Applied Energy 229 (2018) 474–481

Contents lists available at ScienceDirect

Applied Energy

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

Stochastic risk-sensitive market integration for renewable energy: Application to ocean wave power plants

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HIGHLIGHTS

- We present an intraday market design for reserves to accommodate renewable resources.
- Our two-stage risk-aware stochastic MILP derives optimal energy and capacity offers.
- This scheme allows the system operator secure capacity from renewable energy sources.
- There are financial incentives for renewable generators to participate in this market.

ARTICLE INFO

Keywords:
Grid reliability
Market design
Renewable integration
Energy storage
Optimization
Short-term reserve market

ABSTRACT

With the expected increase of intermittent renewable energy resources on the electric power grid, short-term reserve markets can prove to be a critical reliability asset. This paper introduces and tests a potential market structure that includes a short-term reserve market for renewable resources where the realized energy is drawn within the bounds of the hourly capacity offered. The study presents a risk-aware stochastic model that determines, based on the day-ahead offer derived using a classic newsvendor formula, the best intraday offers for a renewable energy power plant. The stochastic approach takes into account the uncertainties of energy production and market prices. The proposed risk-sensitive model aims to maximize the renewable power plant's revenues and minimize potential risks of loss in a multi-product multi-timescale market setup. To demonstrate the effectiveness of the proposed formulation, we study the case of a hypothetical 750-kW wave power plant coupled with energy storage. The study shows that the risk of profit loss is not uniformly distributed across the risk-aversion factor space. We also find that the introduction of the short-term reserve market results in a wider range of conditional value at risk while inducing 5% profit increase and a lower profit reduction across the risk range. In addition, the study reveals that the short-term reserve market is profitable for both the system operator and the wave energy power plant considered.

1. Introduction

One of the main challenges for renewable energy integration into the electric grid remains its inherent intermittency. The uncertainty associated with renewable generation poses a reliability threat to the electric grid in addition to demand variability and the unpredictable contingencies related to generation, transmission, and distribution. Reserves are needed to balance supply-and-demand mismatches. The reserve market constitutes a critical asset for reliable and economic system operation because it provides, whenever necessary, the missing portion of energy at an acceptable cost. Thus, with high penetrations of renewable generation, the capacity of reserve (as an insurance premium) is expected to increase [1]. This can prove to be a handicap for renewable integration because reserve costs could increase as well, limiting the achievable percentage of renewable generation penetration for a reliable grid. To mitigate this reliability issue, it is reasonable to involve renewable power plants in the grid reliability efforts. In the attempt to make renewable power plants responsible for any mismatch

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https://doi.org/10.1016/j.apenergy.2018.07.091
Received 2 May 2018; Received in revised form 1 July 2018; Accepted 19 July 2018

Nomenclature

Sets

$\mathscr{S}$	set of time slots, indexed by s
$\mathscr{T}$	set of times, indexed by t
Ω	set of scenarios, indexed byω

Parameters

α	confidence level
β	risk-aversion parameter
c_d	storage unit depletion cost incurred when the state of charge, *soc*, violates safety operation thresholds
C_o^t	overage unit cost at time t, $\forall\, t \in \mathscr{T}$
C_u^t	underage unit cost at time t, $\forall\, t \in \mathscr{T}$
Δ_s	duration in hours of one time-slot unit ($\Delta_s = 0.0833h$ (5 min))
Δ_t	duration in hours of one time unit ($\Delta_t = 1h$)
$E_G^{ts\omega}$	energy generation of the renewable power plant in scenario ω, time t, and time slot s, $\forall\, t \in \mathscr{T},\ s \in \mathscr{S},\ \omega \in \Omega$
η_C, η_D	charge and discharge efficiency
$F^t(\cdot)$	cumulative distribution function of all possible renewable power realizations at time t, $\forall\, t \in \mathscr{T}$
γ^t	percentage defining price quantile at time t, $\forall\, t \in \mathscr{T}$
$\lambda^{t\omega}$	positive imbalance charge for scenario ω at time t, $\forall\, t \in \mathscr{T},\ \omega \in \Omega$
P_{cap}	storage power capacity
$P_{\max}$	interconnection feeder capacity
p^t	day-ahead market clearing price at time t, $\forall\, t \in \mathscr{T}$
μ^ω	probability of scenario ω, $\forall\, \omega \in \Omega$
$q^{t\omega}$	negative imbalance charge in scenario ω and time t, $\forall\, t \in \mathscr{T},\ \omega \in \Omega$
$r^{ts\omega}$	reserve market energy price ($/kW) for scenario ω at time t and time-slot s, $\forall\, t \in \mathscr{T}, s \in \mathscr{S}, \omega \in \Omega$
$\rho^{t\omega}$	real-time market price for scenario ω at time t, $\forall\, t \in \mathscr{T},\ \omega \in \Omega$
S_-	minimum healthy storage state-of-charge threshold
S_+	maximum healthy storage state-of-charge threshold
S_{cap}	storage energy capacity
σ	storage efficiency
$v^{t\omega}$	reserve market capacity price ($/kWh) for scenario ω at time t, $\forall\, t \in \mathscr{T},\ \omega \in \Omega$
$\hat{y}^{\cdot}$	expected value of the stochastic parameter $y^{\cdot\omega}$ for scenario ω, $\forall\, \omega \in \Omega$
$\zeta^{ts\omega}$	reserve energy signal for scenario ω at time t and time slot s, $\forall\, t \in \mathscr{T},\ s \in \mathscr{S},\ \omega \in \Omega$

