Distributed Energy Storage Sizing for Microgrid Applications

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***Abstract*— The integration of energy storage system (ESS) provides various benefits to microgrids such as mitigating renewable generation variability, reducing operation cost, and supporting frequency and voltage control. Two main factors that affect the ESS function in microgrids include the size and the number of the installed ESS units. This paper investigates these two factors and develops a new mathematical model to determine the optimal size and number of the integrated ESS units in a microgrid. The proposed model is further used to perform a comparison between aggregated and distributed ESS configurations. The proposed problem is formulated using mixed integer linear programming (MILP) and solved with CPLEX. The viability and effectiveness of the proposed model are validated by numerical simulations.**

***Index Terms*—Distributed energy storage, expansion planning, microgrid, renewable generation, energy storage sizing.**

NOMENCLATURE

Indices:

ch	Subscript for ESS charging.
dch	Subscript for ESS discharging.
d	Index for day.
h	Index for hour.
i	Index for distributed energy resources.
n	Index for ESS units.

Sets:

G	Set of dispatchable units.
W	Set of renewable generation units.

Parameters:

CE	Annualized energy rating capital cost.
CP	Annualized power rating capital cost.
C_{ESS}^{max}	Maximum energy rating.
C_{ESS}^{min}	Minimum energy rating.
D	Load demand.
DR	Ramp down rate.
DT	Minimum down time.
FC	Fixed cost of ESS.
P^{max}	Dispatchable unit maximum capacity.
P^{min}	Dispatchable unit minimum capacity.
P_{ESS}^{max}	Maximum power rating for ESS.
P_{ESS}^{min}	Minimum power rating for ESS.
P_M^{max}	Maximum power that can be transferred to or from the main grid.
UR	Ramp up rate.
UT	Minimum up time.
ρ	Electricity market price.
η	ESS round trip efficiency.

Variables:

C_{ESS}	Stored energy in the ESS at each hour.
C_{ESS}^R	ESS rated energy.
I	Commitment state of dispatchable units.
P_{ESS}^R	ESS rated power.
P	DER output power.
P_M	Power transferred to or from the main grid.
SD	Shut down cost.
SU	Start up cost.
T^{ON}	Consecutive on time.
T^{OFF}	Consecutive off time.
u_1	ESS discharging state.
u_2	ESS charging state.
x	ESS installation state.

I. INTRODUCTION

DRIVEN by high electricity demand growth, economic incentives, and desire to reduce pollution, microgrid implementation has grown significantly during the past decade. The implementation of microgrids improves the reliability and flexibility of the system, reduces the cost of energy transmission and distribution, and increases the penetration of renewable sources. The microgrid can be defined in broadly as a small-scale power system that consists of distributed generators (DGs), renewable energy sources (RESs), energy storage systems (ESSs), and local loads. It typically operates in parallel to a utility grid. However, the microgrid has the ability to disconnect itself from the grid and operate in what is known as an isolated (or islanded) mode in the case of disturbances. This feature is of ultimate importance to protect microgrid loads from being affected by external faults especially when the microgrid supplies critical loads [1]-[5].

The ESS is considered as an indispensable component of a reliable microgrid which provides significant benefits in both isolated and grid-connected operation modes. In an isolated microgrid, the ESS is critical to ensure the generation and load power balance. The ESS can be further used to regulate system frequency and maintain a stable operation. In a grid-connected microgrid, the ESS can be used to reduce the microgrid operation cost by storing energy during low price periods and discharging this energy during high price periods, hence making profit for the microgrid. The ESS can also be used for peak shaving, thus saving electric utility the cost of upgrading the system [6]. The ESS can be integrated into the microgrid as an aggregated or community unit (CESS) or as distributed units (DESS) as shown in Fig. 1 [7]. In the aggregated configuration, one ESS with a relatively large size is installed next to the utility substation. In the distributed configuration, however, multiple smaller-sized ESS units are connected to several busses in the microgrid. The ESS units may have identical or different power and energy ratings. A performance comparison between the CESS and DESSs in wind farm application is performed in [8] and [9]. This comparison is focused only on the technical side ignoring the economic issues of the problem. Moreover, the optimal size of the ESS is not determined in the proposed methods even though it is an important factor in the assessment of the ESS performance. Finding the optimal size of installed ESSs in the microgrid is important from both operation and economic perspectives. Undersized ESS may not render the desired benefits whereas oversized ESS introduces high capital costs. Moreover, the ESS must be appropriately sized if it is used in islanding and frequency regulation applications to ensure that sufficient energy will be available when needed. The subject of the ESS sizing in microgrids has been investigated in the literature. In [10] and [11] the optimal size of the ESS that minimizes the total planning cost in a grid-connected microgrid is determined. The mixed-integer linear programing (MILP) is used to formulate the problem. A reliability constraint that limits the loss of load expectation to a specific value is added in [11]. In [12] various ESSs integrated to an islanded microgrid are studied and compared in order to find the technology and the size that reduces the operation cost. An analytical method is used in [13] to size a battery energy storage system (BESS) in an islanded microgrid in response to a spinning reserve constraint. A day-ahead unit commitment problem is solved and the optimal size of the BESS is selected as the one that reduces the daily operation cost. In addition to MILP modeling, other optimization techniques are used for ESS sizing such as particle swarm optimization [14], dynamic programming [15], and genetic algorithm [16].

