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Learning from a 3.275 MW Utility-Scale PV Plant Project: Update and New Remarks

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SUMMARY

This paper presents thorough investigations of a utility-scale PV and battery system operation, connected to an 11 kV distribution feeder. The plant contains 3.275 MW_p solar PV system and 600kW/760kWh battery storage, which is located at the University of Queensland Gatton campus and funded by the Australian Federal Government Department of Education, Education Infrastructure Fund. The PV plant consists of three different PV tracking technologies (namely fixed-tilt, single-axis tracking, and double-axis tracking) and state-of-the-art Li-Polymer battery system. An initial report on the performance and grid integration challenges of the plant of this size was presented in CIGRE 2016 Paris Session [1]. Now, more than two years of PV generation data along with one and a half years of battery operational data is available for analysis. This way, meaningful annual and seasonal operation and performance of the plant can be assessed. This paper is organised in four sections. Section 1 outlines the context of the paper from a general perspective. It is, then, followed by explaining the configuration of the PV and battery systems within the plant in section 2, where the focus is on the battery system configuration and operation algorithm. Section 3 offers in-depth analyses of the plant operation in terms of PV annual and seasonal production, battery operational performance, and voltage regulator operation from different perspectives. In particular, annual performance and the plant yield is calculated based on different tracking systems in subsection 3.1, followed by seasonal effect investigation. Battery operation in terms of energy, power, State-of-Charge (SOC) level, and cell temperature is assessed in subsection 3.2 considering seasonal impact. In subsection 3.3, voltage at the Point of Common Coupling (PCC) is analysed. Most notably, the impact of PV variations on the operation of Step Voltage Regulator (SVR) is evaluated. Finally, the paper is concluded in section 4. Through these analyses, key observations are provided to better understand the plant performance and relevant network impacts.

KEYWORDS

Utility-scale solar PV plant, Grid interconnection, PV tracking technologies, Plant yield, Li-Polymer battery system, Battery cell temperature, Battery cycling, Voltage variation, Step voltage regulator.

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1. INTRODUCTION

Gatton Solar Research Facility (GSRF) is a utility-scale PV/battery plant with 3.275 MW_p of solar PV generation and 600kW/760kWh Li-Polymer battery, located at the University of Queensland (UQ) Gatton campus, Queensland, Australia. The plant hosts three types of solar tracking technologies, namely fixed-tilt (FT), single-axis tracking (SAT), and dual-axis tracking (DAT). The battery storage unit is installed to smooth the PV generation output and shave the peak demand. The battery has been operational since March 2016. The whole plant is interconnected to the local 11kV utility network (i.e., Energex) through four transformers. Several guidelines and operational limits are specified in the agreement with Energex to reduce the plant's adverse impact on the grid. The PV generation together with battery-stored energy is primarily used to meet university campus demand. Excess energy, when available, is purchased by the local grid operator through the 11kV network. A sophisticated smart metering and data collection infrastructure are in place to facilitate the understanding and monitoring of the system's behaviour. Collected data are accessible remotely through the Historian Wonderware platform. A central supervisory system (CSS) operates the whole plant including PV and battery systems.

An initial report on the performance and grid integration challenges of the plant was presented in CIGRE 2016 Paris Session in [1], when only a few months of operational data was available and the battery storage system was not in place. Currently, more than two years of PV operational data as well as one and a half years of battery field data are available for analyses. Therefore, it is possible to assess seasonal variations of PV yield and its related impacts on the plant performance. In addition, battery operation can be evaluated comprehensively based on various technical measures such as state-of-charge (SOC) and operating temperature, and practical issues caused by quick PV generation fluctuation on voltage level and battery operation can be assessed with the available data. In particular, this paper reports analyses for the overall Gatton PV plant as well as individual PV tracking technology on a seasonal basis. This way, the benefit of different PV tracking technologies in a real project can be compared and quantified. Battery operation is also investigated in terms of throughput energy, charge/discharge power level, SOC, and average cell temperature during operation in different season and operational modes. We will also report an investigation of voltage fluctuations considering the interconnection to the 11kV grid. Key observations will be provided from the analyses, which can help plant operators to make informed decisions and develop appropriate control methodologies to improve the efficiency of the plant.

2. A BRIEF DESCRIPTION OF THE PLANT

Fig. 1 shows single-line diagram of the GSRF, including PV arrays and battery systems, loads, onsite diesel engine, capacitor banks, and Point of Common Coupling (PCC) to the local grid. There are five PV arrays, each of which is connected to the UQ substation through an exclusive inverter and a transformer. A comprehensive overview of the PV plant, grid interconnection agreement, plant control and operation, and smart metering and data acquisition systems are presented in [1]. Therefore, we only review battery system configuration and its operation in this paper.

