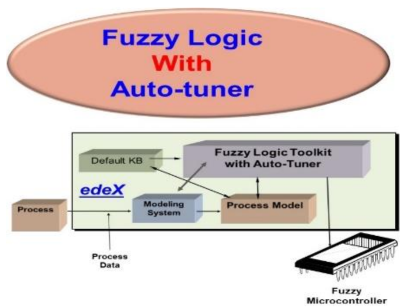
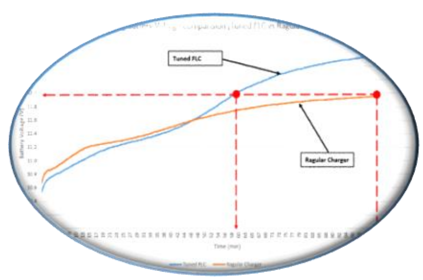
Advanced Battery Charging Management

Using

Xiera's Fuzzy Logic Control (EdeX-FLC)





Prepared by:	K. Nigim and D. Patel, Lambton College- Applied Research https://www.lambtoncollege.ca/research/
Industrial partner:	Dr. Talib Janabi, Alain Marsman, www.xiera.ca; Mehak Ghawar, Cenna Engineering
Sponsor:	GreenCentre Canada - IRAP program, https://greencentrecanada.com/

Acknowledgment:

The report is made of various sections compiled by Lambton College applied research team headed by Dr. Khaled Nigim. Special thanks to the Instrumentation & Control Engineering Technology (ICET) program graduate Mr. Darshankumar Patel for assisting in testing the EdeX-FLC. The research activity is part of Lambton Energy Research Centre (LERC) activities financed through a Greencentre Canada, IRAP program. Furthermore special thanks to LERC project coordinator Ms. Thi Aye and to director Dr. Stephen Reaume for their support throughout the preparation of the report. Special thanks to Xiera team; Dr. Talib Janabi, Alain Marsman and Mehak Ghawar for their fruitful discussion and for their support during the preparation of the report.

Executive Summary:

From the several experiments conducted on the batteries at different loading levels, it is realistic to conclude that the Lithium Ion batteries are more reliable in terms of efficiency, capacity and lifespan than the sealed lead acid batteries.

Using EdeX-FLC control topology resulted in time and energy savings when compared with the market ready battery chargers. In the conducted experiments, almost 10 minutes of energy were saved under EdeX-FLC control.

EdeX-FLC build-in data logging software provides extreme flexibility in collecting data during charging and discharging. Under EdeX-FLC the operator will have the opportunity to control the accumulated battery charge up to 100% in comparison with the market ready chargers that limit the capacity to 80%. Additionally, EdeX-FLC provides more options for safety as it can monitor both over and under voltage levels of the battery and prevent battery from damages.

Using configurable intelligent chargers, such as EdeX-FLC, provides fast, safe charging profile to meet different stacks of Li-ion cells without compromising battery life and safety. The conducted experiment indicated that by using EdeX-FLC controller the battery will accumulate more energy than when off-the-shelf controller is used by 15%.

Using EdeX-FLC set up requires less monitoring instruments to monitor the variable parameters of different sizes of battery cells stacks.

Table of Contents

Table of Figures

Introduction

The focus of the activities is to check the performance of the chargers on Lithium-ion battery using Xiera EdeX-FLC fuzzy logic card. EdeX-FLC is designed to tune process variables in both one input and one output mode and in multiple input multiple output control configuration. In this exercise, one input and one output mode are investigated. Xiera team in collaboration with Lambton College researchers tested auto-tuning knowledge-based fuzzy controller in a battery charging and discharging modes. Two types of batteries are selected for the investigation, namely; sealed lead acid and lithium ion battery. Data acquisition of the battery variables such as charging/discharging voltage and current were monitored during several cycles and tests. Several testing modules are used and data acquisition is specifically designed for the testing purpose. The charging characteristics under EdeX-FLC is compared with market ready battery chargers. The summarized assessment and testing results are presented in the following sections.

Batteries information

The research started by testing two types of batteries as shown in figure 1. The first one was a sealed lead acid battery (BatLAC) rated at 12 V, 4.5 Ah. The second battery was a Lithium ion battery (BatLION) made of three cells in series connection, each cell rated at 3.7 V, 2Ah.

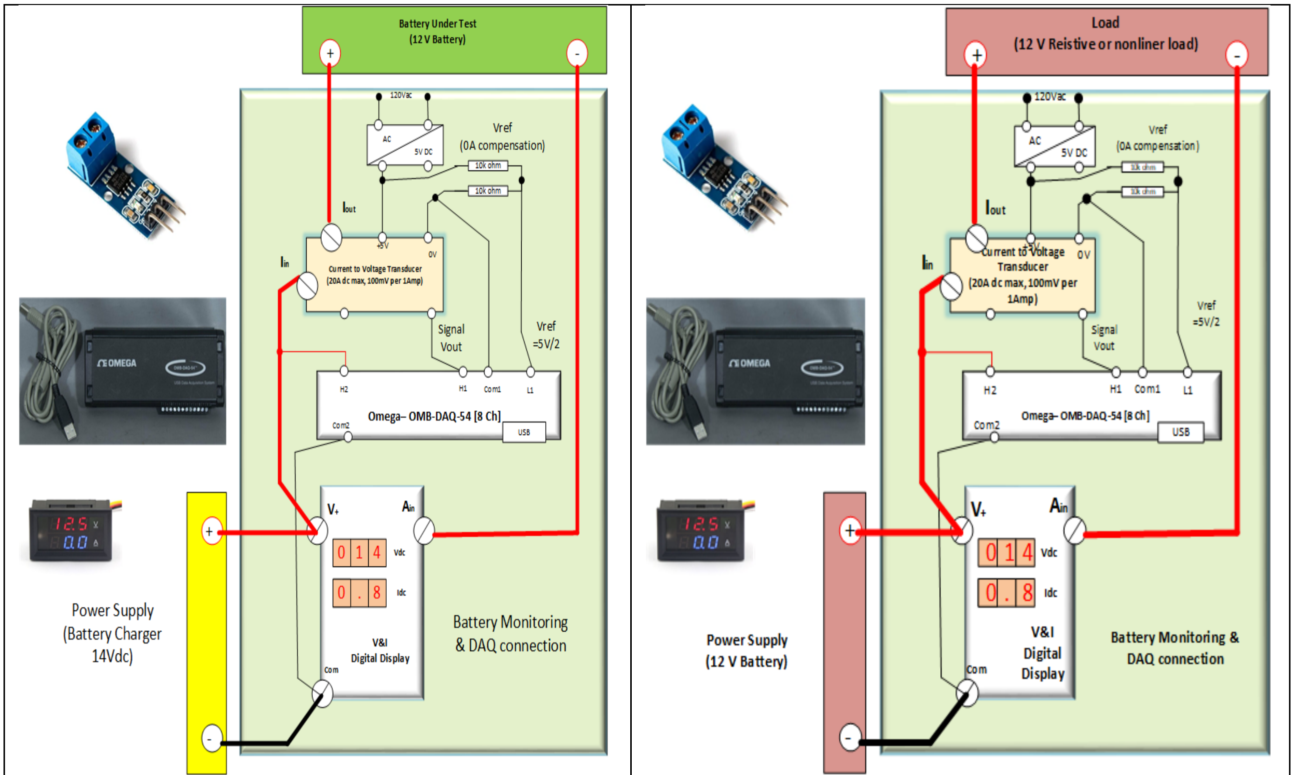
 a- (BatLAC)	 b- (BatLION) (3 cells connected in series)
Figure 1 12V Batteries used in testing a - Sealed lead acid battery , b-Lithium ion battery	

Sealed lead acid battery was charged with the charger shown in figure 2, and Lithium Ion battery was charged with the charger shown in figure 3. Both chargers are self-contained with protection and indicating LED light. A green light is lit once the battery is fully charged. The charger for sealed lead acid battery is rated for 14.5V/3A. The Lithium ion battery charger is rated for 12V/2A. Later, after using the market ready chargers, EdeX-FLC modules were introduced as alternative chargers for both batteries. The focus was to check if EdeX-FLC would minimise the charging period and allow maximum charge gained by the battery under test.

	
Figure 2 Charger for Sealed lead acid battery (SL-Chg)	Figure 3 Charger for Lithium Ion Battery (Li-Chg)

General Testing setup

A developed testing setup as shown in figure 4 is used for safe battery testing and variable data recording using either SL-Chg or Li-Chg chargers. The setup has the capacity to record the charging and discharging values of the voltage and current across the battery, and store the data in analogue data acquisition (DAQ) unit. An external dc voltage and current display was also used to double check the variables values while loading is taking place. For more information on the DAQ unit setup, refer to Appendix A1. Note the battery voltage is captured in volts while the battery current is sensed using 20 A hall-effect current sensor that produces mV output per amperage (120 mV)/A).



a- Charging the battery

b- Discharging the battery

Figure 4 Wiring layout during the charging and discharging of the batteries

Each battery was charged using its regular charger (Sl-Chg or Li-Chg) and was discharged using electronic loading unit, described later, that can be set to discharge a pre-set constant current. Each battery is loaded once, is fully charged and cut-off from the load at about 80 to 85% of its stored charge to avoid deep discharging and damaging the battery during the test.

Each battery was charged and discharged several times. It was observed that Li-ion battery stores and provides more energy than the lead acid battery as demonstrated later in the report. Based on several tests and comparisons between sealed acid and lithium ion batteries showed that the lead acid battery charging current profile differs from the lithium ion current. The same is observed for the voltage profile.

In using EdeX-FLC modules, figure 5 and 6, a protection element is incorporated to limit the charging current so that not to damage the Li-ion battery. Rechargeable batteries are sensitive to overvoltage and over current. Note that the battery variables captured using EdeX-FLC own data acquisition cards and tuning software. This is a key advantage in comparison with low cost market ready charging units particularly if the battery data needs monitoring as the cost of an independent DAQ unit alone might exceed $800.00.

