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# Development and Testing of an Ultracapacitor Based Uninterruptible Power Supply (UPS) System

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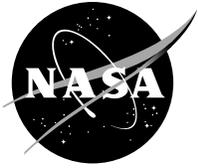
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# Development and Testing of an Ultracapacitor Based Uninterruptible Power Supply (UPS) System

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## Summary

The NASA Glenn Research Center (GRC) initiated the development and testing of an ultracapacitor based uninterruptible power supply (UPS) system as a means to provide backup power for the many critical NASA applications. A UPS system typically utilizes batteries for energy storage. The battery is the most vulnerable part of the UPS system, requiring regular maintenance and replacement. Battery performance is also extremely temperature dependent. Ultracapacitors are ideal for UPS systems where long life, maintenance free operation, and excellent low temperature performance is essential.

State of the art symmetric ultracapacitors were used for these tests. The ultracapacitors were interconnected in an innovative configuration to minimize interconnection impedance, and to provide voltage balancing. Ultracapacitors can be charged extremely rapidly and supply high current, which are essential characteristics for an effective UPS system. Charging ultracapacitors is significantly less complex than charging batteries since there is no chemical reaction occurring while charging ultracapacitors. The report concludes that the implementation of symmetric ultracapacitors in a UPS system can provide significant improvements in power system performance and reliability.

## Introduction

The NASA Glenn Research Center has a wealth of experience in ultracapacitor technology through the Hybrid Power Management (HPM) Program (Ref. 1). The Electrical and Electromagnetics Branch of the Avionics and Electrical Systems Division initiated the HPM Program for the Technology Transfer and Partnership Office. Hybrid Power Management is the innovative integration of diverse, state-of-the-art power devices in an optimal configuration for space and terrestrial applications. The appropriate application and control of the various power devices significantly improves overall system performance and efficiency. The advanced power devices include ultracapacitors and power conditioning equipment. HPM has extremely wide potential. Applications include power generation, transportation systems, biotechnology systems, and space power systems. HPM has the potential to significantly alleviate global energy concerns, improve the environment, and stimulate the economy.

One of the unique power devices being utilized by HPM for energy storage is the ultracapacitor. A capacitor is an electrical energy storage device consisting of two or more conducting electrodes separated from one another by an insulating dielectric. An ultracapacitor is an electrochemical energy storage device, which has extremely high volumetric capacitance energy due to high surface area electrodes, and very small electrode separation. Ultracapacitors have many advantages over batteries.

- Batteries can only be charged and discharged hundreds of times, and then must be replaced. Ultracapacitors can be charged and discharged over 1 million times. The long cycle life of ultracapacitors greatly improves system reliability, and reduces life-of-system costs.
- Long ultracapacitor life significantly reduces environmental impact, as ultracapacitors will probably never need to be replaced and disposed of in most applications.
- The environmentally safe components of ultracapacitors greatly reduce disposal concerns.
- High ultracapacitor power density provides high power during surges, and the ability to absorb high power during recharging. Ultracapacitors are extremely efficient in capturing recharging energy.
- Ultracapacitors are extremely rugged, reliable, and maintenance free.
- Ultracapacitors have excellent low temperature characteristics.
- Ultracapacitors provide consistent performance over time.
- Ultracapacitors promote safety, as they can easily be discharged, and left indefinitely in a safe discharged state.

Hybrid Power Management has been successfully applied to the NASA Hybrid Electric Transit Bus (HETB) project. This is a 40-ft transit bus with a unique hybrid drive. At over 37,000-lb. gross weight, this is the largest vehicle to ever use ultracapacitor energy storage. The ultracapacitor technology utilized for the HETB is being applied to satellite actuation to replace unreliable hydraulic systems. The motor and control technology utilized for the HETB is being applied to flywheel dynamometer systems.

Hybrid Power Management has been utilized to provide power for drop tower research. HPM is being considered for space missions, such as the exploration of Mars, and deep space missions, such as the exploration of Europa.

Through the NASA Glenn Research Center Technology Transfer and Partnership Office, HPM is being applied to power generation, transportation, safety, and biotechnology systems. Some specific examples include photovoltaic power generation, electric vehicles, and safety systems.

An UPS is an electrical apparatus that provides emergency power to a load when the input power source, typically the utility power system, fails. The UPS provides near instantaneous protection from power interruptions by means of a backup energy storage system and the associated electronic circuitry. The UPS typically provides power for a few minutes to permit an orderly shutdown of the protected equipment.

Uninterruptible power supply systems typically use batteries for energy storage, although flywheels and fuel cells have also been used successfully. All of these energy storage systems require regular maintenance and replacement, which is not the case with ultracapacitor energy storage, making it an ideal candidate for UPS systems.

## Test Objectives

Testing of the prototype ultracapacitor UPS system was performed at the NASA Glenn Research Center. Of particular interest is the performance of an ultracapacitor bank in conjunction with an UPS and a dc power supply for charging the ultracapacitors.

## Test Hardware Description

The UPS utilized for these tests is an efficient, compact, maintenance free, rack mount, pure sine wave inverter unit. The UPS is shown in Figure 1 and described in detail in Appendix A. The UPS provides a continuous output power up to 1700 W with a surge rating of 1870 W for up to 1 min at a nominal output voltage of 115 Vac.

The ultracapacitor energy storage system tested in conjunction with the UPS is rated at 5.8 Farads. This is a bank of ten symmetric ultracapacitor modules, and is shown in Figure 2 and described in detail in Appendix A. An individual ultracapacitor module is shown in Figure 3 and described in detail in Appendix A. Each module is actively balanced utilizing a linear voltage balancing technique, in which the cell-to-cell leakage is dependent upon the imbalance of the individual cells. This state-of-the-art technology not only has much longer life than conventional batteries, but also provides much higher current capacity than batteries. Ultracapacitors are reliable, maintenance free, and have excellent low temperature characteristics.



