ULTRACAPACITOR / BATTERY HYBRID DESIGNS: WHERE ARE WE?

Carey O'Donnell, Charles Finin, and Howard Gartland
Mesa Technical Associates, Inc.

Capacitor technology has played a significant role in power transmission and delivery applications for many decades. These traditional thin film and oil based capacitor designs performed a variety of functions, including grid load leveling, power factor correction, peak shaving, and voltage balancing. But in the past decade there has been substantial research and development that has lead to significant evolutionary advances in capacitor design and capabilities; the description today is ultracapacitors. These ultracapacitors are driving increased attention on efforts to determine if there is a future role for ultracapacitors in traditional user-level stationary applications, particularly in conjunction with battery energy storage designs and systems.

Comparison of Batteries and Ultracapacitors

Most traditional power applications for capacitors focus on 'power delivery' issues, like peak shaving and load leveling. But we should understand that the capacitor, while it is first a power delivery device, is also an energy storage device. There are fundamental differences in the characteristics between ultracapacitors and batteries with regard to energy density (Watt-Hours) and power density (Kilowatts). Batteries can store a lot of energy, but are limited in terms of power density and response (ability to discharge and charge quickly). Capacitors have the opposite characteristics: limited in terms of total energy storage, but "power dense", with an ability to discharge high levels of power quickly and re-charge rapidly. Capacitors store charge only on the surface of the electrode (rather than within the entire electrode), which causes them to have a lower energy storage ability and lower energy density. But since capacitors are not limited by the ionic conduction within the bulk of the electrode, they can run at much higher rates and with fast response for short periods of time. Ultracapacitors charge/discharge at least 100 times faster than batteries, and their operating temperature range is typically -40°C to 65°C. 1

Ultracapacitors differ from traditional capacitors in that they utilize nanoscale electric double layers between their electrolyte and electrodes, therefore enabling orders of magnitude greater energy storage capabilities. Due to the chemical reactions that occur within a battery, they have a limited life with regard to cycling. Ultracapacitors, however, have no chemical reaction during charge/discharge, and can be cycled hundreds of thousands of times. Ultracapacitors are easier to work and design with since their state of health (SOH) and depth of discharge (DOD) can be monitored in real time, thereby providing end of life (EOL) forecasting. 2

The ultracapacitor is being viewed increasingly as a potential compromise between batteries and capacitors with regard to energy levels, energy density, and power response. While the ultracapacitor is already perceived as an obvious solution for a wide variety of motive and electric vehicle applications, there is growing interest in finding a role in more traditional stationary power applications for energy storage. Would a hybrid design marrying the ultracapacitor and conventional battery technology lead to the best available complementary system design which could give us the best of both worlds in terms of power performance and energy storage capability? 3

Is There a Role for Ultracapacitors in Traditional Energy Storage Applications?

It doesn't take much to identify potential applications for ultracapacitors involving uninterruptible power supplies, or for compensating for voltage drops in large scale distribution networks, or in load leveling applications. But consider the potential role of a battery/capacitor hybrid in traditional stationary applications like utility T&D (transmission and distribution) and Power Generation.

The DC loads of a typical utility substation are dynamic in nature. The DC supply really has two distinct and separate functions: to provide the long duration back-up of relatively low power 'base' loads while also delivering significant peak current amplitudes required to operate switchgear, circuit breakers, and DC motors. This combination of load requirements in a substation create a unique challenge for the DC system to support those very different loads with DC supply. Other factors affecting DC supply design in substations include growing loads and shrinking space, and the regulatory community's recommendation for DC supply in "Bulk Power Stations" that include the use of independent and redundant DC supply. Substation designers and compliance engineers must wrestle with the competing interests of more and larger battery systems in minimal substation and control building real-estate.

Typical base DC loads in a substation include relays, indicating lamps and LEDs, RTUs and other processors. Base loads of 2 to 15 amps are common in substation design. Designing a DC supply for an 8 hour outage for baseloading in this scenario can be handled by a small battery system of 16 amp-hr to 120 amp-hr.