While existing methods can be used to size the integrated ESS, they ignore the impact of the number of installed ESS units on the microgrid operation. This paper takes this critical issue into consideration and proposes a new mathematical model that enables microgrid planners to determine both the optimal number and the optimal size (i.e., the power rating and the energy rating) of the ESS units to be installed. This model can also be used to perform a comparison between the aggregated ESS configuration and the distributed ESS configuration in microgrids.

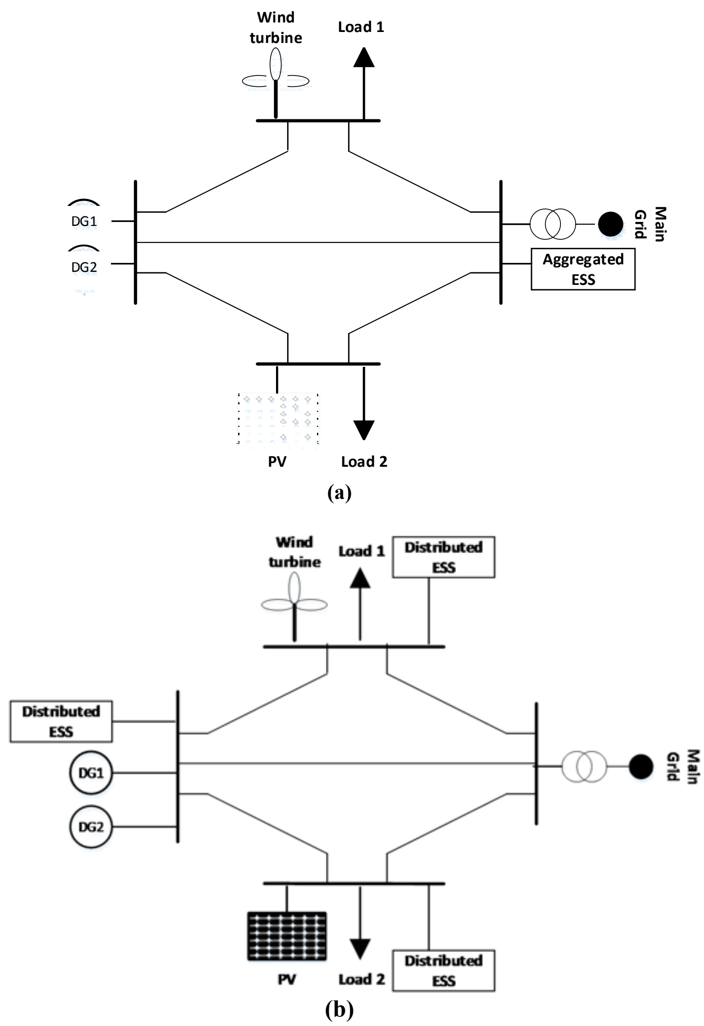

Figure 1. Integrating ESSs in the microgrid; (a) Aggregated, (b) Distributed .

The rest of the paper is organized as follows: Section II develops the microgrid expansion planning model formulation for ESS installation. Section III presents a numerical example to validate the proposed model and exhibit its merits, and Section IV concludes the paper.

II. Problem Formulation

The objective of the proposed microgrid expansion planning problem is to determine the optimal size and number of the installed ESS units that yield the minimum total microgrid expansion planning cost. The proposed model aims at upgrading an existing microgrid with addition of ESS units to reduce its operation cost. The problem is considered from a microgrid developer's prospective, therefore, savings in the upstream grid costs (such as deferred distribution and transmission upgrades, reduced congestion, etc.) are not included. The total microgrid expansion planning cost can be defined as the summation of the microgrid operation cost (MGOC) and the installed ESSs investment cost (IC_{ESS}) as given in (1):

$$min\ [MGOC + IC_{ESS}] \tag{1}$$

The microgrid operation cost consists of dispatchable units' generation cost as well as the cost/benefit of purchasing/selling power from/to the main grid, as expressed as following

$$MGOC = \sum_{i\epsilon G}\sum_d\sum_h F_i(P_{idh})I_{idh} + SU_{idh} + SD_{idh} + \sum_d\sum_h \rho_{dh}\, P_{M,dh} \tag{2}$$