Figure 1.—Complete Prototype Ultracapacitor UPS System.

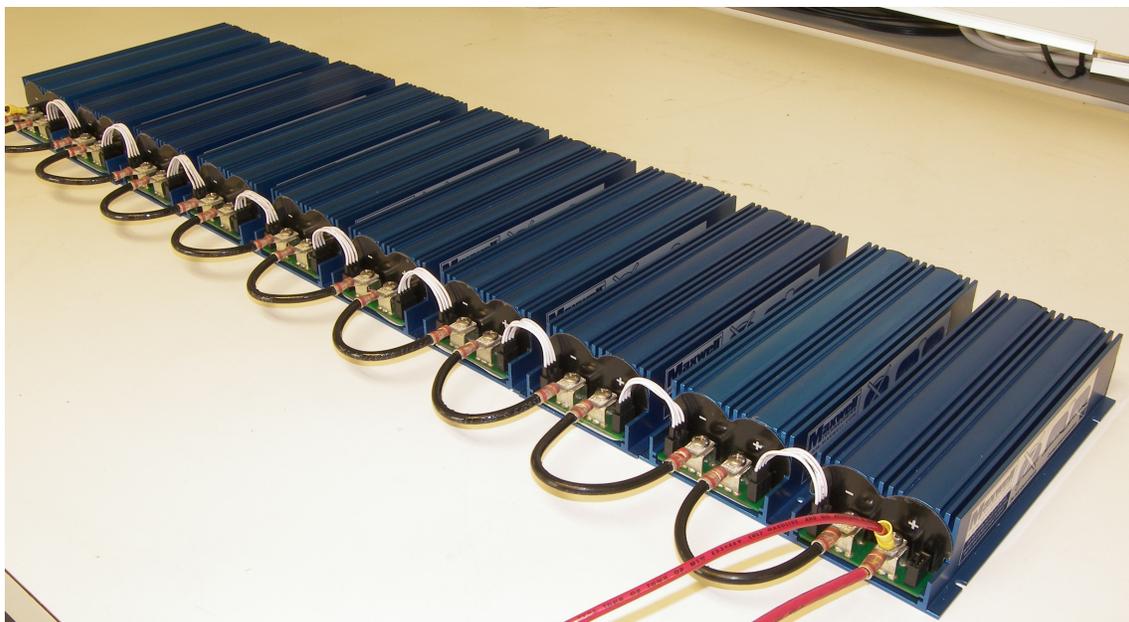


Figure 2.—Bank of Ten Ultracapacitors for the Prototype UPS System.



Figure 3.—Single Ultracapacitor for the Prototype UPS System.

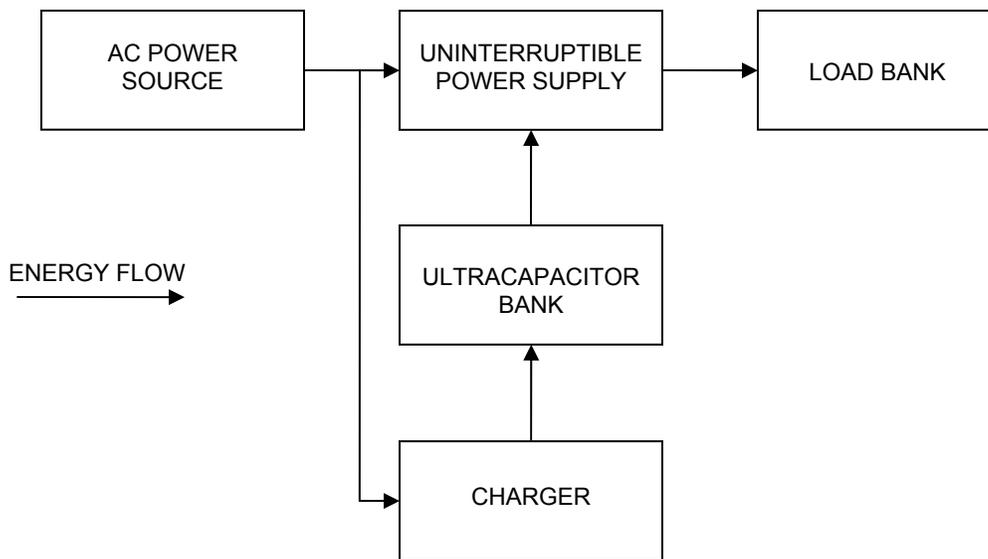


Figure 4.—Ultracapacitor UPS System Test Configuration Block Diagram.

The ultracapacitors are charged by a dc power supply. The power supply can provide up to 300 Vdc at 4 A. A constant voltage, constant current power supply was selected for this application. The power supply is shown in Figure 1 and described in detail in Appendix A.

A block diagram of the UPS system is shown in Figure 4.

## Instrumentation

The UPS, ultracapacitor bank, charger, and load bank were instrumented to measure UPS performance, ultracapacitor performance, and charger performance. Data from the UPS, ultracapacitor bank, charger, and load bank were sent to a digital data acquisition system, sampled continuously, and stored on a PC. Data channels measured UPS voltage and current, ultracapacitor voltage and current, charger voltage and current, and load bank voltage and current. Ambient temperature was also measured. The instrumentation configuration is described in Appendix B.

## Test Procedures

The tests described in this report were conducted at the NASA Glenn Research Center in Cleveland, Ohio. A description of the tests is given in Appendix C. The tests were conducted in accordance with the test matrix provided in Appendix D.

