
Research article

Feeder-constrained co-located BESS sizing for grid-interactive EV fast-charging stations: Branch-loading relief, voltage support, and recharge deliverability

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Abstract: Co-located battery energy storage (BESS) is often sized as a single power and energy rating for electric-vehicle fast-charging stations (EVCSS), although feeder adequacy is governed by different limits. This paper separated five requirements on a single backward/forward-sweep (BFS) model: branch-loading relief, residual voltage support, power conversion system (PCS) apparent-power capability, storage energy, and post-stress recharge. Active power was sized against branch-loading alone; voltage was then restored through unity-power-factor correction and local capacitive support. On the IEEE 33-bus benchmark, two placements and four demand levels produced a nominal branch-loading-relief requirement of 0 to 855.56 kW, yet three of eight cases required no active storage while remaining voltage-infeasible. Exhaustive enumeration of 720 processing orders yielded 0.07% to 96.69% sequential excess. Independent tests with two published current-limit parameterizations showed strong capacity-data dependence: a 275/120 A set left only two cases requiring 20.25 and 158.53 kW, whereas a multi-tier set admitted no current-feasible active-only solution. Unity-power-factor correction was insufficient in all eight nominal cases, leaving 114.77 to 879.94 kVAr of additional support and 0.32% to 96.17% conditional PCS headroom. For a 4-hour design duration, synchronous recharge ranged from the 4.43 h active-rating/efficiency floor to 31.19 h under voltage limitation, while branch-loading never bound. A single MW/MWh rating therefore cannot represent all five adequacy requirements.

Keywords: electric vehicle fast-charging; battery energy storage-sizing; distribution feeder; backward/forward sweep power flow; recharge deliverability

Nomenclature

Symbol	Description
i	Bus index
j	Active EVCS/candidate co-located BESS bus index
l	Branch index
k	BFS iteration index
s	Prescribed EVCS demand-scenario index
J	Set of active EVCS/candidate co-located BESS buses
V_i	Voltage magnitude at bus i
$V_{\min}$	Minimum bus-voltage magnitude over the feeder
V_{thr}	Minimum admissible voltage magnitude
V_{slack}	Slack-bus voltage magnitude
V_{base}	Voltage base
ε	BFS convergence tolerance
S_l	Apparent-power flow through branch l
$S_l^{\max}$	Adopted apparent-power planning limit of branch l
S_{base}	Power base
L_l	Loading of branch l
$L_{\max}$	Maximum branch loading over the feeder
L_{thr}	Branch-loading threshold
β_s	Uniform scaling factor applied to the adopted branch planning limits
P_{loss}	Total feeder active-power loss
P_j^{EVCS}	Prescribed EVCS active-power demand at bus j
$Q_{j,0}^{\text{EVCS}}$	Original lagging EVCS reactive-power demand at bus j
P_j^{BESS}	Co-located BESS active discharge power assigned at bus j for branch-loading relief
$\mathbf{P}^{\text{BESS}}$	Vector of BESS active-power allocations
P_{BL}^{BESS}	Aggregate BESS active-power requirement for branch-loading relief
P_{cen}	Centralized aggregate branch-loading-relief reference
$P_{\text{seq}}(\pi)$	Aggregate sequential requirement obtained for processing order π
$Q_{\text{PFC},j}$	Local EVCS reactive-power correction required to reach unity power factor
Q_{PFC}	Aggregate EVCS power-factor correction
δ	Proportional factor governing additional local capacitive support
δ^*	Minimum proportional factor for voltage restoration
Q_j^{base}	Background reactive-power demand at bus j
Q_j^{net}	Net reactive-power demand at bus j under the load-positive convention
$Q_{\text{add},j}$	Additional local capacitive support at bus j
Q_{add}^*	Aggregate additional support corresponding to δ^*
$S_j^{\text{PCS,req}}$	Apparent-power rating required at bus j if the BESS PCS supplies the local $Q_{\text{add},j}$

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Symbol	Description
$E_{AC,out,j}$	AC-side energy delivered by the BESS at bus j during the prescribed stress duration
$E_{batt,wd,j}$	Battery-side energy withdrawn at bus j ; energy that must subsequently be restored
$E_{nom,j}$	BESS nameplate energy implied by the adopted usable-SoC window
T_{peak}	Prescribed peak-discharge design duration
$P_{ch,j}(T)$	BESS charging power at bus j for candidate common-recharge duration T
T	Candidate common recharge duration used in the recharge-feasibility search
T_{rec}^*	Minimum feasible common recharge duration
α_{off}	Background-load scaling factor in the post-stress recharge sensitivity
η_{dis}	BESS discharge efficiency
η_{ch}	BESS charge efficiency
SoC_{min}	Lower bound of the adopted usable state-of-charge window
SoC_{max}	Upper bound of the adopted usable state-of-charge window
λ_s	EVCS active-demand multiplier for prescribed scenario s
ρ	Ratio of aggregate EVCS active-power demand to feeder base active load
R_l	Resistance of branch l
X_l	Reactance of branch l
I_l	Branch-current magnitude in the external current-limit validation
I_l^{max}	Published current limit of branch l used in the external validation
R_l	Maximum normalized branch-current ratio
β_s^*	Critical uniform planning-limit scaling for zero-storage branch-loading feasibility
BFS	Backward/forward sweep
EVCS	Electric vehicle charging station
BESS	Battery energy storage system
PCS	Power conversion system
PF	Power factor
SoC	State of charge

1. Introduction

Fast electric-vehicle charging stations (EVCSs) concentrate active and reactive demand at a small number of buses on radial distribution feeders. Both components increase feeder current and contribute to voltage drop, but through different terms of the radial voltage-drop relationship: active-power transfer contributes primarily through the resistance–active-power product (RP), whereas reactive-power transfer contributes through the reactance–reactive-power product (XQ) [1]. Active current accumulation on shared upstream segments increases branch-loading. Active-power compensation can improve the voltage profile by reducing active-power transfer and feeder current, but it does not directly cancel the XQ component associated with reactive demand. A co-located active-power battery energy storage system (BESS) can therefore restore branch-loading feasibility while a voltage deficit persists.

This asymmetry has a direct consequence for sizing. When active-power storage-sizing is based on a feasibility condition that simultaneously enforces branch-loading and voltage limits, the resulting active rating is governed by the more restrictive constraint and therefore cannot be interpreted as a branch-loading-specific requirement. Such a test can attribute voltage-driven active-power oversizing to the nominal branch-loading requirement, including cases where no branch-loading deficiency exists.

The distinction matters because the two constraints call for different mitigation mechanisms and because further requirements—the apparent-power capability of the local converter, the stored energy implied by a design discharge duration, and the feeder capacity available to restore the withdrawn battery energy before the next cycle—are governed by other limits.

Existing literature supplies complementary methods across three fronts. On the first, grid-impact assessments quantify voltage deviation, branch-overloading, and loss growth at high charging penetration and identify the remedial measures available to the operator [2]. Large-scale analyses have shown that where and how charging occurs, rather than aggregate energy alone, governs the resulting network stress [3]. Hosting-capacity methods formalize this into a maximum admissible penetration before a voltage or branch-loading threshold is violated [4], with distributionally robust extensions accounting for charging-demand variability [5]. Recent data-driven studies of public ultra-fast charging have further coupled siting and sizing decisions with grid-operational and service performance using large-scale charging-event datasets [6]. Charging-infrastructure planning has in parallel moved from pure location-allocation toward grid-aware deployment that couples station siting with transportation accessibility and distribution-network constraints [7]. Recent formulations embed distribution planning and charging deployment in a single optimization [8] and address siting and sizing under uncertain charging-demand distributions [9]. Grid-impact-aware planning for a tourism-intensive island system has further shown that an optimized charging layout must still be evaluated against feeder voltage, branch-loading headroom, and operating-stress conditions using AC power flow [10]. Recent work has also formulated capacitated fast-charging-station deployment as a location-allocation problem in which both station siting and charger counts are optimized, including Bayesian-optimization-assisted formulations for directed highway networks [11]. Such studies address where and at what capacity charging infrastructure should be deployed, whereas the present study utilizes prescribed station locations and asks which feeder-side BESS adequacy requirements follow from that configuration.

On the second front, storage is used as the mitigation resource. Sizing and dispatch of the BESS at fast-charging sites has been formulated for peak shaving alongside energy and regulation-market participation [12] and as a multi-objective problem over stacked grid services [13]. Recent studies have jointly optimized charging-station deployment, photovoltaic and storage capacity, and charging schedules in radial distribution networks [14]. Such integrated planning determines asset placement and operation, whereas the present work addresses the subsequent feeder-side question of how co-located storage adequacy should be separated into branch-loading active-power, voltage-support, converter, energy, and recharge requirements. Reactive capability is treated separately in interconnection practice, where IEEE 1547-2018 specifies reactive-power and voltage-control capabilities for distributed energy resources (DERs), with active-reactive operation subject to nameplate apparent-power limits [15]. These bodies of work establish both that storage can relieve feeder stress and that converters can supply reactive power; what remains open is how the resulting active, reactive, and apparent-power requirements at a given site relate to one another once branch-loading relief is defined independently of voltage restoration.

