BUSINESS CASE IN SUPPORT FOR REACTIVE POWER SERVICES FROM DISTRIBUTED ENERGY STORAGE

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ABSTRACT

The integration of energy storage (ES) in future low carbon networks can offer significant opportunities to distribution network operators and other players in the electricity industry. The potential of ES to support distribution network by reducing peak demand, provide security of supply and resilience, manage voltage levels and ultimately defer (and avoid) investment in network reinforcements has been widely reported in the literature. This paper, however, sets out to investigate the value of coordinating ES active and reactive power outputs to support network operator activities but also other stakeholders in future low carbon networks.

The proposed model coordinates active and reactive power outputs from an ES plant at the distribution level. Fundamentally, ES plant operation is optimised to deliver maximum benefits by considering its capability to provide active and reactive power in a coordinated fashion. It is demonstrated that the proposed methodology to determine ES power outputs is fundamental to ensure effective (and robust) delivery of network services at critical ES energy levels. The results have also shown that in a multiple service business model, the coordination of active and reactive power may increase total revenue by c. 2,400 £/month, when compared to an active power only operation mode.

INTRODUCTION

The ambitious commitments established by UK to reduce carbon emissions [1] in the electricity industry are leading to significant challenges in the energy sector, particularly in the electricity industry. The penetration of low carbon generation associated with decommission of fossil fuelled generation, and the electrification of heat and transport sectors will undermine the business case of system and network operators.

In this context, the flexibility that energy storage (ES) can provide to both system and distribution network operators (DNOs) is fundamental to ensure a cost-efficient decarbonisation of the electricity market. The potential of ES to defer / avoid network reinforcements, provide security of supply, manage peak demand and ultimately support network operation is widely documented in the literature [2-5].

This paper, however, sets out to investigate the value of coordinating ES active and reactive power outputs to support DNO activities but also other stakeholders in future low carbon networks. The proposed model considers an ES providing multiple services to various sectors of the electricity market while coordinating operation of active and reactive power outputs. Thus, the paper key contribution is to establish the role and value, for the DNO, of coordinating ES active and reactive power. This way, the research conducted herein can support planning and sizing activities for investing in ES plants (and the associated power electronics) but fundamentally it can facilitate the development of new market arrangements and regulatory framework.

MODEL FOR COORDINATED ACTIVE AND REACTIVE POWER

The model studies a real distributed ES plant connected to a primary substation in Leighton Buzzard, UK, [6] providing multiple services to various stakeholders in the electricity industry by coordinating its active and reactive power outputs. It considers provision of balancing services, support to distribution network operation, all while seizing arbitrage opportunities in the energy market.

The model key aspect is the capability of coordinating ES active and reactive power outputs which ensures efficient and effective deliverability of network services but can also increase the value of ES.

Objective Function

The model maximises ES revenues on the energy and balancing markets by determining scheduled outputs for provision of multiple services. Equation (1) shows the model objective function.

$$\mathrm{Max}\left\{\sum_{t\in T}\left[\begin{array}{c} P_t^S \cdot \pi_t^{\mathrm{E}} + \\ \left(Rese_t^{Up} + Rese_t^{Dw}\right) \cdot \pi_t^{\mathrm{Rese}} + \\ \left(Resp_t^{Up} + Resp_t^{Dw}\right) \cdot \pi_t^{\mathrm{Resp}} \end{array}\right]\right\} \tag{1}$$

Energy arbitrage revenue is determined by the bought or sold energy (i.e. ES charging or discharging power, P_t^S, in every period) and multiplied by energy prices (π_t^{E}). Balancing services are remunerated based on their availability price (π_t^{Rese} and π_t^{Resp} respectively for reserve and frequency response) multiplied by the committed volume in each period. Note that revenue for network services is not included in (1), this will be determined as the opportunity cost of allocating ES availability (i.e. power and energy capacities) to provide network services rather than allocating it to other potentially higher remunerating services.