Where F_i represents the function of dispatchable units production cost. The ESSs investment cost can be divided into three terms: power rating capital cost ($/kW), energy rating capital cost ($/kWh), and a fixed cost ($) as proposed in (3):

$$IC_{ESS} = \sum_n P_{ESS,n}^R\, CP + \sum_n C_{ESS,n}^R\, CE + \sum_n x_n\, FC \tag{3}$$

The first term in (3) represents all costs that depend on the ESS power rating including the annual maintenance cost and capital cost of power. The second terms represents the ESS energy rating capital cost, and the last term defines the total fixed cost, which includes any cost that does not depend on the ESS size such as the cost of housing, structuring, and labor [15]. The only factor that affects the ESS fixed cost is the number of the installed ESS units. The binary variable x_n equals 1 if the ESS number *n* is installed, otherwise 0. In this case, the fixed cost is multiplied by the ESS number and added to the investment cost. Other terms are also summed over *n* to model the impact of multiple ESS installations.

A planning horizon of one year is considered which could be extended to the lifetime of the ESS without loss of generality. The objective function is subject to the following constraints:

$$\sum_{i\epsilon\{G,W\}} P_{idh} + \sum_n P_{ESS,ndh} + P_{M,dh} = D_{dh} \quad \forall d, \forall h \tag{4}$$

$$P_i^{min} I_{idh} \le P_{idh} \le P_i^{max} I_{idh} \quad \forall i \in G, \forall d, \forall h \tag{5}$$

$$P_{idh} - P_{id(h-1)} \le UR_i \quad \forall i \in G, \forall d, \forall h \tag{6}$$

$$P_{id(h-1)} - P_{idh} \le DR_i \quad \forall i \in G, \forall d, \forall h \tag{7}$$

$$T_{idh}^{ON} \ge UT_i\big(I_{idh} - I_{id(h-1)}\big) \quad \forall i \in G, \forall d, \forall h \tag{8}$$

$$T_{idh}^{OFF} \ge DT_i\big(I_{id(h-1)} - I_{idh}\big) \quad \forall i \in G, \forall d, \forall h \tag{9}$$

$$-P_M^{max} \le P_{M,dh} \le P_M^{max} \quad \forall d, \forall h \tag{10}$$

$$P_{ESS}^{min}\, x_n \le P_{ESS,n}^R \le P_{ESS}^{max}\, x_n \quad \forall n \tag{11}$$

$$C_{ESS}^{min}\, x_n \le C_{ESS,n}^R \le C_{ESS}^{max}\, x_n \quad \forall n \tag{12}$$

$$P_{ESS,ndh} = P_{ESS,ndh}^{dis} + P_{ESS,ndh}^{ch} \quad \forall n, \forall d, \forall h \tag{13}$$

$$0 \le P_{ESS,ndh}^{dis} \le P_{ESS,n}^R\, u_{1,ndh} \quad \forall n, \forall d, \forall h \tag{14}$$

$$-P_{ESS,n}^R\, u_{2,ndh} \le P_{ESS,nh}^{ch} \le 0 \quad \forall n, \forall d, \forall h \tag{15}$$

$$u_{1,ndh} + u_{2,ndh} \le 1 \quad \forall n, \forall d, \forall h \tag{16}$$

$$\sum_h u_{1,ndh} \le k \quad \forall n, \forall d \tag{17}$$

$$C_{ESS,ndh} = C_{ESS,nd(h-1)} - \frac{P_{ESS,ndh}^{dis}}{\eta_{ESS}} - P_{ESS,ndh}^{ch} \quad \forall n, \forall d, \forall h \tag{18}$$

$$0 \le C_{ESS,ndh} \le C_{ESS,n}^R \quad \forall n, \forall d, \forall h \tag{19}$$