Li-Polymer battery technology is used at GSRF with total 600kW/760kWh power and energy capacity. The battery capacity is divided into two equal battery banks, each of which has 300kW/380 kWh capacity. Each battery bank consists of four racks in parallel, where every rack contains 10 battery modules in series. Furthermore, every module is assembled with 2 strings and 18 battery cells in series in every string. Each battery bank is connected to a 300kVA, 415V, 3-phase inverter capable of sourcing/sinking reactive power at ±0.9. The two inverters are connected to the grid through a 1000 kVA transformer, as shown in Fig. 1. The active and reactive power of the battery inverter is limited to source/sink ±300 kW and ±150 kVAr, respectively. Battery SOC is also limited by the CSS to 95%/15%. Based on the adopted convention, negative battery power represents battery in discharging mode and vice versa. For more information about battery cooling mechanism, please see our previous work in [2].

As explained in [1], CSS shares required charge/discharge power equally between the two banks based on a list of pre-defined rules with specific priority, including the idle mode. In general, battery operational rules can be classified into four categories, which are *charging*, *discharging*, *charging/discharging*, and *idle*. There are four rules in which battery is discharged, while four other rules charge the battery accounting for several technical constraints, battery status, excess PV availability, and time of the day. In only one rule, battery can be either charged and discharged based on the PV ramp rate.

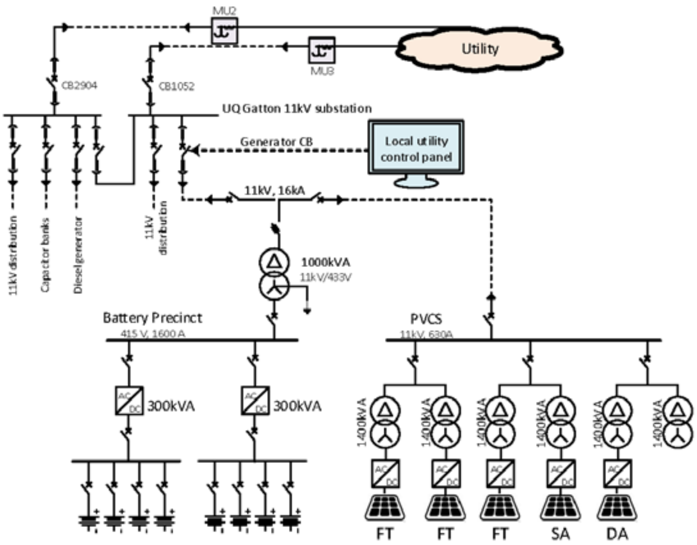


Fig. 1. Schematic of the UQ GSRF and its connection to the local distribution network.

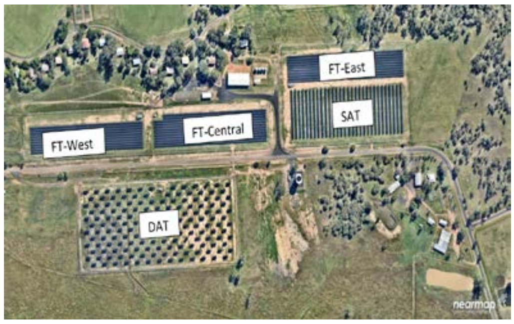


Fig. 2. Aerial picture of the UQ GSRF PV arrays

3. OPERATIONAL DATA ANALYSES AND REMARKS

3.1 PV Performance Analysis

In this subsection, the 2015-2017 comparative performance of GSRF solar PV array technologies will be investigated. Two aspects will be examined: (1) annual performance, given in subsection 3.1.1; and (2) seasonal production gains from different solar tracking, reported in subsection 3.1.2. Fig. 2 shows an aerial picture of GSRF with naming convention adopted for each sub-array components. For analysis of seasonal production gains from solar tracking systems, the three sub-arrays chosen were the FT-Central, SAT and DAT sub-arrays.

3.1.1. Comparison of annual performance

Annual production outcomes cataloguing actual performance of GSRF technologies is reported in Table 1. Production performance is assessed using capacity factor (CF) results calculated as annual production divided by the product of the number of hours in each period and the sent-out AC capacity limit of each sub-array (e.g. 630 kW). Column "**A**" of Table 1 records actual performance of each sub-array and illustrates a number of key results:

(i) FT-West and DAT sub-arrays are significantly down in performance in 2015,

(ii) In 2017, FT-West's performance is lower compared to the neighbouring FT-Central sub-array,

(iii) The FT-East sub-array's performance is relatively lower compared to the FT-Central sub-array especially over 2015 and 2016.

