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Almadni, Hani Mustafataher M; Alkali, Babakalli; Lak, Gyorgy Balint; Ansell, Ray

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Time series analysis of high energy density lithium-ion batteries for electric vehicles applications

Hani Almadni , Dr.Babakalli Alkalli, Dr.Gyorgy Lak and Dr.Ray Ansell
Glasgow, Scotland, G4 0BA, United Kingdom
hani.almadni@gcu.ac.uk, babakalli.alkali@gcu.ac.uk, gyorgy.lak@gcu.ac.uk, rayansell51@outlook.com

Abstract

The use of Lithium-ion secondary batteries in electric vehicles has now become a key component of high-performance energy storage systems. There are various factors that contribute significantly to the reduction in battery performance and subsequent damage of battery cells. The factors associated with battery degradation as a result of the charging and discharge rate is not new and has been investigated widely by many researchers. The maximum amount of electrical charge that a battery can store and deliver normally decreases over time. This capacity fade phenomenon is as a result of various degradation mechanisms within the battery. The degradation mechanisms are random in nature and in this paper, the degradation mechanisms associated with the change of battery cells electrical impedance, capacity and the life cycle are conducted. The 18650 battery cells is tested for 23 cycles on a trickle charge and the designated samples from each battery is subjected to different set temperatures range of (20°C-55 °C) at a constant time per experiment. Statistical analysis of the data is conducted using time series approach, and a reliability model is proposed in an attempt to predict the degradation or failure and hence improve the battery performance.

1. Introduction

There are concerns surrounding the use of petroleum for vehicle propulsion, principally as a result of increased pollution, decreasing petroleum stock and environmnetal regulation. This has increased the awareness of the need to create alternative energy sources for powering vehicles. Electric vehicle or electric drive vehicle (EV) is a vehicle propelled by one or more electric motors, powered by entirely or partially by electro/chemical high energy which is stored in rechargeable battery packs(1). The most developed energy systems are based on lithium ion batteries which is provide an energy source for use in electric vehicles (2). Electric vehicle or electric drive vehicle (EV) is a vehicle propelled by one or more electric motors, powered by entirely or partially by electro/chemical high energy which is stored in rechargeable battery packs(3).

However, the battery pack is a set of any number of battery cells designed in a series, parallel or a combination of both to achieve the required voltage, capacity, or power density for electric vehicles. Likewise, rechargeable battery packs usually contain a Battery Management System (BMS) that regulate the vehicle's software and hardware operations such as voltage, current and temperature as well as balancing the cells during battery pack charge and discharge(4).The Lithium-ion cell is the fundamental unit of current commercial technologies that are used to produce and manufacture the electric vehicles. The Lithium-Ion 18650 Battery Cells are cylindrical high volume cells that have been able to maintain a drop-in rechargeable cell of 3.7V having a capacity of at least 2600mAh as well as has the ability to handle close to 300 charge cycles (2).

The advantages of the Li-Ion battery include the fact that it is cost-effective, there is no requirement for priming when these batteries receive their first charge, low maintenance that ensures performance and the rate of self-discharge in Li-Ion batteries is much lower in comparison to other rechargeable battery sources. These advantages and factors place the use of Li-Ion batteries as an excellent ideal and optimal choice in contrast to technologies such as nickel-metal-hydride and silver–zinc battery options for use in electric vehicles (5).

On the other hand the disadvantages of the Li-Ion battery is that they drop their charge over time (Self-discharge), suffer from ageing depending on the number of charge-discharge cycles and The performance of the battery cell drops drastically at low temperatures (2). The study presnted in this paper is based on the current developments of the electric vehicles in the technological sector that have enabled manufacturers to produce rechargeable electric vehicles powered by the energy stored in lithium-ion battery. The evaluation and investigation of the lithium-ion battery cell 18650 for 23 cycles on trickle charge (+95%) subjected to different set temperatures range of (20°C-55 °C) at a constant time per experiment. The equivalent circuit model is used within the framework of EIS software analyser. A forecasting model of the test data collected using the time series approach is conducted to determine the trend of the impedence and internal resistenace of the lithium-ion observations.

