Computers & Operations Research 66 (2016) 272–283

Contents lists available at ScienceDirect

Computers & Operations Research

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

Envelope modeling of renewable resource variability and capacity

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ARTICLE INFO

Available online 10 September 2015

Keywords:
Renewable intermittency
Generating capacity
Smart grids
Network calculus (NetCal)
Envelope modeling
Legendre transform

ABSTRACT

To unify the analysis of both renewable and conventional fossil-fuel generating resources in electricity systems, we develop an envelope-based modeling method. Built on Network Calculus theory (NetCal) for deterministic queuing systems from the field of telecommunications engineering, this method characterizes the variability of electricity supply and demand by upper and lower envelopes and their respective Legendre conjugates. Differing from all other modeling methods, this method not only quantifies variability across different time scales, but also captures the intrinsic tradeoff between capacity and the corresponding Quality-of-Service (QoS) performance. In particular, the QoS measures represent matching/mismatching patterns between power supply and demand and provide an intuitive interpretation of the role of storage resources. The concept of QoS leads to two QoS-based capacity metrics – guaranteed capacity and best-effort capacity – whose conceptual and numerical properties are analyzed and compared against existing capacity metrics for validation purpose. As illustration, the proposed methods are applied to data from the California Independent System Operator (CAISO), which allows us to explicitly quantify the capacity contribution (via the notion of best-effort capacity) of wind during peak hours and its negative system impact at night, and demonstrates the positive capacity contribution of storage resources even though they are net energy consumer.

1. Introduction

The continuously increasing penetration of renewable energy creates unprecedented challenges for system operators and utility companies, largely driven by the intermittent nature of major renewable resources such as wind and solar. Intermittency implies high variability (undependable), inflexibility (non-dispatchable) and uncertainty (difficult to predict), resulting in an analytical gap with conventional probabilistic/statistical methods. In response, we develop an envelope method that carries the following two features: (i) a worst-case analysis that matches very well with the ultra-high reliability standards in the electricity system; (ii) a unified treatment of constant (e.g. geothermal) and variable generating resources (e.g. wind), load, and supplementary resources including storage and demand response, which enables a systematic renewable integration. In particular, variability is captured at every time scale and reveals the trade-off between capacity and quality of services (QoS) performance. The latter directly links variability modeling to capacity evaluation. To our knowledge, this approach has not before appeared in the power systems literature.

Our methodology draws inspiration from the theory of Network Calculus (NetCal) [5,6] in telecommunications systems. Other applications of this theory can be found in queuing systems [4], the Internet [10] and manufacturing systems [3]. By converting the original NetCal from the time domain to its conjugate domain via Legendre Transform so as to include non-monotone flows in the framework, we effectively turn a queuing theory into a variability theory and transform NetCal into the envelope method.

Underlying the proposed mathematical formulation is a general perspective that takes the electricity system as a special supply chain with limited storage resource and nearly zero tolerance for delay, where variable generating resources are naturally interpreted as a service, forming the basis for the notion of QoS. Conceptually, QoS is understood as matching/mismatching patterns between supply and demand, which is further quantified in terms of the worst-case deficit (of supply) or excess (of demand) via envelope modeling.

In the Operations Research literature, the use of QoS as a performance measure is widespread. For example, in wireless transmission, Ata [1] minimizes the long-run average energy consumption subject to a QoS constraint – expressed as an upper bound on the packet drop rate. In queuing applications, Mandelbaum and Zeltyn [12] study staffing in a system operating in a many-server

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http://dx.doi.org/10.1016/j.cor.2015.07.020
0305-0548/

configuration with general customer patience distributions [2] to satisfy a QoS constraint. While the domains may be different, our adoption of a QoS measure as a factor to quantify service capacity is consistent with earlier applications. For example, Maglaras and Zeevi [11], in a model of service systems, consider different grades of QoS – “guaranteed” processing rate and “best-effort” type service – as two nonsubstitutable services to a market of heterogenous users. With the service provider's objective of maximizing revenues, they find that real-time congestion notification results in increased revenues. Our analysis draws on these concepts to define and evaluate the capacity contributions of intermittent renewable resources.

Currently, the most common electric power capacity metrics are installed capacity (ICAP), unforced capacity (UCAP) or capacity factor, effective load carrying capability (ELCC) or capacity credit, variants of time-period-based methods (i.e., averaged capacity over specific time intervals during the day), and the exceedance method (e.g., median, 70%,95% percentiles) [15]. There is also the concept of “guaranteed capacity,” a metric under which intermittent resources are given a zero capacity rating and then treated as negative loads that offer energy but not capacity. Roughly speaking, the ICAP, UCAP, and guaranteed capacity metrics correspond, respectively, to the maximum, the mean, and the minimum of the power supply, which offer little insights on the variability of renewable resources.

