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Integration of smart grid technologies in stochastic multi-objective unit commitment: An economic emission analysis

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ABSTRACT

This paper proposes a stochastic multi-objective unit commitment (SMOUC) problem incorporating smart grid technologies (SGTs), namely, plug-in electric vehicles (PEVs), demand response programs (DRPs), compressed air energy storage (CAES) units, and renewable distributed generations (DGs). An economic emission analysis of the proposed SMOUC problem with the SGTs is carried out to minimize the total expected operation cost and emission using a new mixed-integer linear programming (MILP) method. A two-stage stochastic programming method is used for dealing with the uncertain nature of power generation from the renewable DGs. Lexicographic optimization in combination with hybrid augmented-weighted ε-constraint method are employed to obtain Pareto optimal solutions of the SMOUC problem, and a fuzzy decision making is applied to select the most preferred non-dominated solution. Besides, mathematical modeling of responsive loads can help the independent system operator (ISO) to use a conservative and reliable model to have lower error in load curve characteristic estimation, such as variation in peak load. In this regard, this paper also contributes to the existing body of knowledge by developing linear and nonlinear economic models of price responsive loads for time-based DRPs (TBDRPs), as well as voluntary and mandatory incentive-based DRPs (IBDRPs) based on the customer's behavior (CB) concept and price ratio (PR) parameter. Also, new mathematical indices are proposed to choose the most conservative and reliable economic model of price responsive loads. Moreover, different widely used DRPs are analyzed and prioritized using the strategy success index (SSI) from the ISO viewpoint to determine the most effective DRP which has more coordination with the SGTs. The proposed MILP-based SMOUC problem with integrated SGTs, is applied to IEEE 10-unit test system and is implemented in General Algebraic Modeling System (GAMS) environment. Simulation analyses demonstrate the effectiveness of integrating SGTs into the proposed SMOUC problem from the economic, environmental, and technical points of view.

1. Introduction

The smart grid is conceived as an electric power system which is able to enhance existing power grids to ones which are more economical, ecological, flexible, and reliable. A host of technologies has been developed to achieve these aims of the smart grid. Some of these technologies include plug-in electric vehicle (PEV), demand response program (DRP), energy storage system (ESS) and renewable distributed generation (DG). However, the integration of the smart grid technologies (SGTs) in the power system operation studies such as economic emission unit commitment (UC) problem causes two major challenges. Firstly, the integration of the SGTs in the generation scheduling problem requires new methodologies for linking the demand-side and supply-side resources scheduling to fully benefit from the advantages of the SGTs. On the other hand, resource scheduling task of the conventional power grid becomes more complex [1]. This complexity is due to increase of number of decision variables and random nature of the new problem which involves numerous constraints and nonlinear objective functions. In the light of the mentioned challenges, it is essential to develop a novel UC model in order to cope with the challenges and fully benefit from the advantages of the SGTs. This paper proposes a novel stochastic multi-objective UC (SMOUC) model including four types of the SGTs such as PEVs, DRPs, ESSs and renewable DGs in order to properly schedule daily power generation in the smart grid environment. The individual and collective effects of the SGTs on the proposed SMOUC problem are analyzed from economic, environmental and technical points of view using a new mixed-integer linear programming (MILP) method.

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Nomenclature

Sets

N_G	set of TGUs
N_J	sets of parking lots
N_K	set of CAES units
N_W	set of wind-based DGs
N_{PV}	set of solar-based DGs

Indices

t, τ, $\acute{\Gamma}_P$	index of time
g	index of TGU unit
k	index of CAES unit
w	index of wind-based DG
pv	index of solar-based DG
j	index of parking lot
l	index of PEV
T_{peak}	index of peak hours
I/P	incentive/penalty adjustment coefficient in IBDRPs
i	index of objective function
r	index of Pareto optimal solution
ki	index of equal intervals in modified ε-constraint method
s	index of scenario

