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Value of corrective network security for distributed energy storage applications

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Abstract: Energy storage can provide services to several sectors in electricity industry, including generation, transmission and distribution, where conflicts and synergies may arise when storage is used to manage network congestion and provide services in energy and balancing markets. In this context, this study proposes an optimisation model to coordinate multiple services delivered to various market participants that uses corrective actions to resolve conflicts between provision of distribution network services (e.g. congestion and security of supply) and other services. The model maximises storage profit by scheduling active and reactive power to provide portfolio of services including distribution network congestion management, energy price arbitrage, frequency response and reserve services remunerated at different prices. The authors demonstrate that adopting corrective security to provide network services and deal with network congestion in a post-fault fashion, is overall more beneficial despite the energy needed to be stored during pre-fault conditions for applying post-contingency actions right after a network fault occurs. Furthermore, the authors' analysis shows that application of corrective security can benefit both (i) storage owners through increased revenues in energy and balancing services markets and (ii) Distribution Network Operators through reduction in payments to storage owners and increased utilisation of network infrastructure.

Nomenclature

Parameters (in normal font)

$\bar{C}^{\mathrm{S}}$	storage maximum charging capacity [MW]
$\bar{D}^{\mathrm{S}}$	storage maximum discharging capacity [MW]
d	duration of standardised period [h]
$\bar{E}$	storage maximum energy capacity [MWh]
E_t^{E}	energy excess for security of supply at period t [MWh]
P_t^{D}	active power demand from distribution network at period t [MW]
Q_t^{D}	reactive power demand from distribution network at period t [MVAr]
M	auxiliary large number used for endogenous constraints relaxation
S^N	installed apparent power capacity of primary substation [MVA]
$\bar{S}^N$	secured apparent power capacity of primary substation ($N-1$ limit) [MVA]
$\bar{S}^{\mathrm{S}}$	storage maximum apparent power capacity [MVA]
α, α'	binary parameters to increase robustness of corrective security mode
β^{Dw}	parameter to detect provision of simultaneous downwards balancing services $\beta^{\mathrm{Dw}} \in [1, 2[$, e.g. $\beta^{\mathrm{Dw}} = 1.5$
β^{Up}	parameter to detect provision of simultaneous upwards balancing services $\beta^{\mathrm{Up}} \in [1, 2[$, e.g. $\beta^{\mathrm{Up}} = 1.5$
δ	parameter used for linearisation of non-linear but convex power constraint
η	storage roundtrip efficiency [%]
π_t^{E}	energy price at period t [£/MWh]
$\pi_t^{\mathrm{Dw.Rese}}$	availability price for downwards reserve at period t [£/MW/h]
$\pi_t^{\mathrm{Dw.Resp}}$	availability price for downwards frequency response at period t [£/MW/h]
$\pi_t^{\mathrm{Up.Rese}}$	availability price for upwards reserve at period t [£/MW/h]
$\pi_t^{\mathrm{Up.Resp}}$	availability price for upwards frequency response at period t [£/MW/h]
τ^{Rese}	reserve maximum utilisation time [h]
τ^{Resp}	frequency response maximum utilisation time [h]

Variables

C_t^{S}	storage charging output at period t [MW]
D_t^{S}	storage discharging output at period t [MW]
E_t	storage energy at period t [MWh]
P_t^N	active power through primary substation at period t [MW]
P_t^{S}	storage scheduled active power output at period t [MW]
Q_t^N	reactive power through primary substation at period t [MVAr]
Q_t^{S}	storage scheduled reactive power output at period t [MVAr]
$\mathrm{Rese}_t^{\mathrm{Dw}}$	downwards reserve commitment at period t [MW]
$\mathrm{Rese}_t^{\mathrm{Up}}$	upwards reserve commitment at period t [MW]
$\mathrm{Resp}_t^{\mathrm{Dw}}$	downwards frequency response commitment at period t [MW]
$\mathrm{Resp}_t^{\mathrm{Up}}$	upwards frequency response commitment at period t [MW]
$X_t^{\mathrm{Dw.Rese}}$	storage commitment status for downwards reserve at period t: 1 if committed, 0 otherwise
$X_t^{\mathrm{Dw.Resp}}$	storage commitment status for downwards frequency response at period t: 1 if committed, 0 otherwise
$X_t^{\mathrm{Dw.R\&R}}$	storage commitment status for simultaneous downwards frequency response and reserve at period t: 1 if committed, 0 otherwise
$X_t^{\mathrm{Up.Rese}}$	storage commitment status for upwards reserve at period t: 1 if committed, 0 otherwise

$X_t^{\text{Up.Resp}}$ storage commitment status for upwards frequency response at period t: 1 if committed, 0 otherwise

$X_t^{\text{Up.R\&R}}$ storage commitment status for simultaneous upwards frequency response and reserve at period t: 1 if committed, 0 otherwise

Sets

T set of operating periods

Δ set of discrete power values for linearisation of $P^2 + Q^2 \le S^2$

1 Introduction

1.1 Motivation

Energy storage technologies have the potential to support future system integration of low-carbon generation and electrification of segments of heat and transport industries, through provision of multiple services to electricity markets that can facilitate more efficient and secured operation and investment in electricity infrastructure. In this context, energy storage can bring benefits to several sectors in electricity industry, including generation, transmission and distribution, while providing services to support balancing of demand and supply, network congestion management and reduce the need for investment in system reinforcement.

These benefits may increase if real-time corrective control is applied to resolve the conflicts arising between distribution network services and other applications of storage plant. For example, rather than using energy storage to limit power transfers through network infrastructure during pre-fault to comply with $N - k$ security limits and thus provide security of supply in a preventive fashion, utilisation of network infrastructure can be increased provided that post-contingency control is applied to reduce power transfers right after a fault occurs and thus provide security of supply potentially more efficiently. Hence a corrective (rather than preventive) control strategy may allow storage to charge and discharge more freely during pre-fault conditions without compromising the levels of security of supply and enhancing the value of energy storage delivered to all market participants. It is not clear, however, to what extent the provision of corrective control in supporting network security can effectively resolve the conflicts between distribution network services and further applications of energy storage since there are energy levels needed to be maintained in storage plant during pre-fault conditions for applying post-contingency actions right after a network fault occurs and this may constrain the value of storage.

1.2 Literature review and contribution

A number of optimisation models for storage plant applications have been reported in the literature [1–20]. Models developed in [1–8] identified and valued the benefits of energy storage for network support, and in particular [5–8] recognised the importance of storage plant in providing peak shaving services and deferring network reinforcements. Optimisation models for further applications of storage plant have also been reported: the authors [9–12] analysed the value and ability of storage to provide price arbitrage services in the energy market; the authors [13–15] optimised storage operation to facilitate integration of renewable generation; and the authors [16–18] presented models to support system operation by managing imbalances and providing frequency control services.

Further studies have identified the potential of storage plant to provide simultaneous services to several electricity markets, such as energy and balancing services markets [18, 19]. Recently, Moreno *et al.* [20] proposes a mixed-integer linear programing (MILP) model to schedule operation of distributed storage by coordinating provision of a range of system services rewarded at different market prices. The model maximises distributed storage's profit while providing distribution network congestion management, energy price arbitrage and various reserve and frequency regulation services through both active and reactive power controls.

In this context, this paper expands on the MILP model for optimising multi-service portfolios of distributed energy storage presented in [20] and introduces a corrective control mode of operation for provision of distribution network congestion management or peak demand shaving service to Distribution Network Operators (DNOs). As explained in [21–25], corrective control can be used to provide network services through post-contingency remedial actions and thus reduce power transfers right after a fault occurs (rather than reducing power transfers in a preventive mode as done in [20]). Hence we demonstrate that adopting corrective security to provide network services and deal with network congestion in a post-fault fashion, is overall more beneficial despite the levels of energy needed to be maintained in storage plant during pre-fault conditions for applying post-contingency actions right after a network fault occurs. Furthermore, our analysis shows that application of corrective security can benefit both (i) storage plant owners through increased revenues in energy and balancing services markets and (ii) DNOs through reduction in payments to storage owners (for provision of post-fault peak demand shaving service) and increased utilisation of network infrastructure.