2. The the cell equivalent circuit

The equivalent circuit model of the internal impedance battery in EIS analyser software is shown in Figure 1;

Figure 1 The Battery Cell Equivalent circuit (ECM)

Algebraic expression of the model is given in equation (1);

$$Z = \mathrm{R1} + \cfrac{1}{jwC1 + \cfrac{1}{R2 + \cfrac{1}{\frac{1}{R3} + jwC2}}} \qquad (1)$$

Where:
Z= Total internal impedance of the battery cell (Ω)
R1 = Total internal resistance (Ω)
R2 = Charge transfer resistance (Ω)
C1 = Charge transfer capacitance (F)

R3 = Solid electrolyte interphase resistance (Ω)
C2 = Solid electrolyte interphase capacitance (F)
j = imaginary part
$\omega = 2\pi f$, ω is the angular frequency or angular speed (rad/s)

f = frequency (Hz)

3. The experiment set-up

3.1 Expermental procedure

Figure 2 shows the schematic diagram of the main experiment considered in this paper. A cylindrical commercial version Lithium-Ion 18650 Battery Cells (LIB) with a capacity of 2600 mAh is investigated in this study, and the LIB was subjected to electrochemical experiments at different controlled temperatures. The first measurements were performed at adjusted 25 C, then the battery was charging from manufacturer SoC 30 % to 100% and charging continually it from 95% to 100% as trickle charge for 23 cycles.