Energy Storage Constraints

ES operation is limited by power capacity – active and apparent power limits – modelled through discharge (D_t^S) and charge (C_t^S) outputs which are combined in a single variable in (2) and comply with ES active power limits in (3). Note that charging actions will be associated with a negative value of P_t^S, whereas discharging actions are associated with positive values of P_t^S.

$$P_t^S = D_t^S - C_t^S \quad \forall\ t \in \mathrm{T} \tag{2}$$

$$-\overline{\mathrm{C}}^{\mathrm{S}} \leq P_t^S \leq \overline{\mathrm{D}}^{\mathrm{S}} \quad \forall\ t \in \mathrm{T} \tag{3}$$

In addition, ES operation (by means of active, P_t^S, and reactive power, Q_t^S) is bounded by apparent power limits, $\overline{\mathrm{S}}^{\mathrm{S}}$, through (4).

$$(P_t^S)^2 + (Q_t^S)^2 \leq \left(\overline{\mathrm{S}}^{\mathrm{S}}\right)^2 \quad \forall\ t \in \mathrm{T} \tag{4}$$

ES energy levels, E_t, modelled in (5) consider previous energy levels (in period t-1) and discharge or charging actions in period t, which are affected by efficiency losses, η, and comply with ES energy limits in (6).

$$E_t = E_{t-1} - (D_t^S - C_t^S \cdot \eta) \quad \forall\ t \in \mathrm{T} \tag{5}$$

$$E_t \leq \overline{\mathrm{E}} \quad \forall\ t \in \mathrm{T} \tag{6}$$

Balancing Services Constraints

Balancing services are procured by the system operator to balance system demand and generation, and therefore resolve supply shortages or excess. ES can facilitate the balance of demand and supply through provision of balancing services.

Provision of reserve and frequency response services (balancing services) should comply with ES power limits. In particular, provision of upwards reserve, $Rese_t^{Up}$, and frequency response, $Resp_t^{Up}$, is limited by maximum discharging capacity, in (7) and provision of downwards reserve, $Rese_t^{Dw}$, and frequency response, $Resp_t^{Dw}$, limited by maximum charging capacity in (8).

$$Rese_t^{Up} + Resp_t^{Up} \leq \overline{\mathrm{D}}^{\mathrm{S}} - P_t^S \quad \forall\ t \in \mathrm{T} \tag{7}$$

$$Rese_t^{Dw} + Resp_t^{Dw} \leq \overline{\mathrm{C}}^{\mathrm{S}} + P_t^S \quad \forall\ t \in \mathrm{T} \tag{8}$$

The model manages ES energy levels when providing reserve or frequency response to ensure real time robust delivery of balancing services. Robust deliverability of upwards reserve service is modelled through (9) which ensures sufficient stored energy to be discharged up to the maximum utilisation time for reserve (τ^{Rese}) and likewise in (11) for upwards frequency response and its maximum utilisation time (τ^{Resp}). On the other hand, when downwards services are provided, (10) and (12) ensure sufficient energy headroom for robust deliverability.

$$\begin{aligned} -\mathrm{M} \cdot \left(1 - X_t^{Up.Rese}\right) &\leq E_{t-1} - \left(P_t^S + Rese_t^{Up}\right) \cdot \tau^{\mathrm{Rese}} \\ &\leq \overline{\mathrm{E}} + \mathrm{M} \cdot (1 - X_t^{Up.Rese}) \quad \forall\ t \in \mathrm{T} \end{aligned} \tag{9}$$

$$\begin{aligned} -\mathrm{M} \cdot (1 - X_t^{Dw.Rese}) &\leq E_{t-1} - (P_t^S - Rese_t^{Dw}) \cdot \tau^{\mathrm{Rese}} \\ &\leq \overline{\mathrm{E}} + \mathrm{M} \cdot (1 - X_t^{Dw.Rese}) \quad \forall\ t \in \mathrm{T} \end{aligned} \tag{10}$$

$$\begin{aligned} -\mathrm{M} \cdot \left(1 - X_t^{Up.Resp}\right) &\leq E_{t-1} - \left(P_t^S + Resp_t^{Up}\right) \cdot \tau^{\mathrm{Resp}} \\ &\leq \overline{\mathrm{E}} + \mathrm{M} \cdot (1 - X_t^{Up.Resp}) \quad \forall\ t \in \mathrm{T} \end{aligned} \tag{11}$$

$$\begin{aligned} -\mathrm{M} \cdot \left(1 - X_t^{Dw.Resp}\right) &\leq E_{t-1} - (P_t^S - Resp_t^{Dw}) \cdot \tau^{\mathrm{Resp}} \\ &\leq \overline{\mathrm{E}} + \mathrm{M} \cdot (1 - X_t^{Dw.Resp}) \quad \forall\ t \in \mathrm{T} \end{aligned} \tag{12}$$