On the third front, temporal flexibility offers alternatives and complements to stationary storage. Vehicle-to-grid planning has been coupled with user equilibrium and distribution-network flexibility [16], and charging-pool flexibility has been quantified through stochastic AC optimal power flow [17]. Coordinated EV fleets can also provide grid-support services through controlled vehicle flexibility, including fast-frequency response [18]; such flexibility may alter the stress presented to

stationary storage, although its dynamic service objective differs from the feeder branch-loading and voltage-adequacy problem considered here. Scheduling studies additionally link fast-charging operation to storage degradation over the daily cycle [19]. Charging demand also evolves, and multi-period deployment under latent demand alters infrastructure decisions relative to a single-snapshot view [20], while operation-level coordination in coupled power–transportation networks can reshape the load that the feeder must serve [21]. These directions complement rather than compete with the feeder-physics question addressed here. Charging-station locations are treated as exogenous inputs so that the study conditions on a fixed infrastructure configuration and isolates the feeder-side adequacy requirements that follow from it. The charging stress is likewise held prescribed rather than optimized, allowing differences in the resulting branch-loading and voltage requirements to be attributed to feeder physics rather than to an assumed charging-control strategy.

Across these fronts, the adequacy of a co-located BESS is commonly reported as a power and energy rating. Such a single quantity cannot represent requirements governed by different constraints: the active power required for branch-loading relief, the residual voltage support remaining afterward, the converter apparent-power requirement implied by that support, the storage energy associated with a design duration, and the feeder capacity to recover that energy before the next cycle. This paper addresses the narrower feeder-planning question of how these requirements should be physically separated, evaluating each on a common backward/forward-sweep (BFS) network model applied to the IEEE 33-bus radial benchmark under two charging placements and four prescribed demand levels. Because the standard benchmark does not provide conductor ampacities, the nominal study uses explicitly declared apparent-power planning limits and separately tests the active-power layer against two independently published IEEE 33-bus current-limit parameterizations. The specific contributions are as follows:

- 1) A feeder-constrained sizing framework is used in which the active storage requirement is physically separated from voltage restoration. The active rating follows from branch-loading feasibility alone, while the residual voltage requirement is quantified in a separate two-part layer distinguishing charger power-factor correction from additional local support. This separation identifies cases in which voltage support is required even though no active storage is needed for branch-loading relief.

- 2) A centralized branch-loading-relief reference under the adopted BFS model is utilized, accompanied by both a processing-order audit and independent branch-capacity validation. Exhaustive enumeration of all 720 bus-processing orders for each branch-overloaded nominal case shows that favorable sequential orders remain within 0.37% of the centralized reference, whereas unfavorable orders increase the requirement by as much as 96.69%. The active-power layer is additionally re-evaluated under two published IEEE 33-bus current-limit parameterizations, demonstrating that the numerical BESS requirement—and under sufficiently restrictive limits, the existence of a finite active-only solution—is conditional on the branch-capacity dataset.

- 3) A converter, energy, and recharge feasibility layer is developed, in which the converter apparent-power requirement is evaluated conditionally and attributed per bus, storage energy is expressed as a planning-level envelope over a prescribed design duration, and recharge is evaluated under a synchronous policy that distinguishes active-rating/efficiency-limited from voltage-limited behavior.

The remainder of this paper is organized as follows: Section 2 describes the feeder, charging representation, and scenarios. Section 3 reports the baseline feeder assessment without the BESS. Section 4 presents the methodology, Section 5 provides the results, and Section 6 concludes the paper.

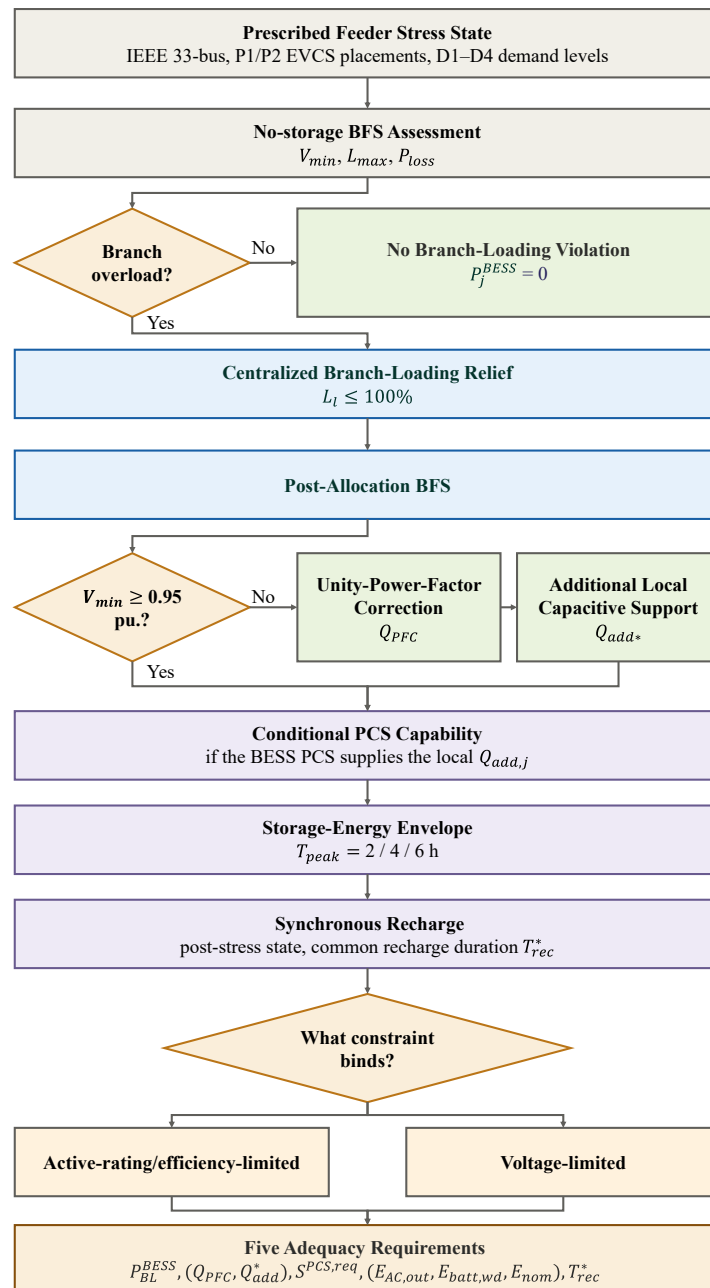


Figure 1. Decomposition of the co-located BESS adequacy into five separately governed requirements: branch-loading-relief active power, residual voltage support, conditional converter capability, storage energy, and recharge deliverability.

Figure 1 presents the central diagnostic logic of the study: the co-located BESS adequacy is decomposed into five physically distinct requirements derived from the same prescribed feeder stress state. The no-storage BFS assessment first identifies the branch-loading and voltage condition. If no branch exceeds its adopted planning limit, $P_{BL}^{BESS} = 0$; otherwise, Eq (3) determines the centralized active-power allocation required to restore $L_l \leq 100\%$ with voltage deliberately excluded from this sizing step. A fresh BFS solution is then used to assess the post-allocation voltage. Any remaining voltage deficit is treated in two stages: Eqs (5)–(8) correct the EVCS reactive demand to the unity power factor and the feeder is re-evaluated, while Eqs (9) and (10) introduce additional local capacitive

support only if $V_{\min} < 0.95$ p.u. persists. In all eight nominal cases, the unity-power-factor recheck remains below the voltage limit, so Figure 1 shows the realized path to additional support. Equation (11) then gives the conditional PCS apparent-power requirement if the BESS converter supplies the local $Q_{\text{add},j}$. Equation (12) maps the branch-loading-relief active-power allocation into the 2/4/6 h storage-energy envelope and Eqs (13)–(15) determine whether the withdrawn battery energy can be restored under the synchronous recharge policy. The workflow is therefore a diagnostic decomposition rather than an operational control sequence: branch-loading-relief (MW), voltage support (kVAr), converter (kVA), storage (MWh), and recharge time are evaluated as separate adequacy requirements governed by different physical constraints. Cross-effects among active power, reactive power, voltage, and branch-loading remain captured through the common nonlinear power-flow model.

