Electric Power Systems Research 145 (2017) 63–72

Contents lists available at ScienceDirect

Electric Power Systems Research

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

Battery energy storage systems in transmission network expansion planning

J.A. Aguado, S. de la Torre, A. Triviño*

Department of Electrical Engineering, University of Malaga, Campus de Teatinos, 29071, Spain

ARTICLE INFO

Article history:
Received 3 March 2016
Received in revised form 2 September 2016
Accepted 16 November 2016
Available online 30 December 2016

Keywords:
Transmission expansion planning
Energy storage system
Battery
Power system
Upgrade deferral

ABSTRACT

To satisfy present or emerging energy demands, the expansion of transmission networks is frequently needed. In conventional approaches, transmission network expansion planning is supported by the construction of new power lines. However, in the general case, expansion cannot be done immediately as the installation of new lines may require facilities and/or authorizations that are not readily available. In this scenario, energy storage systems and batteries in particular may be an alternative since they can reduce the need to procure excess capacity to deal with demand peaks, therefore avoiding unnecessary network expansion. The work in this paper studies the convenience of using this kind of energy system element and what its main features (namely, cost and capacity) should be if positive outcomes are desired. For this purpose, a mathematical formulation for transmission expansion considering energy storage systems in a market-driven environment is presented. It models the impact of new lines and batteries in the transmission network. The proposed framework has been applied to the modified Garver's system and the IEEE 24-bus system. The results show how the deferral of the construction of new lines is feasible if additional batteries are attached to certain nodes.

1. Introduction

Transmission expansion planning is a complex multi-objective optimization problem that aims to determine the new components that need to be included in the electrical transmission network to satisfy present and/or future demands [1]. Once a decision regarding planning has been made, the deployment of definitive installations is deferred until the required facilities (mainly terrains) are available. These facilities are generally obtained through governmental agreements. Nevertheless, while approval is not granted, it is necessary to mitigate network congestion problems and/or to optimize network performance. Energy storage systems (ESS) can then be considered as temporary solutions that may alleviate saturation and electrical problems under these specific circumstances [2]. In contrast with new transmission lines, ESSs are much easier to install [3] and they have already shown some economic benefits for the transmission upgrade deferral as stated in Ref. [4].

In fact, it is expected that ESSs will play a key role as grid assets in the near future [5,6]. Focusing on battery energy storage systems (BESS), the main benefits are related to network operation (voltage control, power flow management and restoration) and to the energy-market [7,8]. In this sense, we can differentiate two main roles for BESSs. Firstly, BESSs can serve as support for lines that suffer from saturation in a reduced percentage of their operational time without the need for investing in expensive new lines. Secondly, while the transmission network is being reinforced with new lines and generators, BESSs can improve the performance of stressed power systems or systems with intermittent and unpredictable sources [9]. To do this, they will be charged during energy excess periods and they will inject energy during peak hours.

The optimal placement, type and size of BESSs are still open issues that need to be defined for stressed power systems [8]. The authors in Ref. [10] propose a first approximation to solve this problem by minimizing the expansion costs based on BESSs and new lines. An updated version of this model is presented in Ref. [11], where the authors incorporate the effects of the line losses in an iterative optimization problem. Given a maximum number of storage units, the solver iteratively analyzes if a decrement in this parameter leads to a reduction in network costs. Alternatively, the authors in Ref. [12] propose a discrete-time mixed integer programming problem without the need for defining a maximum number of storage systems.

Although previous works take into account some physical restrictions of the electrical network (namely the maximum power flow and the maximum number of lines per node in Ref. [10] and

---

* Corresponding author.
E-mail address: atc@uma.es (A. Triviño).

