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Multistage generation expansion planning incorporating large scale energy storage systems and environmental pollution

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ABSTRACT

This paper addresses a multistage electricity generation expansion planning (GEP) incorporating large-scale energy storage systems (ESSs). The proposed coordinated GEP-ESS planning aims at minimizing the planning cost and environmental pollution at the same time, while it considers large-scale ESSs. Problem is expressed as a mixed-integer nonlinear programming and solved using PSO algorithm. Problem is solved subject to practical constraints of the network. ESS capacities are installed to support peak load level and reducing planning cost and environmental pollution. A typical test system including several existing and candidate generating units is considered to evaluate the proposed methodology. ESSs with various capacities are considered as candidate ESSs. Considering a large number of generating units and ESSs capacities increases the flexibility of the planning. Simulation results demonstrate that utilizing ESSs significantly reduces GEP cost as well as decreases the environmental pollution.

1. Introduction

Power system expansion planning can be carried out based on the generating system [1–3], transmission network [4,5], or distribution system [6–8]. The electricity generation expansion planning (GEP) denotes time, location, capacity and technology of new generating units which should be constructed to meet the growing energy demand within the given security criteria over a planning horizon time of typically 10–30 years. GEP is mathematically modeled as a constrained, mixed-integer, and nonlinear optimization problem aiming at minimizing (or maximizing) planning objective function subject to the given constraints. This optimization problem is mainly solved using mathematical methods or Meta-heuristic optimization techniques. The mathematical techniques such as dynamic programming [9], mixed integer programming [10], and linear programming [11] have been successfully applied to solve GEP. In addition, Meta-heuristic optimization techniques such as ant colony [12], tabu search [12], genetic algorithms [13], honey bee algorithm [14], artificial immune system [15], evolutionary programming [12], and PSO [16] have also been used to solve GEP.

GEP has also been studied considering several objective functions such as minimizing planning cost [2,17], maximizing planning profit in deregulated electricity market [18], maximizing reliability [13], minimizing environmental pollution [19], and considering demand-side management programs [20]. As well, GEP has been investigated subject to various constraints such as reliability [3], environmental pollution [21], investment cost [22], and security [23].

In GEP, network planners must build sufficient generating capacity to meet the peak demand, while time duration of peak demand is about five percent of the total time. As a result, supporting peak load through auxiliary systems such as energy storage systems (ESSs) can significantly reduce GEP cost. By installing large-scale ESSs, network planners would need to build only sufficient generating capacity to meet the average electrical demand rather than peak demand [24].

Electrical energy storage is mainly defined as the process of converting electricity into a more convenient storable form for converting back to the electricity when needed [25]. ESSs offer many applications in electric power systems including mitigating renewable resources uncertainties [26], micro-grid applications [27], risk mitigation in electricity market [28], frequency-voltage control, stability enchantment, power quality improvement, congestion relief, peak load shaving, and load leveling [29], reliability improvement [8], and electricity market [30].

