Electrical Power and Energy Systems 116 (2020) 105529

Contents lists available at ScienceDirect

Electrical Power and Energy Systems

journal homepage: www.elsevier.com/locate/ijepes

MILP formulation for generation and storage asset sizing and sitting for reliability constrained system planning

Chandrabhanu Opathella, Ayman Elkasrawy, Amr Adel Mohamed[*,1], Bala Venkatesh

Electrical and Computer Engineering, Ryerson University, 350 Victoria Street, Toronto, Ontario, Canada

ARTICLE INFO

Keywords:
Energy storage
Sizing and siting
Long-term planning

ABSTRACT

Energy storage systems can provide a series of benefits to improve the operation flexibility and reliability of electric power systems, but their size and placement in the power system are critical to achieving expected benefits. An optimal ES sizing and siting study is presented in this paper. The formulation considers long-term economic benefits all generation and ES technologies for optimal sizing and siting.

Unlike other recent studies, the proposed MILP formulation consider reliability as planning parameter. It also considers different lifetimes of ES and other generation assets, and salvage values to compute the present value of benefits. Both long-term (several years) and short-term (hourly) power demand variation are accounted for optimal sizing generators and ES. The developed formulation provides optimal size, location and investment year (a complete investment plan) for all assets. It is a comprehensive, robust production-grade long-term asset planning formulation.

The paper presents a detailed case study conducted with the Ward-Hale 6-Bus test system and IEEE 118-Bus test system. Results show that ES assets can be used to improve system reliability overcome network congestion.

1. Introduction

Grid connected energy storage (ES) systems are becoming popular among planners and policymakers as a component which can improve the operational flexibility and reliability of electric power systems. Energy storage systems can provide a series of services such as voltage regulation support, frequency regulation support, ramp power support, and energy arbitrage. Electrical jurisdictions are starting to integrate ES to improve the operational flexibility of the grid [1,2]. For example, in 2014 Ontario's long-term energy plan recommended adding 50 MW of ES technologies [3]. This integration occurred in two phases, and all procured ES units should be operational by 2019 [4]. The integration of ES in utility grids was investigated in [5] with historical generation and demand data. It suggests that ES can improve the utilization of transmission assists. In [6,7], the impact electricity pricing schemes on the adoption of ES has been studied. Aforementioned studies show that the importance of ES for jurisdictions such as Ontario, Canada, where renewable energy penetration is considerable, negative electricity price hours are common, and grid operation flexibility needs to be improved.

The benefits of ES greatly depend on the connected location in the grid. Article [7–15] discuss different methods for siting and sizing generation assets in power systems. In Traditional generation expansion planning, generation system reliability is an integrated planning parameter [7]. Long-term (15–20 years) investment plans are developed by sizing assets to match the peak of system load duration curve [7,8]. Under this method, daily variations of demand or intermittent generations are overlooked. Furthermore, siting of generation assets is carried out as an independent study. In recent studies, asset siting and sizing studies carried out as one problem considering daily variations of load and intermittent generation [9–15]. It is important to consider such variations to size the energy storage systems because those variations decide the power (MW) /energy (MWh) capacities of ES. A time period of 24 h with 15 min resolution has been considered in [9]. However, recent research fails to generate long-term investment plans which assess the long-term economic benefits of different generation and ES technologies. Furthermore, they do not consider the generation reliability as a planning parameter for the siting and sizing as in [10,11]. Authors in [10] describe an optimal sizing and siting study conducted for the Western Electricity Coordinating Council (WECC) interconnection. The described method minimizes the operation cost of generators, cost of renewable energy spills and investment cost of ES, and it has the ability of analyzing large transmission systems. Authors states that due to computational difficulties, the model does not generate an optimal long-term investment plan. In [11], the optimal

* Corresponding author.
E-mail address: amr.adel@ryerson.ca (A. Adel Mohamed).
[1] Amr is on leave from Cairo University.

https://doi.org/10.1016/j.ijepes.2019.105529
Received 17 April 2019; Received in revised form 25 July 2019; Accepted 1 September 2019
0142-0615/

Nomenclature

Indices

H	index for denoting daily load curve sections
i	index for denoting generators and energy storage
j	index for denoting bus numbers
m	index for denoting power import options
s	index denoting seasons of the year
t	index for denoting years
x	index for denoting a random system generation contingency event