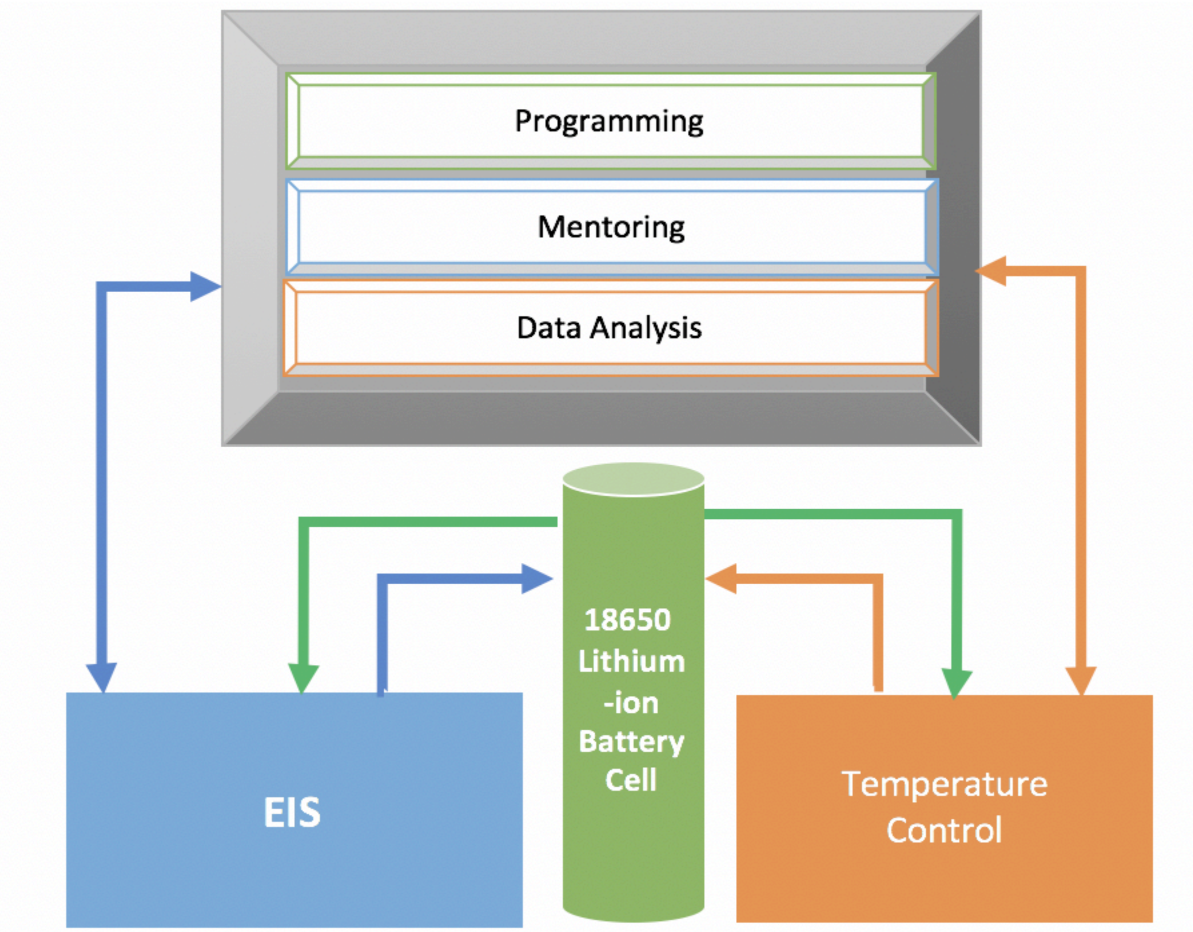

Figure 2 schematic diagram of the experiment main units

Arduino programme is used to set the required temperature and program the Versa stat to set up the LIB cycling. It was used also to monitor the experiment during the cycles. The experiments performed at different temperatures range (20, 25, 30, 40, 45, 55) for 23 cycles. The temperatures was adjusted using the Arduino controller by converting the temperature to the Volt. The charging experimentation was carried out using the Versa stat. For every 1 cycle run, the Versa stat measure and record the cell internal impedance.

The main goal in this paper is to use forecasting technique to conduct time series analysis in order to gain insight and have better control of the battery cell operation temperature, enhance the battery cell performance and increase the battery cell life cycle and state of health (SoH) and predict battery life. In order to achieve this we did the following;

- Measure the effect of the trickle charge on the Li-ion battery SOH.
- investigation the impact of the ambient temperature on Li-ion battery SOH.
- Assess the reliability of the Electrochemical Impedance Spectroscopy for Li-ion battery SOH at different battery temperatures.

3.2 The experiment set up:

The following steps is used for the experiment

1. place the battery cell in the aluminium cube in the right direction
2. Attached the clamp
3. Set up the Arduino software and send it to the microcontroller
4. Versa stat, select instrument active connection with the external experiment cell
5. save as (experiment new number)
6. check you have an active connection with right name on the top
7. click on run the experiment
8. approve data deletion
9. check the polarity (if wrong stop the experiment and repeat from step 1 and change the battery in the right direction)
10. Check the temperature during the experiment with the digital thermometer and calculate the average.

The experiment data is processed by the EIS Spectrum Analyser software program. EIS Spectrum Analyser is a standalone program for analysis and simulation of impedance spectra. Fitting the data processed is displayed on a graph and an example of the imported data from formatted text files is presented. The data displayed on the graphs of the EIS Spectrum Analyser shows the data before and after the data fitting process in Figure 3 and Figure 4 respectively.

