MODELLING AND OPTIMISATION OF ENERGY STORAGE SYSTEMS IN POWER DISTRIBUTION NETWORKS

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ABSTRACT

Energy storage offers an alternative to network reinforcement which could work alongside the implementation of new network architectures to facilitate more effective network operation. This paper presents a method by which energy storage can be represented in a power systems simulation using equivalent generators and a modified optimal power flow (OPF) algorithm. The method is demonstrated by a case study based on the Orkney smart grid.

INTRODUCTION

The use of energy storage systems (ESS) has been proposed for a number of applications in modern power networks [1]. These range from arbitrage systems which produce profit for the owner to systems designed to support network power quality and system stability. Storage can also be used to level peak loads, which in turn could allow more generation to connect in areas where line reinforcement is impractical.

The use of storage however, except large pumped storage units, is still rare despite the theoretical benefits being well known. A lack of knowledge about how well storage is capable of performing these roles is inhibiting practical development [2]. A capability to effectively model energy storage in individual scenarios would facilitate more detailed research and provide a key step towards widespread commercial utilisation of this technology.

MODELLING ENERGY STORAGE

The simplest method for modelling energy storage would be to use one generator, with an output that matches that given for the storage system, before running a power flow study. However, many applications being considered for modern storage systems involve real-time control; the ideal solution would be able to simulate control of the storage without extensive user interaction.

One alternative method would be to produce a full mathematical algorithm for the problem, which can be solved to determine how the storage acts on the network [3]. In addition to constraints such as voltage and thermal limits, the characteristics of the storage system are added to fully define the problem. It would, however, be simpler and preferable to adopt a method that uses existing algorithms. This can be done by using two equivalent generators to represent the storage.

The first has a fixed output as before and describes any pre-programmed control – for example to discharge until empty or to follow a schedule. A second generator is then added which will have a flexible output for the time period; its output is determined by existing techniques to maintain system stability. The limits of these are defined by the properties of the storage.

For example, consider a system with a power rating of 10 MW used to improve energy export from an islanded network. This can be described by two generators as shown in Figure 1; one has a fixed output of 10 MW and a second with varies between -20 and 0 MW, giving the full ±10 MW.

P_R: Fixed – Continuously Discharges Storage
P_F: Flexible – Varies with Network Constraints

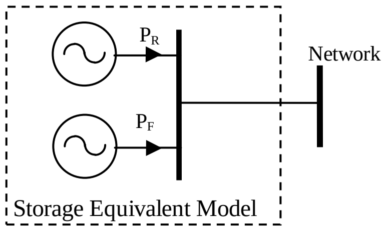

Figure 1 - Energy Storage by Generator Equivalents

Determining the output of the flexible generator for each time period can be done by using an optimal power flow algorithm [4]. By defining an objective that is dependent on the different generators and/or storage on the network, the OPF can be used to identify and alter generation or storage to fit with a desired operating architecture (e.g. the maximisation of energy export)

Modelling storage in this way is useful as there are no new additions that have to be made to the analysis tools available in most commercial power systems packages. This method allows the scenario to be assessed in detail, by considering the storage in relation to the limits of each line and generator on the network, and its location within it.

The disadvantage is that the original objective of the OPF is lost. Whilst it might be possible to accurately cost the use of storage over all other scenarios to produce a totally comprehensive model, this might be very difficult in practice; the objective that is defined may often just be used to prioritise between different technologies in a very simple way. In privatized or regulated markets, this prioritisation might not reflect a feasible solution for the actual network.

Many applications for energy storage are being considered at this time; some of these, along how they can be represented using the equivalent generator model, are shown below in Table 1.

Mathematical Representation

The equivalent generator representation can be derived mathematically following the process below.

By necessity the system must be considered in discreet time intervals. The relationship between the charge, *S(t)*, of two consecutive time intervals is given by [5]

$$S(t+1)=\begin{cases} S(t)-\dfrac{1}{\eta_d}P(t)\Delta t & P(t)\geq 0 \\ S(t)-\eta_c P(t)\Delta t & P(t)<0 \end{cases} \tag{1}$$

Where *P(t)* is the operational power (discharge being positive) of the storage averaged over the time interval, Δt. η_d and η_c represent the charging and discharging efficiencies. *P(t)* is determined by the OPF, but limits must be defined to ensure that the model operates within the specification for the system. Firstly, the charge must remain within limits set by the capacity, *C*, and an acceptable depth of discharge, *d*.

$$C(1-d)\leq S\leq C \tag{2}$$

These limits will restrict the average power that the ESS can operate at, the maximum allowable charge and discharge rates according to the system capacity being given by

$$P_{ca}=-\frac{C-S(t)}{\eta_c\Delta t} \tag{3}$$

$$P_{da}=\frac{[S(t)-C(1-d)]\eta_d}{\Delta t} \tag{4}$$

Discharging is then positive and charging negative, which matches with the use of generators as equivalents. The system will also have a maximum power rating, P_{ESS}, and so these are modified again to give the maximum possible charge and discharge powers for the time interval.