Factoring in the momentary and tripping loads generates the challenge in DC supply design. Combining the current demands of Circuit Switchers (75 amps or more each), with Circuit Breakers (7 -15 amps of trip current each) and other DC loads, a moderately sized substation may require instantaneous current of 300 – 400 amps in order to perform its basic reliability and grid safety duty cycle. This high instantaneous current, often needed at or near the end of a discharge, drives the battery capacity sizing when applying IEEE 485 battery capacity sizing standards. The small battery system needed for the base load must now grow to 400 amp-hr or more, in order to support both functions: long duration back-up of base DC loads, and short duration supply of tripping and switching loads.

Therefore, in the prototypical, moderately sized "Bulk Power Station" we have designed two 125 VDC, 400 amp-hr batteries to meet the IEEE and regulatory guidelines for design of Lead-Acid batteries at the core of the DC Supply. However, what we really need are two distinct functions: a back-up system of <100 amp-hr so that the base DC loads can operate for 8 hours, and an independent, redundant system that can supply the instantaneous current demanded by switchgear. Similar characteristics exist in the design of DC power for Power Generators. Emergency and momentary loads, such as DC pumps, motors, circuit breakers, and circuit switchers, dwarf the current demand of the base loads of relays, processors and controls.

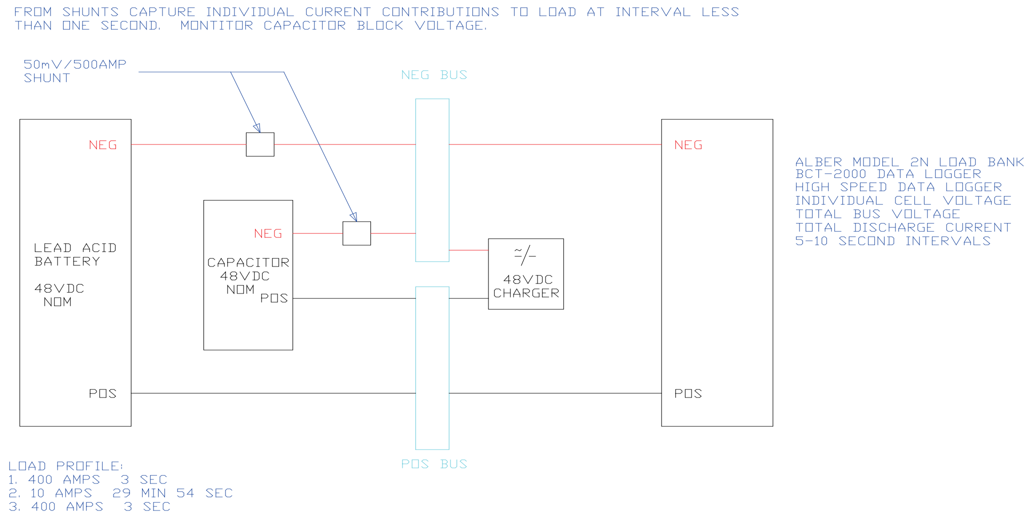
An illustration of these common load profiles can be seen by looking at Fig 1 and Fig. 2. Fig. 1 shows a typical power generation backup load profile, with high momentary inrush (e.g. motor) at the beginning and end of the desired profile. Fig. 2 represents the same load, but with the peak current demands removed. A comparison of these load profiles reveal that if we could remove the impact of the 1 minute rates on the load profile, that it would have a very significant impact in reducing the size of the battery required to support the load (often 50% or greater). We should remember that the 1 minute rates are defined by the IEEE based on the electrical response characteristics of lead acid batteries, where the coup de fouet could cause bus voltage to drop below the minimum operating voltage of the equipment. But in reality, most momentary loads in utility applications often last 2 seconds or less.

<u>Testing a Battery/Ultracapacitor Hybrid System</u>

The following is an overview of tests conducted by Mesa Technical Associates, Inc. and Ioxus, Inc. this spring, involving combinations of lead selenium tubular plate batteries and generation ultracapacitors from Ioxus:

- We'll attempt to demonstrate how a hybrid system would operate, utilizing a 48 volt string of 100 ampere hour tubular plate lead-selenium block batteries and a twenty cell configuration of Ioxus 2000 farad ultracapacitors. For our testing we utilized an Alber 2N load bank with a BCT 128 to control the load bank and capature battery data and an eight port data logger capable of capturing 60 measurments per channel per second. Due to the design parameters and limitations of the testing equipment, we were unable to test at the one second rate as originally planned, so modified our high rate testing to 3 second intervals.

