MANCHESTER 1824
The University of Manchester

Power Flow and Stored Energy Characterisation of a Commercial Battery Energy Storage System

1. Introduction

This document outlines a series of experimental procedures aiming to investigate the instantaneous power losses and the round trip energy efficiency of a commercial Siemens SieStorage, battery energy storage system (BESS). This research is part of the EPSRC-funded MANiFEST project.

2. System Specification

The SieStorage system is rated at 240 kVA and 180 kWh and is located at the University of Manchester. The system is connected 'behind the meter' to the local low-voltage distribution grid via a 260 kVA, 400/433V TMC isolation transformer. The system features two parallel connected two-level Infineon inverters, each connected to a pair of parallel connected battery banks. Each battery bank has an energy capacity of 45 kWh. To achieve this capacity each bank consists of 14 series-connected, 51.8 V NMC Li-ion polymer battery UPB4860 Gen 1 modules, supplied by LG Chem. Each module contains 14 cells connected in series, resulting in 196 cells per bank. The 196 series-connected cells result in a minimum voltage of 550 V when the battery is empty, and 814 V when the system is fully charged. Furthermore, each cell is formed by four separate parallel-connected pouches. Moreover, the room temperature is maintained at 20°C by three 7.1 kW Mitsubishi air-conditioning units. Figure 1 shows the room that hosts the SieStorage system and highlights the critical components.

