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ORIGINAL ARTICLE

Short-term bulk energy storage system scheduling for load leveling in unit commitment: modeling, optimization, and sensitivity analysis

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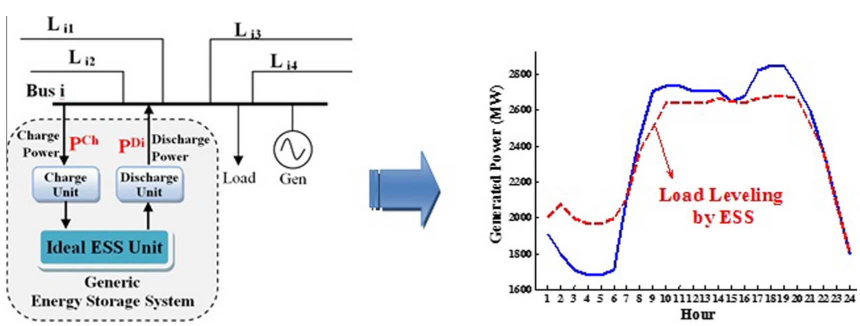
GRAPHICAL ABSTRACT



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ABSTRACT

Energy storage systems (ESSs) have experienced a very rapid growth in recent years and are expected to be a promising tool in order to improving power system reliability and being economically efficient. The ESSs possess many potential benefits in various areas in the electric power systems. One of the main benefits of an ESS, especially a bulk unit, relies on smoothing the load pattern by decreasing on-peak and increasing off-peak loads, known as load leveling. These devices require new methods and tools in order to model and optimize their effects in the power system studies. In this respect, this paper will model bulk ESSs based on the several technical characteristics, introduce the proposed model in the thermal unit commitment (UC) problem, and analyze it with respect to the various sensitive parameters. The technical limitations of

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Load leveling
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Unit commitment

the thermal units and transmission network constraints are also considered in the model. The proposed model is a Mixed Integer Linear Programming (MILP) which can be easily solved by strong commercial solvers (for instance CPLEX) and it is appropriate to be used in the practical large scale networks. The results of implementing the proposed model on a test system reveal that proper load leveling through optimum storage scheduling leads to considerable operation cost reduction with respect to the storage system characteristics.

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Nomenclature

Sets

$I,\ J$	sets of network buses
M	set of piecewise linear generation cost function segments
N	set of thermal units
N_i	set of thermal units located at bus i
S	set of energy storage systems
S_i	set of energy storage systems located at bus i
T	set of time periods

Parameters

BG_n^0	initial on/off state of unit n
C_n^{CSU}	constant start-up cost of unit n at time period t
C_n^{CSD}	constant shutdown cost of unit n at time period t
C_i^{CLS}	constant cost of load shedding at bus i and time period t
$\mathrm{ES}_s^{\mathrm{Rated}}$	rated energy of energy storage system s
ES_s^0	initial stored energy in energy storage system s
k_n	constant coefficient of piecewise linear generation cost function of unit n
N_n^{GC}	number of segments of generation cost function of unit n
P_n^{RD}	ramp-down limit of unit n
P_n^{RU}	ramp-up limit of unit n
P_n^{SDR}	shutdown ramp limit of unit n
P_n^{SUR}	start-up ramp limit of unit n
P_n^{Min}	minimum generation capacity of unit n
P_n^{Max}	maximum generation capacity of unit n
$\mathrm{PD}_{i,t}$	demand at bus i and time period t
$\mathrm{PL}_{i,j}^{\mathrm{Max}}$	capacity of the line between buses i and j
$\mathrm{PS}_s^{\mathrm{Rated}}$	rated power of energy storage system s
$\mathrm{PS}_s^{\mathrm{CRU}}$	charge ramp-up limit of energy storage system s
$\mathrm{PS}_s^{\mathrm{CRD}}$	charge ramp-down limit of energy storage system s
$\mathrm{PS}_s^{\mathrm{DRU}}$	discharge ramp-up limit of energy storage system s
$\mathrm{PS}_s^{\mathrm{DRD}}$	discharge ramp-down limit of energy storage system s
R_t	required reserve at time period t
T_n^D	number of time periods unit n must be initially offline due to its minimum down-time constraint
$T_n^{D_0}$	number of time periods unit n has been offline prior to the first period of the time span
T_n^{MD}	minimum down-time of unit n
T_n^{MU}	minimum up-time of unit n
T_n^U	number of time periods unit n must be initially online due to its minimum up-time constraint
$T_n^{U_0}$	number of time periods unit n has been online prior to the first period of the time span
$\mathrm{XL}_{i,j,t}$	reactance of the line between buses i and j
α_n	constant coefficient of quadratic generation cost function of unit n
β_n	first order coefficient of quadratic generation cost function of unit n
γ_n	second order coefficient of quadratic generation cost function of unit n
η_s^{Ch}	charge efficiency of energy storage system s
η_s^{Di}	discharge efficiency of energy storage system s
$\lambda_{n,m}$	slope of segment m of piecewise linear generation cost function of unit n

Variables

$\mathrm{BG}_{n,t}^{\mathrm{State}}$	binary variable indicating on/off state of generating unit n at time period t
$\mathrm{BG}_{n,t}^{\mathrm{SU}}$	binary variable indicating start-up state of generating unit n at time period t
$\mathrm{BG}_{n,t}^{\mathrm{SD}}$	binary variable indicating shutdown state of generating unit n at time period t
$\mathrm{BS}_{s,t}^{\mathrm{Ch}}$	binary variable indicating charge state of energy storage system s at time period t
$\mathrm{BS}_{s,t}^{\mathrm{Di}}$	binary variable indicating discharge state of energy storage system s at time period t
$C_{i,t}^{\mathrm{LS}}$	load shedding cost at bus i and time period t
$C_{n,t}^{\mathrm{SD}}$	shutdown cost of unit n at time period t
$C_{n,t}^{\mathrm{PG}}$	generation cost of unit n at time period t
$C_{n,t}^{\mathrm{SU}}$	start-up cost of unit n at time period t
$\mathrm{ES}_{s,t}$	stored energy in energy storage system s at time period t
$P_{m,n,t}^{\mathrm{PL}}$	generated power in segment m of piecewise linear generation cost function of unit n at time period t
$P_{i,t}^{\mathrm{LS}}$	load shedding at bus i and time period t
P_t^{Res}	total reserve of the system at time period t
$\mathrm{PG}_{n,t}$	generated power of unit n at time period t
$\mathrm{PG}_{i,t}^{\mathrm{Bus}}$	sum of the generated power of units located at bus i at time period t
$\mathrm{PG}_{n,t}^{\mathrm{Max}}$	maximum producible power of unit n at time period t
$\mathrm{PG}_{n,t}^{\mathrm{Res}}$	spinning reserve of unit n at time period t
$\mathrm{PI}_{i,t}$	power injected at bus i and time period t
$\mathrm{PL}_{i,j,t}$	flow of the line between buses i and j at time period t

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