Our test system was configured as follows:



- Though we were unable to create one second momentary loads given the design limitations of the load bank/BCT tester, we were able to define our load profile as 3 seconds, 400 amps, then 10 amps for 29 minutes, 54 seconds, and then another 3 second pulse at 400 amps. The minimum system voltage for the test was 42vdc. (See Fig. 3.) This is the IEEE 485 battery sizing calculations for this load profile, which recommends an 8 OPzS 800 lead selenium battery.)

- To demonstrate the potential of an ultracapacitor/battery hybrid design, the same load profile was modified by the elimination of the momentary pulses. This was done through the ultracapacitors, which provided the entire peak current needed to support these momentary loads. See Fig. 4, which is the IEEE sizing calculations for the modified load profile, which now calls for a 1 OPzS 50 battery (which is still at 50% design margin). Clearly the potential reduction in battery size is very significant. Our baseline assumptions for predicting the hybrid system test results were based on the formula dV (change in voltage) = (current x time)/capacitor value. We selected ultracapacitor cells rated at 2000F (farads) for the test, creating a 100F ultracapacitor bank (2000F/20 cells = 100F). The ultracapacitors are rated at 2.7 volts per cell, which roughly matched up to our battery cell voltage at float charge. (Note: If we had used 24 ultracapacitor cells, we would have had an 83.3F capacitor; we chose 20 capacitor cells as capacity is divided by the number of cells, unlike batteries.)

  So with 20 cells, at a battery float voltage of 2.25 v/c, bus voltage 54vdc, the capacitors are at 2.7v/c. (This is right at the upper end of the capacitor voltage limit. In fact, Ioxus has both 3000F and 5000F capacitors, but these larger ultracapacitor cells were not immediately available in time for our testing.)

- The battery had a published rate of 112.9 amperes for 1 minute to 1.75v/c, and the ultracapacitor had a theoretical capacity of 400 amperes for 3 seconds. See Chart 1 for the results of the initial battery test. The battery alone provided 148.23 ampers for 4.5 seconds to an end voltage of 42.09 vdc. (Interestingly, the battery clearly provided higher rate current at short duration than predicted by the one minute rate.)

- Next the Ioxus 2000F ultracapacitor was tested alone to determine how it would perform based on the 200 amps for 3 seconds theoretical value. (See Chart 2.) At 220 amps for 3 seconds, the bus voltage dropped to 42.42vdc, just above the 42vdc threshold.

- When the battery and capacitor systems are combined, we get the following results: A thirty minute load profile, consisting of 400 amperes for 3 seconds, 10 amperes for 29 minutes, 54 seconds and 400 amperes for 3 seconds. See Chart 3. Clearly the hybrid system allows for much higher short duration current supplied by the capacitor, with the battery recharging the capacitor during the low current continuous portion of the load profile, and the capacitor providing energy for the final high rate discharge.

Observations:

Putting the ultracapacitors on the front end of the battery configurations tested had a very significant impact on the potential battery sizing requirements for the various load profiles identified for the test. These load profiles were based on actual customer requirements at various utility power generation and sub-station applications.

The implications of our ongoing testing suggest some potentially significant benefits for future energy storage designs and applications. Some of the critical design criteria facing battery design engineers and users include:

- *Initial cost*. Our testing points to potential significant reductions in the initial system cost, with the reductions in battery cost far exceeding the added cost of the ultracapacitors.

- *Footprint.* There is a clear opportunity to significantly reduce the overall size of the battery room back-up system, with better utilization of space and reduced ventilation requirements.

- *Installed Cost*. There would be a large reduction in the logistics and manpower of the initial hybrid system installation vs. a traditional stand alone battery.

- *Long Term Performance and Reliability*. Ultracapacitors have a long life cycle, with no maintenance requirements. Additionally, having the ultracapacitors on the front end of a lead acid battery should significantly improve the life and performance of the lead acid battery system.

