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The Impact of Location and Type on the Performance of Low-Voltage Network Connected Battery Energy Storage Systems

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Abstract

This paper assesses the impact of the location and configuration of Battery Energy Storage Systems (BESS) on Low-Voltage (LV) feeders. BESS are now being deployed on LV networks by Distribution Network Operators (DNOs) as an alternative to conventional reinforcement (e.g. upgrading cables and transformers) in response to increased electricity demand from new technologies such as electric vehicles. By storing energy during periods of low demand and then releasing that energy at times of high demand, the peak demand of a given LV substation on the grid can be reduced therefore mitigating or at least delaying the need for replacement and upgrade. However, existing research into this application of BESS tends to evaluate the aggregated impact of such systems at the substation level and does not systematically consider the impact of the location and configuration of BESS on the voltage profiles, losses and utilisation within a given feeder.

In this paper, four configurations of BESS are considered: single-phase, unlinked three-phase, linked three-phase without storage for phase-balancing only, and linked three-phase with storage. These four configurations are then assessed based on models of two real LV networks. In each case, the impact of the BESS is systematically evaluated at every node in the LV network using Matlab linked with OpenDSS. The location and configuration of a BESS is shown to be critical when seeking the best overall network impact or when considering specific impacts on voltage, losses, or utilisation separately. Furthermore, the paper also demonstrates that phase-balancing without energy storage can provide much of the gains on unbalanced networks compared to systems with energy storage.

Keywords: Energy Storage, Smart Grid, Battery, LV Networks, Control

1. Introduction

The transition to a low carbon economy is a major focus of energy policy in the UK and internationally as governments respond to challenging environmental targets [1, 2]. In particular, the decarbonisation of the heat and transport sectors are areas of significant strategic focus and Low Carbon Technology (LCT) such as photovoltaic (PV) generation, electric vehicles (EV) and heat pumps (HP) are expected to make significant contributions to this transition [3, 4].

As domestic consumers adopt these low-carbon technologies (LCTs) in greater numbers and the penetration of such technologies within the network increases, the distribution networks will come under increased stress. Furthermore, the uptake is expected to not be evenly distributed with clusters forming in the early stages

of adoption leading to certain LV networks exceeding their constraints even at low national adoption rates [5]. However, traditional planning approaches are not fit-for-purpose for this uptake of LCTs. For low-voltage (LV) networks, traditional planning commonly utilises established understanding of diversity where After Diversity Maximum Demand (ADMD) values are applied to voltage drop and loading calculations. Unchanged for many years, these methods are based on historical load analysis and incorporate standard load growth assumptions that are no longer valid. Furthermore, once installed, the networks are generally unmonitored.

DNOs are aware that changes are needed in the planning process and analysis of future network trends has predicted distribution network operators will become more active in operating via innovation in the use of existing and new technologies [6]. The Smart Grid which, although varying definitions exist, is often described in terms of a power system with increased use of innova-

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36 tive technology is considered essential in order to fa- 88
37 cilitate the low carbon transition [7, 8, 9], and so these 89
38 changes and associated challenges can not be avoided. 90

39 Traditional network reinforcement solutions involve 91
40 adjustment of secondary transformer tap settings fol- 92
41 lowed by asset upgrade (e.g. transformer upgrade and 93
42 line re-conductoring) where the impact from changing 94
43 the tap settings is insufficient. As a technical solu- 95
44 tion that avoids directly interfacing with customers to 96
45 alter demand and generation profiles, Battery Energy 97
46 Storage Systems (BESS) are receiving increased atten-
47 tion in academic studies and industrial trials. By lo-
48 cating BESS at strategic locations within the distribu-
49 tion network, power flows can be managed and benefits
50 achieved in terms of voltage profile, cable loading (line
51 utilisation) and losses. Appropriate charging and dis-
52 charging can offset excessive voltage rise and reverse-
53 power flow due to PV installations, excessive voltage
54 drop and thermal overloads due to new LCT load, and in
55 general improve losses through peak demand reduction.
56 However, these benefits are often assessed in aggrega-
57 tion, and so don't consider the location of the BESS
58 within the LV feeder, or are considered in isolation and
59 assume that a location that is ideal for voltage, for ex-
60 ample, is also ideal for peak power flow. This paper
61 will demonstrate that this assumption is in most cases
62 not valid and the in general location within the feeder
63 is a critical consideration when trying to maximise the
64 benefits from BESS.

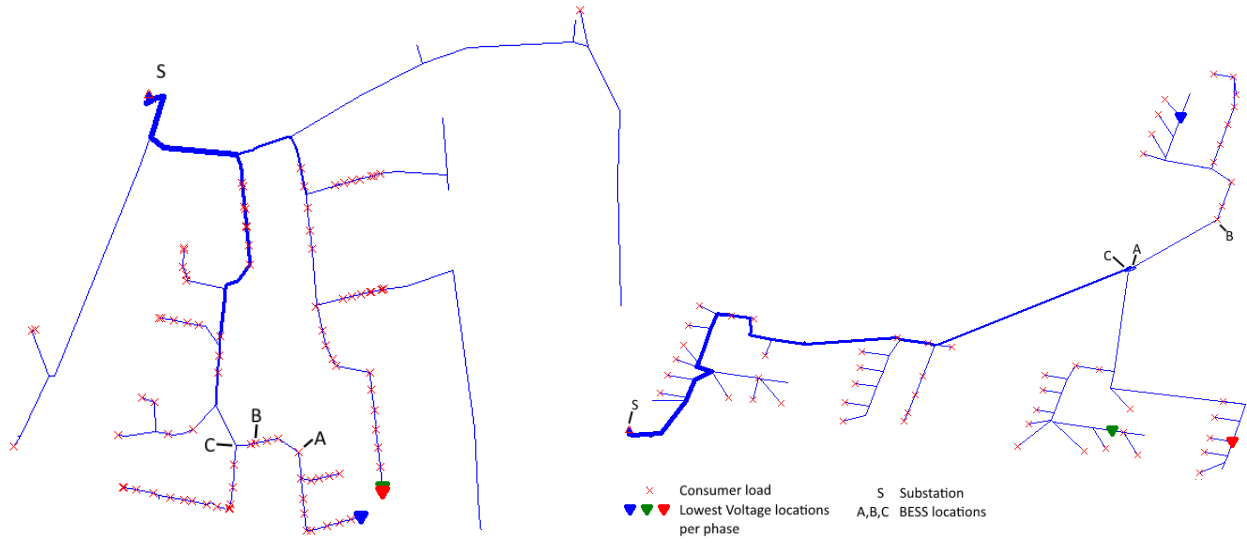
65 A number of BESS were installed and trialled in the 112
66 UK distribution networks. Above the LV level, the main 113
67 purpose of BESS is to provide support for primary sub- 114
68 stations and mitigate operational constraints [10, 11] or 115
69 provide balancing services and reduce curtailment of 116
70 renewable generation [12]. In these cases, the antici- 117
71 pated impact of BESS is known, as the distribution net- 118
72 works at medium voltage are closely monitored. On the 119
73 LV network, BESS have been installed within the cus- 120
74 tomer premises aiming to increase self-consumption of 121
75 domestic PV generations and making use of time-of-use 122
76 tariffs [13]. Community energy storage has been trialled 123
77 to support the LV feeder through peak shaving and re- 124
78 active power injection/absorption [14]. BESS have also 125
79 been deployed on LV feeders at the street-level, owned 126
80 and controlled by the DNO, in order to reduce peak de- 127
81 mand on a given feeder as well as to address voltage 128
82 constraints and harmonics [15]. 129

83 In all the cases described above, forecasting at least 130
84 day-ahead power and energy demand is essential in or- 131
85 der to optimise management of the BESS. Set-point 132
86 based control methods, that operate a battery rather like 133
87 a thermostat regulates temperature and charge or dis- 134
135

charge based on one or more thresholds, are able to 88
demonstrate a net positive impact but achieve far from 89
optimal performance and so often require bigger batter- 90
ies for the same gain compared to forecast-based meth- 91
ods. By incorporating an expectation of future demand, 92
albeit with a level of uncertainty that must be taken 93
into account, control methods that include forecasts are 94
able to outperform set-point based methods by reserving 95
headroom for the periods of lowest demand and capaci- 96
ty for the periods of highest demand in the day [16, 17]. 97

