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The Impact of Temperature On Battery Degradation for Large-Scale BESS in PV Plant

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Abstract—**Excessive high temperature is an important factor for battery power and capacity degradation. Every charge-discharge activity escalates cell temperature, which results in higher degradation rates. Therefore, considering the impact of charge-discharge activities on battery temperature and consequently degradation rate is an indispensable step in establishing an optimal operation strategy for batteries. This paper describes a comprehensive investigation on the effect of battery charge-discharge on temperature and degradation. One year of operational data from a utility-scale solar photovoltaic (PV) plant with battery storage facility is used for this investigation. A strong correlation between battery temperature and discharge activities is identified, which can result in an excessive degradation of the battery.**

Index Terms—**Battery Energy Storage System (BESS), Battery Degradation, PV, Zhurkov model**

I. INTRODUCTION

With the advances in photovoltaic (PV) technology, battery has become an essential part for storing excess solar energy and utilising it effectively. Additionally, the unpredictable nature of the PV generation requires storage devices to smooth their generation output. Despite the most recent technical improvement and cost reduction of the electrochemical storage devices, battery degradation remains a serious obstacle to its further acceptance in large-scale PV plant. Degradation occurs during charging and discharging as well as during the idle time [1] - [3]. Extreme temperature is another factor accelerating the battery degradation faster than it is expected [4]. Typically, the acceptable operating temperature of the Li-ion battery technology is between 25 °C to 30 °C [5], [6]. Any deviation from this range may adversely affect the battery life.

Although manufacturers of battery recommend maintaining the temperature in a range of 25ºC to 30ºC for extending battery life [7], temperature deviates from the range due to instantaneous battery activity of charging and discharging. In [8], it is shown that maximum battery cell temperature increases with the change of charge and discharge current where the ambient temperature is below the cell temperature. According to [9] - [11], temperature rise accelerates the battery life degradation. They showed that the rate of change in battery degradation is significant for the upper bound values. According to the extensive experimental analysis carried out in [12], 10 ºC increase in cell temperature would double the battery degradation. Depending on the temperature, different charge and discharge cycles combination lead to different capacity loss [13]. In addition to battery degradation, excessive heat generation in the battery cells accelerates the cooling system operation. This, in turn, escalates the cost of operation of the whole plant.

While a significant number of papers dealt with thermal management of hybrid electric vehicle and electric vehicles in cold weather [14], no research studies have investigated thermal issues in an upper range of temperature in large-scale battery energy storage systems (BESS). In this paper, the impact of charge-discharge activities on the temperature and degradation of BESS is investigated for a large-scale PV power plant in a tropical weather condition. Illustrative examples and analysis are provided to show how battery cell temperature varies with respect to charging and discharging current. The illustrative cases are based on actual BESS operation, and therefore realistic results are rendered.

The rest of the paper is organized as follows: Section II explains the system under study. Section III presents an analysis for the selected charging and discharging events and its impact on the battery degradation. Finally, the paper is concluded in Section IV and future work is outlined.

II. SYSTEM UNDER STUDY

In this study, a grid-tied 3.275MWp PV plant with Lithium-Polymer battery storage system is considered. The plant is located in the University of Queensland Gatton campus, and it is connected to the 11kV local distribution network. It is a large research facility, funded by the Australian Federal Government, which contains state-of-the-art technologies, such as different PV tracking systems, Li-Polymer battery storage, and smart metering and control systems. In the following sub-section, a complete overview of the BESS and data acquisition system within the plant is presented.

A. Battery System Configuration and Specifications

A 600 kW/760 kWh Li-Polymer BESS is installed in the plant. Figure. 1 shows the configuration of the battery in the plant. The battery is partitioned into two 300-kW banks. Each bank is interfaced to the grid using two 300 kVA bi-directional inverter with 415 V, 3-phase AC output. The inverters are connected to the grid using a 1-MVA step-up transformer, as shown in Fig. 1. The voltage of each bank varies between 576 and 748 V DC. The BESS is capable of sourcing/sinking reactive power at ±0.9 power factor.