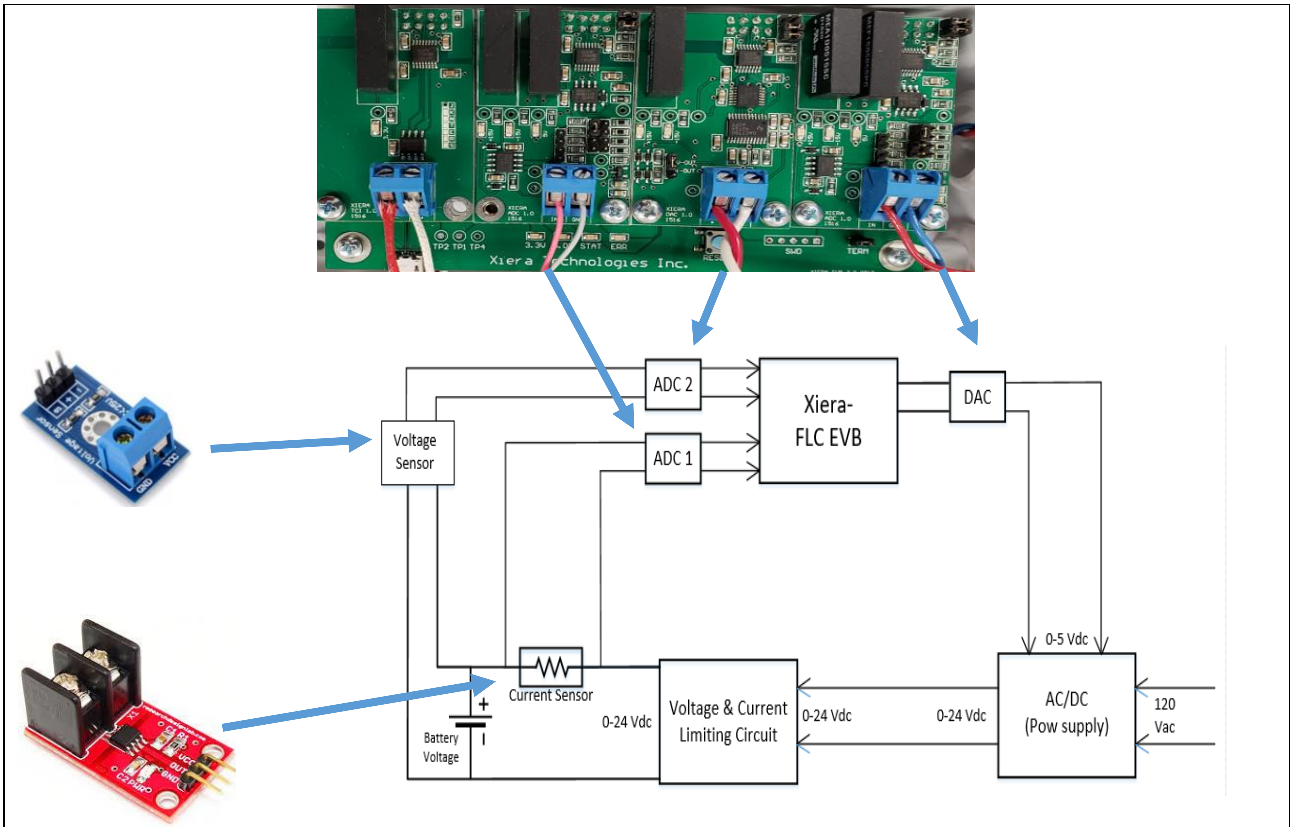


Figure 5 Wiring layout while using EdeX-FLC modules for charging batteries.
(Note the limiting circuit is specially adopted to this application).

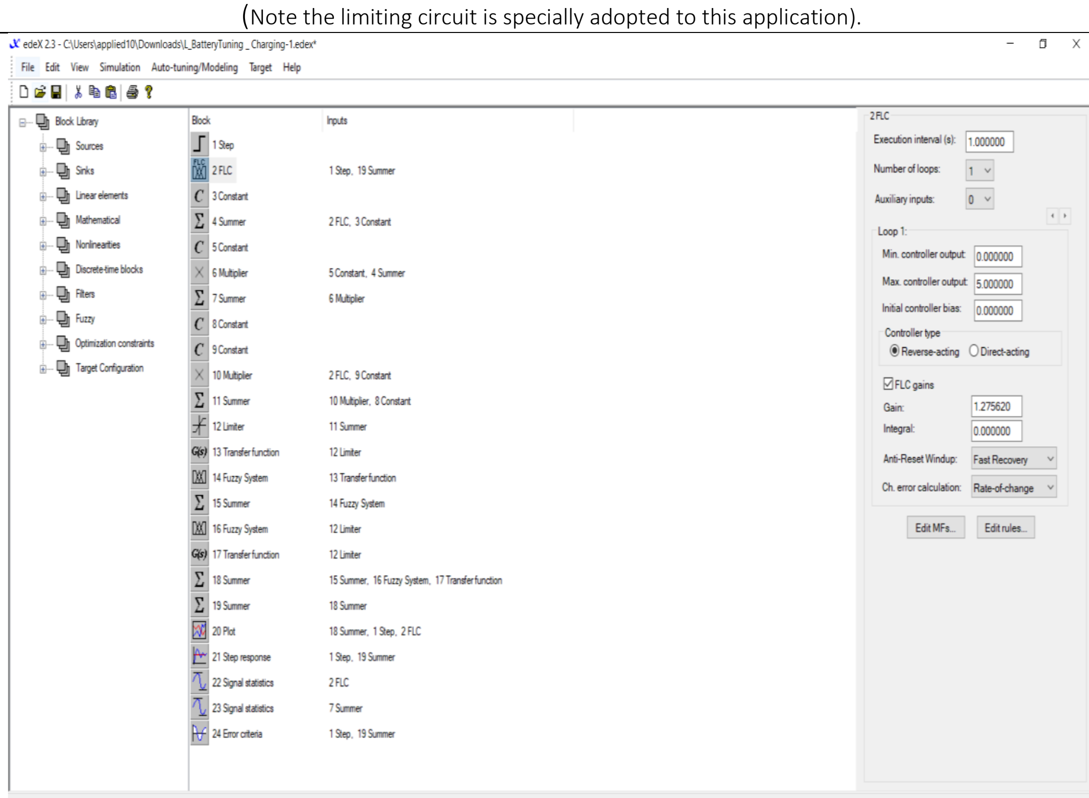


Figure 6 Screen print of EdeX modelling blocks of the fuzzy logic control loop needed for battery charging exercise

Electronic Discharging Unit

To protect the batteries during discharging, an electronic module used, figure 7. The unit configured to draw pre-set constant current and voltage. The loading unit can draw up to 10 A and has a cooling fan, which is activated once the internal component temperature exceeds 40ºC. When the fan is running, it will draw around 200 mA current. The fan current will cause minor fluctuations in the tested battery voltage.

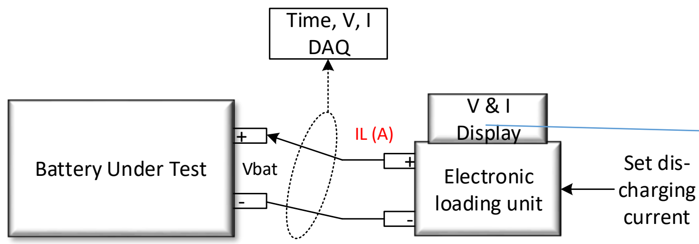


Figure 7 The electronic loading configuration

EdeX – FLC proposed battery charging control strategy

EdeX-FLC modules are modular in design with multiple controlling cards for interfacing various possibilities. This means, that several sensing cards needed integration as applicable to the required process control. Hence, EdeX-FLC needs configuration to work as battery charger for the intended purpose. In addition to EdeX-FLC modules, additional interfacing circuit is needed to ensure safe operation of charging the batteries. The battery charging current is maintained at constant value as specified in the manufacturer instruction. This is achieved by using constant current and constant voltage circuit as shown in figure 8. This circuit interface with EdeX-FLC cards prevents damage to batteries.

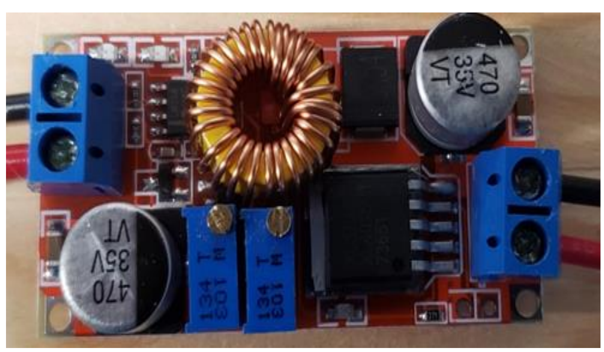


Figure 8 Constant current/voltage charger

To record the battery variables, a voltage sensor is used in which 25V is scaled down to 5V since EdeX-FLC modules can only accept a maximum of 10 V. The sensor calibration table is shown in appendix A3. Hall Effect current sensor used to measure the flowing current and used for interface with the EdeX-FLC modules. Therefore, the battery current is measured in V and scaled into ampere, appendix A4 shows the calibration table. In addition, appendix A5 shows the calibration table for EdeX-FLC digital to analogue card (EdeX-DAC) used to generate the output signal to control the charging voltage during the charging cycle.

Charging characteristics of the Lithium ion battery

Lithium ion batteries offer an excellent level of performance. To gain the best from them, they must be charged correctly. If lithium ion battery charging is not undertaken in the proper manner, the battery operation can be impaired and they can even be destroyed. Figure 9 shows typical charging characteristics of the lithium ion battery. Charging lithium ion batteries split into two main stages:

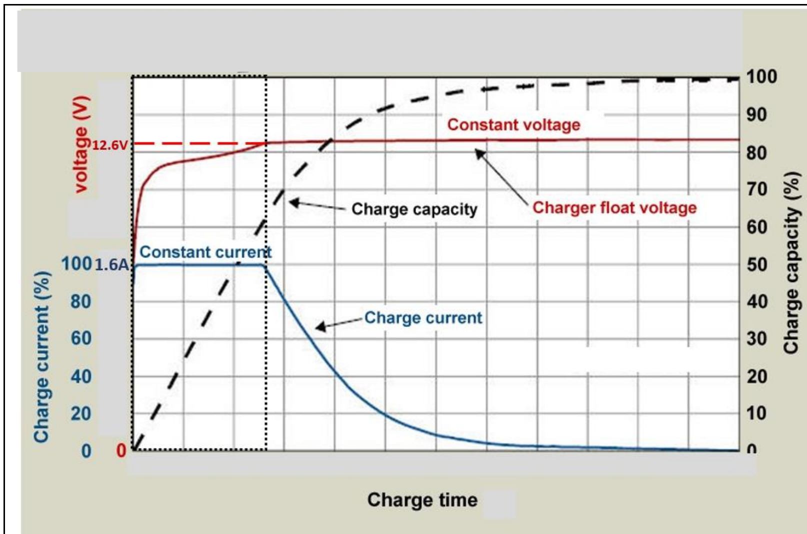


Figure 9 Charging characteristics of the Lithium ion battery
(https://batteryuniversity.com/learn/article/charging_lithium_ion_batteries)

Constant current charge: In the first stage of charging a li-ion battery or cell, the charging current is controlled. A charging rate of a maximum of 0.8C is recommended where C is 2.0 Ah for the Lithium ion battery pack. Hence, the recommended current is (0.8 x 2Ah = 1.6A). During this stage, the voltage across the lithium ion cell increases for the constant current charge.

Saturation charge: After a time the voltage peaks at around 4.2 Volts for a Li-ion cell. At this point the cell or battery must enter a second stage of charging known as the saturation charge. A constant voltage of 4.2 volts is maintained and the current steadily falls. The end of the charge cycle is reached when the current falls to around 15-20% of the rated current.

There are few important parameters that are needed to consider during the charging.

