SCHEDULING POWER AND ENERGY RESOURCES IN THE SMARTER NETWORK STORAGE PROJECT

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ABSTRACT

Electrical Energy Storage (EES) has many applications within power networks. However, installing EES for a single application or to solve a single problem will rarely justify the required investment. Consequently, the aim of Smarter Network Storage (SNS) is to install large scale EES to engage in a variety of network and commercial services. Prioritizing which services to engage in, selecting the most profitable commercial services and managing the battery's power and energy resources are all new challenges brought about by this approach. The solutions presented in this paper demonstrate that this deployment of EES is realizable, and provides a route to wide-scale adoption.

INTRODUCTION

Electrical Energy Storage (EES) has many applications within power networks; examples include peak shaving, frequency response, short-term operating reserve and supporting intermittent generation. However, installing EES for just one application is typically insufficient to make the capital investment worthwhile. The principle goal of Smarter Network Storage is to install large scale EES for a variety of system benefits to maximize its value. , the project is installing the largest battery in Europe – 10 MWh/6 MW/7.5 MVA of lithium-ion storage – at a primary substation (33/11kV) in Bedfordshire, England. The primary purpose of the EES is to defer the need to invest in new network infrastructure by reducing the peak demand. To offset investment costs, revenue will be gained from contracts to provide frequency response and short term operating reserve, as well as being offered in a tolling contract to energy traders.

Figure 1: A picture showing the site of the storage (left) and the battery racks (right)

The aim of the project is to demonstrate that EES on this scale can serve as a network asset, while providing a return on investment. The success of this demonstration project will build confidence in commercial deployment of EES, and prove a route to wide scale adoption.

To achieve this, there are commercial and technical challenges. Electricity demand at the substation needs to be forecast over long term time horizons (to allow tendering for commercial contracts) and short term time horizons (to schedule services and state of charge adjustments in the face of demand volatility). Services must be identified, and scheduled to maximize revenue from the EES. A daily schedule is passed to the real-time energy storage management system to control the state of charge, and real and reactive power set-points needed to dispatch the battery in line with contracted services and DNO requirements.

TRIAL SITE AND EES SYSTEM

Leighton Buzzard primary sub-station was selected as the site for the project. The site is connected to a grid supply point via two 33kV overhead lines. The peak demand is sufficiently high that, for several days per year, one of these lines would not be sufficient to supply all customers in the event of an outage; consequently, the UK distribution network standards state that reinforcement is required [1]. Conventionally, an additional overhead line and 38MVA transformer would be installed; however, this would be far in excess of the reinforcement required. The proposed alternative was to use EES to supply the demand locally when the demand is high, alleviating the load on the overhead lines. These options, along with the local network topology, are shown in Figure 2. The winter demand and line limits are shown in Figure 3.

However, the EES is more expensive than building a new overhead line. Consequently, the EES will tender for commercial balancing services when it is not being used for the Peak Shaving service in order to justify its cost and, ultimately, demonstrate a range of ways to achieve a return on the investment.

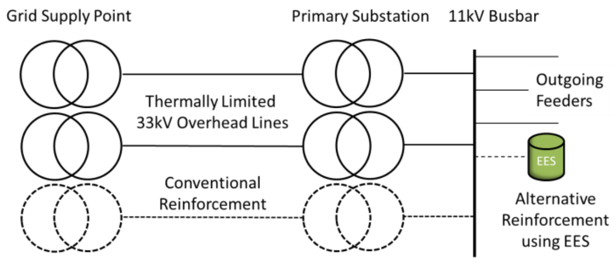

Figure 2: A comparison of the conventional reinforcement option, and the alternative using EES

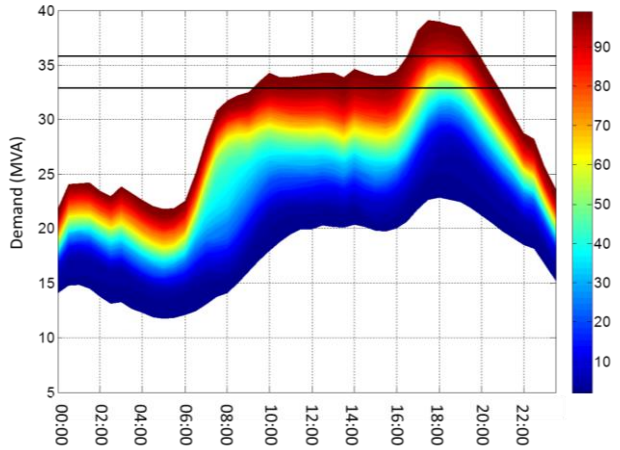

Figure 3: A plot of demand probability for winter, along with the 50°C and 60°C line limits

DEMAND FORECASTING

Motivation

Demand forecasting is essential to the success of SNS for the following three reasons:

- High demand peaks must be identified ahead of time to ensure that a conflicting service is not scheduled and that state of charge can be allocated to peak shaving.
- The required level of charging capacity leading up to the peak can be identified ahead of time. This is an issue because the network capacity can restrict charging at certain times, particularly before the demand peak.
- Commercial services need to be tendered for weeks, and even months in advance.