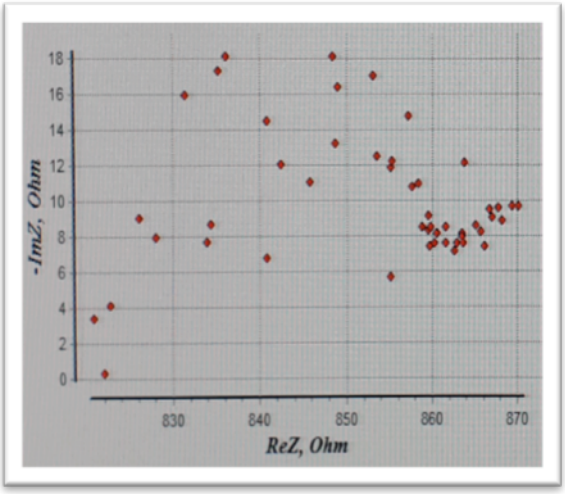

Figure 3. Spectrum analyser data before

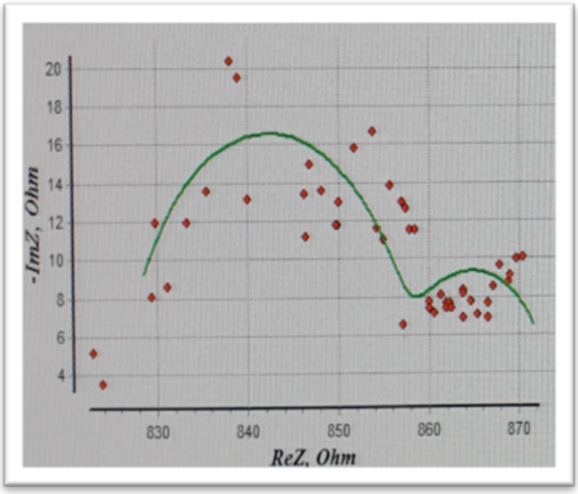

Figure 4. Spectrum analyser data after fitting process

Six experimental test run are conducted and the result in Table 1 summarise the temprature and the converted temperature to mV for all experiments.

During the experiment the some vital observation were made and the information recorded, the overall experiment event recorded include :

1. The system is overshooting for 110 Sec.
2. The system undershooting for 90 Sec.
3. The system takes 380 Sec. to be stable
4. Switch of the battery after each cycle to rest

Table 1. The summary of experiments set up in mV

Sample Code	T(°C)	T°C(mV)
01-T20	20°C	44.202
02-T25	25°C	55.252
03-T35	35°C	66.303
04-T40	40°C	88.404
05-T45	45°C	99.455
06-T55	55°C	121.555

4. The experimental results

The experiment result is summarised and presented in Table 2. Notice from the result the changing percent for each equivalent circuit components values for each battery cell after its experiment.

Table 2. The ECM values at after experiments

	20°C	25°C	30°C	40°C	45°C	55°C
R1	+1.868%	+ 1.41 %	+0.019%	+ 0.78 %	+ 0.69 %	+ 0.178 %
R2	- 5%	-18.98%	-24.98%	- 40.98%	+18%	+32.42
C1	+ 33.2%	+47.91%	+ 34.45%	+ 38.88	-70.78%	- 46.57
R3	+19.63%	+14.09%	-19.65%	+1.04%	+8.4%	+23.70
C2	+83.44%	+90.67%	+83.84%	+93.488%	-31.81%	- 23.52%

4.1 Forcasting

Quantitative forecasting model often look at time series. The time series is the seried of observation taken at regular inyterval. Is the case in the studet presented in this paper oberververvations are made and data recorded at different temperature intervals. The main interest is the observe the patterns of the series of observation and to do that it is always useful to plot a graph to show the underlying pattern. A times series plot is fitted to the model observations at various temperature.

There are three most common patterns in time series and these are

- Constant series
- Series with trent
- Seasonal series

4.2 Time Series plot of (R1) Total Internal Ohmic Resistance of Li-ion Battery Cell

The graph in Figure 5 display the different of the total internal Ohmic Resistance for each Li-ion Battery Cell at different maintaining temperatures during the test period. Notice on the graph, temperature 25°C shows a significant change in resistance over the experiment period compared to the other cell operating temperatures.