Note that (9) - (12) should not limit ES operation if balancing services are not provided, thus status commitment variables ($X_t^{Up.Rese}$, $X_t^{Dw.Rese}$, $X_t^{Up.Resp}$and $X_t^{Dw.Resp}$) are included to control provision of balancing services (i.e. 1 if committed and 0 otherwise) and ensure that (9) - (12) are not bounding if those are not committed. Commitment of reserve and frequency response services are modelled by (13) – (16) which determine the commitment status of each service, by using big M method (in which M represents a very large number).

$$Rese_t^{Up} \leq \mathrm{M} \cdot X_t^{Up.Rese} \quad \forall\ t \in \mathrm{T} \tag{13}$$

$$Rese_t^{Dw} \leq \mathrm{M} \cdot X_t^{Dw.Rese} \quad \forall\ t \in \mathrm{T} \tag{14}$$

$$Resp_t^{Up} \leq \mathrm{M} \cdot X_t^{Up.Resp} \quad \forall\ t \in \mathrm{T} \tag{15}$$

$$Resp_t^{Dw} \leq \mathrm{M} \cdot X_t^{Dw.Resp} \quad \forall\ t \in \mathrm{T} \tag{16}$$

Due to discretisation of continuous variables – such as ES energy levels, E_t – (9) to (12) ensure sufficient energy levels if balancing services are exercised at the beginning of period t. Hence to increase solution's robustness, an additional set of constraints should be included to manage energy levels when balancing services are exercised at any point in time. Thus, by replicating (9) to (12) and replacing E_{t-1} for E_t, robust deliverability of balancing service is ensured. For the sake of simplicity, it is assumed that reserve and frequency response services are not instructed simultaneously.

Network Constraints

Deliverability of network service is achieved by a set of constraints which ensure ES operation complies with distribution network capacity limits and supports security of supply during peak demand periods. Active power through distribution network (P_t^N), local demand ($\mathrm{P_t^D}$) and ES operation (P_t^S) are balanced in (17) and likewise for reactive power in (18).

$$P_t^N = \mathrm{P_t^D} - P_t^S \quad \forall\ t \in \mathrm{T} \tag{17}$$

$$Q_t^N = \mathrm{Q_t^D} - Q_t^S \quad \forall\ t \in \mathrm{T} \tag{18}$$

Distribution network capacity limits are modelled in (19) by means of apparent power capacity which ensures that ES efficiently delivers network service by means of active and reactive power. The model robustness ensures that real time utilisation of balancing services also comply with distribution network capacity limits

$$(P_t^N + Rese_t^{Dw} + Resp_t^{Dw})^2 + (Q_t^N)^2 \leq (\bar{S}^N)^2 \quad \forall\, t \in T \qquad (19)$$

Additional Modelling Constraints

Constraints (4) and (19) model respectively ES and distribution network apparent power limits, albeit they define a convex region, they are nonlinear. Thus, the nonlinear constraints are approximated by a finite family of linear constraints defined by (20).

$$-\frac{-\delta \cdot P + S^2}{\sqrt{S^2-\delta^2}} \leq Q \leq \frac{-\delta \cdot P + S^2}{\sqrt{S^2-\delta^2}} \quad \forall\, \delta \in \Delta \qquad (20)$$

Fig. 1 illustrates the region defined by (20) and obtained by constructing supporting hyperplanes at sample points in the boundary of the convex region.

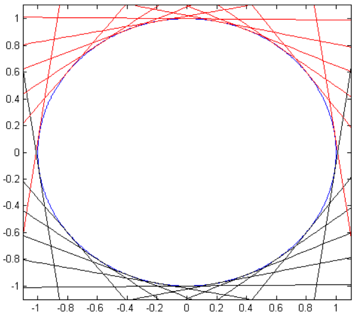

Fig. 1 Linearization of constraints (4) and (19) with a set of lines.

