar to other ESDs, such as batteries. US Navy shipboard power systems are designed to operate within the tolerance specifications of MIL-STD-1399 (MIL-STD 1339, 2008). The standard explicitly states what voltages, frequencies, etc., would be considered out of specification on a shipboard power system, but it does not provide the exact system components that a designer might require to derive a proper control algorithm for the HESM. If an engineer had knowledge of both the capabilities of a HESM and the requirements of a shipboard power system, this would be enough information to design a fuzzy logic control system (Cohen, Wetz, Heinzel, & Dong, 2016).

When choosing a control method for a HESM, there are many different options that could be chosen. The simplest would be simple digital logic control, also thought of as if-then-else control, which has either on or off distinction with no intermediate steps available. Fuzzy logic control (FLC) employs an if-then rule-base with mathematical fuzzification and defuzzification in order to achieve an expert response with a digital controller's speed and efficiency. In other words, it behaves exactly how a human would if they had expert knowledge on the desired behaviors of the system. Fuzzy systems typically achieve utility in assessing more conventional and less complex systems (T. J. Ross, 1995), but on occasion, FLC can be useful in a situation where highly complex systems only need approximated and rapid solutions for practical applications. FLC can be particularly useful in nonlinear systems such as this HESM which shifts between four different operation states. One key difference between crisp and fuzzy sets is their membership functions. The uniqueness of a crisp set is sacrificed for the flexibility of a fuzzy set. Fuzzy membership functions can be adjusted to maximize the utility for a particular design application. The membership function embodies the mathematical representation of membership in a set using notation Ω_i, where the functional mapping is given by μ_(Ω_i) (x)∈[0,1]. The symbol Ω_i (x) is the degree of membership of element x in fuzzy set Ω_i and μ_(Ω_i) (x) is a value on the unit interval which measures the degree to which x belongs to fuzzy set Ω_i. A primary advantage of FLC is that the solution to the problem can be cast in terms that human operators can understand, so that their experience can be used in the design of the controller (W. Pedrycz, 1993). A disadvantage is that all factors are given the same priority and it is not possible to assign a higher weight to one particular factor. This paper aims to evaluate a fuzzy logic controller in a shipboard power system setting. The next section will present the experimental setup and the final section will present the results of the experiment and offer conclusions.

2. Fuzzy Logic Control System Evaluation

To evaluate the effectiveness of a fuzzy logic controller in a shipboard power system, a table-top level battery-ultracapacitor testbed was constructed to observe the capability of the system to maintain a constant bus voltage. A bi-directional load profile was utilized that would be representative of the stochastic nature of the integration into a shipboard power system. A system diagram of this setup can be seen below in Figure 2, a schematic diagram of the battery, capacitor, and power electronic converter is shown in Figure 3, and a photograph of the setup is shown in Figure 4.