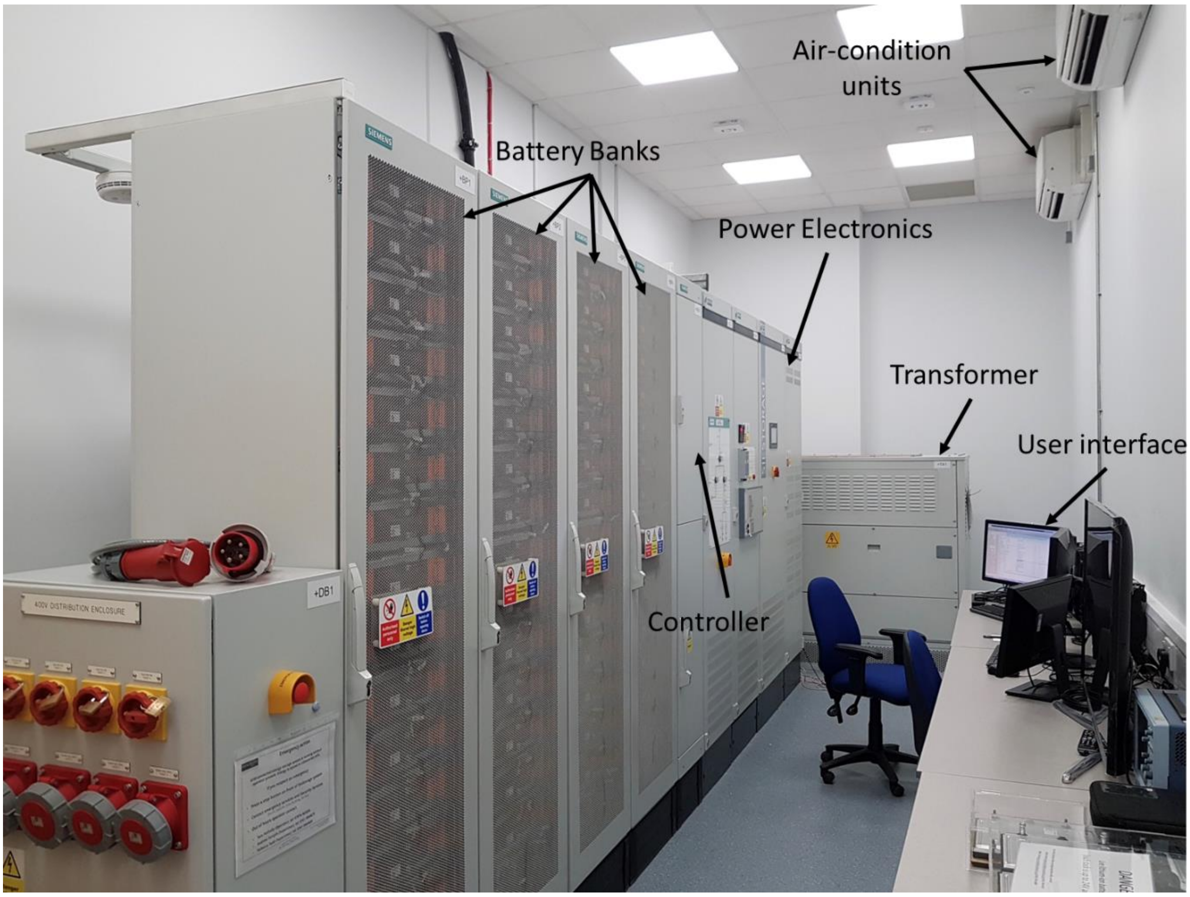

Figure 1. UoM BESS research facility.

3. Test Procedure

The objective of the experimental procedure is to identify the instantaneous power losses and measure the round-trip energy efficiency of the system over small changes in SoC across the full operational range of the system. To investigate if the state-of-charge (SoC) range denoted, ΔSoC, has any effect on efficiency or the losses of the system, three different ΔSoC ranges, 5%, 10% and 20% SoC, have been tested.

The instantaneous power losses may be derived by comparing the battery power to the grid power. The round-trip energy efficiency of the system for a cycle can be calculated by comparing the energy used by the system to charge and discharge. The energy needed to charge the battery can be calculated by integrating the power of the system over the time needed for the SoC to reach the upper SoC limit from the low SoC level. Similarly, the discharge energy is given by integrating the power over the time needed for the SoC of the system to return to the low SoC limit.

Two test sequences have been conducted. The first one assessed the system over medium to high power set-points, from 45 kW to 240 kW. To obtain a more comprehensive view, the second experiment evaluated the system over low to medium power set-points, from 9 kW to 36 kW.

3.1. Medium to High Power Set-Points

The first experimental schedule comprised seven medium to high power set-points, from 45 kW to 240 kW, across the full 5% to 90% SoC operating range. The seven power set-points used to assess the SieStorage performance over the different SoC ranges are shown in Table 1, where P_{NOM} refers to the power rating and C-rate to the energy capacity of the system.

Table 1: Medium to high real power set-points used in UoM tests.

	Test points for comparison with:	
Power, kW	P_{NOM}	C-rate
45		0.25 C
60	0.25 P_{NOM}	
90		0.5 C
120	0.5 P_{NOM}	
135		0.75 C
180	0.75 P_{NOM}	1 C
240	1 P_{NOM}	

Figure 2 shows the test schedule for the first experiment of the medium to high power set-points, initial SoC, and ΔSoC ranges. The numbers in circles indicate the test order where a specific initial SoC, and ΔSoC range is considered as a group. After the last test for a group, SieStorage was commanded to the minimum SoC for the next group at a set-point of 45 kW, then rested for 10 minutes before the next group of tests commenced. The combination of 45 kW and 10 minutes of rest were selected to minimise cell degradation and any effects of heating, while not incurring an excessively long test duration. After the completion of the test schedule, the system was returned to 50% SoC at 45 kW. Figure 3 shows the system's SoC, and power alongside the battery bank 3 and 4 voltage and current respectively for the 9th group of tests with initial SoC of 55%, and 5% ΔSoC.

3.2. Low to Medium Power Set-Points

The second test sequence evaluated the system's instantaneous power losses and round-trip energy efficiency on low power set-points at 9 kW, 18 kW, and 36 kW, corresponding to 0.05 C, 0.1 C and 0.2 C respectively, and from 10% to 90% SoC for all three ΔSoC ranges mentioned above. The need for evaluating the system's behaviour at low power set-points became clear after examining the behaviour of the system when participating in grid support services. Figure 4 shows the test schedule for the second experiment at the low to medium power set-points, initial SoC, and ΔSoC ranges from 90% to 10% SoC for all three power set-points and ΔSoC ranges.

