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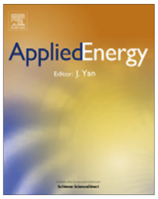

Virtual power plant mid-term dispatch optimization

Hrvoje Pandžić *, Igor Kuzle, Tomislav Capuder

University of Zagreb, Faculty of Electrical Engineering and Computing, Department od Power Systems, Zagreb, Croatia

HIGHLIGHTS

- Mid-term virtual power plant dispatching.
- Linear modeling.
- Mixed-integer linear programming applied to mid-term dispatch scheduling.
- Operation profit maximization combining bilateral contracts and the day-ahead market.

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ABSTRACT

Wind power plants incur practically zero marginal costs during their operation. However, variable and uncertain nature of wind results in significant problems when trying to satisfy the contracted quantities of delivered electricity. For this reason, wind power plants and other non-dispatchable power sources are combined with dispatchable power sources forming a virtual power plant. This paper considers a weekly self-scheduling of a virtual power plant composed of intermittent renewable sources, storage system and a conventional power plant. On the one hand, the virtual power plant needs to fulfill its long-term bilateral contracts, while, on the other hand, it acts in the market trying to maximize its overall profit. The optimal dispatch problem is formulated as a mixed-integer linear programming model which maximizes the weekly virtual power plant profit subject to the long-term bilateral contracts and technical constraints. The self-scheduling procedure is based on stochastic programming. The uncertainty of the wind power and solar power generation is settled by using pumped hydro storage in order to provide flexible operation, as well as by having a conventional power plant as a backup. The efficiency of the proposed model is rendered through a realistic case study and analysis of the results is provided. Additionally, the impact of different storage capacities and turbine/pump capacities of pumped storage are analyzed.

1. Introduction

Due to increasing concerns over environmental impact of the conventional fossil-fueled power plants, during the last couple of decades renewable energy sources (RESs) have been experiencing an outstanding growth. Since RES cannot yet provide levels of return on investment like fossil fuels do [1], various incentive schemes for RES have been introduced. These include feed-in tariff scheme, feed-in premium scheme and the quota scheme. Due to these significant incentives, wind power and photovoltaics have imposed as the most propulsive RES technologies. In 2010 the worldwide wind power capacity reached 196 GW with annual growth rate of 24% [2], while the installed photovoltaic (PV) capacity in the same year reached 40 GW, with annual growth rate of over 60% [3].

Nevertheless, the government incentives have a time limit after which RESs will become non-favorized agents in the market. Exposing RES to the rigorous market environment poses a serious challenge for RES owners. The prime reason is the uncertainty of forecasted power output of RES. For instance, wind power plants (WPPs) are inherently intermittent due to stochastic nature of wind, and PV power plants' output depends on solar irradiation and clouds [4]. Thus, the risk of not meeting long-term and mid-term electricity delivery contracts is immanent. In order to diversify this risk, different types of renewable and non-renewable generators and storage devices are combined into a single virtual power plant (VPP). VPP enables the associated RES to participate in the electricity market as a single power plant with defined hourly outputs [5]. A virtual power plant, sometimes referred to as virtual utility [6], contains a mixture of different generators. A well-chosen mix of generating technologies can offset the inherent unreliability of RES generators in order to set up a VPP which can be treated as a conventional one [7]. From the point of view of any other market agent, a VPP is a unique entity, although in reality it represents a mixture of multiple distributed energy resources (DERs) and conventional power plants [8]. Incorporating distributed power plants into a single legal subject with substantially

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* Corresponding author. Tel.: +385 1 6129 509; fax: +385 1 6129 890.
E-mail addresses: hrvoje.pandzic@fer.hr (H. Pandžić), igor.kuzle@fer.hr (I. Kuzle), tomislav.capuder@fer.hr (T. Capuder).

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Nomenclature

Acronyms

CPP	Conventional Power Plant
DER	Distributed Energy Resources
EEX	European Energy eXchange
PHS	Pumped Hydro Storage
PV	Photovoltaic
RES	Renewable Energy Sources
TSO	Transmission System Operator
VPP	Virtual Power Plant
WPP	Wind Power Plant

