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Capacity value of energy storage in distribution networks

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A B S T R A C T

Security of supply in electricity distribution networks has been traditionally delivered by conventional assets such as transformers and circuits to supply energy to consumers. Although non-network solutions, such as energy storage (ES), can also be used to provide security of supply by carrying out peak shaving and maintaining supply for the duration of a network outage, present network design standards do not provide a framework for quantifying their security contribution and corresponding capacity value. Given the fundamentally different operating principles of ES, it is imperative to develop novel methodologies for assessing its contribution to security of supply and enable a level playing field to be established for future network planning. To this end, a novel probabilistic methodology based on chronological Monte Carlo simulations is developed for computing the Effective Load Carrying Capability (ELCC) of an energy storage plant. Substantial computational speed-up is achieved through event-based modelling and decomposing between energy and power constraints. The paper undertakes, for the first time, the in-depth analysis of key factors that can affect ES security contribution; plant and network outage frequency and duration, network redundancy level, demand shape, islanding operation capability and ES availability. ES capacity value is shown to decrease in networks with an unreliable connection to the grid; time to restore supply is shown to be more important that frequency of faults. Capacity value increases in cases of peaky demand profiles, while the ability to operate in islanded conditions is shown to be a critical factor. These findings highlight the need for sophisticated network design standards. The proposed methodology enables planners to consider ES solutions and allows network and non-network assets to compete on an equal basis for security provision.

1. Introduction

Energy storage (ES) is uniquely positioned to increase operational flexibility of electricity systems and provide a wide range of services to the grid [1], providing whole-system economic savings across multiple timeframes and voltage levels [2]. These services include temporal energy arbitrage and peak reduction [3,4], ancillary services provision to the TSO [5], improving power quality [6] as well as reinforcement deferral management of long-term investment uncertainties [7]. Similar services can be provided at the distribution level through embedded ES resources. For example, the authors have published on ES's potential for deferring network upgrades [8] and peak shaving [9,10]. In this vein, National Grid in their annual Energy Futures report [11], states that the volume of distribution-connected storage could be up to 13.2 GW by the year 2040.

1.1. Problem statement

Despite the immense potential of ES to revolutionize the energy landscape, the relevant policy and regulatory developments in many jurisdictions are not yet mature enough to support this transition [12]. To achieve system-efficient levels of deployment, it is imperative that ES owners can access all possible services that ES can provide and be remunerated accordingly. However, the present distribution network design standards do not recognize the contribution of ES to security of supply. The present network design standards consider only traditional network solutions, such as transformers and circuits. This prevents ES from competing fairly with other assets; having a *level playing field* across technologies is essential for fostering the efficient level of investment in storage projects. This gap is a topical discussion point across many jurisdictions. For example, in the UK's ongoing standard review by ENA, establishing level a playing field between traditional assets based network reinforcement and the application of non-network technologies (such as ES) through quantifying their security contribution is a very prominent issue. In a similar tone, CAISO stakeholders are in discussions on how to incorporate ES in resource adequacy studies [13].

The first step towards formally remunerating an asset's ability to

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contribute to security of supply is to compute its capacity value. The term *capacity value* refers to the dependable capacity a storage plant can provide upon which a network planner can rely so as to avoid network reinforcements triggered by an increase in demand. Until now, research has been primarily focused on distributed generation (DG) resources. Comprehensive overviews of different methods for calculating the contribution of conventional and renewable generation are provided in [14–16]. In contrast, there have been few efforts to extend the concept of capacity value to ES and a number of conceptual and methodological obstacles remain unaddressed. The objective of this paper is to develop a comprehensive framework for computing the capacity value of energy storage. The developed methodology is necessary for enabling the further development of new security standards that allow distribution network planners to compare traditionally-used network assets, such as transformers, against energy storage.

1.2. Energy storage vs. conventional assets

ES is fundamentally different to other energy assets, warranting the development of a new capacity value calculation method.

(i) First of all, whereas DG is solely power-constrained i.e. its output depends solely on technical/resource availability and power rating, ES is also energy-constrained i.e. it must have both sufficient power output capability and energy stored to supply the load. In other words, whereas conventional assets typically face only power constraints, storage facilities face both power and energy constraints, rendering their preceding operation history highly relevant.