Conclusion

While the present day role of ultracapacitors in many traditional stationary battery applications is still unclear, there is no confusion or serious disagreement about the huge potential of this technology. The only question is: When? The primary drawback is the fact that ultracapacitors currently store only about 10 % of the energy as comparably sized batteries, which clearly point to the need for hybrid ultracapacitor/battery designs for the foreseeable future. We should keep in mind that current research being done at facilities like Ioxus and MIT are making headway with new types of electrode materials, all of it nanotechnology based, which points to ultracapacitor designs that could store as much as 25%, near term, of the energy vs. similar sized batteries, which could be a potential disruptive technology in the power industry. 4

APPENDIX A

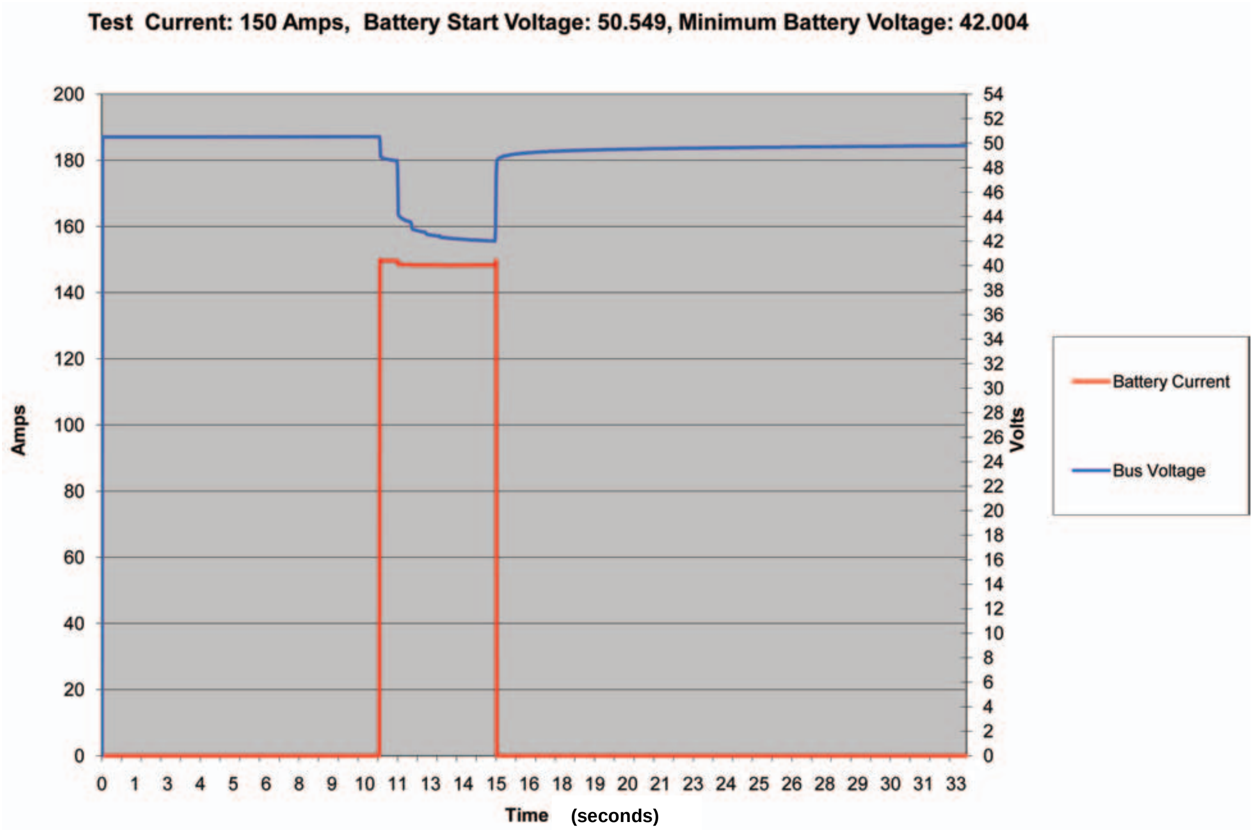
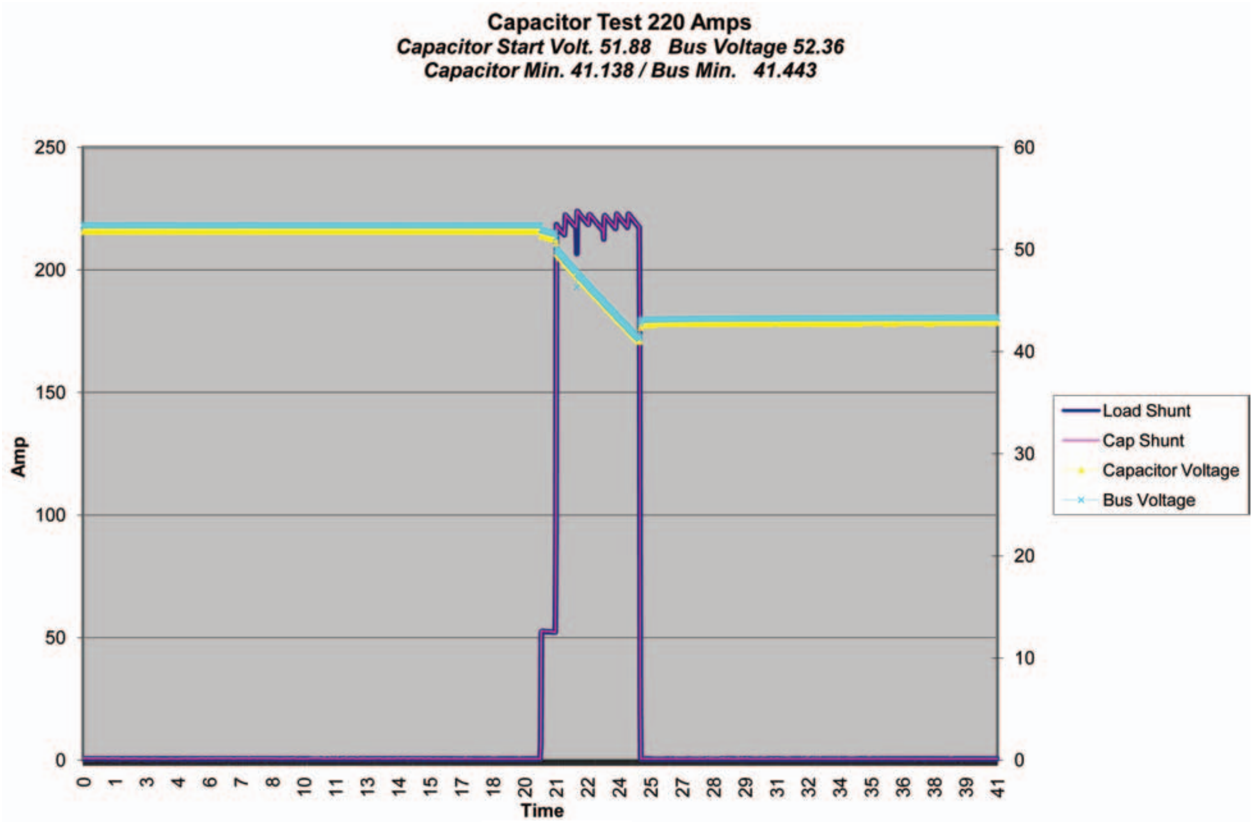
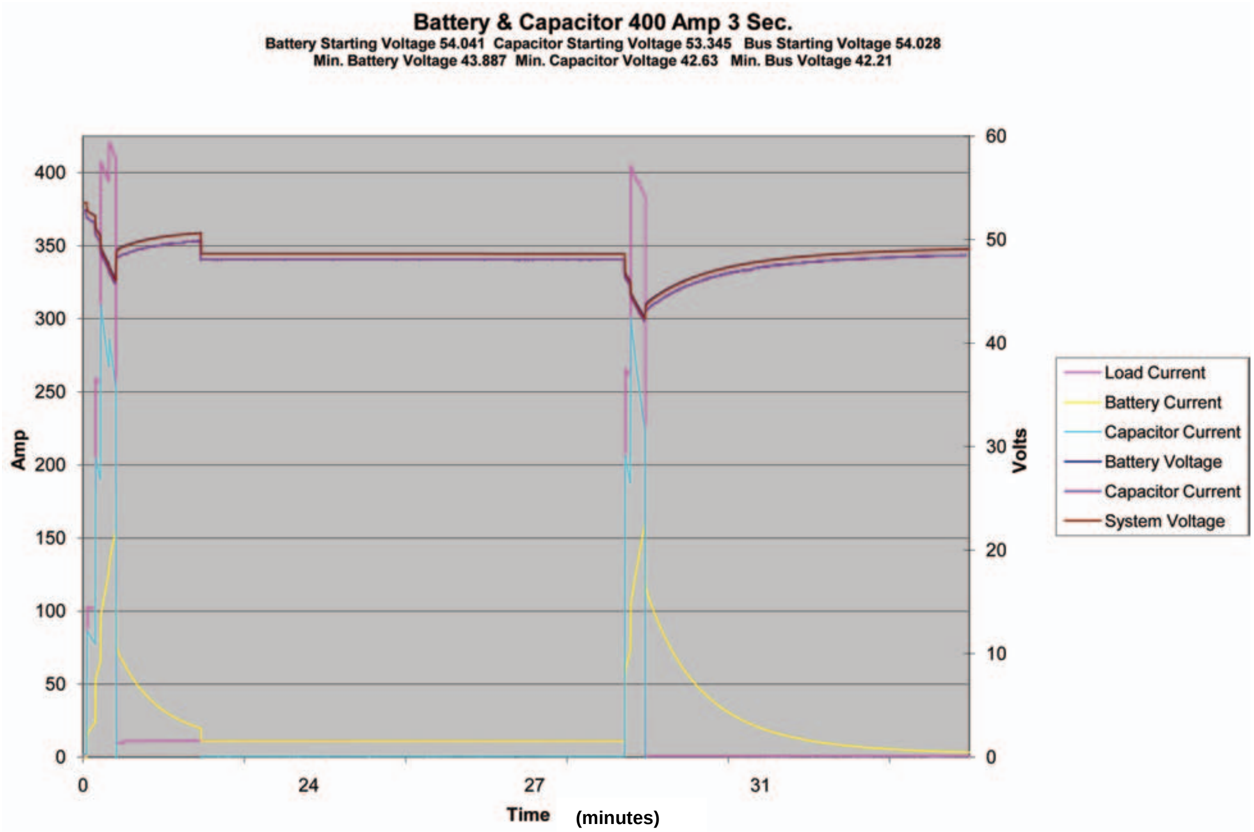