One of the most important applications of ESSs can be regarded

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Nomenclature

Symbols, indexes, and parameters

CC_t	total installed generation capacity from initial stage until stage t
CE_t	total installed ESSs capacity from initial stage until stage t
CG	vector of candidate generating units capacity (MW)
$Cinv_t^{ESS}$	investment cost of the ESSs capacity at stage t ($/kWh)
$Cinv_t^j$	investment cost for technology j at stage t ($)
CIT_t	maximum permitted level for technology j at stage t
CO_2	carbon dioxide
Cop_t^{ESS}	operational costs of the new ESSs at stage t ($/kWh)
Cop_t^j	operational cost for technology j at stage t ($/MWh)
Cp_t^j	environmental pollution cost for technology j at stage t ($/tons)
d	discount rate
d and nd	day number and set of days
dt_t	time duration of the tth stage (hours)
E^c	energy reservoir capacity of a storage (kWh)
E_{ch}, E_{disch}	charged and discharged energy of the ESSs (kWh)
$E^d{}_{ch}$, $E^d{}_{disch}$	charged and discharged energy of the ESSs at dth day (kWh)
EG	vector of existing generating units capacity (MW)
ESS_t^c	ESSs capacity at stage t (kWh)
E_t	number of the ESSs at stage t
E_t^{max}	maximum permitted number of the ESSs at stage t
LCI_t	maximum permitted level for the planning cost
$LOLE^{max}$	maximum permitted LOLE (h/year)
M, j	number and type of the candidate technologies
MIC_t	maximum permitted level for all technologies at stage t
NO_X	a generic term for the mono-nitrogen oxides NO and NO2 (nitric oxide and nitrogen dioxide)
O	total planning cost ($)
Of_1	investment and operational costs of the existing and new generating units over the planning horizon ($)
Of_2	investment and operational costs of the new ESSs over the planning horizon ($)
Of_3	environmental pollution costs over the planning horizon ($)
P_{ch}, P_{ch}^{rate}	charged power to the ESSs and its rate (kW)
$P^d{}_{ch}$, $T^d{}_{ch}$	charging power rate (kW) and charging time (hours) at dth day
P_{disch}, P_{disch}^{rate}	discharged power from the ESSs and its rate (kW)
PX_t^j	environmental pollution of technology j at stage t (tone/kWh)
RM_t	reserve margin of the system
RM_t^{max}	maximum permitted reserve margin (%)
RM_t^{min}	minimum permitted reserve margin (%)
SO_2	sulfur dioxide
T	number of stages
t	tth stage of the planning horizon
T_{ch}^{max}	maximum charging time (hour)
X_0^j	integer vector showing the existing units
X_t^{ESS}	integer vector showing the installed ESSs at stage t
X_t^j	integer vector showing the installed candidate units at stage t
α_t^j	capacity factor (%)
η_{ESS}	ESSs efficiency (%)

Abbreviations

CCGT	combined cycle gas turbines
EENS	expected energy not served
ESS	energy storage system
FOR	forced outage ratio
GEP	generation expansion planning
IC Engine	internal combustion engine
LOLE	loss of load expectation
LOLP	loss of load probability
Oil CT	oil combustion turbine
PSO	particle swarm optimization

as mitigating the renewable resources uncertainties [6,31]. Irregular renewable power production from sun and wind needs considerable backup generation to support the power demand permanently. This issue should be done even if wind and sun work on their full capacity. Furthermore, large penetration of renewable resources would need more backup generation. In such systems, backup generation can be decreased by proper utilizing ESSs. Paper [31] investigates the interaction of renewable resources and ESSs regarding reduction of required backup energy and it demonstrates that total cost of system is reduced following such planning. Application of wind energy along with compressed air energy storage (CAES) also shows suitable results [32]. Wind–CAES system lets switch from the CAES to the Brayton cycle once the stored energy is insufficient to meet demand. Wind–CAES reduces fuel cost and CO_2 emission, and it improves energy supply security even in areas with relatively low-quality wind potential. Wind–CAES is cost-effective comparing the other alternatives [32]. Paper [33] investigates the impact of utility-scale energy storage on large-scale integration of renewable sources and increasing system flexibility. In [33], the potential to prevent electricity exchange from European countries with higher CO_2 pollution factor to European countries with lower CO_2 pollution factor is assessed for different levels of energy storage. The outcomes illustrate that application of grid-scale energy storage systems could offer a structure for a fair burden sharing of emissions' allocation in Europe to support an adaptable energy supply scheme.

ESS utilizing in electricity market has also been investigated [34,35]. It has been demonstrated that if the generation sector is completely competitive, adding energy storage system is always welfare-enhancing. If the generation sector is strategic, adding perfectly competitive or strategic energy storage can decrease social welfare [34]. Paper [35] investigates the impact of negative prices on storage systems. It demonstrates that negative prices can substantially alter the optimal storage policy structure for fast storage systems. As well, for slow storage systems, it is indicated that ignoring negative prices could cause a significant loss of value when negative prices occur more than 5% of the time. As well, in the presence of the negative prices, a broker might buy negatively priced electricity surpluses and dispose of them by locally load banks [35].

Paper [36] reviews the renewable energy sources (RES) in the Greek electricity generation system from the perspective of social support offered to RES-based power stations (e.g., initial cost subsidy opportunities and feed-in-tariff mechanism) and financial benefits from the operation of RES-based power stations (e.g., substitution of the fossil-fuel based power stations' operation,