This paper is organised as follows: Section 2 develops the proposed 'storage centric' approach for profit-maximisation operation of energy storage through corrective security. Section 3 presents and discusses our main results for a real-storage plant located within the region of UK Power Networks, London, UK. Finally, Section 4 concludes the paper.

2 Description of the proposed optimisation model: storage plant operation with corrective security

This paper expands on the MILP model for optimising multi-service portfolios of distributed energy storage presented in [20] and introduces the concept of corrective security for the provision of peak demand shaving service to DNO. Hence the model proposed in this paper is used to optimise storage plant schedules that consider post-contingency (corrective) control right after a distribution network fault occurs, which are compared against preventive control storage plant operations. Main features of our proposed optimisation model are detailed next, where we emphasise representation of corrective security. Further features and constraints together with an alternative model to schedule storage plant outputs under preventive security (originally proposed in [20]) can be found in the Appendix.

2.1 Overview

The model proposed in this paper determines scheduled operation of storage plant connected to a distribution network with co-optimising multiple services delivered to various market participants. Multi-service coordination aims at maximising storage plant's revenues and is sensitive to market and system conditions such as prices of energy and frequency control services, and demand levels at the primary substation. The unique feature of the model proposed in this paper is its ability to provide DNO service in a corrective control mode, allowing net substation load to exceed $N - 1$ security limit as long as storage plant maintains sufficient margin to respond in real-time against a fault in a substation's transformer or line.

A scheme of the storage represented in the model is depicted in Fig. 1.

The analysis comprises the following services:

- *Energy arbitrage*, which is undertaken by charging storage during low price periods and discharging during periods with higher prices.
- *System balancing services*. Storage plant can additionally provide various system balancing services that include several types of

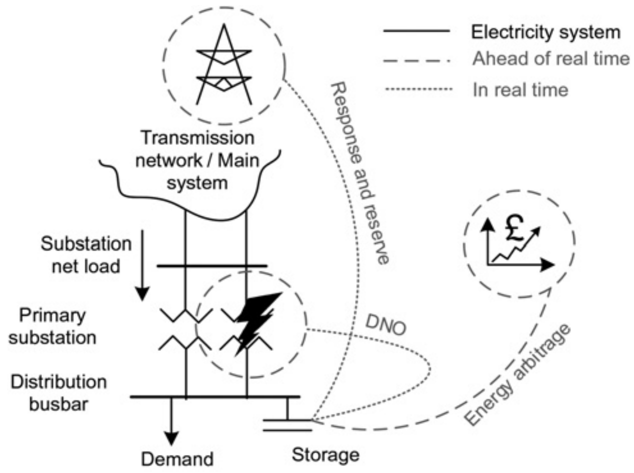

Fig. 1 *Electricity system and services provided by distributed energy storage*

frequency response applications and short-term operating reserve. In particular, we model:

- Upwards and downwards reserve.
- Upwards and downwards frequency response.

Reserve and frequency response services are differentiated by the time they are provided during the day (while frequency response services are typically required in the morning, reserve services are used in the afternoon) and duration of the real-time action (frequency response is delivered very fast and during a short-time period, while reserve is related to demand–supply balancing over longer timescales).

- *DNO service through corrective security*. Storage plant can also provide peak demand shaving through active and reactive power in post-fault conditions right after a distribution network fault occurs (rather than pre-fault like in preventive mode) in order to avoid network overloads.

In contrast to the preventive control framework for provision of DNO service presented in [20] that secures substation operation by limiting its net load to the $N-1$ capacity limit, the model proposed in this paper considers the possibility of net substation's load to exceed the $N-1$ capacity limit. When doing so, the model ensures that sufficient energy is maintained in the storage plant in case a transformer or a line outage occurs. Hence corrective control mode can ensure same levels of security of supply as a preventive control mode does. Furthermore, the model fundamentally allows storage to determine an optimum balance between preventive (e.g. constraining net substation's load) and corrective control actions (e.g. maintaining sufficient energy in the storage plant in case an outage occurs when net substation's load is beyond the $N-1$ limit), taking advantage of flexibility of storage operation to rapidly change real-time outputs and hence enhancing value of energy storage.

2.2 Optimisation model

2.2.1 Objective function: The model's objective function maximises storage plant's net revenues associated with energy arbitrage and balancing services such as provision of frequency response and reserve services. Balancing services' revenues are determined based on storage plant's scheduled output rather than real-time output, and hence revenue of a system balancing service (upwards and downwards frequency responses and reserves) in a given period is equal to the multiplication of the committed capacity margin, the associated price, and the period duration. Similarly, energy arbitrage revenue in a given period is equal to the multiplication of bought or sold energy (power times duration) and the associated energy price of that period, according to scheduled output. All revenues are summed across various periods (through a month or season) and this is shown in (1). DNO service's revenue is not considered in (1) and this is determined through sensitivity analysis on distribution network capacity which is explained in Section 3.4.2.

2.2.2 DNO service constraints with corrective security: With corrective security, substation capacity S^N used to limit power transfers in (2) corresponds to (post-contingency, short-term emergency) transformers' nameplate ratings rather than the $N-1$ secured capacity used under preventive security mode [(11) in Appendix]. Note that local demand P_t^{D} is unlikely to exceed total substation installed capacity S^N and therefore storage output is unlikely to reduce DNO peak demands during pre-fault conditions (due to substation overloads), which is fundamentally different to energy storage operation with preventive security

$$\left(P_t^N\right)^2+\left(Q_t^N\right)^2\leq\left(S^N\right)^2\quad\forall t\in T\tag{2}$$

If a fault occurs, however, storage output will be rapidly increased to reduce peak demand down to substation's $N-1$ security limit. To do so, storage plant should maintain sufficient energy stored so as to, if a fault occurs, supply the energy associated with upcoming peak demands and this is ensured by the following equation

$$E_{t-1}\geq E_t^{\mathrm{E}}\quad\forall t\in T\tag{3}$$

E_t^{E}, namely energy excess or surplus, is the energy associated with peak demands above the $N-1$ security limit from period t onwards and therefore that needs to be supplied by storage plant if a substation fault occurs. Calculation of E_t^{E} (which is a parameter) also considers that there may be multiple peak demands within a day and so that storage can charge while demand is below the substation secured capacity and this is illustrated in Figs. 2*a* and *b*.

Note that none of the two operating modes (preventive or corrective security) will be able to provide DNO service if local demand exceeds substation $N-1$ security limit by more than the storage maximum discharge capacity (in terms of both power and energy).

