Electrical Power and Energy Systems 104 (2019) 401–413

Contents lists available at ScienceDirect

Electrical Power and Energy Systems

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

Virtual storage plant offering strategy in the day-ahead electricity market

Kristina Pandžić[a], Hrvoje Pandžić[b,*], Igor Kuzle[b]

[a] Croatian Transmission System Operator – HOPS Ltd., Croatia
[b] Department of Energy and Power Systems, Faculty of Electrical Engineering and Computing, University of Zagreb, Croatia

ARTICLE INFO

Keywords:
Virtual storage plant
Energy storage
Bilevel programming
Mathematical problem with equilibrium constraints

ABSTRACT

Energy storage is gaining an important role in modern power systems with high share of renewable energy sources. Specifically, large-scale battery storage units (BSUs) are an attractive solution due to their modularity, fast response and ongoing cost reduction.

This paper aims to formulate, analyze and clarify the role of merchant-owned BSUs in the day-ahead electricity market. It defines virtual storage plant (VSP) as a set of BSUs distributed across the network. A VSP offering model is formulated as a bilevel program in which the upper-level problem represents the VSP profit maximization and operation, while the lower-level problem simulates market clearing and price formation. This mathematical problem with equilibrium constraints (MPEC) is converted into a mixed-integer linear program (MILP). This is afterwards expanded to a game of multiple VSPs formulating an equilibrium problem with equilibrium constraints (EPEC), which is solved using the diagonalization procedure.

The proposed model is applied to an updated IEEE RTS-96 system. We evaluate the impact VSPs have on the locational marginal prices and compare the coordinated approach (all BSUs operated under a single VSP), i.e. the MPEC formulation, to the competitive approach (multiple VSPs competing for profit), i.e. the EPEC formulation.

1. Introduction

1.1. Motivation

The increasing share of renewable energy sources (RES) is changing the paradigm of modern power systems. The term power itself indicates a constant balance between demand and supply. However, an increased share of non-controllable RES, i.e. solar and wind, results in less dispatchable capacity at the disposal to the system operator. Thus, the technical ability to meet the uncertain net demand is reducing because RES output can vary within a market interval [1]. Many studies report that intermittent non-dispatchable RES increase reserve requirement, e.g. Italian historical data analyzed in [2] report a decrease of energy prices and increase of reserve costs as a result of the RES integration. These technical and economic conditions make large-scale energy storage solutions attractive, as they enable switching to the energy system paradigm, as opposed to the power system paradigm. As opposed to the current power system paradigm, where generation and demand need to be balanced at each point in time, in an energy system, generation and demand need to be balanced over a longer time period, e.g. hours, while energy storage acts as a buffer that voids the short-term generation-load imbalances. In other words, energy storage enables secure and stable power system operation even without the constant generation-demand balance since it acts as a generation and demand asset interchangeably. Rassmussen et al. [3] claim that large distributed energy storage would enable covering the entire electricity demand in Europe using only RES. Related to this, electricity generation of wind turbines is already reaching high levels. In 2015, Danish wind turbines generated an equivalent of 42 percent of the overall electricity demand in that country [4].

Regulative authorities have not yet issued clear regulating mechanisms governing the use of energy storage in electricity markets. Joint European Association for Storage of Energy and European Energy Research Alliance recommendations for European Energy Storage Technology Development Roadmap towards 2030 [5] recognizes that energy storage technology can be used to provide regulated services to system operators and non-regulated services in electricity markets (see the model presented in [6]). In the USA, Federal Energy Regulatory Commission (FERC) has issued orders to help facilitate energy storage in regulated markets. FERC Order 555 issued a pay-per-performance incentive for resources that can provide quicker and more precise responses to frequency regulation signals. This enables energy storage technologies which outperform the conventional regulation providers, such as gas- and coal-fired power plants, to receive higher

---

* Corresponding author.
E-mail addresses: kristina.pandzic@hops.hr (K. Pandžić), hrvoje.pandzic@fer.hr (H. Pandžić), igor.kuzle@fer.hr (I. Kuzle).

https://doi.org/10.1016/j.ijepes.2018.07.006
Received 14 January 2018; Received in revised form 26 May 2018; Accepted 5 July 2018
0142-0615/ © 2018 Elsevier Ltd. All rights reserved.

Nomenclature

Sets

Ω^{B}	set of piecewise linear segments of each generating unit's offer curve, indexed by b.
Ω^{C}	set of piecewise linear segments of each bus' demand bid curve, indexed by c.
Ω^{H}	set of BSUs, indexed by h.
Ω^{I}	set of generating units, indexed by i.
Ω^{J}	set of VSP owners, indexed by j.
Ω^{L}	set of transmission lines, indexed by l.
Ω^{S}	set of buses, indexed by s.
Ω^{T}	set of hours, indexed by t.
Ω^{W}	set of wind farms, indexed by w.

Binary variables

$x_{t,h}^{\mathrm{ch}}$	BSU charging status (1 if BSU h is charging during hour t, 0 otherwise).
$x_{t,h}^{\mathrm{dis}}$	BSU discharging status (1 if BSU h is discharging during hour t, 0 otherwise).