Reserve services in GB framework are procured within prescribed time windows defined by the system operator [7]. Hence, for GB studies, an additional set of constraints were included for provision of reserve services at prescribed time windows and to ensure committed volumes of reserve services to be constant during the windows. In addition, although frequency response services are typically provided at any hour for the sake of clarity these services were also modelled in prescribed time windows.
The MILP model was implemented in FICO Xpress [8] and solved through the application of standard branch-and-bound and simplex algorithms.

BUSINESS CASE FOR COORDINATION OF ACTIVE AND REACTIVE POWER

Real GB time series data of prices from the energy market and local distributed demand from DNO metering at the primary substation level with a power factor of 0.96 - as shown in Fig. 2 - were used in the studies presented herein.

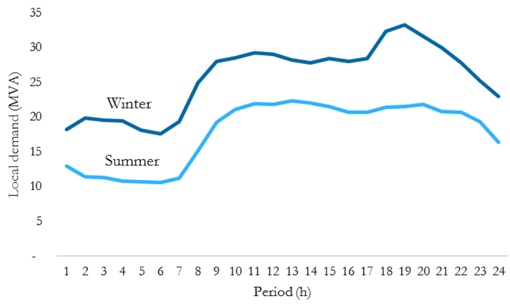

Fig. 2 Local demand in a typical day in summer and winter.

The ES characteristics were modelled considering its power capacity, differentiated in charge and discharge active power capacities, energy capacity and roundtrip efficiency. Table 1 summarises the ES modelling characteristics.

Table 1 ES modelling characteristics used in GB case studies.

Maximum charging capacity ($\bar{C}^S$)	6 [MW]
Maximum discharging capacity ($\bar{D}^S$)	6 [MW]
Apparent power capacity ($\bar{S}^S$)	7.5 [MVA]
Energy capacity (E_t)	10 [MWh]
Roundtrip efficiency (η)	85 %

Power systems infrastructure are exposed and sensitive to weather conditions - such as temperature and wind - which can affect network capacity ratings. A brief study on GB monthly maximum temperatures (from 1981 to 2012) was performed to determine secured power capacities of primary substation depending on seasonal temperatures. As shown in Fig. 3 primary substation secured capacity will be adjusted to account for thermal effects.

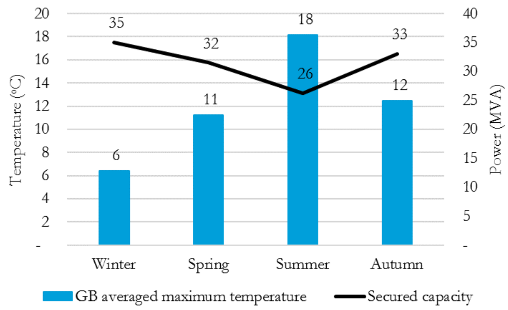

Fig. 3 Season averages of GB maximum temperatures (1981-2010) and adjusted primary substation secured capacity.

Procurement of balancing services in GB is achieved through auctions within prescribed time windows, which are defined by the system operator according to its needs; additional information on procurement of balancing services can be found in [9-10]. In the studies presented next, frequency response window was defined in the morning between 6 h and 9 h all year round and reserve window was defined between 19 h and 22 h in the months of March to August and between 16 h and 21 h in the remaining months.
Balancing services availability prices are determined through contractual arrangements between system operator and each service provider, which according to [9] in 2014 had an average value of 5.83 £/MW/h for short term operating reserve and typically lower than 8 £/MW/h for firm frequency response (FFR) services according to [10]. Thus, availability prices for reserve services were set at 5 £/MW/h and frequency response services at 7 £/MW/h. However, note that current market conditions for provision of FFR service have been significantly improved with availability prices up to 18 £/MW/h.

Reactive Power Supporting Effective Delivery of

Network Services

Active and reactive power coordination is fundamental to support distribution network operation since demand at the distribution level is comprised of active and reactive power components. Hence, to effectively provide security of supply to the DNO, provision of network service should be implemented by means of active and reactive power.