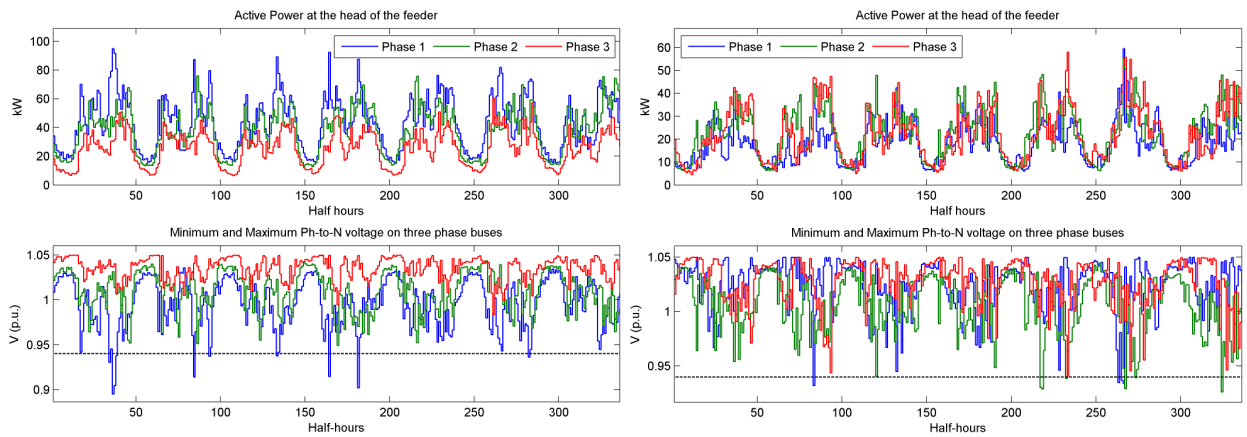
98 In practical situations, the feasible installation loca-
99 tions and configurations of storage units may be lim-
100 ited. Field trial deployments have used engineering
101 judgement and product availability to configure and lo-
102 cate BESS in distribution networks to evaluate bene-
103 fits [18, 14]. Further evaluation indicates that practi-
104 cal BESS deployments can support voltage and power
105 flow events but should not be expected to provide a so-
106 lution to all events at all times. Establishing the busi-
107 ness case requires maximising the benefits against multiple
108 objectives and realising the full potential of the technol-
109 ogy. Paying attention to the impact of the location of the
110 BESS within a feeder is one key part maximising these
111 benefits.

112 The work presented in this paper is motivated by
113 the LCNF New Thames Valley Vision Project (NTVV)
114 where BESS have been installed on the LV network at
115 the street level and are operated by the DNO [19]. As-
116 suming access to retrospective smart meter data but lim-
117 ited real-time network monitoring, the existing control
118 strategy for these BESS is to forecast individual end-
119 point (e.g. household) load profiles, aggregate them at
120 the substation level, and then determine the charge and
121 discharge schedule for the BESS on a per phase basis
122 that minimises the overall daily peak demand seen at the
123 substation. However, although the result of this peak re-
124 duction is improved voltage profile, cable loading and
125 losses upstream of the BESS, LV feeder conditions are
126 not explicitly included in the control strategy and the
127 potential benefits to the LV network are not considered.
128 This paper builds on the existing scheduling algorithm
129 work and addresses this issue of how best to locate and
130 operate such BESS units in LV networks for maximum
131 overall benefit within the LV network itself. The pa-
132 per develops an analytical method for the positioning of
133 known configurations of BESS, operating in the peak re-
134 duction mode described above, on LV feeders for max-
135 imum benefit to the LV network conditions.



(a) Network 1

(b) Network 2



(c) Network 1: 118 customers.

(d) Network 2: 56 customers.

Figure 1: Case Study Feeder Schematics and Baseline Results

2. Methodology

The impact of various BESS peak configurations and associated control algorithm, on real LV networks under worst case loading conditions, is assessed in order to establish the key considerations and trade-off's between a range of network performance metrics and BESS location. The LV networks selected, described in detail in Section 2.1, are real urban LV feeders with common characteristics such as multiple branches and single phase spurs. Furthermore, existing demand is pushing the operational conditions of these networks outside the statutory limits. Examining real networks instead of a theoretical, simple radial feeder helps to highlight the

complexities of real networks. However, as discussed further in Section 2.1.1, real smart meter data for individual customers from a separate study is used to drive the models in this paper. Nevertheless, network constraints on the two networks are also breached in the results presented later in the paper suggesting that the reason for these violations is partially due to the existing network structure.

The configurations and algorithms, explained in detail in Section 3, illustrate a range of operational examples and highlight key issues, but are not necessarily intended as optimal or best-in-class exemplars. The selected configurations and algorithms do highlight the separate role of power electronics and energy storage

163 in terms of both phase-balancing and peak reduction, 211
164 which is not commonly considered in the literature. The 212
165 algorithms used in this paper seek to reduce the peak 213
166 power demand during day and do not take into account 214
167 voltage, losses or utilisation. However, the impact of 215
168 those peak-reduction algorithms are on voltage, losses 216
169 and utilisation is considered and forms the main body 217
170 of results. Although algorithms could certainly be writ- 218
171 ten that do seek to balance all of these metrics, it is not 219
172 necessary to do so for the impact study presented in this 220
173 paper. 221

174 In order to assess the impact of the location of the 222
175 BESS, in each configuration, the BESS is located at 223
176 each node in each networks and the network is then sim- 224
177 ulated using OpenDSS. 225

178 2.1. LV Network Models 226

179 The two LV network models used in this paper are 227
180 based on two real LV networks located within the 228
181 Thames Valley Vision Project. Network 1, shown in 229
182 Figure 1a, was selected to represent a typical a LV 230
183 feeder with an unbalanced number of end-points on 231
184 each phase whereas Network 2 (42 customers on phase 232
185 1, 43 customers on phase 2, and 32 customers on phase 233
186 3), shown in Figure 1b, was selected to represent a typ- 234
187 ical a LV feeder a more balanced number of end-points 235
188 on each phase (18 customers on phase 1, 20 customers 236
189 on phase 2, and 18 customers on phase 3). 237

190 These two LV networks have been modelled in 238
191 OpenDSS, the open source distribution system simu- 239
192 lator developed by EPRI. In OpenDSS all phases are 240
193 modelled, allowing unbalanced load flow and examina- 241
194 tion of neutral currents. Utilising the COM interface of 242
195 OpenDSS, all data processing and scripting is carried 243
196 out in Matlab with OpenDSS providing network mod- 244
197 elling and load flow functionality. 245

198 2.1.1. Demand Data 246

199 Smart meter trial data made publicly available by Ire- 247
200 lands Commission for Energy Regulation [20] has been 248
201 used to allocate real domestic load profiles to the case 249
202 study feeders. An estimated worst case winter week was 250
203 chosen from the smart meter data set. Profiles were then 251
204 randomly selected from the pool and allocated to each 252
205 of the case study loads. The profiles are half hourly 253
206 kW and for simplicity, the power factor is assumed to 254
207 be unity. 255

208 2.1.2. Baseline Simulation 256

209 For each network shown in Figure 2.1, the chosen 257
210 winter week has been simulated to provide a baseline of 258
259

network performance for node voltages, kW profile at 211
the feeder head (substation), and maximum cable load- 212
ing under the simulated load conditions. Nodal voltages 213
are assessed against the ESQCR standards adopted by 214
UK DNOs under the Distribution Code; supply voltage 215
must be within +10/-6% of nominal 230v [21]. Cable 216
loading is assessed against the rated continuous capac- 217
ity. 218

As can be seen in Figure 1c the unbalanced load con- 219
nection of Network 1 causes significant overloading of 220
Phase 1 (blue trace) with minimum voltage on days 1 221
and 4. The locations of the worst observed minimum 222
voltage are highlighted in Figure 1a with blue, green 223
and red triangle for phases 1, 2 and 3 respectively. 224

Although Network 2 has a more balanced load con- 225
nection a degree of unbalance is still evident, as is in- 226
evitable at this level of disaggregation of load and asyn- 227
chronous consumer behaviour. Under these worst case 228
conditions, minimum voltage level on phase 1 and 2 has 229
breached the limit on several occasions. On the day 6, 230
due to high demand on all three phases, phases 1 and 2 231
breach the minimum voltage limit within the same hour. 232