## Test Results

### System Performance

Seven tests were conducted to determine ultracapacitor UPS system performance, per Table 1:

TABLE 1.—PERFORMANCE TESTS CONDUCTED ON THE ULTRACAPACITOR UPS SYSTEM

Test number	Energy source	Ultracapacitor bank	Load	Test mode
1	dc Power supply	Series of 10	N/A	Charge test
2	Ultracapacitors	Series of 10	None	Self discharge test
3	Ultracapacitors	Series of 10	None	Balance test
4	ac Source	Series of 10	99.1 $\Omega$	Load test
5	Ultracapacitors	Series of 10	99.1 $\Omega$	Load test
6	ac Source	Series of 10	99.1 $\Omega$	UPS efficiency
7	Ultracapacitors	Series of 10	99.1 $\Omega$ s	UPS efficiency

Plots have been included in Appendix E for the various system tests:

- a. Charging test results
- b. Load test results
- c. Self discharge test results

A summary of the test results is shown in Table 2 at the end of this section.

#### Charge Test

The bank of ten ultracapacitors was charged to 134.0 Vdc at a current limit of 4 A with a constant voltage, constant current dc power supply. The ultracapacitors were completely discharged prior to the test. The time to charge the bank of ultracapacitors under these conditions was 180 sec. A dc power supply with greater current capacity could be used to charge the bank of ultracapacitors faster, although the ultracapacitors are limited to a maximum current of 1,500 A. Higher charging current also results in higher ultracapacitor temperature, which is limited to 65 °C. Higher charging current also requires larger conductors and connectors to handle the higher current levels. A dc power supply with a lower current capacity could be used to charge the bank of ultracapacitors at a slower rate. Such a power supply would be smaller, less expensive, and produce less heat.

The 134.0 Vdc, 4 A power supply efficiency was quite low when the completely discharged ultracapacitor bank charging was initiated, and increased as the ultracapacitor bank voltage increased. The dc power supply average efficiency was 41.1 percent and the maximum efficiency was 59.2 percent.

The voltage of each of the ten ultracapacitors was monitored individually during the charge test as a balance test. The average voltage was 13.40 V, the minimum voltage was 13.26 V, and the maximum voltage was 13.82 V.

Charge and balance test results are indicated in Table 2.

#### Self Discharge Test

The self discharge of the bank of ten ultracapacitors was determined at no load with the ultracapacitors precharged to 134.0 V. The bank discharged to the minimum operating voltage of the UPS, which is 90 V, in 45.5 hr.

Self discharge results are indicated in Table 2.

## Load Test

The UPS was tested with the output set to 115.2 Vac. The load was 99.1  $\Omega$ . The UPS system was first operated with ac power and the bank of ten ultracapacitors precharged to 134.0 Vdc, which is the maximum operating voltage of the UPS. The efficiency of the ac operation was determined to be an average of 96.6 percent, and very constant under all operating conditions. The ac power system was then switched off, and the UPS system automatically switched to dc operation from the bank of ultracapacitors. The efficiency of the UPS system with the dc power source was determined to be an average of 75.8 percent and very constant under all operating conditions. The operating time for the UPS with the bank of ultracapacitors was 170.3 sec, limited by the voltage of the ultracapacitors. Increased capacitance of the ultracapacitor bank, easily accomplished through paralleling additional ultracapacitors, would increase the UPS operating time. Expanding the operating voltage range of the UPS system would also increase the UPS operating time.

Discharge times are indicated in Table 2.

## Summary

An overall summary of the UPS testing is shown in Table 2.

TABLE 2.—SUMMARY OF TEST RESULTS FOR THE ULTRACAPACITOR UPS SYSTEM

Parameter	Configuration	Test conditions	Test results	Remarks
<b>Charge test</b>				
Time	DC power supply and bank of ten ultracapacitors	134.0 Vdc at 4 A output	180 sec	Ultracapacitors completely discharged to start
Efficiency	AC power supply and bank of ten ultracapacitors	120 Vac input	41.1% Av 59.2% Max	Power supply efficiency
<b>AC source load test</b>				
Efficiency	120 Vac input	99.1 $\Omega$ load	96.6% Av	
<b>DC source load test</b>				
Efficiency	Bank of ten ultracapacitors	99.1 $\Omega$ load	75.8% Av	Ultracapacitors precharged to 134.0 Vdc and discharged to 90 Vdc
Time	Bank of ten ultracapacitors	99.1 $\Omega$ load	170.3 sec	Ultracapacitors discharged to 90 Vdc
<b>Self discharge test</b>				
Time	Bank of ten ultracapacitors	No load	45.5 hrs	134.0 to 90 Vdc
<b>Balance test</b>				
Average voltage Minimum voltage Maximum voltage	Bank of ten ultracapacitors	No load	13.40 Vdc 13.26 Vdc 13.82 Vdc	Ultracapacitors precharged to 134.0 Vdc

## Concluding Remarks

The prototype ultracapacitor UPS system has been tested very successfully with symmetric ultracapacitor energy storage. The primary focus of this report is the test results with symmetric ultracapacitor energy storage. The UPS, nor the energy storage system, nor the charging system, exhibited any problems under the rigorous test conditions that it was exposed to. The performance of the UPS and the ultracapacitor bank proved to be excellent.

The bank of ten ultracapacitor modules was assembled to provide a maximum voltage rating of 150.0 V to match the maximum input voltage rating of the UPS. The modules were connected in a fashion to minimize interconnection impedance. Each module is actively balanced using a linear voltage-balancing technique. The bank of ultracapacitors were completely discharged, and then charged to 134.0 Vdc, which is the maximum operating voltage of the UPS, with a constant voltage constant current power supply set to 4 A. The bank of ultracapacitors charged in 180 sec under these conditions. The efficiency of the charger was an average of 41.1 percent with a maximum of 59.2 percent. Ultracapacitors can typically be charged much more efficiently than batteries because there is no chemical reaction taking place when charging ultracapacitors. A much more efficient charger can be developed for this application with existing technology to provide a charging efficiency exceeding 90 percent. The bank of ultracapacitors balanced extremely well with an average voltage of 13.40 V, a minimum voltage of 13.26 V, and a maximum voltage of 13.82 V. The bank of ultracapacitors were charged and discharged numerous times without failure.

