Design and Construction of a Battery Monitor for Wind-Diesel Hybrid Systems

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Abstract

The Creation of a Battery Monitoring System for Wind-Hybrid Applications. Rebecca Jones (Princeton University, Princeton NJ 08544). Stephen Drouilhet (National Renewable Energy Laboratory, Golden, Colorado 80401).

Batteries are often used in wind-hybrid systems to store excess wind energy and then provide supplementary energy when the wind cannot generate sufficient power to meet the electric load. A battery monitoring system is therefore needed to track and display battery usage characteristics, and to estimate and detect trends in battery state-of-charge (SOC). From these measurements the state-of-health (SOH) of the battery can be estimated. However most commercial monitoring systems are designed for batteries that are used for other applications, and thus a more suitable battery monitoring system for wind-hybrid systems is needed. Such a system was created, using a Direct Logic 250 Programmable Logic Controller (PLC). The PLC was programmed to log, manipulate and conveniently store the battery bank DC voltage, the DC current of each battery string, and the temperature at up to 4 different locations on the battery bank. When the battery is fully charged, the PLC takes a DC resistance measurement, which is compared with previous measurements to determine the approximate SOH of the battery. A Quickpanel touchscreen was then programmed to display the data from the PLC, as well as to provide an interface for user input to the PLC. The hardware was then tested with simulated inputs to ensure a working battery monitor had been constructed, that can now be fully assembled and tested on an actual battery bank that is subject to charge cycling.

Research Category (Please Circle)

ERULF: Physics Chemistry Biology Engineering Computer Science Other_____

TYPE ALL INFORMATION COMPLETELY AND CORRECTLY

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Introduction

Batteries have the ability to improve the efficiency of wind-diesel hybrid power systems. These systems use a variable combination of available wind and diesel-generated electricity to meet their load. They have developed as an effective way to incorporate wind power into reliable off-grid power systems and they are being implemented in remote areas where fuel costs are very expensive. Wind is a highly variable and non-dispatchable energy source, but the diesel generator(s) provide power when the available wind power is insufficient. It is desirable, both economically and environmentally, to minimize the use of diesel power in such systems. However because the amount of wind energy generated is not consistent (since wind speeds themselves are not consistent), some type of energy storage system is often used to maximize the wind energy capture and therefore minimize the use of diesel fuel.

The energy storage system, typically a battery bank, stores the excess generated wind energy (if the battery bank is not already fully charged) and then later provides it for short periods when the load demands more power than the wind turbines can supply. If the wind power is deficient for longer periods of time, the diesel system will be brought on-line to provide the necessary additional power. Because there is a minimum run-time for many diesel generators, they cannot be started and stopped exactly to fit with the dips in the generated wind power. Thus even a relatively small battery is capable of decreasing the amount of time that the diesel generators need to run, by preventing the need to start the generator every time that the wind power is insufficient.

As the battery bank is so integral to the optimal functioning of a hybrid system, monitoring the battery's usage and state-of-health (SOH) has an important role in maintaining the system and understanding its operation. This paper discusses the design of a battery monitoring device for wind-diesel hybrid systems.

Battery Basics

The amount of charge in Ampere-hours that a battery can supply at a specified voltage is the battery capacity. For example, a fully charged battery with a capacity of ten Amp-hours, rated at a five-hour discharge rate, could provide approximately two Amps current for five hours. A faster discharge (i.e. at a higher current) would typically yield a reduced capacity. A cell is generally considered to be fully discharged when the voltage drops below a certain level at a specified current, though the cell may be able to supply current at a lower voltage for an additional period of time. The state-of-charge of a battery is the number of Amp-hours it currently has stored in comparison with its rated capacity level.

The type of battery that is capable of being charged and discharged is called a secondary, or rechargeable, battery. A primary battery can only be discharged once, and cannot be recharged. Secondary batteries are used in wind-hybrid applications.

Individual cells can be connected together in series (i.e. the positive end of one battery is connected to the negative end of another battery, and so on) to increase the total voltage that they are able to supply for the same number of Amp-hours. Cells can also be connected in parallel (i.e. all of the positive ends of the cells are connected and all of the negative ends are connected) to increase their capacity at the same voltage. Cells can be joined in some combination of series and parallel strings in order to create a battery bank with a specific voltage and capacity.

Desired Characteristics in a Battery Monitor for Hybrid Systems

There are many limitations to batteries. They are expensive, and periodically need to be replaced when they reach the end of their lifetime. Battery capacity decreases as batteries age, for a number of reasons, but the time it takes for a battery to reach the end of its life is very difficult to predict. Battery manufacturers generally specify a battery cycle life that is the number of charge-discharge cycles before failure. This is the number of times that a battery can be taken from a full charge to a complete discharge and then back to a full charge, and still be expected to provide 80% of its rated capacity. But in wind-diesel hybrid systems, the battery does not usually go through complete cycles (instead it goes through a wide range of depths of discharge); hence the manufacturer's rated lifetime is not very useful.

There have been studies done on the battery lifetime and battery capacity of different types of batteries, mainly Uninterruptable Power Supply (UPS) system batteries and automotive batteries. For these types of batteries, there are commercial battery monitors available that attempt to accurately assess battery SOH. These monitors are again not very useful for hybrid battery bank systems because the batteries have such different usage characteristics. UPS batteries exist mainly to provide backup against very occasional power failures. Thus they usually need replacement because they have decayed gradually over time, from causes like leakage, not because they have exceeded their cycle life. Automotive batteries are cycled often, but are designed to provide a lot of power over a very short period of time, while hybrid system batteries need to provide power for a longer duration of time and at varying power levels.