Both case study examples represent LV networks that 233
are experiencing voltage and thermal breaches of oper- 234
ational limits. As discussed in the introductory sec- 235
tions, the application of BESS to resolve such LV net- 236
work issues is an increasingly viable option for DNOs. 237
For example, power injection on Phase 1 at the end of 238
the branch with the worst voltage problem during peak 239
hours would alleviate the voltage issues. The following 240
sections of this paper will investigate in detail the role 241
the BESS can play in supporting operation of these two 242
networks and the impact of location on performance. 243

244 3. BESS Configurations and Scheduling Algorithms 245

Four different BESS operational configurations are 246
considered in this paper: a single-phase BESS con- 247
nected to the most heavily loaded phase on a feeder; 248
three single-phase, independently operated and co- 249
located BESS's, connected to all three-phases at a com- 250
mon location on a feeder; a three-phase BESS that 251
is able to use power electronics to move energy be- 252
tween phases and performs this phase-balancing func- 253
tion without using any energy storage capacity; and fi- 254
nally a three-phase BESS that is able to perform both 255
phase-balancing and peak reduction using battery en- 256
ergy storage. The following subsections describe each 257
of these configurations in more detail and also the algo- 258
rithm that is used in each case to determine the opera- 259
tional power profile of the BESS. Once the charge and

discharge power profile for the BESS has been determined based on aggregated data, this profile is re-used for every location on the feeder that the BESS is trialled. The algorithms and presented here are intended to facilitate an investigation into the impact of such approaches on the resulting performance of the BESS. More advanced algorithms can certainly be developed and such development should be encouraged.

Several assumptions are made in the generation of the BESS charge and discharge schedules in the interest of simplifying the control approach:

- The scheduling algorithm has access to perfect forecasts of daily energy demand. The authors, and other researchers, have developed algorithms that don't make this assumption and include a real-time correct element [17, 22, 23]. However, such algorithms do not significantly impact the key points addressed in this paper.
- The aim of the BESS scheduling algorithm is to reduce the maximum daily energy demand peak on the feeder as measured at the substation. Although alternative strategies exist, such as direct voltage control, peak reduction is commonly used in the literature and is an appropriate choice for comparison purposes.
- Energy stored within the BESS for the minimum amount of time in order to release the resources of BESS for other functions e.g. arbitrage or peak reduction at higher levels of distribution network. In the content of the New Thames Valley Vision project, as well as much of the emerging literature, it is recognised that for BESS to be cost effective, they will need to perform more than one function [16, 24, 25].
- The maximum charge and discharge rate is constant for all levels of BESS state of charge. This approximation does not have a significant impact on the key issues addressed in this paper.
- The BESS scheduling algorithm presented in this paper is not intended for long-term control and hence does not take into account impact of storage cycling on the operational lifetime of the battery.

The following sub-sections describe each of the BESS configurations and associated control algorithms. Example charge and discharge schedules are generated for day 1 of the worst-case week previously identified for network 1 only.

3.1. Configuration 1: Single-phase BESS on one phase

One use-case for a BESS is to alleviate voltage and current issues on the most heavily loaded phase of a three-phase feeder. It may be considered unnecessary to install a BESS on every phase, or install a three-phase system when the the heavy loading on one phase is due to more customers being connected to that phase compared to the others. In this case, the cause of the phase-imbalance is a fundamental part of the feeder structure. Configuration 1 seeks to represent this case of a single-phase BESS connected to a single-phase of a feeder. Phase-balancing in this configuration is impossible as the BESS is only connected to one phase.

The algorithm used for Configuration 1 uses the Matlab optimisation solver to minimise the cost function given in equation (1). This cost function aims to minimise the maximum peak demand under the BESS operation within the control horizon such that the time duration of energy stored in the battery is also minimised, in line with the assumptions previously stated.

$$\text{minimise } \max \left(\sum_k^{48} (D_f(k) + P(k))^2 \right) + \alpha \sum_k^{48} C(k) \quad (1)$$

Subject to following constraints:

$$C_{min} \leq C(k) \leq C_{max} \quad (2)$$

$$-P_{max} \leq P(k) \leq P_{max} \quad (3)$$

$$C(k) = C(k-1) + \eta\tau P(k) \quad (4)$$

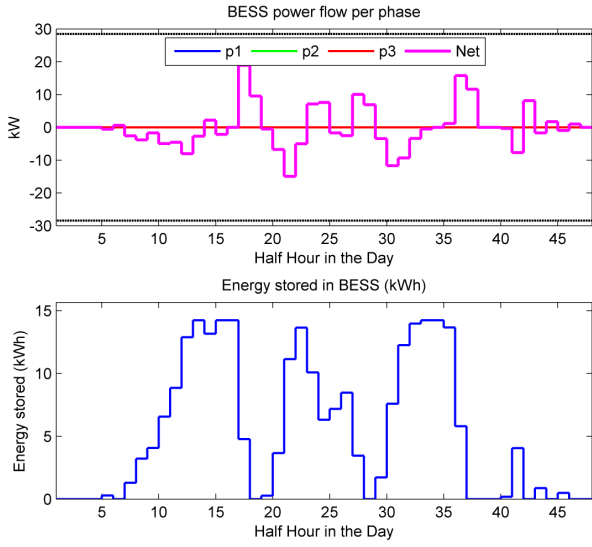
$$\eta = \begin{cases} \eta & \text{if } P(k) \geq 0, \\ \frac{1}{\eta} & \text{if } P(k) < 0. \end{cases} \quad (5)$$

where $D_f(k)$ - vector of forecasted aggregate demand at time k for the feeder in question and the phase where BESS is installed; $P(k)$ - power flow from BESS to network; α - weighting of total energy stored in BESS over the day; $C(k)$ - energy stored in BESS in kWh; C_{max} and C_{min} - maximum and minimum constrains on BESS energy capacity; P_{max} - maximum rating of BESS for charge and discharge; η - BESS efficiency and τ - duration of time period in hours. Constraints given in equations (2) - (5) represent the physical constraints on power electronics, energy storage capacity and energy storage model with separate charge and discharge efficiencies.

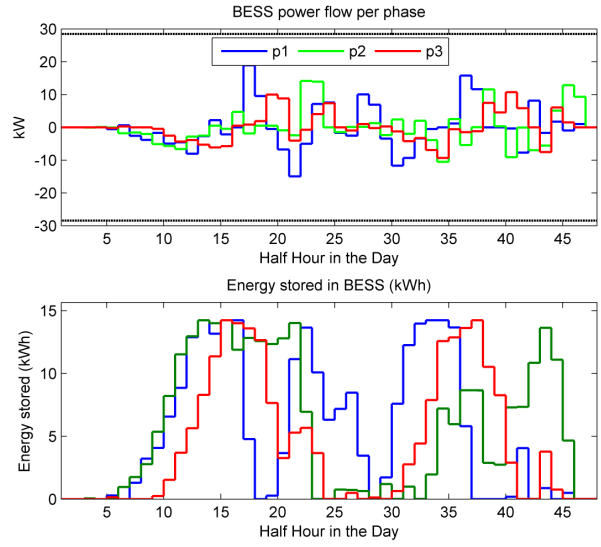
The resultant BESS schedule and state of charge profile for phase 1 of day 1 of network 1 is given in figure 2a.

3.2. Configuration 2: Three single-phase storage

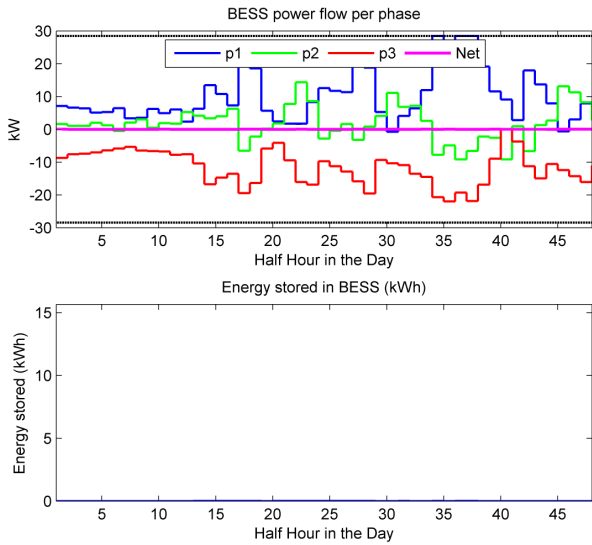
Previous trials showed that separate single-phase storage can be effective in supporting network operation