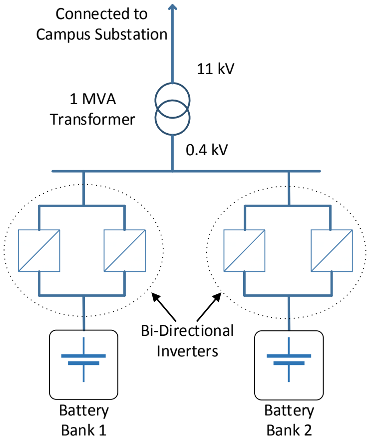

Fig. 1. One-line diagram showing battery arrangement in the PV plant

B. Battery Bank and Cell Configuration

Every battery bank includes four racks in parallel where each rack contains ten series of battery modules. In each module, two parallel strings of 18 series battery cells are integrated. The battery cell specifications are given in Table I.

A sophisticated Battery Management System (BMS) for battery bank and rack is installed, which can provide critical information such as cell temperature, voltage, current, etc. at different level.

C. BESS Control System Integration

As a part of the plant, the BESS system is operated by the central supervisory system (CSS) through a Programmable Logic Controller (PLC) and SCADA data communication and acquisition. The BESS control commands are generated by the CSS based on the collected measurements and processed information of the campus load and PV generation. There are eight modes of operation for the BESS such as PV charging, off-peak charging, and export to the grid. Multiple operation modes can be enabled at the same time. However, only one mode of operation at each moment drives the BESS based on a pre-defined priority list.

D. Battery Cooling Mechanism

In order to keep the battery cell and battery room temperature within an acceptable range, a cooling system is employed in the battery container. Battery module and cell ventilation are achieved through a) passive cooling mechanism including air vent holes along the side of the battery casing and spacing of cells, which ensures an even temperature distribution between the cells, and b) active cooling consists of rack fans and air-conditioning unit consuming 7.7 kW at a rated capacity. Three fans are placed at the top of each battery bank to draw air up through vents in the front panel by passing through the modules and out at the top. The fans start operating when cell temperature reaches 29℃. Battery modules are spaced inside the rack with gaps to allow airflow. The air conditioner is designed for maximum 30ºC internal ambient for 50ºC outside temperature.

TABLE I. BATTERY CELL SPECIFICATIONS

Description	**Specification**
Battery Cell Type	Lithium Polymer
Cell Capacity	75Ah
Cell Voltage	2.7V to 4.1V, average 3.7V
Maximum Continuous Discharging Current	2C(150A) at 23±3 °C
Maximum Continuous Discharging Current	5C (375 A) at 23±3 °C
Peak Discharging Current	8C
Cycle-Life	4000 Cycles at 80% DoD (Depth of Discharge),1C(Charge)/1C(Discharge)
Charging Temperature	10 to 35 °C
Discharging Temperature	-10 to 55 °C

E. Measurement and Data Logging

All data collected from the BESS PLC is stored in a Historian Wonderware system, which is easily accessible via a remote platform. The plant data logging, including BESS, is performed using a Delta Mode operation. About 1390 points within the BESS is monitored through measurement and data logging system, which gives detailed insights into the battery operation on the cell and module levels. Although data is sampled at a 1-second rate, the Delta Mode procedure stores the measured data when the value is different from the previous measurement by a certain pre-set threshold [15]. 1-minute data of a year from 26th March 2016 to 25th March 2017 has been considered for this investigation.

More than 100 incidents of charging and discharging have been selected from 365 days of data to observe the charge-discharge effects on the battery cell temperature. To eliminate the impact of ambient temperature, only incidents with battery cell temperature above the ambient temperature for the whole period of charge-discharge are selected for this investigation. Also, it is made sure that the ambient temperature is not increasing during the period of charge-discharge to further neglect the ambient temperature impact.

III. DATA ANALYSIS FOR DEGRADATION STUDY

This section discusses the battery temperature behaviour during charging and discharging states. The plan is to evaluate the impact of charging-discharging current, rate of change, and charge on the battery temperature. The impact of excessive heat, caused by charge and discharge, on the battery degradation is shown. To this end, an accumulated extra degradation is estimated for the charging and discharging incidents above 30ºC.

In an attempt to find a relationship between effective parameters and battery temperature, a wide range of studies is carried out. Several effective parameters are defined, as follows:

- Temperature Rising Slope (ºC/min): the slope of the straight line going through the minimum and maximum temperature values during an event.
- Peak Temperature (ºC): the maximum temperature occurred during an event.
- Absolute Temperature Change (ºC): the difference between the maximum and minimum temperature during an event.
- Peak Current (A): the peak value of current during the event under study.
- Charge (C): total current of a charging or discharging event

in hourly rate.