Consequently some type of monitoring system specifically designed for wind-diesel hybrid systems is needed. To be most useful, it should be able to monitor and describe battery usage characteristics, such as temperature, current, voltage, charging/discharging rates and magnitudes, and state-of-charge (SOC), as well as assess the SOH of the battery. It is desired that the battery monitor be flexible enough to work with any type of secondary battery.

A Proposed Application for the Battery Monitor

An immediate application for this battery monitor is the wind-hybrid system currently being installed by NREL engineers in Wales, Alaska. It is a pilot high-penetration system, which means that the wind power is expected to provide the majority of the annual energy requirement. Wales is a coastal village in northwest Alaska, with a population of approximately 160 people, the majority of whom are Inupiat Eskimo. Diesel generators presently supply their power, and the necessary fuel is shipped in by barge once a year and stored in large tanks. This makes fuel and therefore energy costs very expensive. The environmental costs are high, as well, because of fuel spills, leaks in the fuel storage tanks, and the diesel exhaust emissions. The wind turbines and battery bank installed in Wales will be integrated with the existing diesel generators to form a hybrid system. The energy storage provided by the battery bank will reduce the need to run the diesel generators for the short periods of time when the wind turbines cannot generate enough power to meet the load. The battery bank chosen for Wales is made up of 200 cells connected in series. It has an overall voltage of 240 Volts and a capacity of 130 Amp-hours, which means that can support entire average Wales load, which is 75kW, for about 15 minutes, since in practice only about

60% of the nominal battery capacity is usable. The regulation between the usage of battery power, wind power and diesel power is controlled by a Programmable Logic Controller (PLC) that is now on-site.

The long-term goal for this project is to use a smaller PLC to create a complete self-contained battery monitor package that can be attached to the battery bank of any photovoltaic, wind, or hybrid power system. It is also hoped that some of the battery monitor's software can be integrated into the software of the Wales PLC.

The Battery Monitoring Algorithm

My project began with the development of an algorithm and a flowchart (see appendix) specifying how the battery monitor should perform. The monitor should first check for new user inputs or reset commands. A new user input would cause some of the parameters to be recalculated, and reset commands would cause certain types of variables and totals to be reset to zero. The monitor will then continuously log the voltage of the battery bank, the current in each string, and the temperature at up to four different locations. It checks these values to determine if they are new maxima or minima for their respective channels. Next the power that is flowing into or out of the battery (and each string separately) is calculated.

At one-second second intervals, average voltage, current and power values are calculated. This average current is converted to the number of Amp-hours into or out of the battery bank in the past second, which is then used to calculate the state-of-charge (SOC) of the battery. The updated SOC level is subsequently checked to see if it is a new maximum or minimum value. The total number of Amp-hours and kilowatt-hours of power coming into or out of the battery are also updated each second.

At one-minute intervals, the one-minute average voltage, current, temperature and SOC are calculated, and these are used to update the overall voltage, current, temperature and SOC averages. The one-minute temperature and SOC averages are added to the data being used to create temperature and SOC distribution histograms.

Next, the monitor checks to see if the current through the battery has changed directions. If it has not, then the accumulating totals for event magnitude and duration continue to be updated. If it has, then the battery has just switched either from charging to discharging, or from discharging to charging. For illustration, say the battery has just switched from charging to discharging, meaning that the current has gone from positive to negative. (The same process is used when the battery has switched from discharging to charging.) First, the magnitude in Amp-hours and duration in hours of the past charge are calculated. If the magnitude is greater than one percent of the battery capacity, it is significant enough to be considered a separate charge event. In this case, the magnitude, rate and duration of the charge event are used to update their respective distribution histograms. These histograms characterize the battery's cycling profile. A count is also kept of the total number of charge events and it is increased by one. If the magnitude is less than one percent of the battery capacity, however, the past charge is not counted as an event, and its statistics are instead combined with the previous and subsequent discharges to make one large discharge event.

Finally, if the hybrid control system signals that the end of a boost charge has occurred, then an internal DC resistance measurement is requested. (A boost charge is the use of a specific, controlled current to equalize all battery cells at full charge. It is the only time that the battery bank is certain to be at 100% SOC.) To make a DC resistance measurement, two distinct and relatively static current and voltage readings are needed, so that the change in voltage can be divided by the change in current: $\Delta V/\Delta I = R$. The measurements and their characterizing statistics are stored in structures similar to arrays, so that each piece of data from the same measurement can be easily accessed at the same time. In addition, their storage arrangement will make it easier to compare the resistance values over time so trends in the health of the battery bank can be inferred. To be able to compare these values, though, they need to have been made at the same SOC level. That is why DC resistance measurements are requested only after a boost charge.

When a DC resistance measurement is requested, statistics describing the time, date and state of the battery bank are first recorded. The monitor then checks to see if the first current level (Current1) has been determined. If it has not, it checks if the instantaneous current reading is within the allowed deviation from the value stored as the candidate Current1. If it is not, then a new current and voltage level are stored as the new candidates for the first current level. If it is within this deviation, then the current is considered to still be "constant." The monitor then checks the timer to see if the current has been "constant" for long enough to qualify as Current1 for the resistance measurement. If it has not been long enough, then the timing continues until the next scan through the program. If it has been long enough, then the first current and voltage levels have been determined, and a candidate value for the second current level (Current2) is stored. Next the battery monitor checks if the current has changed direction since Current1 was determined. If it has, and as long as Current1 is not approximately zero, the search for Current1 must begin again. (The DC resistance measurement must be made while current is flowing in the same direction, or it cannot be accurate. But if Current1 is approximately zero, which is the ideal case, then the current has not actually changed directions.) If it has not, or if Current1 is approximately zero, then the monitor checks if the instantaneous current is too close to the value for Current1, or if it is not within the acceptable deviation from the candidate for Current2. If either of these are the case, then a new value is stored as the candidate for Current2 and the timer for a "constant" Current2 is reset. If the current is significantly different from Current1 and it is still "constant," then the monitor checks if it has been "constant" for long enough. If it has not, then the timing continues until the next scan through the program. If it has, then a value for Current2 is determined and the voltage at this level is stored. The change in voltage can then be divided by the change in current to get the DC resistance, and the request for a DC resistance measurement is ended. Throughout the search for Current1 and Current2, the monitor also checks if the SOC level is at least 98% and if the time limit for the DC resistance measurement is exceeded. If either of these is ever true, then the request for a DC resistance measurement is ended, but without having calculated a resistance value.