Chart 1



(seconds)

Chart 2



Battery & Capacitor 400 Amp 3 Sec.
Battery Starting Voltage 54.041 Capacitor Starting Voltage 53.345 Bus Starting Voltage 54.028
Min. Battery Voltage 43.887 Min. Capacitor Voltage 42.63 Min. Bus Voltage 42.21
Amp
Volts
Time (minutes)
Load Current
Battery Current
Capacitor Current
Battery Voltage
Capacitor Current
System Voltage

Chart 3

Project: Station Battery A&B 100% Load Each

Date: 12/04/10

Nominal Temperature 77 °F (Lowest 61 °F, Highest 77 °F)	Minimum Cell Voltage: 1.75	Cell Mfg: HOPPECKE	Cell Type: OSP.HC	Sized By: MESA (MESA)

(1) Period	(2) Load (Amperes)	(3) Change in Load (Amperes)	(4) Duration of Period (minutes)	(5) Time to End of Section (minutes)	(6) Capacity at T Min Rate Amps/Pos(Rt)	(7) Required Section Size (3) / (6) = Positive Plates Pos. Values	Neg. Values
Section 1 - First 1 Period(s) Only - if A2 is greater than A1, go to Section 2							
1	A1 = 1548.00	A1-A0 = 1548.00	M1 = 1.00	t = 1.00	93.07	16.6	0.0
					Sec Sub Total	16.6	0.0
					1 Total	16.6	0.0
Section 2 - First 2 Period(s) Only - if A3 is greater than A2, go to Section 3							
1	A1 = 1548.00	A1-A0 = 1548.00	M1 = 1.00	t = 61.00	52.12	29.7	0.0
2	A2 = 338.50	A2-A1 = -1209.5(	M2 = 60.00	t = 60.00	52.39	0.0	-23.1
					Sec Sub Total	29.7	-23.1
					2 Total	6.6	0.0
Section 3 - First 3 Period(s) Only - if A4 is greater than A3, go to Section 4							
1	A1 = 1548.00	A1-A0 = 1548.00	M1 = 1.00	t = 239.00	22.47	68.9	0.0
2	A2 = 338.50	A2-A1 = -1209.5(	M2 = 60.00	t = 238.00	22.56	0.0	-53.6
3	A3 = 155.50	A3-A2 = -183.00	M3 = 178.00	t = 178.00	27.75	0.0	-6.6
					Sec Sub Total	68.9	-60.2
					3 Total	8.7	0.0
Section 4 - First 4 Period(s) Only - if A5 is greater than A4, go to Section 5							
1	A1 = 1548.00	A1-A0 = 1548.00	M1 = 1.00	t = 240.00	22.39	69.1	0.0
2	A2 = 338.50	A2-A1 = -1209.5(	M2 = 60.00	t = 239.00	22.47	0.0	-53.8
3	A3 = 155.50	A3-A2 = -183.00	M3 = 178.00	t = 179.00	27.61	0.0	-6.6
4	A4 = 468.00	A4-A3 = 312.50	M4 = 1.00	t = 1.00	93.07	3.4	0.0
					Sec Sub Total	72.5	-60.5
					4 Total	12.1	0.0
Random Equipment Load Only (if needed)							
0	A0 = 0.00	A0-A-1 = 0.00	M0 = 0.00	t = 0.00	0.00	0.0	0.0