The self discharge of the bank of ten ultracapacitors was determined at no load with the ultracapacitors precharged to 134.0 V. The bank discharged to the minimum operating voltage of the UPS, which is 90 V, in 45.5 hr. In typical UPS systems, the ultracapacitors would be continuously charged to 134.0 V to provide the maximum UPS operating time. The low self discharge of the ultracapacitors minimizes the power requirement for maintaining the ultracapacitor charge.

The UPS was tested with the output set to 115.2 Vac with a load of 99.1  $\Omega$ . The UPS system was first operated with ac power and the bank of ten ultracapacitors precharged to 134.0 Vdc. The efficiency of the ac operation was determined to be an average of 96.6 percent, and very constant under all operating conditions. The ac power system was then switched off, and the UPS system automatically switched to dc operation from the bank of ultracapacitors. The efficiency of the UPS system with the dc power source was determined to be an average of 75.8 percent and very constant under all operating conditions. The operating time for the UPS with the bank of ultracapacitors was 170.3 sec, limited by the voltage of the ultracapacitors. This operating time is adequate for most UPS applications. Increased capacitance of the ultracapacitor bank, easily accomplished through paralleling additional ultracapacitors, would increase the UPS operating time. Expanding the operating voltage range of the UPS system would also increase operating time.

Ultracapacitors are ideal energy storage system for UPS systems due to their exceptionally long cycle life, high reliability, high efficiency, high power density, ease of charging, and excellent low temperature performance.

## References

1. Eichenberg, D.J., "Hybrid Power Management (HPM)," NASA Technical Memorandum 2007-214913, August 2007.

## Appendix A.—Equipment Under Test Summary Data Sheet

### 1.0 Uninterruptible Power Supply (UPS)—Schaefer Model AEP-U2000R-1101

1.1	Continuous output power	1700 W (2 KVA)
1.2	Surge rating	1870 W for 1 min
1.3	Input voltage	90 to 140 Vdc
1.4	Output voltage regulation	100 to 120 Vac RMS $\pm 2\%$
1.5	Frequency (Switch selectable)	50/60 Hz $\pm 0.05\%$
1.6	Peak output current	25 A
1.7	Low voltage alarm	95 Vdc
1.8	High voltage alarm	135 Vdc
1.9	Low voltage shutdown	90 Vdc
1.10	Full load efficiency	90%
1.11	Output waveform	<3% THD sine wave (resistive load)
1.12	Output voltage range	100 to 120 Vac
1.13	Power factor	0.85
1.14	Output protection	Overload, short circuit
1.15	Input protection	Over/under voltage
1.16	Internal protection	Over temperature
1.17	AC input voltage	90 to 130 Vac, single phase
1.18	AC input frequency	50 to 60 Hz
1.19	Bypass time	4 to 6 ms
1.20	Operating temperature	-30 to 60 °C (-22 to 140 °F)
1.21	Storage temperature	-30 to 70 °C (-22 to 158 °F)
1.22	Weight	9.8 kg (21.6 lb)
1.23	Height	88.4 mm (3.48 in.)
1.24	Width	424.0 mm (19.0 in.)
1.25	Depth	435.0 mm (17.12 in.)
1.26	Control interface	RS-232C

### 2.0 Ultracapacitor—Maxwell Model BMOD0058-E015-B01

2.1	Configuration	Symmetric, dual layer, module
2.2	Capacitance	58 F
2.3	Energy rating	6.525 kJ
2.4	Voltage rating	15 V continuous
2.5	Maximum series resistance	19.0 m $\Omega$
2.6	Maximum specific power density	8.2 kW/kg
2.7	Maximum specific energy density	2.67 Wh/kg
2.7	Maximum current	1500 A
2.8	Leakage current	1.0 mA
2.9	Operating temperature	-40 to 65 °C (-40 to 149 °F)
2.10	Storage temperature	-40 to 70 °C (-40 to 158 °F)
2.11	Height	44.0 mm (1.73 in.)
2.12	Width	85.0 mm (3.35 in.)
2.13	Depth	218.0 (8.58 in.)
2.14	Weight	680.0 g (1.50 lb)

### 3.0 Ten Ultracapacitor Bank—Maxwell Model BMOD0058-E015-B01

3.1	Configuration	10 series ultracapacitor modules
3.2	Capacitance	5.8 F
3.3	Energy rating	65.25 kJ
3.4	Voltage rating	150 V continuous
3.5	Maximum series resistance	190.0 mΩ
3.6	Maximum specific power density	8.2 kW/kg
3.7	Maximum specific energy density	2.67 Wh/kg
3.8	Maximum current	1500 A
3.9	Leakage current	1.0 mA
3.10	Operating temperature	−40 to 65 °C (−40 to 149 °F)
3.11	Storage temperature	−40 to 70 °C (−40 to 158 °F)
3.12	Height	44.0 mm (1.73 in.)
3.13	Width	850.0 mm (33.5 in.)
3.14	Depth	218.0 (8.58 in.)
3.15	Weight	6.8 kg (15.0 lb)

### 4.0 Charger—Xantrex Model XFR-300-4

4.1	Configuration	Constant voltage, constant current
4.2	Input voltage	85 to 130 Vac, single phase, 60 Hz
4.3	Output voltage	0 to 300 Vdc
4.4	Output current	0 to 4 Adc
4.5	Weight	8.16 kg (18.0 lb)
4.6	Height	44.4 mm (1.75 in.)
4.7	Width	482.6 mm (19.0 in.)
4.8	Depth	444.5 mm (17.5 in.)

## Appendix B.—Description of the Instrumentation System

A block diagram of the instrumentation system is shown in Figure 5.

All measurements were obtained with an Agilent Model 34970A data acquisition system. Type K thermocouples were used for all temperature measurements. Hall Effect transducers were used for all current measurements. These data were transmitted to a PC via a serial interface. The PC logged the data.