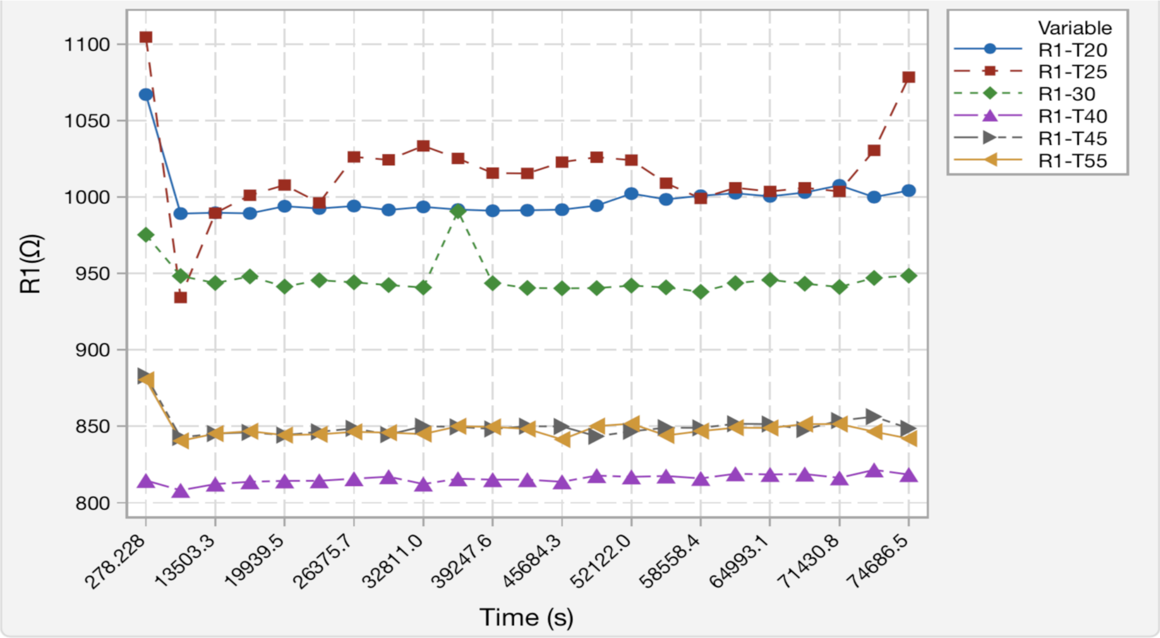

Figure 5. The effect of the different temperatures over the experiment period

The cell internal ohmic resistance at temperature 30 °C has an unusual blip at time 3947.6 seconds, this could be a result of electrical change during the test or software error.

Table 4 give a summary of the range of the Total Internal Ohmic Resistance R1 of Li-ion Battery Cell at Various Temperature tests:

Table 4 Time series analysis of R1 at different temperatures

	Minimum	Maximum
R1-T20	989.22	1067.10
R1-T25	934.31	1104.70
R1-30	938.03	990.75
R1-T40	808.140	821.540
R1-T45	842.750	882.970
R1-T55	840.500	880.480

The experimental data for each operating temperature shows the effect over the test. The minimum change of R1 is during T30°C over the test period indicate good battery performance. The maximum change of R1 is T20° over the test period, and this indicate low battery performance.

4.3 Time Series Plot of (R2) charge transfer resistance (Ω) of Li-ion Battery Cell

The graph in Figure 6 display the difference of charge transfer resistance for each Li-ion Battery Cell at different maintaining temperatures during the test period. The charge transfer resistance reducees as battery temperatures increases. This is an intresting observation compared to the internal ohmics resisitance.