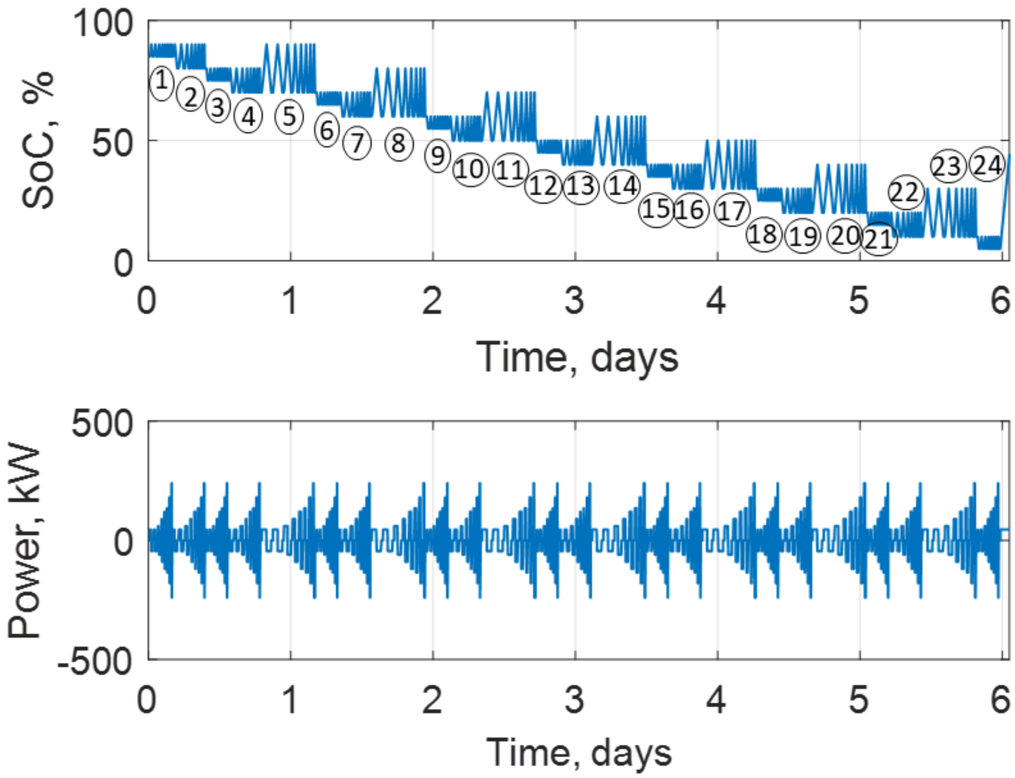

Figure 2. Efficiency test sequence, including sequence order for medium to high real power set-points.