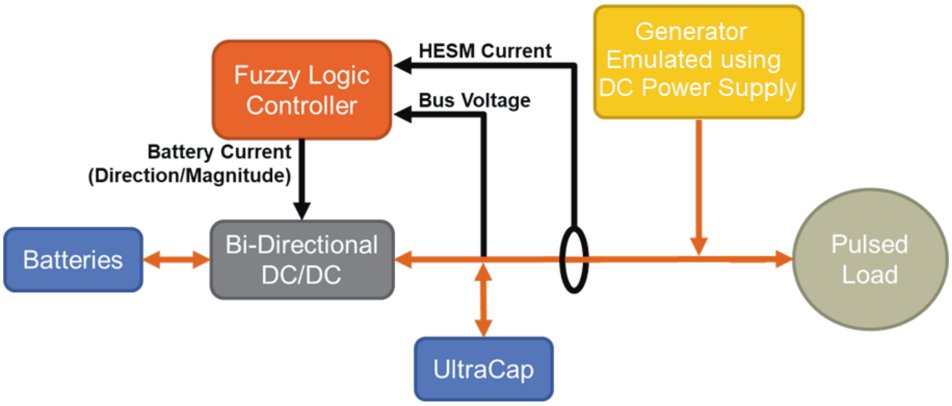

Figure 2 - System diagram of control system testbed

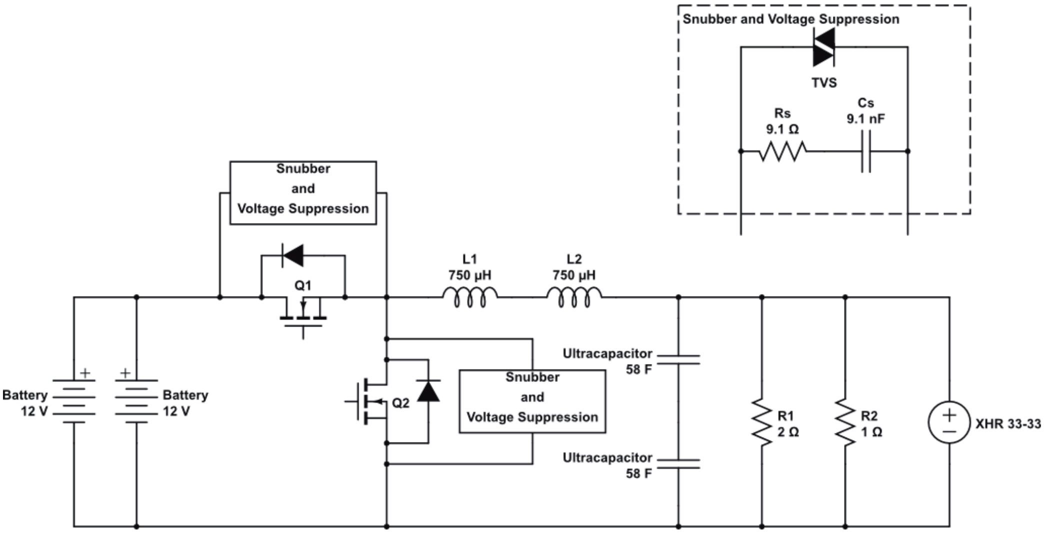

Figure 3 - Schematic of the Tabletop HESM

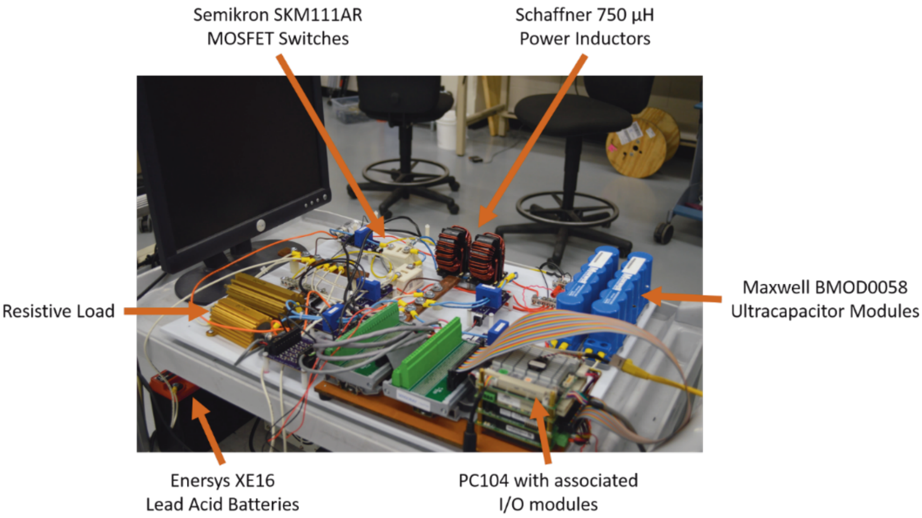

Figure 4 - Photo of the tabletop setup

Starting on the left side of Figure 3, the batteries implemented are two 12 V Enersys XE16 lead acid batteries placed in parallel. These batteries serve as the energy dense device in the HESM topology. Moving to the right, the MOSFETs used as switches in this testbed were Semikron SKM 111AR power MOSFETs, which were driven by a Semikron SKHI 21A IGBT/MOSFET driver. These MOSFETs are rated to operate at up to 50 kHz with a current rating of up to 200 A and a voltage rating of up to 100 V. It is intended to use Q1 as the switch for the buck converter and Q2 as the switch for the boost converter in the opposite direction. The body diode of Q2 serves as the freewheeling diode for the buck operation and the body diode of Q1 serves as the feed-forward diode for the boost converter. Attached in parallel to both MOSFET switches are RC snubbers and transient voltage suppression (TVS) diodes. Moving to the right, the power inductors used in this tabletop testbed were Schaffner 750 µH inductors that are rated up to 50 amps. Two of these inductors were placed in series to achieve an equivalent inductance of 1.5 mH. The next components serve as the power dense device in the HESM topology, the ultracapacitors. The two ultracapacitors used in this testbed are Maxwell BMOD0058 E016 B02 ultracapacitor modules. These modules are rated up to 16.2 V and have 58 F of capacitance. It is important to keep in mind that the load and 'generator' can be seen as a general disturbance to the HESM. With this in mind, it was decided to keep the load static and allow the power supply to change programmatically. The load is made up of simple resistors that were on hand in the laboratory, 2 Ω and 1 Ω in parallel (to keep within power ratings). The programmable power supply which mimics the generator is a Xantrex XHR 33-33 power supply which is rated to supply up to 1 kW of power with a voltage rating of up to 33 V and a current rating of up to 33 A while allowing controllability from a GPIB bus. A simple LabVIEW program was written in order to allow the user programming capabilities to run the power supply as a transient load with different current levels to represent different operational scenarios.