The relatively poor performance of FT-West and DAT in 2015 could be associated with technical issues, which are common at the beginning of a plant operation. Column "**B**" of Table 1 shows the CF values recalculated by considering inverter outages. From this column, it is clear that the issue of inverter outages is not the principle driver of the poor performance of the FT-West and DAT sub-arrays in 2015, which requires further investigation. In all other cases, the removal of inverter outages served to significantly reduce the gap between the performance of the FT-West and FT-East sub-arrays with that of the FT-Central sub-array. The FT-East sub-array experienced negative impacts on PV yield performance attributable to shading from near-by trees, which adversely affect performance during 2015 and early 2016. These trees were removed in April 2016 and the gap in performance between FT-East and FT-Central sub-arrays subsequently declined. It was also evident that inverter outages have significantly affected the DAT sub-array's performance in 2016 (which is normal at the beginning of a plant operation), but was less pronounced in 2017. Instead, in 2017 the driver for the reduced productive performance of the DAT sub-array was enforced shutdown of different configurations for maintenance reasons.

Year	FT-West		FT-Central		FT-East		SAT		DAT		Total Array	
	A*	**B****	**A***	**B****	**A***	**B****	**A***	**B****	**A***	**B****	**A***	**B****
2015	18.0	18.5	20.6	20.7	19.9	20.0	24.1	24.2	19.4	19.9	20.2	20.3
2016	20.3	20.5	20.2	20.6	19.6	20.3	23.7	23.9	25.0	27.1	21.6	21.8
2017	20.1	20.4	20.8	20.8	20.4	20.5	23.7	23.7	25.0	25.5	21.8	21.9
2015-2017	19.5	19.9	20.5	20.7	19.9	20.3	23.8	23.9	23.4	24.4	21.3	21.4

* With inverter outages included, ** With inverter outages removed

Table 1: Actual annual production outcomes for representative GSRF solar array technologies-CFs (%)

3.1.2. Comparison of production gains from solar tracking

In this sub-section, a comparison of seasonal production gains from solar tracking is undertaken. Table 2 illustrates how the three representative GSRF sub-array technologies performance varies across different seasons with the production concept being CF results of the three representative sub-arrays.

Year	Season	CF_FT (%)	CF_ SAT (%)	% Difference	CF_FT (%)	CF_ DAT (%)	% Difference
2015	Autumn	20.5	21.9	7.2	--	--	--
	Winter	17.6	18.6	5.6	--	--	--
	Spring	23.3	29.0	24.4	--	--	--
2016	Summer	22.5	29.0	29.2	22.4	30.8	37.8
	Autumn	20.2	20.2	-0.3	20.2	26.4	30.6
	Winter	16.6	17.4	4.4	16.6	21.8	31.3
	Spring	22.9	28.9	26.3	22.7	30.0	32.4
2017	Summer	23.3	30.5	31.1	23.5	30.0	28.0
	Autumn	19.4	21.4	10.7	19.4	22.6	16.7
	Winter	20.1	19.8	-1.4	20.1	25.3	26.3
Total		20.6	23.7	14.8	20.7	26.7	29.2

Table 2: Actual seasonal production outcomes for representative GSRF solar array technologies- FT-Central, SAT and DAT sub-arrays

Analysis proceeds by standardising the operational details between the FT sub-array and each of the SAT and DAT sub-arrays. This entailed removing inverter outages of the respective technologies from hourly production records of both sets of technologies. It ensures that the operational profiles of both sub-arrays are standardised in terms of hourly structure and total number of hours. Different periods were applied in relation to the 'FT-SAT' and 'FT-DAT' comparisons because DAT tracking was in operation only from early December 2015.

The results of the 'FT-SAT' comparison are reported in columns 3-5 of Table 2. Assessment of the seasonal CF results in columns 3 and 4 indicates lower values during autumn and winter for both array technologies. In contrast, noticeably higher CF values are obtained during spring and summer, especially for the SAT technology. The "% Difference" values reported in column 5 are the percentage change in total output of the SAT technology relative to the total output of the FT-Central sub-array calculated for each season. During the autumn and winter seasons, the percentage change results (i.e. production gain from solar tracking of the SAT sub-array) are between -1.4% and 10.7%. In contrast, during the spring and summer seasons, the equivalent percentage increase is in the range of 24.4% and

31.1%. From the last row of Table 2, the average production gain from solar tracking associated with the SAT sub-array over the whole 2015-2017 period was 14.8%.