Consequently both long term (up to 12 months) and short term (up to 2 weeks) forecasting methods have been implemented.

Method

Multiple Linear Regression (MLR) has been widely used in forecasting, including demand forecasting [2]. In MLR, the term to be predicted, Y, is calculated as the sum of a number of explanatory variables, X_i, each weighted by pre-calculated factor, β_i, and an error term e. Hence an MLR model is of the form:

$$Y = \beta_0 + \beta_1 X_1 + \beta_2 X_2 + \beta_3 X_3 + \cdots + \beta_n X_n + e \quad (1)$$

The β terms are calculated through offline analysis of historical data. The main challenge in creating an MLR model is determining which subset of the available explanatory variables result in the most accurate forecast. The variables used for long term forecasting are shown in Table 1. Temperature and past demand can only be used in the short term forecasts.

Variable	Range
Time of Day	1-48
Day of Week	1-7
Month	1-12
Season	1-4
Daylight Savings	0-1
Type of Day	1-3
Special Day	0-1
Daylight	0-1
Temperature	n/a
Previous Demand	n/a

Table 1: The variables used in demand forecasting and their ranges

The MLR accounts for a linear relationship between the predictor variables and the response variable. In the case of electricity demand though, these relationships may vary throughout the year. This can be accounted for by using interactions between the predictor variables; the models used in this paper use an interaction between month, time of day and daylight. This effectively creates 24 separate models, a daytime and night-time model for each month.

Model Accuracy

Error statistics were used to determine how accurate the models are. These are shown in Table 2.

Model	Adjusted R^2	MAE (MVA)
Short-Term	0.9981	0.2869
Long-Term	0.8687	1.5333

Table 2: Adjusted R^2 and Mean Absolute Error (MAE) for the long- and short-term models

The short-term model is more accurate than the long-term model, because the short-term model has additional predictor variables to explain the variation in the demand. However, as the forecast moves further away from the present time (when demand and temperature measurements are available), forecasted values are used in these inputs, and the model's accuracy begins to degrade.

SERVICE SCHEDULING

Peak Shaving

Peak shaving refers to the reduction of electricity demand at times of peak consumption. Electricity demand varies throughout the day; in the UK this peak typically occurs in the early evening. In the majority of cases, the peak demand only occurs for a small fraction of the time [3], but the generation, transmission and distribution systems are constrained by it. A peak shaving scheme attempts to reduce the demand peak either literally, through demand side response or by offsetting the demand by supplying power locally through distributed generation or energy storage

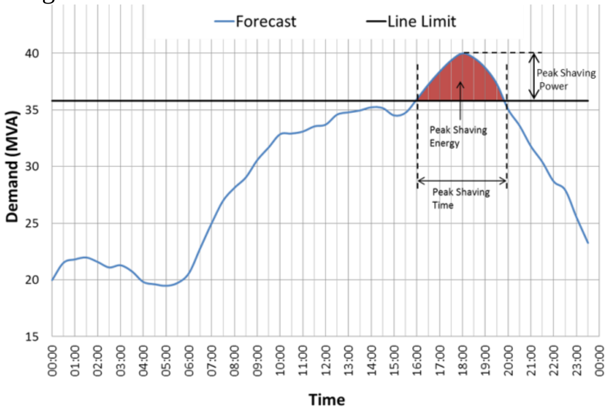

Figure 4: Peak shaving needs to take place when the existing infrastructure cannot support the demand peak. A storage system must meet both power and energy requirements to successfully offset the peak.

Electricity demand is highly variable, depending on time of day, day of week, month and season, as well as physical variables such as temperature and whether it is light or dark. Consequently, the peak shaving time, power and energy will all vary from day to day.

Figure 4 shows the demand over 24 hours at Leighton Buzzard during a winter day. Between 16:00 and 20:00, the demand exceeds the overhead line limit, so the EES would need to offer peak shaving for those 4 hours in the event of a circuit or transformer outage. The highest peak exceeds the demand by around 4 MVA, so the EES would need a converter rated at 4 MVA to successfully offset the peak. Finally, the total area between the demand curve and the line rating is around 8 MWh; this is the energy capacity that would be required for the EES to meet the peak shaving (PS) demand.