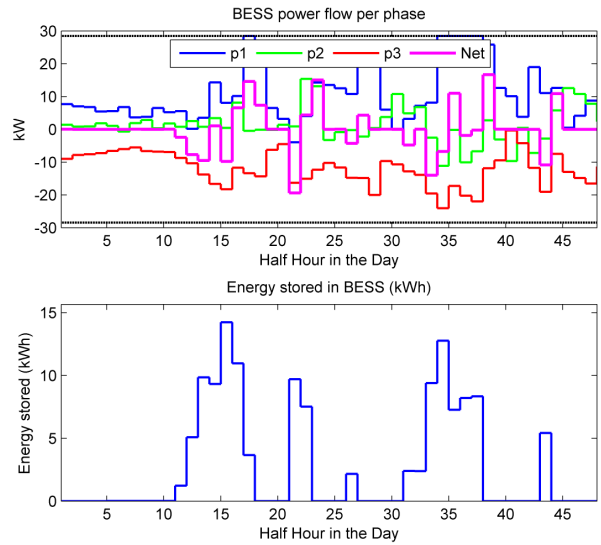
(a) BESS schedule and SoC for Configuration 1 (single-phase BESS) for network 1, day 1



(b) BESS schedule and SoC for Configuration 2 (three single-phase BESS) for network 1, day 1



(c) BESS schedule and SoC for Configuration 2 (three-phase power electronics) for network 1, day 1



(d) BESS schedule and SoC for Configuration 4 (three-phase BESS) for network 1, day 1

Figure 2: Scheduled power flows from the BESS into network and the resultant state-of-charge profiles for each BESS configuration

346 to maintain voltage levels and perform peak reduction 355
 347 [14]. Configuration 2 represents this case by co-locating 356
 348 three-single phase BESS. Each single-phase BESS is 357
 349 treated in the same way as in configuration 1 (including 358
 350 capacity and rating) and the schedule is developed 359
 351 to reduce peaks on each phase independently. Although
 352 uncoordinated between phases in this example, coordinated
 353 BESS across multiple phases can potentially perform
 354 limited phase-balancing using the energy storage

component.

Similarly to configuration 1, figure 2b shows three
 BESS schedules, one per phase, and state of charge profiles
 based on demand data for each phase on day 1 of
 network 1.

3.3. Configuration 3: Three-phase power electronics for phase balancing

Volatile customer behaviour and unbalanced customer
 connections means power flow across phases are

```

Data:  $\mathbf{D}_f(k), P_{max}$ 
initialise:  $\mathbf{P}(k), D_a(k)$ ;
for  $k = 1$  to  $48$  do
     $D_a(k) = \frac{\sum_{p=1}^3 D_f^p(k)}{3}$ ;
    NumCapedPhs  $\leftarrow 0$ ;
    UncapedPhs  $\leftarrow \emptyset$ ;
    for  $p = 1$  to  $3$  do
         $\mathbf{P}^p(k) = D_a(k) - \mathbf{D}_f^p(k)$ ;
        if  $|\mathbf{P}^p(k)| > P_{max}$  then
             $\mathbf{P}^p(k) = P_{max} \text{sign}(\mathbf{P}^p(k))$ ;
            NumCapedPhs  $++$ ;
        else
            UncapedPhs  $\leftarrow \{p\}$ ;
        end
    end
    if NumCapedPhs  $> 0$  then
        for  $p = \text{UncapedPhs}$  do
             $\mathbf{P}^p(k) = \text{sign}(\mathbf{P}^p(k)) (|\mathbf{P}^p(k)| - \frac{|\sum_i \mathbf{P}^i(k)|}{3 - \text{NumCapedPhs}})$ ;
        end
        if NumCapedPhs  $== 3$  then
             $j = \arg \max(\mathbf{P}(k))$ ;
            for  $p = \forall 1 \leq p \leq 3 \setminus \{j\}$  do
                 $\mathbf{P}^p(k) = \frac{-\mathbf{P}^j(k)}{2}$ ;
            end
        end
    end
end

```

Algorithm 1: Algorithm for arithmetic phase balancing function

364 rarely balanced, causing voltage unbalance [26, 27].
365 Consequently, balancing of active power could reduce
366 individual peaks on each phase and improve voltage.
367 Furthermore, the cost of three phase power electronics
368 would be lower than a lithium ion-based energy stor-
369 age device. In contrast to Configuration 2, a three-phase
370 connected BESS is capable of phase balancing without
371 using the storage element.

372 The algorithm used for Configuration 3 for arithmetic
373 phase balancing is given below in algorithm 1. This al-
374 gorithm computes the average power across all phases
375 for each time-step and then determines the BESS power
376 flow on each phase that will bring the current power as
377 close to this average as possible.

378 Applying phase balancing algorithms to the fore-
379 casted demand for day 1 of network 1 creates the power
380 flow schedule for each phase depicted in figure 2c. The
381 SoC plot for configuration is included for completeness

382 but shows no data as the energy storage component is
383 not used in this configuration.

384 3.4. Configuration 4: Three phase balancing combined 385 with energy storage

386 The benefit of phase-balancing function is evident
387 for unbalanced feeders with asynchronous customer be-
388 haviour. However, social events or TV programmes
389 could cause synchronous customer demand causing
390 peaks on all three phases simultaneously that cannot be
391 resolved with phase balancing only.

392 BESS configuration 4 is designed to represent the en-
393 ergy storage and management devices deployed in the
394 Bracknell area in UK as part of NTVV project. Each
395 device consists of three-phase power electronics capa-
396 ble of performing a phase balancing function and mod-
397 ular energy storage with total capacity of a single-phase
398 BESS presented in configuration 1. Therefore, this de-
399 vice combines the benefits of balancing power between
400 phases with energy time shifting with energy storage.

401 A day-ahead schedule for each phase is generated
402 from forecasted demand with an aim to minimise fol-
403 lowing cost function:

$$\text{minimise } \max \left(\sum_k^{48} (\hat{\mathbf{D}}_f(k))^2 \right) + \alpha \sum_k^{48} C(k) + \sum_k^{48} (\max(\Phi(k))) \quad (6)$$

where

$$\hat{\mathbf{D}}_f(k) = \mathbf{D}_f(k) + \mathbf{P}(k) \quad (7)$$

$$\Phi(k) = \left\{ (\hat{\mathbf{D}}_f^1(k) - \hat{\mathbf{D}}_f^2(k))^2, (\hat{\mathbf{D}}_f^2(k) - \hat{\mathbf{D}}_f^3(k))^2, (\hat{\mathbf{D}}_f^3(k) - \hat{\mathbf{D}}_f^1(k))^2 \right\} \quad (8)$$

Subject to following constraints:

$$C_{min} \leq C(k) \leq C_{max} \quad (9)$$

$$-P_{max} \leq P^p(k) \leq P_{max}, p = 1, 2, 3 \quad (10)$$

$$C(k) = C(k-1) + \eta\tau \sum_p^3 P^p(k) \quad (11)$$

$$\eta = \begin{cases} \eta & \text{if } \sum_p^3 P^p(k) \geq 0, \\ \frac{1}{\eta} & \text{if } \sum_p^3 P^p(k) < 0. \end{cases} \quad (12)$$

404 where, $\hat{\mathbf{D}}_f(k)$ is the expected demand under BESS oper-
405 ation per phase, $\Phi(k)$ is the demand difference between
406 phases under BESS operation, $\mathbf{D}_f(k)$ is the vector with

407 forecasted aggregated demand on each phase at time k ,
408 $\mathbf{P}(k)$ is the power flow on each phase from BESS at time
409 k . Constraints given in equations (9) - (12) are equivalent
410 to (2) - (5) for three-phase operation.

411 As per the other configurations, the resulting power
412 flow schedule per phase, and SoC, can be seen in 2d.

413 4. Case Study Analysis

414 In this section, scheduling algorithms are applied to
415 the case study LV networks and the impact of location
416 on key network parameters are evaluated for each BESS
417 configuration. The networks are simulated across the
418 full week but for clarity, the worst case day, with high-
419 est peak power, is used for the results presented below.
420 For each network and BESS configuration, the mini-
421 mum voltage, maximum line overload per phase and
422 total losses observed during the day are taken as the per-
423 formance metrics. This process is repeated for each pos-
424 sible location (all three-phase buses) of the BESS on the
425 network. Detailed results are presented for Network 1
426 and then comparative summary results are presented for
427 Network 2.