- Temperature Rising Delay (min): the difference between the time of beginning the incident and the time in which battery temperature starts to increase. This parameter is important for battery thermal modelling.

The initial study revealed a similar behaviour among different battery cells and modules regarding temperature and current. Therefore, the temperature of a single battery module is considered in the analysis representing the overall BESS. Moreover, due to different behaviours and performances of the battery during charging and discharging modes, their analysis is carried out separately. For the degradation analysis, however, both charging and discharging modes are combined.

A. Discharging

One of the primary operations of the BESS is to discharge to smooth PV output during any sporadic changes in solar irradiance and export energy to the grid during peak-time periods. Performing in these occasions, battery cell temperature rises significantly based on the peak discharge current and duration of the discharge event. In this study, 50 discharging events have been selected to observe battery temperature behaviour.

As an example, a discharging event from 18:00 to 23:00 on 25/03/2017 has been shown in Fig. 2. It is noticeable that the battery cell temperature increases with the discharging current while the ambient temperature is below battery cell temperature. It indicates that the ambient temperature does not affect the rising cell temperature in this occasion. The cell temperature starts rising at 19:08 with 4 minutes delay from discharge starting time (19:04). It then ramps up to the peak temperature at 27.25ºC, steadily.

It can be seen from Fig. 2 that, the temperature starts to fall gradually when the discharging current decreases. In this case, the rate of temperature change (from point B to point C) is lower than the increasing rate. The reason is twofold: reduction in current discharge rate and cooling system operation.

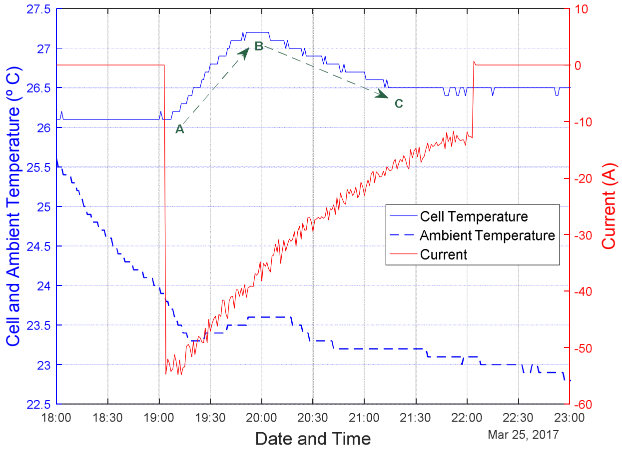

Fig. 2. The typical discharging event, cell and ambient temperature's effect on battery cell temperature.

Figure. 3 shows a meaningful relationship between peak current and battery cell temperature. Most of the discharging events demonstrate that the temperature is rising slope increases with increase in peak discharging current. The events with higher current (110A-125A) verify the same hypothesis as the lower discharge current events (42A-65A). Due to inadequate data in between the highest and lowest range, it is difficult to conclude the entire range of peak current.

In Fig. 4, the peak temperature values are plotted against the peak current where a strong association can be realised. It appears that the peak discharge current can describe the peak temperature behaviour for the lower and upper range of peak current. In addition, the cell temperature increases linearly with an upsurge of the peak discharge current with a linear function.

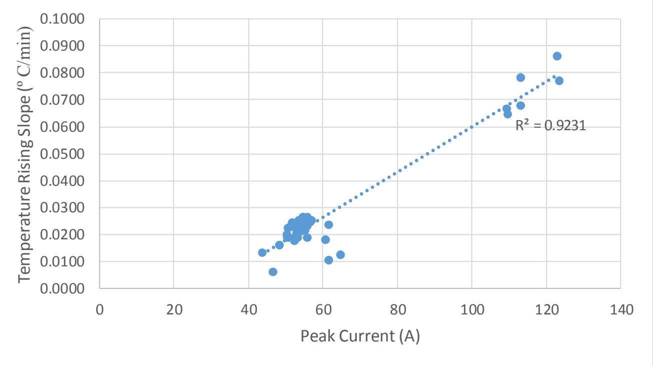

Fig. 3. Peak current and temperature rising slope: A linear relationship for discharging events.

The impact of charge on the temperature rising slope is shown in Fig. 5. As analysis shows, two different clusters can be recognised. While the charge of the event is below 80C, the temperature follows a linear relationship with a small slope. When the value of the charge reaches around 80C and beyond, it is noticeable that temperature rising slope jumps to upward. It proves that the higher charge accelerates battery temperature rising slope.