A 99.1  $\Omega$ , 250 W power resistor was used for all load tests. A Xantrex XFR 300 V, 4 A power supply was used to precharge the ultracapacitors when necessary.

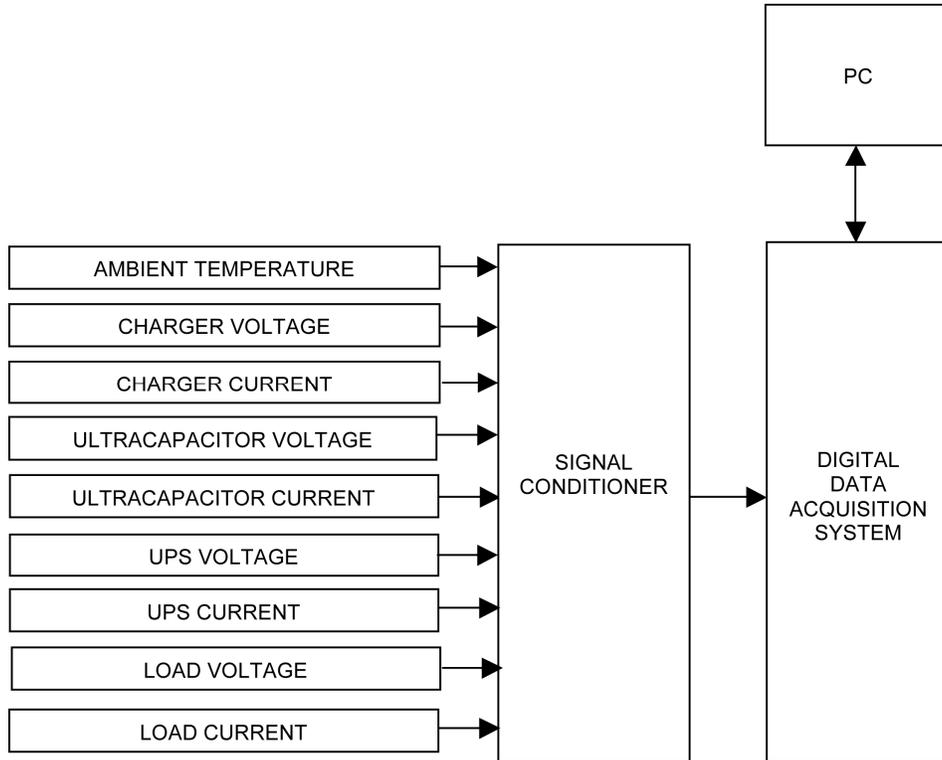


Figure 5.—Ultracapacitor UPS Instrumentation System.



## Appendix C.—Description of Digital Data Acquisition System

The digital data acquisition system used for testing is an Agilent Model 34970A. It is a high performance, microprocessor controlled, portable, data acquisition system. It consists of a half-rack mainframe with an internal 6 1/2-digit (22 bit) digital multimeter. Three module slots are built into the rear of the unit to accept a combination of switch and control modules.

Tests documented in this report were conducted with the digital data acquisition system programmed to meet the test matrix requirements.



## Appendix D.—Description of Test Cycles

Testing of the system was based on the test matrix shown in Table 3.

TABLE 3.—ULTRACAPACITOR UPS TEST MATRIX

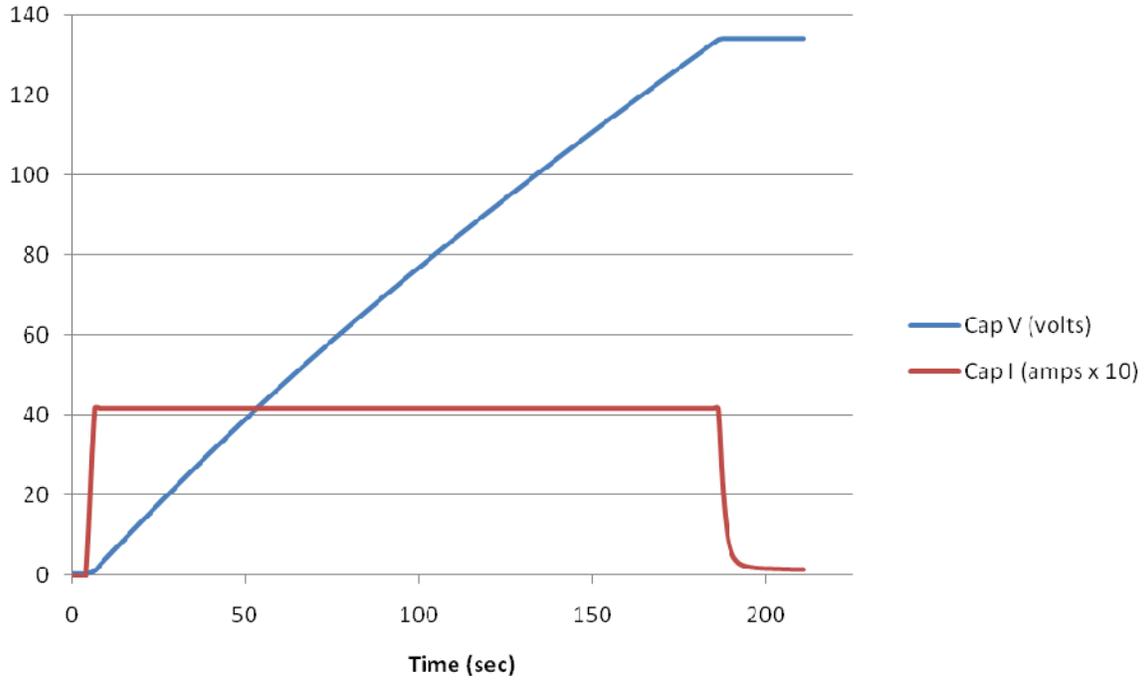
Parameter	Conditions
Charge test	Bank of ten ultracapacitors charged by a dc power supply to 134.0 Vdc limited to 4 A.
Load test	UPS connected to a 99.1 $\Omega$ load. Power provided by 120 Vac power source, then 120 Vac power source disconnected, automatically transferring power source to a bank of ultracapacitors precharged to 134.0 Vdc.
Self discharge test	Self discharge bank of ten ultracapacitors precharged to 134.0 Vdc and discharged to 90.0 Vdc.
Balance test	Voltage of individual ultracapacitors precharged as a bank of ten ultracapacitors to 134.0 Vdc.



