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Demonstration of a 200 kW/200 kWh Energy Storage System on an 11kV UK Distribution Feeder

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Abstract—A 200kW/200kWh energy storage system connected to a UK 11kV distribution network has been used to demonstrate a range of operational duties. To maximize the information that can be gathered during the operation of the device, primary and secondary sites have been instrumented to provide power and voltage measurements. Control algorithms have been devised to perform adaptive peak-shaving operations that track the daily variations in time and magnitude of peak power flows. Results are presented from actual network measurements of scheduled power exchange operations and both simulations and trial results of peak-shaving operations. Simulation results are used in an ageing model to determine the battery lifetime effects when allowing alternative depth-of-discharge to be reached.

Index Terms—energy storage, power distribution, power system control, smart grids.

I. INTRODUCTION

Energy storage systems (ESS) could serve as a useful tool for distribution network operators if economically viable applications are shown to be feasible [1], [2]. As well as around the world, a number of energy storage system trials are taking place in the UK, designed to provide practical evidence for the worth of using ESS within the GB power system [3].

Structured trials of a 200 kW (nominal)/200 kWh energy storage system (ESS) built by ABB on UK Power Network's 11kV distribution network commenced in June 2012. This project is serving as a demonstration of the benefits to network operation that can be obtained by including an energy storage system within the 11kV distribution network. Benefits include the regulation of network voltages and management of power flows within the network.

To provide the data necessary to evaluate the trials carried out on the ESS, a deployment of instrumentation has been undertaken in addition to the actual ESS. Control algorithms have been produced so that many trials can be carried out under automatic control. Trials have shown the effect of operating the ESS under a range of control methodologies.

In this paper we describe the network, ESS and instrumentation that has been installed, then explain the

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control system that has been built to control the ESS. Results and conclusions from simulations and trials are given.

II. NETWORK

This network, close to Great Yarmouth in the UK, has been described in previous publications [4]. In brief, the ESS is located as shown in Fig. 1, at a normally open point at the remote ends of Feeder 1A and Feeder 2B. A 2.25 MW windfarm, comprising ten Vestas V27 225 kW turbines, is located mid-way along Feeder 1A. The feeders are predominantly built of over head line and serve a semi-rural combination of domestic, farming and holiday park customers. The area is not on the gas grid so there is a significant electric heating load. Feeder 1A has peak demand (2.4 MW) occurring between 1 and 2am due to night storage heating, whereas Feeder 2B has a contrasting daytime peak (4.6 MW) when holiday parks have a high occupancy.



Figure 1. Primary and seconary instrumentation points in demonstration network 11kV feeder.

III. ENERGY STORAGE SYSTEM

ABB supplied the energy storage system to UK Power Networks in April 2011 and this was followed by an extensive period of testing and troubleshooting. This was the first installation on a GB distribution network of large scale energy storage and it brought several practical challenges across a range of topics including protection and safety. Although significant and important when considering the learning achieved from demonstrating an ESS, these challenges are not the focus of this paper.

The ESS is based on ABB's SVCLight product, with the addition of battery modules supplied by Saft to provide real power capabilities. The system can operate in four quadrants, simultaneously exchanging real and reactive power with the network in either forward or reverse direction. The converter is rated at 850 kVA which permits 600 kW and 600 kVAr to be transferred simultaneously. The battery modules are able to deliver 600 kW of power, but the nominal rating of the system is 200 kW equating to a 1-hour operation. Using the nominal power rating will also limit the ageing effects of high current levels in the battery stacks. Battery lifetime is significantly affected by depth of discharge; the number of times the battery can be cycled before reaching its end of life drops dramatically if discharged deeply. The effect of this can be seen in Fig. 2 [5].

The ESS is controlled by ABB's Mach2 system, which is also used in their HVDC and STATCOM products. It presents an operator with a Human Machine Interface (HMI) that can be accessed remotely to enable operation by UK Power Networks staff from any location. Real and reactive power setpoints can be set explicitly and a wide range of system parameters are reported back to the operator. An automatic voltage control function is provided by ABB which uses a voltage slope characteristic to control the reactive power output of the ESS. The slope characteristic shown in Fig. 3 illustrates how increases in voltage above the deadband cause a draw of reactive power, whereas under-voltages cause an output of reactive power. The slope parameter indicates how much reactive power is applied for the given voltage deviation outside of the deadband.

A logging function is implemented in the Mach2 system to record a wide range of system parameters at a configurable interval down to a 1-minute resolution.