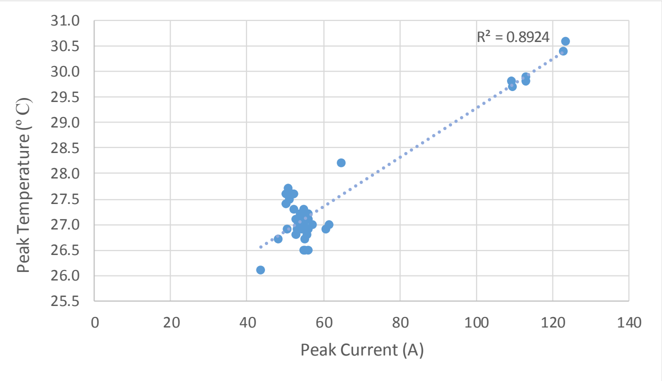

Fig. 4. Peak current and peak temperature: A linear relationship for discharging events.

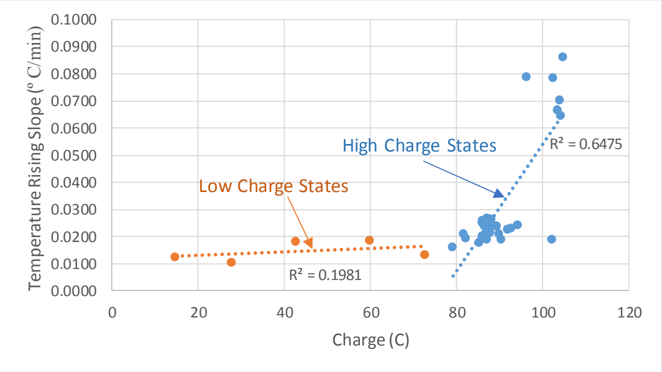

Fig. 5. Temperature rising slope vs charge of discharging events.

As battery temperature increases gradually after starting an event, cell temperature takes time to reach its peak value due to heat convection delay, cooling system operation, and the physical battery layout in the container. The average temperature rising delay is 5.5 minutes, where the standard deviation is 5 minutes. A couple of incidents shown in Fig. 6 have 9 minutes delay. The average time delay shows a reduction to 5 minutes without these incidents. The different ambient temperature and/or the condition of the cooling system at the beginning of the discharging event might have caused the differences. Future works will be carried out to investigate this.

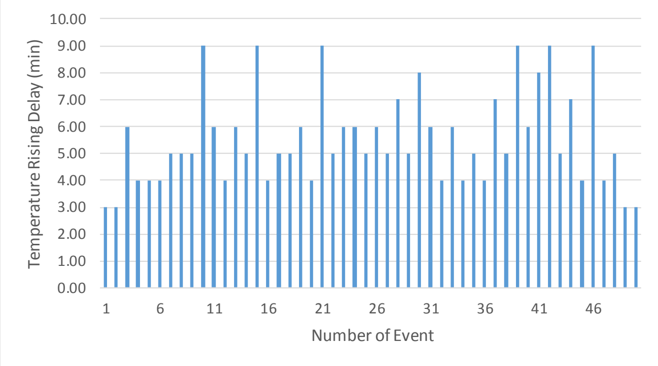

Fig. 6. Temperature rising delay for each discharging event.

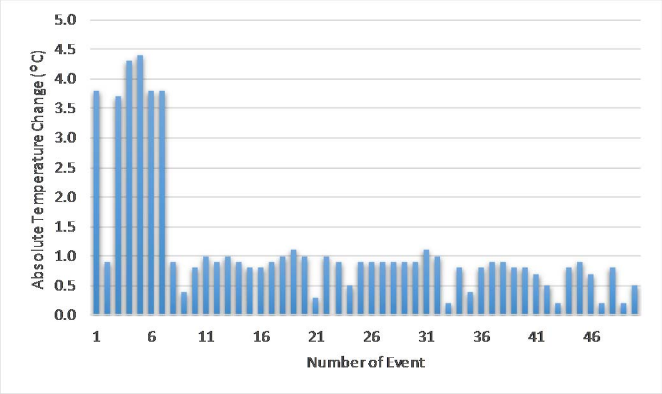

Fig. 7. Absolute temperature change during each discharging event.