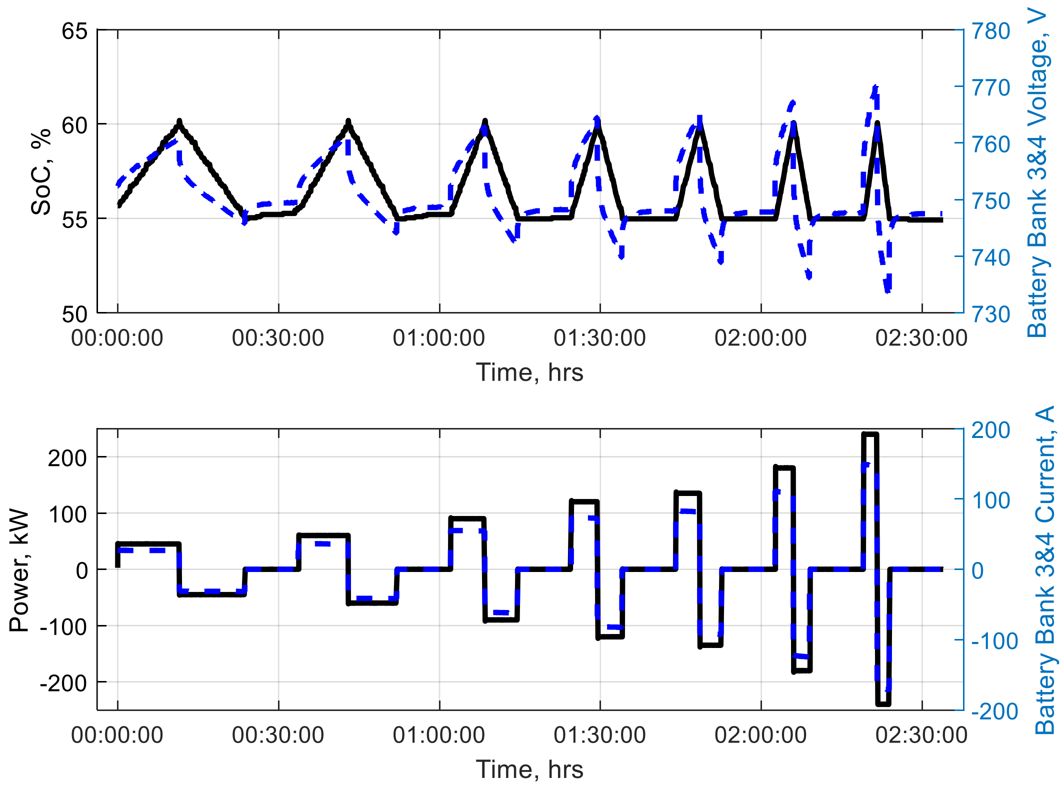

Figure 3. SieStorage SoC, and power alongside the battery bank 3 and 4 voltage and current respectively for the 9th group of medium to high power set-point tests. Initial SoC =55%, ΔSoC = 5%.

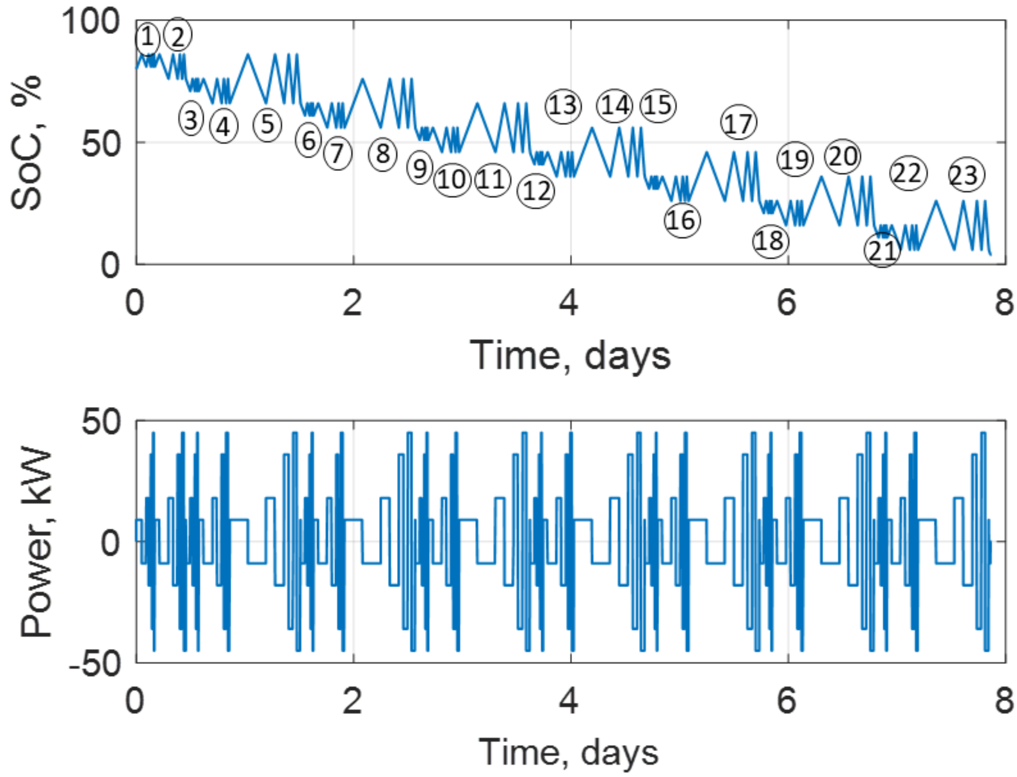

Figure 4. Efficiency test sequence, including sequence order for low to medium real power set-points.

4. Instantaneous Power Losses

The included data can be used to derive the system's instantaneous power losses however, the data analysis is beyond of the scope of this document.

5. Round-trip Energy Efficiency

The round-trip energy efficiency of the system can be derived from the included data. However, the analysis and derivation of the system's efficiency is outside the scope of this document.

6. Data Format

The data is captured through a Profibus communications link. The measurements from the SieStorage can be divided in two categories; 250 ms sampled data where the data is available every sample, and three multiplexed data channels which enable access to 29 variables, and so this data is only available at specific user defined multiples of 250 ms. The data is presented using comma-separated values (CSV), with the following columns:

- Column 1: Time in data-point ISO 8601 timestamp (yyyy-mm-dd hh:mm:ss.ssss).
- Column 2: Remaining energy (kWh), as measured by SieStorage.
- Column 3: Capacity (kWh), as measured by SieStorage.