In columns 6-8 of Table 2, the ‘FT-DAT’ comparison results are reported. Columns 6 and 7 again indicate lower values during autumn and winter for both solar PV array technologies. During the spring and summer seasons, higher CF values are recorded. During the autumn and winter periods, the “% Difference” results in column 8 are between 16.7% and 31.3%. In contrast, during spring and summer, the equivalent percentage increases are between 28.0% and 37.8%. The average production gain from solar tracking of the DAT sub-array over the whole 2015-2017 period is 29.2%. This is substantially larger than the equivalent results of the SAT technology, which was 14.8%.

A key difference between the two tracking sub-arrays is the better performance of the DAT sub-array during autumn and winter because of the DAT technology’s ability to vary its tilt angle in order to optimise solar PV yield as the sun’s elevation becomes lower in the sky. In contrast, the SAT technology installed at GSRF is a horizontal SAT array whose tilt angle of zero degrees, by design, cannot be changed. The SAT array can track the sun’s position as it moves east to west in the sky. However, its design as a horizontal SAT array (e.g. with zero tilt angle) means that the plane-of-array irradiance narrows significantly in winter as the sun becomes lower in the sky, adversely affecting its performance compared to the FT array which, in contrast, has a 20 degree tilt angle.

The themes mentioned-above can also be discerned from assessing seasonal clear sky daily PV yield profiles of the representative solar sub-arrays at GSRF. The choice of clear sky days in Fig 3 means that the seasons are not centred and reflected their actual incidence at GSRF. Comparison of Fig. 3(a) with Fig. 3(b)-(d) confirms the superior performance of both tracking technologies during summer. In contrast, in winter (e.g. Fig. 3(c)), the PV yield of the SAT sub-array deteriorates markedly relative to the DAT sub-array and also relative to the FT sub-array in the middle of the day. Fig. 3(b) and (d) indicate that gains from solar tracking are more prominent in spring than in autumn, backing up the results cited in Table 2. Thus, the best performing seasons in descending order are summer, spring, autumn and then winter.

A key consideration in assessing the commercial viability of the different sub-arrays is whether the increase in cost for the more complex tracking systems is justified in financial terms by increased energy output. While detailed assessment is outside the scope of the current paper, analysis in [3] and [4] indicates that the SAT sub-array is the most competitive technology when both capital cost and output performance are jointly considered.

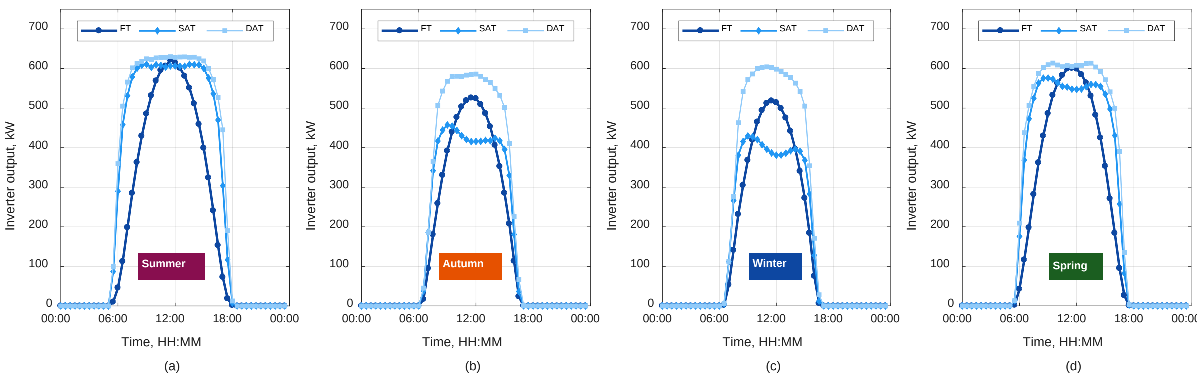


Fig. 3. PV Array yield profiles in (a) summer on 14/2/2016, (b) autumn on 13/5/2016, (c) winter on 8/6/2016, and (d) spring on 24/9/2016

3.2 Battery Operation Assessment

In this subsection, battery operation and performance are investigated in terms of energy and power of cyclic regime, SOC level, and cell temperature. To do so, battery operational data between May 1st, 2016 and October 31st, 2017 is considered for analysis with 1-minute resolution. Since battery bank 2 have almost identical behaviour as bank 1, which is aligned with the CSS control philosophy, the data from battery bank 1 is only be analysed. Nevertheless, observations derived from battery bank 1 can be extended to battery bank 2.