Although temperature rising slope differs from one event to another, most of the events yield only 1° C increase on average. As per results are shown in Fig. 7, six discharging periods are yielding significantly higher changes in temperature. The root-cause of the unusual behaviour is possibly due to high discharge current and comparatively higher cell temperature before discharging period together with a possible malfunction in the cooling system.

B. *Charging*

Like discharging operation, charging is an indispensable operation in large-scale PV plant where excess solar energy is stored for later utilisation. Through the year from April 2016 to March 2017, BESS was in different operational mode for research purposes. A total number of 61 charging events from one-year available data have been considered in this study for analysis.

Charging event on 11th February, 20:00 to 12th February 08:00 in 2017 depicted in Fig. 8 to show a relationship between cell temperature and the charging current. The cell temperature is higher than the ambient temperature for the period of charging. More importantly, the ambient temperature decreases over the same period, which does not correlate with the cell temperature increase. Cell temperature increases with the starting of charging current at a high value. Then, it starts to decrease from peak point, B to post charging minimum point, C, because of the reduction in the magnitude of the charging current.

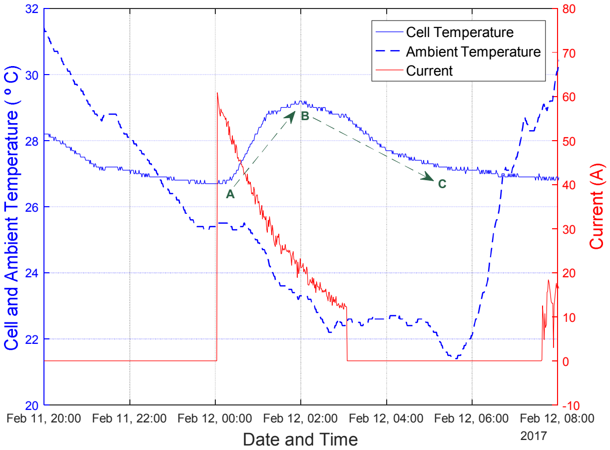

Fig. 8. Typical charging event's effect on battery cell temperature.

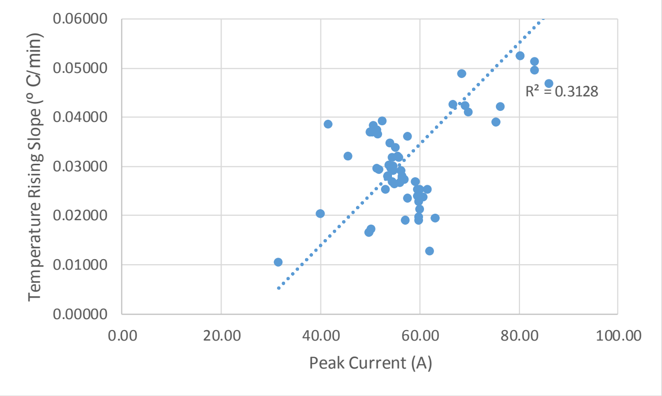

Fig. 9. Peak current and temperature rising slope: No significant linear relationship for charging incident.

Figures. 9 and 10 show relationships between temperature changes rate and peak current for each charging event. Only 30% of charging incidents show a correlation between temperature changes and peak current. The R-squared value is not large enough to show a strong correlation. Therefore, it is not possible to explain cell temperature changes with these two predictors individually. To find the reasons for this phenomenon, a couple of hypotheses can be drawn:

- Although the ambient temperature never exceeds the battery temperature over the period of the charge event, its changes can have an impact on the battery cell temperature. For instance, the ambient temperature in Fig. 2 is slightly decreasing while the one in Fig. 8 is decreasing quickly. The absolute change in the ambient temperature is more significant in the charging event, as shown in Fig. 8, which can contribute to reducing the temperature rising slope. Therefore, a thermal model of the battery, cooling system, and container accounting for the ambient environment is necessary to remove the external effects completely.

- In this paper, a linear relationship between the battery temperature and effective parameters are investigated. However, the relationship might be of higher order and nonlinear nature with a combination of multiple effective parameters.
- As it was mentioned earlier, only charging-discharging events are selected for analysis where battery temperature is always higher than the ambient temperature. Therefore, a small sample of events remained for this study. For a strong statistical analysis, a larger sample size is required.

These issues will be addressed in our future research.

