



Smart Battery Energy Storage System for Distribution Congestion Management

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ABSTRACT—

Distribution feeders are being pushed towards their thermal limits by evening demand peaks, while solar generation adds variability that conventional feeder planning handles poorly. This paper presents a MATLAB/Simulink study of a smart battery energy storage system (BESS) that relieves congestion on a modelled 11 kV, 5.0 MW feeder. A 2 MW / 2 MWh lithium-ion battery with a battery management layer is supervised by a four-mode, threshold-based energy management system (EMS) that performs peak shaving, solar-surplus absorption, valley filling and standby operation, and restricts every command by the battery's State of Power. The model tracks State of Charge, State of Health, State of Energy, State of Power, Depth of Discharge, C-rate and round-trip efficiency, together with feeder voltage, current, frequency and loading. Over a 24-hour run, the evening peak of 5.31 MW is cut to 4.50 MW (15.2 %), the 1.99 h of daily congestion and 0.58 MWh of thermal overload disappear, 1.04 MWh is shifted into the peak, round-trip efficiency is 90.25 %, and the modelled State of Health falls by only 0.02 %. Simple hand calculations are used to cross-check the reported numbers. The study is simulation-only, and its limitations and the route to hardware-in-the-loop validation are discussed.

Index Terms—battery energy storage system, distribution congestion, energy management system, peak shaving, State of Health, solar PV.

INTRODUCTION

Electrification of transport, cooking and cooling is steadily lifting evening demand on distribution feeders. Rooftop and community solar does the opposite at midday, pulling net demand down, but it does very little once the sun has set. The result is a feeder that sits lightly loaded for most of the day and is then asked to carry a sharp, short peak in the evening. A line or transformer is rated by its thermal limit, so even a peak that lasts only a couple of hours can overheat conductors and age equipment. Reinforcing the network is the traditional answer, yet it is slow and expensive when the problem is a narrow peak. Storage placed on the feeder offers a non-wires alternative that can be installed and dispatched far more flexibly [1]–[3].

A battery can do much more than shave a peak. The literature lists frequency regulation, output smoothing, ramp-rate control, energy arbitrage, voltage support and congestion management among its grid services [4]–[6]. Recent reviews of renewable integration add an important point: the hardware is only half of the story, because the controller that decides when to charge or discharge, and how much the battery is allowed to age while doing so, largely determines whether the investment pays off [4], [7].

Many published schemes rely on optimisation, which can be powerful but is often hard for an operator to inspect. Threshold rules are easier to read, easier to audit and a common starting point in practice, provided they never ask the battery for something it cannot deliver. This work therefore builds a transparent rule-based EMS and ties it closely to a battery management system (BMS) model, so that every command is limited by the battery's present capability. The main contributions are as follows.

- A Simulink model of an 11 kV, 5.0 MW feeder with a time-varying consumer load (peak 5.31 MW), a 1.5 MW solar source and a 2 MW / 2 MWh lithium-ion BESS.
- A four-mode EMS covering peak shaving, solar-surplus absorption, valley filling and standby, with commands clipped by State of Power and fed by SoC and SoH feedback.
- A BMS block that outputs seven battery indicators, together with grid-side measurements of voltage, current, frequency, power factor and loading, logged through 20 workspace variables.
- A with-and-without-BESS comparison, supported by independent hand calculations that check the current limit, the feeder voltage and the energy balance.

Section II reviews related work. Section III describes the system, Section IV the EMS, Section V the battery model and Section VI the grid model. Section VII covers the simulation set-up, Section VIII presents results, and Sections IX and X discuss limitations and conclude.

RELATED WORK

A. Storage services and reviews

Datta et al. sort battery functions into active-power services, such as frequency regulation, peak shaving, smoothing, ramp-rate control and congestion management, and reactive-power services, such as voltage regulation and ride-through support. They also name the open problems: charging strategy, converter efficiency, battery lifetime and sizing [4]. Ahmad et al. widen the view to BMS design, power conversion, hybrid storage, economics and future

directions including AI-assisted energy management [7]. Earlier overviews compare storage technologies and applications [2], [3], [6], [8], Hesse et al. discuss how stationary lithium-ion systems should be designed for different duties [9], and a review by Yang et al. covers sizing [10].