2. System model and study scenarios

2.1. Feeder and EVCS model

The test network is the standard IEEE 33-bus radial distribution system introduced by Baran and Wu [22], operating at 12.66 kV with 33 buses and 32 branches supplied from Bus 1, with a nominal base load of 3.715 MW and 2.300 MVar. Its radial topology, moderate scale, and widely reported data provide a reproducible platform for isolating the relationship between charging placement, branch-loading, and storage requirements. Table 1 summarizes the adopted test system, operating scenarios, and modeling parameters.

Table 1. Test system, operating scenario, and modeling parameters.

Parameter	Value
Test feeder	IEEE 33-bus radial distribution system
Number of buses	33
Number of branches	32
Slack bus	Bus 1
Nominal voltage	12.66 kV
Power base	100 MVA
Base active load	3.715 MW
Base reactive load	2.300 MVar
Validation slack voltage	1.00 p.u.
Planning slack voltage	1.05 p.u.
Power-flow method	Backward/forward sweep
Production BFS convergence tolerance	10^{-5} p.u.
Production maximum BFS iterations	50
Voltage threshold	$V_{\text{thr}} = 0.95$ p.u.
Branch-loading threshold	$L_{\text{thr}} = 100\%$
Branch apparent-power planning limits	2.0–6.0 MVA, assigned by feeder hierarchy
EVCS active power at $\lambda_s = 1.0$	0.150 MW per active EVCS bus
EVCS power factor	0.95 lagging
EVCS placements	P1: Buses 6, 10, 14, 18, 22, 26; P2: Buses 14, 16, 17, 18, 30, 33

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Parameter	Value
Demand multipliers	D1 = 0.6, D2 = 1.0, D3 = 1.3, D4 = 1.6
BESS model	Co-located BESS with separately evaluated branch-loading active-power, voltage-support, PCS, energy, and recharge requirements
SoC range	0.20–0.90
Discharge/charge efficiency	$\eta_{\text{dis}} = \eta_{\text{ch}} = 0.95$
Peak discharge duration envelope	2, 4, and 6 h
Off-peak background-load multipliers	$\alpha_{\text{off}} = 0.50, 0.70, 0.85, 1.00$

Note: The original IEEE 33-bus dataset provides bus-load and branch-impedance data but does not specify conductor types or branch ampacities. The 2.0–6.0 MVA values adopted in the nominal study are therefore treated as apparent-power planning limits rather than conductor-derived thermal ratings; the exact branch connectivity, impedance parameters, and adopted limits are reported in Table 2. The 10^{-5} p.u. tolerance and 50-iteration limit are the production BFS settings used for the baseline feeder simulations. For the centralized branch-loading-relief optimization and its independent numerical replay in Section 4.1, a stricter BFS convergence tolerance of 10^{-12} p.u. and a 200-iteration limit were used.

All power flows are solved by the BFS method, which exploits the radial topology and avoids Jacobian inversion, enabling repeated full-network feasibility checks at low cost [23]. A solution is accepted when

$$\max_i |V_i^{(k)} - V_i^{(k-1)}| < \varepsilon \quad (1)$$

within the iteration limit; only converged BFS solutions are used and non-converged candidates are rejected rather than interpolated. The per-unit bases are $S_{\text{base}} = 100$ MVA and $V_{\text{base}} = 12.66$ kV. The BFS formulation applies to the radial benchmark considered here; extension to meshed networks requires a modified power-flow formulation.

Two network admissibility limits are used in the study: $V_i \geq V_{\text{thr}} = 0.95$ p.u. and $L_l \leq L_{\text{thr}} = 100\%$. These limits are evaluated within the layer relevant to each adequacy quantity; in particular, voltage is not imposed in the branch-loading-relief problem of Section 4.1. The planning voltage threshold is set to 0.95 p.u.; ANSI/NEMA C84.1 is cited as the general voltage-range practice [24].

The original Baran–Wu IEEE 33-bus dataset does not specify conductor types, conductor cross-sections, line lengths, installation conditions, ambient conditions, allowable conductor temperature, or branch ampacities. Consequently, the 2.0–6.0 MVA values adopted in the nominal study cannot be identified as physical thermal ratings of the benchmark and are treated instead as apparent-power planning limits. At the nominal line-to-line voltage of 12.66 kV, these limits correspond to three-phase current equivalents of approximately 91.2–273.6 A through $I_l^{\text{eq}} = S_l^{\text{max}}/(\sqrt{3}V_{LL})$. This conversion is used only to establish an engineering scale and does not assign a conductor type or physical ampacity to any branch. IEEE Std 738-2023 relates the current-carrying capability of bare overhead conductors to conductor characteristics, conductor temperature, and weather conditions, and does not prescribe a unique set of conductor or environmental parameters for line-rating calculations [25]. Therefore, a unique physical ampacity dataset cannot be reconstructed from the original benchmark alone.

Table 2. Adopted IEEE 33-bus branch parameters and apparent-power planning limits.

Branch	From bus	To bus	$R_l (\Omega)$	$X_l (\Omega)$	$S_l^{\max} (\text{MVA})$
1	1	2	0.0922	0.0470	6.0
2	2	3	0.4930	0.2511	5.0
3	3	4	0.3660	0.1864	4.0
4	4	5	0.3811	0.1941	4.0
5	5	6	0.8190	0.7070	3.5
6	6	7	0.1872	0.6188	3.5
7	7	8	1.7114	1.2351	3.0
8	8	9	1.0300	0.7400	3.0
9	9	10	1.0440	0.7400	3.0
10	10	11	0.1966	0.0650	3.0
11	11	12	0.3744	0.1238	2.5
12	12	13	1.4680	1.1550	2.5
13	13	14	0.5416	0.7129	2.5
14	14	15	0.5910	0.5260	2.5
15	15	16	0.7463	0.5450	2.0
16	16	17	1.2890	1.7210	2.0
17	17	18	0.7320	0.5740	2.0
18	2	19	0.1640	0.1565	4.0
19	19	20	1.5042	1.3554	3.5
20	20	21	0.4095	0.4784	3.0
21	21	22	0.7089	0.9373	3.0
22	3	23	0.4512	0.3083	3.5
23	23	24	0.8980	0.7091	3.0
24	24	25	0.8960	0.7011	2.5
25	6	26	0.2030	0.1034	3.5
26	26	27	0.2842	0.1447	3.0
27	27	28	1.0590	0.9337	2.5
28	28	29	0.8042	0.7006	2.5
29	29	30	0.5075	0.2585	2.5
30	30	31	0.9744	0.9630	2.0
31	31	32	0.3105	0.3619	2.0
32	32	33	0.3410	0.5302	2.0

The nominal limits in Table 2 are assigned by feeder hierarchy, from 6.0 MVA on the source-side trunk to 2.0 MVA on remote downstream branches, to represent differentiated planning headroom along the radial feeder. To provide independent engineering anchors rather than relying solely on this author-defined hierarchy, Section 5.1 additionally evaluates two published current-limit parameterizations used in IEEE 33-bus studies. A published conductor-anchored IEEE 33-bus parameterization [26] represents the first five main feeder lines by Pigeon conductors with 275 A current limits and the remaining lines by Swallow conductors with 120 A limits. The corresponding line lengths are derived from conductor resistances of 0.3366 Ω/km and 1.0742 Ω/km , respectively, maintaining internal consistency among conductor type, resistance, implied line length, and current

limit. Only the published current limits are imported here as an independent capacity parameterization; conductor identities are not reassigned to the nominal feeder model used in this study. A second published IEEE 33-bus study [27] provides a separate multi-tier branch-current parameterization. In the external validation, both published current-limit sets are enforced directly in amperes on the same BFS network model used for the nominal study, without conversion to the nominal MVA limits or modification of the branch parameters in Table 2. Table 2 therefore remains the nominal planning parameterization, while the independent current-limit sets are used to quantify how branch-capacity assumptions affect the active BESS requirement and feasibility.

The study uses the IEEE 33-bus radial benchmark topology and load data [22] with the adopted branch-impedance parameterization reported in full in Table 2. This parameterization is applied unchanged to every baseline, optimization, and sensitivity case. With this dataset, the base case at $V_{\text{slack}} = 1.00$ p.u. gives $V_{\text{min}} = 0.9038$ p.u. at Bus 18 and $P_{\text{loss}} = 211.0$ kW. All planning simulations use $V_{\text{slack}} = 1.05$ p.u. to represent regulated substation voltage under the tap-changer operation, so that the pre-charging feeder operates within admissible limits.