Implementation of the Battery Monitor

The battery monitor is implemented on a DirectLogic 250 PLC, with the capability to use up to eight input/output modules. It currently has five input/output modules: an eight-bit input simulator, an eight-bit output relay, an eight-channel analog input, an eight-channel analog output, and a four-channel temperature module. Two of the modules are used only for debugging the program: the digital input simulator and the analog output module. The digital input simulator has eight input channels that can be switched on or off to simulate digital input bits. The analog output module is capable of generating up to eight output channels. They are fed directly into the analog input module to simulate the analog voltage and current inputs (up to eight channels as well) that would in practice come from transducers measuring the battery bank voltage and currents. The third module, an eight-bit output relay module, is not yet in use, but could later be incorporated if the battery monitor is made to perform additional functions, such as connecting a dump load to the battery for a DC resistance measurement or applying an AC voltage for an impedance measurement. The two modules that will be currently used by the monitor are the analog input module and the thermocouple module. The analog input module will read in the battery bank voltage, and the current of each of the battery strings in the bank, up to three. It has reserved four channels to read in the AC voltage and current if an impedance test were later implemented. The thermocouple module will read in the temperature at up to four locations on the battery bank. Temperature is measured because it is an important factor in battery life (a high operating temperature can lead to premature failure), and it also affects the battery's performance characteristics.

A Quickpanel Jr. five-inch color touchscreen has been programmed as the interface between the PLC and the user. It contains several different panels that display all of the battery usage data that has been logged, including all of the distribution histograms. It will also allow the user to enter several parameters that affect the program calculations. Both the touchscreen and the PLC were programmed using specialized computer application software.

Results

At this point, a program for the battery monitor has been constructed that performs all of the above functions. The analog output module has been used to debug the program by wiring its outputs directly to the analog input module. Three different sets of data have been used to test the functioning of the PLC. A graphical representation of one set of test inputs and some of the data generated by the PLC in response to them are shown in the Appendix. The inputs of this particular set are a repetition of two distinct charge-discharge cycles. They were used especially to test the effectiveness of the program section that calculates charge and discharge statistics. It was found that the values calculated by the PLC for the charge and discharge statistics (i.e. magnitude, duration and rate) were within 5% of the theoretical values.

Most of the touchscreen panels have been programmed as well, and the touchscreen has been linked to the PLC. It appears to accurately display the data stored by the PLC. (Two sample touchscreen panels are shown in the Appendix, as well.) The complete monitor has not yet been assembled into a single compact package, and it remains to be tested on an actual battery bank.

It has been observed that the program scan time is not consistent, and this has the ability to affect average values when they change rapidly. Because the calculations assume that each reading of temperature, voltage or current is equally spaced, and the test inputs are cycled repeatedly through the same thirty to fifty values, unequal scan times weighted some values more than others. This has the potential to introduce a source of error into the program.

Discussion and Conclusions

The test data used for debugging the PLC program changed more rapidly and discontinuously than is realistic, and so it is reasonable to assume that the error discussed above will not be a factor in the actual operation of the battery monitor. However this assumption should be tested with more realistic data sets. If necessary, one way to fix the problem would be to multiply each value by the instantaneous scan time of the program (a value generated by the PLC itself), instead of averaging all of the values for each second. This way the values would not be weighted disproportionately to their scan times.

There are several previously mentioned tasks that remain to be completed before the battery monitor can be implemented in the field. Some additional testing with more realistic sets of data would be beneficial. The complete battery monitor package, with voltage and current sensors, and thermocouples, also needs to be designed and assembled.

After construction, the battery monitor will likely be tested at the Battery Test Facility at the National Renewable Energy Laboratory, and then tested on the system in Wales. If it is successful, it is hoped that the monitor can be then be reproduced and used with other wind-diesel hybrid systems, as well as with wind and solar power systems that use battery banks for energy storage.