B. Peak shaving and congestion relief

Oudalov et al. treat the sizing and operation of a battery for peak shaving as a design problem in its own right [11]. Leadbetter and Swan examine peak-demand reduction in dwellings [12], and Neubauer and Simpson study demand-charge reduction with behind-the-meter storage [13]. For network congestion, Elliott et al. coordinate one storage asset between a transmission and a distribution operator through mixed-integer programming, so that services are stacked on the same battery [1]. Our study is complementary: it has a single operator, sits on the distribution side, and uses simple rules instead of optimisation.

C. Battery management and degradation

Lawder et al. describe what a grid-scale BMS has to do: monitor cells, estimate states and protect the system [14]. Plett provides the modelling foundation [15], while reviews of State of Charge estimation and State of Health monitoring summarise the available methods [16], [17]. Ageing mechanisms are explained in [18], cycle-life models in [19], and degradation models suited to dispatch studies in [20]. We use a deliberately simple throughput-based fade law, in keeping with the scope of a feeder-level study.

D. Position of this work

The studies above either focus on services and optimisation or on the battery itself. Here the two are joined in one runnable model: the EMS reads the BMS state at every step, and the grid model returns feeder quantities that can be compared directly with and without storage.

METHODOLOGY

A. SYSTEM DESCRIPTION

Fig. 1 shows the structure. An 11 kV, 50 Hz source with 100 MVA short-circuit capacity feeds a 6.5 MVA, 11 kV/415 V transformer and a 5 km feeder. The consumer load, the 1.5 MW solar source and the battery connect at the point of common coupling (PCC). The battery is interfaced through a 2.2 MVA four-quadrant voltage-source converter, and the EMS sits above the whole arrangement. Table I lists the main parameters. Distributed-resource interconnection is assumed to follow the usual practice described in [21].

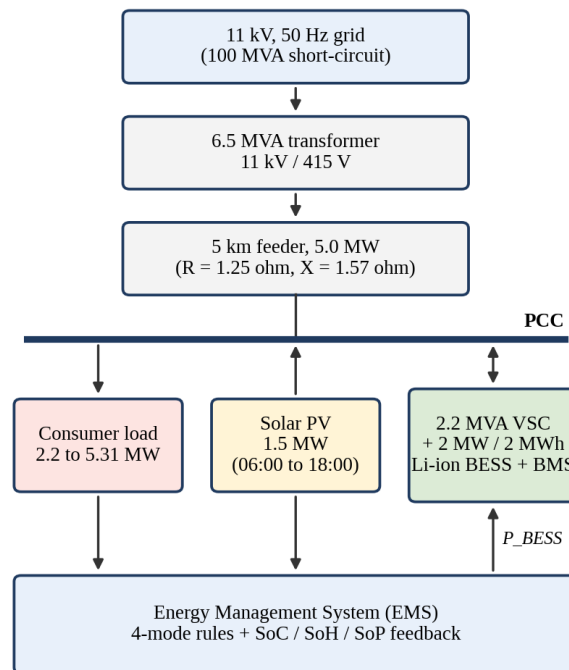


Fig. 1. Single-line architecture of the Smart BESS system.

TABLE I MAIN SYSTEM PARAMETERS

Parameter	Value
Grid voltage / frequency	11 kV RMS / 50 Hz
Short-circuit capacity	100 MVA
Transformer	6.5 MVA, 11 kV / 415 V
Feeder length / rating	5.0 km / 5.0 MW
Feeder R, X	1.25 Ω , 1.57 Ω

Parameter	Value
Feeder current limit	262.4 A
Consumer load	2.2 MW base, 5.31 MW peak
Solar PV	1.5 MW, 06:00–18:00
BESS rating	2.0 MW / 2.0 MWh, Li-ion
Converter	2.2 MVA, four-quadrant VSC
DC-link (as reported)	800 V
SoC operating window	20 % to 90 %
Charge / discharge efficiency	95 % / 95 %
Peak-shaving threshold	4.50 MW
Valley-filling threshold	3.25 MW
Run length / sample time	24 h / 0.01 h (36 s)

The load follows a 24-hour residential and commercial profile with a base of 2.2 MW, a rise to about 3.0 MW through the afternoon and an evening peak of 5.31 MW near 19:30, which exceeds the 5.0 MW rating. The solar source is a smooth daytime curve that peaks at 1.5 MW around noon and is zero outside 06:00–18:00. Because the lowest load (2.2 MW) is higher than the largest PV output (1.5 MW), solar never exports to the grid in this profile. Its effect is to lower net demand around noon.

