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A multi-timescale hybrid stochastic/deterministic generation scheduling framework with flexiramp and cycliramp costs

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A R T I C L E I N F O

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A B S T R A C T

Flexible ramping products (flexiramp), provided by entitled resources to meet net demand forecast error, are the underpinning for the accommodation of the substantial uncertainties associated with variable wind power. This paper proposes an enhanced flexiramp modeling approach, cast in a hybrid stochastic/deterministic multi-timescale framework. The framework employs a chance-constrained day-ahead scheduling method, as well as deterministic scheduling on intra-hourly basis (real-time scheduling), to allow optimal procurement planning of the flexiramp products in both timescales. A stepwise and piecewise demand price curve is also proposed to calculate the flexiramp surplus procurement price. Non-generation resource (NGR), referring to energy storage, is implemented to provide extra flexibility. Additionally, cycling ramping cost (cycliramp), introduced to model operational and maintenance costs and reduce the wear and tear of generators, is also included as a penalty. Numerical tests are conducted on 6-bus and 118-bus systems. Results demonstrate the merits of the proposed scheduling model as well as the effects of flexiramp and cycliramp costs in the multi-timescale scheduling.

1. Introduction

Flexibility issues are drawing increased attention due to the growing penetration levels of variable renewable generation. Such a challenge is more imminent with the variability and uncertainty of wind generation, especially in the intra-hour timescales, which may lead to difficulties in energy balancing, and a compromise on power system's efficiency and reliability [1]. *Variability* is defined in this paper as the difference of expected net load between time intervals, while *uncertainty* is the unpredictability or the net load forecast error.

Along with the requirement to improve power system flexibility, a new market product, called the flexible ramping (flexiramp), has been recently proposed by CAISO [2,3] and MISO [4] to accommodate net load uncertainty. Currently, CAISO only procures flexiramp in the deterministic short-term scheduling, while MISO procures it in both deterministic day-ahead and real-time scheduling. *Flexiramp*, also known as "ramp capacity" (as in MISO), is defined as the sufficient ramping capacity provided by eligible resources in time interval t to meet the upward and downward net load forecast error in the subsequent intervals, $t+1$, with a high confidence level [1–4].

Cycling, defined as the changes in the power output of conventional thermal units (ramping or on/off switching), is the source of operational flexibility in the electricity generation system [5]. Along with the introduction of flexiramp market and the increase in net load variability, frequent cycling ramp (cycliramp) would result in additional planned outages and higher operation and maintenance (O&M) costs [6]. *Cycliramp* cost, as an inherent feature of thermal units, ought to be considered explicitly in flexiramp markets.

Multi-timescale scheduling is becoming a regular practice in power system markets [7]. It mainly consists of; (a) day-ahead scheduling, which runs every 24 h at 1-h time resolution. (b) real-time or hourly-ahead online rolling scheduling that is performed every 1 h, to determine the generation output in the upcoming 3 or 4 h, with a time resolution of 15-min. Real-time scheduling can use the newly updated information of load profile, weather forecast and wind power generation to improve the prediction precision.

1.1. Flexible ramp capacity market

Research on flexible ramping products started only recently, focusing on generation scheduling and economic dispatch, with deterministic models [8,9] and stochastic models [8,10,11]. Wang and Hobbs [10] conducted a comparative analysis for a deterministic flexiramp dispatch model versus a stochastic model. Results demonstrated

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Nomenclature

Parameters

$p_i^{\max(\min)}$ max(min) generation of unit i [MW]
$\phi^{up(dn)}$ up(down) flexiramp surplus procurement [MW]
$c_f^{frus(frds)}$ price of step f of up(down) flexiramp surplus award [\$/MWh]
$\chi_f^{\max,up(dn)}$ step size f of up(down) flexiramp surplus [MW]
$d_{s,t}^{net}$ net load discrete realization level s at time t [MW]
$\varepsilon^{up(dn)}$ up(down) flexiramp surplus confidence level
hr_i^g incremental heat rate of unit i [Btu/kWh]
π_i^g incremental fuel cost of unit i [\$/Btu]
sr_t spinning reserve at time t [MW]
$T_i^{on(off)}$ minimum on/off time of unit i [hour]
$q_j^{\max,c(d)}$ max charge(discharge) rate of storage j [MWh]
$q_j^{\min,c(d)}$ min charge(discharge) rate of storage j [MWh]
$e_{j,m}^{\max(\min)}$ max(min) capacity of storage j at time m [MWh]
E_j^0 initial state of charge (SOC) of storage j at the initial horizon [%]
$\eta_j^{c(d)}$ efficiency rate to charge/(discharge) of storage j
τ real-time slot [h]
$p_m^{w,\max}$ maximum wind generation at time m [MW]

Binary variables at time t/time m

$o_{i,t(m)}$ on/off status of units i
$x_{j,t(m)}$ charge/discharge status of storage j
$\gamma_{s,t}$ expected net load auxiliary variable of level s
$\alpha_{s,t}$, $\beta_{s,t}$ ramp up, down auxiliary variable of level s
$z_{s,t}$ probabilistic auxiliary variable of level s
$y_{h,t}$ probabilistic auxiliary variable of level h