428 4.1. Network 1 Location Analysis

429 4.1.1. Configuration 1: Single Phase BESS on One 430 Phase

431 Due to highest peak demand, caused by greater num-
432 ber of customers on phase 1, the single phase BESS de-
433 vice connected to phase 1 and was tried on all three-
434 phase locations. The BESS is sized at 30% of the high-
435 est peak half-hourly energy consumption on the phase
436 and scheduled to reduce peak demand as per cost func-
437 tion in 1.

438 In Figure 3a, the losses, utilisation per phase and mini-
439 mum voltage per phase is plotted as a function of the
440 nodal location of the BESS. The impact of BESS loca-
441 tion on losses is not significant reaching 95 kWh around
442 Buses 60-95 and up to 100 kWh at the end of the feeder.
443 However, the minimum voltage on phase 1 can be sig-
444 nificantly improved by locating the BESS around Buses
445 66-81.

446 Single-phase BESS only impacts the power flow on
447 one phase therefore line utilisation is only improved on
448 the phase that the BESS is connected to. The lowest
449 line utilisation on phase 1 is achieved by locating BESS
450 on buses 18-95, yet the current flow through the feeder
451 is still above the recommended line rating. Beyond bus
452 95, the BESS is located on a branch of the feeder and
453 therefore can only offset power flow from the consumers
454 down the line.

455 4.1.2. Configuration 2: Single Phase BESS on All 456 Three Phases

457 Similarly to single-phase BESS, in Figure 3b, a sim-
458 ilar improvement in the worst-case minimum voltage
459 is achievable but only if the BESS is installed between
460 nodes 60-63, a smaller range than for Configuration 1.
461 As expected, the BESS is now having an influence on
462 all three phases, but the greatest benefit is still achieved
463 by locating the BESS according to Phase 1. Therefore,
464 in this particular example and perhaps more generally
465 for unbalanced LV feeders with one phase more heavily
466 loaded than the others, there is no significant benefit in
467 installing three single-phase BESS, as a similar benefit
468 can be obtained with just one. The impact of additional
469 BESS devices connected to other phases does not im-
470 prove the overall network condition. Voltage and line
471 utilisation on the heaviest phase still violates the con-
472 straints.

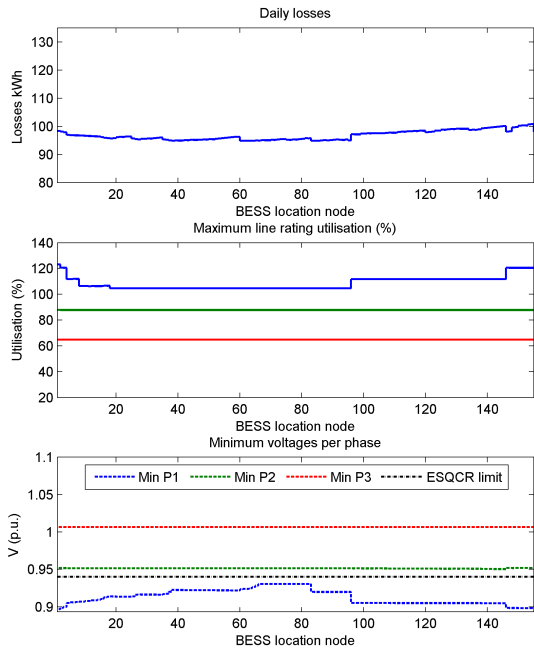
473 4.1.3. Configuration 3: Three Phase BESS Using 474 Phase Balancing only

475 With reference to Figure 3c, for the phase balancing
476 without storage configuration, more significant varia-
477 tions in impact occur by location. As power is being
478 pulled down one phase to be discharged on another, the
479 trade-off on impacts between phases becomes more ev-
480 ident with location, as does the influence of location on
481 losses. The minimum voltage on phase 1 improves dra-
482 matically between buses 20 and 95. This improvement
483 occurs against a corresponding degradation in voltage
484 of phases 2 and 3. Losses vary significantly by location
485 with best positions found around bus 38 and between
486 buses 60-65.

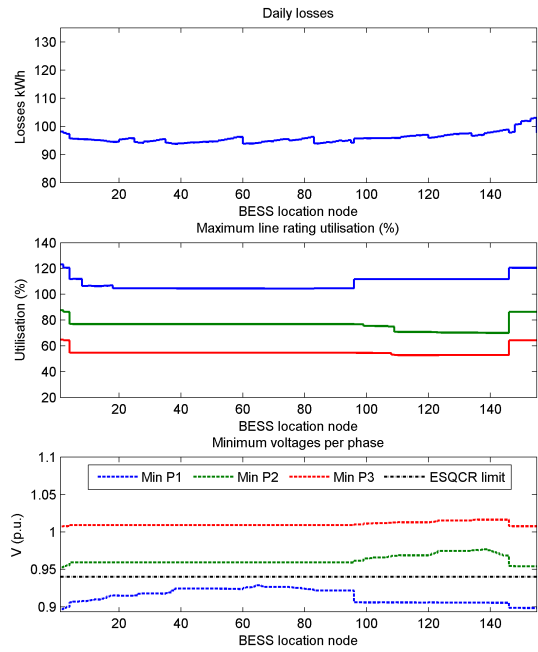
487 Fundamentally, the overall network performance is
488 significantly improved by using phase-balancing with-
489 out storage. Locating BESS between buses 38 and 95
490 mitigates voltage violations on phase 1 and reduced line
491 utilisation to a level below the maximum recommended
492 rating.

493 4.1.4. Configuration 4: Three Phase BESS with Full 494 Functionality

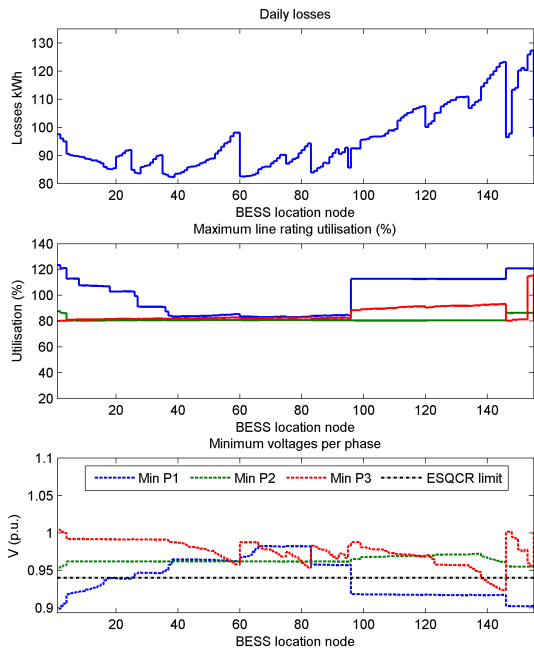
495 As seen in Figure 3d, when storage capacity is
496 added to the phase balancing functionality, the pattern
497 is very similar to the previous configuration with phase-
498 balancing without storage. Instead of transferring power
499 from phases 2 and 3 to phase 1, energy storage is used
500 to inject power to phase 1. Consequently, phase 2 and
501 3 have better line utilisation and higher minimum volt-
502 age. Given that for many BESS systems the cost of the
503 energy storage is much higher than for the power elec-
504 tronics, the results presented here suggest that for



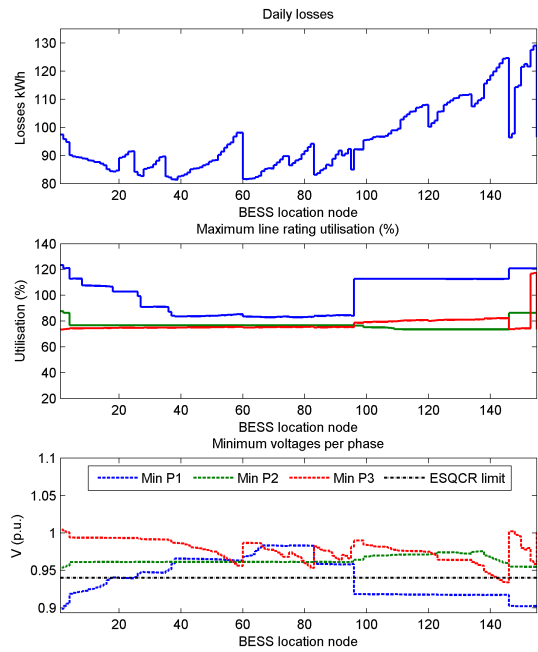
(a) Impact of Configuration 1 (one single-phase BESS on phase 1)



(b) Impact of Configuration 2 (three single-phase BESS).