The feeder is described by a resistance of 0.25 Ω /km and an inductance of 1.0 mH/km, as is typical in distribution modelling [22]. For the 5 km length,

$$R_f = 0.25 \times 5 = 1.25 \Omega \quad (1)$$

$$X_f = 2\pi f L \ell \approx 1.57 \Omega \quad (2)$$

and the current corresponding to the 5.0 MW rating at unity power factor is

$$I_{lim} = P_{max} / (\sqrt{3} V_{LL}) = 262.4 A \quad (3)$$

which reproduces the limit used in the project.

B. ENERGY MANAGEMENT STRATEGY

The EMS is the supervisory controller. At each step it receives the load power, the PV power and the delayed SoC and SoH from the battery model, and forms the net feeder demand

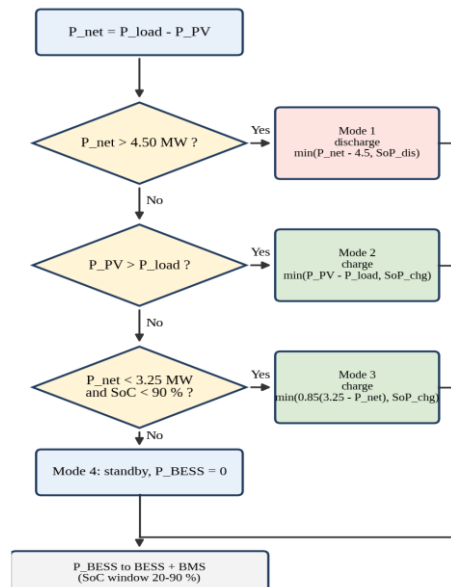
$$P_{net} = P_{load} - P_{PV} \quad (4)$$

It then selects one of four modes (Table II, Fig. 2). Positive P_{BESS} means discharging.

TABLE II EMS OPERATING MODES

Mode	Trigger	BESS action
1. Peak shaving	$P_{net} > 4.50$ MW	Discharge, limited by SoP_{dis}
2. Solar surplus	$P_{PV} > P_{load}$	Charge with the surplus, limited by SoP_{chg}
3. Valley filling	$P_{net} < 3.25$ MW and $SoC < 90$ %	Charge at 0.85 of the gap below 3.25 MW
4. Standby	$3.25 \leq P_{net} \leq 4.50$ MW	Idle, $P_{BESS} = 0$

Fig. 2. Decision flow of the four-mode EMS. The checks are drawn in sequence for readability.



The commands for the three active modes are

$$P_{BESS} = \min(P_{net} - 4.50, SoP_{dis}) \quad (5)$$

$$P_{BESS} = -\min(P_{PV} - P_{load}, SoP_{chg}) \quad (6)$$

$$P_{BESS} = -\min(0.85(3.25 - P_{net}), SoP_{chg}) \quad (7)$$

with all powers in MW.

Several design choices are worth explaining. The 4.50 MW trigger is 90 % of the feeder rating, which leaves an operating margin instead of waiting until the thermal limit is reached. The factor 0.85 in the valley-filling rule means that charging raises the line power towards, but never up to, the 3.25 MW threshold, so the battery cannot create a new peak while it recharges. The dead band between 3.25 MW and 4.50 MW keeps the battery idle and avoids small, shallow cycles that wear it without helping the feeder. Finally, because every command is capped by the State of Power, the EMS never asks for more than the battery can presently supply or absorb.

BATTERY AND BMS MODEL

The battery is modelled as an energy store E with a power rating of 2.0 MW and an energy rating E_{rated} of 2.0 MWh. With charging power P_{chg} and discharging power P_{dis} (both non-negative) over a step Δt , the stored energy evolves as

$$E_{k+1} = E_k + \eta_c P_{chg} \Delta t - P_{dis} \Delta t / \eta_d \quad (8)$$

where $\eta_c = \eta_d = 0.95$. The BMS block derives the indicators below from this state [14], [15]:

$$SoC = 100 E / E_{rated} \quad (9)$$

$$DoD = 100 - SoC \quad (10)$$

$$C = |P_{BESS}| / E_{rated} \quad (11)$$

$$RTE = \eta_c \eta_d = 90.25 \% \quad (12)$$

SoE is the stored energy itself, and SoP_{dis} and SoP_{chg} are the present discharge and charge power capabilities. The SoC is clamped to the 20–90 % window. Cycling is counted as equivalent full cycles (EFC),