ES can reduce local demand by discharging active and reactive power but complying with its apparent power capacity, albeit active power operation is also limited by ES energy capacity. Thus, ES operation by means of reactive power is not affected by its energy limits (assuming these are provided by power electronics). In this context, coordination of active and reactive power for provision of network service is crucial to ensure that distribution network secured capacity limits are not violated when ES energy levels are insufficient to do so by means of active power only. A particular day in autumn in which ES energy levels are insufficient to deliver effective network service by means of active power only is presented in Fig. 4.

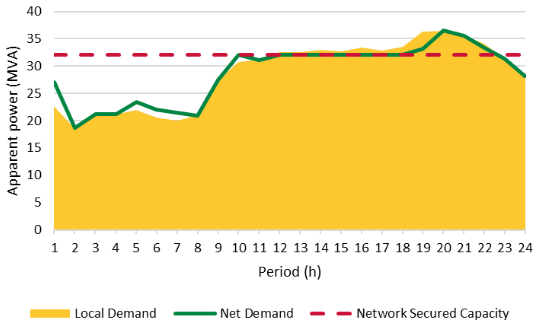

Fig. 4 Local and net demand in a typical day in autumn with ES operation by means of active power only.

As shown in Fig. 4, provision of network service by means of active power only would not be sufficient to reduce local peak demand between 19 h and 22 h, and thus comply with network secured capacity. Note that the service is delivered between 13 h and 18 h, as net demand (i.e. local demand affected by ES discharge operation) is complying with network secured capacity, albeit ES energy levels are not sufficient to continue delivering the service after 18 h.

In contrast, Fig. 5 shows for the exact same day in autumn as in Fig. 4, the net demand in the distribution network when ES is providing network services by coordinating its active and reactive power outputs.

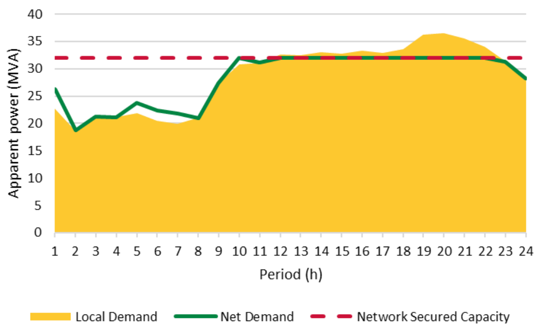

Fig. 5 Local and net demand in a typical day in autumn with ES coordinated operation of active and reactive power.

When ES active and reactive power outputs are coordinated to provide network services, as shown in Fig. 5, peak demand is effectively reduced to comply with network secured capacity and thus provide security of supply. Fig. 6 shows ES energy levels for both cases, i.e. energy levels when considering provision of network services by means of active power only and by coordinated operation of active and reactive power.

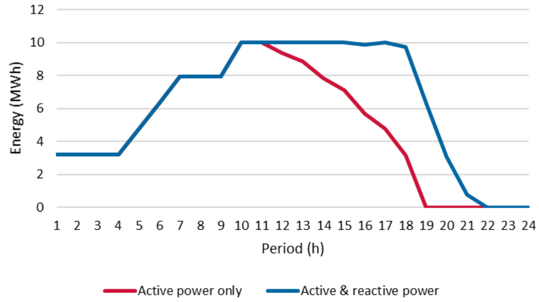

Fig. 6 ES energy levels when providing network service by active power only and coordinated active and reactive power.

Note that as described and shown in Fig. 4, ES energy levels are depleted at hour 19 and provision of network service is curtailed from that period onwards.

Coordination of ES active and reactive power outputs is thus fundamental to ensure effective (and robust) delivery of network services to the DNO. As demonstrated, in the case of a long-lasting peak demand (i.e. with high energy needs), provision of network service by means of active power only may not be sufficient.

Value of Coordinating Active and Reactive Power

Coordinated active and reactive power outputs have been demonstrated to effectively support operation of distribution networks and provide the DNO with an alternative solution to defer / avoid network reinforcement. Moreover, coordinated operation of active and reactive power may also support provision of other services such as energy arbitrage and balancing services as shown next.