$$P_{cm}=\max(P_{ca},-P_{ESS}) \tag{5}$$

$$P_{dm}=\min(P_{da},P_{ESS}) \tag{6}$$

To produce the two equivalent generators, an appropriate algorithm should be developed to describe what we want the storage to do under normal conditions, denoted P_R. This would relate to the intended objective of the storage, e.g. charging or discharging according to a spot price or maintaining a target system charge. The output of the fixed generator is calculated by comparing P_R to the practical limits determined previously.

$$P_{Fixed}=\begin{cases} P_{cm} & P_R<P_{cm} \\ P_{dm} & P_R>P_{dm} \\ P_R & \end{cases} \tag{8}$$

The limits of the flexible generator are then defined. Since the system has to operate within the limits,

$$P_{cm}\leq P\leq P_{dm} \tag{9}$$

where

$$P_{Min}\leq P_{Flex}\leq P_{Max} \tag{10}$$

$$P=P_{Fixed}+P_{Flex} \tag{11}$$

We can rearrange these to determine the limits for the flexible generator

$$P_{Max}=P_{dm}-P_{Fixed} \tag{12}$$

$$P_{Min}=P_{cm}-P_{Fixed} \tag{13}$$

The flexible generator represents the fact that, due to network constraints, the desired operation cannot always be achieved. The objective of the OPF should be designed to prioritise between elements such as the storage and generation, selecting which of the two is varied first.

Application	*Description*	*Purpose of Fixed Generator*	*Purpose of Flexible Generator*
Arbitrage	Generates profit by storing and releasing energy according to the spot price	Charges or discharges storage according to energy price – an exact value or profit margin	Models network constraints preventing use of the system
Load Levelling	Lowers peak line loads and increases non-peak loads to average the load over time	Charges or discharges according to an expected schedule or to keep a specific line load constant	Varies freely to model storage constraints restricting the desired operation
Constraint Removal	When generation is higher than acceptable, stores excess energy to release later – preventing curtailment	Discharges the storage at all times to release energy onto the network	Models network limits, and charges when generation levels are too high
Network Support	Energy storage charges or discharges to improve network stability, e.g. frequency and voltage levels.	Maintains a fixed level of charge, with energy to discharge but also spare capacity to allow charging	Allows divergence from target charge, using the system to improve network operation

Table 1 - Modelling Different Storage Applications

The limits already incorporate the effects of efficiency. To account for self-discharge, we can modify the charge on the system at each interval by a multiplier to provide a reasonable approximation of energy loss over one interval.

$$S_{actual}(t+1) = S(t+1) \times (1-\Phi)^{\Delta t / T} \qquad (14)$$

Where Φ is the fractional self-discharge measured over a time period, T; the power term scales the self discharge down to that experienced in a time interval.

CASE STUDY

To demonstrate this model, a case study was implemented using MATPOWER [6]. The Orkney distribution system, shown in Figure 2, was chosen as the test network; actual network data is obtained from the network owner. It is a good example of where storage could be applied in a real scenario. Orkney is a Scottish island located in the northern part of the country. It contains a large amount of renewable generation, some of which is curtailed during periods of high output due to limited export capacity. Energy storage could be configured to store this curtailed energy and release it in times of low load, which over the year would increase the amount of energy exported from the network.

The model is representative of the network over the period of a year which is required to fully model seasonal variations of the network loads and generators.

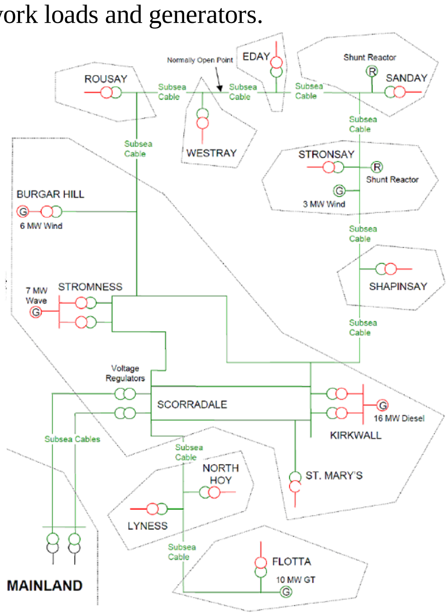

Figure 2 - Orkney Distribution Network [7]

The storage model is as described in Table 1; the fixed generator model is configured to empty the storage in the absence of other factors. Cutting off excess generation is given a 'cost' higher than that of the flexible generator, so that the OPF algorithm will curtail generation as a last resort, using the storage to accommodate excess energy first. The grid connection is assumed to have a demand for any exported energy; this effectively models a system where storage is used to prevent wastage of renewable resource. Where spare capacity is available, the storage system is discharged, represented by the fixed generator in the model.

SIMULATIONS

A number of empirical tests were performed to better understand the storage model's impact on the performance of the network. In this case, looking at how the amount of energy exported from the island network to the grid can be increased.

Figure 3 shows one study, where the effects of both the system power rating and capacity are considered. It also shows individual points of interest (e.g. the low performance relative to the general curve at approximately 2 MW). This lead to the discovery that for systems of this size the storage would become saturated, as the low power rating prevents effective use of gaps between generation to discharge the system; emphasising the importance of choosing a power rating based not only on the requirements for absorbing excess generation, but also for discharging the system in a short time-scale.