$$EFC = \int |P_{BESS}| dt / (2 E_{rated}) \quad (13)$$

and the State of Health is reduced in proportion to the throughput,

$$SoH_{k+1} = SoH_k - 100 \beta \Delta EFC_k \quad (14)$$

where β is the fade per equivalent full cycle used inside the model. Throughput-based fade is a common simplification of the more detailed ageing behaviour described in [18]–[20]. In the captured run, SoP_{dis} tracks the product of the power rating and SoH, so it falls only fractionally as the battery ages.

Feeding SoC and SoH back to the EMS would normally create an algebraic loop, since the EMS output drives the battery and the battery output drives the EMS. The model breaks the loop with two Unit Delay blocks (initial values 60 % and 100 %, sample time 0.01 h) followed by gains of 0.01 that convert percentages into ratios.

DISTRIBUTION GRID MODEL

The grid block turns the three power signals into feeder quantities. The power drawn from the source with the battery in service, and in the baseline without it, are

$$P_{grid} = \max(0, P_{load} - P_{PV} - P_{BESS}) \quad (15)$$

$$P_{line,0} = \max(0, P_{load} - P_{PV}) \quad (16)$$

and the feeder loading is

$$Loading = 100 P_{grid} / P_{max} \quad (17)$$

with $P_{max} = 5.0$ MW. Feeder current and voltage follow from the usual relations for a short distribution line [22], [23],

$$I = P_{grid} / (\sqrt{3} V_{LL} \cos \phi) \quad (18)$$

$$\Delta V \approx (R_f P + X_f Q) / V_{LL} \quad (19)$$

with $Q = P \tan \phi$. The model is a continuous, average-value behavioural representation, not an electromagnetic-transient one, so voltage and frequency excursions reflect power-flow relations rather than detailed converter switching.

SIMULATION SET-UP

The model was built in Simulink [24] and generated programmatically through the Simulink API (add_block, set_param and add_line), which makes it reproducible and easy to rescale if the battery or feeder ratings change. The blocks fall into seven groups: simulation clock, generation and demand, EMS, feedback and normalisation, battery with BMS, distribution grid, and two monitoring scopes. Twenty To Workspace blocks log the signals needed for post-processing, including sim_SOC, sim_SoH, sim_P_bess, sim_P_line_with_bess, sim_P_line_no_bess, sim_I_line, sim_V_rms, sim_freq and sim_loading_pct. The screenshot of the complete model is reserved in Fig. 3.

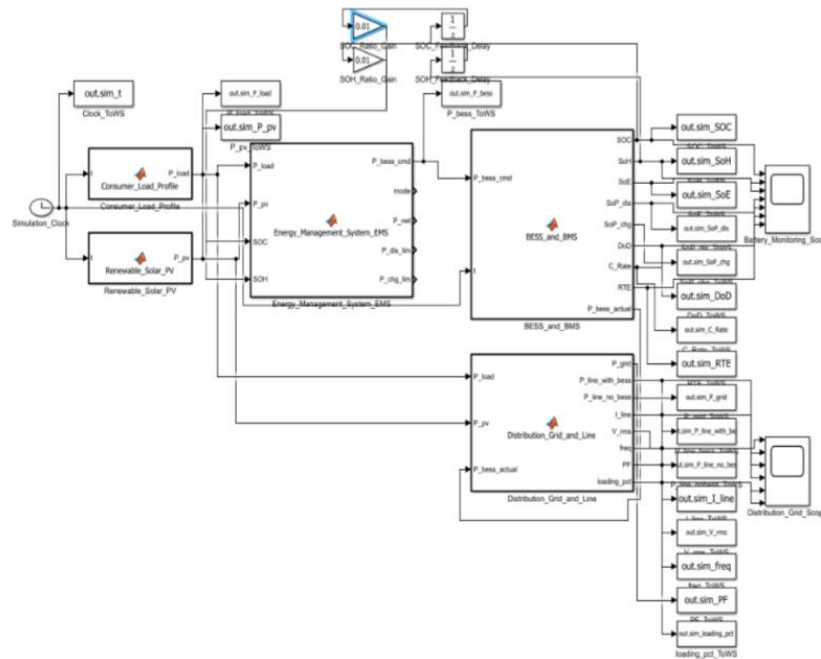


Fig. 3. Complete Smart_BESS Simulink model

RESULTS AND DISCUSSION

A. Summary of performance

Table III compares the feeder with and without the battery over the 24-hour run. The feeder loading row is derived here as 5.31/5.0 and 4.50/5.0; the other values come from the project's logged results.