1. *Charging current*: The charging current must be limited for li-ion batteries. Typically, the maximum value is 0.8C. Even for batteries or cells that can withstand higher current charges, there is an impact on the lifetime. If it is possible to keep the charging rate down and not use fast charging, this will improve the useful life of the cell.
2. *Charge temperature*: The li-ion battery charge temperature should be monitored. The cell or battery must not be charged when the temperature is lower than 0°C or greater than 45°C.
3. *Charging Voltage*: The lithium ion cell has nominal voltage of 3.7V for each cell. It can charge to a voltage of 4.2. Charging beyond this causes stress to the cell and results in oxidation, which reduces service life and capacity. It can also cause safety issues as well. Therefore, when connecting three cells in series to generate 12 V battery pack, each cell is well charged and balanced. Twelve volts Li-ion batteries normally include charge-balancing elements as part of the pack.

Based on the charging characteristic of lithium ion battery, for our experiment the charging current must be set to 1.6A i.e. 0.8C or lower as the battery is rated for 2 Ahr capacity. The maximum charging voltage will be "12.6V" to charge the battery to its full capacity. The battery testing was conducted at the lab temperature (22degC) at all times; therefore, it was not necessary to monitor the temperature in the data logger.

Battery Charging Control strategy to tune the Li-Ion 12 V battery

After setting up the system to tune the FLC, an initial test is performed to identify the system boundaries. Based on the gathered data, a model is developed as shown in the figure 10. The generated output is shown in figure 10.

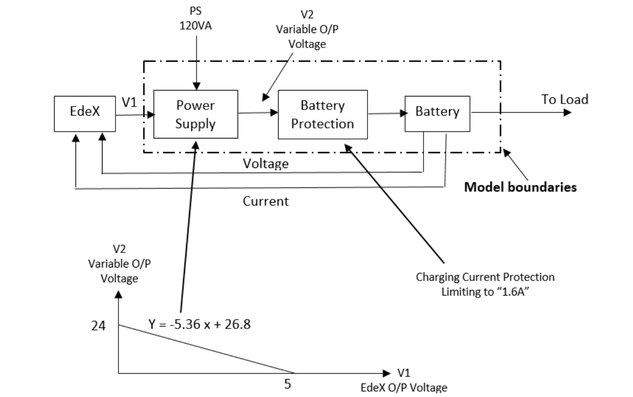


Figure 10 Control strategy used for tuning the EdeX - FLC

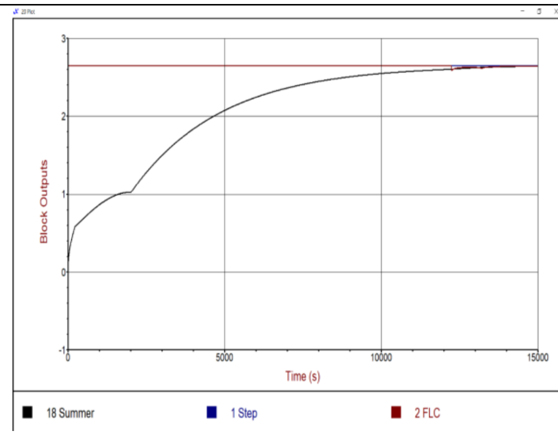


Figure 11 Response of the tuned FLC (Simulation)

The information is important to generate the tuned knowledge-base of the FLC. It is clear that the controller depicted the required charging profile as recommended by the manufacturer. The graph in figure 12 shows the Lithium Ion battery charging characteristics using the tuned FLC.

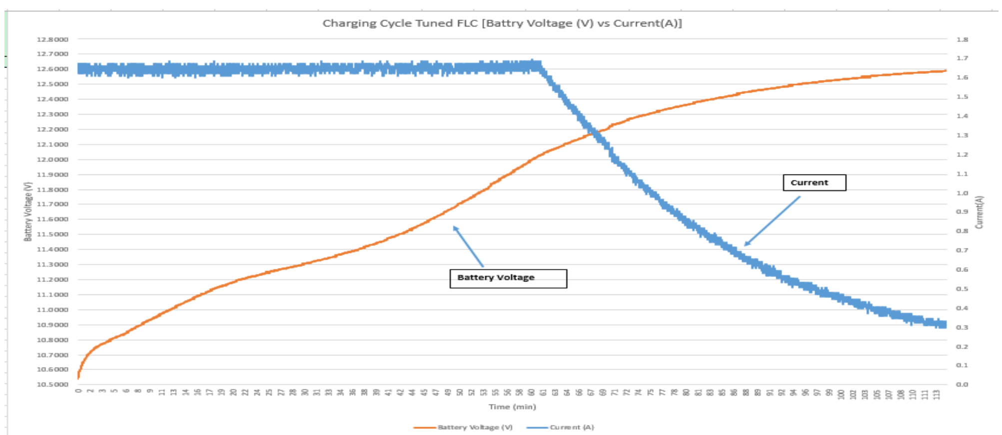


Figure 12 Charging Characteristics using tuned EdeX-FLC

The first phase of the charging cycle is constant current phase. During this time the charging current remain constant at "1.6V" while the battery voltage increases. From the graph, the charging current is constant for almost an hour. After that it proceeds into the second phase called the saturation phase, during which the battery voltage increases slowly while the charging current starts dropping gradually. The battery considered as fully charged when the charging current drops to 250 mA and battery voltage reaches 12.6V. The recommended charging rate for lithium ion battery is "0.8C". The regular charger (Li-Chg) uses the charging rate of "1C", but for FLC uses the "0.8C". The FLC charger has the flexibility to change this rate according to the user's requirement, which is not possible for regular chargers. Such characteristics would not be clearly visible if the Li-Chg is used.

Charging and discharging data recorded by EdeX-FLC software

Several tests were carried out using the testing set up shown in figure 4. However, it was more practical to use EdeX-FlC data collection and therefore, the next section focuses on the chargers behaviour recorded using

EdeX-FlC software. Using EdeX-FLC software has good advantage as there was no need for extra DAQ unit and its associated software. Figure 13 displays the data recorded for sealed acid, left column, and the lithium ion batteries, right column. This time batteries tested using the assigned regular controller, SL-Chg or Li-Chg, and later replaced by EdeX-FLC controller. In every set up the protection element shown in figure 5 was included.

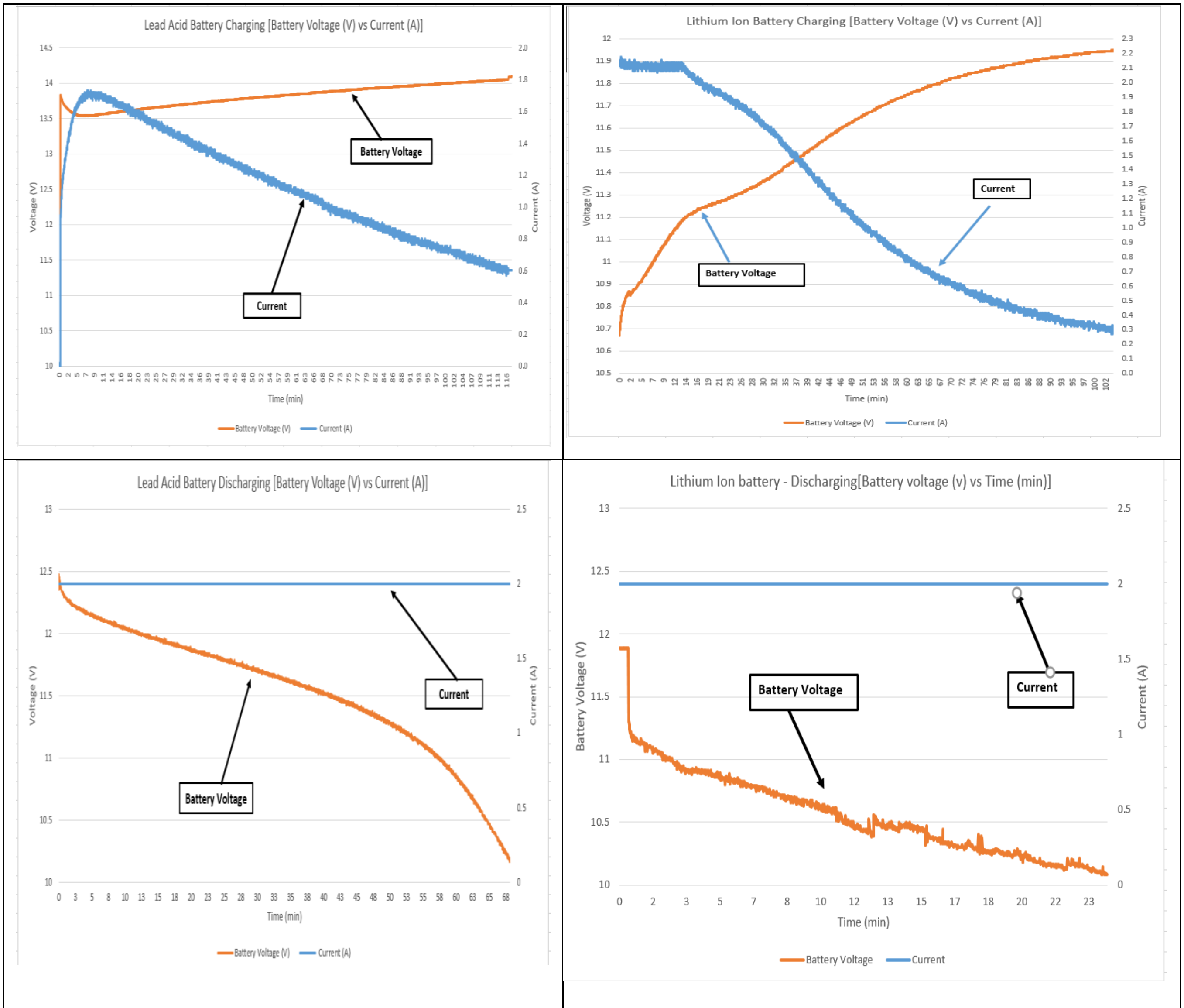


Figure 13 Charging and discharging characteristics of the tested batteries (data recorded using EdeX)

From figure 13, during the charging period EdeX controller followed the expected charging profile for both batteries. In particular, for the Li-ion battery, EdeX controller passed constant current and slowly decreased current as the battery accumulate more charge and the terminal voltage approached the desired value of the 12 V potential. It was concluded that EdeX-FLC controller followed exactly the recommendation of both batteries for safe charging profile under the specified safe limits of charging and discharging criteria. The following section will now focus on the Li-Ion battery performance under Li-Chg and under EdeX-FLC controllers respectively.

