Reliability-Constrained Optimal Sizing of Energy Storage System in a Microgrid

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***Abstract*—This paper presents a model for calculating the optimal size of an energy storage system (ESS) in a microgrid considering reliability criterion. A larger ESS requires higher investment costs while reduces the microgrid operating cost. The optimal ESS sizing problem is proposed which minimizes the investment cost of the ESS, as well as expected microgrid operating cost. Utilizing the ESS, generation shortage due to outage of conventional units and intermittency of renewable units is handled; hence microgrid reliability criterion is satisfied. A practical model for ESS is utilized. Mixed-integer programming (MIP) is utilized to formulate the problem. Illustrative examples show the efficiency of the proposed model.**

***Index Terms*—Energy storage system, expansion planning, microgrid.**

NOMENCLATURE:

ρ_t	Electricity price.
CIF_B	Capital investment funds for ESS.
DR_i	Ramp down rate limit of unit i.
F_i	Production cost function of unit i.
h	Index for hour.
i	Index for conventional unit.
I_{ith}^s	Commitment state of unit i at day t at hour h in scenario s.
IC	Microgrid total investment cost.
ICP_B	ESS power rating investment cost.
ICE_B	ESS energy rating investment cost.
k	Depth of discharge.
LS_{th}^s	Load curtailment at day t at hour h in scenario s.
NG	Number of conventional units.
NR	Number of renewable units.
NT	Number of days.
NH	Number of hours.
NS	Number of scenarios.
OC	Microgrid total operating cost.
p_s	Probability of scenario s.
$P_{D,th}^s$	Microgrid load demand at day t at hour h in scenario s.
$P_{M,th}^s$	Power imported (exported) from (to) the main grid at day t at hour h in scenario s.
$P_M^{\max}$	Power import (export) limit.
$P_{B,th}^s$	Power generated (consumed) by the ESS at day t at hour h in scenario s.
P_B^R	ESS Rated power.
P_{ith}^s	Generation of conventional unit i at day t at hour h in scenario s.
P_{rth}^s	Generation of renewable unit r at day t at hour h in scenario s.
$P_i^{\min}$	Minimum power generation of unit i.
$P_i^{\max}$	Maximum power generation of unit i.
r	Index for renewable unit.
SD_{ith}^s	Shutdown cost of unit i at day t at hour h in scenario s.
SU_{ith}^s	Startup cost of unit i at day t at hour h in scenario s.
s	Index for scenario.
t	Index for day.
DT_i	Minimum down time of unit i.
UT_i	Minimum up time of unit i.
UR_i	Ramp up rate limit of unit i.
$UY_{M,th}^s$	Contingency state of line connected to the main grid at day t at hour h in scenario s.
UX_{ith}^s	Contingency state of unit i at day t at hour h in scenario s.
y_{ith}^s	Startup indicator of unit i at day t at hour h in scenario s.
z_{ith}^s	Shut down indicator of unit i at day t at hour h in scenario s.
λ_{th}	Value of lost load at day t at hour h.

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I. INTRODUCTION

THE application of energy storage systems (ESS) in future grids is receiving more attention recently than ever from system operators as the storage technologies continue to evolve and are becoming economically justifiable to be employed in power systems. The ESS proposes extensive applications in power system operation, such as improving control, mitigating volatility and intermittency problems of renewable energy resources, load following, voltage and frequency stability, peak load management, power quality improvement, and deferment of system upgrades. However, high investment costs necessitate accurate modeling and optimal sizing of ESS to justify its economic viability and further prevent over or underutilization. An accurate and practical ESS model would enhance modeling of system operation from both economic and security perspectives [1]–[3].