Parameters

a	fixed production cost of CPP (€)
$bc(t)$	bilaterally contracted electricity delivery in time period t (MW)
$g_{\mathrm{conv}}^{\max}$	CPP installed capacity (MW)
$g_{\mathrm{conv},j}^{\max}$	capacity of the jth CPP production level (MW)
$g_{\mathrm{conv}}^{\min}$	CPP technical minimum (MW)
k_j	slope of the jth segment of the CPP production cost curve (€/MW)
$g_{\mathrm{pump}}^{\max}$	pump capacity of the PHS (MW)
$g_{\mathrm{turbine}}^{\max}$	turbine capacity of the PHS (MW)
$g^{s}(t)$	PV output in time period t for sth solar scenario (MW)
$g^{w}(t)$	WPP output in time period t for wth wind scenario (MW)
hd	allowed hourly discrepancy between bilaterally contracted and delivered electricity
m	number of parts of linearized CPP production cost curve
n_p	number of electricity market price scenarios
n_s	number of PV output scenarios
n_w	number of WPP output scenarios
$ramp$	CPP maximum hourly increase/decrease of electricity production (MW/h)
$storage^{\max}$	energy capacity of the PHS upper basin (MWh)
S_{conv}	CPP start-up costs (€)
T	number of time periods
$\lambda^{p}(t)$	electricity price in the market in price scenario p (€/MWh)
μ	PHS efficiency factor
$\pi(p)$	probability of pth electricity market price scenario
$\pi(s)$	probability of sth PV output scenario
$\pi(w)$	probability of wth WPP output scenario

Variables

$C^{wsp}(t)$	cost of CPP electricity production in time period t, WPP output scenario w, PV output scenario s and price scenario p (€/MWh)
$d^{wsp}(t)$	electricity delivered due to bilateral contracts in time period t, WPP output scenario w, PV output scenario s and price scenario p (MWh)
$g_{\mathrm{conv}}^{wsp}(t)$	CPP output in time period t, WPP output scenario w, PV output scenario s and price scenario p (MW)
$g_{\mathrm{conv},j}^{wsp}(t)$	CPP production level j output in time period t, WPP output scenario w, PV output scenario s and price scenario p (MW)
$g_{\mathrm{pump}}^{wsp}(t)$	pump output of the PHS in time period t, WPP output scenario w, PV output scenario s and price scenario p (MW)
$g_{\mathrm{turbine}}^{wsp}(t)$	turbine output of the PHS in time period t, WPP output scenario w, PV output scenario s and price scenario p (MW)
$G^{wsp}(t)$	if positive, electricity sold in the market, if negative, electricity purchased in the market in time period t, WPP output scenario w, PV output scenario s and price scenario p (MWh)
$r^{wsp}(t)$	electricity surplus in time period t, WPP output scenario w, PV output scenario s and price scenario p (MWh),
$storage^{wsp}(t)$	energy stored in the upper basin of PHS in time period t, WPP output scenario w, PV output scenario s and price scenario p (MWh)
$x_{\mathrm{conv}}^{wsp}(t)$	binary variable equal to 1 if CPP is producing electricity in time period t, WPP output scenario w, PV output scenario s and price scenario p, and 0 otherwise
$y_{\mathrm{conv}}^{wsp}(t)$	binary variable equal to 1 if CPP is started-up in time period t, WPP output scenario w, PV output scenario s and price scenario p, and 0 otherwise

higher installed capacity obligates the VPP owner to connect its power plant to the transmission instead of the distribution grid. From the point of view of the Transmission System Operator (TSO), a VPP is connected to the transmission network in a single node using unique electricity meter. Therefore, the VPP internal dispatch is strictly the problem of its owner and is crucial in order to achieve optimal results in the both directly contracted electricity delivery and electricity market.

In case of a voluntary pool, generating companies have both open market and bilateral contracts at their disposal. Bilateral contracts are usually concluded in the long-term. Major reasons for bilateral contracting are price volatility and possible TSO constraints. Each generating company decides how much of its capacity will be contracted bilaterally in advance, and how much will be offered in the market. On the other hand, market trading may have various time effects, ranging from the day-ahead to the balancing real-time market [9]. In this paper the day-ahead market based on hourly bids is considered.

1.1. Related literature and contributions

Various wind producer bidding strategies are reported in the literature. In [10] a stochastic model, which minimizes the imbalance costs, is developed to generate the optimal wind power producer bids in a short-term market. A technique which results in best offering strategy of a wind power producer at different trading stages is presented in [11]. A suitable trading option for wind power, based on wind power impact on market clearing prices, is proposed in [12]. Offering strategies of interest to wind power producers are examined in [13].

The aforementioned papers do not include any kind of support technology that could improve the wind power plant revenue. In [14] a combined strategy for bidding and operating in a power exchange is presented. This strategy considers the combination of a wind-generation company and a hydro-generation company. Authors in [15] examine the economic viability of a wind-based pumped hydro storage (PHS) system which provides guaranteed electricity during the peak load demand periods to the local electrical grid. A methodology for the sizing of PHS systems that exploit the excess wind energy amounts produced by local wind farms, otherwise rejected due to imposed electrical grid limitations is presented in [16]. A study on optimal size of the WPP and the elements of the PHS are made in [17]. An optimization problem of PHS changing its production to compensate wind power prediction errors is tackled in [18].

Ref. [19] presents a stochastic optimization technique that maximizes the joint profit of hydro and wind generators in a pool-based electricity market, taking into account the uncertainty of