Acknowledgments

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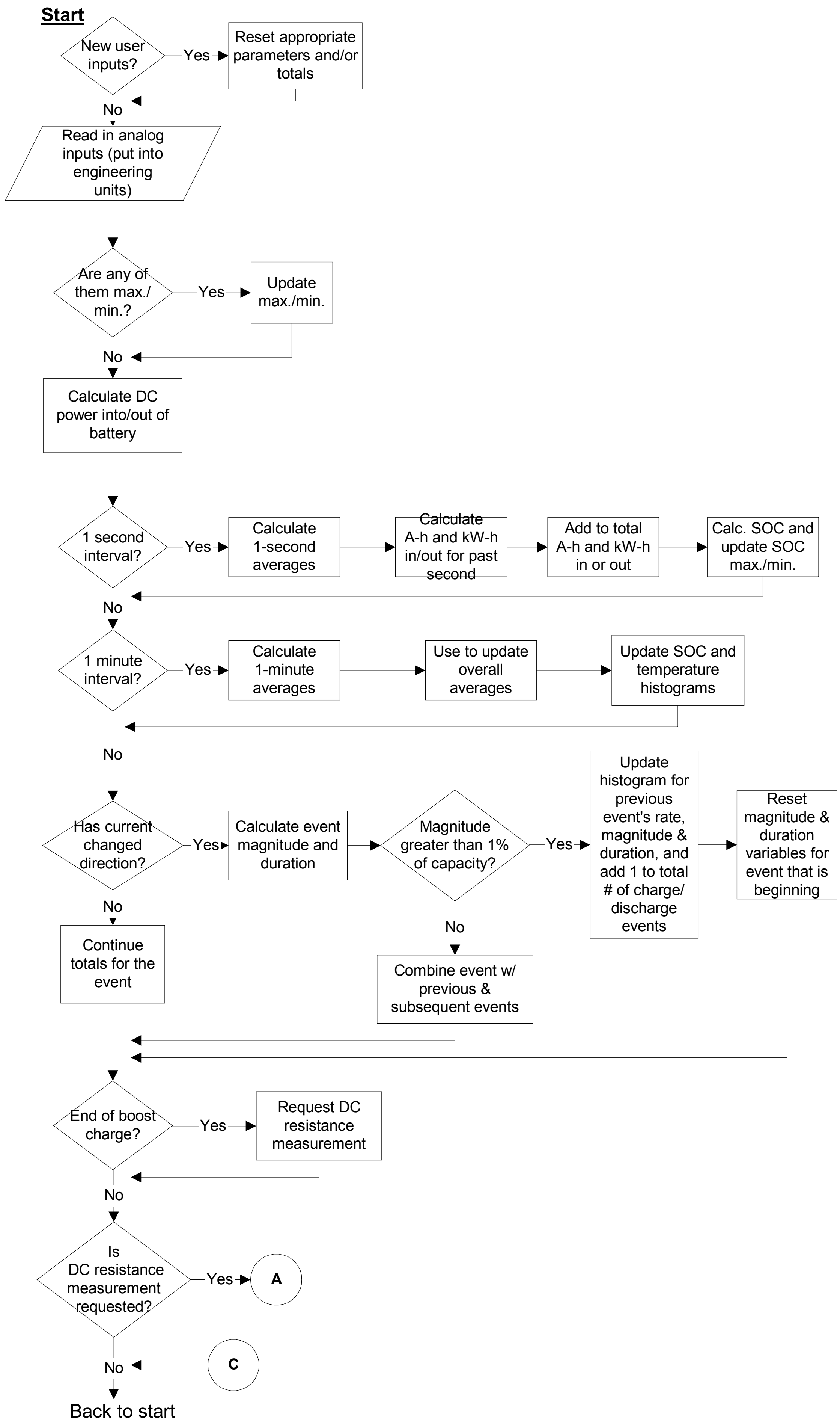
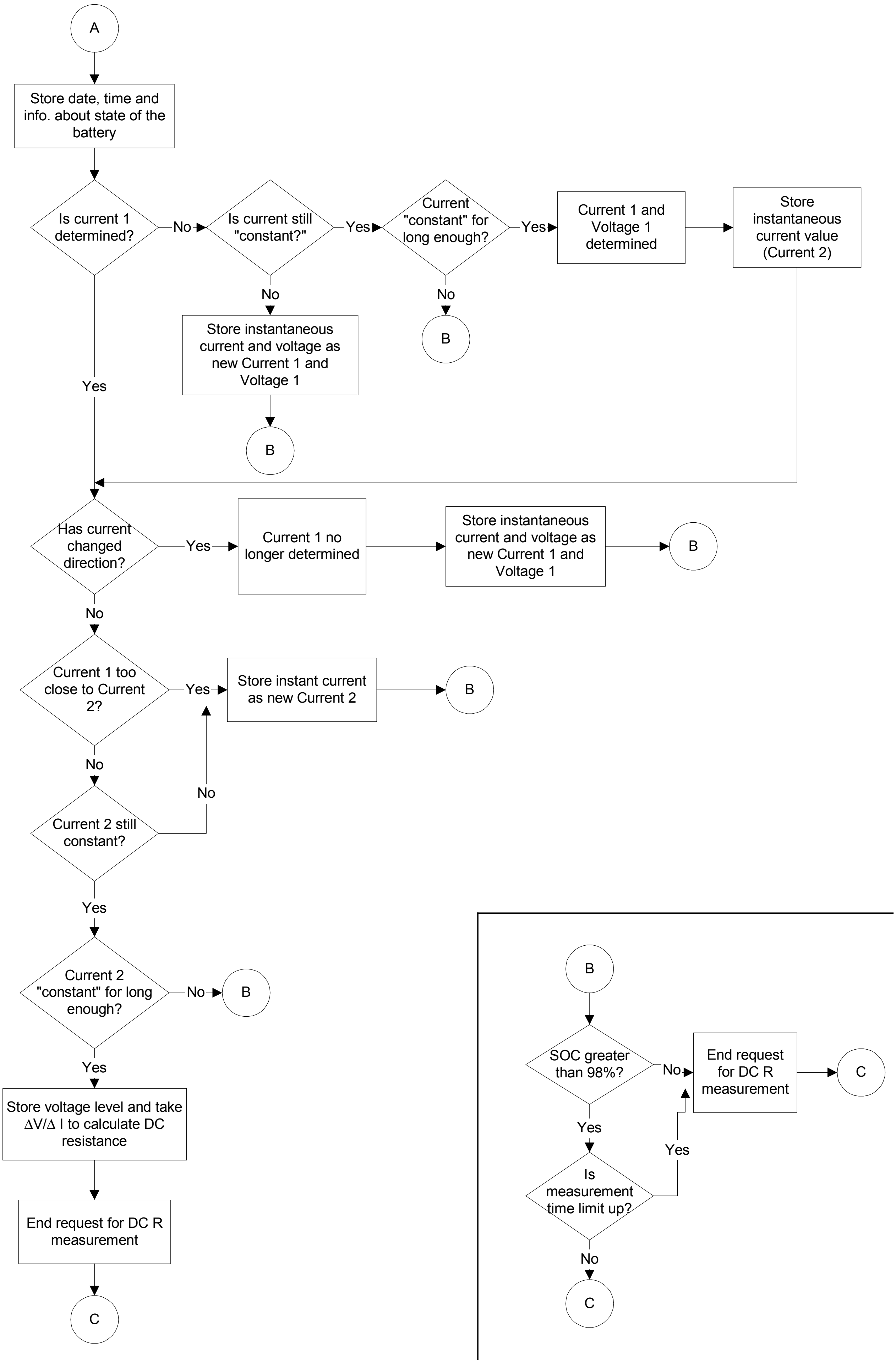
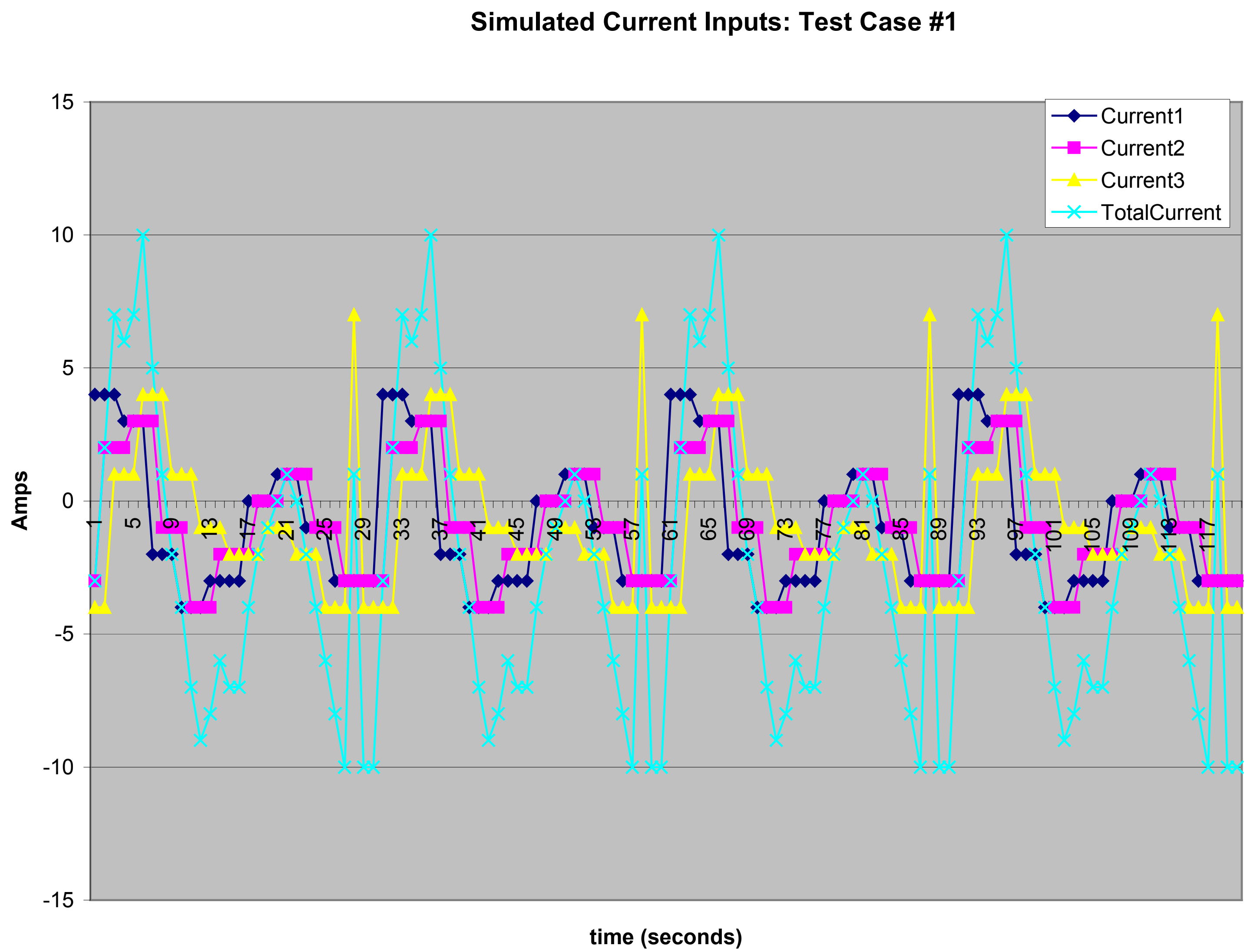