2.2.3 Constraints for system balancing services: In a multi-service framework, it is critical to ensure that storage scheduled outputs are robust and can be adapted in real-time to deliver the services contracted in advance. In this context, (4)–(6) ensure real-time deliverability of downwards balancing services even if substation capacity is reduced due to a fault ($\alpha=1$). Alternatively, it can be assumed that most of the time real-time net substation load could be allowed to go beyond its $N-1$ security limit when storage provides a downwards balancing service, provided that storage output will be increased – if a fault occurs ($\alpha=0$).

$$\left(P_t^N+\mathrm{Rese}_t^{\mathrm{Dw}}\right)^2+\left(Q_t^N\right)^2\leq\left(\alpha\cdot\bar{S}^N+(1-\alpha)\cdot S^N\right)^2+M\cdot\left(1-X_t^{\mathrm{Dw.Rese}}\right)\quad\forall t\in T\tag{4}$$

$$\mathrm{Max}\left\{\sum_{t\in T}\left[P_t^{\mathrm{S}}\cdot\pi_t^{\mathrm{E}}+\mathrm{Rese}_t^{\mathrm{Up}}\cdot\pi_t^{\mathrm{Up.Rese}}+\mathrm{Rese}_t^{\mathrm{Dw}}\cdot\pi_t^{\mathrm{Dw.Rese}}+\mathrm{Resp}_t^{\mathrm{Up}}\cdot\pi_t^{\mathrm{Up.Resp}}+\mathrm{Resp}_t^{\mathrm{Dw}}\cdot\pi_t^{\mathrm{Dw.Resp}}\right]\cdot d\right\}\tag{1}$$

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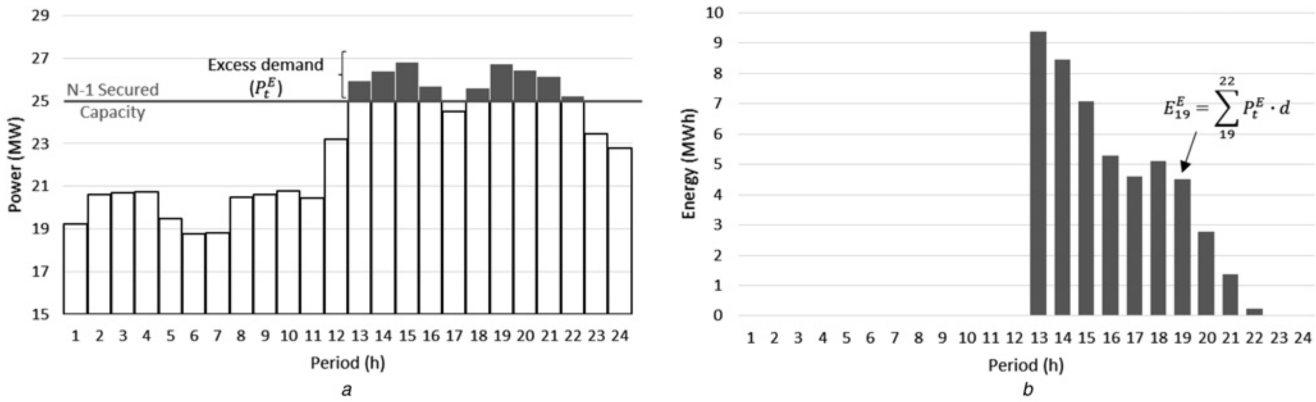

Fig. 2 *Illustrative example for determining excess demand parameter (E_t^E)*
a Local demand and demand excess or surplus in a day
b Energy required (at every period *t*) to exercise DNO service in post-fault conditions

$$\left(P_t^N + \mathrm{Resp}_t^{\mathrm{Dw}}\right)^2 + \left(Q_t^N\right)^2 \le \left(\alpha \cdot \bar{S}^N + (1-\alpha)\cdot S^N\right)^2 + M \cdot (1 - X_t^{\mathrm{Dw.Resp}}) \quad \forall t \in T \qquad (5)$$

$$\left(P_t^N + \mathrm{Rese}_t^{\mathrm{Dw}} + \mathrm{Resp}_t^{\mathrm{Dw}}\right)^2 + \left(Q_t^N\right)^2 \le \left(\alpha \cdot \bar{S}^N + (1-\alpha)\cdot S^N\right)^2 + M \cdot (1 - X_t^{\mathrm{Dw.R\&R}}) \quad \forall t \in T \qquad (6)$$

Note that if a balancing service is not contracted or committed, upper bound of the associated constraint [in (4)–(6)] will become a very large number (M), relaxing the optimisation problem.

Likewise, (7)–(9) ensure robustness of scheduled outputs against multiple potential real-time operating conditions by maintaining sufficient margins of energy stored if simultaneous services are exercised at the maximum contracted volumes (i.e. worst-case scenario optimisation). More robust solutions can be obtained when assuming that storage plant has to maintain sufficient energy to deliver all balancing and DNO services simultaneously and through independent post-contingency actions ($\alpha' = 1$). Alternatively, it can be assumed that a single post-contingency action could deliver both DNO and balancing services ($\alpha' = 0$) and thus (3), (7)–(9) will ensure that energy stored is sufficient to deliver the service with the most demanding energy requirements. For the sake of simplicity, we do not show (7)–(9) for downwards balancing services albeit they are modelled.

$$-M \cdot \left(1 - X_t^{\mathrm{Up.Rese}}\right) \le E_{t-1} - \left(P_t^S + \mathrm{Rese}_t^{\mathrm{Up}}\right) \cdot \tau^{\mathrm{Rese}} - \alpha' \cdot E_t^{\mathrm{E}} \le \bar{E} + M \cdot (1 - X_t^{\mathrm{Up.Rese}}) \quad \forall t \in T \qquad (7)$$

$$-M \cdot \left(1 - X_t^{\mathrm{Up.Resp}}\right) \le E_{t-1} - \left(P_t^{\mathrm{S}} + \mathrm{Resp}_t^{\mathrm{Up}}\right) \cdot \tau^{\mathrm{Resp}} - \alpha' \cdot E_t^{\mathrm{E}} \le \bar{E} + M \cdot (1 - X_t^{\mathrm{Up.Resp}}) \quad \forall t \in T \qquad (8)$$

$$-M \cdot \left(1 - X_t^{\mathrm{Up.R\&R}}\right) \le E_{t-1} - \left(P_t^{\mathrm{S}} + \mathrm{Rese}_t^{\mathrm{Up}}\right) \cdot \tau^{\mathrm{Rese}} - \mathrm{Resp}_t^{\mathrm{Up}} \cdot \tau^{\mathrm{Resp}} - \alpha' \cdot E_t^{\mathrm{E}} \le \bar{E} + M \cdot (1 - X_t^{\mathrm{Up.R\&R}}) \quad \forall t \in T \qquad (9)$$

Further constraints of the corrective security model can be found in Appendix and they refer to those that maintain the stored energy balance across time periods, keep power and energy of storage plant within its limits, ensure real-time deliverability of committed balancing services and model active and reactive power production, consumption and transfers. Description of the preventive security model can also be found in Appendix.

In the above formulation $\mathrm{Rese}_t^{\mathrm{Up}}$, $\mathrm{Rese}_t^{\mathrm{Dw}}$, $\mathrm{Resp}_t^{\mathrm{Up}}$, $\mathrm{Resp}_t^{\mathrm{Dw}}$ and E_t are positive decision variables, i.e. greater or equal to zero, and $X_t^{\mathrm{Up.Rese}}$, $X_t^{\mathrm{Dw.Rese}}$, $X_t^{\mathrm{Up.Resp}}$, $X_t^{\mathrm{Dw.Resp}}$, $X_t^{\mathrm{Up.R\&R}}$ and $X_t^{\mathrm{Dw.R\&R}}$ are binary variables.

2.2.4 Further modelling considerations:

Prescribed windows for the provision of balancing services: Committed volumes of balancing services are assumed to be constant within a prescribed time window. For example, if a prescribed time window is defined between 16:00 and 21:00 h for a given balancing service, its committed volume (e.g. 3 MW) must remain constant during the whole window. Thus we added additional constraints to the above model in order to ensure that balancing services can only be provided in certain hours of the day (within the prescribed windows) and its provision must remain constant throughout the window.

Linearisation: The model in this paper optimises active and reactive powers and hence is clearly non-linear [see (2), (4)–(6)]; therefore we use the same technique illustrated in [20] that fundamentally determines a set of tangent planes over a bounded convex region (i.e. described by $P^2 + Q^2 \le S^2$) to linearise the problem and solve it through a commercial optimisation suite such as FICO® Xpress [26], which applies branch and bound algorithm to solve the proposed MILP model.