Each active charging bus is assigned 0.150 MW at $\lambda_s = 1.0$, adopted as the nominal fast-charging rating in this study. Converter-related reactive demand is retained by adopting a 0.95 lagging power factor, consistent with a distribution-level EVCS representation used in [28]; this is a modeling assumption rather than a universal measured characteristic of fast chargers:

$$Q_{j,0}^{\text{EVCS}} = P_j^{\text{EVCS}} \tan\left(\cos^{-1}(0.95)\right). \quad (2)$$

Storage operates with $\eta_{\text{dis}} = \eta_{\text{ch}} = 0.95$ and a usable state of charge (SoC) window of 0.20–0.90, adopted as planning assumptions; general design and operation guidance for stationary storage is given in [29].

2.2. Placement and prescribed demand scenarios

Two placements activate six charging buses at identical total installed capacity, so any difference in voltage, loading, or storage requirements follows from spatial distribution rather than aggregate demand. Placement P1 (Buses 6, 10, 14, 18, 22, 26) is spatially distributed. Placement P2 (Buses 14, 16, 17, 18, 30, 33) concentrates demand on the 16–18 and 30–33 downstream corridors, which are supplied through longer cumulative impedance paths.

Table 3. EVCS placement and demand scenarios.

Scenario Group	Case	Definition	Interpretation
Placement	P1	Buses 6, 10, 14, 18, 22, 26	Spatially distributed placement
Placement	P2	Buses 14, 16, 17, 18, 30, 33	Downstream-concentrated placement
Demand	D1	$\lambda_s = 0.6$	Lower prescribed EVCS demand
Demand	D2	$\lambda_s = 1.0$	Reference prescribed EVCS demand
Demand	D3	$\lambda_s = 1.3$	Elevated prescribed EVCS demand
Demand	D4	$\lambda_s = 1.6$	High-stress prescribed EVCS demand

Four demand scenarios apply a multiplier $\lambda_s \in \{0.6, 1.0, 1.3, 1.6\}$ to charging demand only, leaving the base load unchanged. The resulting charging-to-base-load ratios ρ are 14.54%, 24.23%,

31.49%, and 38.76%, respectively, falling within the adopted 5–40% scenario envelope used to examine increasing charging penetration. These are adopted scenario levels rather than an empirical distribution. The eight placement–demand combinations are denoted as P1/D1 through P2/D4. Table 3 summarizes the placement and demand definitions used throughout the study.

3. Baseline feeder assessment without the BESS

At the planning slack voltage, the base feeder is feasible, with $V_{\min} = 0.9591$ p.u. and $L_{\max} = 81.53\%$. Adding charging demand degrades both indices and two distinct constraint patterns emerge in Table 4.

The branch-loading-critical location migrates with demand. Branch 2–3 is the most heavily loaded branch at D1, reaching 92.32% under P1 and 95.07% under P2. From D2 onward, Branch 5–6 becomes the critical branch because it supplies both the 6–18 corridor and the 26–33 lateral, and therefore accumulates charging current on a segment with a 3.5 MVA adopted apparent-power planning limit.

Voltage violation precedes branch-overloading, while branch-loading violations escalate more sharply with demand. $V_{\min}$ falls below 0.95 p.u. already at D1 under both placements, driven by cumulative impedance toward Bus 18, whereas a branch-loading violation first appears at D3 under P1 and at D2 under P2. Three cases—P1/D1, P1/D2, and P2/D1—show voltage violation without branch overload; the remaining five violate both criteria. Branch-loading feasibility alone is therefore insufficient to establish overall feeder admissibility, whereas voltage feasibility alone does not quantify the active-power requirement specifically associated with branch-loading relief.

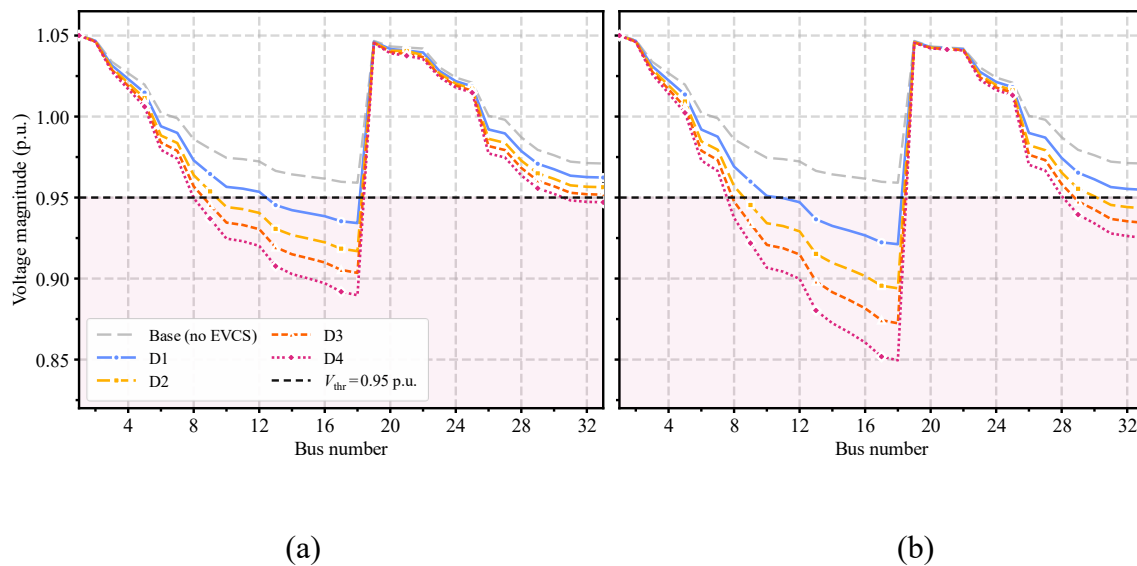


Figure 2. Baseline voltage profiles without the BESS: (a) distributed placement P1 and (b) downstream-concentrated placement P2.

Placement amplifies both effects at equal installed capacity. All six P2 charging buses route current through Branch 5–6—four via the 6–18 corridor and two via the 26–33 lateral—whereas bus 22 in P1 bypasses that corridor through the 2–19 lateral. This routing difference is why P2/D2 exceeds the adopted branch-loading limit at 106.40% while P1/D2 remains at 99.87%, and why at D4,

$V_{\min}$ reaches 0.8496 p.u. under P2 against 0.8897 p.u. under P1. P2/D4 is the critical stress case, with $L_{\max} = 126.87\%$ and $P_{\text{loss}} = 570.08$ kW.

The corresponding bus-wise voltage trajectories are shown in Figure 2. The distributed P1 placement produces a less-severe downstream voltage depression than P2 at each common demand level, while Bus 18 remains the limiting voltage location. The scalar voltage, loading, loss, and constraint-status indices associated with these profiles are summarized in Table 4.

Table 4. Baseline grid-impact indices without the BESS.

Case	$V_{\min}$ (p.u.)	$L_{\max}$ (%)	Critical branch	P_{loss} (kW)	Status
P1/D1	0.9342	92.32	2–3	257.25	Voltage
P1/D2	0.9169	99.87	5–6	313.51	Voltage
P1/D3	0.9035	107.48	5–6	361.74	Branch overload + voltage
P1/D4	0.8897	115.24	5–6	415.60	Branch overload + voltage
P2/D1	0.9212	95.07	2–3	292.65	Voltage
P2/D2	0.8940	106.40	5–6	385.74	Branch overload + voltage
P2/D3	0.8724	116.42	5–6	470.43	Branch overload + voltage
P2/D4	0.8496	126.87	5–6	570.08	Branch overload + voltage

4. Feeder-constrained BESS adequacy methodology

Five requirements are evaluated on the same network model and per-unit base, so results remain mutually comparable without introducing an additional power-flow approximation. Voltage is excluded from the active-sizing constraint so that the active rating carries a single physical meaning. A unified P – Q objective would instead answer a joint dispatch or investment question and would obscure which physical constraint determines each capacity; the staged formulation is retained here for diagnostic attribution.

4.1. Branch-loading-relief formulation and order audit

The branch-loading-relief requirement follows from a centralized nonlinear optimization with BFS power-flow evaluation in the constraint loop:

$$\begin{aligned}
 & \underset{P^{\text{BESS}}}{\text{minimize}} && \sum_{j \in J} P_j^{\text{BESS}} \\
 & \text{subject to} && L_l(P^{\text{BESS}}) \leq L_{\text{thr}}, \quad \forall l \\
 & && 0 \leq P_j^{\text{BESS}} \leq P_j^{\text{EVCS}}, \quad \forall j \in J
 \end{aligned} \tag{3}$$

where $L_l = (|S_l|/S_l^{\max}) \times 100$ is evaluated from the converged BFS solution and $S_l^{\max}$ denotes the adopted apparent-power planning limit of branch l . Voltage does not enter Eq (3) and is assessed diagnostically afterward. For the evaluated cases, increased active compensation reduced the relevant branch loading; feasibility is nonetheless determined numerically from the converged BFS solution at every candidate allocation, with the loading condition imposed as individual per-branch constraints rather than through a single non-smooth maximum.