Variables

$CVaR_\alpha$	conditional value at risk, at the confidence level α
DA^t	day-ahead energy offer at time t, $\forall\, t \in \mathscr{T}$
$\delta_C^{ts\omega}$	charge energy for scenario ω at time t and time slot s, $\forall\, t \in \mathscr{T},\ s \in \mathscr{S},\ \omega \in \Omega$
$\delta_D^{ts\omega}$	discharge energy for scenario ω at time t and time slot s, $\forall\, t \in \mathscr{T},\ s \in \mathscr{S},\ \omega \in \Omega$
$E_{\text{net}}^{t\omega}$	net energy output of the renewable power plant after reserve energy in scenario ω and time t, $\forall\, t \in \mathscr{T},\ \omega \in \Omega$
$E_{\text{out}}^{ts\omega}$	energy output of the renewable power plant in scenario ω, time t, and time slot s, $\forall\, t \in \mathscr{T},\ s \in \mathscr{S},\ \omega \in \Omega$
$\pi^{t\omega}$	power plant profit for scenario ω at time t, $\forall\, t \in \mathscr{T},\ \omega \in \Omega$
$R_g^{ts\omega}$	energy output in the reserve market for scenario ω at time t and time slot s, $\forall\, t \in \mathscr{T},\ s \in \mathscr{S},\ \omega \in \Omega$
RT^t	real-time market bid at time t, $\forall\, t \in \mathscr{T}$
RV^t	reserve market bid at time t, $\forall\, t \in \mathscr{T}$
$soc^{ts\omega}$	state of charge for scenario ω at time t and time slot s, $\forall\, t \in \mathscr{T},\ s \in \mathscr{S},\ \omega \in \Omega$
VaR_α	value at risk at confidence level α
$x_z^{t\omega}$	output energy deviation binary variables of zone z (z$\in\{1, 2, 3\}$) for scenario ω at time t, $\forall\, t \in \mathscr{T},\ \omega \in \Omega$
Y^ω	CVaR's slack variable for scenario ω, $\omega \in \Omega$
$z_{DA}^{t\omega}$	day-ahead energy shortage for scenario ω at time t, $\forall\, t \in \mathscr{T},\ \omega \in \Omega$
$z_{ES+}^{ts\omega}$	deviation above the healthy storage operation upper threshold for scenario ω at time t and time slot s, $\forall\, t \in \mathscr{T},\ s \in \mathscr{S},\ \omega \in \Omega$
$z_{ES-}^{ts\omega}$	deviation below the healthy storage operation lower threshold for scenario ω at time t and time slot s, $\forall\, t \in \mathscr{T},\ s \in \mathscr{S},\ \omega \in \Omega$
$z_{ES}^{ts\omega}$	Total state-of-charge deviation in scenario ω, time t, and time slot s, $\forall\, t \in \mathscr{T},\ s \in \mathscr{S},\ \omega \in \Omega$
$z_{\text{out}}^{t\omega}$	market energy excess for scenario ω at time t, $\forall\, t \in \mathscr{T},\ \omega \in \Omega$
$z_{RT}^{t\omega}$	real-time energy shortage for scenario ω at time t, $\forall\, t \in \mathscr{T},\ \omega \in \Omega$

between their day-ahead commitment and their actual power output, some market policies impose supply shortfall penalties [2]. The review of different real-time market structures around the world allows to establish that distributed energy resources can significantly participate in relieving the burden of expensive control reserves from the grid [3]. This work proposes, for renewable energy plants, a market integration strategy that improves their ability to effectively participate in grid reliability and flexibility.

1.1. Related work

The focus of a significant amount of research in the literature is on devising better methods of integrating renewable energy converters (RECs) into the existing power grid. A first category of work addresses this problem by developing more accurate short-term (24–36 h) forecasting techniques [4–6]. Nevertheless, forecasting errors cannot be completely eliminated. Thus, even though improving forecasting accuracy could significantly contribute to reliability, there are still open questions regarding additional renewable integration strategies from the market design standpoint. Bathurst et al. [4] evaluate several market structures to suggest to policy makers and market operators one that promotes fair and reliable wind power integration. They conclude that the market clearing price calculation should exclude wind generation. Makarov et al. [7] contemplate intraday markets as critical to improving the reliability of offered wind contracts given that short-term forecasts tend to be more accurate. Castronuovo and Lopes [8] designed a combined wind and hydropower system where the pumped storage is aimed at shifting the output of the wind energy converter in time. Dukpa et al. proposed an optimal participation strategy for a wave energy converter coupled with an energy storage system (ESS) that maximizes profit and mitigates the risk of supply shortfalls. The authors confirm that it is imperative to combine a REC with an ESS to increase reliability and profitability, as storage increases dispatchability for intermittent energy resources [9]. Dicorato et al. came to the same conclusion in their work on planning and operating a combined wind and ESS [10]. Other works further take into account uncertainties. Bathurst et al. [4], Matevosyan and Soder [11], and Morales et al. [12] studied the wind power plant profit maximization problem using a stochastic programming approach. Botterud et al. [13] and Morales et al. [12] further added a risk sensitivity term, the conditional value at risk