Maximum Section Size (8) 16.6 + Random Section Size (9) 0.0 = Uncorrected Size (US) (10) 16.6
US (11) 16.6 X Temp Corr. (12) 1.04 X Design Margin (13) 1.10 X Aging Factor (14) 1.25 = (15) 23.8 Positive Plates
When the cell size (15) is greater than a standard cell size, The next larger cell is required.

Calculated Capacity: 23.82 Positive Plates

Recommended Battery: 1 X 60 X 24 OSP.HC 2520

Nominal Capacity: 2520.00 Ah

Figure 1

IEEE
Std 485

IEEE RECOMMENDED PRACTICE FOR SIZING

Project: Station Battery A&B Caps for 1st min and last minute

Date: 13/04/10

Nominal Temperature 77 ℉ (Lowest 61 ℉, Highest 77 ℉)	Minimum Cell Voltage: 1.75	Cell Mfg: HOPPECKE	Cell Type: OSP.HC	Sized By: MESA (MESA)

(1) Period	(2) Load (Amperes)	(3) Change in Load (Amperes)	(4) Duration of Period (minutes)	(5) Time to End of Section (minutes)	(6) Capacity at T Min Rate Amps/Pos(Rt)	(7) Required Section Size (3) / (6) = Positive Plates Pos. Values	Neg. Values
Section 1 - First 1 Period(s) Only - if A2 is greater than A1, go to Section 2							
1	A1 = 338.50	A1-A0 = 338.50	M1 = 60.00	t = 60.00	49.41	6.9	0.0
					Sec Sub Total	6.9	0.0
					1 Total	6.9	0.0
Section 2 - First 2 Period(s) Only - if A3 is greater than A2, go to Section 3							
1	A1 = 338.50	A1-A0 = 338.50	M1 = 60.00	t = 240.00	18.49	18.3	0.0
2	A2 = 155.50	A2-A1 = -183.00	M2 = 180.00	t = 180.00	23.39	0.0	-7.8
					Sec Sub Total	18.3	-7.8
					2 Total	10.5	0.0
Random Equipment Load Only (if needed)							
0	A0 = 0.00	A0-A-1 = 0.00	M0 = 0.00	t = 0.00	0.00	0.0	0.0

Maximum Section Size (8) 10.5 + Random Section Size (9) 0.0 = Uncorrected Size (US) (10) 10.5
US (11) 10.5 X Temp Corr. (12) 1.04 X Design Margin (13) 1.10 X Aging Factor (14) 1.25 = (15) 15.0 Positive Plates
When the cell size (15) is greater than a standard cell size, The next larger cell is required.

Calculated Capacity: 15.01 Positive Plates

Recommended Battery: 1 X 60 X 16 OSP.HC 1360

Nominal Capacity: 1360.00 Ah

Figure 2

Project: Breaker Trip

Date: 14/04/10

Nominal Temperature 77 ℉ (Lowest 50 ℉, Highest 77 ℉)	Minimum Cell Voltage: 1.75	Cell Mfg: HOPPECKE	Cell Type: OPzS	Sized By: MESA (MESA)