Fig. 4 shows boxplot (or box-and-whisker plot) representation of the battery average SOC, power, and average cell temperature for four categories of battery operation. From **Fig. 4**, it can be seen that battery is idle with relatively high SOC level. In one hand, it is good because battery has more stored energy to respond to unpredictable situations. On the other hand, it can be problematic in terms of battery calendar aging, particularly when battery room temperature is high. Since battery temperature is maintained well within an acceptable range for most of the time, calendar-ageing effect is not prominent in this case. While SOC median is understandably lower in *discharging* category, the 25th percentile (or 1st quartile) is about 40%, which is relatively good for a battery operation. However, the 1.5 interquartile of the samples (about 99.3% of the samples) extends to lower SOC levels, around 10%. It means that the discharge regime in some cases is relatively intense. Charging battery more often could be a solution to avoid such deep discharge incidents. In *charging* category, the median and 25th percentile is relatively high which is good for battery health. However, the 1.5 interquartile stretched out to lower limits, around 20%. The reason could be the fact that battery charging typically starts when the SOC level is low. Therefore, many incidents of low SOC level can be expected. In *charging/discharging* category, the SOC level is maintained within a range that is recommended for extending battery lifetime. In the last three categories, very low incidents of SOC are marked as anomalies in **Fig. 4**, presumably caused by temporary malfunction in the CSS or battery inverter controller.

Temperature is yet another important factor to be evaluated for battery operation in such applications, as shown at the bottom of **Fig. 4**. According to the figure, cooling mechanisms maintained battery average temperature within [20°C, 30°C] band in different category. This has a positive impact on the battery lifetime. Moreover, average cell temperature does not show sporadic behaviour in a statistical sense, which may improve battery life-cycle cost. Very high temperature can be seen in different categories, which rarely observed in the dataset.

Table 3 summarises battery operation data under various conditions. It can be seen that battery is idle for more than 75% of the time. In one hand, it is good that battery has been given enough resting periods because intensive charge and discharge regime escalates battery degradation. On the other hand, it could be disadvantageous for the battery economic return. Therefore, there is an opportunity for the battery system to participate in the energy and/or ancillary services markets while satisfying PV plant requirements. Several key remarks can be inferred from Table 3, as follows:

- The worst power fluctuations occurred in *charging/discharging* category, where the standard deviation is the highest (69.76 kW). This is not surprising since battery is smoothing quick fluctuations in the PV output power in this mode. Highly fluctuating charge/discharge regime is harmful to the battery health.
- Battery system experienced the largest average power during discharging events. Based on the boxplot of battery power during discharging mode in Fig. 4, battery power exceeds 200 kW in 25% of the time. It may escalate battery degradation, which needs to be addressed by proper operational algorithms.
- While battery operated in *charging* category for about 14.5% of the time, the accumulated charge incurred in this mode was about 96.2 MWh (158.2 cycles accumulatively). This is about 54% of total throughput charge on the battery. This could lead to higher degradation of the battery capacity and power capability.

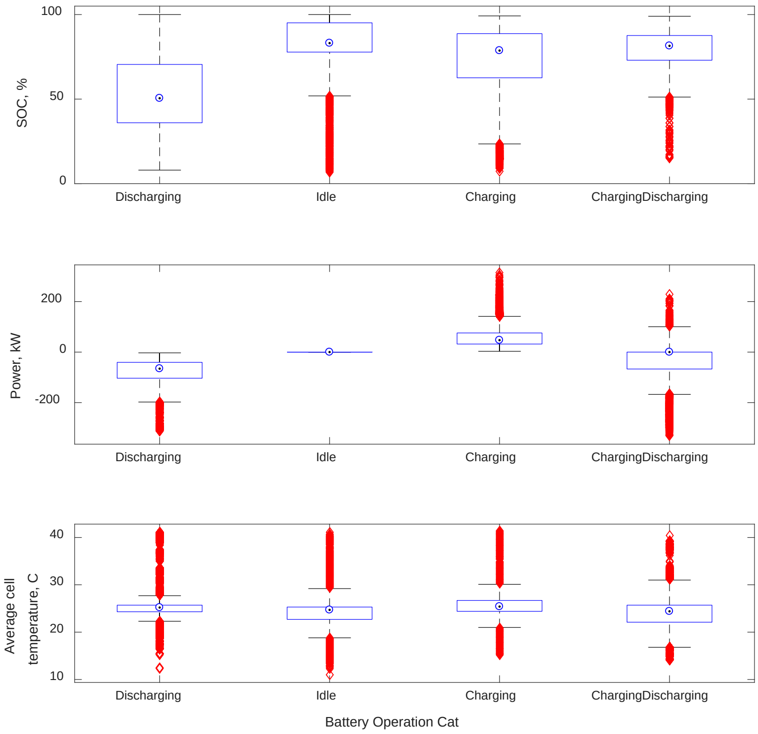


Fig. 4. Battery operation under different operation rules, derived from annual data of battery bank 1.