3 Results and discussion

3.1 Input data

Energy prices and distributed local demand at the level of primary substation from real Great Britain (GB) time series with hourly resolution are used in this paper to optimise energy storage operation. Monthly profiles for energy prices and demand were considered in order to account for credible operating and market conditions in the GB market. Figs. 3*a* and *b* show energy prices and demand profiles for a typical week in winter and summer.

Figs. 4*a* and *b* show histogram of energy prices and load duration curve of local demand, respectively, for a month in winter and summer.

In this paper, we assume a maximum duration to exercise upwards and downwards reserves and frequency response services up to 2 h and 30 min, respectively, (i.e. $\tau^{\mathrm{Rese}} = 2$ h and $\tau^{\mathrm{Resp}} = 0.5$ h). Following actual practices observed for the provision of balancing services in GB, we define the prescribed window for frequency response in the morning between 4:00 and 8:00 h. For reserve services, we define a prescribed window in the evening from 19:00 to 22:00 h during April–August, and from 16:00 to 21:00 h during September–March. Availability prices to remunerate provision of balancing services are assumed as follows:

- Up and down reserve: 6 £/MW/h
- Up and down response: 7 £/MW/h

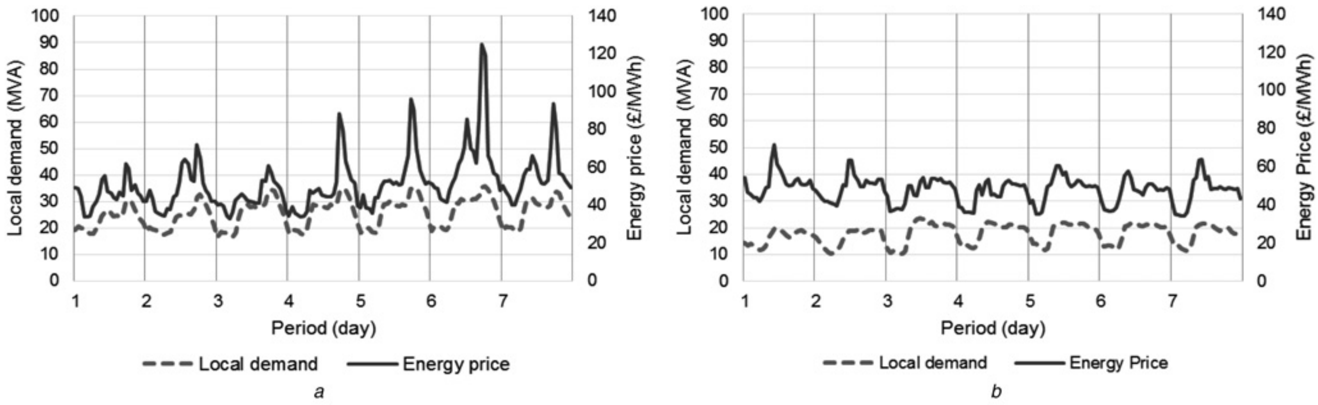

Fig. 3 *Energy price and local demand profiles during a typical week in*

a Winter
b Summer

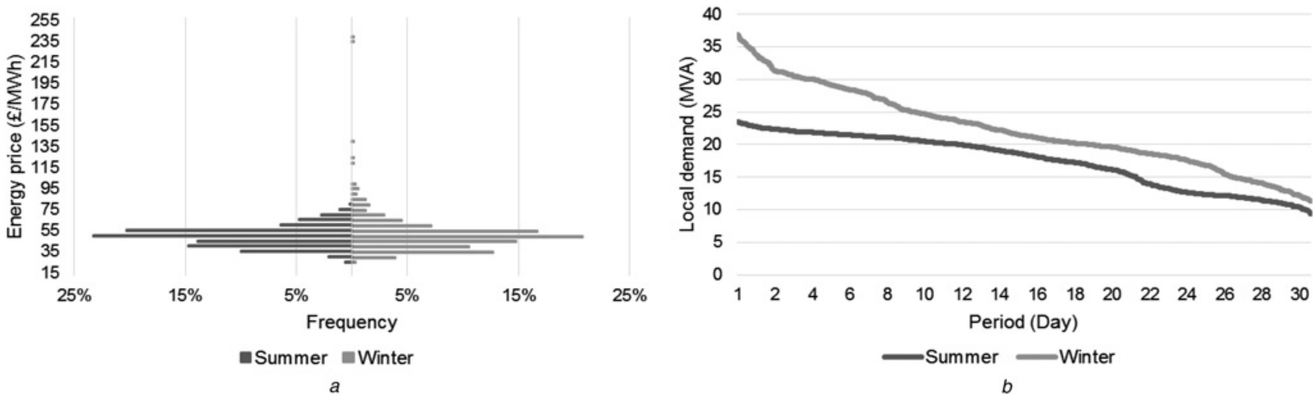

Fig. 4 *Characteristics of input data associated with energy prices and local demand*

a Histogram of energy prices in a month during summer and winter
b Load duration curve in a month for summer and winter

Storage power and energy capacities, efficiency and substation capacity ratings are assumed as follows:

- Storage power and energy capacities: 6 MW, 7.5 MVA and 10 MWh.
- Storage roundtrip efficiency: 95%.
- Primary substation's transformer (short-term emergency) rating: 2×31.9 MVA (which is derated in summer up to 70%). Transformer short-term emergency rating takes into account a 20% overload factor with respect to long-term rating. The maximum recommended duration of the overload is assumed to be sufficiently long (considering that on average local demand before overload in pre-fault conditions is below 60% of transformer long-term rating) to provide post-fault peak shaving or, if necessary, deploy further remedial actions (e.g. network reconfiguration, various forms of demand response etc.) that may be needed irrespective of the operating mode of storage plant (preventive or corrective), and this is beyond the scope of this paper.

The characteristics of this particular storage plant are those of a real plant installed at Leighton Buzzard substation in London (owned by UK Power Networks). Note that larger apparent power capacity is associated with the ability of storage plant to provide reactive power support, even at full active power output (that can be driven by high energy prices, and exercise of balancing and DNO services). Both this paper and our previous work explained in [20], co-optimise active and reactive power controls.

3.2 Storage operation with corrective network security in a day

This section presents a set of results, all for the day shown in Fig. 5 (observed in a real GB distribution network substation), which will be used to compare storage operation under preventive and corrective security modes. This section also serves to validate our model and show its main features.

3.2.1 Optimised storage scheduled output with corrective network security: Fig. 6 shows the storage scheduled operation when providing multiple services and its effect on net substation load under (a) preventive and (b) corrective network security mode.