Li-Ion Charge and discharge performance

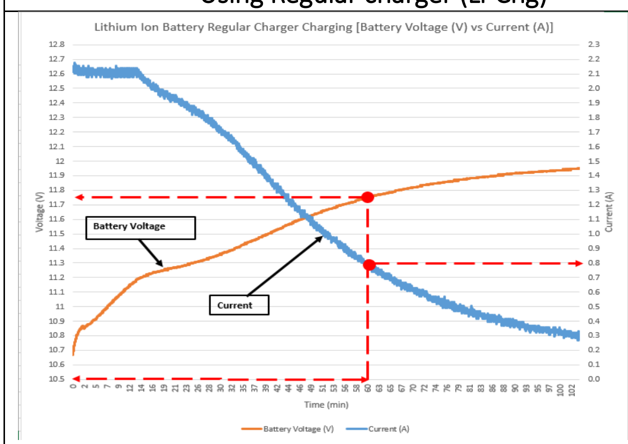
Figure 14 shows comparison of the Lithium ion battery charging and discharging characteristics under the control of the regular (Li-Chg) and Edex-FLC chargers. Figure 14 (a) the battery voltage increased by more than 10% after 20 minutes. While under the EdeX-FLC control, figure 14 (b), the voltage increased by 12.5%.

Using Li-Chg, battery voltage reached 98% of the rated voltage (11.8 V) in 67 minutes, while under EdeX-FLC it took 56 minutes, 10 minutes less. *Hence, the tuned EdeX-FLC is 15% faster than the regular charger that will result in more than 15% energy savings.*

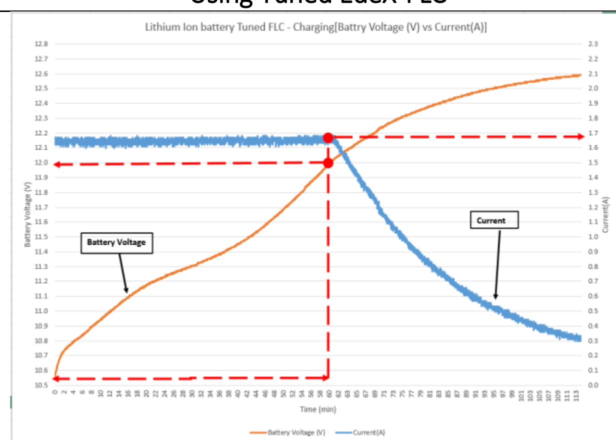
The maximum charging current was limited to 1.6A for almost 60 minutes under the tuned EdeX-FLC to ensure safe charging level. Meanwhile with the Li-Chg it was not possible to have control of the initial charging current that started at 2.2A and remained at 2.2A around 12min. *Hence, the tuned EdeX-FLC provides flexibility in controlling the initial charging current and therefore used safely to charge different stacks of cells assembly.*

During the discharging cycle, figure 14(c), the battery voltage dropped by 14.6% from its no load level meanwhile, it dropped by 10.4% from the no load level with Edex as shown in Figure 14(d). *This indicated that EdeX-FLC accumulated more charge in the battery in comparison with the regular charger. No load term is when the battery is in ideal state. When the load is applied to the battery the battery voltage will drop due to the load. We can observe this from the discharging graphs.*

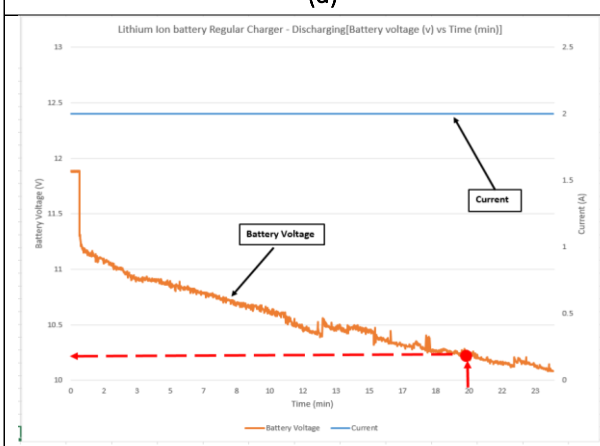
Using Regular charger (Li-Chg)	Using Tuned EdeX-FLC



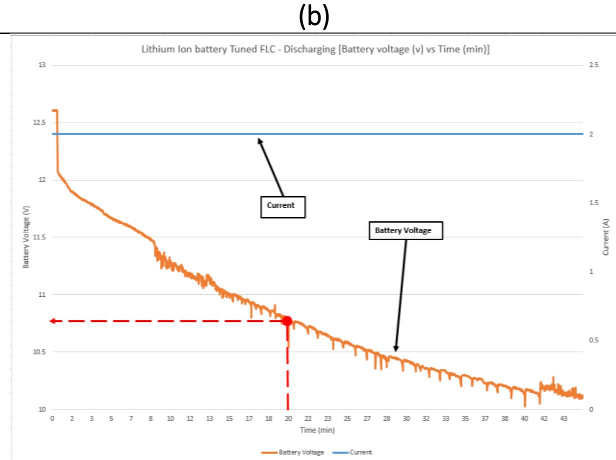
(a)



(b)



(C)



(d)

Figure 14 Charging and discharging characteristics Lithium ion battery

Closer comparison between the two controllers shown in figure 15. In figure 15(a) it took the battery voltage 104 minutes to reach the rated voltage level when the battery charged under the Li-Chg charger. Meanwhile, it took only 60 minutes under EdeX-FLC charging controller. In figure 15 (b) it took 52 minutes for the charging current to drop by 15% under the regular controller. Meanwhile, it took 75 minutes with the EdeX-FLC controller. This allows increase in accumulated battery capacity and provide more operational time for the connected load. The battery accumulated more charge to supply, figure 15(c) under EdeX-FLC and the load supplied longer than the battery when charged under Li-Chg.

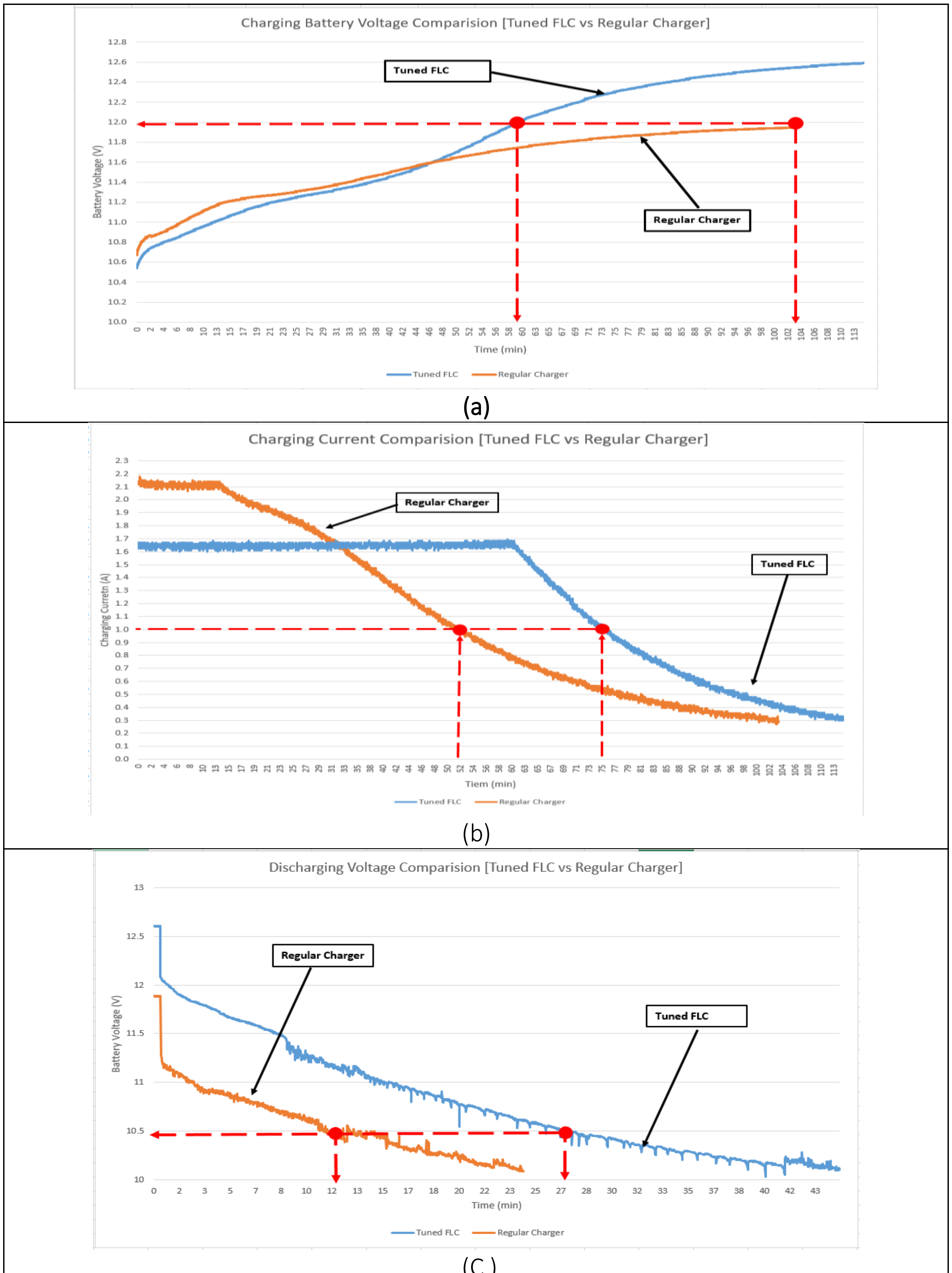


Figure 15 Closer comparison of battery voltage and current under the different battery charging controllers

It is important to note that battery voltage is not good indicator to how much is the battery accumulated energy. Battery voltage can reach the rated level after short period of charging time, while the charging current dropped to 50% of its initial charging level. It recommended that the charging current used to indicate to the accumulated energy. Once the battery stop consuming charging current it can be safely stated that the battery is fully charged.

Conclusion

This reported work was focused on testing the charging profile of Lead acid battery and Lithium ion batteries under two different controllers. Each battery was charged and discharged several times and only most relevant data is presented in this report.

From the several experiments conducted on the batteries at different loading levels, it is realistic to conclude that the Lithium Ion batteries are more reliable in terms of efficiency, capacity and lifespan than the sealed lead acid batteries.

Using configurable intelligent chargers, such as EdeX-FLC, provides fast, safe charging profile to meet different stacks of Li-ion cells without compromising battery life and safety.

The regular chargers can only charge the batteries up to 80-85% of its full capacity and the operator has no control on the initial charging current. EdeX-FLC provides 100% capacity under controlled charging current once tuned to the battery pack.

Furthermore, the EdeX's data logging function can be very useful for analysing the charging and discharging characteristics of the battery and eliminate the need for extra DAQ unit to monitor battery variables.