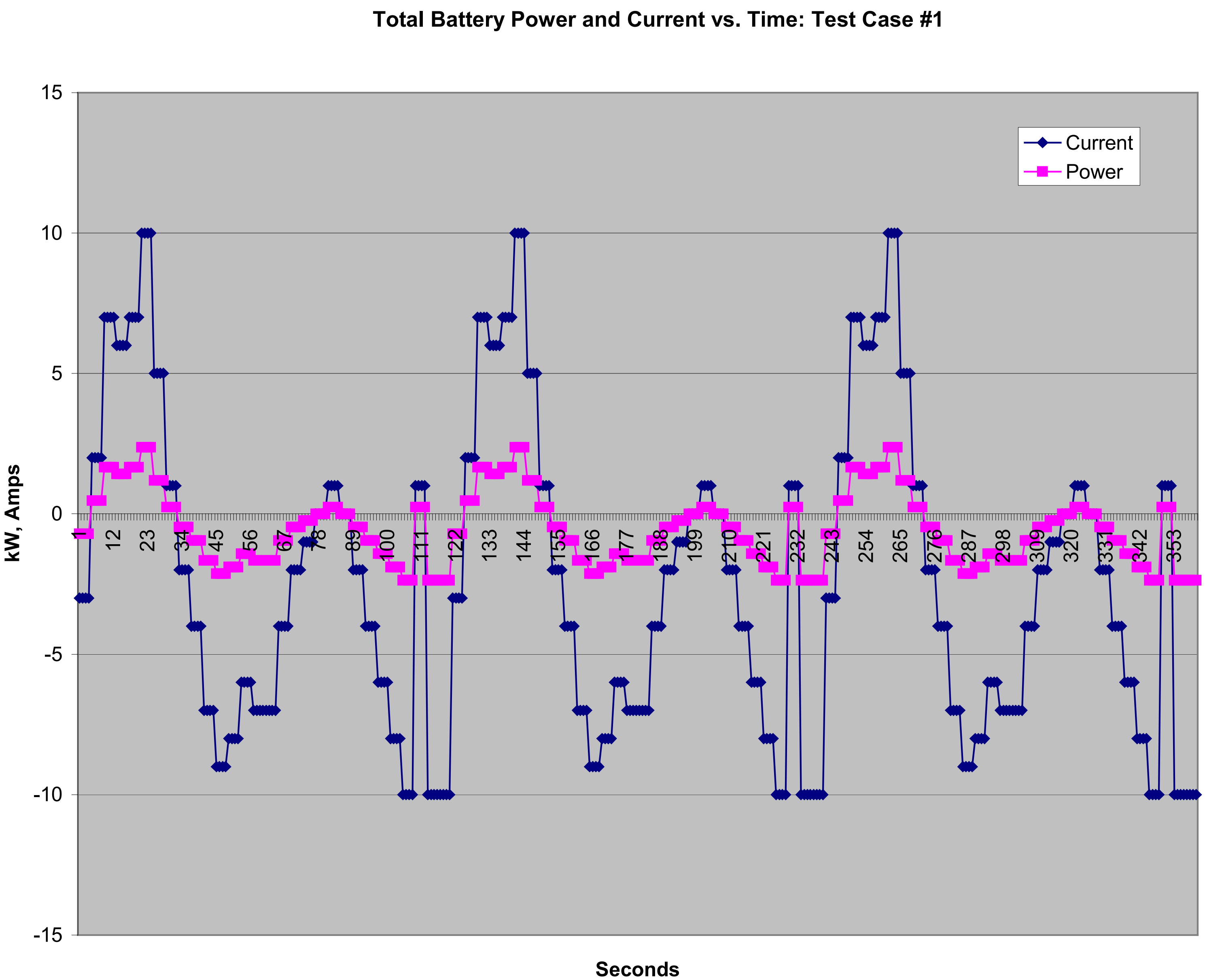
I would also like to thank my mentor Steve Drouilhet for his guidance in the development of my project, and also Mari Shirazi and the rest of the staff at the National Wind Technology Center. In addition, my thanks go to Linda Lung as the representative of the ERULF program at NREL.