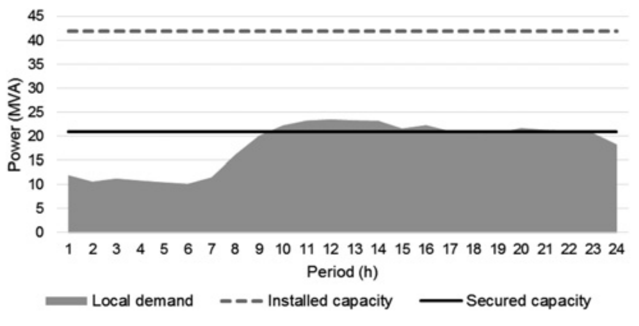

Fig. 5 *Local demand, substation installed and $N-1$ secured capacity (during summer)*

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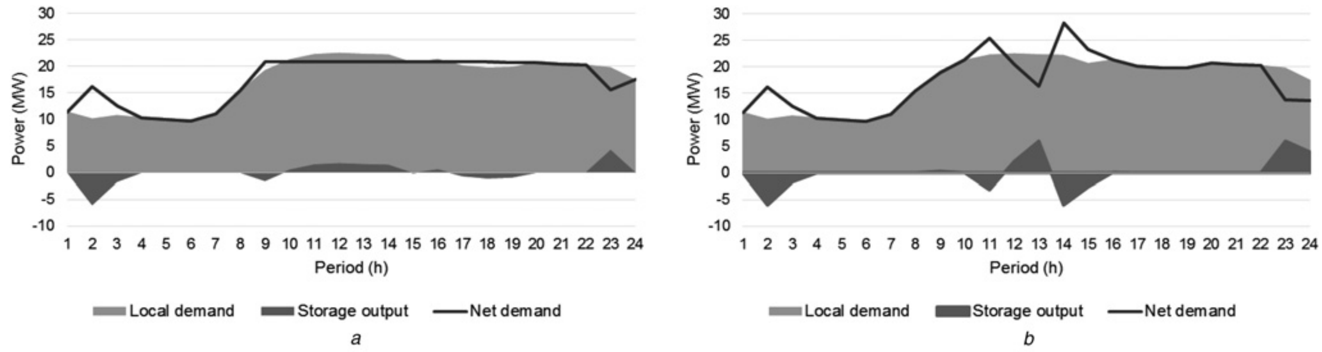

Fig. 6 *Storage scheduled operation, local and net demand with*
a Preventive network security
b Corrective network security

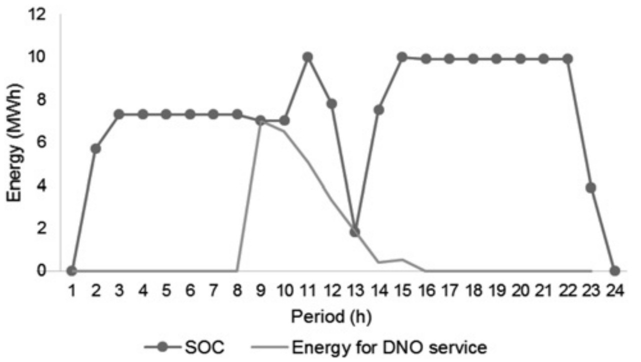

Fig. 7 *Storage SOC and levels of energy required to deliver DNO service in post-contingency conditions*

Fig. 6*a* clearly shows that storage operation is constrained to discharge and provide peak demand shaving services to the DNO (from period 10:00 to 16:00 h) in a preventive fashion to maintain net substation load below its secured capacity limit. Fig. 6*b*, in contrast, shows that storage scheduled output is not constrained to maintain net substation load below its $N-1$ security limit. Moreover, note that in Fig. 6*b* storage plant even charges at maximum output during peak demand. Next, we will analyse deliverability of DNO service in real-time and economic efficiency of storage plant's scheduled outputs in energy and balancing services markets.

3.2.2 Deliverability of DNO service and security of supply: Although Fig. 6*b* shows that net substation load can be above its $N-1$ security limit since storage is not constrained to discharge during peak demand, we can demonstrate that network operation is still $N-1$ secured. Indeed, Fig. 7 shows that energy stored in the storage plant is above the levels needed to supply peak demand surplus (i.e. the proportion of demand beyond $N-1$ security limit) at all times. This means that sufficient energy is stored to adapt storage output in real time if a network outage occurs and so discharge during peak demand in order to decrease substation load down to the capacity of the remaining infrastructure.

Furthermore, Fig. 8 illustrates scheduled and real-time storage output (Figs. 8*a* and *c*) and the state of charge (SOC) (Figs. 8*b* and *d*) under two possible network contingencies. Figs. 8*a* and *b* show scheduled and real-time operation when a network contingency occurs at 10:00 h (which will require large amounts of energy stored to discharge and supply demand peak surplus beyond the $N-1$ security limit between 10:00 and 16:00 h); and Figs. 8*c* and *d* show scheduled and real-time operation when a contingency occurs at 14:00 h (when net substation load is maximum). Hence Fig. 8 clearly illustrates that the model determines robust scheduled outputs that can deliver DNO service through efficient corrective control actions, while maximising pre-fault revenues without being constrained to derate net substation load.

3.2.3 Increased energy arbitrage revenue through corrective security: Corrective network security allows storage to charge and discharge more freely without compromising the levels of security of supply and increase revenue in energy market. In this context, Fig. 9*a* shows storage operation under preventive and corrective security mode and Fig. 9*b* presents the associated revenues due to energy arbitrage actions. Interestingly, under corrective security mode, arbitrage opportunities arise where storage needs to charge and discharge while local demand is high. These opportunities cannot be taken under a preventive security mode since charging storage at high demand periods is clearly problematic.

3.2.4 Increased balancing services revenues through corrective security: As shown in Fig. 10, storage plant under corrective security mode may also provide higher volumes of balancing services to system operator and thus collect higher revenues. Fig. 10*a*, for example, shows that storage can provide limited upwards reserve service since its energy stored has been importantly reduced earlier after providing (pre-fault) DNO peak demand shaving services. On the other hand, Fig. 10*b* shows higher provision of upwards reserve service (increase from 2.1 to 5.0 MW) since there is no need to discharge storage plant during peak demand (if a network outage does not occur) which results in higher levels of energy stored for the subsequent reserve period.

3.3 Value of storage capacity and impacts of local demand profiles

We calculate total daily revenues of storage plant under various (local) demand conditions aiming to determine the value of power and energy capacity of storage plant under different demand profiles. In this context, (i) Fig. 11 shows five profiles of local demand, ranging from more constant ($\lambda = 1$) to more variable and spiky demand profile ($\lambda = 5$), that comprise same levels of energy volumes; and (ii) Figs. 12*a* and *b* present total daily revenues (associated with provision of energy and balancing services) when either storage plant energy or power capacity is increased.

Fig. 12 shows that extra power capacity (e.g. +1 MW) presents a larger impact on storage revenue than extra energy capacity (e.g. +1 MWh) irrespective of (local) demand profile, and this is so because applications that are more capacity intensive (rather than energy intensive), such as frequency response services, are significantly more profitable (details of profitability of different services are studied in the following section). Fig. 12 also shows that spiky profiles of local demand cause revenue losses (i.e. less revenue) in energy and balancing services markets since more storage plant capacity will need to be utilised to provide DNO services, albeit – in principle – such revenue loss will need to be compensated