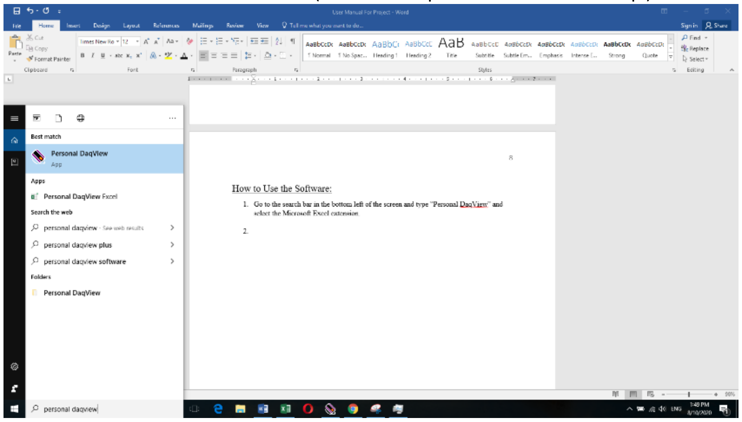
Additionally, EdeX-FLC provides more options for safety as it can monitor both over and under voltage levels of the battery and prevent battery form damages.

Using EdeX-FLC set up requires less monitoring instruments to monitor the variable parameters of batteries and can be used in various configurable battery cells stacks.

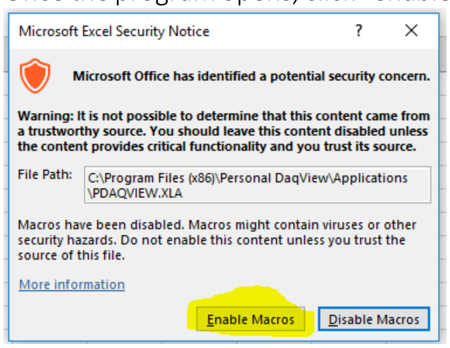
Appendices

Appendix A1 – DAQ setup

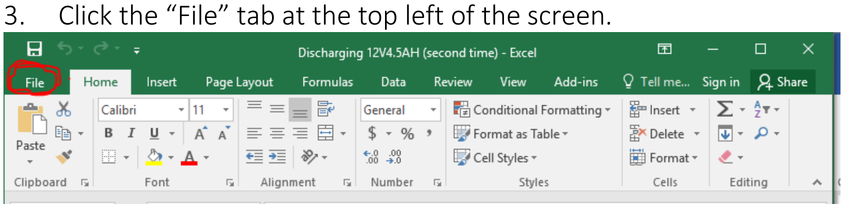
1. Go to the search bar in the bottom left of the screen and type "Personal Daqview" and select the Microsoft Excel extension (second option from the top).



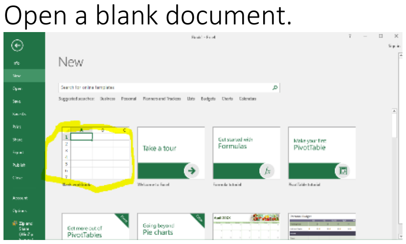
2. Once the program opens, click "enable macros" to be able to use personal Daqview and excel together.



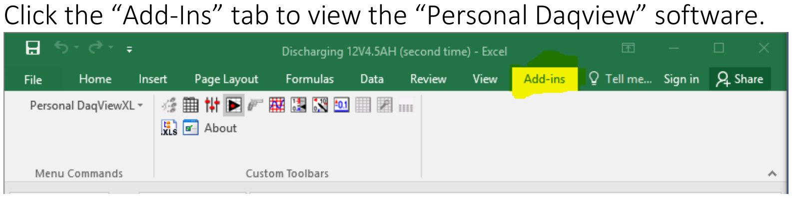
3. Click the "File" tab at the top left of the screen.



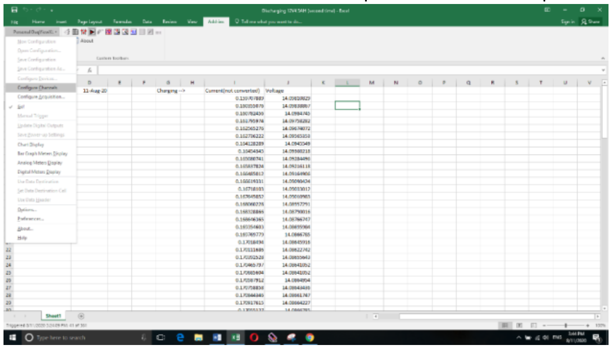
4. Open a blank document.



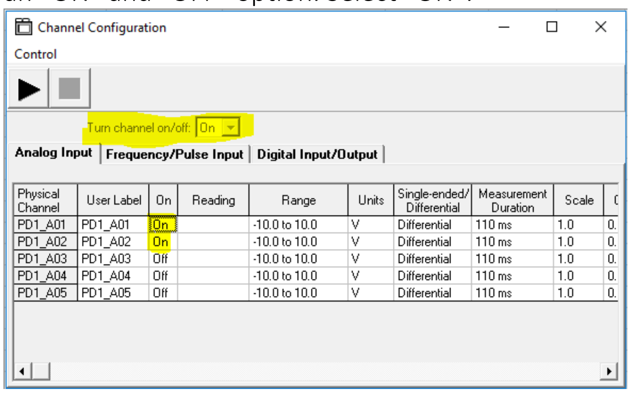
5. Click the "Add-Ins" tab to view the "Personal Daqview" software.



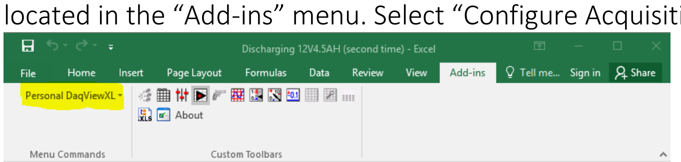
6. From the “Personal DaqViewXL” drop down menu, select “Configure Channels”.



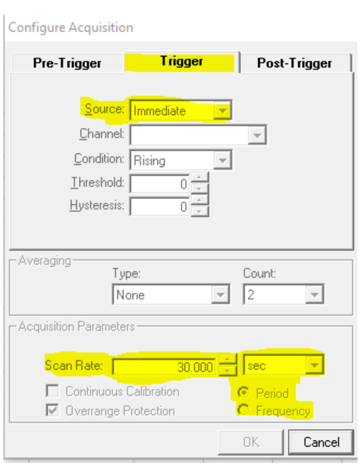
7. At this screen, click the first two channels under the “ON” row. To make sure both are turned on, click once where it says off next to the channel, then the drop down (highlighted above the chart) will have an “ON” and “OFF” option. Select “ON”.



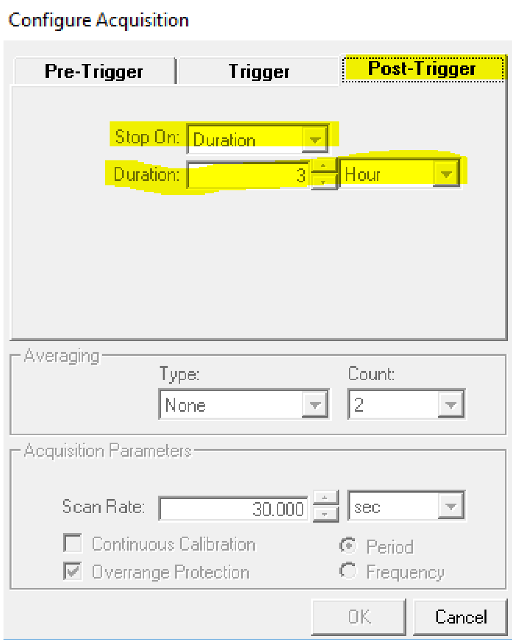
8. Close the “Channel Configuration” menu and return to the “Personal DaqViewXL” drop down menu located in the “Add-ins” menu. Select “Configure Acquisition”.



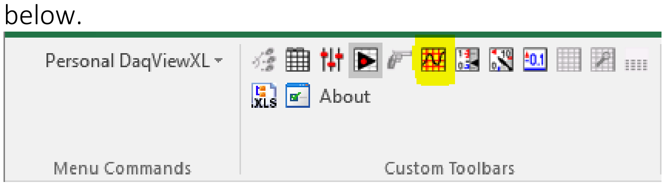
9. To set how often a scan will occur, at the bottom of the window, there is an option to choose whether the scan will happen based on period or frequency. For instance, in this example the program will be set to scan every thirty seconds as soon as the trigger button is clicked. (Note: Make sure under the “Trigger” menu the “Source” option is set to “Immediate”.)



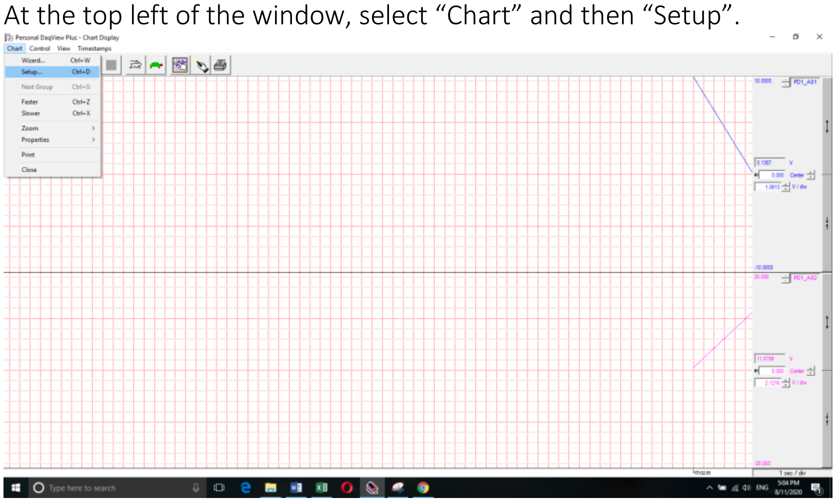
10. Without closing the above window, click the "Post-Trigger" tab. Set the "Stop On:" menu to "Duration" and select however long needed. In this example, the program is set to three hours. Select "OK" to apply settings and close the window.



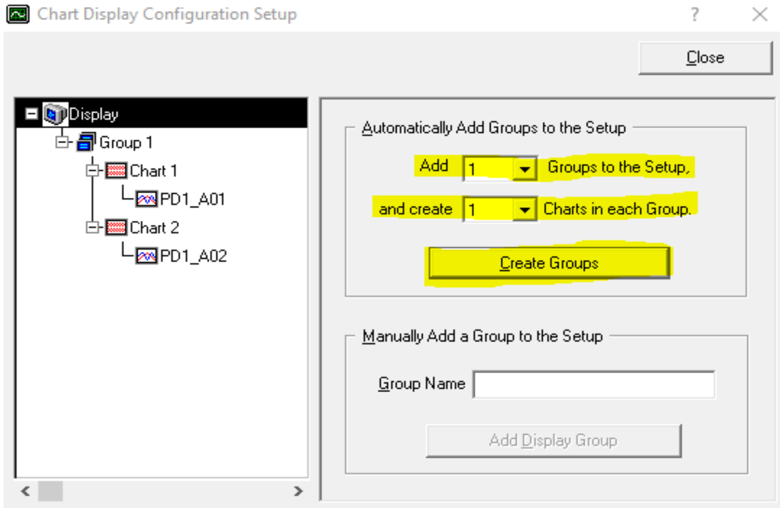
11. To view a live reading of the two channels that are "ON" in graph form, select the highlighted option below.