The research described in this paper was performed at the National Wind Technology Center, which is part of the National Renewable Energy Laboratory in Golden, Colorado.

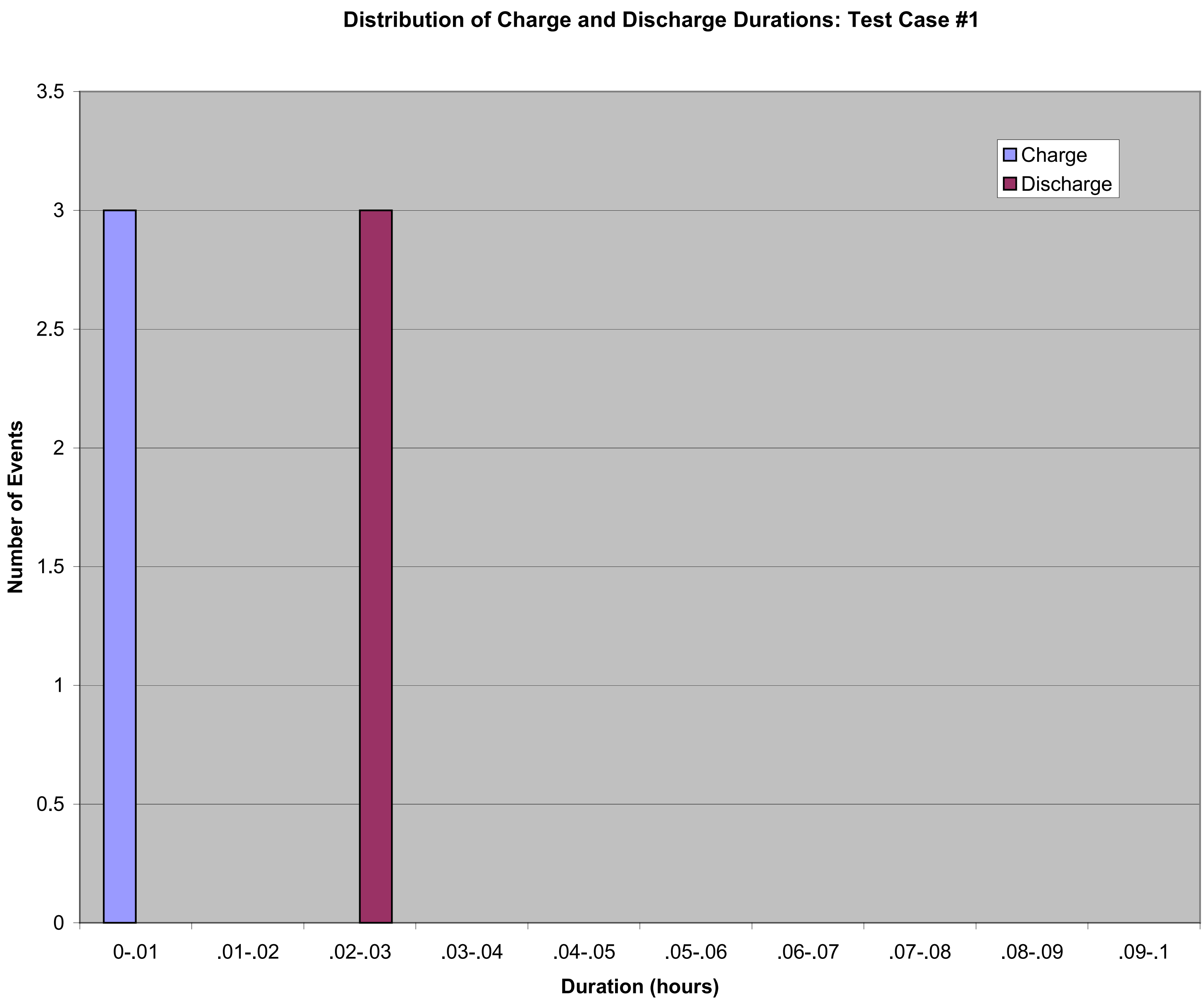

Start
New user inputs?
Yes
Reset appropriate parameters and/or totals
No
Read in analog inputs (put into engineering units)
Are any of them max./min.?
Yes
Update max./min.
No
Calculate DC power into/out of battery
1 second interval?
Yes
Calculate 1-second averages
Calculate A-h and kW-h in/out for past second
Add to total A-h and kW-h in or out
Calc. SOC and update SOC max./min.
No
1 minute interval?
Yes
Calculate 1-minute averages
Use to update overall averages
Update SOC and temperature histograms
No
Has current changed direction?
Yes
Calculate event magnitude and duration
Magnitude greater than 1% of capacity?
Yes
Update histogram for previous event's rate, magnitude & duration, and add 1 to total # of charge/discharge events
Reset magnitude & duration variables for event that is beginning
No
Combine event w/ previous & subsequent events
No
Continue totals for the event
End of boost charge?
Yes
Request DC resistance measurement
No
Is DC resistance measurement requested?
Yes
A
No
C
Back to start


A
Store date, time and info. about state of the battery
Is current 1 determined?
No
Is current still "constant?"
Yes
Current "constant" for long enough?
Yes
Current 1 and Voltage 1 determined
Store instantaneous current value (Current 2)
No
Store instantaneous current and voltage as new Current 1 and Voltage 1
B
No
B
Yes
Has current changed direction?
Yes
Current 1 no longer determined
Store instantaneous current and voltage as new Current 1 and Voltage 1
B
No
Current 1 too close to Current 2?
Yes
Store instant current as new Current 2
B
No
No
Current 2 still constant?
Yes
Current 2 "constant" for long enough?
No
B
Yes
Store voltage level and take ΔV/Δ I to calculate DC resistance
End request for DC R measurement
C
B
SOC greater than 98%?
No
End request for DC R measurement
C
Yes
Yes
Is measurement time limit up?
No
C


Simulated Current Inputs: Test Case #1
Amps
time (seconds)
Current1
Current2
Current3
TotalCurrent
15
10
5
0
-5
-10
-15



Total Battery Power and Current vs. Time: Test Case #1
15
10
5
0
-5
-10
-15
kW, Amps
Current
Power
1
12
23
34
45
56
67
78
89
100
111
122
133
144
155
166
177
188
199
210
221
232
243
254
265
276
287
298
309
320
331
342
353
Seconds


Distribution of Charge and Discharge Durations: Test Case #1
Charge
Discharge
Number of Events
3.5
3
2.5
2
1.5
1
0.5
0
0-.01
.01-.02
.02-.03
.03-.04
.04-.05
.05-.06
.06-.07
.07-.08
.08-.09
.09-.1
Duration (hours)

