ARTICLE IN PRESS

Applied Energy xxx (2014) xxx–xxx

Contents lists available at ScienceDirect

Applied Energy

journal homepage: www.elsevier.com/locate/apenergy

Technoeconomic feasibility of grid storage: Mapping electrical services and energy storage technologies

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HIGHLIGHTS

- Metrics for characterizing grid services relevant to energy storage are presented.
- Metrics for the characterization of energy storage technologies are examined.
- A method for comparing these characteristics is developed.
- A technoeconomic strategy is developed to identify overlap between services and storage tech.

ARTICLE INFO

Article history:
Received 7 January 2014
Received in revised form 3 March 2014
Accepted 16 April 2014
Available online xxxx

Keywords:
Storage
Energy
Electricity
Battery
Arbitrage
Regulation

ABSTRACT

Energy storage technologies can provide services to the electricity grid that are necessary for its usability, stability, and reliability. The services, such as power factor correction and renewable energy arbitrage, are defined by duration, cycling occurrence, power, and market price. Storage technologies suitable to these applications, such as pumped hydro and batteries, are defined by their usable energy, power, efficiency, operating range, availability, lifetime, and cost.

In this article, grid services and storage technologies are examined using a range of metrics. Through a series of figures and discussions, the reader is provided with a method for comparing universal characteristics with regional/technology specific values. This provides a guiding strategy to help identify overlap between service needs and storage technology capabilities, so as to aid in the specification and selection of systems for present and future grid storage opportunities.

1. Introduction

In modern day electricity systems the uncontrolled load of end-use consumers (i.e. industrial, commercial, and residential) is supplied with electricity from generators in real-time through transmission/distribution infrastructure. The uncontrolled load may vary dramatically throughout the day and seasons depending upon end-uses, schedules, and climate, although it is reasonably predictable. Generators and transmission/distribution are both limited in absolute power capability, while generators also experience constraints on ramp-rate, start-up/shutdown, and minimum operating power. Beyond bulk generation, the variation in load necessitates electricity grid services that can respond appropriately and thereby maintain system stability and reliability. These services can be classified into two groups, those needed for expected events such as increasing or decreasing load (e.g. load following and frequency regulation), and those needed in case of unexpected events (e.g. contingency reserves and black start capacity).

With the recent and continuing addition of substantial quantities of non-dispatchable renewable electricity generators, such as wind turbines and solar photovoltaic, a growing fraction of generation has now also become "uncontrolled". These new generation variations have therefore increased the intensity and range of necessary electricity grid services; for example, load may be increasing in the evening while the sun is setting, and the associated photovoltaic output decreases. Numerous researchers discuss the need for enabling technology to facilitate the integration variable generation sources [1,2], and storage is often considered the most viable [3–5]. The need to provide such services is an opportunity for energy storage technologies, such as pumped

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http://dx.doi.org/10.1016/j.apenergy.2014.04.050
0306-2619/© 2014 Published by Elsevier Ltd.

hydro [6–9], compressed-air [3,10–13], batteries [5,14–17], and flywheels [18–19].

Several tools have been developed to evaluate the suitability and economics of storage to grid services. These have been categorized by [20] into two groups. The first use existing market prices, implicitly inferring that the system under investigation will not significantly change market conditions. The second do not make that assumption, but require extensive knowledge of economic dispatch and unit commitment, and revise system operation to reflect the effects of the investigated system. The former group includes ES-Select from Sandia National Laboratory [21], and EPRI's Energy Storage Valuation Tool [22], while the later class of tools, referred to by [20] as 'Commercial Production Cost Models' includes energy system modelling software such as PLEXOS [23,24], PROMOD [25], and PROSYM [26].

Before the implementation of such complex models, there is a need for a simple scoping and viability tool. In response to evolving opportunities, the USA Department of Energy and Electric Power Research Institute have recently published the Energy Storage Handbook [27]. The Handbook is intended as a guide for engineers, planners, and decision makers to propose and implement energy storage projects in their respective electricity systems. We find the Handbook to be a tremendous source of technical information on services, storage technologies, and system considerations. However, we feel that the short section on methods and tools for storage system specification and evaluation could be enhanced by additional a technical analysis and descriptive guide to facilitate project pre-qualification.