After constructing the tabletop, the controller for this system had to be designed. In this case, the hardware being used is a PC104 running Simulink RTOS with an analog input module and a PWM module. Simulink not only supports deploying simulations to the PC104, but also provides toolboxes for interfacing with the two modules attached to the unit. The controls implemented in this system include four PI controllers and a fuzzy logic controller. For both directions of power conversion, there are two PI controllers. The first PI controller is responsible for regulating the voltage output and produces an output that corresponds to a duty cycle between the ranges of 0-100%. The second PI controller is responsible for exerting current limit on the power conversion by pulling back the reference voltage as the current exceeds the limit. The Simulink block diagram used in this experiment can be seen in Figure 5. Looking at the diagram, it is seen that the PI controller outputs are either driven by the PI output or are held to a zero value based on the sign of the value determined by the fuzzy logic controller. This is to ensure that power only flows in one direction at a time and that the half-H switches never enter a shoot-through configuration.

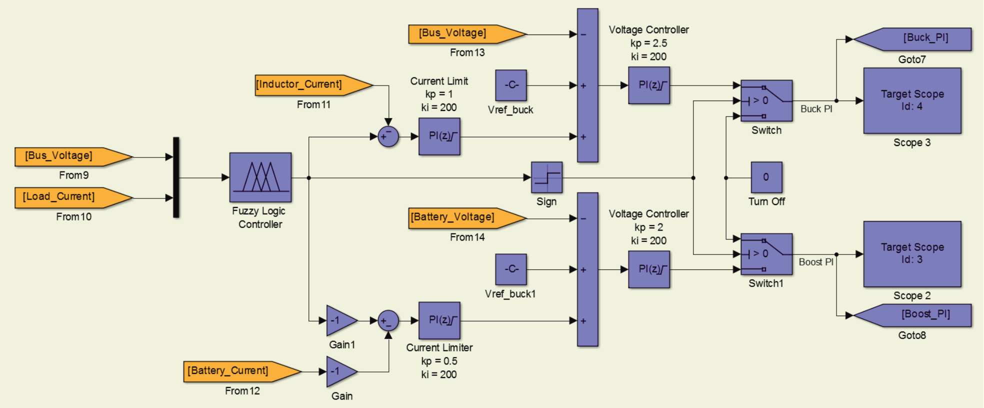

Figure 5 - Controller block diagram

Fuzzy logic control systems utilize input and output membership functions to map pertinent system values to output control values. These input and output membership functions are typically best defined using a hybridization of mathematical calculations based on system boundary conditions as well as general experimental knowledge of behavior and ideal response. The fuzzy logic membership functions can be seen in Figure 6, Figure 7, and Figure 8. These membership functions interpret the users intended performance into the processor so that it can adjust the inputs and outputs in a way that best obtains the intended results. The rule-base used is shown in Table 1 and the input to output relationship between the fuzzy membership functions can be seen in the surface plot in Figure 9. To describe the fuzzy logic inputs and outputs, they can be seen in Table 2. These linguistic values chosen in this controller along with their ranges were chosen based on both previous experience with HESM topologies and generalized system requirements. They can be tweaked as necessary to achieve a slightly different response, but these values have been shown as being capable of producing the desired results.