The ESS is an indispensable component of a microgrid. A microgrid is defined as a small-scale intelligent power network which includes at least one load and one distributed energy resource. The microgrid is regarded as a controllable load from the system operator's point of view as it would supply its own load and respond to real-time electricity price variations. By microgrid implementation, the cost of supplying energy is lowered, local reliability and power quality is improved, and system emission is reduced [4]. The optimal ESS sizing is to be performed in a microgrid as small ESS may not provide economical benefits, desired flexibility or predefined reliability objectives in the microgrid and the large ESS impose higher investment and maintenance costs to the microgrid. Therefore, ESS needs to be optimally sized hence the reduction in operating costs justifies the investment on ESS. In [4] a practical model for ESS with predefined charge and discharge profile is proposed. Coordination of ESS with intermittent renewable energy resources is explored in [5]–[7], where the goal is to smooth out the intermittent generation of wind and solar generators and obtain a dispatchable output. An analytical approach to determine the size of a backup storage unit in a power system, considering reliability requirements is proposed in [8]. The backup could be in the form of electrical energy storage or fuel storage. The ESS sizing problem for time-of-use rates industrial customers is investigated in [9]. In [10] an analytical approach to find the most-profitable rating of ESS that is installed with wind farms to increase their power dispatchability is proposed. Similar problem is solved in [11] considering the application of ESS in a photovoltaic-energy storage for autonomous small islands. In [12] a sensitivity analysis of a variety of ESS sizes and technologies in an isolated wind-diesel microgrid is performed, in which ESS is used to improve the penetration of renewable energy sources to microgrids.

This paper explores a reliability-constrained optimal ESS sizing in a microgrid. The ESS size includes power rating and energy rating. The proposed optimal ESS sizing problem minimizes the total microgrid cost, which includes ESS investment cost and microgrid operating cost. A stochastic approach is used to generate power system operation scenarios. In each scenario the state of system components as well as generation of renewable energy resources are obtained. The scenarios are reduced using a scenario reduction method as a tradeoff between computational burden and solution accuracy. The expected load curtailment in each reduced scenario is determined and consequently a reliability index, i.e., loss of load expectation (LOLE), is calculated. Fig. 1 depicts the total microgrid cost as a function of ESS size. As the ESS size is increased the investment cost added to the microgrid is increased in a linear fashion while the microgrid operating cost is reduced. The optimal ESS size would minimize the total microgrid cost. A mixed integer programming (MIP) model is used to formulate the optimal ESS sizing problem.

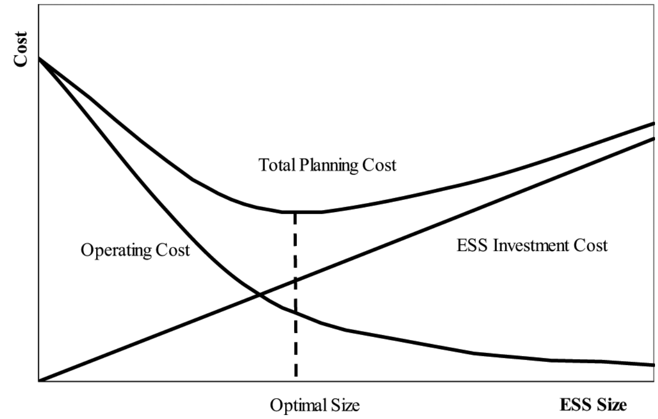

Fig. 1. Optimal ESS sizing.

This paper follows the work proposed in [4], however in this paper the reliability constraints are considered in optimal ESS sizing using a practical stochastic model, both power rating and energy rating of ESS are optimally sized, a more comprehensive ESS model is proposed, and a diverse energy generation mix (including thermal and renewable resources) is modeled.

The rest of the paper is organized as follows: Section II presents the model outline of the proposed optimal ESS sizing problem while Section III formulates the problem. Section IV presents the numerical simulations on a test system. Numerical simulations reveal the effectiveness of the proposed approach while considering reliability criterion in the microgrid. Discussions and concluding remarks are provided in Sections V and VI, respectively.

II. Model Outline

The objective of the optimal ESS sizing problem includes the ESS investment cost and the microgrid expected operating cost. Expected operating cost includes the energy production cost of units inside the microgrid and cost of purchasing energy from the main grid. The proposed objective would be considered as a decision tool to provide the information on long-term planning decisions, which will further help microgrid planners make better decisions on economics and reliability of the proposed planning options. The optimal ESS sizing problem is subject to prevailing system, unit and ESS constraints [13]–[19]. The microgrid reliability requirement is taken into account to satisfy an efficient, coordinated and economical microgrid operation and ensure continuous availability of sufficient energy supply for local loads. Reliability is of economic and security importance in a microgrid which would provide an adequate margin between supply and demand and guarantee a degree of built-in redundancy. The microgrid reliability in this paper is evaluated in terms of LOLE, which is defined as the expected fraction of unserved load in the microgrid during the study period. This