Figure 2. The effect of depth of discharge on lithium-ion battery cycle life



Figure 3. Automatic voltage control voltage-reactive power characteristic.

IV. INSTRUMENTATION

Distribution networks are usually instrumented as far as the primary substation, where busbar voltage and feeder current are reported to the DNO control room over a SCADA system. In this project, instrumentation has been progressively added to the primary substations and at strategic secondary sites to bring a 1-minute temporal resolution measurement capability at key points in the system. Typical locations for these measurements are indicated by the 'measurement points' in Fig. 1.

Secondary sites communicate with core IT infrastructure using GPRS modems, while primary sites connect to the core over ADSL lines. At each site, measurements are made of some or all of; three-phase real power, reactive power and voltage. There are two reasons for adding instrumentation to the network; the provision of measurements and inputs to the control system. Each of these purposes are listed in Table I.

TABLE I. PURPOSE OF NETWORK INSTRUMENTATION

Measurement	Control
Verification of	Input to control algorithm
Model accuracy	Wind farm power output
Invervention with ESS	Feeder real power flows
Network characteristics	Feeder reactive power flows
	Feeder voltages

ABB's COM600 substation computer is used to gather the network data, host the control algorithms and issue control commands to the ESS. The COM600 is located at the ESS where it is directly connected to the MACH2 control system. Remote terminal units (RTUs) at the primary and secondary sites (distribution transformers, distributed generation sites and breakers) are polled by the COM600 at regular intervals. All the gathered values populate an OPC server on the COM600, which can be read by the control algorithm software. To control the ESS, real and reactive power setpoints are written to the OPC server which then transfers them for implementation at the ESS.

For trial purposes a logging system has been put in place to continually record all available network data points for analysis. Python programming language code writes data from the OPC server to a MySQL database at 1-minute intervals.

V. AUTOMATIC CONTROL

To carry out a substantial series of trials, it is necessary to operate the energy storage system under automatic control. A manual operator would not be able to track and respond to the required control variables. The control algorithms are written in Python. The algorithm can read required variables from the OPC server, process them in a flexible manner and issue setpoints for implementation on the ESS. Control algorithms run at a 1-minute interval, reflecting the update rate of the network measurement system.

The core control algorithm can be configured to respond to any of the values from instrumentation points on the network; this is called an 'event', with an associated 'location'. The chosen network measurement is compared against a threshold value; when the value is exceeded, a set-point (the 'action') is calculated for implementation on the ESS via the OPC server. The calculation of the set-point is dependent on the specific detail of the event and action that is being processed.

As an extension to the basic event, location, threshold, action, process described above, an algorithm has been developed to track time and magnitude of peak power flow occurring on the feeder. This function is required for this demonstration project because the daily and seasonable variability in feeder power flow would lead to either limited use or frequent saturation of the ESS's energy capability if a fixed peak-shaving threshold was selected. By adapting the switching time window and trigger level for peak-shaving, the battery energy resource is used in a way that will maximize the operating time of the ESS. This is vital in a demonstration project because increased learning will be obtained from increased operational experience.

The adaptive peak-shaving algorithm operates at a specific measurement point in the network, typically the feeder power measured at the primary substation. Historical data is used to identify a time window during which the peak event is expected to occur. Within this window a threshold power value is used to initiate the peak-shaving action. This has been tested in simulation and practice, the results from both are presented here.

Further to the event driven algorithms described previously, a scheduling system has been developed to provide a facility to run repeated set-point combinations on the ESS. This provides the capability to carry out sequences of tests on the ESS that are designed to verify the operating parameters of the system. Efficiency, power and energy tests will be repeated in a variety of combinations to build up a picture of behavior over many operating cycles.

VI. RESULTS

The high-resolution 1-minute resolution monitoring at the ESS has provided detailed records of the interaction between the real power exchange, voltage at the point of common coupling (PCC) and reactive power compensation action. In Fig. 4, scheduled real power exchanges are seen to take place, with a charging operation beginning at 13:00 and a discharge (to cover peak demand) from 17:00. During the discharge operation a voltage rise takes place on the network at the PCC.



Figure 4. Real and reactive power exchanges and corresponding voltage measured at the ESS point of common coupling (PCC).

This is compensated for by a draw of reactive power from the network according to the slope characteristic described in Fig. 3.

The adaptive peak-shaving algorithm has been simulated with recorded historical network data to verify its behavior before operating in a live network environment. Fig. 5 shows how the feeder power is modified by the application of a peakshaving operation with 150 kWh made available from the total 200 kWh system energy capacity. Recharging operations are carried out in the lowest demand period found during night time.