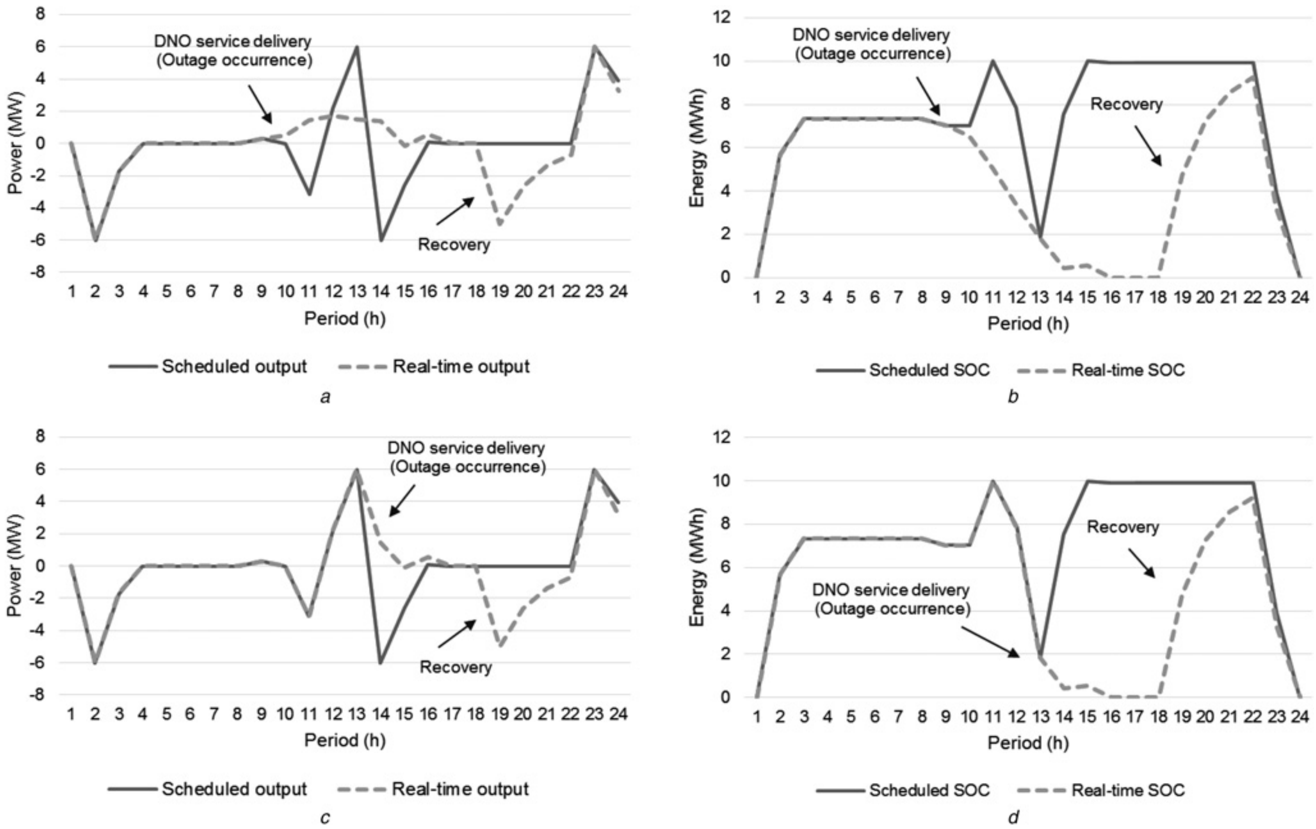

Fig. 8 *Storage plant scheduled and a potential real-time operation*

a Power output for a contingency at 10:00 h
b SOC for a contingency at 10:00 h
c Power output for a contingency at 14:00 h
d SOC for a contingency at 14:00 h

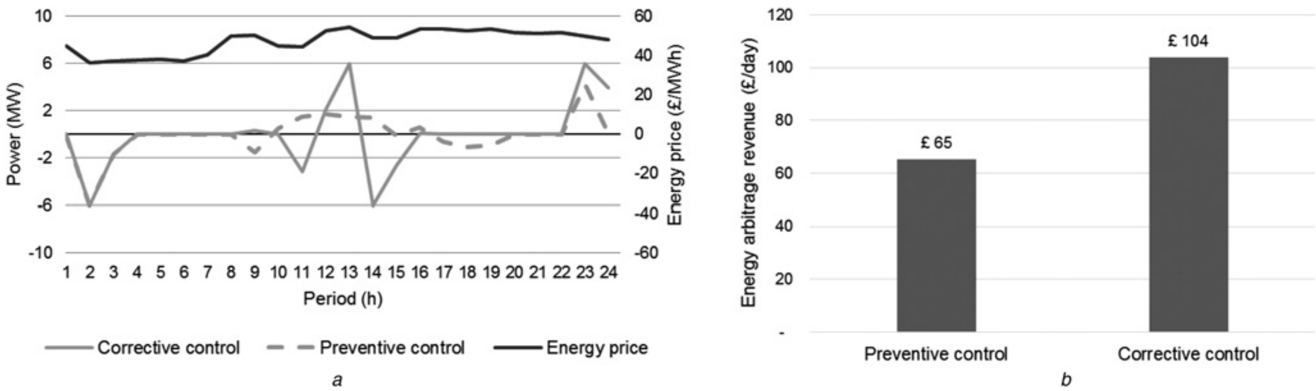

Fig. 9 *Comparison between preventive and corrective security modes*

a Storage output with preventive and corrective security and energy prices
b Revenue associated with energy arbitrage activity under preventive and security modes

through DNO payments (these payments will be further explored in Section 3.4.2). Finally, value of (extra) energy capacity is smaller when demand presents a more constant profile, especially if energy capacity is high (e.g. 160% in Fig. 12*a*) and this is because lower levels of energy stored are needed to provide DNO service.

3.4 Business case in support of corrective security: yearly impact assessment

3.4.1 Yearly revenues in energy and balancing services markets: Fig. 13 shows the revenues of storage plant in a year under preventive and corrective security modes when assuming different levels of robustness in the application of corrective security (through adjustment of binary parameters α and α'). In particular, Fig. 13*a* shows that, although all revenue components are increased under corrective control operation, reserve revenue significantly escalates, demonstrating that conflicts between DNO and reserve services can be more efficiently managed through corrective security.

Interestingly, the increase in storage revenue is higher during April, June–August (i.e. spring and summer) rather than during period between November and March (i.e. winter) and this is so due to the higher number of congested hours during summer (decrease in substation's thermal rating during summer is disproportionally higher than the decrease in demand). Clearly, the value of corrective

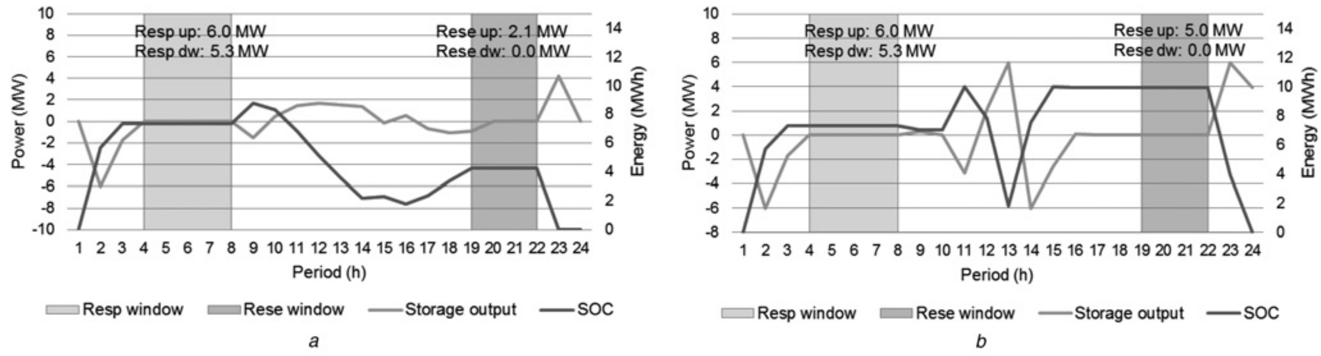

Fig. 10 *Storage output, SOC and balancing services provided under*

a Preventive security mode
b Corrective security mode

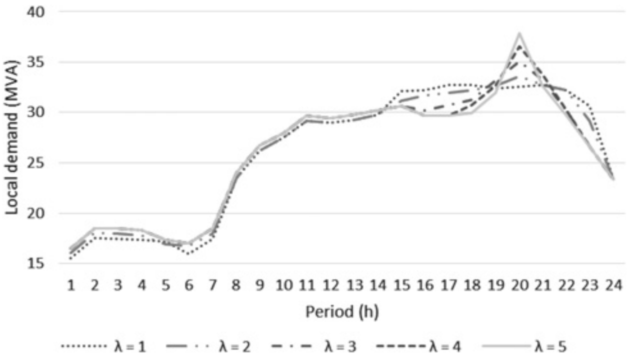

Fig. 11 *Set of five local demand profiles, ranging from more constant (λ = 1) to more variable and spiky (λ = 5)*

security (i.e. revenue difference between preventive and corrective securities) is higher when more severe substation congestions occur. Also, Fig. 13*a* shows that corrective security can improve yearly revenue in energy and balancing services markets by circa 5% (in this particular GB case).