As a result of problems with UCAP and ICAP, there has been a shift toward using ELCC to evaluate capacity contribution. This metric essentially is a reliability-oriented estimate of generation capability. ELCC is obtained by replacing the generating source under consideration with an equivalent generator of constant capacity that maintains the same system reliability standard. The most commonly used reliability measures for this purpose are loss of load expectation (LOLE) and its dimensionless counterpart, loss of load probability (LOLP). For both of them, the target value is typically chosen as one day in 10 years [13]. In practice, various entities frequently use ELCC to value wind capacity, including ERCOT, MISO, PacifiCorp, Colorado PUC/Xcel Energy and Quebec Balancing Authority Area [13,14,7,8,15].

However, an ELCC-based evaluation also presents several complications and shortcomings: (1) first, because of the system nature of the ELCC metric, renewable resources are commonly evaluated at the resource class level. For instance, ERCOT calculated wind ELCC as 8.7% in 2007 [13], a value that is subject to change from year to year. This definition can be problematic because a class-level evaluation is not sufficient for some individualized incentive mechanisms. (2) Second, the value of ELCC is system-dependent and is neither transparent nor intrinsic to the resources themselves. In particular, the value decreases monotonically as the penetration rate of intermittent resources goes up. Such a well-known negative correlation of capacity value and penetration level is driven by the dependence of renewables on the rest of the system for backup. (3) Further, ELCC measures how the generating resource performed *ex post*, but not what it can promise *ex ante*. In other words, it reflects the notion of “best effort” as opposed to performance (or, equivalently, Quality of Service) guarantees. This is not a trivial distinction. In essence, the capability to guarantee a quality of capacity service level or its lack is what differentiates conventional resources from renewables. To be more concrete, what can be counted on for wind capacity in the day-ahead market is substantially different from what will actually be realized, given the relatively low precision of wind forecasting techniques. The forecast error is inherent to the intermittent nature of the wind resource, which is, however, not modeled in the ELCC model. (4) Finally, ELCC effectively treats power supply/demand for all time instances in isolation, which falls short to model the supply–demand interaction across time scales, consequently, captures the capacity contribution of storage resources.

From the standpoint of QoS performance guarantee, evaluating the capacity of intermittent resources at the class level is inadequate. If the performance of an individual producer (or consumer) cannot be differentiated from the rest of the generators in its class, little can be done to incentivize high performance service during scarcity periods. The method we propose addresses this dilemma directly by evaluating the capacity contribution of individual generating resources (conventional and renewable) and reward high QoS performance with high capacity rating.

2. Envelope method

A fundamental deviation from existing approaches is that we model cumulative power generation and consumption without loss of information. In this way, we capture not only the instantaneous power generation (in MW) characteristics, but also the pattern of energy generation and consumption (in MWh) on different time scales. More important, the method not only applies to conventional and renewable generators, but also naturally incorporates supplementary capacity resources such as storage and demand response. Simply put, a generating resource matches supply and demand from the supply side; a demand resource does the same from the demand side; and a storage resource can do the same from both supply and demand sides, albeit at the expense of some energy conversion loss.

The proposed methodology is inspired by the theory of Network Calculus (NetCal) that was developed for deterministic queuing systems and, in particular, for the Internet (see, e.g., [4,10] for reference). The essence of NetCal is to model input and output flows by their respective upper and lower envelopes, through which QoS performance bounds including delay and backlog are derived. Details of the formulation and involved symbols and notation are presented in an Appendix. Below we describe with Fig. 1 the basic ideas of the proposed capacity evaluation methodology in NetCal spirit.

To describe the QoS characteristics of a given load, the first step is to convert the raw load data (Panel 1) from the power domain (MW against time) to the energy domain (MWh against time) (Panel 2). Then, an upper envelope is constructed to bound the energy flow from the above (Panel 3). Construction of this upper envelope is effectively performed in the Legendre conjugate domain, where the net excess of electricity demand (in MWh) with respect to the constant demand flow at any given capacity level (in MW) is captured. This computational procedure corresponds to the Leaky Bucket mechanism (Panel 4) that can be implemented with an efficient recursive algorithm. More detailed discussion on leaky bucket can be found in Section 3.1.1. As each choice of leaking rate corresponds to an affine upper-envelope, the family of these envelopes results in a convex upper envelope, which is nothing but the minimum of all these affine envelopes. It is worthy of noting here that leaky bucket, while borrowed from a different engineering field, should be understood as a generic data modeling tool rather than a domain-specific physical device.

By further taking intermittent resources (for example, wind) as a negative load (Panel 5), lower envelopes (Panel 6) of wind power supply can also be obtained. Intuitively, the lower envelope of supply reveals the minimum output (in MWh) over any period of a given duration. In particular, when the wind resource claims a certain capacity credit, the Legendre conjugate of the lower envelope gives the maximum net deficit in electricity production of this wind generator in comparison against a constant generator at the claimed capacity level. We view this maximum deficit as the corresponding QoS measure of claimed capacity. In this way, the dependence of this wind generator on the system for backup is explicitly quantified.

2.1. Conjugates envelopes and additivity of bounds

The above bound-based QoS characterization fall into the category of worst-case analysis. While it is philosophically very