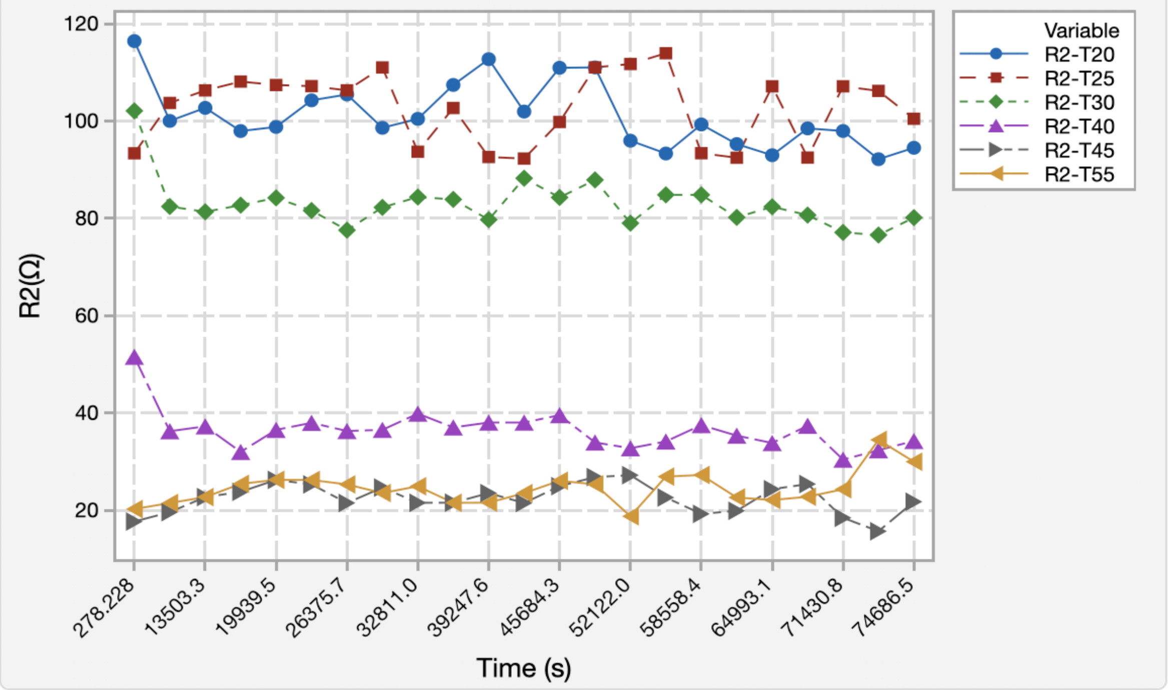

Figure 6. Effect of Deferent Temperature on R2 over experiment period

The next result in Table 5 is a summary of the range of the charge transfer resistance R2 of Li-ion Battery Cell at Various Temperature tests.

The experimental data for each operating temperature shows the effect over the test. In this case the minimum change of R2 takes place at T30°C over the test period, this indicate good battery performance. The maximum change of R1 is T20°C over the test period, indicate low battery performance.

Table 5 Time series analysis of R2 at deferent temperature

	Minimum	Maximum
R2-T20	92.171	116.440
R2-T25	92.303	113.940
R2-T30	76.591	102.110
R2-T40	30.436	51.575
R2-T45	15.713	27.234
R2-T55	18.791	34.489

4.4 Time Series Plot of (C1) Charge transfer capacitance (F) of Li-ion Battery

Figure 7 displayed the difference of Charge transfer capacitance for each Li-ion Battery Cell at different maintaining temperatures during the test period. The Charge transfer capacitance increases as battery temperatures increases.

