Applied Energy xxx (xxxx) xxx–xxx

Contents lists available at ScienceDirect

Applied Energy

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

Optimal sizing and placement of distribution grid connected battery systems through an SOCP optimal power flow algorithm

Etta Grover-Silva[a,b,*], Robin Girard[a], George Kariniotakis[a]

[a] MINES ParisTech, PSL – Research University, PERSEE – Center for Processes, Renewable Energies and Energy Systems, France
[b] ADEME – French Environment and Energy Management Agency, France

HIGHLIGHTS

- Optimal power flow algorithm used for the optimal sizing and placement of batteries.
- Second order cone program OPF to guarantee algorithmic performance.
- Integration of smart grid operations into the planning phase of distribution grids.
- Techno-economic analysis of benefits in comparison to investment cost of batteries.

ARTICLE INFO

Keywords:
Optimal power flow
Storage
Smart grids
Renewable energy
Distribution grid planning

ABSTRACT

The high variability and uncertainty introduced into modern electrical distribution systems due to decentralized renewable energy generators requires new solutions for grid management and power quality assurance. One of these possible solutions includes grid integrated energy storage. The appropriate size and placement of decentralized storage is highly dependent on purpose of the battery system and expected operational strategy. However, battery operational strategies are difficult to simulate simultaneously during a sizing and placement planning calculation. The motivation of this paper is to propose an algorithm that is capable of integrating sizing, placement and operational strategies of batteries into an Optimal Power Flow (OPF) distribution grid planning tool. The choice of the OPF approach permits to account for grid constraints which is more adapted for grid-connected storage devices compared to other approaches in the state of the art that are based only on an email balance analysis. This paper presents an alternating current (AC) multi-temporal OPF algorithm that uses a convex relaxation of the power flow equations to guarantee exact and optimal solutions with high algorithmic performance. The algorithm is unique and innovative due to the fact that it combines the simultaneous optimization of placement and sizing of storage devices taking into account load curves, photovoltaic (PV) production profiles, and distribution grid power quality constraints. The choice to invest in battery capacity is highly sensitive to the price of battery systems. The investment in battery systems solely for reducing losses an operational costs was proven not to be cost effective, however when battery systems are allowed to buy and sell electricity based on variable market prices they become cost effective. The assumptions used for this study shows that current battery system prices are too high to be cost effective even when allowing battery system market participation.

1. Introduction

The increasing environmental concerns, is one of the main drivers behind the large scale development of distributed energy resources (DER) in electric distribution grids. This development involves connection of decentralized generators to the electric grid primarily photovoltaic (PV) and wind turbines and also micro-hydroelectric generators bring about new challenges for the distribution grid operators. Decentralized renewable energy generators can introduce bi-directional flow within the network, while their production is uncertain and variable due to its inherent dependence on weather conditions. Other specific challenges of the distribution grid include higher uncertainty due to reduced aggregation effects of DER generators, voltage profile deviation and increased power flow in electric lines. These challenges are generally localized therefore creating local voltage perturbations that may not be visible by the distribution operator.

* Corresponding author at: MINES ParisTech, PSL Research University, PERSEE – Center for Processes, Renewable Energies and Energy Systems, France.
E-mail addresses: etta.grover-silva@mines-paristech.fr (E. Grover-Silva), robin.girard@mines-paristech.fr (R. Girard), georges.kariniotakis@mines-paristech.fr (G. Kariniotakis).

http://dx.doi.org/10.1016/j.apenergy.2017.09.008
Received 3 April 2017; Received in revised form 31 August 2017; Accepted 7 September 2017
0306-2619/

Nomenclature

Parameters

- η_{st} charging and discharging efficiency of the battery system
- $\overline{P}_{pv,j,t}$ ideal PV production for node j at time step t
- $\overline{S}_{pv,j,t}$ PV maximum apparent power flow at node j
- $\overline{V}_j$ voltage maximum at node n
- $\underline{V}_j$ voltage minimum at node n
- c_{st}^{inv} investment costs of the battery system for the nominal capacity in €/MWh-day
- c_{st}^{om} operations and maintenance costs of using the battery system for the power use in €/MWh-day
- $c_{e,t}$ price of electricity at time step t
- I^{max} total capital cost limit of project
- $P_{ld,j,t}$ active power load at node j
- $Q_{ld,j,t}$ reactive power load at node j
- r_{jk} resistance of branch jk
- t duration of timestep
- x_{jk} reactance of branch jk

Sets

- J set of all nodes $j \in J$
- J_{st} set of nodes chosen for battery placement $j \in J_{st}$