Percent State-of-Charge Distribution: Test Case #1

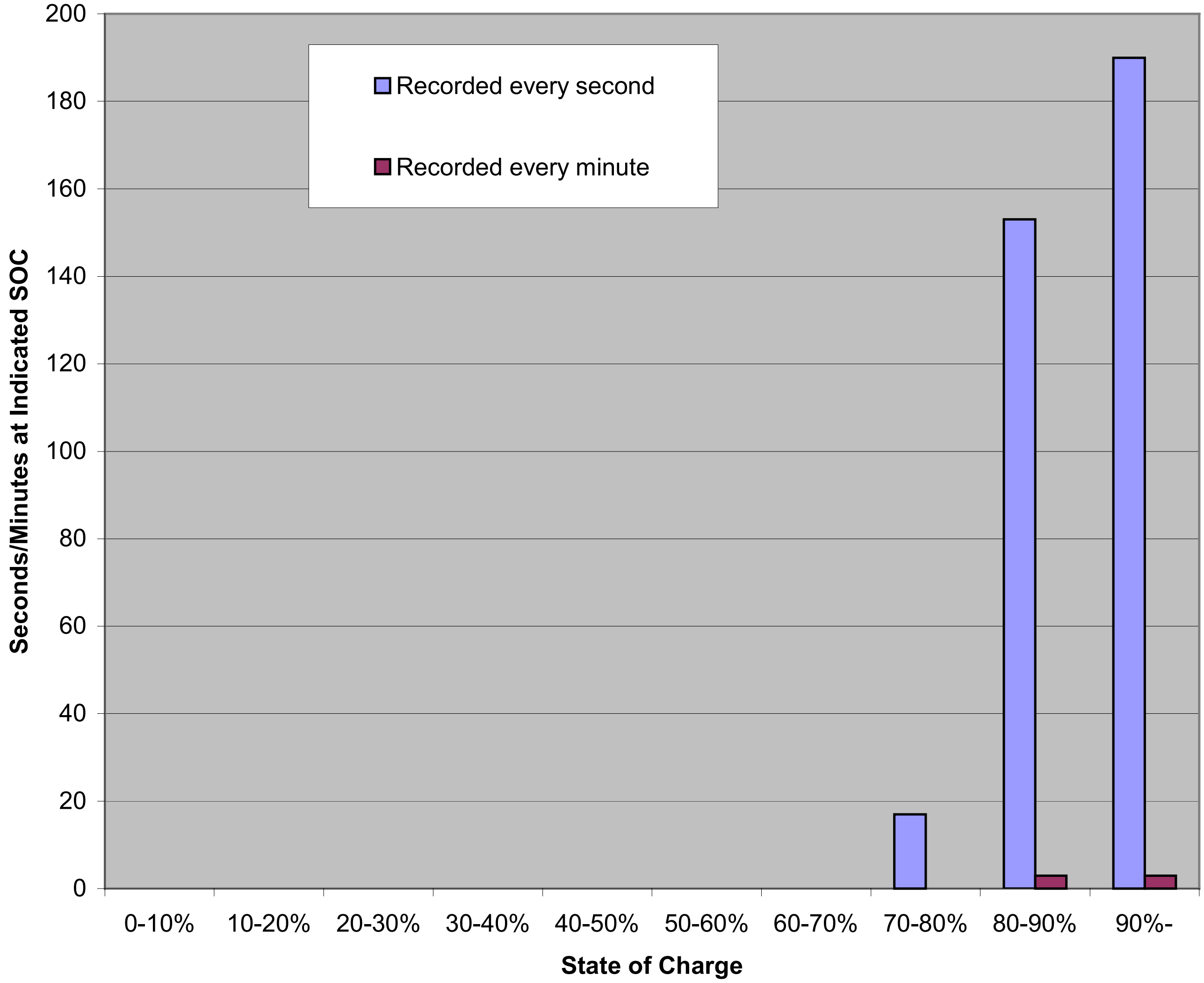
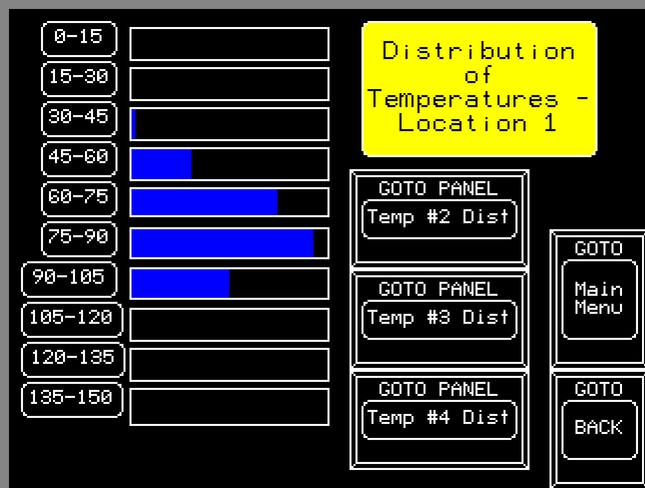


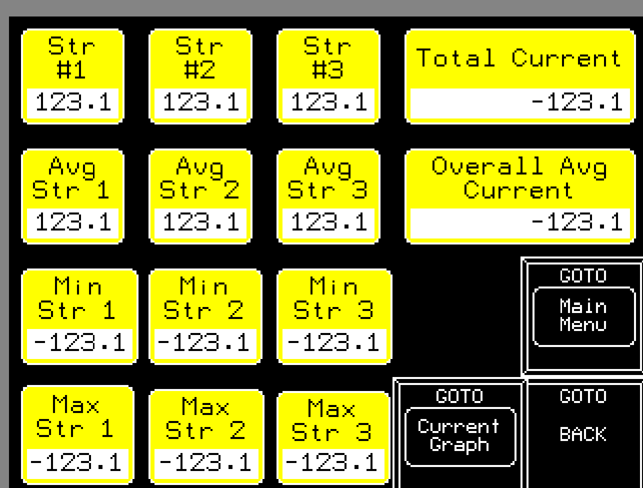
Table of Minimum, Maximum and Average Values: Test Case #1

	Min	Max	Average
V	237	237	237
Cur1	-4	4	-0.8
Cur2	-4	3	-0.75834
Cur3	-4	7	-0.76667
TotCur	-10	10	-0.775
SOC	0.766667	1.038889	0.91312

All Data is for first 6 minutes of runtime!



Sample touchscreen panel showing a temperature distribution histogram.



Sample touchscreen panel showing data on current strings, and overall current in battery.