http://dx.doi.org/10.1016/j.epsr.2016.11.012
0378-7796/

Nomenclature

Constants

b_{srk}	Susceptance of line k in corridor (s, r)
g_{srk}	Conductance of line k in corridor (s, r)
K_{srk}	Building cost of line k in corridor (s, r)
L	Number of blocks of the piecewise linearization of power losses
M	Large enough positive constant
N	Number of all nodes in the electrical network
N_d	Number of blocks of the dth demand
N_g	Number of blocks of the gth generation
$\bar{p}^c_{D_{dh}}$	Size of the hth block of the dth demand in scenario c
$P^{max}_{G_g}$	Capacity of the gth generating unit
$\bar{p}_{G_{gb}}$	Size of the bth block of the gth generating unit
p^{max}_{srk}	Capacity of line k in corridor (s, r)
W^c	Weight of scenario c
D_B	Factor accounting for the degradation of the battery capacity
S^{min}	Lower limit of the energy stored in a battery
S^{max}	Upper limit of the energy stored in a battery
$S^{max}_{B_a}$	Upper limit of the energy stored in a type-a battery
$P^{max}_{B_a}$	Upper limit of output power of a type-a battery
$P^{min}_{B_a}$	Lower limit of output power of a type-a battery
T_{man}	Placing cost of a type-a battery at bus m
η	Global efficiency coefficient of energy storage batteries
η_d	Discharging efficiency coefficient of energy storage batteries
η_c	Charging efficiency coefficient of energy storage batteries
$\alpha_{sr}(l)$	Slope of the lth block of the voltage angle linearization for the corridor (s, r)
$\Delta\delta_{sr}$	Upper bound of the angle blocks of corridor (s, r)
$\bar{\lambda}$	Average nodal price for all the buses
$\overline{\lambda}_s$	Average nodal price for bus s
$\lambda^c_{D_{dh}}$	Price bid by the hth block of the dth demand in scenario c
$\lambda^c_{G_{gb}}$	Price offered by the bth block of the gth generating unit in scenario c
$\lambda^{+c}_{B_{man}}$	Purchase price offer of the nth type a placed in bus m in scenario c
$\lambda^{-c}_{B_{man}}$	Sales price offer of the nth type a placed in bus m in scenario c
σ	Weighting factor to make investment and operational costs comparable
ε_L	Scaling factor of transmission line construction costs
ε_B	Scaling factor of battery installation costs
t	Payback on investment in years
r	Financial interest rate
τ_{sr}	Annual amortization rate of the new lines
τ_{B_a}	Annual amortization rate of the new batteries
I_{max}	Maximum investment budget
I_{L_max}	Maximum investment budget in new lines
I_{B_max}	Maximum investment budget in new batteries
N_{max}	Maximum number of batteries allowed in a bus

Scenario-dependent variables

f^c_{srk}	Lossless power flow in line k of corridor (s, r) in scenario c
$p^c_{D_d}$	Total power consumed by the dth demand in scenario c
$p^c_{D_{dh}}$	Power consumed by the hth block of the dth demand in scenario c
$p^c_{G_d}$	Total power produced by the gth generating unit in scenario c
$p^c_{G_{gb}}$	Power produced by the bth block of the gth generating unit in scenario c
p^c_s	Power injection at bus s in scenario c
p^c_{srk}	Power injection in line k of corridor (s, r) in scenario c
q^c_{srk}	Power losses in line k of corridor (s, r) in scenario c
$p^{+c}_{B_{man}}$	Charge power battery n type a in bus m in scenario c
$p^{-c}_{B_{man}}$	Discharge power battery n type a in bus m in scenario c
$p^c_{B_{man}}$	Power battery n type a in bus m in scenario c, which takes a positive value if it is charging, and negative if it is discharging
$S^c_{B_{man}}$	Level of energy storage battery n, which is type-a, in bus m in scenario c
δ^c_s	Angle at bus s in scenario c

Global variables

w_{srk}	Binary variable that is equal to 1 if line k from corridor (s, r) is functional, and 0 otherwise
y_{man}	Binary variable that is equal to 1 if type-a nth battery n from bus m is functional, and 0 otherwise
$y_{1_{man}}$	Binary variable that is equal to 1 if type-a nth battery from bus m is discharging

Sets

Ψ^s_D	Set of all demands located at bus s
Ψ^s_G	Set of all generators located at bus s
Ψ^s_L	Set of all lines connected to bus s
Ψ^s_B	Set of all batteries connected to bus s
Ω_c	Set of all scenarios
Ω_d	Set of indexes of the blocks of the dth demand
Ω_D	Set of indexes of the demands
Ω_g	Set of indexes of the blocks of the gth generating unit
Ω_G	Set of indexes of the generating units
Ω_L	Set of all possible transmission lines, prospective and existing
Ω_{L+}	Set of all prospective transmission lines
Ω_N	Set of all network buses
Ω_B	Set of all possible batteries, prospective and existing
Ω_{B+}	Set of all prospective batteries

Metrics

i_c	Congestion index of the network
i_s	Saturation index of the network
$\mu_1, \ldots, \mu_4$	Metrics to assess the impact of new transmission lines on the network

the line losses in Ref. [11]), the objective function does not consider consumer benefits maximization. Moreover, they do not follow a market-driven approach. Both shortcomings are overcome in our present research, which accounts for market-driven generation offers and demand bids as in a non-BESS based model presented in Refs. [13] and [14].