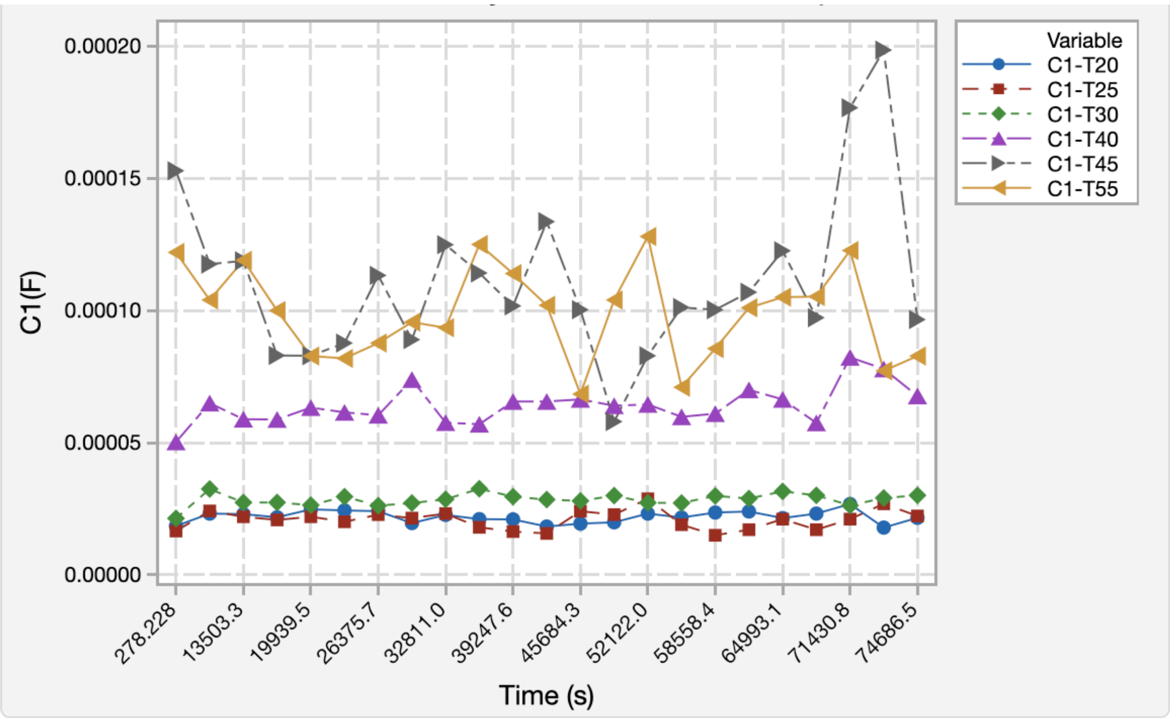

Figure 7. Effect of Deferent Temperature on C1 over experiment period

Table 6 summarise the range of the Charge transfer capacitance C1 of Li-ion Battery Cell at Various Temperature tests:

Table 6. Summary of C1 changing over the experimental period

	Minimum	Maximum
C1-T20	0.00001790	0.00002680
C1-T25	0.00001500	0.00002880
C1-T30	0.00002140	0.00003260
C1-T40	0.00005030	0.00008230
C1-T45	0.00005800	0.00019854
C1-T55	0.00006840	0.00012802

4.5 Time Series Plot of (C2) Solid electrolyte interphase capacitance (F) of Li-ion Battery

The graph in Figure 8 display the different of Solid electrolyte interphase capacitance for each Li-ion Battery Cell at different maintaining temperatures during the test period. The Solid electrolyte interphase capacitance increases as battery temperatures increases.

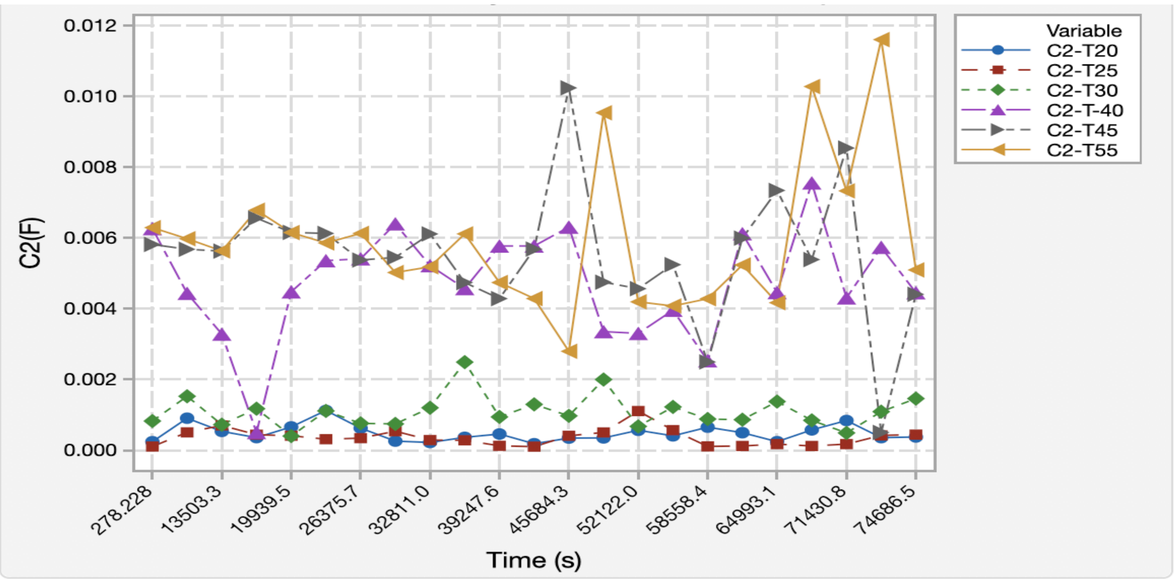

Figure 8. Effect of temperatures on C2 over experimental period

Table 7 summarise the range of the Solid electrolyte interphase capacitance C2 of Li-ion Battery Cell at Various Temperature tests:

Table 7. Summary of the range C2 of Li-ion Battery Cell at Various Temperatures

	Minimum	Maximum
C2-T20	0.0001863	0.0011255
C2-T25	0.0001035	0.0011103
C2-T30	0.0004026	0.0024924
C2-T-40	0.000505	0.007558
C2-T45	0.000505	0.010244
C2-T55	0.002798	0.011608

4.6 Time Series Plot of (R3) Solid electrolyte interphase resistance (Ω) of Li-ion

Figure 9 displayed the different of Solid electrolyte interphase resistance for each Li-ion Battery Cell at different maintaining temperatures during the test period. The Solid electrolyte interphase resistance (Ω) decreases as battery temperatures increases.