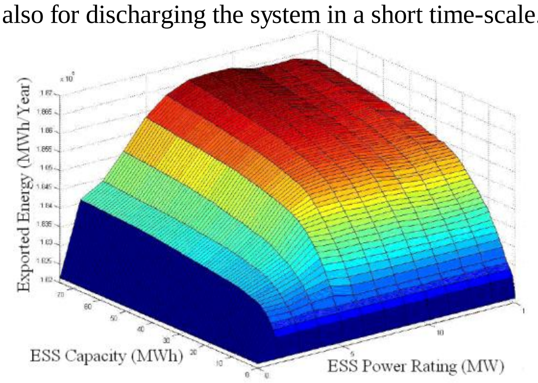

Figure 3 – Energy Storage Rating Study

The one disadvantage of the OPF method used here is that the algorithm may fail to converge. If the power rating is higher than the network capacity then there is a risk of convergence failure which would then understate the benefits of the system. This is shown in Figure 3 by the decreasing effectiveness at high power ratings, which in the operational case would plateau instead. This can be avoided through appropriate selection of the maximum power rating.

The model can be used to compare different technologies. For the application considered here, a variety of systems were considered with a base cost of €10 million, the results are shown in Table 2 (The base export is 182,120 MWh). It was found that the traditional lead-acid battery is an effective choice. A larger system can be built using lead acid cells than any other. The system may fall behind though due to other issues such as lifespan. Flow batteries show promise as a potentially more effective system, but lack maturity. Four different flow batteries were compared due to the variability of the systems and their predicted costs; as can be seen, the effectiveness can vary greatly.

Storage Technology	*Exported Energy*	*Flow Battery*	*Exported Energy*

	(MWh/Year)	*Technology*	*(MWh/Year)*
Sodium Sulphur	185,321	**A**	185,713
Lithium Ion	185,876	**B**	186,529
Lead Acid	186,334	**C**	186,137
CAES	185,555	**D**	185,202

Table 2 – Comparison of Storage Technologies

OPTIMISATION

The analysis presented here can be made more powerful by the inclusion of an optimisation tool, which would allow users to determine the most effective storage system for a particular application and network automatically, as well as aiding other studies. Genetic algorithms (GA) have been considered previously for energy storage problems [8]. These are useful for multiple objective problems that contain non-linear constraints such as trying to achieve more than one function with the storage, or performing cost-benefit analysis.

Using a GA to perform the optimisation, based on the Strength Pareto Evolutionary Algorithm 'SPEA2' [9] the test problem was extended. The new formulation can optimise any combination of the storage system's characteristics, including its location on the network, based on one or more objectives.

An example of the GA applied to the test network is shown in Figure **4**, where the algorithm tries to improve energy export, whilst minimising the system cost, two objectives that could reflect different stakeholder's points of view. Flow battery technology is considered, using representative figures for the cost of the system. A Pareto front [9] is produced, showing the most effective storage systems for a range of costs. Since the increase in export from the network will have associated revenue, it is then possible to consider profitability or return of each system.

An expected system lifetime of 20 years is marked. Given optimistic figures for cost and revenue the system appears to be at least cost-neutral, although more realistic figures would suggest that the system is not cost-effective at this time (for this network and application).

CONCLUSIONS

The model presented here allows storage systems to be readily incorporated into an optimal power flow algorithm, removing the need to prepare an algorithm especially for solving storage problems. It also allows the use of optimisation techniques to provide effective solutions.

The Orkney case study shows how energy export from an islanded network can be increased without the need for infrastructure reinforcement by the use of storage; demonstrating commercial analysis that could be performed to evaluate the economic value of a system or the storage technology which should be employed.

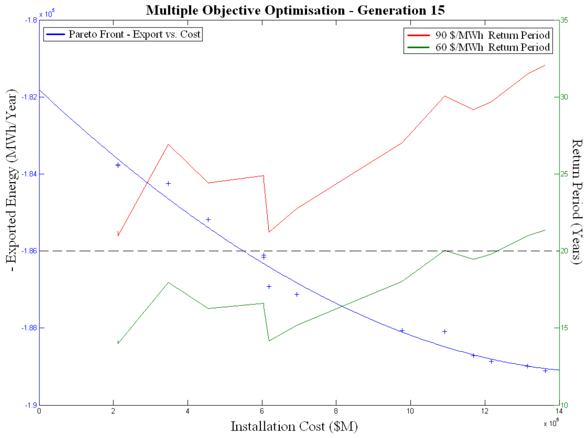

Figure 4 - Optimisation Using Genetic Algorithms

There are a range of applications (see Table 1) which storage could be applied to; future work would consider the use of multiple storage systems and incorporate the effects of frequent use and system's effective lifetime.

Wide-scale adoption of energy storage, particularly small distributed units matched to local distribution networks could make the network more efficient. Microgrids with appropriate storage would facilitate autonomous operation managed in real-time, with the effect of reducing the need for large infrastructure at both local and national levels.

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