- Column 4: Battery SoC (%), as reported by SieStorage BMS.
- Column 5: Calculated SoC (%), the ratio of Capacity and Remaining Energy given by SieStorage.
- Column 6: Real Power (kW), as measured by SieStorage.
- Column 7: Room Temperature (°C), as measured by Syxthsense meter.
- Column 8: Data multiplex ID value, as given by the Siemens Profibus.
- Column 9: Multiplex output 1, as measured by SieStorage.
- Column 10: Multiplex output 2, as measured by SieStorage.
- Column 11: Multiplex output 3, as measured by SieStorage.
- Column 12: Battery Bank 1 and 2 SoC (%), as reported by SieStorage BMS.
- Column 13: Battery Bank 3 and 4 SoC (%), as reported by SieStorage BMS.

Table 2 shows the multiplexer ID sequence used in these tests. The numbers within the squared brackets in Table 2 indicate which converter the data relates to.

Table 2. Full 4.5 s multiplexer ID sequence, multiplexer output mapping and frequency of variables selected.

ID	Multiplexer Output 1	Multiplexer Output 2	Multiplexer Output 3
6	CONVERTER[1] P (W)	CONVERTER[1] T_{STACK} (°C)	BATTERY BANK 1&2 U_{MIN_CELL} (V)
7	CONVERTER[2] P (W)	CONVERTER[2] T_{STACK} (°C)	BATTERY BANK 3&4 U_{MAX_CELL} (V)
1	BATTERY BANK 1&2 U_{DC} (V)	BATTERY BANK 1&2 I_{DC} (A)	BATTERY BANK 1&2 Module
2	BATTERY BANK 3&4 U_{DC} (V)	BATTERY BANK 3&4 I_{DC} (A)	BATTERY BANK 3&4 T_{MAX} (°C)
61	CONVERTER[1] U_{DC} (V)	CONVERTER[2] U_{DC} (V)	0
62	CONVERTER[1] U_{AC_L1} (V)	CONVERTER[2] U_{AC_L1} (V)	0
64	CONVERTER[1] I_{RMS_L1} (A)	CONVERTER[2] I_{RMS_L1} (A)	0
3	BATTERY BANK 1&2 U_{DC} (V)	BATTERY BANK 1&2 I_{DC} (A)	BATTERY BANK 1&2 T_{MIN} (°C)
4	BATTERY BANK 3&4 U_{DC} (V)	BATTERY BANK 3&4 I_{DC} (A)	BATTERY BANK 3&4 T_{MIN} (°C)
65	CONVERTER[1] P (W)	CONVERTER[2] P (W)	0
66	CONVERTER[1] Q (Var)	CONVERTER[2] Q (Var)	0
1	BATTERY BANK 1&2 U_{DC} (V)	BATTERY BANK 1&2 I_{DC} (A)	BATTERY BANK 1&2 T_{MAX} (°C)
2	BATTERY BANK 3&4 U_{DC} (V)	BATTERY BANK 3&4 I_{DC} (A)	BATTERY BANK 3&4 T_{MAX} (°C)
65	CONVERTER[1] P (W)	CONVERTER[2] P (W)	0
51	BATTERY BANK 1&2 U_{MAX_CELL} (V)	BATTERY BANK 1&2 U_{MIN_CELL} (V)	0
63	CONVERTER[1] Frequency (Hz)	CONVERTER[2] Frequency (Hz)	0
67	CONVERTER[1] T_{STACK} (°C)	CONVERTER[2] T_{STACK} (°C)	0
52	BATTERY BANK 3&4 U_{MAX_CELL} (V)	BATTERY BANK 3&4 U_{MIN_CELL} (V)	0

7. Included Data Files

In total 47 files have been produced and are included with this report. 24 of them were produced during the medium to high real power set-points investigation in 2018 and they are named "Energy_Efficiency_xxx.csv". The remaining 23 files were produced during the low real power set-points investigation in 2020 and they are named "Low_Power_Energy_Efficiency_xxx.csv". In both cases, "xxx" indicates each group of data.