Variables

- $\ell_{jk,t}$ square of current in branch jk
- $v_{j,t}$ square of voltage at node j
- $C_{st,j,d}^{nom}$ final nominal capacity of battery systems for each node j for each day d
- F_{inj} function describing the cost of power injected into the feeder at the substation
- F_{inv} function describing the cost of investment of the battery nominal capacity and power
- $F_{O\&M}$ function describing the cost of operation and maintenance of the battery devices
- F_p function describing the cost of losses within the system including PV curtailment
- $F_{st,p}$ function describing the cost of battery losses due to charging/discharging efficiency
- $N_{st,j,d}^{nom}$ the number of hours of nominal autonomy of the battery system at node j
- $P_{st,j,d}^{nom}$ final nominal power of battery systems for each node j for each day d
- $P_{0,t}$ active power flow at the substation
- $P_{jk,t}$ active power of branch jk
- $P_{pv,j,t}$ photovoltaic injection at node j at time t after eventual curtailment
- $P_{st,j,t}$ power injected by battery devices connected at node j
- $Q_{jk,t}$ reactive power of branch jk
- $Q_{pv,j,t}$ PV reactive power injection at node j after eventual curtailment
- $S_{jk,t}$ apparent power of branch jk
- $S_{pv,j,t}$ PV apparent power flow at node j
- $soc_{st,j,t}$ state of charge of the storage unit as a cumulation of energy at node j and time step t
- $V_{j,t}$ voltage at node j

Solutions to these challenges include infrastructure upgrades such as electric line reinforcement or automation and integration of smart grid functionalities such as on-line tap changers (OLTC), DER generation curtailment, storage devices, demand side management (DSM) [1]. Specific technologies related to flexibilities include privately owned grid connected batteries such as electric vehicles [2] or larger grid operator owned storage used to improve overall economic exploitation of the feeder. Demand side management optimization in smart grids and efficient smart grid technologies have been thoroughly explored for a variety of use cases [3–7]. Infrastructure upgrades are easily quantified. However, new control and flexibility functionality is difficult to quantify economically and integrate into the planning phase of distribution grids. The cost benefit analysis of varying smart grid technologies and management strategies will become more important as DER penetration increases in future distribution grid systems.

Grid storage elements are presented in the literature as a cost effective solution to deal with the above challenges in distribution grids with high DER penetration. A techno-economic analysis of energy storage elements as a solution to intermittency of DER is presented in [8]. That paper details the cost-effectiveness of different grid storage applications including regulation of transmission and distribution power quality, voltage regulation and control, energy management, smoothing of intermittent renewable energy production, energy back-up, peak shaving, etc. For each specific application, taking into account the operational strategy of the storage device is important when sizing and placing the unit.

The optimal sizing and placement of storage devices in distribution grids has been addressed through various mathematical modeling methods presented in the literature. The problem of calculating the optimal placement and size of storage devices of an electric grid is highly dimensional and non-convex. The resolution of this highly dimensional non-convex problem has been successful with multiple mathematical techniques including analytical techniques, classical techniques, artificial intelligence techniques and other miscellaneous techniques [9]. In a different review of energy storage allocation, four main categories are defined to solve this highly dimensional non-convex problem: analytical methods, mathematical programming, exhaustive search and heuristics [10]. The different existing methods are of different complexity, some being simple, i.e. based on an energy balance of the examined system to size the storage. However, for grid connected systems the placement involves analysis of the impact of storage devices to the grid. For this reason, techniques based on mathematical programming such as power flow and optimal power flow (OPF) are more appropriate. These methods can be used to simulate distribution system functionality with generators and storage devices while taking into account grid constraints as seen in [11]. OPF algorithms are capable of taking into account decision variables and therefore capable of analyzing active management of distribution grids. An example of an OPF that analyzes hosting capacity of an active distribution grid is found in [12], where curtailment strategies and dynamic line rating are explored to increase renewable energy penetration.

OPF algorithms are efficient at analyzing active distribution networks for operation and planning. The two primary problem resolution techniques for solving this highly dimensional non-convex problem include heuristic techniques or linear convex relaxations of the power flow equations. Heuristic algorithms have been used to solve the optimal placement and sizing of storage devices. For example, a two-step process with a master and a sub-problem is proposed in [13]. This method firstly uses a heuristic algorithm to solve optimal placement and sizing of batteries. Secondly, a daily AC OPF multi-objective function takes into account optimal voltage control, minimization of network losses and total energy costs. Another paper presents a comprehensive sizing and siting algorithm using particle swarm optimization [14]. A different type of heuristic method was used to simultaneously size and place storage units using an artificial bee colony