TABLE III BASELINE VERSUS SMART BESS WITH EMS

Metric	Without	With	Change
Peak line power (MW)	5.31	4.50	-0.81 (15.2 %)
Peak feeder loading (%), derived	106.2	90.0	-16.2 points
Peak current (A RMS)	289.8	245.1	-44.7 (15.4 %)
Time above 4.5 MW (h/day)	1.99	0.00	eliminated
Energy above 5.0 MW (MWh)	0.58	0.00	eliminated
Energy shifted into peak (MWh)	0.00	1.04	+1.04
Energy absorbed in charging (MWh)	0.00	1.78	+1.78
Equivalent full cycles per day	0	0.70	controlled use
State of Health (%)	100	99.98	-0.02
Round-trip efficiency (%)	—	90.25	—

B. Battery behaviour

Fig. 4 (full width, next page) shows the battery scope. The horizontal axis is time in hours: the daily profile fills the first 24 h, with the evening peak near 19.5 h, and the run was left to $T = 100$ h, so every trace simply holds its final value afterwards.

At the start the SoC climbs from its 60 % initial value to the 90 % ceiling. This is valley filling at the low early-morning load, with a C-rate burst of roughly 0.45. The SoC then stays at 90 % through the solar period, because none of the rules asks the battery to move. Between about 18 h and 23 h it falls to roughly 35 % while the battery supports the peak, the DoD rises to about 65 %, and the battery is then recharged to 90 % by valley filling. The SoE trace follows the SoC and moves between about 1.8 and 0.7 MWh, which is 90 % and 35 % of 2.0 MWh (the axis label in the capture reads MW, but the quantity is energy). The round-trip efficiency stays flat at 90 %.

The traces agree with simple arithmetic. The peak requires at most $5.31 - 4.50 = 0.81$ MW from a 2 MWh battery, which is 0.405 C and matches the burst of about 0.4 C seen during the peak. The SoC swing of $0.90 - 0.35 = 0.55$ stores 1.10 MWh, and with a discharge efficiency of 0.95 this delivers about 1.045 MWh, in line with the reported 1.04 MWh. The two charging episodes (60 % to 90 %, then 35 % to 90 %) store $0.60 + 1.10 = 1.70$ MWh, which needs $1.70/0.95 \approx 1.79$ MWh from the grid, close to the reported 1.78 MWh. Together, 1.70 MWh charged and 1.10 MWh discharged give an EFC of $(1.70 + 1.10)/4 = 0.70$, exactly the reported figure.

The SoH trace falls from 100 % to about 99.979 % in small steps that coincide with battery activity, and the discharge power capability follows it from 2.0 MW to about 1.9996 MW, as expected if $\text{SoP}_{\text{dis}} \approx 2 \text{ MW} \times \text{SoH}$.

C. Feeder behaviour

Fig. 5 (full width, next page) shows the grid scope. The line power with the battery is clipped flat at 4.5 MW during the peak, whereas the baseline rises smoothly to about 5.3 MW. The feeder loading is flat-topped at 90 % instead of exceeding 100 %. The current peaks at about 246 A, safely below the 262.4 A limit, and the midday dip of both power and current is caused by the solar source, which pulls net demand down to roughly 1.4 MW. During the recharge after the peak, the with-battery line power is higher than the baseline, which is the expected price of refilling the battery.

The voltage follows the loading. It settles at about 10.67 kV at the base load, dips to about 10.33 kV during the congested window (6.1 % below 11 kV), and recovers afterwards. This stays inside the ± 10 % band commonly used for medium-voltage supply [25]. A hand calculation with the voltage-drop relation and an assumed power factor of 0.96 lagging gives about 10.30 kV at 4.5 MW and about 10.66 kV at 2.2 MW, and the same assumption gives currents of 246 A and 290 A at 4.50 MW and 5.31 MW, both within about 0.4 % of the reported 245.1 A and 289.8 A. The frequency stays between roughly 49.977 Hz and 50.008 Hz, inside ± 0.05 Hz. Voltage and frequency for the no-BESS case are not plotted, so no improvement in those two quantities is claimed here; the evidence for the battery's benefit is in power, current and loading.