It is therefore our objective in this article to provide a description of a method, supported by technical figures that augment the Handbook, which enable engineers and planners to contrast and compare electricity grid services and storage technologies in the context of their regional electricity grid power requirements and market pricing. First, specific services are examined by universal characteristics such as duration and cycling occurrence, and then by regional power value and market price so as to determine opportunities and necessary characteristics of the storage. Second, specific storage technologies are examined by their usable energy, power, efficiency, operating range, availability, lifetime, and cost.

It is intended that through the series of figures and discussions, the reader will identify overlap between their specific service needs and available storage technology capabilities. This will aid the engineer and planner in the specification and selection of storage systems for present and future grid service opportunities.

2. Electricity grid services

Electricity grid services may be broadly defined by characteristics such as duration, cycling occurrence, power, and market value. Within the industry, these services are grouped in categories according to market definition and system operation, and are labeled with industry terms such as "regulation" and "reserves". In this section we examine these characteristics and service groups and provide definition to the terms. We then examine the categories to determine relationships and constraints which necessarily define and bound the performance that services will demand from energy storage.

2.1. Service characteristics, categories, and operational envelope

Electricity grid services, distinguished here from bulk energy, share certain common characteristics, regardless of the specific electricity grid and its generation, transmission, distribution, and load. These common characteristics are:

- *Duration*: the length of time over which a service is provided. Duration is dictated by natural time constants such as load variation, generator start-up period, and renewable resource (e.g. solar day).
- *Cycling occurrence*: the number of times a service is implemented within a period of time, such as a year. Note that availability to provide a service may be continuous, but that it may only be implemented (i.e. called upon) infrequently.

Within a specific electricity grid, several regionally unique aspects arise due to the type and scale of generation, transmission, distribution, and load. The regionally specific service characteristics are:

- *Power*: the power requirement is specific to the size, features, and interconnectivity of the regional grid. Note that provision of services by storage requires that power be both taken from and delivered to the electricity grid.
- *Market value*: the price paid for delivery of the service at the time and location necessary for the electricity grid.

In addition to these common characteristics, services can be labeled and categorized according to where within the grid they are implemented. These categories and services are dictated by the electricity grid topology and are: generation side, transmission/distribution side, and load side, as defined in Table 1.

Time-shifting and peak/valley limiting involve transfer of energy by up to several hours, and have market values based upon energy (MW h) and possible power provision (MW). Other services tend to be based upon power (MW) due to a focus of power provision "as necessary", or for contingencies (e.g. black start). The reader should note that the service titles given in Table 1 may not be consistent with their specific electricity grid, as terms are not entirely uniform across the industry.

The services listed in Table 1 may be compared by examining common characteristics of duration and cycling occurrence. The operating envelope of particular services according to these terms is shown in Fig. 1. Load side services have been excluded for clarity and to focus on assets owned by electricity utilities (i.e. generation and transmission/distribution). The envelopes are mostly rectangular as a matter of convenience, but illustrate typical values. A black dashed line corresponding to "constant cycling" has been added to Fig. 1, and represents the maximum number of cycles possible within a year given the service duration. The reader should recognize that energy storage necessitates a charge period following discharge, so a 1 h service duration results in 4380 cycles/year, not 8760. Thus, any service extending to the right of that line must be asymmetrical with respect to charge and discharge time (e.g. a discharge service having a much higher charge rate).

Fig. 1 shows that services cross several orders of magnitude with respect to both duration and occurrence. This indicates that a similarly broad range of capabilities will be required of energy storage [29,30,32,33].

2.2. Technical requirements of grid services

Technical requirements of grid services are dictated by the common characteristics of service duration, cycling occurrence, and the regionally specific characteristics of power.

Historically, many grid services have been provided by generators operating at 50% power output, giving them the ability to increase or decrease output as required by the electricity grid.

Please cite this article in press as: Pearre NS, Swan LG. Technoeconomic feasibility of grid storage: Mapping electrical services and energy storage technologies. Appl Energy (2014), http://dx.doi.org/10.1016/j.apenergy.2014.04.050