Parameters and variables

$P_{Vch}(t)/P_{Vdch}(t)$	aggregated charging/discharging power of PEVs at time t (MW)
$N_{Vch}(j,t)/N_{Vdch}(j,t)$	number of charging/discharging PEVs in parking lot j at time t
T	scheduling hours
P_{V_l}	capacity (power) of PEV l (MWh)
$N_V^T(j)$	total number of PEVs in parking lot j
ψ_{pre}/ψ_{dep}	present/departure state of charge
ψ_{min}/ψ_{max}	minimum/maximum state of charge
$N_{Vch}^{max}(j)/N_{Vdch}^{max}(j)$	maximum number of charging/discharging PEVs in parking lot j at time t
η_{Vch}/η_{Vdch}	charging/discharging efficiency of a PEV
$E(t,t)$	self-elasticity of demand
$E(t,\tau)$	cross-elasticity of demand
$EPr_0(t)$, $EPr(t)$	initial/secondary electricity price at time t ($/MWh)
$D_0(t)$	value of initial demand at time t (MW)
$D_{DRP}(t)$	value of demand after implementing DRP at time t (MW)
$D_{DRP_{CBPR}}(t)$	value of demand after implementing CBPR-based DRP at time t (MW)
$\zeta(t)$	price ratio parameter at time t
$INC(t)$	incentive of DRPs at time t ($/MWh)
$PEN(t)$	value of penalty at time t ($/MWh)
$CL(t)$	I/C and CAP programs contract level (MW)
Ψ	the potential of DRPs implementation
Ω_I	incentive's weighting coefficient
Ω_P	penalty's weighting coefficient
INC^{min}/INC^{max}	minimum/maximum limit of an incentive offered by the ISO at time t ($/MWh)
PEN^{min}/PEN^{max}	minimum/maximum limit of a penalty offered by the ISO at time t ($/MWh)
$B_{inj}(k)/B_P(k)$	the efficiency of injected/pumped power by CAES k
$U_P(k,t)$	binary variable; is equal 1 if air pumped from storage by CAES k at time t, otherwise 0
$V_P^{min}(k)/V_P^{max}(k)$	the minimum/maximum level of pumped air from CAES k to combustion chamber (MW/h)
$V_{inj}^{min}(k)/V_{inj}^{max}(k)$	the minimum/maximum level of injected air into CAES k (MW/h)
$U_{inj}(k,t)$	binary variable; is equal 1 if air injected to storage by CAES k at time t, otherwise 0
$A^{min}(k)/A^{max}(k)$	the minimum/maximum stored energy level of CAES k (MWh)
$A_{initial}(k)$	initial state of charge of CAES k at the beginning of Scheduling horizon (MWh)
$B_{initial}(k)$	percent of initial energy level of CAES k
$\acute{\Gamma}(Z(g,t))$	start-up cost of TGU g at time t ($)
$cost_0(g)$,$cost_h(g)$,$cost_c(g)$	NC, hot and cold start-up costs for TGU g ($)
$HST(g)$	hot start-up time of TGU g (h)
$CST(g)$	cold start-up time of TGU g (h)
$U^{off}(g,t)$	continuous off duration of TGU g at time t (h)
$SUC(g,t)/SUC_l(g,t)$	nonlinear/linear start-up cost of TGU g at time t ($)
$Y^0(g,t)$	binary variable; is equal 1 if start-up type of TGU g is NC at time t, otherwise 0
$Y^{hot}(g,t)$	binary variable; is equal 1 if start-up type of TGU g is hot at time t, otherwise 0
$Y^{cold}(g,t)$	binary variable; is equal 1 if start-up type of TGU g is cold at time t, otherwise 0
$F_q(g,t,s)/F_l(g,t,s)$	nonlinear/linear fuel cost function of TGU g at time t in scenario s ($)
$E_q(g,t,s)/E_l(g,t,s)$	nonlinear/linear emission function of TGU g at time t in scenario s (tons)
$a(g)$,$b(g)$,$c(g)$	fuel cost coefficient of TGU g ($/h, $/MWh, $/MW^2 h)
$b_n(g)$	slope of block n of fuel cost curve of TGU g ($/MWh)
$\beta_n(g,t)$	binary variable; is equal 1 if block n of fuel cost curve of TGU g is selected
$be_n(g)$	slope of block n in emission curve of TGU g (ton/MWh)
$\alpha(g)$,$\beta(g)$,$\gamma(g)$	emission coefficient of TGU g (ton/h, ton/MWh, ton/MW^2 h)
$P^{min}(g)/P^{max}(g)$	minimum/maximum power output of TGU g (MW)
$P_n^d(g)$	lower limit of segment n of TGU g (MW)
N	number of blocks of the piecewise linearization
$RU(g)/RD(g)$	allowed ramp-up/ramp-down of TGU g (MW/h)
$U(g,t)$	binary variable; is equal to 1 if the TGU g be on at time t, otherwise 0
$Y(g,t)$	binary variable; is equal to 1 if the TGU g is started at time t, otherwise 0
$Z(g,t)$	binary variable; is equal to 1 if the TGU g is turned off at time t, otherwise 0
$MU(g)$	the minimum up time of TGU g (h)
$MD(g)$	the minimum down time of TGU g (h)
$\mu(k,t)$	offered energy cost of CAES k at time t ($/MWh)
$SP(t)$	day-ahead spot electricity price ($/MWh)
$R(t)$	system spinning reserve requirement at time t (MW)
ρ_{PV}^{μ}	the probability of solar power generation in interval μ
ρ_W^{φ}	the probability of wind power generation in interval φ
F^{Cost}	first objective function (Total expected operation cost)
$F^{Emission}$	second objective function (Expected emission generated)
w_i	relative importance of the objective function i
S_i^{ki}	slack variables for the constraints of the objective function i in equal interval ki
r_i	the range of objective function i
q_i	number of equal intervals (grid points) of objective function i
M	number of objective functions
μ_i^r	individual membership function for the objective function i in the Pareto optimal solution r
μ^r	total membership function of the Pareto optimal solution r
f_i^r	value of objective function i in Pareto optimal solution r
f_i^{min}/f_i^{max}	minimum/maximum value of objective function i
$P_W(w,t,s)$	active power output of wind-based DG w at time t in scenario s (MW)