Renewable Energy 94 (2016) 651–659

Contents lists available at ScienceDirect

Renewable Energy

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

Optimal placement and sizing of the storage supporting transmission and distribution networks

Mahdi Motalleb*, Ehsan Reihani, Reza Ghorbani

Renewable Energy Design Laboratory (REDLab), Department of Mechanical Engineering, University of Hawai'i Manoa, Honolulu, HI 96822, USA

ARTICLE INFO

Article history:
Received 5 October 2015
Received in revised form
28 January 2016
Accepted 27 March 2016
Available online 6 April 2016

Keywords:
Battery energy storage system (BESS)
Optimal location
Optimal capacity
Economic dispatch (ED)

ABSTRACT

Developments of renewable energy resources imposes many uncertainties and variabilities in power grids. One of the best approaches to mitigate these stochastic disturbances is thought the use of Battery Energy Storage System (BESS). Besides application of the BESS such as decreasing the disturbances in distribution system, the grid frequency can be controlled in contingencies using the appropriate storage in transmission network to compensate the power shortage. Thus, the optimal siting and sizing of the BESS is important to have the minimum costs and losses. This paper describes a heuristic method to find the optimal location(s) and capacity of a multi-purpose BESS including transmission and distribution parts. In the transmission storage part, a sensitive analysis is performed using Complex-Valued Neural Networks (CVNN) and Time Domain Power Flow (TDPF) in order to detect the optimal BESS location(s). Additionally, running TDPF and Economic Dispatch (ED) leads to the optimal BESS size. In the distribution storage part, the optimal BESS size is calculated to perform distribution grid services such as peak load shaving and load curve smoothing. The proposed method has been applied to a real model (Maui island in Hawai'i -United States) to calculate the optimal results for both transmission and distribution sides.

1. Introduction

High penetration of renewable energy generation poses some challenges in the operation of power systems. The main issue inherent with renewables is intermittency of power which will cause fluctuations in voltage and frequency of the power grid. BESS is one of the leading means to solve problems caused by these fluctuations. Applications of BESS have other benefits in the power grid such as frequency control, reserve providing, and flattening the load curve. The capacity and location of the BESS are important for cost-effectiveness of storage applications. Allocation of BESS in the appropriate locations increase losses in the grid [1].

This paper proposes a framework to optimize the location(s) and size of the BESS for two purposes including: decreasing the fluctuations from the renewable energy sources in the distribution side, and controlling the frequency under contingencies in the transmission side. The transmission BESS compensate for the power shortage in the abnormal conditions in order to help the grid to reliably cope with the contingencies with less impact on frequency. The distribution BESS mitigates the fluctuations caused by renewables and also shifts the load from peak to low load time. These multi-purpose optimizations increase the reliability of the power grid considering the issues of the transmission and distribution networks. The proposed method in this paper solves a few problems of the transmission and distribution networks through calculation of optimal two-purpose BESS.

1.1. Literature review

The majority of published papers in the storage area only focus on operation related to the distribution network. There are less publications about optimal location(s) of the BESS in comparison with optimal sizing due to the complexity of the finding of the optimal locations [2,3]. Thus, in many of the previous studies, it was posited that BESS is located near wind farms and large loads. The literature review can be divided into two categories: the first contains storage purposes while the second includes storage sizing and siting.

1.1.1. Storage purposes

The majority of studies in the operation area are based on uncertainty and fluctuations related to distributed generations.

* Corresponding author.
E-mail addresses: motalleb@hawaii.edu (M. Motalleb), ereihani@hawaii.edu (E. Reihani), rezag@hawaii.edu (R. Ghorbani).

http://dx.doi.org/10.1016/j.renene.2016.03.101
0960-1481/

Nomenclature

TDPF Formulation:

I_{Bus}	Injected current vector to the buses which is positive in generation buses (PV-buses and slack bus) and negative in loads (PQ-buses).
Y_{Bus}	Admittance matrix of the grid
V_{Bus}	Voltage vector of the buses
f,g	Algebraic and differential equations to solve time domain problem
f_n	A function dependent on the method of the integration
A_c^i	A matrix dependent on the algebraic and state Jacobian matrices
x^{i+1}, y^{i+1}	Calculated values of x and y in time $t = i+1$

ED Formulation:

$C(P_{GEN})$	Generation cost function *($/hr)*
$C_{GEN,i}^{local}$	Generation cost of the i^{th} local generator *($/hr)*
$C_{GEN,j}^{dist}$	Generation cost of the j^{th} distant generator *($/hr)*
$C_{BESS,k}^{total}$	Total generation cost of the k^{th} BESS (located in the k^{th} sensitive bus) *($/hr)*
$NGlocal$	Number of the local generators (located in the sensitive buses)
$NGdist$	Number of the generators located far from than the sensitive buses
$NBESS$	Number of the required BESS stations (is equal to the number of the sensitive buses)
$a_{local,i}$	The first coefficient of the quadratic cost function of the i^{th} local generator
$b_{local,i}$	The second coefficient of the quadratic cost function of the i^{th} local generator
$c_{local,i}$	The third coefficient of the quadratic cost function of the i^{th} local generator
$a_{dist,j}$	The first coefficient of the quadratic cost function of the j^{th} distant generator
$b_{dist,j}$	The second coefficient of the quadratic cost function of the j^{th} distant generator
$c_{dist,j}$	The third coefficient of the quadratic cost function of the j^{th} distant generator
$P_{GEN,i}^{local}$	Generated power of the i^{th} local generator *(MW)*
$P_{GEN,j}^{dist}$	Generated power of the j^{th} distant generator *(MW)*
$C_{j,l}^{trans}$	Power transmission cost between the j^{th} and l^{th} bus
$C_{BESS,k}^{st}$	Cost of storage unit in the k^{th} BESS *($/hr)*
$C_{BESS,k}^{pcs}$	Cost of power conversion in the k^{th} BESS *($/hr)*
$R_{j,l}$	Resistance between j^{th} and l^{th} bus (Ω)
$X_{j,l}$	Reactance between j^{th} and l^{th} bus (Ω)
$I_{j,l}$	Passing current from j^{th} to l^{th} bus (kA)
$P_{j,l}^{flow}$	Transmitted active power from j^{th} to l^{th} bus (MW)
$V_{j,l}$	Voltage difference between j^{th} and l^{th} bus (kV)
$C_{BESS,k}^{st,unit}$	Unit cost of the storage in the k^{th} BESS *($/MWhr)*
$P_{BESS,k}$	Generated power of the k^{th} BESS (located in the k^{th} sensitive bus) (MW)
$C_{BESS,k}^{pcs,unit}$	Unit cost of the power conversion in the k^{th} BESS *($/MWhr)*
$P_{GEN\min,i}^{local}$	The minimum allowed power generation of the i^{th} local generator (MW)
$P_{GEN\max,i}^{local}$	The maximum allowed power generation of the i^{th} local generator (MW)
$P_{GEN\min,j}^{dist}$	The minimum allowed power generation of the j^{th} distant generator (MW)
$P_{GEN\max,j}^{dist}$	The maximum allowed power generation of the j^{th} distant generator (MW)
$P_{req,m}$	The required power for the m^{th} sensitive bus to cope with the contingency (MW)

Peak Shaving:

$P_{bat}(t)$	Battery power flow at time t (kW)
$P_{cir}(t)$	Circuit power demand at time t (kW)
SOC_{min}	The minimum allowed state of charge of BESS
SOC_{max}	The maximum allowed state of charge of BESS
E_{tot}	Total capacity of distribution part of BESS (kWh)
$E(t)$	Energy level of distribution part of BESS at time t (kWh)
Δt	Optimization time interval (hr)
$P_{ref}(t)$	Reference power curve at time t (kW)

Load Curve Smoothing:

$P_L(t)$	Smoothing power line (kW)
t_k	The k^{th} time step

Varkani et al. [4] modeled these uncertainties using Artificial Neural Networks (ANN) and stochastic programming. They discussed joint bidding design by a wind farm and a pumped hydro plant in the day-ahead and ancillary services markets. Forecasting electricity price and wind generation are two good optimization parameters which Gonzalez et al. [5] used in their study for a pumped hydro storage plant. In their study, another approach for joint market participation was proposed by a wind power plant and a pumped hydro storage plant. Pandžić [6] proposed a method based on bilateral contracts and one day-ahead pricing in order to maximize the power plant profit considering the storage system, photovoltaic system, and a conventional generating unit. This model was for bilateral contracts and a day-ahead market. The conclusions were based on the importance of an accurate evaluation of the storage unit's energy and power ratings. Another stochastic model, based on real-time marketing, was proposed by Pandžić [7] for a similar power plant utilizing wind generation instead of photovoltaic system. Pandžić used a real-time market to balance the day-ahead market bids and the actual generation. Another scheduling method was proposed by Korpaas [8] based on dynamic programing in order to calculate the optimal electricity exchanges considering one transmission line constraints related to wind generation and storage. However, only one transmission line (between the storage and the rest of the transmission network) was considered. Simulation results show that energy storage enables the owners of the wind power plant to take advantage of variations in the spot price, therefore, increasing the value of wind power in the electricity market. An optimal commitment policy considered conversion losses and energy prices in a grid which included wind farm and storage [9]. Zhou et al. [10] modeled a system, based on Markov decision prices and investigated wind farms, storage, and transmission systems. They proved that storage can increase the monetary value of the system. Cahndy et al. [11] performed optimal power flow on a power grid including the storage system and considered the integration of renewable energy resources. Therefore, this study was technical rather than economical. One economical study was done by Faghih et al. [12] with the goal of investigating optimal utilization of storage and the economic value of storage. They considered ramp-rate constraints and different electricity prices and they proved that optimal utilization of storage