Operation mode	Aggregated. Time, minute	% of time	Total charge MWh (cycles)	Total discharge MWh (cycles)	Average Abs. power†, kW	Std. Abs. Power*, kW
Idle	521,474	75.6	--	--	--	--
Charge	100,219	14.5	96.2 **(158.2)**	--	39.7	39.1
Discharge	53,116	7.8	--	68.5 **(112.7)**	65.8	24.6
Charge/Discharge	15,016	2.2	1.1 **(1.8)**	11.0 **(18.1)**	48.2	69.76

† Average of absolute battery power * Standard deviation of the absolute battery power

Table 3: General statistics of the operation of battery bank 1 in different mode using annual data.

Overall, battery operation in *charging* category is relatively intense in terms of charge throughput while battery experiences intense power magnitude in *discharging* category. The cooling mechanisms work properly by keeping battery temperature within an acceptable range despite some intensive charge and discharge events.

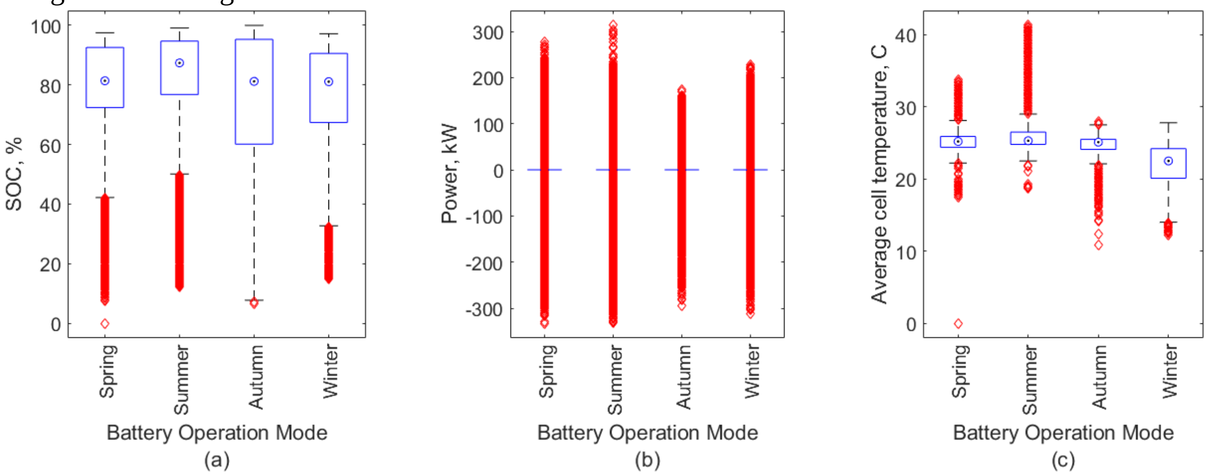


Fig. 5. SOC, power, and average cell temperature in different seasons for battery bank 1.

Fig. 5 shows boxplot representation of the battery operational data in terms of average SOC, power, and average cell temperature of battery bank 1 in different seasons. It can be seen from Fig. 5(a) that the SOC median is the highest in summer due to more opportunities to charge the battery in longer summer days. On the other end, autumn shows the worst battery SOC condition with the lowest median. The 25^{th} percentile is the lowest in autumn, reaching to almost 60%. It implies more instances of low SOC levels in this category. It can also be verified by the 1.5 interquartile lower limit in autumn, which is extended all the way to very low SOC range. The deep discharge regime in this case can be harmful to the battery health. While there are instances of very low SOC in other seasons, they are considered as outliers by the boxplot algorithm. It can be concluded that the battery operation algorithm could be improved in autumn to charge battery more often.

In Fig. 5(b), battery power samples are shown for different seasons. The median power in all four seasons is close to zero, which means that battery power during charging and discharging are similar over the entire samples. Also, overlaying 25^{th} and 75^{th} percentiles with whisker lines (i.e., 1.5 interquartile) shows that many instances of battery charge and discharge power are close to zero. This further implies that battery is charged and discharged partially most of the time, which may adversely affect battery health in long-term [3]. A combination of battery and super-capacitor in this case could be useful to avoid unnecessary battery degradation. On the higher range of power variations, summer and spring impose the most intense operation on the battery by large active power charge and discharge regime. While this could escalate battery degradation, they rarely occurred in the samples. In any case, it can be concluded that seasonal battery operation algorithms might help to mitigate some of the battery intensive operation, which could consequently avoid excessive degradation.