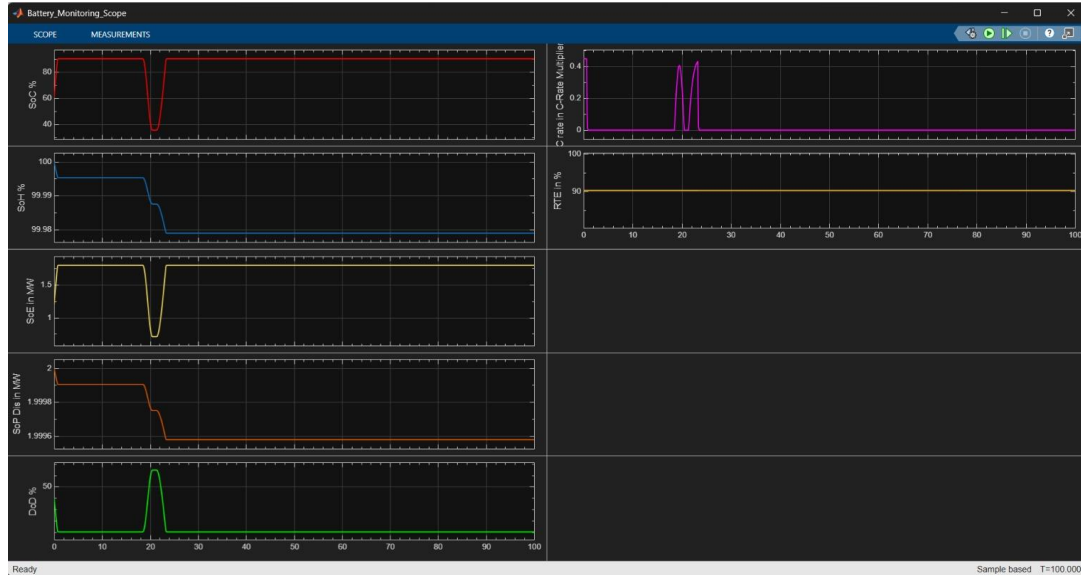


Fig. 4. Battery_Monitoring_Scope output from the Simulink model: SoC, SoH, SoE, SoP (discharge), DoD, C-rate multiplier and round-trip efficiency over the simulated run.