Parameters

a	lower bound of binary variable a
A	amortization factor (unitless)
AV	available generator and ES vector in the event x
β / γ	charge/discharge efficiency of energy storage
B	price of power imports (Million $/MWh)
CCS	carbon capture and storage
CG	conventional generators
CMC	combined cycle
CT	combustion turbine
DT	minimum downtime of generators (hrs)
$\bar{EES}$, $\underline{EES}$	maximum, minimum of energy storage energy (MWh)
ES	energy storage
H	duration of hours of a load curve section (hrs)
IGCC	integrated gasification combined cycle
IG	intermittent generators
K1	power rating-based capital cost coefficient of CG and IG (Million $/MW)
K2	power rating-based capital cost coefficient of ES (Million $/MW)
K3	generation based cost coefficient of CG and IG (Million $/MWh)
K4	power rating based fixed operation and maintenance cost coefficient of CG and IG (Million $/MW)
K5	power rating based fixed operation and maintenance cost coefficient of ES (Million $/MW)
K6	energy ratings-based capital cost coefficient of ES (Million $/MWh)
K7	energy rating based fixed operation and maintenance cost coefficient of ES (Million $/MWh)
K8, K9, and K10	constants of the approximated linear LOLP curve (MW-1)
LF	lifetime of generators and energy storage (years)
η	self-discharge efficiency of energy storage (%)
NB	number of buses in the transmission system
NCG	number of conventional generators
ND	number of days in a season
NES	number of energy storage
NH	number of sections of the daily load curve
NI	number of power import options
NIG	number of intermittent generators
NS	number of seasons of the year
NT	number of years of the planning period
PC	pulverized coal-fired
PD	real power demand (MW)
$\bar{PES}$, $\underline{PES}$	maximum, minimum of energy storage real power (MW)
$\bar{PG}$, $\underline{PG}$	generators real power limits: maximum, minimum (MW)
$\bar{PI}$	maximum real power import limit (MW)
PLL	power flow limit of the line (MW)
Pr	discrete probability distribution function
PV	present value factor (unitless)
Ramp	power ramp limit (MW)
RS	resource profiles of intermittent generators (%)
RT	minimum run time of generators (hrs)
SDC	shut down cost of CG (Million $)
SUC	start-up cost CG (Million $)
T^{Down}	time duration that generator need shut down for the maintenance (hrs)
X	number of all generation contingency events
Yb	imaginary parts of elements of bus admittance matrix of the transmission network (Ω)

Integer variables

A	binary variable to denote annual selections of GC, IG or ES (if selected 1, else 0)
C+	binary variable to denote investment selection year of CG, IG or ES (if selected 1, else 0)
C–	redundant binary variable required for modelling
u	binary selection variable for CG to operate in an hour
v, w	binary variables to denote start-up and shutdown of CG

Variables

CC	amortized cost of capacity (Million $)
δ	bus voltage angle
EES	stored energy in the energy storage (MWh)
IC	annual power import cost (Million $)
ICG	amortized investment cost (Million $)
FOC	annual fixed operation and maintenance cost (Million $)
GC	cost of generation (Million $)
LFL	lifetime left of generators and energy storage at the end of each year (years)
LOLP	loss of load probability
PES	real power supplies from energy storage (MW)
PES+, PES¬	real power discharge/charge (MW)
PG	real power generation (MW)
PI	real power imports (MW)
SVG	amortized salvage value (Million $)

storage locations are determined by minimizing the generation cost and investment cost of ES over a year.

Authors in [11], presents a three-stage planning procedure to identify the optimal locations and parameters of distributed ES units. Another similar study for optimal siting and sizing of ES for the operation planning of power systems with large-scale wind power integration is presented in [12]. Similar to the traditional asset planning, it has two separate algorithms for siting and sizing. For the optimal siting algorithm, all the buses are assumed to have ES installations with unlimited amounts of power and energy. For the optimal sizing algorithm, additional power and energy constraints are incorporated in the optimization problem. These siting and sizing [11,12] studies use multilevel solution approaches, which could not guarantee the global optimal solution.

In transmission system planning, it a common practice to use DC power flow equations to formulate a linear problem [11,12]. If nonlinear AC power flow equations are used, nonlinear or heuristic solution methods need to be adopted [13,16]. Recently, several planning studies have been conducted including energy storage system [17–20]. An extensive literature review on optimal sitting, sizing and control of ES have been presented in [17]. A stochastic expansion planning model considers wind farms and energy storage accompanied by transmission