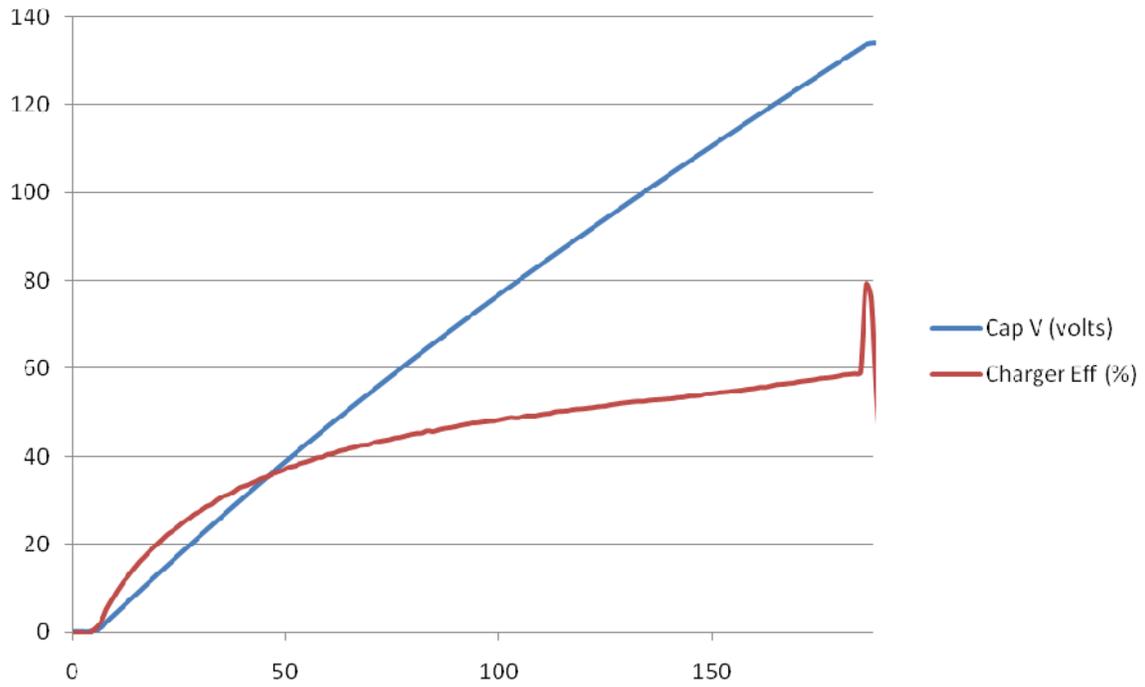
## Appendix E.—System Performance Test Results

A complete set of plots of the test results are included here. Table 1 identifies the tests that were conducted.

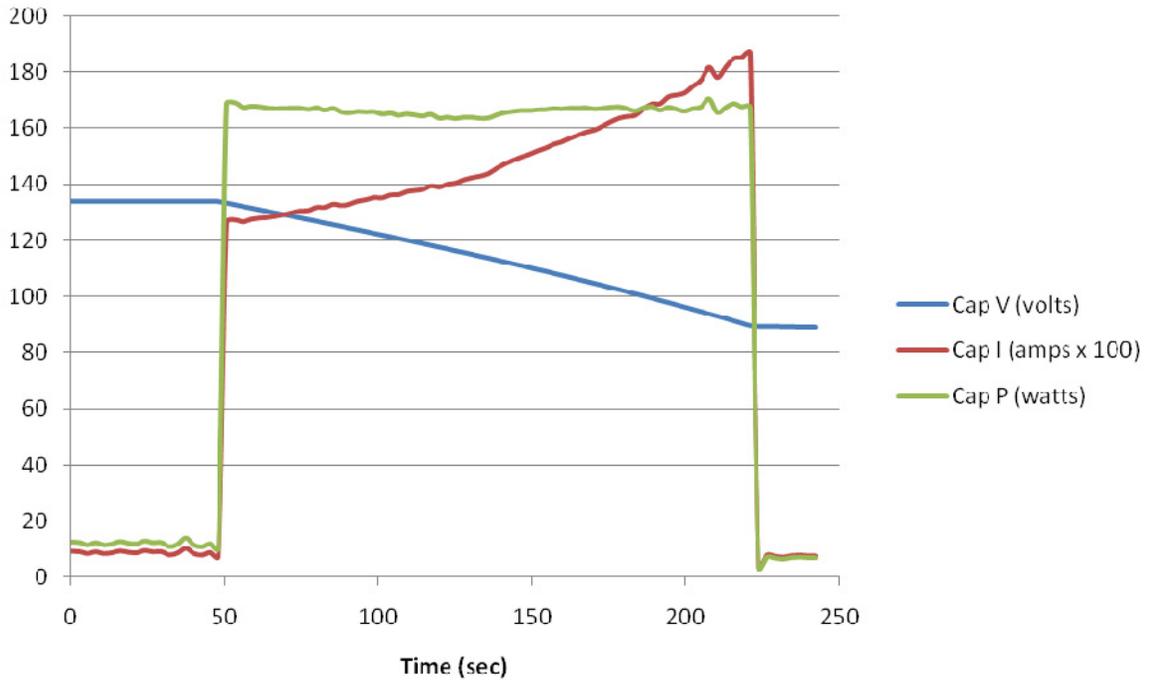
### Ultracapacitor UPS Charging (5.8 F)