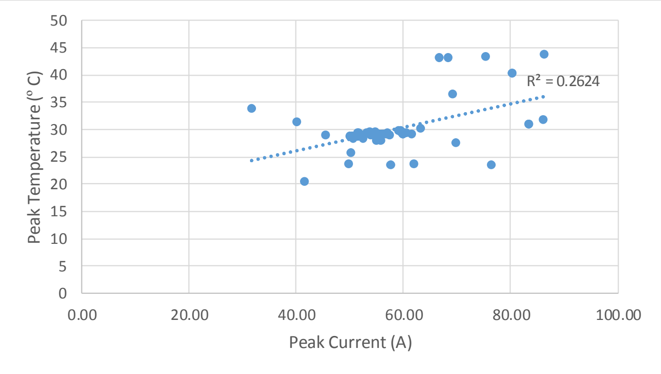

Fig. 10. Peak current and peak temperature: No significant linear relationship for charging incidents.

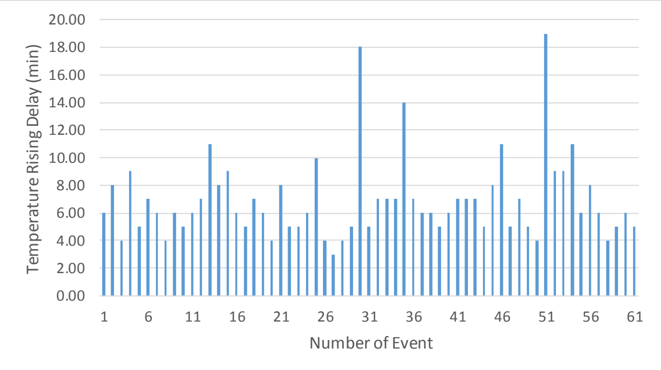

Fig. 11. Temperature rising delay for every charging incident.

Although the temperature rising delay is more than 14 minutes occasionally, as shown in Fig. 11, the average delay is around 6.4 minutes without these events. The average rising time will rise to around 7 minutes with the incidents with higher delay. On average, an absolute temperature change is 2.5ºC for the charging event. It is about 60% more compared to the average value of discharge events. Only one charging event is shown in Fig. 12 has less change (0.5ºC) in battery cell temperature.

According to Fig. 13, the relationship between the rate of temperature changes and the charge is negligible as the R-squared value is very small. As explained earlier, it might be linked to the effect of ambient temperature, cooling system operation, and small sampling size. It requires further investigation to identify the effective parameters on the battery temperature in charging mode.

C. Battery Life Degradation

So far, it has been shown that different charge-discharge events increase battery temperature beyond the safe range. Quantification of the extra degradation, imposed on the battery because of excess temperature is discussed in this subsection. To do so, the modified Zhurkov model is used for battery degradation analysis from [16]. It estimates the impact of battery temperature on its degradation compared to the reference temperature, as follows:

$$Degradation\ Rate = e^{\left(T_{fact}\cdot(T-T_{nom})\cdot\frac{T_{nabs}}{T_a}\right)}. \qquad (1)$$

where $T_{fact} = 0.0693$ is the coefficient of temperature in thermal ageing model; T is the actual battery temperature in °C; T_{nom} is the reference battery temperature (25°C in this study); T_{nabs} is the reference battery temperature in Kelvin (K) and is calculated as $T_{nabs}=T_{nom}+273$; and Ta is the battery absolute temperature in Kelvin (K) which is $T_a=T+273$.

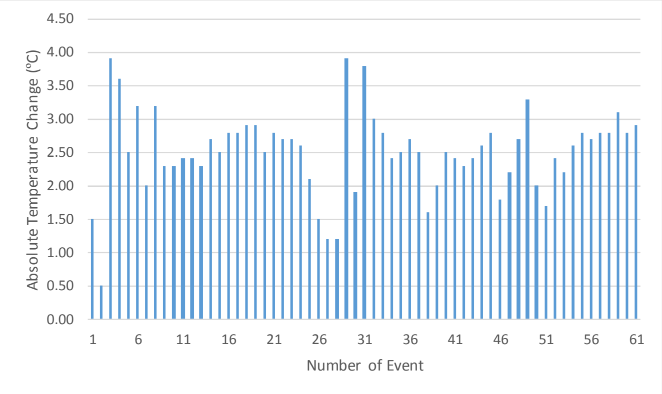

Fig. 12. Absolute temperature change during each charging event.