(1) Period	(2) Load (Amperes)	(3) Change in Load (Amperes)	(4) Duration of Period (minutes)	(5) Time to End of Section (minutes)	(6) Capacity at T Min Rate Amps/Pos(Rt)		(7) Required Section Size (3) / (6) = Positive Plates Pos. Values	Neg. Values
Section 1 - First 1 Period(s) Only - if A2 is greater than A1, go to Section 2								
1	A1 = 400.00	A1-A0 = 400.00	M1 = 1.00	t = 1.00	81.50		4.9	0.0
					Sec	Sub Total	4.9	0.0
					1	Total	4.9	0.0
Section 2 - First 2 Period(s) Only - if A3 is greater than A2, go to Section 3								
1	A1 = 400.00	A1-A0 = 400.00	M1 = 1.00	t = 29.00	68.80		5.8	0.0
2	A2 = 10.00	A2-A1 = -390.00	M2 = 28.00	t = 28.00	69.60		0.0	-5.6
					Sec	Sub Total	5.8	-5.6
					2	Total	0.2	0.0
Section 3 - First 3 Period(s) Only - if A4 is greater than A3, go to Section 4								
1	A1 = 400.00	A1-A0 = 400.00	M1 = 1.00	t = 30.00	68.00		5.9	0.0
2	A2 = 10.00	A2-A1 = -390.00	M2 = 28.00	t = 29.00	68.80		0.0	-5.7
3	A3 = 400.00	A3-A2 = 390.00	M3 = 1.00	t = 1.00	81.50		4.8	0.0
					Sec	Sub Total	10.7	-5.7
					3	Total	5.0	0.0
Random Equipment Load Only (if needed)								
0	A0 = 0.00	A0-A-1 = 0.00	M0 = 0.00	t = 0.00	0.00		0.0	0.0

Maximum Section Size (8) 5.0 + Random Section Size (9) 0.0 = Uncorrected Size (US) (10) 5.0
US (11) 5.0 X Temp Corr. (12) 1.11 X Design Margin (13) 1.00 X Aging Factor (14) 1.25 = (15) 6.9 Positive Plates
When the cell size (15) is greater than a standard cell size, The next larger cell is required.

Calculated Capacity: 6.94 Positive Plates

Recommended Battery: 1 X 24 X 8 OPzS 800

Nominal Capacity: 800.00 Ah

Figure 3

IEEE
Std 485

IEEE RECOMMENDED PRACTICE FOR SIZING

Project: Breaker Trip

Date: 14/04/10

Nominal Temperature 77 ℉ (Lowest 50 ℉, Highest 77 ℉) | Minimum Cell Voltage: 1.75 | Cell Mfg: HOPPECKE | Cell Type: power.bloc OPzS | Sized By: MESA (MESA)

(1) Period	(2) Load (Amperes)	(3) Change in Load (Amperes)	(4) Duration of Period (minutes)	(5) Time to End of Section (minutes)	(6) Capacity at T Min Rate Amps/Pos(Rt)	(7) Required Section Size (3) / (6) = Positive Plates Pos. Values	Neg. Values
Section 1 - First 1 Period(s) Only - if A2 is greater than A1, go to Section 2							
1	A1 = 11.30	A1-A0 = 11.30	M1 = 30.00	t = 30.00	35.00	0.3	0.0
					Sec Sub Total	0.3	0.0
					1 Total	0.3	0.0
Random Equipment Load Only (if needed)							
0	A0 = 0.00	A0-A-1 = 0.00	M0 = 0.00	t = 0.00	0.00	0.0	0.0

Maximum Section Size (8) 0.3 + Random Section Size (9) 0.0 = Uncorrected Size (US) (10) 0.3
US (11) 0.3 X Temp Corr. (12) 1.11 X Design Margin (13) 1.00 X Aging Factor (14) 1.25 = (15) 0.4 Positive Plates
When the cell size (15) is greater than a standard cell size, The next larger cell is required.

Calculated Capacity: 0.45 Positive Plates

Recommended Battery: 1 X 4 X 12 V 1 OPzS 50

Nominal Capacity: 50.00 Ah

Figure 4

FOOTNOTES

1. Lamonica, Martin. Green Tech. “Ultracapacitors Look to Fit Into Energy Storage.” September 29, 2009.

2. Patsos, Alex. Ioxus Inc. “Select The Right Ultracapacitor Solution.” November 5, 2009

3. Maher, Bobby. Maxwell Technologies. “A Backup Power System Using Ultracapacitors.” September 1, 2004.

   Barrade, P. Laboratorie d’Electronique Industrielle, LEI. “Energy Storage and Applications With Supercapacitors.”

4. Lamonica, Martin. Green Tech. “Ultracapacitors Look to Fit Into Energy Storage.” September 29, 2009.

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