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Estimating ramping requirements with solar-friendly flexible ramping product in multi-timescale power system operations

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HIGHLIGHTS

- A multi-timescale unit commitment and economic dispatch model is developed to estimate the ramping requirements.
- A solar power ramping product (SPRP) is developed and integrated into the multi-timescale dispatch model.
- A surrogate-based optimization model is developed to solve the ramping requirements problem.
- SPRP can reduce the total cost of flexible ramping reserves.

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ABSTRACT

The increasing solar power penetration causes the need of additional flexibility for power system operations. Market-based flexible ramping services have been proposed in several balance authorities to address this issue. However, the ramping requirements in multi-timescale power system operations are not well defined and still challenging to be accurately estimated. To this end, this paper develops a multi-timescale unit commitment and economic dispatch model to estimate the ramping requirements. Furthermore, a solar power ramping product (SPRP) is developed and integrated into the multi-timescale dispatch model that considers new objective functions, ramping capacity limits, active power limits, and flexible ramping requirements. To find the optimal ramping requirement based on the level of uncertainty in netload, a surrogate-based optimization model is developed to approximate the objective function of the multi-timescale dispatch model that considers both economic and reliability benefits of the balancing authorities. Numerical simulations on a modified IEEE 118-bus system show that a better estimation of ramping requirements could enhance both the reliability and economic benefits of the system. The use of SPRP can reduce the flexible ramping reserves provided by conventional generators.

1. Introduction

Renewable energy is significantly impacting the economic and reliable operations of the power systems, especially with the rapid increase of renewable penetration [1–3]. As an important renewable source, solar power in the electric power grid rises continuously. Due to the effects of microclimates (e.g., solar irradiance, temperature, and passing clouds), solar power ramps occur frequently [4,5]. These solar power ramps, in addition to the uncertainty and variability of solar power, present new challenges to the balancing authorities. Multiple independent system operators (ISOs) have proposed a flexible ramping product to help improve the dispatch flexibility to integrate these variable and uncertain renewables such as wind and solar [6–8].

Recently, wind has been proposed to provide ramping service for the flexible operations of the power system [9–11], which also makes solar possible for balancing authorities to provide a solar-friendly ramping product in a similar manner. Solar power ramping product (SPRP) is essentially different from wind power ramping product (WPRP) that can be provided by any significant wind power ramp. SPRP should be provided by actual solar power ramp events (not due to diurnal pattern) that are caused by changes in short-term micro-climates. In addition, SPRP could potentially reduce the production cost by reducing the ramping reserve requirement provided by conventional thermal generators, and also possibly enhance the reliability of power system operations. Thus in this paper, we are exploring the capability of solar to provide such flexibility service, and also evaluating the values of solar-friendly flexible ramping product in terms of the reliability and economic benefits for power system operations [12,13].

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Nomenclature

Acronyms

SPRP	solar power ramping product
ISO	independent system operator
WPRP	wind power ramping product
MISO	midcontinent independent system operator
CAISO	California independent system operator
FESTIV	flexible energy scheduling tool for integration of variable generation
DU	day-ahead security-constrained unit commitment
RU	real-time security-constrained unit commitment
RE	real-time security-constrained economic dispatch
AGC	automatic generation control
OpSDA	optimized swinging door algorithm
FRP	flexible ramping product
MILP	mixed-integer linear programming
ACE	area control error
CPS2	control performance standard 2
NERC	North American electric reliability corporation
AACEE	absolute area control error in energy
KA	Kriging approximation
LHS	Latin hypercube sampling