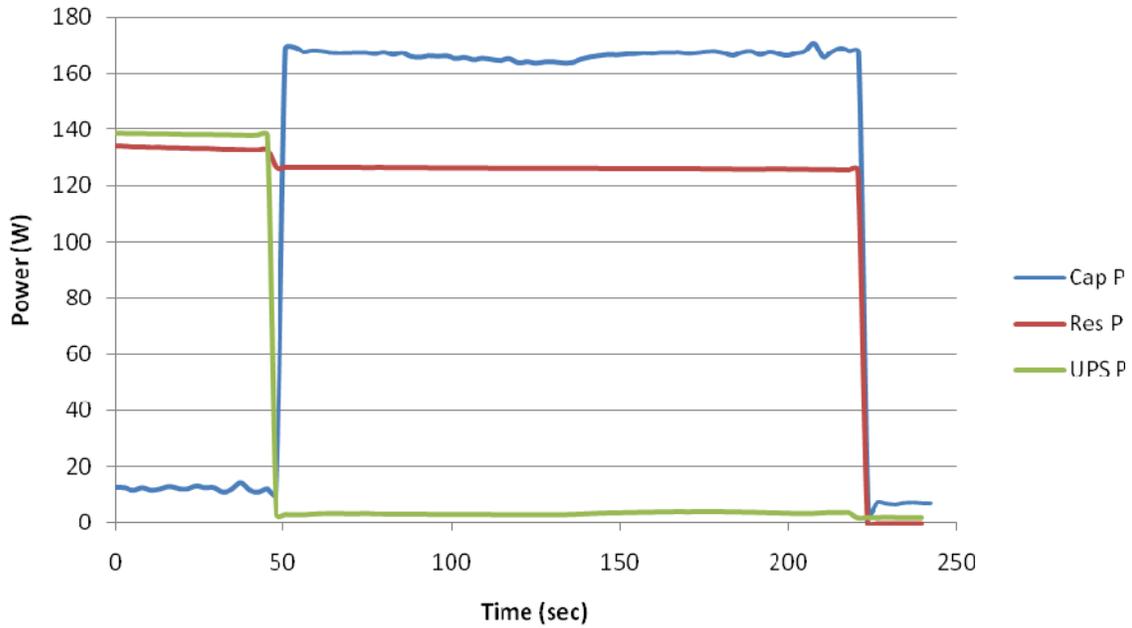
## Ultracapacitor UPS Charging Efficiency (5.8 F)



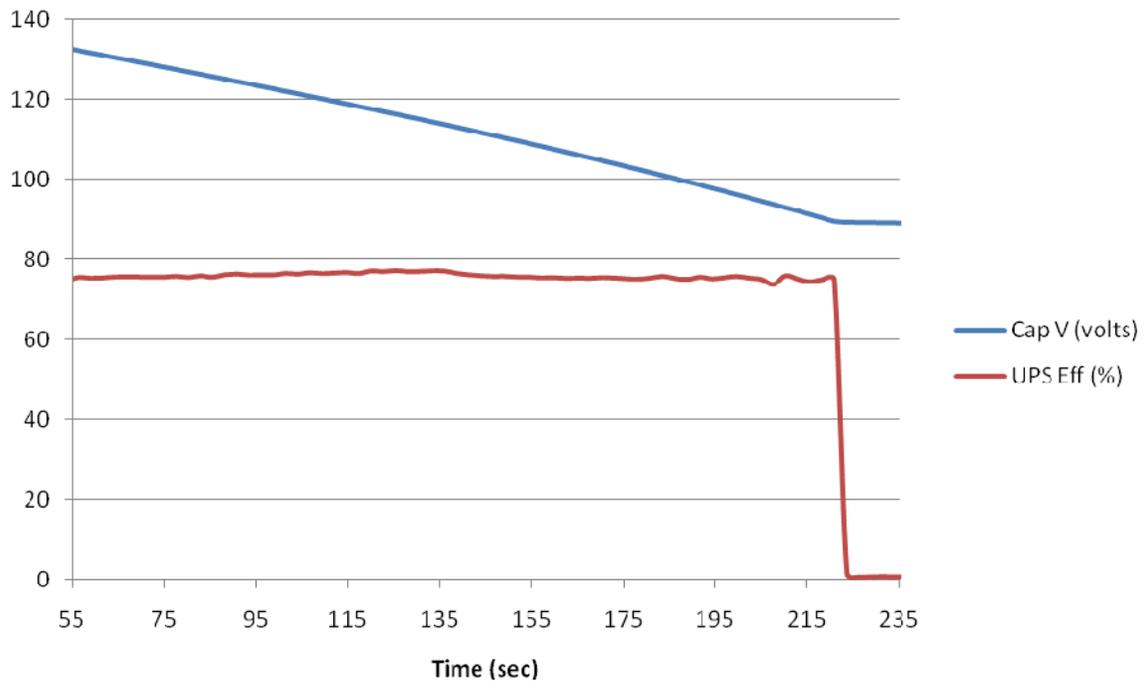
## Ultracapacitor UPS Discharge (UPS Load = 99.1 ohms resistive)