Commercial Services

In order to justify investing in SNS rather than conventional reinforcement, the EES must offer commercial services. Due to the regulations in the UK, distribution network operators (DNOs) are not permitted to own generation licences; because storage is classed as a generator, DNOs are therefore not allowed to own large scale storage requiring a generation licence, or trade directly in the energy markets [4]. Consequently, it is important to demonstrate that large scale energy storage can make a return on investment [5].

There are various services that are available for SNS to tender for. These services are primarily available through the UK Transmission System Operator (TSO), National Grid, and are concerned with transmission system operation. Additional services are available through energy supply companies and distributed energy resource aggregators.

Short-Term Operating Reserve (STOR)
STOR services are offered to provide energy in times of likely shortfalls. They are usually provided by standby generators such as open cycle gas turbines, because once energy delivery is triggered a fast response is required. A fee is paid to the provider for being available, with a further fee for actually delivering energy. STOR services are power-to-grid.

Firm Frequency Response (FFR)
Commercial FFR services are used to either maintain the frequency within regulations (50 ± 0.5 Hz) or to bring the frequency back to 50 Hz following a period of deviation (such as particularly high or low demand). As with STOR, FFR is operated using a market framework, and fees are paid for both availability and delivery. Some FFR services can be offered continuously for entire days or weeks. This is not always an option for EES, because following any delivery the State of Charge (SoC) must be adjusted before the EES is available to perform the service again. FFR services can be power-to-grid, power-from-grid or bidirectional. There are currently two varieties of commercial FFR procured by the TSO:

- Dynamic FFR: The amount of power delivered is directly governed by the system frequency,
- Static FFR: The service power is pre-determined, and is delivered in full following a frequency deviation of a certain size.

Tolling
A tolling service differs from STOR and FFR in that it is not offered by National Grid to solve a network issue. Instead, tolling represents handing over the operation of the EES to a third party for a fixed fee. The EES will be delivered and returned at a pre-arranged state of charge. During the tolling window, the third party operator is free to charge and dis-charge the battery as they see fit, for example to manage imbalance risk or arbitrage, and they are responsible for any energy costs, and in receipt of any profits.

Triad
Triad is not a commercial service as such, but it does represent an opportunity for significant revenues from the EES. In the UK, the three highest demand half hours in a year (not within 10 days of one another) are the Triad periods. The mean energy demand within these half hours

contributes a significant proportion of the annual network use charges imposed by National Grid [6]. By providing energy during the Triad periods, EES can generate revenue by either receiving the inverse of the charge directly or, if metered by an energy supply company as is the case with SNS, by reducing the cost to the energy supply company and receiving an agreed proportion of the saving. EES operating in this manner has already been demonstrated elsewhere [7].

Power and Energy Allocation

When scheduling services, whether they are commercial or required by the network, the EES must have sufficient energy, available power and, in some cases, sufficient network capacity to actually deliver the service. If these resources are not properly managed, services may not be delivered; this would lead to financial penalties for commercial services and could lead to customer disconnection and associated penalties for a PS service. To avoid this occurrence, a method for scheduling services, accounting for the constraints on power and energy of the EES, has been developed.

Step 1: Peak Shaving Priority

Because the first priority of SNS is to ensure security of supply for customers, PS must be added into the schedule before any commercial services are considered. The demand forecast is used to identify the periods of high demand. The power needed to supply the demand above the network capacity is reserved, as is the energy this will require. Finally, SoC adjustment is added to complete the scheduling. This can take the form of charging prior to the service (if the battery is being kept empty), or recharging after the service (if the battery is being kept full. In either case, the SoC adjustments can be overwritten by future services, provided the new services will leave the EES in a position to perform the PS service if required.

Step 2: Commercial Service Layering

Following the PS, commercial services are added one at a time, with each service forming a new layer. The time and duration of the service are specified, as are the maximum power and the delivery time (for example, a service may be available for 3 hours, but only contracted to deliver energy for a 30 minute window). The power tendered by the service is also constrained by the energy and power requirements already set aside for PS. When adding new services, the potential SoC ranges based on the service being either delivered or not delivered are considered, to ensure no future service is dependent on a previous service having been delivered.

Many combinations of services are considered at this stage, with each new service committing as much power as the constraints allow. An example of this service layering is shown in Figure 5. Initially, in (a), the need for peak shaving is identified and the required power and energy are added to the schedule. Next, a power-from-grid service is considered. Fulfilling this service requires the battery to be almost empty, so the need to discharge prior to the service is added. The minimum SoC shows the last point at which the discharge could begin, due to the rate of discharge being limited by the rating of the converters. Finally, a power-to-grid service is added. This service is concurrent with the peak shaving, so the power that can be offered is limited by the amount of power not already reserved. The minimum SoC line shows the last point at which the battery could be charged prior to the service. At the end of the charging period there is a line capacity constraint, leading to charging taking place at a reduced rate compared with the rest of the charging.