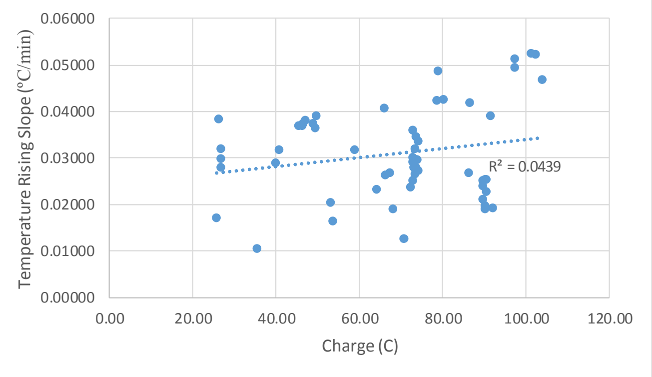

Fig. 13. Temperature rising slope vs charge of charging events.

To quantify the excess battery degradation occurred by the excessive temperature, Eq. (1) has been used in two scenarios. In Scenario I, the extra degradation rate is calculated for the actual measured temperature. In Scenario II, however, it is assumed that the battery temperature never exceeds 30 ºC, which is an ideal case [5], [6]. By comparing Scenario I against Scenario II, the excess degradation imposed on the battery by the charge-discharge events and the resultant excessive heat, can be quantified.

Figures. 14 and 15 illustrate the extra degradation rate because of higher temperature during charging and discharging events. It is observed from couple of incidents illustrated in Fig. 15 that same charging or discharging event causes extra degradation for temperature above 30 ºC. Therefore, battery degradation rate would be significantly lower if the temperature can be kept at the maximum allowable range, i.e., 30 ºC. The degradation rate jumps to 87.29% from 46.04% for only 3.9 ºC excess temperature. The extra degradation can be avoided by regulating charge-discharge current.

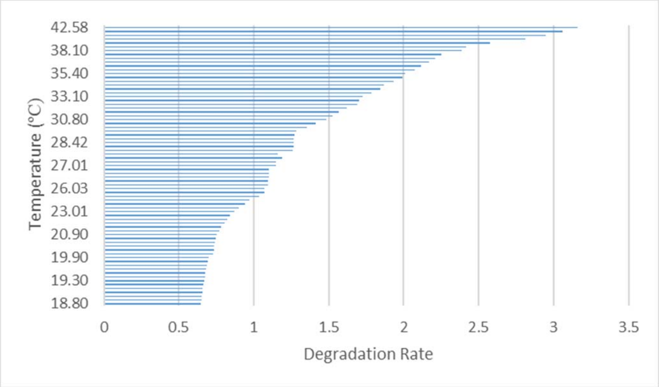

Fig. 14. Average extra degradation rates for the actual temperature in each charge-discharge event.

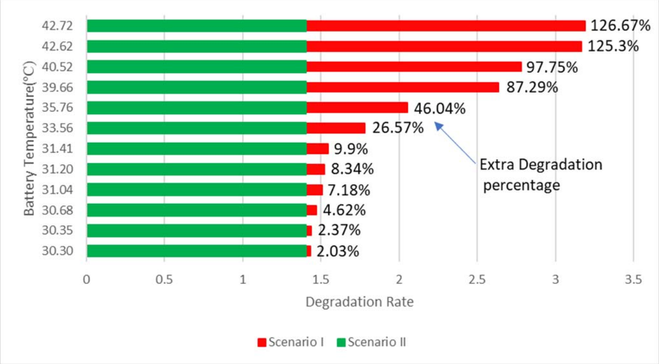

Fig. 15. Comparing degradation rates in Scenario I and II.

IV. CONCLUSION AND FUTURE WORK

This paper has made an effort to render a preliminary investigation on the battery degradation caused by excessive temperature for the charge-discharge regime in a large-scale PV plant. Actual BESS field data has been used to investigate temperature behaviour based on charging and discharging current. Both states, i.e., charging and discharging, show that the battery temperature starts increasing due to high current. While there is a strong correlation between the battery temperature and the temperature rising slope, peak current, and charge in discharging incidents, no particular correlation have been identified for the charging events. Finally, the illustration of degradation rate shows that a significant number of events in a year are responsible for extra battery degradation.

For future work, a thermal model of the BESS container will be developed accounting for each heat sources namely battery cell and the ambient environment, heat sink sources (i.e., cooling system). We hope that the model will help to determine a relationship between battery temperature and charging events. We are planning to use the thermal model to develop an optimal battery operation algorithm in the CSS of the plant.

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