3.4.2 Yearly revenues of DNO service: According to [20], revenue associated with DNO service is equal to the opportunity cost of providing such service and it refers to the revenue increase in energy and balancing services markets when no storage capacity is allocated to provide DNO services (i.e. $\bar{S}^N = \infty$ and $\tilde{S}^N = \infty$). In this context, Fig. 14 shows the opportunity cost of providing DNO service under preventive and corrective security mode.

Figs. 14 shows that the opportunity cost of providing DNO service decreases when corrective security is applied since conflicts between provision of DNO service and further applications can be managed more efficiently. Moreover, the reduction in opportunity cost of providing DNO service (e.g. £14.592−£2.597 = £11.995 in Fig. 14) is equal to the value of corrective control (e.g. £291.333−£279.338 = £11.995 in Fig. 13*a*). It is therefore worth discussing whether the actual revenue of DNO service should be proportionally reduced according to its opportunity cost under corrective control (benefiting DNO) or whether part of the savings in opportunity cost should be kept by storage owner in order to incentivise deployment of advanced corrective control technology.

4 Conclusion

Energy storage can bring benefits to several sectors in electricity industry, including generation, transmission and distribution, while providing services to support balancing of demand and supply, network congestion management and reduce the need for investment in system reinforcement.

In this context, we propose a novel 'storage centric' framework for coordinating multi-service portfolios of distributed energy storage that supports distribution network operation through application of corrective security (i.e. post-fault rather than pre-fault peak demand shaving service). Through a MILP model that schedules storage plant outputs (in terms of active and reactive power) by coordinating various services to multiple market participants, we demonstrated that adopting corrective security to provide network services and deal with network congestion in a post-fault fashion, is overall more beneficial despite the levels of energy needed to be maintained in storage plant during pre-fault conditions for applying post-contingency actions right after a network fault occurs. Furthermore, our analysis shows that application of corrective security can benefit both (i) storage plant owners through increased revenues in energy and balancing services markets and (ii) DNOs through reduction in payments to storage owners and increased utilisation of network infrastructure.

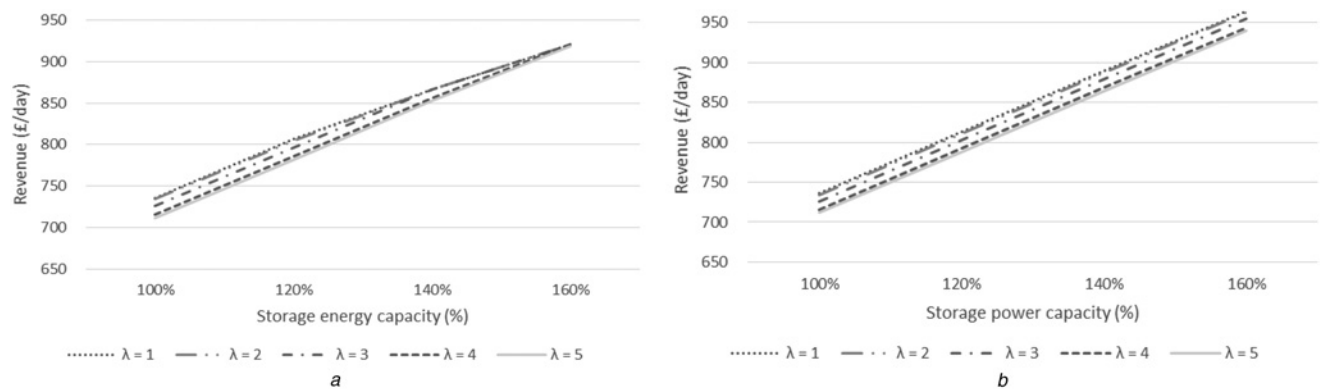

Fig. 12 *Storage plant revenue for various demand profiles (presented in Fig. 11) associated with increased*

a Energy capacity (100% represents base case energy capacity)
b Power capacity (100% represents base case power capacity)

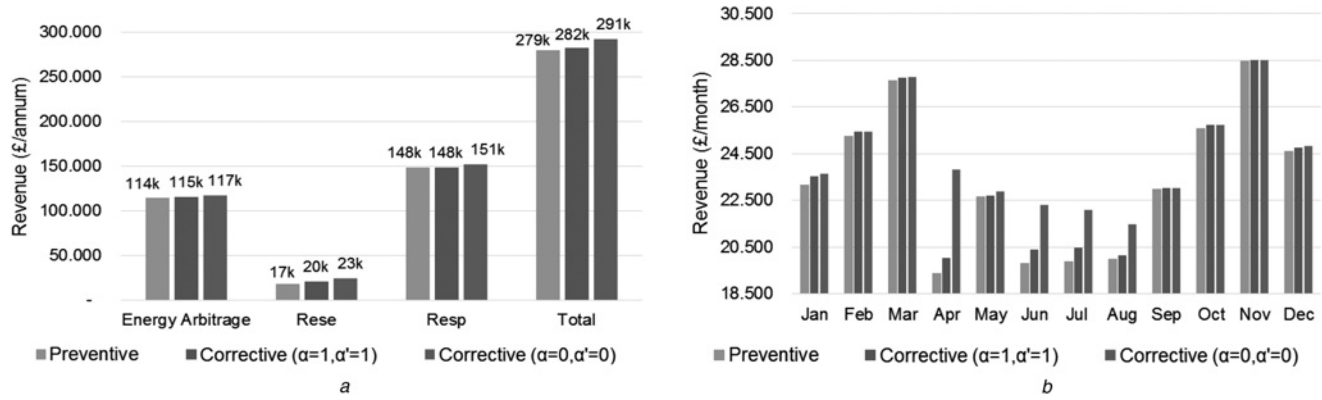

Fig. 13 *Revenues under preventive and corrective control strategies by*
a Component
b Month

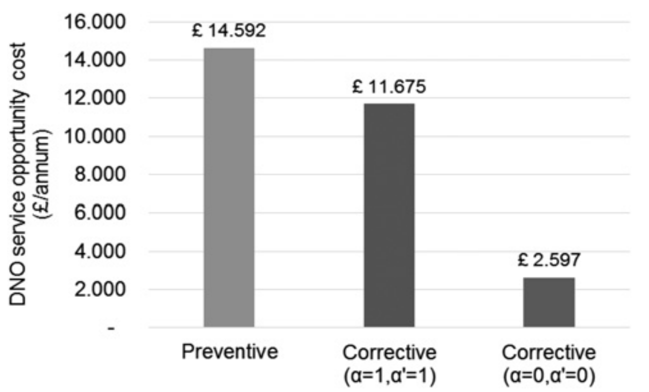

Fig. 14 *Opportunity cost of providing DNO service under different security modes*

Our model and developed framework can promote efficient integration of new distributed storage projects and new smart grid technology that can enable application of corrective network security. The developed framework can also provide insights associated with the development of appropriate market mechanisms to ensure that investors in energy storage and those interested in providing services through advanced corrective control technology, are adequately rewarded for the delivery of value to multiple electricity sectors.