Table 1 - Fuzzy Logic Rule-Base

		Bus Voltage				
		Very Low	Low	Good	High	Very High
HESM Current	High In	No Flow	Low Recharge	High Recharge	High Recharge	High Recharge
	Low In	Low Discharge	No Flow	Low Recharge	High Recharge	High Recharge
	No Flow	High Discharge	Low Discharge	No Flow	Low Recharge	High Recharge
	Low Out	High Discharge	High Discharge	Low Discharge	No Flow	Low Recharge
	High Out	High Discharge	High Discharge	High Discharge	Low Discharge	No Flow

Table 2 - Fuzzy Logic Inputs and Outputs

Input/Output	**Linguistic Value**	**Range**
Input 1	"Very Low"	< ~5.7 V
Input 1	"Low"	~5.5 V – ~5.95 V
Input 1	"Good"	~5.7 V – ~6.3 V
Input 1	"High"	~6.05 V – ~6.5 V
Input 1	"Very High"	> ~6.35 V
Input 2	"High In"	< ~-8 A
Input 2	"Low In"	~-15 A – ~0 A
Input 2	"No Flow"	~-10 A – ~10 A
Input 2	"Low Out"	~0 A – ~15 A
Input 2	"High Out"	> ~9 A
Output	"High Recharge"	< ~-17 A
Output	"Low Recharge"	~-30 A – ~0 A
Output	"No Flow"	~-3 A – ~3 A
Output	"Low Discharge"	~0 A – ~14 A
Output	"High Discharge"	> ~7 A