Parameters

t,τ	indexes for time intervals
$T^{(\cdot)}$	number of time periods. $T^{\mathrm{RU}} = 4$ with 15-min time resolution in RU model and $T^{\mathrm{RE}} = 3$ with 5-min time resolution in RE model
NI	number of thermal units
NS	number of solar generators
NB	number of buses
$C_i^{t^{(\cdot)}}$	operation cost of thermal unit i during period t^{RU} and t^{RE}, in $
$S_i^{t^{(\cdot)}}$	start-up cost of thermal unit i during period t^{RU} and t^{RE}, in $
$\gamma_{i,t^{(\cdot)}}^{\mathrm{up}}$, $\gamma_{i,t^{(\cdot)}}^{\mathrm{dn}}$	bidding price of flexible up/down ramping reserves of thermal unit i during period t^{RU} and t^{RE}, in $/MWh
$p_s^{t^{(\cdot)}}$	power output of solar generator s at the end of period t^{RU} and t^{RE}, in MW
$P_i^{\min}$, $P_i^{\max}$	minimum/maximum generation of thermal unit i
$d_b^{t^{(\cdot)}}$	expected load of bus b at time $t^{(\cdot)}$, in MW
$\mathbf{PL}^{\max}$	vector of power limit for transmission lines
$\mathbf{D}$	vector of expected load or demand
$\mathbf{K_P}$, $\mathbf{K_S}$, $\mathbf{K_D}$	bus-thermal unit, bus-solar unit, and bus-load incidence matrices
$\mathbf{P}$, $\mathbf{P_S}$	vector of thermal dispatch and PV generation
$\mathbf{SF}$	shift factor matrix
$X_{i,\mathrm{on}}^{t^{(\cdot)}}$, $X_{i,\mathrm{off}}^{t^{(\cdot)}}$	ON/OFF time of thermal unit i at time $t^{(\cdot)}$
$T_{i,\mathrm{on}}$, $T_{i,\mathrm{off}}$	minimum ON/OFF time limits of unit i
R_i^{up}, R_i^{dn}	maximum up/down ramping rate of thermal unit i, in MW/min
L_C	a sufficient large constant
$UP_s^{t^{(\cdot)}}$, $DP_s^{t^{(\cdot)}}$	up/down solar power ramping product of solar generator s during period t^{RU} and t^{RE}, in MW
$URR_{t^{(\cdot)}}$	total flexible upward ramping reserve requirements during period t^{RU} and t^{RE}, in MW
$DRR_{t^{(\cdot)}}$	total flexible downward ramping reserve requirements during period t^{RU} and t^{RE}, in MW
m, n	index of time points in the solar power data
$R(\cdot)$	ramp rule for measured or forecasted solar power
$C(\cdot)$	natural ramp rule for the clear-sky solar power
$p_{\mathrm{C},s}^{t^{(\cdot)}}$	solar power generation in clear sky
p_t^{NL}	actual netload at time t
$\hat{p}_{t+5\mathrm{min}\mid t}^{\mathrm{NL}}$	forecasted netload for the next 5 min at time t
$\hat{p}_{t+15\mathrm{min}\mid t}^{\mathrm{NL}}$	forecasted netload for the next 15 min at time t
$\sigma_{t,5\mathrm{min}}$	standard deviation of netload in the RE model
$\sigma_{t,15\mathrm{min}}$	standard deviation of netload in the RU model
λ_e, λ_r	penalty multipliers for the economic and reliability benefits
$\underline{\alpha}$, $\overline{\alpha}$	minimum/maximum values of times of the standard deviation of netload in RE model
$\underline{\beta}$, $\overline{\beta}$	minimum/maximum values of times of the standard deviation of netload in RU model
x, μ_x, σ_x	variable to be normalized, its mean value, and standard deviation
$ACE_{t,inst}$	instantaneous ACE value at time period t
T_n, K_1, K_2	parameters used for the smoothed AGC mode
$\varphi_{(\cdot)}$	sensitivity coefficients
I_{RTD}, H_{RTD}	time resolution and horizon of the RE model
P_{WIND}, P_{LOAD}	amount of wind power and load on the system
P_{RAMP}	amount of total ramping available from the resources to manage the variability
T_{CPS2}	CPS2 interval, i.e., 10 min
$\mathbf{\Lambda}$	coefficient vector containing all the regression parameters and $\mathbf{\Lambda} = [\lambda_1,\ldots,\lambda_6]^{\mathrm{T}}$
q, N_{S}	index and total number of sampled points (α_q, β_q)
$\lambda_{(\cdot)}$, θ, ω	parameters of the KA model
μ_α, μ_β	mean values of sampled α_q and β_q
σ_α, σ_β	standard deviations of sampled α_q and β_q

Variables and Functions

$p_i^{t^{(\cdot)}}$	dispatch of thermal unit i at the end of period t^{RU} and t^{RE}, in MW
$u_i^{t^{(\cdot)}}$	1 if unit i is scheduled on during period t^{RU} and t^{RE}; and 0 otherwise
$fu_i^{t^{(\cdot)}}$, $fd_i^{t^{(\cdot)}}$	scheduled flexible up/down ramping reserves of thermal unit i during period t^{DU}, t^{RU}, and t^{RE}, in MW
α, β	times of the standard deviation of netload in RU and RE models
α_{N}, β_{N}	normalized times of the standard deviation of netload in RU and RE models
$S_c(\cdot)$	positive score function used in the dynamic programming
$f(\cdot)$	multi-objective function for obtaining reliability benefits and minimizing dispatching cost
$\hat{f}\,(\alpha,\beta)$	Kriging approximation surrogate model
$f_E\,[\cdot]$	functional relationship between the economic metrics and times of standard deviation
$f_R\,[\cdot]$	functional relationship between the reliability metrics and times of standard deviation
$\mathscr{F}(\cdot)$	realization function of a regression model in KA
$\mathscr{R}(\cdot)$	correlation function in KA
$\mathbf{f}(\alpha,\beta)$	polynomial function vector set containing polynomials of orders 0, 1, and 2: $\mathbf{f}(\alpha,\beta) = [1,\alpha_{\mathrm{N}},\beta_{\mathrm{N}},\alpha_{\mathrm{N}}^2,\alpha_{\mathrm{N}}\beta_{\mathrm{N}},\beta_{\mathrm{N}}^2]$
$\nabla\hat{f}\,(\cdot)$	gradient matrix of KA
$H(\hat{f}\,(\cdot))$	Hessian matrix of KA
ρ	control factor used to limit the provision of SPRP
$p_{\mathrm{ESS}}^{t^{(\cdot)}}$	charged power of ESS at time $t^{(\cdot)}$