The aggregate active-power requirement obtained from Eq (3) is denoted by

$$P_{BL}^{BESS} = \sum_{j \in J} P_j^{BESS} \quad (4)$$

Equation (3) was solved in MATLAB using *fmincon* with the sequential quadratic programming (SQP) algorithm. An analytic gradient was supplied for the linear objective, while the branch-loading limits were imposed as individual per-branch nonlinear inequalities. The constraint and optimality tolerances were 10^{-9} , the step tolerance was 10^{-12} , and the limits were 1000 iterations and 5000 function evaluations. Sixteen starting points were used: the full-compensation upper bound, one-half of that bound, and fourteen uniformly distributed random starts within the bus-level bounds under a fixed random seed. For the five branch-overloaded nominal cases, all 16 starts produced independently branch-loading-feasible accepted solutions. A case without a branch-loading violation at zero storage is feasible with respect to the adopted branch limits without storage and is assigned $P_j^{BESS} = 0$.

The maximum objective and bus-level allocation spreads across the accepted starts were 2.01×10^{-3} kW and 1.89×10^{-2} kW, respectively. The selected allocation for each case was subsequently re-evaluated by a fresh BFS call decoupled from the optimizer state. At these allocations, the signed branch-loading residual, defined as $L_{\max} - 100\%$, did not exceed $7.11 \times 10^{-14}\%$, while the BFS convergence residual, defined as the maximum bus-voltage change between successive sweeps, did not exceed 9.73×10^{-13} p.u. These results provide strong numerical evidence for the stability of the centralized objective and reported allocation. The result is therefore referred to as the centralized feeder-constrained branch-loading-relief reference under the adopted BFS model and nominal planning-limit parameterization; a formal global-optimality certificate is not claimed.

For diagnostic comparison, the sequential bus-by-bus procedure was re-evaluated under exactly the same branch-loading-only feasibility definition as the centralized problem in Eq (3). The same BFS network model, adopted branch planning limits, EVCS active and reactive demands, and bus-level active-power bounds were retained, while voltage was excluded from the sequential feasibility test. For each of the five branch-overloaded nominal cases, all $6! = 720$ processing orders were enumerated. Let $P_{\text{seq}}(\pi) = \sum_{j \in J} P_{j,\pi}^{BESS}$ denote the total sequential requirement obtained for processing order π . Its deviation from the centralized reference is reported as the relative excess $100[P_{\text{seq}}(\pi) - P_{\text{cen}}]/P_{\text{cen}}$. The sequential rule is retained only as a diagnostic because its result depends on processing order rather than defining a unique feeder-wide requirement.

4.2. Residual voltage support and conditional converter capability

After branch-loading relief, the minimum voltage may remain below the admissible limit because EVCS and background reactive-power demand persist. The voltage-support assessment is therefore performed with the active BESS allocation fixed. First, the original lagging EVCS reactive demand is corrected to the unity power factor. At each active charging bus j , the required local power-factor correction is

$$Q_{\text{PFC},j} = Q_{j,0}^{\text{EVCS}} \quad (5)$$

Thus, power-factor correction neutralizes the original EVCS reactive demand but does not

constitute net capacitive injection beyond the unity power factor. The aggregate correction is

$$Q_{\text{PFC}} = \sum_{j \in J} Q_{\text{PFC},j} \quad (6)$$

A load-positive sign convention is adopted for reactive power. Before power-factor correction, the net reactive demand at bus j is represented as

$$Q_{j,\text{net}} = Q_j^{\text{base}} + Q_{j,0}^{\text{EVCS}} - Q_{\text{PFC},j} - Q_{\text{add},j} \quad (7)$$

After correction to the unity power factor, $Q_{\text{PFC},j} = Q_{j,0}^{\text{EVCS}}$, so

$$Q_{j,\text{net}} = Q_j^{\text{base}} - Q_{\text{add},j} \quad (8)$$

Accordingly, positive $Q_{\text{add},j}$ denotes local capacitive support acting against the remaining background reactive demand. If unity-power-factor correction alone does not restore $V_{\min} \geq 0.95$ p.u., additional support is applied according to the prescribed proportional local policy,

$$Q_{\text{add},j} = \delta Q_{j,0}^{\text{EVCS}}, \quad \delta \geq 0 \quad (9)$$

and the minimum δ^* restoring $V_{\min} \geq 0.95$ p.u. is obtained by bisection after numerically verifying that $V_{\min}(\delta)$ is non-decreasing over the searched interval. The corresponding aggregate additional support is

$$Q_{\text{add}}^* = \sum_{j \in J} Q_{\text{add},j}(\delta^*) \quad (10)$$

Because this additional support is distributed proportionally while the voltage limit is determined by a single limiting bus, Q_{add}^* is policy-specific and should not be interpreted as the unrestricted global minimum reactive injection; a spatially targeted allocation could restore the voltage limit with less total support. Q_{PFC} and Q_{add}^* represent distinct quantities and are therefore reported separately rather than summed.

Where the branch-loading-relief solution places storage at bus j , the apparent-power rating required, if that BESS PCS is also selected to supply the local additional capacitive support, is

$$S_j^{\text{PCS,req}} = \sqrt{(P_j^{\text{BESS}})^2 + (Q_{\text{add},j})^2} \quad (11)$$

Equation (11) is conditional rather than mandatory: the support may equally come from the charger converter, power-factor-correction or capacitor equipment, or another local Volt-VAr resource. At buses without storage, no such converter exists and the support is attributed to external or other local reactive resources.

4.3. Storage-energy envelope

Storage energy is a planning-level technical envelope over a design peak duration $T_{\text{peak}} \in \{2, 4, 6\}$ h rather than an empirical charging-duration model, since reported commercial EVCS load profiles are

context-dependent; a recent example linking the load profile and business characteristics is reported in [30]. Because P_j^{BESS} is delivered on the AC side,

$$E_{\text{AC,out},j} = P_j^{\text{BESS}} T_{\text{peak}}, \quad E_{\text{batt,wd},j} = \frac{E_{\text{AC,out},j}}{\eta_{\text{dis}}}, \quad E_{\text{nom},j} = \frac{E_{\text{batt,wd},j}}{\text{SoC}_{\text{max}} - \text{SoC}_{\text{min}}} \quad (12)$$

Only $E_{\text{batt,wd},j}$ is the energy to be restored inside the battery; $E_{\text{nom},j}$ is the nameplate capacity implied by the usable-SoC window.

4.4. Synchronous recharge deliverability

Recharge is evaluated in a post-stress state distinct from the stress state: the stress charging demand is removed, background load is scaled by α_{off} as a reduced-background sensitivity scenario, all units recharge simultaneously as active load at the unity power factor, and no reactive support from Section 4.2 is carried over. The α_{off} levels are sensitivity states rather than measured diurnal load profiles; actual background-loading is time-varying and a data-driven trajectory could shift both the recharge durations and the transition between the two binding regimes. For a common duration T ,

$$P_{\text{ch},j}(T) = \frac{E_{\text{batt,wd},j}}{\eta_{\text{ch}} T}, \quad 0 \leq P_{\text{ch},j} \leq P_j^{\text{BESS}} \quad (13)$$

where the charging cap uses a symmetric active charge and discharge rating, stated as an engineering assumption rather than a universal battery property; apparent-power headroom associated with any reactive capability is deliberately not used to raise it. The reported quantity is

$$T_{\text{rec}}^* = \min \{ T : V_i \geq 0.95 \text{ p.u. } \forall i, L_l \leq 100\% \forall l, P_{\text{ch},j} \leq P_j^{\text{BESS}} \forall j \in J \} \quad (14)$$

which is the minimum common-recharge duration under the adopted synchronous policy, not a globally minimum time under arbitrary per-unit scheduling. Substituting the battery-side energy definition from Eq (12) into Eq (13) and enforcing the per-unit active charging cap gives an active-rating/efficiency floor that is independent of the feeder,

$$T \geq \frac{T_{\text{peak}}}{\eta_{\text{dis}} \eta_{\text{ch}}} \quad (15)$$

Before bisection, $V_{\text{min}}(T)$ is verified as non-decreasing and $L_{\text{max}}(T)$ as non-increasing over the searched interval. T_{rec}^* is then bracketed upward from Eq (15).