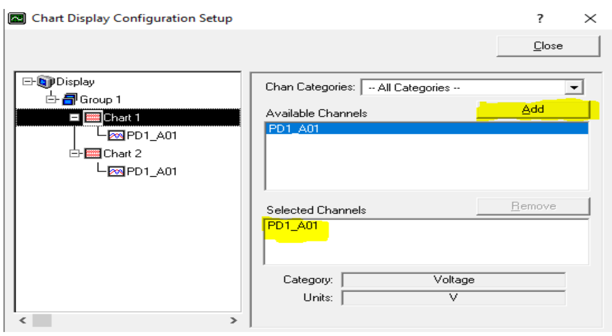
12. At the top left of the window, select "Chart" and then "Setup".



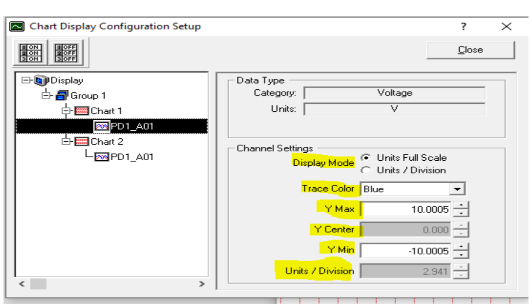
13. To add a group of charts to be displayed, select how many you would like to create and select how many charts you would like in each group. Then select “Create Groups”. Once this is completed, the groups and charts will show up on the left, just like in the picture below.



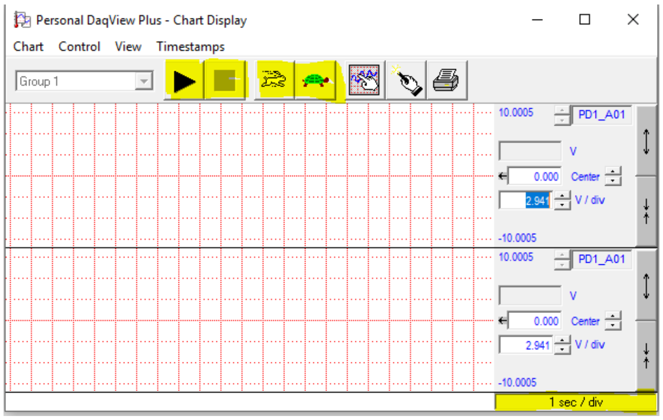
14. Click on the “Chart 1” portion of the drop-down menu on the left of the window. Then click on “PD1_A01” under the “Available Channels” section so it becomes highlighted in blue, and then click “Add”. This will make the reading from the L1 and H1 on the OMB-DAQ-54 be displayed on the top graph. Click “Chart 2” and repeat this process, except select “PD1_A02” instead of “PD1_A01” to show the reading from H2 in the OMB-DAQ-54 on the bottom graph.



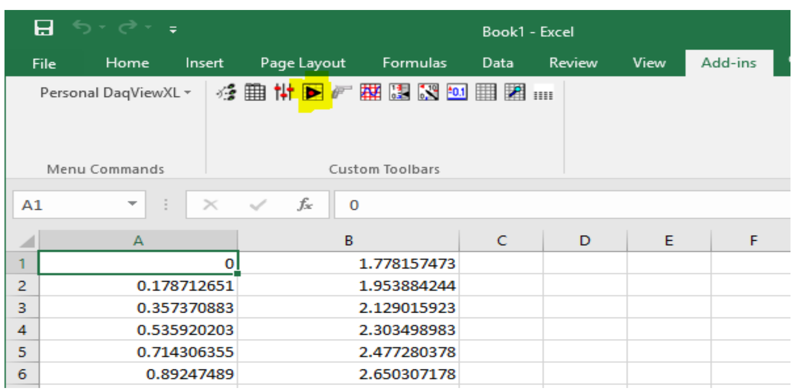
15. Click on the first channel (PD1_A01) to edit the scale the data will be displayed on the graph. For “Display Mode”, select the “Units Full Scale” option to set maximum and minimum values for the graph, or select the “Units / Division” option to select what value the middle of the graph should be and how many units should be measured per square on the graph. The “Trace Color” option allows the user to change the color of the line being displayed. Repeat this step for the second channel under “Chart 2” (PD1_A02).



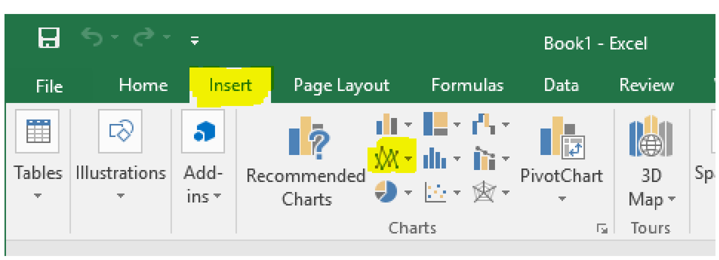
16. Close out of that window so the live reading window is open. Select the triangle button highlighted in the picture below to start showing live data. To change the speed the graph scrolls, select the rabbit button to speed up or the turtle to slow down. Doing so will change the "(time)/division" at the bottom right of the window. Press the square button next to the triangle button to stop reading live data.



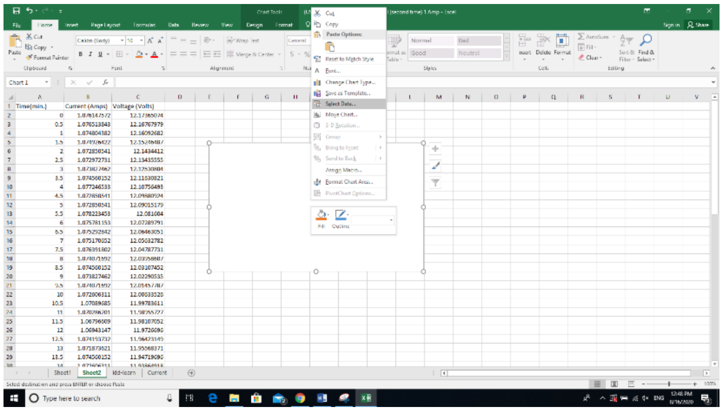
17. Once the user begins taking a live reading from the OMB-DAQ-54, select any cell in the Microsoft Excel spreadsheet. To begin recording the numerical values of what is being projected on the graph, select the trigger button. The data will start to be recorded based on what the "Trigger" menu and "Post-Trigger" menu were set to. The numbers being recorded in the left cells are from the "PD1_A01" channel and the numbers being recorded in the right cells are from the channel "PD1_A02".



18. To make a graph using the collected data in excel, select the "Insert" tab and select the insert "Line or Area Chart" option. In the drop down menu, select the option "Line" under the "2-D Line" heading.

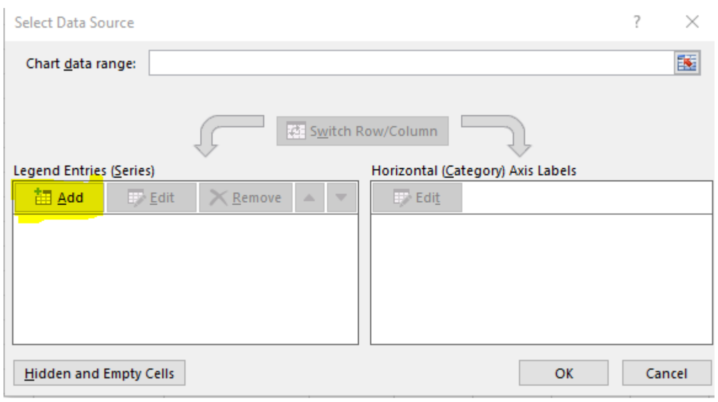


19. Right click the blank graph and select the "Select Data" option.

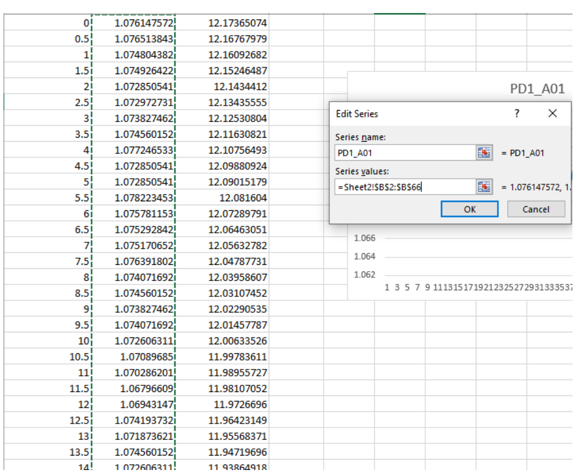


Note: The "Time" seen in the above picture was manually put into the Excel sheet.

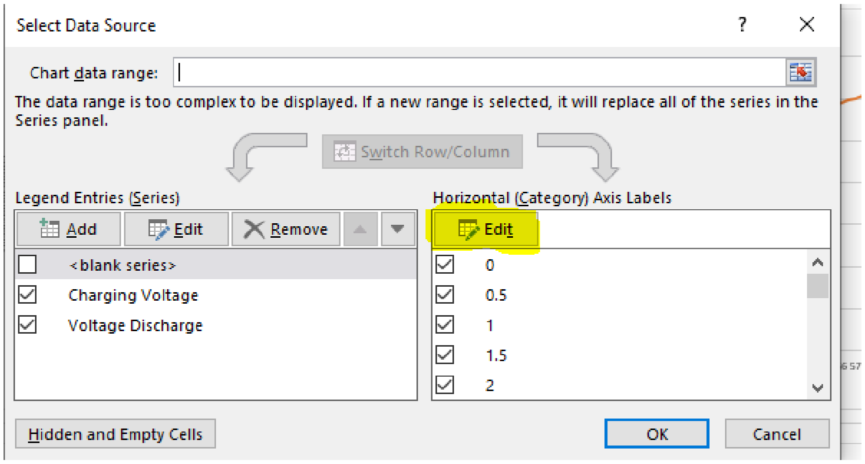
20. Select "Add" to make a new series of numbers that will be projected onto the graph.



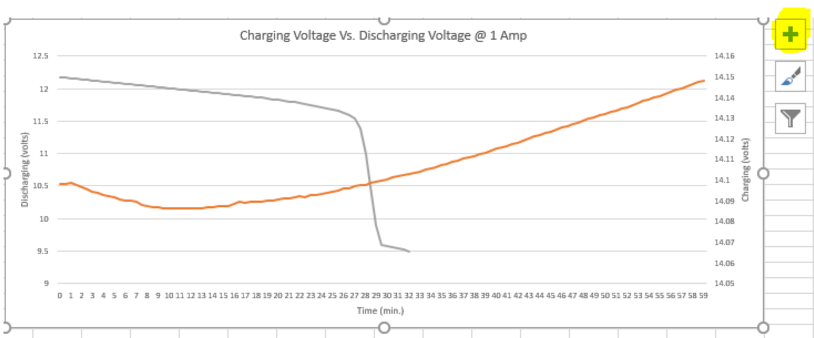
21. Type in a name for the series being made under "Series Name". After, click in the "Series Value" box, then click and drag the mouse to highlight the values that should be in this series (the cells will be highlighted with a dotted green box if selected for the series). Then click "OK". Repeat this step with the values from the channel "PD1_A02".