(c) Impact of Configuration 3 (three phase phase balancing BESS).



(d) Impact of Configuration 4 (three phase balancing with storage function BESS).

Figure 3: Impact of BESS location on the key network operation metrics for each BESS configuration assessed on network 1.

505 a LV network feeder with significant phase imbalance 507
506 it would be more cost effective to install a three-phase

power electronics systems without energy storage.

Table 1: Table for Both Networks showing the optimal locations of the BESS for each algorithm and each network

BESS configuration		Net 1 Best Location (bus number)				Net 2 Best Location (bus number)			
		Losses	Volts	min p.u.	Overload	Losses	Volts	min p.u.	Overload
One single phase BESS	p1	38	66	0.93	94	69	78	0.94	86
	p2		123	0.95	145		37	0.93	85
	p3		1	1.01	82		65	0.95	79
Three single phase BESS	p1	37	64	0.92	82	70	78	0.94	86
	p2		138	0.97	142		64	0.95	54
	p3		135	1.02	109		38	0.99	73
Phase balancing only	p1	38	68	0.98	68	37	50	0.95	78
	p2		137	0.98	4		65	0.94	1
	p3		1	1.00	1		70	1.00	29
Phase balancing with storage	p1	37	68	0.98	68	38	38	0.96	38
	p2		136	0.98	140		59	0.96	85
	p3		1	1.00	1		38	1.01	72

508

509 4.2. Best Location Analysis

510 The results presented above inform and set the con-
511 text for the question of best location of BESS on LV
512 networks. The results obtained in the above analysis
513 identify a best location for each metric, for each phase
514 and are summarised in Table 1. Network 2 has been
515 similarly analysed and results for this network are also
516 included in this table. For network 1, the best location
517 for improved phase 1 voltage, regardless of BESS con-
518 figuration, is around bus 66. A wider set of locations for
519 maximum cable overload can be observed: buses 25 to
520 95. For losses, the impact of BESS configuration on best
521 location is more evident. With single phase storage, the
522 location of best voltage improvement and cable load-
523 ing reduction is near the location with minimum losses,
524 making bus 66 optimal. However, for phase balancing
525 only and phase balancing with storage, the location for
526 (a significant) loss reduction and voltage improvement
527 is between buses 38-44 or 60-68.

528 There are several interesting points to be drawn from
529 these results. Firstly, the unbalanced nature of the LV
530 network is essential when considering the impact of
531 BESS at this level of the network. The variation in load-
532 ing between phases results in clear trade-offs regard-
533 ing best location for each phase. Secondly, where the
534 BESS is operated in three-phase mode, in an unbalanced
535 fashion, the positive and negative power flows of either
536 charge/discharge cycles or phase balancing, heavily in-
537 fluence losses. Finally, although there are trade-offs be-
538 tween phases in impact of location, the extent of the
539 network unbalance and relative importance of impact to

540 certain phases must be taken into account when deter-
541 mining the final best location, i.e. for Network 1, phase
542 1 conditions are clearly the main priority.

543 To determine the overall best location for each of the
544 BESS configurations a weighted ranking process is pro-
545 posed. As described above, for each of the known BESS
546 configurations under assessment, the worst case week
547 scenario is simulated and results recorded. A ranked
548 list of the tested locations can then be derived for each
549 phase and for each metric. If there are known priori-
550 ties for a specific network, then an appropriate weight-
551 ing can be applied to each ranked list. For example,
552 with network one, minimum voltage and maximum cable
553 loading on phase 1 would be prioritised above other
554 metrics as these parameters are exceeding operational
555 limits. The following prioritisation method is proposed
556 based on the assumption that DNO priorities are firstly
557 to operate within the specified limits and secondly to
558 minimise losses. Voltage is assessed in terms of the Volt-
559 age Profile (*VP*) metric across all phases as shown be-
560 low. Reference voltage, V_{ref} , is 1p.u. or 230V nominal,
561 N is the total number of nodes. A minimum *VP* repre-
562 sents the least deviation from reference voltage across
563 the network. Nodes on phases with particular voltage
564 problems will dominate and best location for network
565 voltages will be most weighted to locations with most
566 influence on problem nodes and phases.

$$VP = \sum_i^N (V_i - V_{ref})^2 \quad (13)$$

567 A similar metric, *CP* for cable capacity profile is applied
568 to rank location based on cable loading. M is the total
569 number of cables (counting 3 per three phase line), C_{ref}

570 is the specified maximum% cable rating (100% in this 608
571 case). The objective is to minimise CP . 609

$$CP = \sum_i^M (C_i/C_{ref})^2 \quad (14) \quad 610$$

572 Using the above assumptions and metrics, the pro- 611
573 posed process is: 612

- 574 1. Identify all locations where the network is within 613
575 operational limits
- 576 2. Rank these locations in terms of losses to identify 614
577 the best location
- 578 3. If no locations achieve operational limits, rank loca- 615
579 tion in terms of voltage and cable loading 616

Table 2: Highest ranked BESS locations for Both Networks 617

BESS configuration	Network 1	Network 2
One single phase BESS	66	43
Three single phase BESS	63	70
Phase balancing only	38	38
Phase balancing + storage	38	38

580 Table 2 shows the highest ranked locations for each 620
581 BESS configuration and network as evaluated on the 621
582 network improvement metrics on a day with the heavi- 622
583 est loading. 623

584 The highest ranked location for one single-phase con- 624
585 figuration is marked 'A' on the figures 1a and 1b. For 625
586 network 1 this location corresponds to the best improve- 626
587 ment on phase with lowest voltage as it experiences the 627
588 heaviest loading and hence is the priority for improve- 628
589 ment. For the network 2, the highest ranked location for 629
590 single-phase BESS configuration is a three phase bus 630
591 just before the branching of the feeder. 631

592 BESS configuration 2 in network 1 has highest 632
593 ranked location close to the top of the of the branch with 633
594 weakest voltage, whereas for network 2 it is the same loca- 634
595 tion as for the one single-phase BESS. Highest ranked 635
596 location for configuration 2 is marked 'B' on figures 1a 636
597 and 1b, for network 1 and 2 respectively. 637

598 Phase balancing and phase balancing with stor- 638
599 age configurations provide overall improvement on all 639
600 phases and reduction of network losses. The greater ef- 640
601 fect from these configurations can be achieved by plac- 641
602 ing BESS higher on the feeder, closer to substation, to 642
603 supply greater number of loads with balanced voltages, 643
604 yet close enough to weakest node to provide the neces- 644
605 sary support. Intuitively, best location for BESS config- 645
606 uration 3 and 4 would be at or before feeder branching. 646
607 Highest ranking locations for phase balancing and phase 647

608 balancing with storage for both networks are marked 609
610 with 'C' on figures 1a and 1b, for network 1 and 2 re- 611
612 spectively. In both cases, the locations are at the top 613
613 of two branches, allowing BESS to improve the lowest 614
614 voltage nodes until within the statutory limits (see table 615
615 1). 616

614 4.3. Impact of BESS at the highest ranked Location

615 For each of the network case studies, the worst case 616
616 winter week scenario has been simulated with each 617
617 BESS configuration located at the best location iden- 618
618 tified in Table 2. The resulting 'best possible' impacts 619
619 for each BESS are described in the following sections.