ES charging actions can further aggravate local demand (or potentially create a new demand peak), thus reactive power can be used to offset the increase in demand due to active power operation. Fig. 7 and Fig. 8 show a day with ES active and reactive power outputs, respectively.

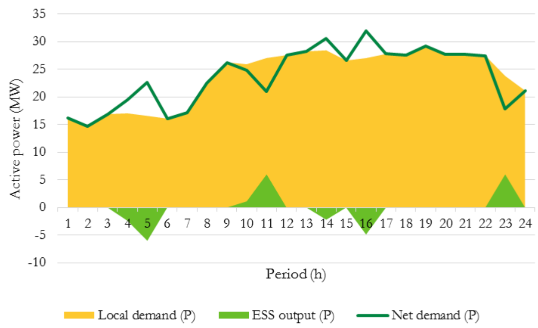

Fig. 7 Active power ES operation, local and net demand.

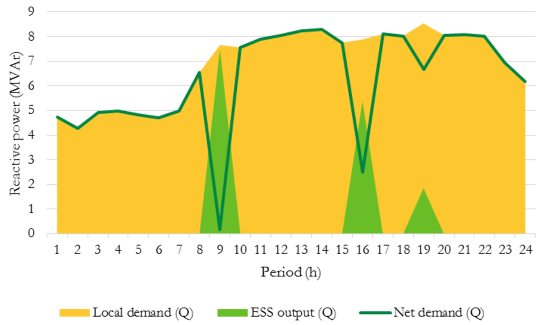

Fig. 8 Reactive power ES operation, local and net demand.

In Fig. 8 reactive power in period 16h is effectively offsetting the increase in net demand by ES charging actions (in Fig. 7). This shows that reactive power can support active power charging actions, for example for seizing arbitrage opportunities (i.e. by charging at low prices as in period 16h). Additionally, in periods 9 h and 19h reactive power is also supporting active power operations but in this case in stand-by operation. This shows that ES can further adjust its active power operation for maximum revenue in the energy and balancing markets, by charging or (being in stand-by) during peak demand periods. In this context, Fig. 9 shows the monthly average value of coordinating ES active and reactive power.

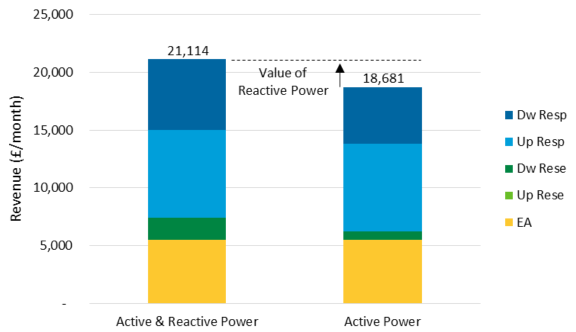

Fig. 9 Monthly average revenues for ES coordinated operation of active and reactive power and active power only.

An efficient ES operation with coordinated active and reactive power outputs is more beneficial and increases ES revenues, in this case, on average by 2,433 £/month. Nevertheless, under current market conditions, considering recent market reports from provision of FFR service, the value of reactive power may increase up to twofold, albeit revenue from frequency response services represents less than 65% of total revenue.

CONCLUSION

This paper sets the business case in support for coordinating ES active and reactive power outputs. Coordinated active and reactive power outputs have been demonstrated to effectively support operation of distribution networks and provide the DNO with an alternative solution to defer / avoid network reinforcement. Effective delivery of network services is only achieved by means of active and reactive power, and this is even more crucial during critical ES energy levels.

It has been demonstrated that reactive power can also support provision of active power services only, as in the case of energy arbitrage and balancing services. Reactive power can offset charging actions (by means of active power) which aggravate local demand and may create a new peak of demand. The value of coordinating active and reactive power on average exceeds 2,400 £/month, which can potentially accumulate up to 20,000 £ p.a.

To conclude, when planning and sizing ES plants, the value of reactive power should be considered to enhance the business case for deployment of ES. Although, it is fundamental to ensure that ES investors are remunerated accordingly to the benefits delivered to support its cost-efficient deployment.

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