In Fig. 5(c), average cell-temperature data is plotted for different season. On average, battery temperature is maintained within 25-30°C in different season. The higher average temperature in summer and spring compared to autumn and winter shows the impact of ambient temperature on the battery operation within the battery container. In addition, it can be seen from the figure that there are some instances in summer and spring where battery temperature was above 30°C. This could be particularly harmful to battery lifetime as every 10°C increase in temperature (e.g. 40°C) would double battery degradation rate [6]. In addition to the ambient temperature, higher temperature in summer and spring might be caused by excessive charge and discharge power in these two seasons, as explained in the previous paragraph. In winter, the lower whisker line goes below 15°C, which is again harmful to the battery lifetime, though not as much as high temperature. This also could be avoided to some extent by improving the cooling system operation and container's insulation. In general, battery operation is found to be acceptable in terms of cell temperature.

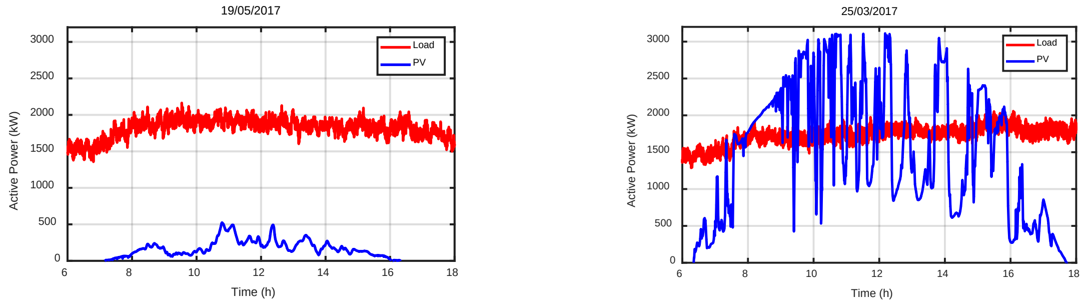
3.3 Voltage Analysis

3.3.1. Impact of the PV fluctuations to Step Voltage Regulators

With the 3.275 MW_P PV plant connection to the Gatton distribution network, it presents new operational challenges, such as voltage fluctuation and reverse power flow. The impacts of the large-scale PV integration to the medium-voltage networks may propagate to upstream networks. Furthermore, the 3.275 MW_P PV plant is connected to the Gatton zone substation through an 11kV 7.45km line, where an open-delta step SVR is installed in the middle for voltage regulation at the PCC. After PV system installation, excessive tap operations of SVR arise after PV system integration due to PV power fluctuation. Since SVRs are designed to deal with the slow load variation, the excessive tap operations can affect their lifetime.

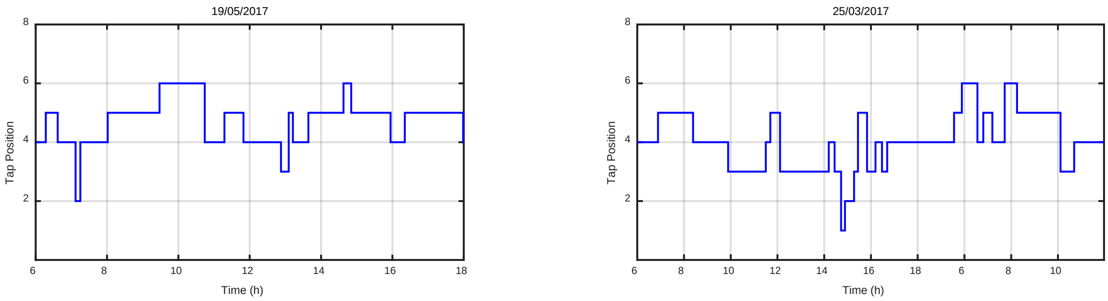
In order to realise the impact of the PV power fluctuations on the open-delta SVRs, the tap changes with and without PV integration should be investigated. However, open-delta SVRs are normally installed in the rural areas with poor communications. Thus, there are missing data issues, while high-resolution data may not be available. Moreover, upstream open-delta SVR tap positions are usually not accessible to customers. Therefore, a remote tap position estimation approach proposed in our previous work [7], which was used to estimate tap positions based on reverse line drop compensation (LDC), statistical unbalance offset and complete voltage vector trigonometry. Moreover, the general inputs to obtain the tap position are the high resolution data (phase-to-neutral and phase-to-phase voltage magnitudes, real power and reactive power) measured in the downstream at PV site.

By using the proposed estimation approach in [7], it has been proved that the fluctuation of the solar PV power output can cause excessive SVR tap changes in cloudy days. For example, as shown in Fig. 6 and Fig. 7, the number of tap changes is 18 during the daytime (6:00am to 6:00pm) in an overcast day, while the corresponding number is 32 in a cloudy day with a similar load profile. In other words, the number of tap changes is almost double due to PV power output variations. Therefore, the SVR lifetime would be affected after PV plant installation, and its maintenance costs would be inevitably increased.