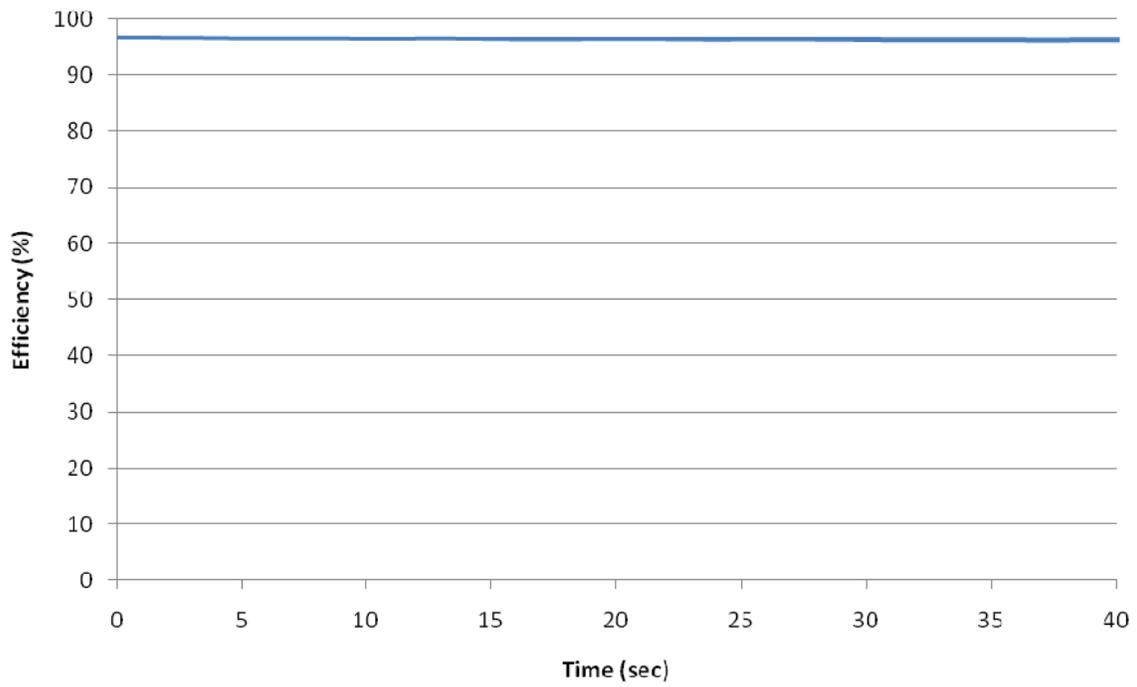
## Ultracapacitor UPS Power (UPS load = 99.1 ohms resistive)



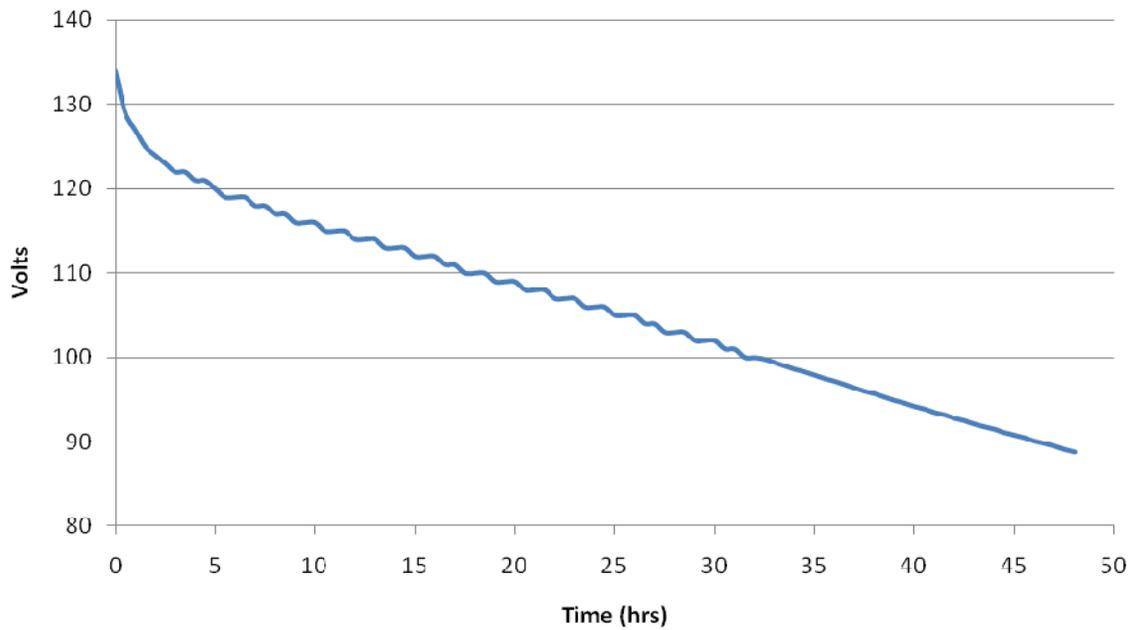
## Ultracapacitor UPS Efficiency (UPS Load = 99.1 ohms resistive)



### Ultracapacitor UPS AC Efficiency (UPS Load = 99.1 ohms resistive)



### Ultracapacitor Self Discharge (5.8 F ultracapacitor bank precharged to 134.0 VDC)



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<b>13. SUPPLEMENTARY NOTES</b>				
<b>14. ABSTRACT</b> The NASA Glenn Research Center (GRC) initiated the development and testing of an ultracapacitor based uninterruptible power supply (UPS) system as a means to provide backup power for the many critical NASA applications. A UPS system typically utilizes batteries for energy storage. The battery is the most vulnerable part of the UPS system, requiring regular maintenance and replacement. Battery performance is also extremely temperature dependent. Ultracapacitors are ideal for UPS systems where long life, maintenance free operation, and excellent low temperature performance is essential. State of the art symmetric ultracapacitors were used for these tests. The ultracapacitors were interconnected in an innovative configuration to minimize interconnection impedance, and to provide voltage balancing. Ultracapacitors can be charged extremely rapidly and supply high current, which are essential characteristics for an effective UPS system. Charging ultracapacitors is significantly less complex than charging batteries since there is no chemical reaction occurring while charging ultracapacitors. The report concludes that the implementation of symmetric ultracapacitors in a UPS system can provide significant improvements in power system performance and reliability.				
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