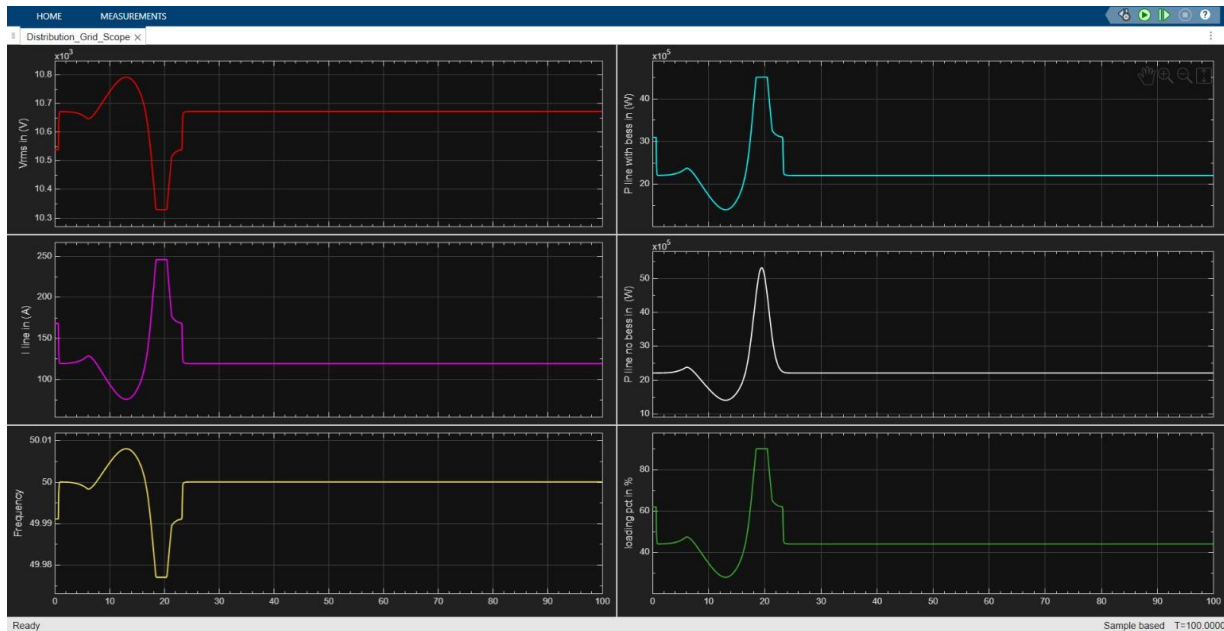


Fig. 5. Distribution_Grid_Scope output: RMS voltage, feeder current, frequency, line power with and without the BESS, and feeder loading.

D. Dispatch interpretation

Three periods describe the day. During the solar period the battery is already full, so it stays in standby even though net demand is low. During the evening peak the EMS discharges only as much as is needed to hold 4.50 MW. After the peak, valley filling refills the battery at a controlled rate. One consequence of the load and PV profiles deserves mention: because PV never exceeds the load, Mode 2 is never triggered in this run, and all charging observed here comes from Mode 3. The solar-surplus path therefore remains untested and needs a scenario with a larger PV rating or a lower load. Figs.

6 and 7 are reserved for the line-loading comparison and the 24-hour dispatch plots.

E. Battery health and grid quality

Figs. 8 and 9 are reserved for the post-processed battery-health and grid-quality plots produced from the logged workspace variables.

F. Discussion

The result confirms that a simple, readable rule set can remove a modelled thermal overload. It also shows how much headroom the chosen rating leaves. The peak needs only 0.81 MW of the 2 MW converter and 0.405 C, and the 1.04 MWh delivered uses roughly three-quarters of the 1.4 MWh available between the 20 % and 90 % limits. This leaves a margin of about 0.36 MWh. The same figures show where the scheme would stop working: if the evening peak grew taller or wider, the energy needed would approach the usable window, and the flat-topped 4.50 MW line would start to rise. Sizing the battery to the real requirement, rather than to a round number, is a natural extension [10], [11].

The comparison also shows why the battery state must stay in the control loop. Without the SoP cap, a command at the start of a long peak could not be honoured late in the event, and without the SoC window the daily cycle would use more of the battery than it needs.

LIMITATIONS AND FUTURE WORK

The study has clear limits. It is software-only: no hardware or hardware-in-the-loop test has been carried out. The grid is an average-value model, so converter switching, harmonics and protection are not represented. A single 24-hour load and PV profile is used, and the thresholds are fixed rather than adaptive. The EMS has no load or PV forecast, so it reacts instead of anticipating. The ageing law is a simple throughput model whose coefficient is not calibrated against cell data, and reactive-power services [4] and the frequency-support role of storage [26] are not exercised. Energy trading, listed among the project objectives, is not implemented. Finally, the time axis of the captured scopes extends well beyond 24 h, and the numerical summary comes from the 24-hour post-processing.

Future work will (1) test the solar-surplus mode with a higher PV share, (2) add load and PV forecasting to the EMS, (3) replace fixed thresholds with adaptive or optimisation-based ones and compare them with the present rules [1], (4) calibrate the degradation law against published cycle-life data [19], [20], (5) optimise the battery size, and validate the controller on a hardware-in-the-loop platform before a laboratory-scale prototype.

CONCLUSION

A smart BESS with a four-mode, State-of-Power-limited EMS was modelled on an 11 kV, 5.0 MW feeder with a 5.31 MW evening peak and 1.5 MW of solar. The controller cut the peak from 5.31 MW to 4.50 MW (15.2 %), removed 1.99 h of daily congestion and 0.58 MWh of thermal overload, moved 1.04 MWh into the peak, and did so at 90.25 % round-trip efficiency with a modelled SoH loss of 0.02 %. Hand calculations reproduced the current limit, the energy balance, the cycle count and the feeder voltage and current, which supports the internal consistency of the model. The work also exposes what is still to be done: a scenario that actually exercises the solar-surplus mode, right-sizing of the battery, forecasting, calibrated ageing, and validation beyond simulation.

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