Continuous variables

$d_{t,s,c}$	power consumption on segment c at s during hour t (MW).
$g_{t,i,b}$	power output on segment b of generator i during hour t (MW).
$k_{t,w}$	power output of wind farm w during hour t (MW).
$pf_{t,s,m}$	power flow through line $s{-}m$ during hour t (MW).
$q_{t,h}^{\mathrm{ch}}$	power purchased by BSU h during hour t (MW).
$q_{t,h}^{\mathrm{dis}}$	power sold by BSU h during hour t (MW).
$soe_{t,h}$	state of energy of BSU h during hour t (MWh).
$\alpha_{t,h}^{\mathrm{ch}}$	charging bid of BSU h during hour t (MW).
$\alpha_{t,h}^{\mathrm{dis}}$	discharging offer of BSU h during hour t (MW).
$\theta_{t,s}$	voltage angle of bus s during hour t (rad).
$\lambda_{t,s(h)}$	locational marginal price at bus s where BSU h is located (\$/MW).

Parameters

$ch_h^{\max}$	charging capacity of BSU h (MW).
$dis_h^{\max}$	discharging capacity of BSU h (MW).
$d_{t,s,c}^{\max}$	capacity of demand block c at bus s during hour t (MW).
η_h^{ch}	charging efficiency of BSU h.
η_h^{dis}	discharging efficiency of BSU h.
$g_{i,b}^{\max}$	capacity of offering block b of generator i (MW).
$k_{t,w}^{\max}$	available wind generation of wind farm w (MW).
λ_h^{ch}	bidding price of BSU h (\$/MW).
λ_h^{dis}	offering price of BSU h (\$/MW).
$\lambda_{s,c}^{\mathrm{D}}$	bidding price of demand block c at bus s (\$/MW).
$\lambda_{i,b}^{\mathrm{G}}$	offering price of block b of generator i (\$/MW).
$pf_{s,m}^{\max}$	transmission capacity of line $s{-}m$ (MW).
$soe_h^{\max}$	energy capacity of BSU h (MWh).
$soe_h^{\min}$	minimum energy stored in BSU h (MWh).
sus_{sm}	susceptance of line connecting nodes s and m (S).

remuneration. An evaluation of the utility of energy storage for different market paradigms and ownership models is available in [7].

The main disadvantages of conventional large-scale energy storage, i.e. pumped hydro and compressed air energy storage, are geographical constraints and bulkiness. Due to these limitations, conventional storage technologies are less suitable than modular storage devices that can be installed at virtually any location without a significant ecological footprint. A review of the current state of energy storage technologies indicates that batteries are generally a versatile energy storage technology that can be installed at almost any location [8]. A common grid-scale battery technology today is lithium-ion, which is suitable for providing frequency regulation [9]. Energy-to-power ratio of lithium-ion battery installations is usually lower than 1 and installed capacities are much lower than the ones of traditional energy storage, i.e. pumped hydro [10]. On the other hand, NaS batteries are more suitable for congestion relief as their energy-to-power ratio is 7 [11]. On top of this, the cost of batteries has been reducing due to their use in electric vehicles [12]. A review on battery energy storage technologies is available in [13].

Large-scale use of battery storage has a wide range of applications, providing different values to the power system. Battery storage units (BSUs) can help in peak shaving [14] and increasing the system flexibility and reliability providing power regulation services [15]. Fast-response energy storage, such as BSU, has the potential to replace fast-ramping generation resources [16]. Economics of transmission or capacity investment deferral are addressed in [17]. Therefore, the development of energy storage technology, especially battery technology, might offer solutions for many critical challenges in smart grids [18,19]. Combining these applications reduces the payback period making the investment more attractive.

Storage operation highly depends on its ownership. For instance, Terna's BSUs are used to ensure safety and cost-effective management of the Italian transmission grid [9]. In a vertically integrated utility, BSUs are used to reduce the overall operating cost [20]. Finally, merchant-owned BSU is operated in a way to maximize its profit [21]. In case multiple BSUs are operated by different owners, they compete with each other to make profit. This resembles an equilibrium problem with equilibrium constraints (EPEC), i.e. a multiple-leader-common-follower game, as introduced in [22]. EPEC structure is particularly common in the analysis of deregulated electricity markets [23,24], where players maximize their benefit in the form of mathematical problems with equilibrium constraints, MPECs, e.g. [25], while adhering to the same market-clearing rules. For instance, in [26] an EPEC model is derived to find equilibria reached by strategic producers in a pool-based transmission-constrained electricity market using KKT conditions, while in [27] the authors use diagonalization method to find multiple equilibria of generator maintenance schedules in electricity market environment.

The goal of the presented model is to formulate, model and analyze storage operation in the day-ahead electricity market. A VSP owns and operates its BSUs distributed across the system in order to maximize their overall market performance. It derives an optimal strategy centrally and sends control signals to all its BSUs to charge/discharge.

1.2. Literature review

Generally, integration of energy storage in power systems can be observed either from the system-wide perspective or the merchant perspective. The system-wide perspective is usually modeled as a unit commitment model whose goal is to minimize overall system operating costs, regardless on the profit an energy storage is making. An exception in the literature is [28], which minimizes the overall system costs while ensuring the profitability of a merchant-owned energy storage. On the other hand, there are models which take perspective of a storage owner, thus aiming at maximizing the profit a storage is making in electricity markets. In these models, energy storage can be a significant market player able to affect the market prices, i.e. price maker models, or its

Download English Version:

https://daneshyari.com/en/article/6859067

Download Persian Version:

https://daneshyari.com/article/6859067

Daneshyari.com