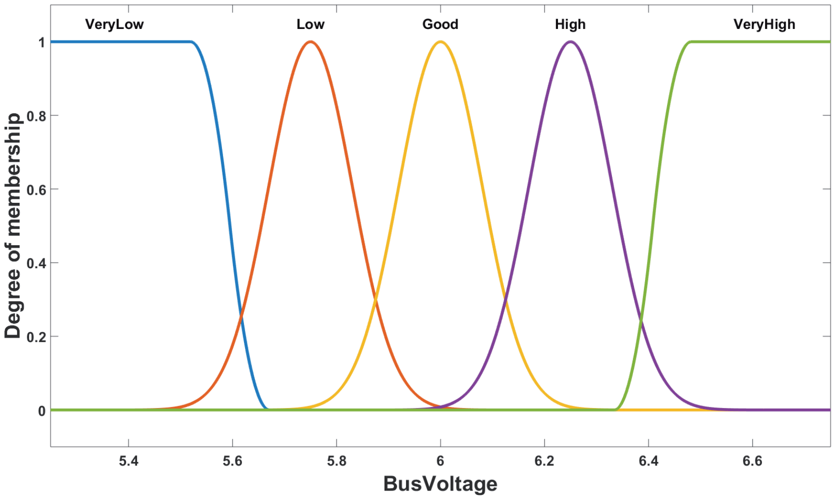

Figure 6 - First input fuzzy membership function

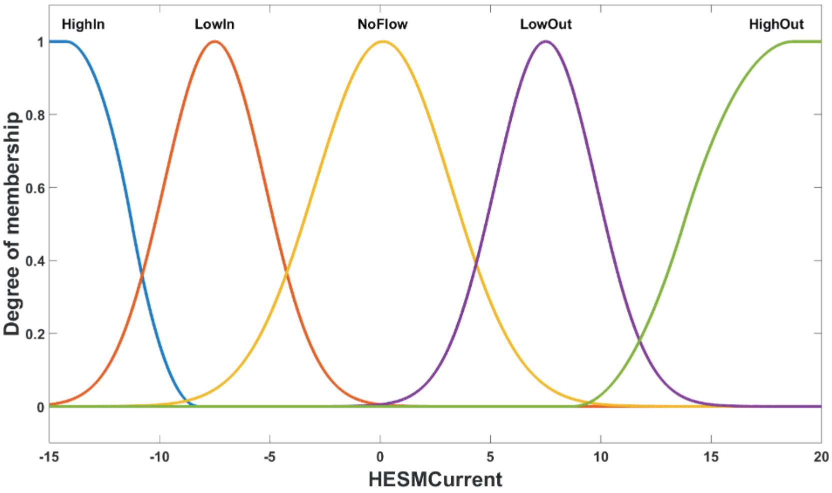

Figure 7 - Second input fuzzy membership function

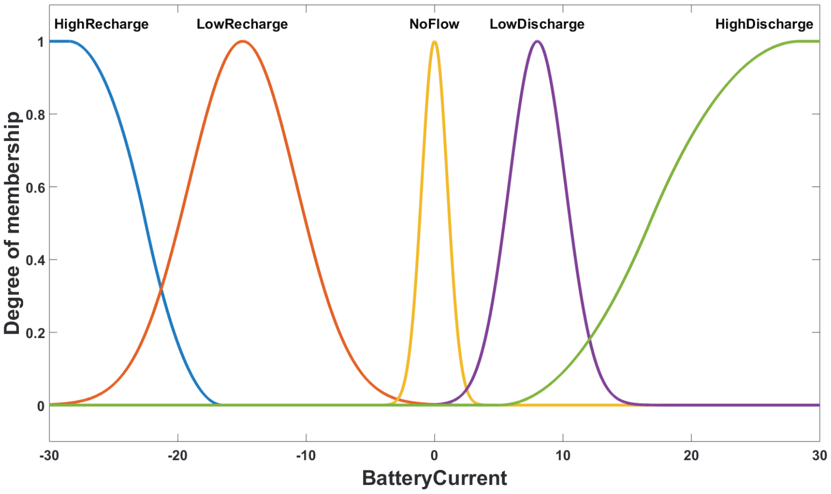

Figure 8 - Output fuzzy membership function

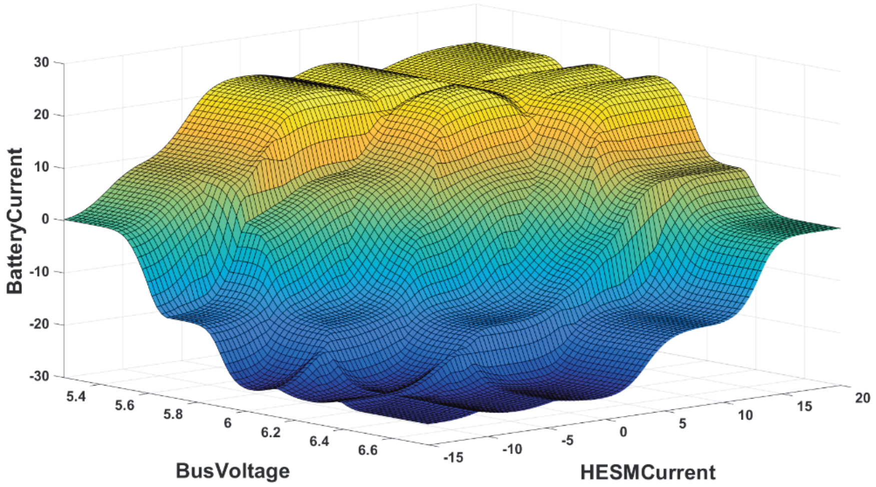

Figure 9 - Surface plot depicting the fuzzy logic control inputs vs the output

A ‘5 second on – 1 second rest’ pulsed profile, which can be interpreted as having a high power load active for 5 seconds followed by a low power load for active 1 second, is utilized here as detailed in Table 3. This pulse train is typically continued for the entirety of an experiment. The first half of the test utilizes a lower overall contribution from the programmable power supply to emulate a situation where the HESM contributes to powering the load. The second half of the test utilizes a higher overall contribution from the programmable power supply to emulate a situation where there is excess power available from the load/generation component and there is power available to be used to recharge the HESM’s batteries. This is a situation where a constant load may have dropped off for lack of need and although the pulsed load is still operating, it requires less power than the prime generator is producing.

Table 3. Load Profile for HESM Tabletop Experiment

Period	**Time**	**Value**
First half of test		
High Power	5 seconds	-9 A
Low Power	1 second	21 A
Second half of test		
High Power	5 seconds	11 A
Low Power	1 second	21 A

3. Results and Conclusion

The experimental results are shown in Figure 10 and Figure 11 below. In Figure 10, the orange voltage plot shows the output bus voltage being maintained by the HESM using fuzzy logic control. The blue voltage plot shows the charge voltage of the batteries. In Figure 11, the bi-directional current being demanded or supplied by the simulated surrounding shipboard system is shown in yellow. The blue (battery) and orange (ultracapacitor) current plots combine to make the total HESM current. These results demonstrate the capability of a fuzzy logic controller to be utilized for maintaining a bus voltage when integrating a HESM into a shipboard power system despite transient power changing in both magnitude and direction. These results are important because this concept could be applied to many different transient load buffering applications such as may be seen in many uninterruptable power supply applications, electric vehicle applications (Lu, Hess, & Edwards, 2007), and peak load shaving applications. The results demonstrate that the voltage at a point of common coupling can be maintained if actively controlled energy storage is available to buffer the bus during periods of high loading or inactivity. More research should be done to analyze the optimal energy storage sizing for a given transient loading condition and understanding where this HESM fits on a Ragone Chart when compared to more traditional energy storage devices.