5. Numerical results and discussion

5.1. Branch-loading requirement, sizing stability, and capacity-data validation

Storage is required only when the no-storage state violates an adopted branch-loading limit. Under the nominal planning-limit parameterization, three of the eight cases are branch-loading feasible

without active storage, whereas the remaining five require 205.34–855.56 kW. In each nonzero case, the selected allocation restores the maximum branch loading to the 100% boundary within the declared numerical tolerance, showing that the branch-loading constraint is active under the nominal parameterization. The requirement increases with demand and is larger for the downstream-concentrated placement at equal aggregate charging power because a larger fraction of the EVCS demand traverses the shared Branch 5–6 corridor. At D3, for example, P2 requires 525.47 kW compared with 248.53 kW for P1.

Figure 3 decomposes the prescribed EVCS active-power demand into grid-supplied and co-located BESS-supplied components under the nominal centralized branch-loading-relief reference. The BESS contribution is zero for P1/D1, P1/D2, and P2/D1, but increases once the adopted branch-loading boundary is exceeded. At D4, the BESS supplies 510.09 kW under P1 and 855.56 kW under P2, while the feeder supplies 929.91 and 584.44 kW, respectively. This contrast illustrates the effect of charging location even when aggregate EVCS demand is identical.

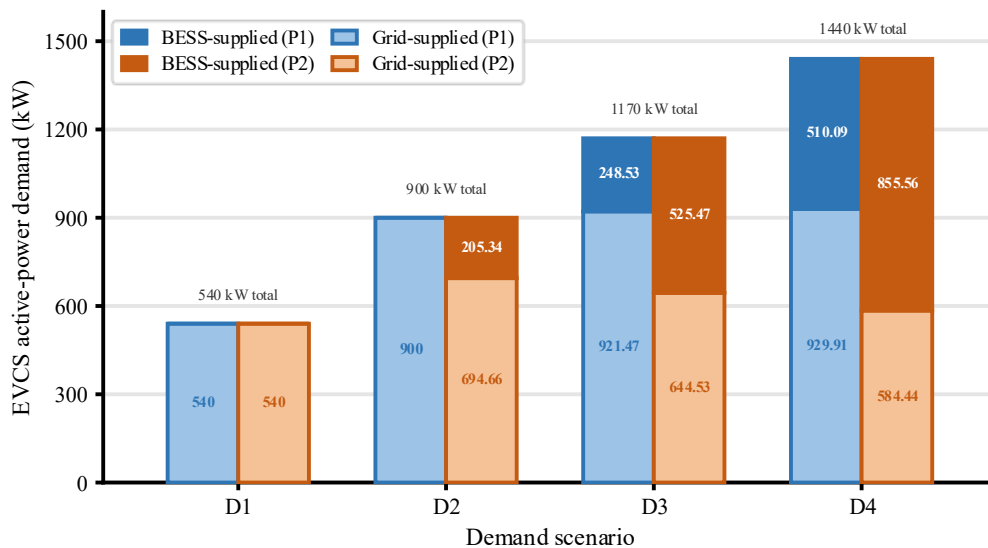


Figure 3. Decomposition of prescribed EVCS active-power demand into grid-supplied and co-located BESS-supplied components under the nominal centralized branch-loading-relief reference for placements P1 and P2.

The centralized solution is spatially selective rather than uniform across the co-located candidate sites. Figure 4 shows the D4 allocations. Under P1, nonzero storage is assigned only to Buses 10, 14, and 18, with 30.09, 240, and 240 kW, respectively, while Buses 6, 22, and 26 require no active allocation for branch-loading relief. Under P2, the nonzero allocations are 135.56 kW at Bus 14 and 240 kW at Buses 16, 17, and 18, while Buses 30 and 33 remain at zero. Thus, co-location defines the admissible storage sites but does not imply that every EVCS bus requires a positive BESS allocation.

The three zero-storage cases provide a direct illustration of why branch-loading and voltage adequacy should remain separated. Each remains below 0.95 p.u. despite requiring no active BESS for branch-loading relief. A combined branch-loading-and-voltage-sizing constraint would therefore assign active storage to a voltage-driven deficiency even though the nominal branch-loading criterion is already satisfied. Table 5 summarizes the exhaustive processing-order results relative to the centralized reference.

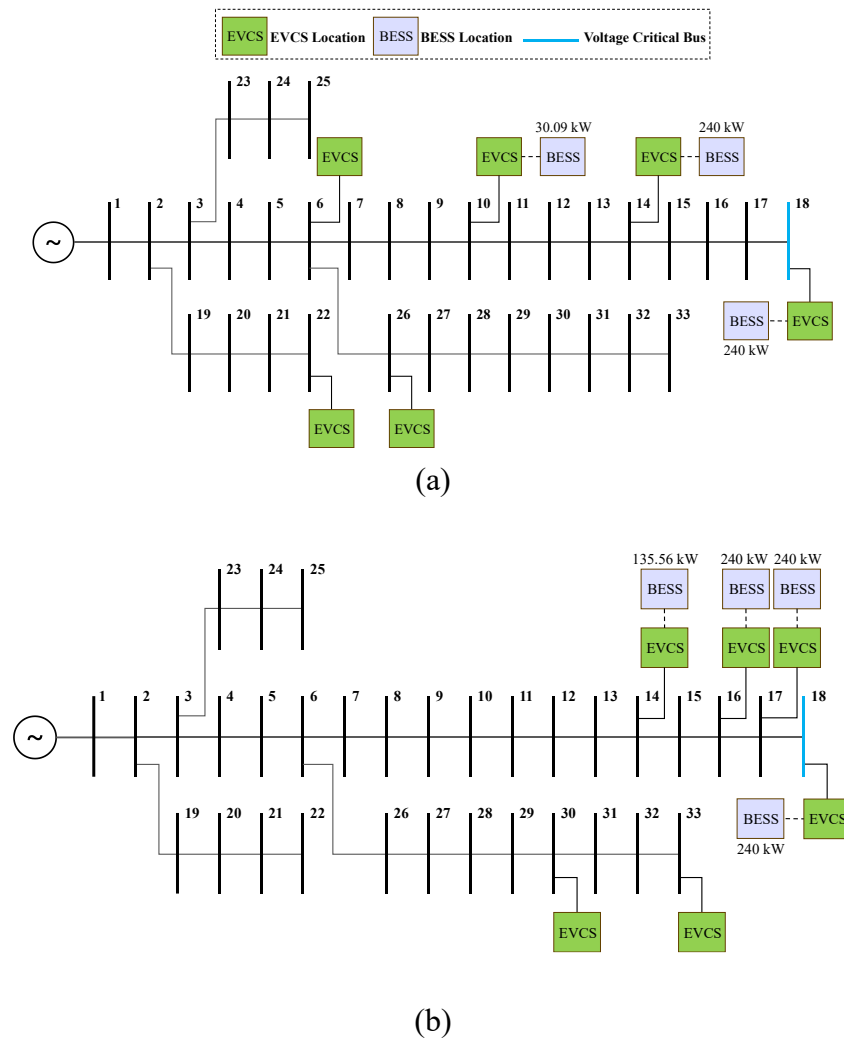


Figure 4. Bus-level centralized branch-loading-relief BESS allocation under D4: (a) distributed placement P1 and (b) downstream-concentrated placement P2. BESS markers denote only buses with nonzero active-power allocation.

Table 5. Processing-order sensitivity of the branch-loading-only sequential allocation relative to the centralized reference.

Case	Centralized reference (kW)	Best sequential (kW)	Best excess (%)	Worst sequential (kW)	Worst excess (%)
P1/D3	248.53	249.46	0.37	488.83	96.69
P1/D4	510.09	510.94	0.17	824.30	61.60
P2/D2	205.34	205.96	0.30	236.72	15.28
P2/D3	525.47	526.16	0.13	577.00	9.81
P2/D4	855.56	856.17	0.07	909.61	6.32

Note: Relative excess is defined with respect to the centralized reference under the same branch-loading-only BFS feasibility definition. All reported best and worst sequential endpoints passed an independent BFS branch-loading-feasibility replay.

The exhaustive processing-order audit confirms that the sequential rule is strongly path-dependent. Across the five branch-overloaded nominal cases, the most-favorable sequential orders remain close to the centralized reference, with relative excesses of only 0.07–0.37%. The least-favorable orders are substantially more conservative, with excesses ranging from 6.32% to 96.69%; the largest occurs for P1/D3, where the requirement increases from the 248.53 kW centralized reference to 488.83 kW. Independent fresh-BFS replay of both the best and worst allocation for every case confirmed branch-loading feasibility. The spread therefore reflects processing-order dependence rather than infeasible endpoints. When several charging buses share upstream branches, compensation assigned early alters the remaining branch-loading headroom available to later buses. Consequently, the sequential result depends on the allocation path even though each final endpoint satisfies the same branch-loading criterion.