22. To change the value of the x-axis, select the "Edit" option highlighted below. Click and drag to select values, like in step 21, to select the values you wish to display on the x-axis.



23. Select okay and the values will be displayed on the graph. To give the graph a title and the axis labels, click the green plus sign next to the top right of the graph and make sure those boxes are checked off. This is an example showing the charging value and the discharging values of the voltage in a 12V battery.



Appendix A2 – Procedure to obtain data file using EdeX software

1. We have followed the following procedure to obtain the data file for normal method]
2. Connect the EdeX, battery and power supply as shown in the Figure A2-1.
3. Open the tuning file and click on the “Configuration and Testing “ from “Target menu”

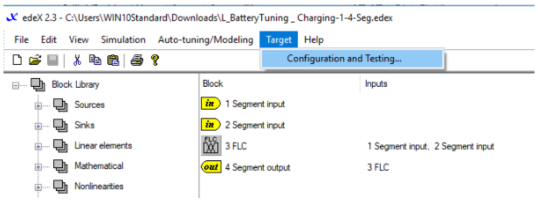


Figure A2-1 EdeX Interface

4. In the Configuration and Testing window select the appropriate com port from the drop down menu and then click on “connect to target” button

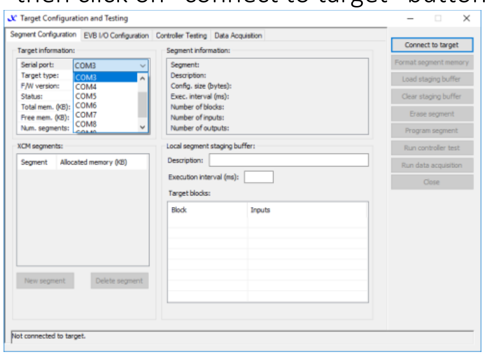


Figure A2-2 Target Configuration and Testing window

5. Upon successful communication between FLC and EdeX it will show “Ready” at the bottom left corner. As shown in the image below.

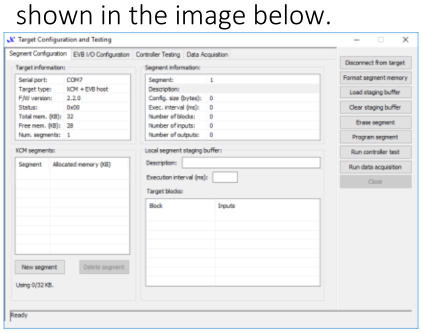


Figure A2-3 Target Configuration and Testing window

6. Add description and Evaluation interval then click on the new segment.

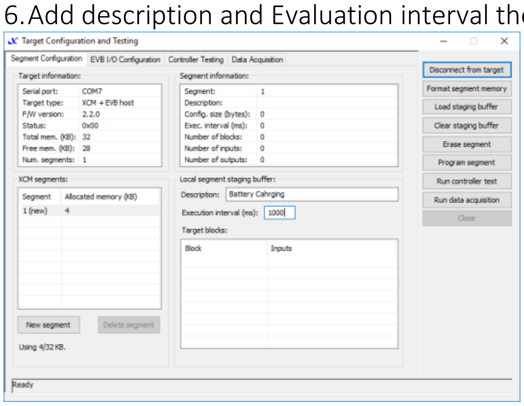


Figure A2-4 Target Configuration and Testing window

7. Press "Load staging buffer", which will prepare the data format for the segment. The "Target blocks" list view will populate with the list of blocks written to the XCM.

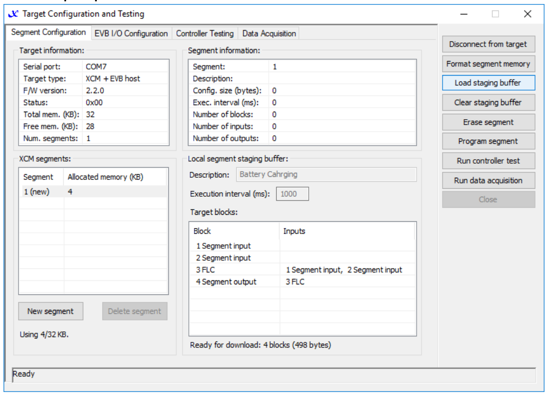


Figure A2-5 Target Configuration and Testing window

8. Press "Program segment" to write the data to the XCM Flash memory. The Segment information list view refreshed to show the updated segment contents: description, config. Size, # blocks, inputs and outputs, etc. The segment inputs and outputs will show the same tags, ranges, and units from the EdeX project blocks.

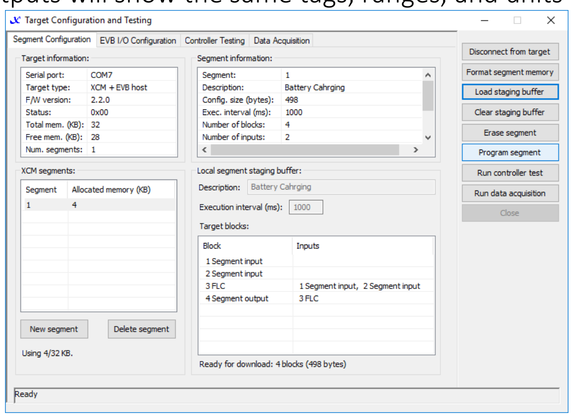


Figure A2-6 Target Configuration and Testing window

9. Now, go to the I/O configuration tab and replicate the following configurations shown below.

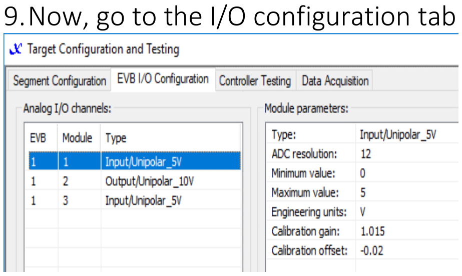


Figure A2-7 I/O Configuration 1.1

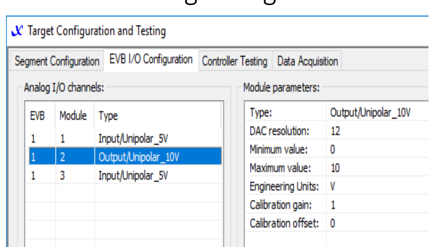


Figure A2-8. I/O configuration 1.2

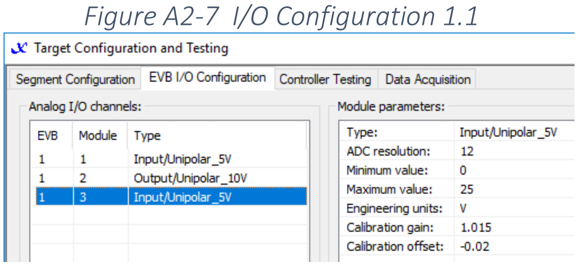


Figure A2-9. I/O configuration 1.3

10. Now, go to the “Controller Testing” tab and select “Active controller monitoring” from the drop down menu.

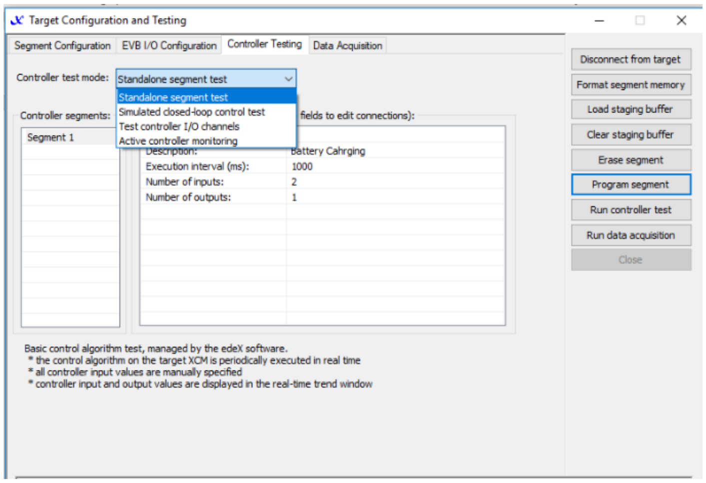


Figure A2-11 Controller Testing Tab

11. Select the I/O connection from the drop down menu. As shown below.

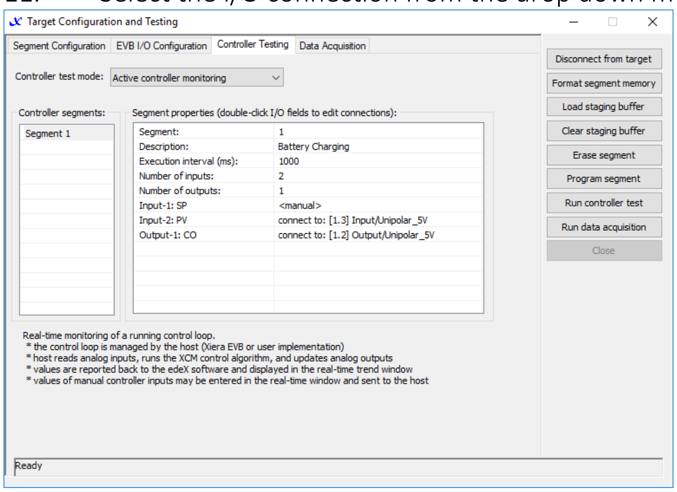


Figure A2-12 Controller Testing Tab

12. Click on the "Run Controller test" and ten click on the "Setup data logging" button.

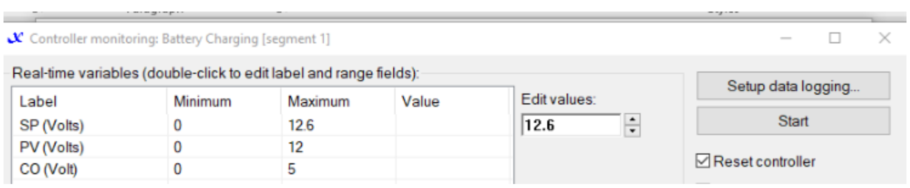


Figure A3-13 Data Acquisition window

13. Select a location and give a file name. Click ok

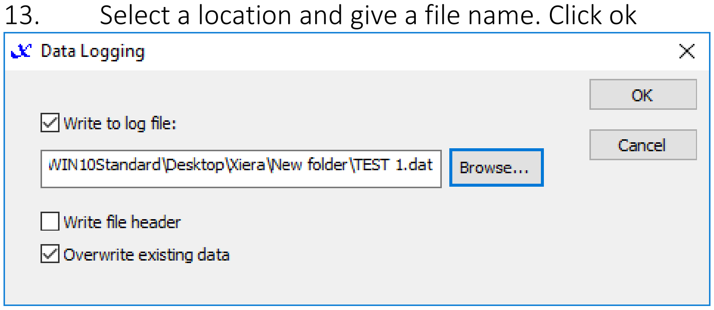


Figure A2-14 Data Logging file setup

14. Connect the battery to the charger and set the constant input current to "1.6A" using potentiometer on the constant current circuit.