620 4.3.1. Network 1

621 The impact of each BESS configuration network op- 622
622 eration on day 1 at the half-hourly basis is shown on 623
623 figure 4. 624

625 The impact of phase balancing function compared to 626
626 single-phase BESS is immediately visible: power flow 627
627 and line utilisation are in close proximity to each other 628
628 an all phases throughout most of the day. The only sig- 629
629 nificant deviation in power flow and line rating occurs 630
630 around 6 pm where a peak consumption occurs on all 631
631 three phases, with phase 1 having significantly higher 632
632 peak. At this point BESS configurations 3 and 4 reach 633
633 maximum power output on phase 1 and cannot inject 634
634 more power on phase 1. The difference between config- 635
635 uration 3 and 4, is that for phase balancing during peak 636
636 reduction, power is transferred from other phases at the 637
637 same time as the peak as opposed to absorbed from 638
638 other phases by storage before the peak. For single- 639
639 phase BESS, the improvement is only achieved on the 640
640 phase the BESS is connected to with insignificant im- 641
641 pact on other phases. 642

643 The results showing impact of each BESS configura- 644
644 tion at their optimum locations are summarised in Fig- 645
645 ure 6a. For this network, the best results for all network 646
646 parameters are obtained from the phase-balancing ap- 647
647 proach. 648

649 The summary of impact of each BESS configura- 649
649 tion against baseline on network 1 is given in figure 650
650 6a. Overall, each BESS configuration improves the net- 651
651 work operation by increasing minimum voltage, reduc- 652
652 tion of line utilisation and losses. However, configura- 653
653 tion 3 and 4 increase minimum voltage above the statu- 654
654 tory constraint, reduce maximum line utilisation below 655
655 recommended maximum and significantly reduces net- 656
656 work losses. 657

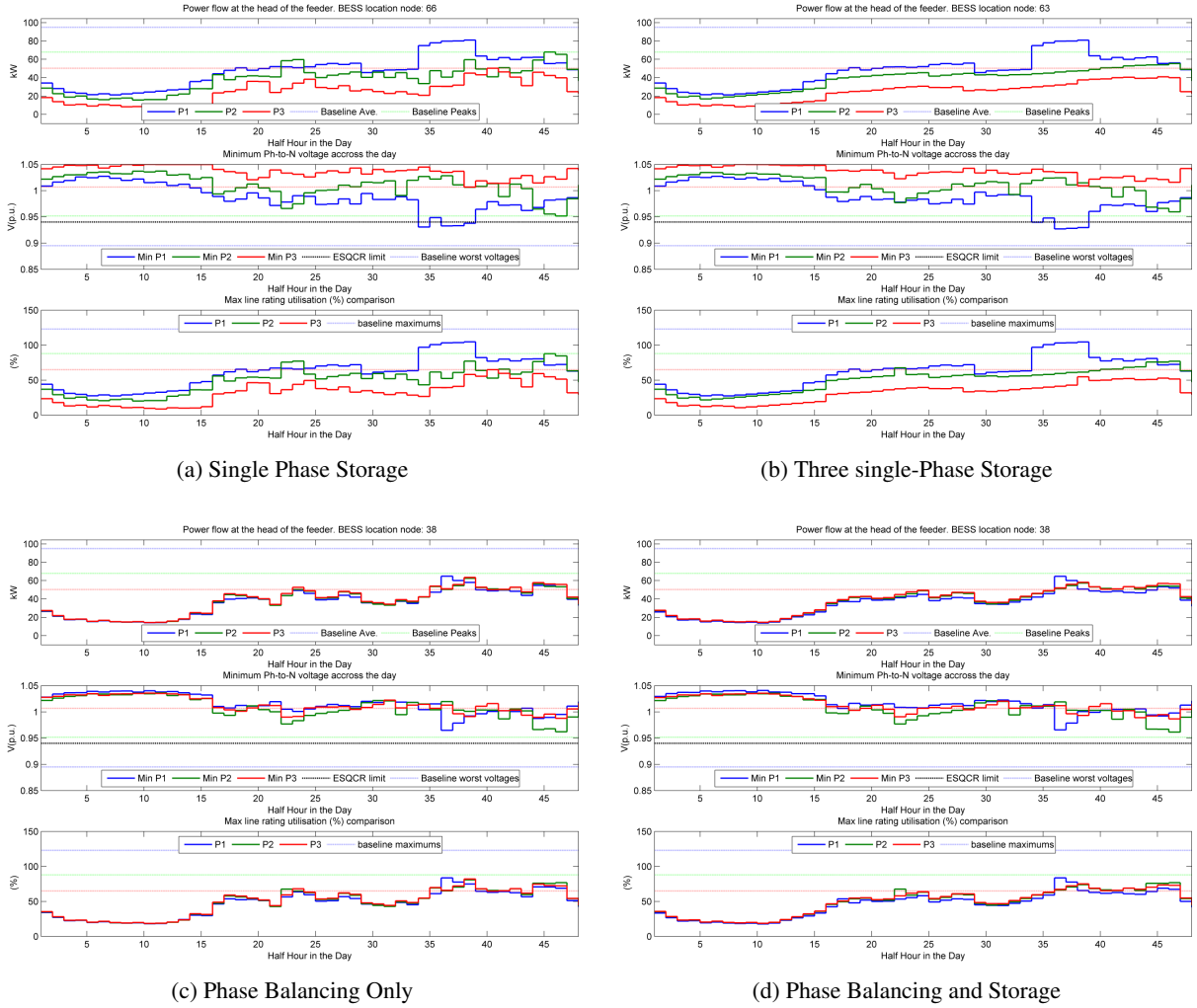


Figure 4: Comparison of losses, minimum voltage and line utilisation for Network 1

4.3.2. Network 2

With reference to Figure 6a, since network 2 is more balanced compared to network 1, pure phase balancing configuration does not perform as well as phase balancing with storage. At the time of highest demand, around 27th half hour of the day (see figure 5a and 5d), the loading on three phases is more or less equal. This balanced condition does not provide any margin for configuration 3 to provide peak reduction. The addition of storage capacity to phase balancing allows further reduce peak power demand on all three phases, hence further improving minimum voltage and losses.

5. Discussion

Previous sections covered the impact of each BESS configuration and its location on the network perfor-

mance. The metrics for evaluating the performance are based on voltage constraints, maximum line utilisation rating and total daily losses. Figure 6 summarises the impact of each BESS configuration on the networks if BESS is installed at the recommended locations given in table 2.

BESS configuration 1, single-phase storage rated to deal with 30% of the peak and located on the most loaded phase, have improved the network operation for both networks. However, the improvement is only evident on the phase the BESS is connected to and the constraints are not resolved: phase 1 voltage on network 1, phase 2 voltage on network 2, line utilisation on phase 1 network 1, and phase 2 on network 2.

BESS configuration 2, co-located three single-phase storage each rated to deal with 30% of the peak, also