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7 Appendix

7.1 Full preventive and corrective security models

7.1.1 Preventive security model: *Objective function:* The objective function [i.e. (10)] maximises storage plant's net revenues through energy price arbitrage and commitment of upwards and downwards reserve and frequency response services (see (10))

DNO constraints: Equation (11) ensures that power transfers through primary substation respect distribution network $N-1$ security limit at all times, even if committed downwards balancing services are exercised in real time. Balance of active and reactive power among local demand, storage plant outputs and substation transfers is ensured through (12) and (13), respectively,

$$\left(P_t^N + \text{Resp}_t^{\text{Dw}} + \text{Rese}_t^{\text{Dw}}\right)^2 + \left(Q_t^N\right)^2 \le \left(\bar{S}^N\right)^2 \quad \forall t \in T \tag{11}$$

$$P_t^N = P_t^{\text{D}} - P_t^{\text{S}} \quad \forall t \in T \tag{12}$$

$$Q_t^N = Q_t^{\text{D}} - Q_t^{\text{S}} \quad \forall t \in T \tag{13}$$

Storage plant capacity constraints: Storage plant's charge and discharge outputs are combined in a single variable in (14) which respects storage plant active power capacity as shown in (15). Storage active and reactive powers are also limited through (16). Energy stored along with storage plant's charge and discharge actions and roundtrip losses are balanced across time periods as shown in (17). Energy stored is limited by storage plant capacity according to (18)

$$P_t^{\text{S}} = D_t^{\text{S}} - C_t^{\text{S}} \quad \forall t \in T \tag{14}$$

$$-\overline{C}^{\text{S}} \le P_t^{\text{S}} \le \bar{D}^{\text{S}} \quad \forall t \in T \tag{15}$$

$$\left(P_t^{\text{S}}\right)^2 + \left(Q_t^{\text{S}}\right)^2 \le \left(\bar{S}^{\text{S}}\right)^2 \quad \forall t \in T \tag{16}$$

$$E_t = E_{t-1} - \left(D_t^{\text{S}} - C_t^{\text{S}} \cdot \eta\right) \cdot d \quad \forall t \in T \tag{17}$$

$$E_t \le \bar{E} \quad \forall t \in T \tag{18}$$

Balancing services deliverability constraints: If committed balancing services are exercised in real time, outputs must respect storage plant capacity (i.e. maximum discharging and charging capacities) as shown in (19) and (20) for upwards and downwards balancing services, respectively. Deliverability of committed balancing services is ensured through (21)–(32) which maintain sufficient levels of energy stored in case a single balancing service and simultaneous balancing services are exercised during their maximum utilisation times (i.e. worst-case optimisation)

$$P_t^{\text{S}} + \text{Rese}_t^{\text{Up}} + \text{Resp}_t^{\text{Up}} \le \bar{D}^{\text{S}} \quad \forall t \in T \tag{19}$$

$$P_t^{\text{S}} - \text{Resp}_t^{\text{Dw}} - \text{Rese}_t^{\text{Dw}} \ge -\bar{C}^{\text{S}} \quad \forall t \in T \tag{20}$$

$$-M \cdot \left(1 - X_t^{\text{Up.Rese}}\right) \le E_{t-1} - \left(P_t^{\text{S}} + \text{Rese}_t^{\text{Up}}\right) \cdot \tau^{\text{Rese}} \le \bar{E} + M \cdot (1 - X_t^{\text{Up.Rese}}) \quad \forall t \in T \tag{21}$$

$$-M \cdot \left(1 - X_t^{\text{Dw.Rese}}\right) \le E_{t-1} - \left(P_t^{\text{S}} - \text{Rese}_t^{\text{Dw}}\right) \cdot \tau^{\text{Rese}} \le \bar{E} + M \cdot (1 - X_t^{\text{Dw.Rese}}) \quad \forall t \in T \tag{22}$$

$$-M \cdot \left(1 - X_t^{\text{Up.Resp}}\right) \le E_{t-1} - \left(P_t^{\text{S}} + \text{Resp}_t^{\text{Up}}\right) \cdot \tau^{\text{Resp}} \le \bar{E} + M \cdot (1 - X_t^{\text{Up.Resp}}) \quad \forall t \in T \tag{23}$$

$$-M \cdot \left(1 - X_t^{\text{Dw.Resp}}\right) \le E_{t-1} - \left(P_t^{S} - \text{Resp}_t^{\text{Dw}}\right) \cdot \tau^{\text{Resp}} \le \bar{E} + M \cdot (1 - X_t^{\text{Dw.Resp}}) \quad \forall t \in T \tag{24}$$

$$-M \cdot \left(1 - X_t^{\text{Up.R\&R}}\right) \le E_{t-1} - \left(P_t^{\text{S}} + \text{Rese}_t^{\text{Up}}\right) \cdot \tau^{\text{Rese}} - \text{Resp}_t^{\text{Up}} \cdot \tau^{\text{Resp}} \le \bar{E} + M \cdot (1 - X_t^{\text{Up.R\&R}}) \quad \forall t \in T \tag{25}$$

$$-M \cdot \left(1 - X_t^{\text{Dw.R\&R}}\right) \le E_{t-1} - \left(P_t^{\text{S}} - \text{Rese}_t^{\text{Dw}}\right) \cdot \tau^{\text{Rese}} + \text{Resp}_t^{\text{Dw}} \cdot \tau^{\text{Resp}} \le \bar{E} + M \cdot (1 - X_t^{\text{Dw.R\&R}}) \quad \forall t \in T \tag{26}$$

$$\text{Rese}_t^{\text{Up}} \le M \cdot X_t^{\text{Up.Rese}} \quad \forall t \in T \tag{27}$$

$$\text{Rese}_t^{\text{Dw}} \le M \cdot X_t^{\text{Dw.Rese}} \quad \forall t \in T \tag{28}$$

$$\text{Resp}_t^{\text{Up}} \le M \cdot X_t^{\text{Up.Resp}} \quad \forall t \in T \tag{29}$$

$$\text{Resp}_t^{\text{Dw}} \le M \cdot X_t^{\text{Dw.Resp}} \quad \forall t \in T \tag{30}$$

$$X_t^{\text{Up.Rese}} + X_t^{\text{Up.Resp}} - \beta^{\text{Up}} \le M \cdot X_t^{\text{Up.R\&R}} \quad \forall t \in T \tag{31}$$

$$X_t^{\text{Dw.Rese}} + X_t^{\text{Dw.Resp}} - \beta^{\text{Dw}} \le M \cdot X_t^{\text{Dw.R\&R}} \quad \forall t \in T \tag{32}$$

Approximation of active and reactive power constraints: Equation (33) linearises the bounded convex region associated with (11) and (16) (i.e. $P^2 + Q^2 \le S^2$, where P and Q are variables and S is a constant) through a set of tangent planes

$$-\frac{-\delta \cdot P + S^2}{\sqrt{S^2 - \delta^2}} \le Q \le \frac{-\delta \cdot P + S^2}{\sqrt{S^2 - \delta^2}} \quad \forall \delta \in \Delta \tag{33}$$

7.1.2 Corrective security model: The corrective security model is composed by (1)–(9) (described in Section 2) and (12)–(20). As explained in Section 2, (7)–(9) are also used to ensure deliverability of downwards balancing services (albeit they are not explicitly shown in this paper). In addition, (33) is used to linearise relationship among active, reactive and apparent powers of substation and storage. Further constraints are used to keep provisions of balancing services constant throughout a prescribed window.

$$\text{Max}\left\{\sum_{t \in T}\left[P_t^{\text{S}} \cdot \pi_t^{\text{E}} + \text{Rese}_t^{\text{Up}} \cdot \pi_t^{\text{Up.Rese}} + \text{Rese}_t^{\text{Dw}} \cdot \pi_t^{\text{Dw.Rese}} + \text{Resp}_t^{\text{Up}} \cdot \pi_t^{\text{Up.Resp}} + \text{Resp}_t^{\text{Dw}} \cdot \pi_t^{\text{Dw.Resp}}\right] \cdot \text{d}\right\} \tag{10}$$