Continuous variables at time t/parameters at time m

$r_{i,t(m)}^{up(dn)}$ ramp up(down) rate limit of unit i [MWh]
$p_{i,t(m)}^{(DA,sch)}$ (Day-ahead, online rolling schedule) dispatch of unit i [MW]
$q_{j,t}^{c(d)}$ charge(discharge) rate of storage j [MWh]
$e_{j,t(m)}^{(DA,sch)}$ (Day-ahead, online rolling schedule) SOC of storage j [%]
$\bar{d}_t^{net}$ expected net load [MW]
$FRU_{i(j),t}$ up flexiramp award of unit i (storage j) [MW]
$FRD_{i(j),t}$ down flexiramp award of unit i (storage j) [MW]
$CRU_{i,t}$ up cycliramp award of unit i [MW]
$CRD_{i,t}$ down cycliramp award of unit i [MW]
$FRUS_{t(m)}^{(DA,sch)}$ (Day-ahead, online rolling schedule) up flexibility surplus award [MW]
$FRDS_{t(m)}^{(DA,sch)}$ (Day-ahead, online rolling schedule) down flexibility surplus award [MW]
$FRUR_t$ up flexibility reserve award [MW]
$FRDR_t$ down flexibility reserve award [MW]
$\omega_{s,t}$ linearization variable of level s
$g_{j,t}$ PDR auxiliary variable
$pr_{s,t}$ probability of net load level s

Continuous variables at time m

$\Delta_{i,m}^{pg}$ generation deviation of unit i [MW]
$\Delta_{i,m}^{e}$ SOC deviation of storage j [%]
$\Delta_m^{frus(frds)}$ up/down flexiramp surplus deviation [MWh]
$\Delta_i^{\max,pg}$ deviation limit of generation unit i in [MW]
$\Delta_j^{max,e}$ deviation limit of SOC of storage j [%]
$\Delta_j^{max,frus(frds)}$ deviation limit of up(down) flexiramp surplus [MWh]

Matrices and vectors

SF shift factor
PL^{max} vector of upper limit for power flow
P^G, P^D vector of generation dispatch, load demand
K_G, K_D bus-generator, bus-load incident matrix

that the deterministic model is inefficient and the amount of flexiramp procurement strongly affects results. Marneris et al. have proposed deterministic and stochastic scheduling models in [8], considering the variability and uncertainty reserves, in a day-ahead scheduling model with 60 and 15 min intra-hour timescales. The proposed model of intra-hour uncertainty and variability reserves could be massive, since they were predicted day-ahead. The respective reserves were not re-allocated in a real-time dispatch model, however, which may lead to inefficient flexiramp procurement. In addition, the day-ahead model utilizes full stochastic programming without transmission network constraints. Stochastic programming suffers from the dimensionality problem, leading to a long computation time, even with the nine net load scenarios considered. Wu et al. [11] incorporated flexiramp costs in a security-constrained stochastic scheduling along with other non-generation resource (NGR) options, such as energy storage (ES), in providing flexiramp. However, the proposed flexiramp cost function model is rather generic, since the formulation considers cycliramp and flexiramp surplus as an aggregate amount, to cope with the net load variability and uncertainty.

1.2. Cycling ramp cost

The work presented herein also fits into an uptrend in the literature on generation cycling cost [5,6,12,13]. Increased cycliramp with rising wind penetration levels, as established in [12], causes growing concern about wear-and-tear of thermal generation and the related O&M costs. Current market operation practices consider thermal generation ramp rate constraints rather than cycliramp cost. The additional cost sustained by generation companies (GENCOs) for frequent ramping to compensate for the net load variability, are not included with the ramp rate constraints [13]. Troy et al. [14] presented linear, piecewise and step-shaped long-term cycling start-up and cycliramp cost functions. Results showed an overall saving for the system as the cycling operation was subsequently reduced. On the other hand, generation commitment may be altered as new generator units will have a much lower cycling cost. Wu et al. [6] proposed an energy based cycliramp calculation with demand response in a day-ahead stochastic scheduling model. The resultant model is nonlinear and was solved with the MIQCP solver. The latter is not in tandem with state-of-the-art MILP models currently adopted by most ISOs [2,4].

1.3. Aims and contributions of this paper

Although the literature is not lacking in the modeling and application analysis regarding the implementation of flexiramp product in real-time market [10], a committed study of the respective product procurement planning in a hybrid day-ahead stochastic model and real-time deterministic model, is not adequately addressed yet. Two important issues need to be specifically addressed in such undertaking: (a) the necessity for an optimal positioning of the day-ahead flexiramp procurement, in order to efficiently coordinate and respond to net load deviation and the uncertainty in real-time operation. (b) the need for appropriate penalties or demand curves that would ensure optimal flexiramp to be acquired and avoid over-procurement.