15. Put the "12.6" in the text box to set the set point. And click on "Start" button to start the data recording.

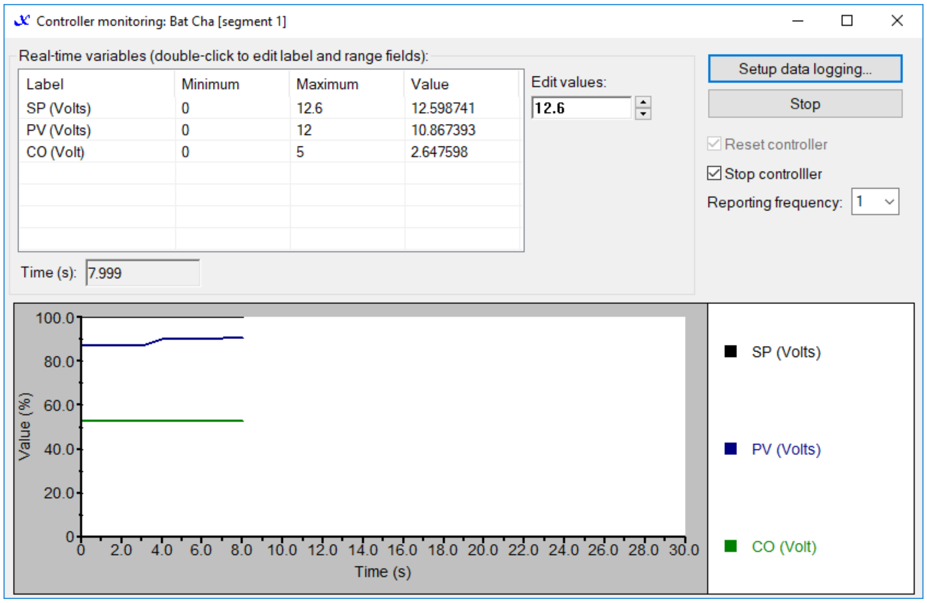


Figure A2-15 Data Acquisition window

16. When the battery is fully charged, stop the data recording. Then disconnect the charger.

Appendix A3 - Voltage sensor calibration table

Battery Voltage(V)	Voltage Signal (V)
0	0
1	0.2
2	0.4
3	0.6
4	0.8
5	1
6	1.2
7	1.4
8	1.6
9	1.8
10	2
11	2.2
12	2.4
13	2.6
14	2.8
15	3
16	3.2
17	3.4
18	3.6
19	3.8
20	4
21	4.2
22	4.4
23	4.6
24	4.8
25	5

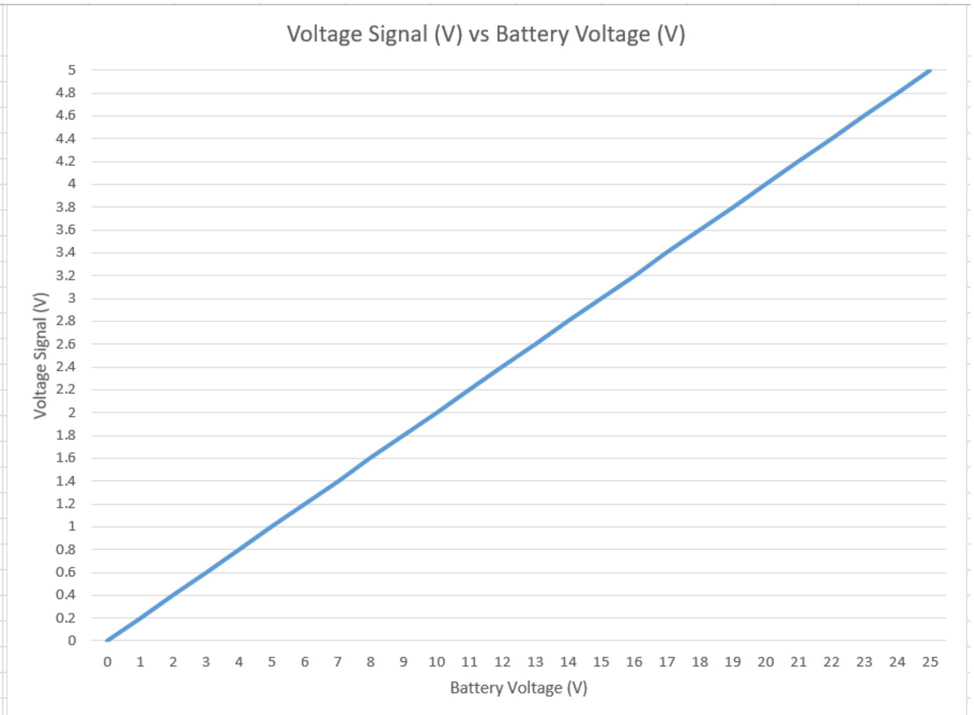


Figure A3-1 Voltage Sensor calibration

Appendix A4 – Current sensor calibration table

Current (A)	Voltage signal (V)
0	2.5
1	2.6
2	2.7
3	2.8
4	2.9
5	3
6	3.1
7	3.2
8	3.3
9	3.4
10	3.5
11	3.6
12	3.7
13	3.8
14	3.9
15	4
16	4.1
17	4.2
18	4.3
19	4.4
20	4.5
21	4.6
22	4.7
23	4.8
24	4.9
25	5

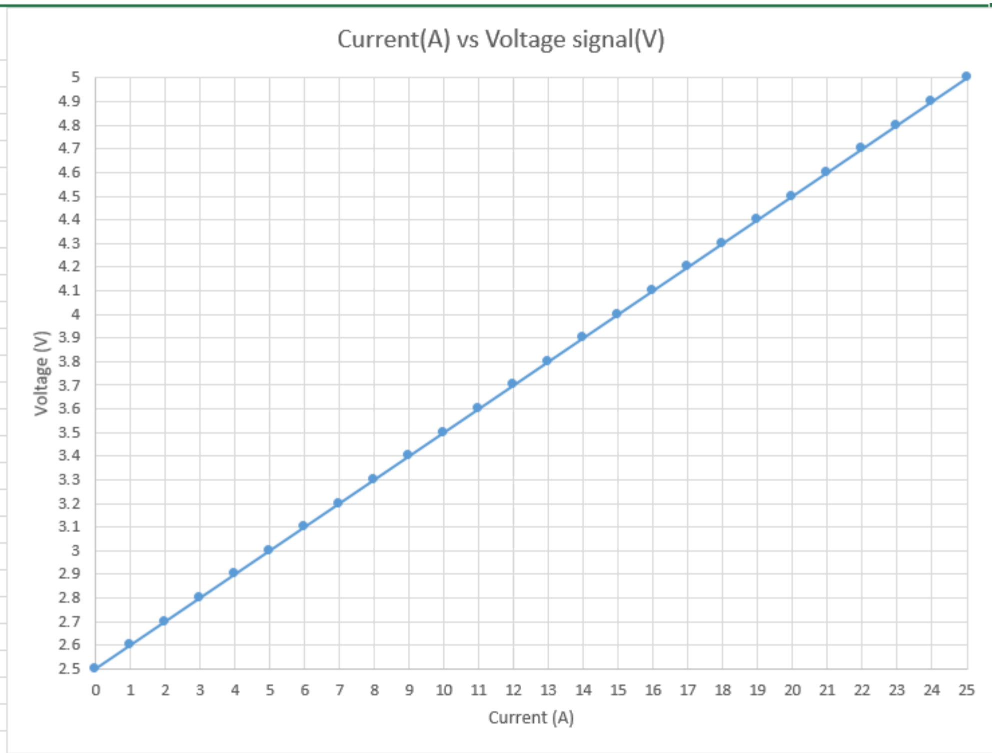


Figure A4-1 Current Sensor Calibration

Appendix A5 – Analog output card (DAC) calibration

DAC output (V)	Charging Voltage (V)
0	26.80
0.2	25.73
0.4	24.66
0.6	23.58
0.8	22.51
1	21.44
1.2	20.37
1.4	19.30
1.6	18.22
1.8	17.15
2	16.08
2.2	15.01
2.4	13.94
2.6	12.86
2.8	11.79
3	10.72
3.2	9.65
3.4	8.58
3.6	7.50
3.8	6.43
4	5.36
4.2	4.29
4.4	3.22
4.6	2.14
4.8	1.07
5	0.00

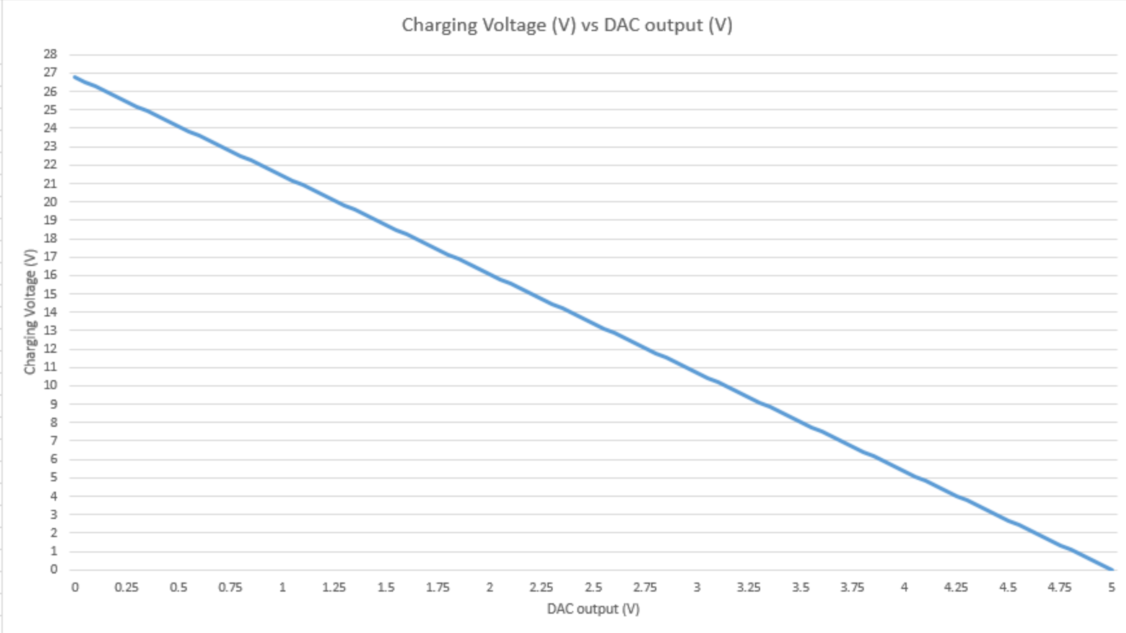


Figure A5-1 DAC calibration