Table 6 reports the effect of uniformly scaling the adopted apparent-power planning limits by $\beta_s = \{0.90, 1.00, 1.10\}$ across all eight placement–demand cases. Because the original benchmark specifies no conductor ampacities, this experiment is interpreted as a local sensitivity of the nominal planning-limit parameterization rather than as statistical uncertainty in a physical conductor rating. The resulting BESS requirement is materially capacity-dependent: for P2/D4, it changes from 855.56 kW at $\beta_s = 1.00$ to 1343.35 kW at 0.90 and 506.69 kW at 1.10. Marginal cases can also change classification: the three nominally storage-free cases require storage at $\beta_s = 0.90$, while P1/D3 and P2/D2 become storage-free at 1.10. By contrast, P1/D4, P2/D3, and P2/D4 require nonzero storage throughout the evaluated range. Thus, the nominal numerical magnitudes should be interpreted conditionally on the adopted branch-capacity data rather than as universal IEEE 33-bus BESS ratings.

Table 6. Branch-loading-relief requirement under $\pm 10\%$ uniform scaling of the nominal planning limits (kW).

Case	$\beta_s = 0.90$	$\beta_s = 1.00$	$\beta_s = 1.10$
P1/D1	107.95	0.00	0.00
P1/D2	461.12	0.00	0.00
P1/D3	738.80	248.53	0.00
P1/D4	1019.29	510.09	165.24
P2/D1	231.92	0.00	0.00
P2/D2	668.14	205.34	0.00
P2/D3	1003.03	525.47	193.87
P2/D4	1343.35	855.56	506.69

The classification boundary can be characterized exactly for the no-storage state. Under uniform scaling $S_l^{\max}(\beta_s) = \beta_s S_l^{\max}$, the no-storage branch flows are unchanged because the planning limits do not enter the BFS equations. Hence $L_l(\beta_s) = L_l(1)/\beta_s$, and the exact scaling at which a case changes between branch-overloaded and branch-loading-feasible is $\beta_s^* = L_{\max,0}/100$, where $L_{\max,0}$ denotes the no-storage maximum branch loading (%) at $\beta_s = 1$. For P1/D1 through P2/D4, respectively, the resulting thresholds are 0.9232, 0.9987, 1.0748, 1.1524, 0.9507, 1.0640, 1.1642, and 1.2687. These values reproduce the classification changes in Table 6. P1/D2 is marginal: a uniform reduction of the adopted limits by more than 0.13% would place it in the branch-overloaded class, whereas P2/D4 requires $\beta_s = 1.2687$ before the no-storage state becomes branch-loading feasible. This closed-form relation applies only to the zero-storage classification boundary; once BESS power is nonzero, the branch

flows depend on the optimized allocation and the full nonlinear sizing problem must be resolved.

To move beyond perturbations of the author-defined nominal limits, the active-power sizing layer was next re-evaluated using independently published IEEE 33-bus branch-current parameterizations while retaining the same network impedances, EVCS scenarios, BFS model, active-power bounds, and numerical controls. Under the conductor-anchored parameterization reported in [26], the first five main feeder branches are limited to 275 A and the remaining branches to 120 A, with the limits imposed directly as $|I_l| \leq I_l^{\max}$. The unmodified feeder is current-feasible, with a maximum normalized current ratio $R_I = \max_l |I_l|/I_l^{\max} = 0.7260$. Six of the eight EVCS cases also remain current-feasible without active BESS support. Only P1/D4 and P2/D4 exceed the published limits, requiring minimum active BESS allocations of 20.25 kW and 158.53 kW, respectively, to restore $R_I \leq 1$. Both sizing results were reproduced across all 16 accepted multistart solutions; the objective spreads were 3.01×10^{-12} kW and 3.58×10^{-12} kW for P1/D4 and P2/D4, respectively, with fresh-BFS residuals on the order of 10^{-13} p.u.

A second external test used the multi-tier current-limit parameterization reported in [27]. In the source study, these limits were applied to a configuration containing distributed energy resources (DERs) injecting 2.55 MW and 1.16 MW at Buses 3 and 30, respectively. The present test imports only the published branch-current limits while retaining the no-DER feeder configuration of this study. Consequently, the unmodified feeder already carries 199.65 A against the 200-A head-end limit, giving $R_I = 0.998264$. This case is therefore interpreted as a transfer stress test of the published capacity data rather than as a competing estimate of the physical ampacity of the original benchmark.

All eight EVCS stress states violate at least one branch-current limit. A 16-start minimax diagnostic over the admissible active-power domain $0 \leq P_j^{\text{BESS}} \leq P_j^{\text{EVCS}}$ shows that the minimax solution coincides numerically with full admissible active compensation in all eight cases, yet the minimum achievable R_I remains between 1.02199 and 1.06966. Because full compensation offsets the prescribed EVCS active demand at each co-located bus, the remaining current increase above the already near-saturated base state is induced by the retained EVCS reactive demand and its associated network-loss effects, which an active-power-only resource cannot remove. The external current-based test therefore independently reproduces the physical separation between active-power and reactive-power adequacy that motivates the staged formulation of this paper. Under this parameterization, the appropriate planning conclusion is not a larger finite active-BESS rating, but that mitigation beyond active-power compensation alone is required.

The different sizing outcomes can also be traced to a relocation of the binding network constraint. Under the nominal planning hierarchy, Branch 5–6 is the principal limiting branch from D2 onward, with Branch 2–3 limiting at D1. Under both external current-limit tests, the dominant constraint moves to the head-end Branch 1–2. The mechanisms, however, differ: the 275/120-A parameterization [26] removes the nominal downstream bottleneck through its 275 A limits on the first five main feeder lines, whereas under multi-tier parameterization [27], the 200 A head-end limit is already nearly saturated by the present no-DER base feeder. The variation in BESS requirements therefore follows from where each capacity dataset places the binding constraint and the associated available headroom, rather than from a change in the sizing formulation itself.

Taken together, the nominal sensitivity, exact β^* s thresholds, and two external current-limit tests establish a clear boundary on the numerical results. The proposed branch-loading-relief formulation is not tied to the nominal 2–6 MVA hierarchy, but the resulting BESS magnitude—and under sufficiently restrictive branch capacities, even the existence of a finite active-only solution—is conditional on the specified branch-capacity dataset. The nominal 0–855.56 kW results should therefore be interpreted

as planning outcomes under the Table 2 parameterization, while the external tests demonstrate how the same formulation responds to independently specified capacity data.

5.2. Residual voltage support and converter implications

After the nominal branch-loading-relief allocation, the minimum voltage remains below 0.95 p.u. in all eight cases. Correcting the chargers to the unity power factor raises it only to 0.9255–0.9451 p.u. and is insufficient in every case: removing the charging reactive component eliminates one term of the local voltage drop but not the drop produced by background reactive demand and by active-power transfer along the feeder. Charger-side reactive cancellation is therefore not equivalent to feeder voltage restoration, and additional local voltage support remains necessary. That additional support ranges from 114.77 to 879.94 kVAr, as summarized in Table 7. Post-support branch-loading remains below 100%, so voltage restoration does not reintroduce a branch-loading violation.

Table 7. Aggregate residual voltage-support requirements after the nominal centralized branch-loading-relief allocation.

Case	$V_{\min}$ after branch-loading relief	$V_{\min}$ at unity PF	Q_{PFC} (kVAr)	Q_{add}^* (kVAr)
P1/D1	0.9342	0.9393	177.49	384.31
P1/D2	0.9169	0.9255	295.82	879.94
P1/D3	0.9248	0.9359	384.56	505.21
P1/D4	0.9292	0.9428	473.31	258.83
P2/D1	0.9212	0.9291	177.49	495.67
P2/D2	0.9131	0.9263	295.82	560.41
P2/D3	0.9195	0.9366	384.56	316.52
P2/D4	0.9242	0.9451	473.31	114.77

Note: Q_{PFC} denotes the aggregate correction of the original lagging EVCS reactive demand to the unity power factor, whereas Q_{add}^* denotes the aggregate additional capacitive support under the adopted proportional policy. The two quantities represent distinct functions and are therefore reported separately rather than summed. Bus 18 is the limiting voltage bus in all evaluated cases and post-support $L_{\max}$ remains between 87% and 93%.

In the evaluated nominal cases, the additional capacitive-support requirement generally becomes larger as the branch-loading-relief allocation decreases. The storage-free P1/D2 case requires 879.94 kVAr, the largest value in the study, whereas the most heavily compensated case, P2/D4, requires only 114.77 kVAr. Active injection at the charging buses already reduces the resistive component of the voltage drop, so a larger branch-loading-relief allocation recovers part of the voltage margin as a by-product. Conversely, a case with no branch-loading deficiency receives no such active-power benefit and must close the entire voltage deficit reactively. Bus 18 is the limiting voltage bus in all evaluated cases, consistent with its long cumulative impedance path. Within the two placements studied here, changing the charging placement alters the voltage magnitude but not the identity of the limiting bus.