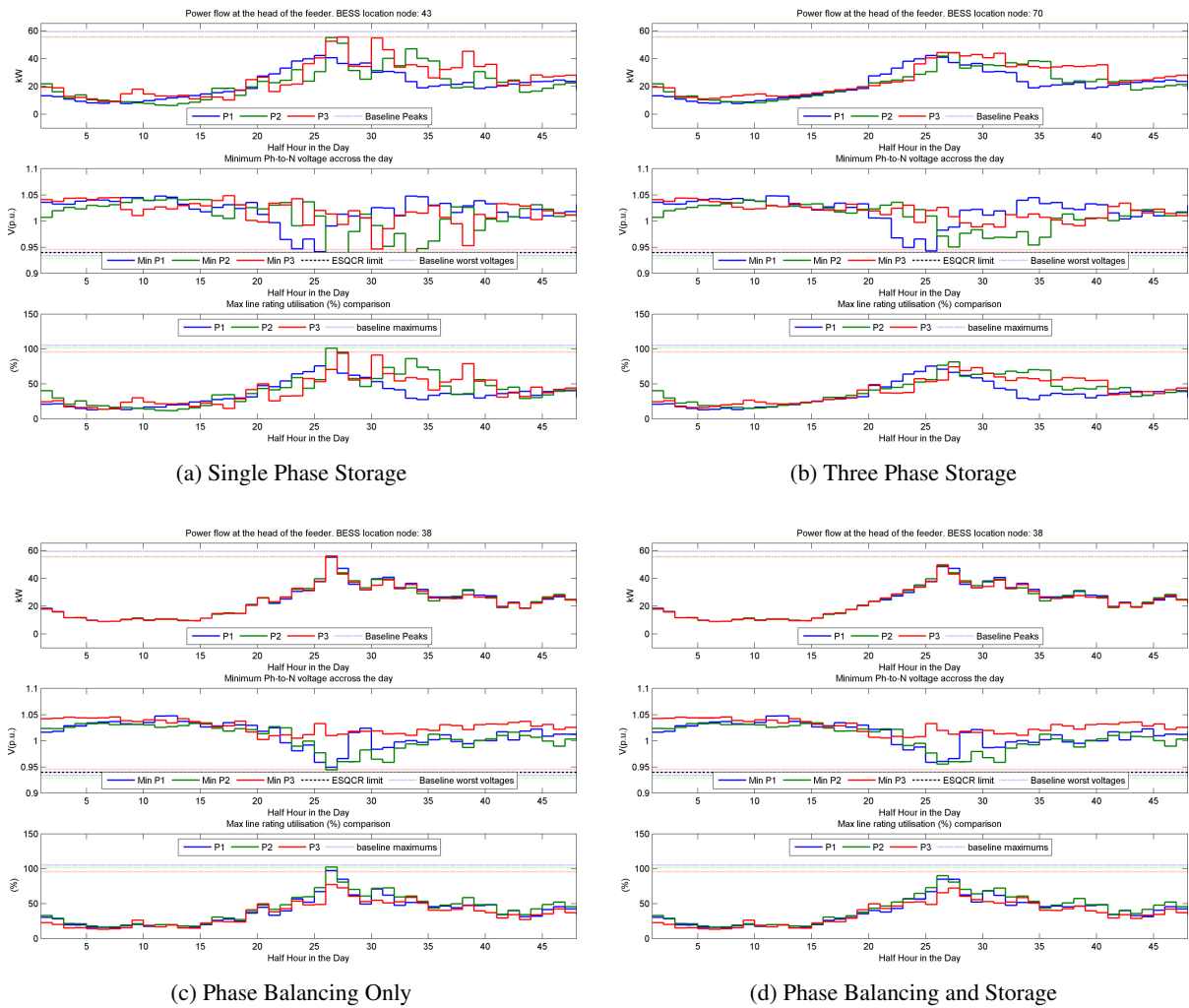


Figure 5: Comparison of losses, minimum voltage and line utilisation for Network 2

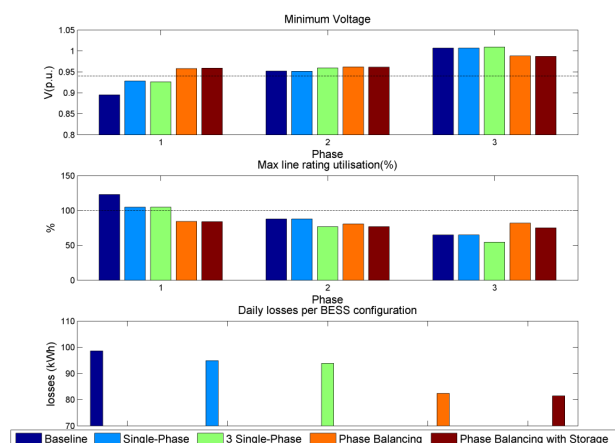
686 improved the network operation for both networks, but 702
 687 for network 1 not all constraints are resolved for phase 703
 688 1. Network 2, on the other hand, all constraints are res- 704
 689 solved and BESS configuration 2 achieved lowest daily 705
 690 losses. 706

691 Due to the unbalanced nature of network 1, phase- 707
 692 balancing configurations of BESS have sufficiently im- 708
 693 proved network operation to alleviate voltage and 709
 694 thermal constraints as well as achieve significantly lower 710
 695 losses. The addition of storage to the phase-balancing 711
 696 power electronics provides greater reduction in thermal 712
 697 constraints and losses. 713

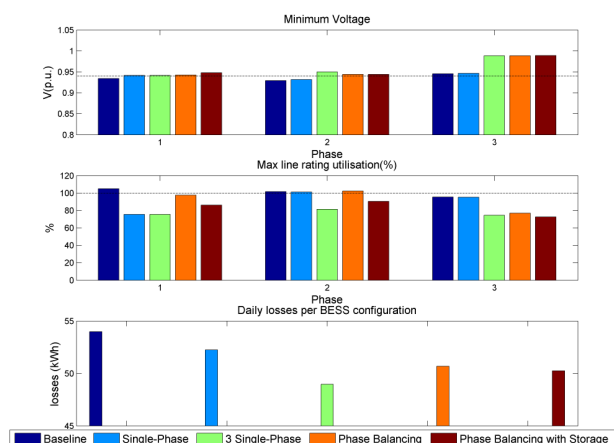
698 Network 2, however, is more balanced and three- 714
 699 phase BESS configurations do not have the same ef- 715
 700 fect as on network 1. A purely phase balancing solu- 716
 701 tion does not resolve thermal constraints on phases 1 717

and 2. However, the addition of storage sized to deal 702
 with 30% of a peak on the heaviest phase achieves sim- 703
 ilar performance in thermal constraint management as 704
 the three single-phase BESS configuration, with three 705
 times as much of storage capacity and hence cost. 706

The best location of the BESS is governed by the 707
 BESS configuration aligned with the structure of the 708
 network and customer behaviour. Intuitively, the great- 709
 est impact on voltages occurs when the storage is lo- 710
 cated nearest to the nodes with worst voltage drop, 711
 which is true for single-phase storage (see Figure 1a and 712
 1b, location A). By incorporating phase-balancing, the 713
 best location for a BESS moves towards the top of the 714
 branch due to the influence of lower losses caused by 715
 supplying more balanced voltages to a greater number of 716
 customers. 717



(a) Comparison of minimum voltage, maximum cable loading and losses per BESS configuration for network 1



(b) Comparison of minimum voltage, maximum cable loading and losses per BESS configuration for network 2

Figure 6: Summary of the impact of BESS locations.

718 Clearly the extent of the network unbalance influ- 748
 719 ences the requirements on the BESS and in cases such 749
 720 as described above, phase balancing operation appears 750
 721 to have most value. However, the fact that phase bal- 751
 722 ancing increases load on weaker phases introduces the 752
 723 potential for additional problems to be introduced. Yet, 753
 724 additional load on the weaker phases can be mitigated 754
 725 by including an energy storage device in combination 755
 726 with phase balancing. Comparison of the configurations 756
 727 above shows that for the given networks, similar perfor- 757
 728 mance can be achieved with a third of a storage capacity 758
 729 compared to three single-phase BESS configuration. 759

730 6. Conclusions

731 This paper has presented an impact assessment of 763
 732 Battery Energy Storage Systems (BESS) configuration 764
 733 and location on the Operation of LV feeders. Two 765
 734 real UK urban networks LV feeders, with unbalanced 766
 735 and balanced customer connection, were analysed un- 767
 736 der worst case winter demand from real domestic pro- 768
 737 files. The main goal of the BESS that was trialled in to 769
 738 the two networks was to reduce peak-demand, although 770
 739 performance was assessed in terms of losses, voltage 771
 740 and line utilisation. Four BESS configurations, with as- 772
 741 sociated control algorithms, were considered: a single- 773
 742 phase BESS unit, three single-phase co-located storage 774
 743 units, three-phase power electronics unit without stor- 775
 744 age, and a three-phase BESS unit with storage. 776

745 These BESS configurations were trialled at each node 777
 746 in the two networks in order to determine the impact of 778
 747 the location and configuration of the BESS on peak re- 779

duction, voltage, losses and line utilisation. For both 748
 networks, the best locations for each BESS configura- 749
 tion followed a similar pattern: single phase solutions 750
 were most beneficial if placed on the branch with lowest 751
 phase voltage, and for phase-balancing configurations, 752
 the best location tended to the top of branches. 753

754 Even at the best location, single-phase configurations 754
 755 rated at 30% of the peak half-hourly demand did not 755
 756 resolve voltage and thermal constraints for the unbal- 756
 757 anced network 1. In contrast, phase-balancing solu- 757
 758 tions, placed at a top of two branches within this unbal- 758
 759 anced network were shown to balance the power flow 759
 760 across phases and significantly improved network oper- 760
 761 ation, resolving all voltage and thermal issues. 761

762 For Network 2, being more balanced, the pure phase- 762
 763 balancing configuration did not provide the required im- 763
 764 provement. Voltage and thermal issues were only re- 764
 765 solved by placing three single-phase BESS or phase- 765
 766 balancing with storage; the storage was essential to mit- 766
 767 igating peak demand that was synchronised across all 767
 768 phases. However, the required energy storage capac- 768
 769 ity of the phase-balancing and storage configuration was 769
 770 shown to be only a third of the three single-phase stor- 770
 771 age units. 771

772 Fundamentally, this work and results presented in this 772
 773 paper has demonstrated that the location and configura- 773
 774 tion of a BESS has a significant impact on the resulting 774
 775 impact the BESS has on the local network. Key obser- 775
 776 vations are that for an unbalanced network, the most 776
 777 cost effective solution may be to deploy either a single- 777
 778 phase BESS or a power-electronic system without stor- 778
 779 age. On balanced networks, a three-phase BESS can be 779

780 configured with less storage capacity than single-phase
781 BESS and achieve the same or better performance.

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