In addition to allowing testing of the peak-shaving algorithm, the simulation has been run with a series of allowable battery depth of discharge (DoD) settings. This has allowed exploration of the effect of the operating regime on the ageing of the battery. Under three alternative allowable



Figure 5. Simulation results from peak-shaving algorithm, with 150 kWh allocated for use from the ESS.

DoD levels, the algorithm produces a different pattern of usage for the ESS. These can be seen in Fig. 6. The maximum DoD is reached on the Monday afternoon shown in the figure.

The battery manufacturer, Saft, has run the power data through their battery ageing model, to predict the resulting lifetime under these different conditions. The results show that the battery lifetime will change as shown in Table II, if the allowable DoD is 50%, 62.5% or 75%.

TABLE II. LIFETIME WITH ALTERNATIVE DEPTH OF DISCHARGE

Depth of Discharge	Capacity loss per annum
50%	1.1%
62.5%	1.2%
75%	1.5%

This process provides an input to economic considerations of using energy storage under alternative operating regimes.

Several examples from peak-shaving operations on the actual network are shown in the following Figs. 7—9. It should be noted that these are initial results that confirm successful operation under automatic algorithmic control, but do not necessarily provide the best results that can be achieved after further experience of operating the algorithm is obtained.

Charging operations are programmed to take place at night time, during periods of low demand. Measurements are taken from the network at 1-minute intervals and exhibit a high degree of variability from the rolling average. In Fig. 7 the behavior of the algorithm during a charging operation can be seen. The actual feeder power of the solid black line 'Feeder-P' is contrasted with the power would have flowed '[feeder-P]' without using the ESS. Also shown are the power received by the ESS 'ESS-P' and the resulting battery state-ofcharge 'SoC'. It can be seen that during the charging operation the feeder power is raised to provide the battery



Figure 6. Battery energy level during adaptive peak-shaving algorithm operation with alternative allowable depth of discharge. Power exchanged is shown for the 75% DoD case to indicate the pattern of power exhange.



Figure 7. Overnight charging of ESS during period of low feeder demand.

charge, but modulated so as to ensure substantial power increases are not applied to the feeder.

Two contrasting examples of peak-shaving operations are given in Figs. 8 and 9. In the first the underlying peak is of a relatively high absolute level and is sustained for three hours above the trigger level of ~1.8 MW. This is a challenge to address with the 130 kWh available (chosen allowable SoC range of 20-85%). However the result in the first hour is to successfully limit the maximum power, even though by the second hour of the peak, the battery power is exhausted.

In Fig. 9 the main peak is caught by the algorithm, and then followed by a dynamic period where the operation threshold is crossed repeatedly. The ESS adjusts the power level in direct response to the measured feeder power.



Figure 8. Peak-shaving operation in which a steady increase in power exhausts the available battery energy capacity before the evening peak is complete.



Figure 9. Peak shaving operation in which the evening peak period is covered within the battery energy capacity.

VII. DISCUSSION

This project has proven automatic, algorithmic control of an ESS connected to the remote end of a 11kV distribution feeder on a UK distribution network. Instrumentation is collecting high resolution measurements of key network parameters that allow detailed assessment of the behavior of the ESS and network during peak-shaving and future planned operations.

The primary purpose of this project has been to explore practical and technical features of planning, deploying and operating energy storage on an 11kV distribution network. Detailed evaluation of the financial benefits that can be derived from installing and operating energy storage on distribution network is an important and closely related activity. This project will provide valuable data for informing financial assessments.

A recently funded project has been designed specifically to develop a business model that will enable cost effective use of energy storage in a distribution network. This will defer the reinforcement of an overloaded primary substation and participate in other markets when not required for use by the DNO. UK Power Networks are running this 'Smarter Network Storage' project, more information can be found on the Ofgem (UK energy regulator) website [6].

VIII. CONCLUSIONS

Energy storage systems are being widely investigated as a means to provide distribution network operators with a new tool in their network design and control operations. This project has begun to deliver comprehensive data about both the network performance and ESS itself which will give DNOs the capability to make a detailed assessment of the value of operating an ESS within their network.

High resolution network and ESS data is being recorded to ensure that the operational behavior is recorded for full analysis. This will ensure that previous assumptions are verified so that device and network models can be relied on for this project and future studies.

Operation of the storage device has been proven with a combination of both real and reactive power flows. An algorithm for adaptive peak-shaving has been implemented that will provide a considerable quantity of events for analysis purposes within this demonstration project. Battery lifetime analysis can be produced for all operating regimes that are tested during the trials.

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