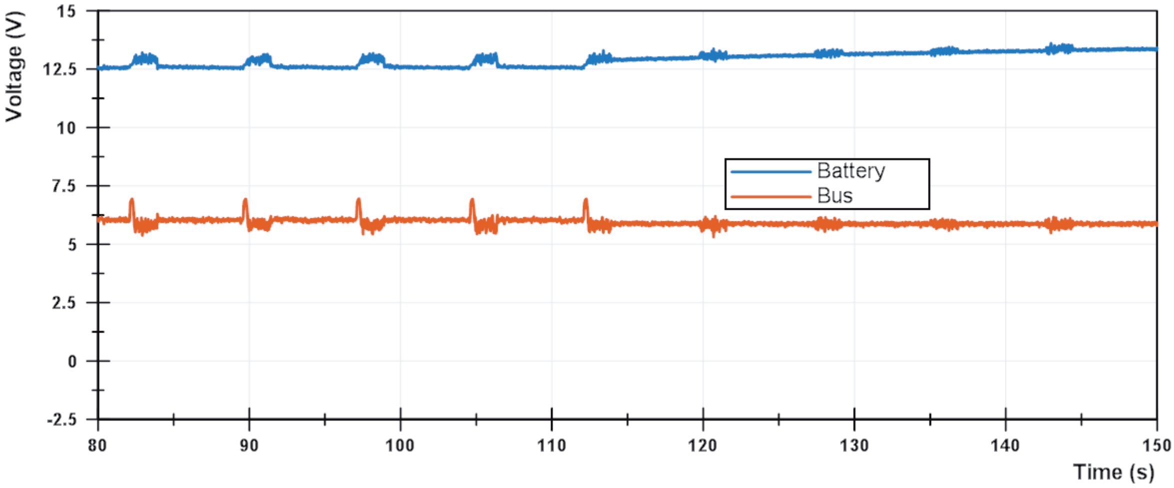

Figure 10 - Experimental Voltage Plot (Cohen, 2016)

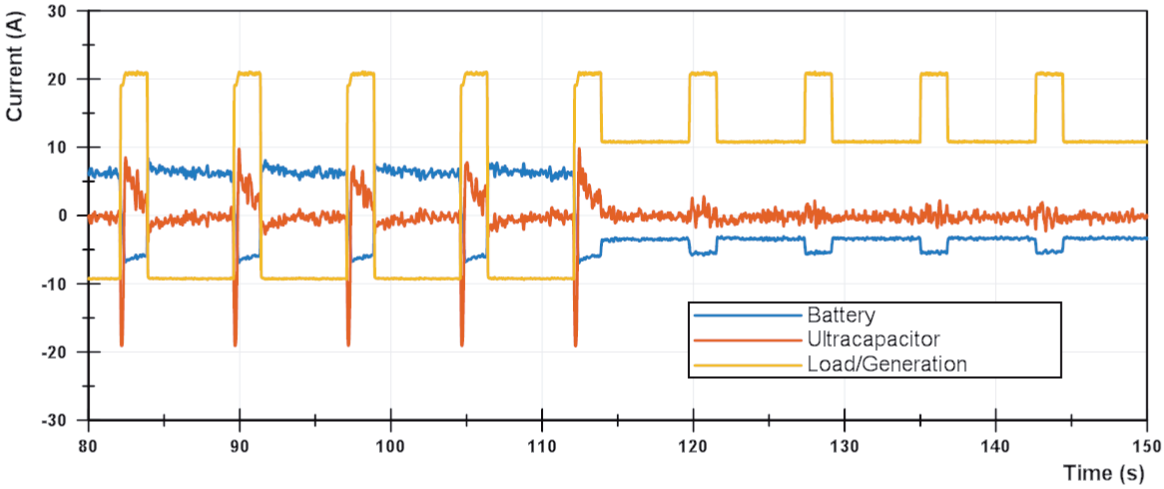

Figure 11 - Experimental Current Plot (Cohen, 2016)

4. Acknowledgment

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