(ii) A second point is that whereas the fuel supply of DG is considered unconstrained (e.g. diesel generators) or stochastic (e.g. wind generators), ES's state-of-charge (SOC) is tightly linked to the network's available transfer capability. ES does not generate power but rather makes use of existing network assets to draw power from the upstream grid. This has two implications:
- Network outages and other supply-side faults have an impact on ES ability to charge. In contrast, supply-side faults have no bearing on DG performance provided it can operate in islanded mode.
- Both the magnitude and the shape of demand are relevant since they dictate the available network import capability which can be used for ES charging. In contrast, electrical demand has no profound effect on the performance of conventional asset such as DG and network assets.

  To summarize, whereas the security contribution of a transformer or DG depends solely on the asset's rated output and resource availability, ES contribution depends on:

(iii) Energy, power and efficiency ratings of the storage plant;

(iv) Frequency and duration of network and ES outages;

(v) Redundancy level at which the network is being operated (e.g. N-0.5 instead of a strict N-1 criterion);

(vi) Magnitude and temporal characteristics of demand

It is important to note that the above-listed factors driving the capacity value of energy storage have not been yet considered in existing approaches, resulting in a lack of methods and tools capable of quantifying ES contribution to security of supply.

1.3. Literature review

Given the stochastic nature of network outages and the time-coupling introduced by energy constraints, chronological Monte Carlo simulations are required to study the operation of an ES plant. Note that although there have been efforts to develop analytical methods bypassing the need for chronological simulations (e.g. [17]), these have used simplifications such as unlimited energy capacity and entail strong assumptions on the independence between sequential state-of-charge (SOC) states, that do not hold in practice. In a similar fashion, authors in [18] analyse the contribution of an ES plant under the assumption that it is sufficiently small such that it can always be fully recharged overnight, thus ignoring the impact of charging constraints and network outages. Authors in [19] compute the capacity value of transmission-connected ES; this is a price-taker analysis where the storage operator is assumed to know prices ahead of time. The authors provide a simple analytic formula for estimating the ES energy level at a particular time instant. However, this approach assumes that ES cannot charge during outage conditions. In contrast, the present paper shows that the ability for ES to charge during partial outage conditions (e.g. when only one of the two transformers is online) is a very critical function and contributes greatly to its capacity value. Authors in [20] compute the capacity value of storage when used to smooth output of a wind farm; static analysis of 100 peak periods is undertaken with no consideration of the plant's energy constraints. A similar static approach is adopted in [21] when computing capacity value of transmission-connected storage. Even in industry standard tools, such as in the commercial software MARS [22], the presence of an ES plant is modelled as a deterministic load modifier, while not explicitly capturing highly relevant operational principles. Chronological simulations have been used in the past in cases where outage duration is of interest (e.g. [23,24]) but have only recently been extended to include time-coupling storage elements.

The authors in [9] proposed a method to compute EFC of an ES plant connected to a distribution system. However, they focus solely on the use of ES for peak reduction and do not consider network failures which, as shown in this paper, are of paramount importance. A similar approach is taken in [27] (chronological simulation while ignoring network failures) and extended to other capacity value metrics. Authors in [28] carry out similar studies on the capacity value of ES but ignore network failures. Researchers in [25] build a chronological Monte Carlo model to analyze the reliability of hybrid systems combining DG with ES. A similar approach is taken in [26], focusing on the contribution of ES to PV systems. However, note that both those papers adopt a copper plate approach (i.e. all assets are on the same bus) and thus do not model network outages. In this paper, we expand upon the methodology presented in [25] and [26] by introducing event-based modelling which offers an order of magnitude speed-up (see Section 3.10). In addition, in this paper the impact of a wide range of factors on storage capacity value is analysed. These factors include network reliability, demand shape and ability for islanding operation and have never before been analysed in the past.

In this context, the present paper is the first to develop a fully tractable chronological simulation model for storage combined with the modelling of unreliable network assets and the outages that arise, aiming for the first time to fill critical methodological and conceptual gaps around the quantification of ES capacity value.

1.4. Research contributions and structure

In this research a novel model capable of computing the capacity value of an ES plant is proposed and then used to carry out a large number of studies to inform the design of distribution networks in the future to leverage the ability of ES to increase supply reliability. The three main contributions of the present research can be summarized as:

- Proposal of a novel methodology that computes the capacity metric Equivalent Load Carrying Capability (ELCC) of ES, shown in Section 2.3. All relevant operational characteristics that uniquely pertain to ES, such as time-coupling, ability to support supply during outage events and the inextricable link with the available import capacity, are considered. The authors are aware of only two other publications that compute ELCC of ES. Ref. [23] computes ELCC of ES when installed at an islanded microgrid not connected to the main grid.

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