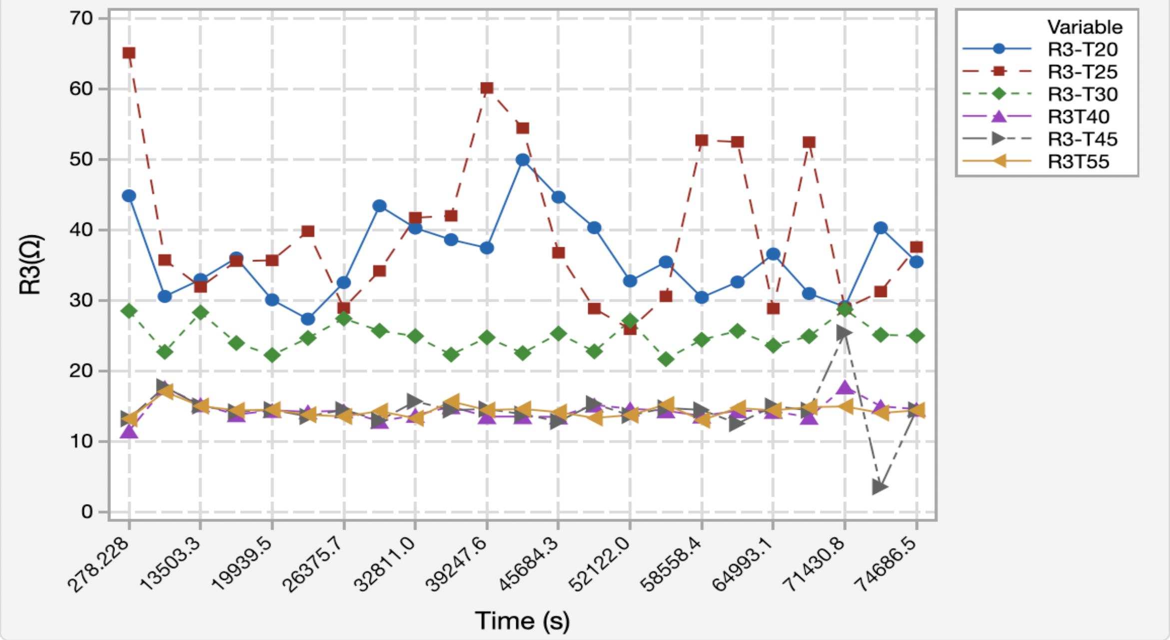

Figure 9 Effect of Deferent Temperature on R3 over experiment period

Table 8 give a summary of the range of the Solid electrolyte interphase resistance R3 of Li-ion Battery Cell at Various Temperature tests:

Table 8 Time series analysis of R3 at deferent temperature

	Minimum	Maximum
R3-T20	27.319	49.914
R3-T25	25.88	65.07
R3-T30	21.637	28.680
R3T40	11.469	17.727
R3-T45	3.535	25.394
R3T55	12.9800	17.0140

5. Conclusions

The times series analysis is conducted on the data collected from the experiment test run in this study. Graphical display of results presented show differences in the patterns of the underlying temperatures of the internal impedence of the battery cell. These differences appear to be a random noise which is superimposed by yhe underlying patterns as shown in all the time series graphs presented in the paper. Because of the noise, there is almost always an errors in the forecast, and if we measure the error, we will thereby have a way of measuring the the accuracy of the forcast and minimizing the errors of the data. The results presented give a very good insight about the underlying impedence at different temperature range. The research and data analysis from this experiment is still on going and we intend to present further result in future publications.

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