Converter adequacy is a bus-level question because the apparent-power requirement depends on the local combination of branch-loading-relief active power and additional capacitive support. If the BESS PCS at bus j is also selected to provide $Q_{\text{add},j}$, its conditional apparent-power requirement follows Eq (11). Table 8 reports this requirement for every bus with a nonzero BESS allocation in the nominal

branch-loading-relief solution. The required PCS headroom varies markedly across locations: it is only 0.32% at the 240-kW P2/D4 installations, but reaches 86.38% at P1/D3 Bus 14 and 96.17% at P2/D2 Bus 17. The latter corresponds to a 55.34 kW branch-loading-relief allocation that would require 108.57 kVA if the same PCS also supplied 93.40 kVAr of additional capacitive support. Hence, adequacy in MW does not by itself guarantee adequacy in MVA when branch-loading relief and local voltage support are assigned to the same converter.

Table 8. Conditional BESS PCS apparent-power requirements at buses with nonzero nominal branch-loading-relief BESS allocation.

Case	Bus	P_j^{BESS} (kW)	$Q_{\text{add},j}$ (kVAr)	$S_j^{\text{PCS,req}}$ (kVA)	PCS headroom (%)
P1/D3	14	53.53	84.20	99.78	86.38
P1/D3	18	195.00	84.20	212.40	8.92
P1/D4	10	30.09	43.14	52.59	74.81
P1/D4	14, 18	240.00	43.14	243.85	1.60
P2/D2	17	55.34	93.40	108.57	96.17
P2/D2	18	150.00	93.40	176.70	17.80
P2/D3	16	135.47	52.75	145.38	7.31
P2/D3	17, 18	195.00	52.75	202.01	3.59
P2/D4	14	135.56	19.13	136.90	0.99
P2/D4	16, 17, 18	240.00	19.13	240.76	0.32

Note: PCS headroom is defined as $100(S_j^{\text{PCS,req}} - P_j^{\text{BESS}})/P_j^{\text{BESS}}$. Zero-storage buses are omitted.

The zero-storage cases are therefore deliberately absent from Table 8. Although they still require additional capacitive support to restore the voltage limit, attributing that support to a BESS converter would be physically inappropriate where no storage unit is installed. More generally, Eq (11) is a conditional capability check rather than a requirement that the BESS PCS supply $Q_{\text{add},j}$, charger-side compensation, dedicated capacitor or inverter equipment, or another local Volt–VAr resource may instead be used. Selection and economic optimization of the reactive-power technology are outside the present scope.

5.3. Energy and recharge deliverability

The energy envelope distinguishes three quantities that serve different planning purposes: the AC-side discharge energy $E_{\text{AC,out}}$, the battery-side energy withdrawn $E_{\text{batt,wd}}$, and the nominal storage capacity E_{nom} implied by the adopted usable state-of-charge window. For P2/D4, the corresponding ($E_{\text{AC,out}}$, $E_{\text{batt,wd}}$, E_{nom}) envelopes are approximately (1.71, 1.80, 2.57) MWh at 2 h, (3.42, 3.60, 5.15) MWh at 4 h, and (5.13, 5.40, 7.72) MWh at 6 h. Only $E_{\text{batt,wd}}$ must subsequently be restored during recharge: using $E_{\text{AC,out}}$ would understate the recharge task, whereas using E_{nom} would overstate it by about 43% under the adopted efficiency and usable-SoC assumptions. Because all three quantities scale linearly with T_{peak} , the 2-, 4-, and 6 h values provide a compact planning envelope rather than an empirical charging-duration model. Storage-free cases have a zero storage-energy requirement at every duration.

Recharge deliverability exhibits two regimes distinguished by the binding constraint rather than by the background-loading factor alone. When feeder voltage headroom is sufficient, all installed units

can recharge at their active-power rating limits and the common recharge duration reaches the analytical active-rating/efficiency floor in Eq (15), equal to 4.43 h for the 4 h stress duration. As background loading increases—or, for sufficiently stressed spatial allocations, even at lower background factors—the limiting downstream voltage reaches 0.95 p.u. before the active-rating-limited charging power can be sustained and recharge becomes voltage-limited. Across Table 9, the voltage-limited durations range from 4.78 to 31.19 h. The most stressed allocation, P2/D4, is already voltage-limited at $\alpha_{\text{off}} = 0.50$, requiring 4.95 h. Branch-loading does not bind in any evaluated recharge state and peaks at approximately 84%.

The constraint determining the nominal branch-loading-relief BESS requirement is therefore not necessarily the constraint governing post-stress recharge. During the stress event, the adopted branch-loading limits determine the active-power requirement in cases requiring nonzero storage, whereas they do not bind in any evaluated recharge state. Instead, feeder voltage headroom determines whether the installed units can be returned to their pre-stress energy state within the available charging conditions. A planning study that verifies only peak-period branch-loading feasibility would therefore miss this post-stress deliverability limit. Under the synchronous recharge policy, the charging power satisfies

$$P_{\text{ch},j} = \left(\frac{P_j^{\text{BESS}}}{\eta_{\text{dis}} \eta_{\text{ch}}} \right) \left(\frac{T_{\text{peak}}}{T_{\text{rec}}^*} \right) \quad (16)$$

so, for a fixed background factor and spatial BESS allocation, the network charging state depends on the ratio $T_{\text{rec}}^*/T_{\text{peak}}$. Numerical replay confirmed this ratio to be invariant to numerical precision over $T_{\text{peak}} = 2, 4, 6$ h. Consequently, the 2 h and 6 h recharge durations are obtained by linear scaling of the 4 h values reported in Table 9.

Table 9. Minimum common recharge duration T_{rec}^* (h) at $T_{\text{peak}} = 4$ h under synchronous charging; analytical active-rating/efficiency floor = 4.43 h.

Case	$\alpha_{\text{off}} = 0.50$	0.70	0.85	1.00
P1/D3	4.43	4.43	4.43	9.54
P1/D4	4.43	4.43	6.70	17.51
P2/D2	4.43	4.43	4.43	8.25
P2/D3	4.43	4.78	7.69	20.06
P2/D4	4.95	7.42	11.95	31.19

Note: Values equal to 4.43 h attain the active-rating/efficiency floor; larger values are voltage-limited. Branch-loading does not bind in any evaluated recharge state. Storage-free cases are omitted because their recharge-energy requirement is zero.

6. Conclusions

Storage adequacy for feeder-integrated EV fast-charging cannot be represented by a single power or energy quantity. Under the nominal planning limits, the centralized branch-loading-relief requirement ranges from 0 to 855.56 kW across two placements and four demand levels, yet three of eight cases require no active storage while remaining voltage-infeasible. Branch-loading and voltage inadequacy are therefore distinct, so a combined feasibility test can assign active storage to a

voltage-driven deficiency rather than to branch-loading need. The remaining layers separate likewise: unity-power-factor correction is insufficient in all eight cases, leaving 114.77 to 879.94 kVAr of local support. Supplying it from the BESS PCS raises the required apparent-power headroom by 0.32% to 96.17%, and at the 4 h design duration, synchronous recharge ranges from the 4.43 h active-rating/efficiency floor to 31.19 h under voltage limitation, while branch-loading does not bind.

The active-power requirement is also conditional on the branch-capacity dataset. Under the published 275/120 A parameterization [26], only P1/D4 and P2/D4 require an active BESS, at 20.25 and 158.53 kW. Under the multi-tier current limits [27], no admissible active-only allocation restores current feasibility in any EVCS stress case. The formulation therefore transfers across specified capacity datasets, whereas the BESS magnitude and even the existence of a finite active-only solution do not.

The principal methodological result is the physical separation of branch-loading relief, voltage support, converter capability, storage energy, and recharge deliverability. The study remains limited to a balanced radial benchmark, deterministic charging scenarios, exogenous station locations, a prescribed reactive-support policy, and synchronous recharge. Future work should address additional feeders with documented conductor data, probabilistic multi-period demand, joint EVCS–storage planning, degradation-aware sizing, and coordinated charging or vehicle-to-grid operation.

Use of AI tools declaration

The authors declare they have not used Artificial Intelligence (AI) tools in the creation of this article.

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Conflict of interest

The authors declare no conflicts of interest.

Author contributions

Thi-Minh-Chau Le: Supervision, validation, critical review, and writing—review and editing. Tien-Khai Nguyen: Conceptualization, methodology, software implementation, numerical simulation, formal analysis, and writing—original draft. Trong-Nghia Le: Conceptualization, research direction, methodology review, supervision, and writing—review and editing.

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