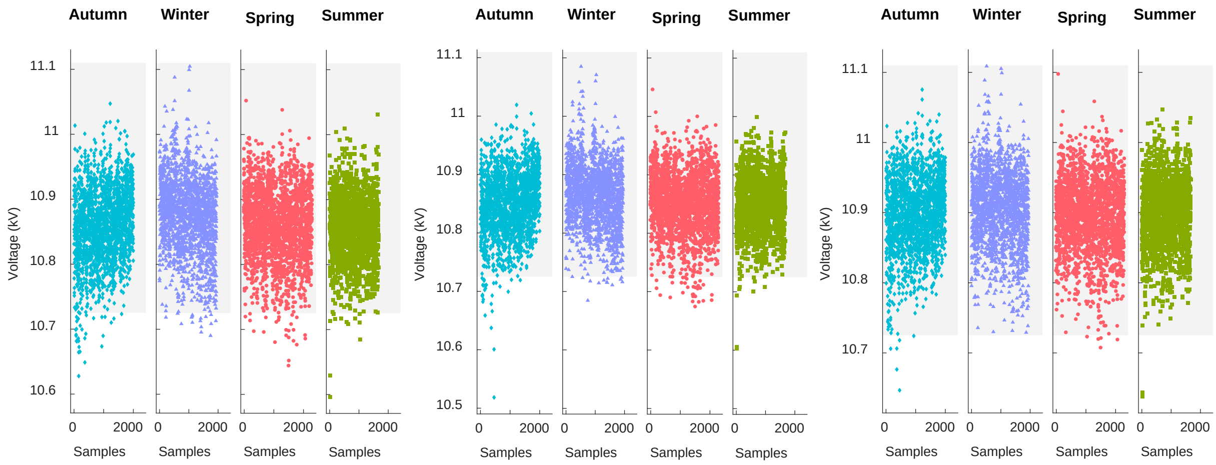
(a) Overcast day (b) Cloudy day

Fig. 6. UQ Gatton campus load and solar PV plant power output



(a) Overcast day (b) Cloudy day

Fig. 7. SVR tap positions



(a) V12 (b) V23 (c) V31

Fig. 8. Line-to-line voltages at the MU3 point of connection, shown in Fig. 1.

Fig. 8 depicts line-to-line voltages with one-minute resolution at the MU3 point of connection for different seasons. The data is collected from 2nd of December 2016 until 28th of November 2017. The standard limit of voltage variations is highlighted in grey in Fig. 8. In general, the voltage between phase 1 and 2 shows slightly more variations. In addition, voltage behaviour is more sporadic during autumn, which is associated with more cloudy days. Nevertheless, it can be seen that the voltage level is typically well maintained within the upper and lower limits (i.e., 1.01 and 0.975 p.u., respectively).

4. CONCLUSIONS

This paper presented a few remarks on the performance of PV tracking technologies and battery system, and voltage variations at the GSRF. An examination was undertaken of the productive performance of each array component of GSRF. The SAT sub-array experienced the uniform performance over the 2015-2017 period, closely followed by the FT Central sub-array.

Results in Table 2 indicate that seasonal production gains from solar tracking point to summer and spring being the best seasons. Production gains from tracking associated with the horizontal SAT technology deteriorated markedly during autumn and winter when compared to the other two solar PV array technologies installed at GSRF, as also shown in Fig 3(a) and 3(c) (for summer and winter comparison). This principally reflected the combined effect of lower elevation of the sun in the sky together with the horizontal tilt of the SAT sub-array. A number of operational implications immediately suggest as: (i) minimise outages and curtailments over spring and summer; (ii) schedule planned Operation and Maintenance (O&M) during winter; and (iii) schedule any module cleaning for late September to early October to maximise the PV yield potential over spring and summer.

In terms of battery, the overall operation and performance has been found to be satisfactory. However, there are a couple of matters that could be improved to extend battery lifetime. Battery operation algorithm should charge battery more often in autumn and winter to maintain SOC level within the upper level. During discharging, battery has undergone intense discharging power, which could be harmful for the battery operation. This observation also suggests an improvement in the battery operation to discharge more gently in longer times to avoid any excessive degradation on the battery. In general, the cooling mechanism are operating properly to maintain battery temperature between 20°C and 30°C. However, some improvement on the operation and insulation system could decrease the number of excessive temperature in summer and spring. In terms of voltage fluctuations, the plant is in a good situation. However, excessive operations are identified in cloudy days because of sporadic changes in PV generation due to cloud movement.

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