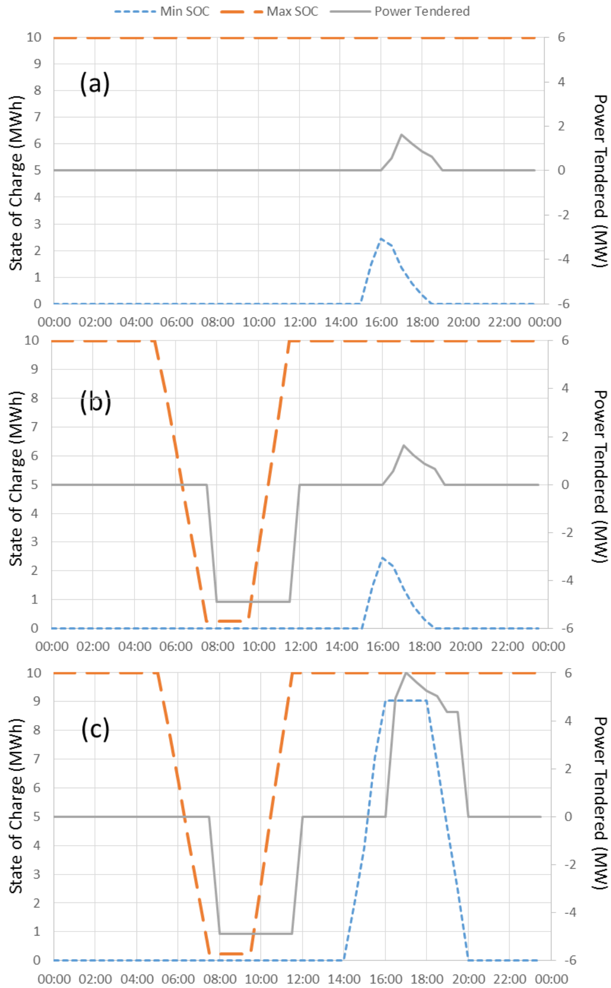

Figure 5: This figure shows layers of services being added to the service schedule, with the minimum and maximum state of charge positions, as well as the amount of power that is being tendered, being shown: (a) shows a peak-shaving service; (b) shows a power-from-grid service being added; (c) shows a power-to-grid service, concurrent with the peak shaving, being added.

The example shows just one combination of services. In operation, each possible combination of services would be considered, and the one with the greatest commercial value would be added to the schedule.

Step 3: Service Valuation and Selection
Once the levels of power and energy which can be tendered for each service combination have been evaluated, the commercial value must be estimated. The value of any service is a combination of:

- Service Availability Fee
- Service Delivery Fee
- Service Energy Value
- Likelihood of the service being delivered

Of these, the energy value is the most complex to calculate. The availability and delivery fees are based on the power tendered and time for which the service is available or delivered. The energy value is dependent on when the state of charge was adjusted and when the service was delivered. In some cases, the SoC may have to be adjusted even if the service is not delivered, reducing the overall value of the services. The price of energy varies throughout the day, with the market always being against the EES (the buying price is always higher than the selling price at a given time).

To consider an example, an ideal situation for EES would appear to be scheduling alternating power-to-grid and power-from-grid services. In this situation, the EES would receive revenue for both charging and discharging. However, in reality the services may not be delivered the majority of the time. This means that costly SoC adjustments must take place between the services resulting in a reduction in value and degradation of the battery. It would be more profitable in this case to schedule only power-to-grid services, meaning that the SoC would only have to be adjusted after service delivery actually takes place.

CONCLUSION

This paper has described the Smarter Network Storage project, which has constructed 6 MW/7.5 MVA/10 MWh of EES at a primary substation in the south of England. The paper described the forecasting and scheduling methods used to ensure that the EES can both solve a network issue, through a peak shaving service, and participate in commercial markets such as STOR and FFR.

The forecasting method uses a Multiple Linear Regression to link electricity demand to factors such as time of day, month and day of week, as well as factors such as recent demand and temperature, which can only be used on short time scales. The error statistics for these models suggest they are in line with the state of the art, implying that the forecasted demand can be reliably used to inform scheduling decisions.

The service scheduling method, which has been developed specifically for this application allows commercial and network services to be added into a service calendar. When these services are added, their impact on the power and energy resources is taken into account. Similarly, the levels of power and energy which can be scheduled are constrained by the available resources. Different combinations of services are considered, and a value calculation is used to select which services will be added into the final calendar.

Although the methods described here have been developed for use with battery based energy storage, they could just as easily be applied to other storage technologies.

Acknowledgments

The work in this paper was supported by Ofgem through the Low Carbon Network Fund. The authors would also like to thank their project partners at AMTSybex, Younicos, National Grid, S&C Electric, Smartest Energy KiWi Power and the Energy Storage Network.

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