The set of constraints include microgrid-level constraints (4) and (10), dispatchable unit constraints (5)-(9), and ESS constraints (11)-(19). The load balance equation (4) ensures that the total generation in the microgrid, the ESSs output power, and the power that are either purchased from (i.e., positive) or sold to (i.e., negative) the main grid matches the demand at all times. Dispatchable units generation is limited by the maximum and minimum capacities in (5). Moreover, the output power variations between any two consecutive hours are restricted by ramp up and ramp down limits, respectively represented by (6) and (7). Once the generation unit starts up, it must remain on for a minimum up time limit (8). Similarly, when the generation unit shuts down, it must remain off for a certain minimum down time limit (9). The exchanged power with the main grid is restricted by both the capacity of the line that connects the microgrid to the main grid and by the capacity of the substation transformer (10). It is also possible to limit the volatility of the power exchanged with the main grid by imposing certain cap values [17]. The ESSs size (i.e., the power rating and the energy rating) are restricted by given maximum and minimum values as represented in (11) and (12), respectively. The binary variable x_n denotes the ESS installation state for ESS unit n. If the ESS unit is installed x_n is 1, otherwise it is 0. The ESS power is defined as the summation of its discharging and charging powers (13), where it is made sure that only one is active in any given time period. The ESS discharging power is positive (14) whereas the charging power is negative (15). Binary variables u_1 and u_2 are used to represent discharging mode and charging mode, respectively. When u_1 is 1, the ESS is discharging whereas when u_2 is 1 the ESS is charging. Equation (16) assures that the ESS is not simultaneously being charged and discharged. The number of charging/discharging cycles has a significant impact on the ESS lifetime [18]. In this paper a cycle limit is imposed on the ESS charging/discharging cycles in order to prolong its lifetime (17). The stored energy in each ESS is calculated by (18) and restricted by (19).

III. Numerical Simulation

A test microgrid consisting of two gas turbine units, a PV array, a wind generator, and an aggregated load is used to investigate and validate the proposed model. The technical characteristics of the gas units are given in Table I. The PV array power rating is 1.5 MW and the wind generator power rating is 1 MW. The hourly output power of the PV array, the hourly output power of the wind generator, the hourly microgrid aggregated load, and the hourly electricity market price are obtained from [19].

TABLE I
DISPATCHABLE GENERATION UNITS CHARACTERISTICS

Unit	Cost Coefficient ($/MWh)	Min.-Max. Capacity (MW)	Ramp Up/Down Rate (MW/h)	Min Up/Down Time (hour)
1	75.7	0.8-8	2.5	1
2	80.1	0.5-5	2.5	1

TABE II
ESS CHARACTERISTICS

Maximum Power Rating (MW)	Maximum Energy Rating (MWh)	Power Rating Capital Cost ($/MW/year)	Energy Rating Capital Cost ($/MWh/year)	Fixed Cost ($/year)	Round Trip Efficiency (%)
10	20	20,000	11,000	10,000	90

The maximum power that can be transferred to the main grid is assumed to be 10 MW. Two cases are considered: base case operation (without ESS installation) and ESS case. The studied ESS characteristics are given in Table II. The annual maintenance cost is embedded into the power rating capital cost. The results are given below:

Base Case: In this case the only cost considered is the microgrid operation cost since the ESS is not installed. The total generation cost is $2,163,984/year. The microgrid profit of exchanging energy with the main grid is $823,862/year. This yields a total microgrid operation cost of $1,340,122/year.

ESS Installation Case: In this case the proposed model is used to find the optimal size and number of installed ESS units that minimizes the microgrid total expansion planning cost. The maximum number of ESSs that can be installed in the system is assumed to be 4 to reduce the computation burden. The discharged cycles of each ESS is limited to two cycles as imposed by (19). The optimal number of installed ESSs in this case is 2. The power rating and energy rating of each ESS is given in Table III. The microgrid total cost reduces to $1,266,863/year compared to the base case. This cost is composed of a total ESSs investment cost of $420,000/year, the generation cost of $1,689,341/year, and the benefit of exchanging energy with the main grid of $842,478/year. The installed ESSs charging/discharging cycles for one sample day are depicted in Fig. 2. Both ESSs are charged during low price periods (hours 1, 2, and 3) and discharged during high price periods (hours 17-20). This helps the microgrid to reduce its operation cost by selling the low price energy to the main grid during high price hours (i.e., an energy arbitrage). The ESSs also follow a rather similar patterns in other days.

TABLE III
DESS OPTIMAL SIZE DETERMINED BY THE PROPOSED MODEL

DESS unit number	Rated Power (MW)	Rated Energy (MWh)
1	4.05	9
2	4.95	11

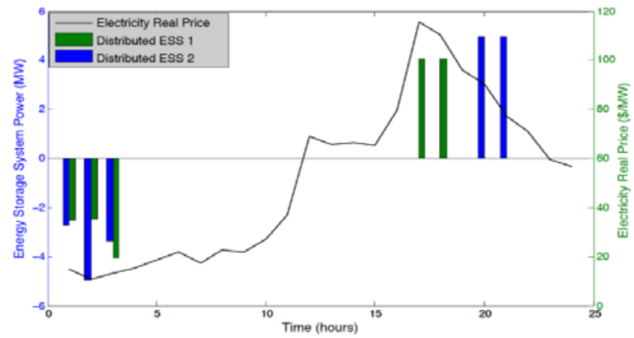

Figure 2. The charging/discharging power of DESS units and the electicity price for one sample day.

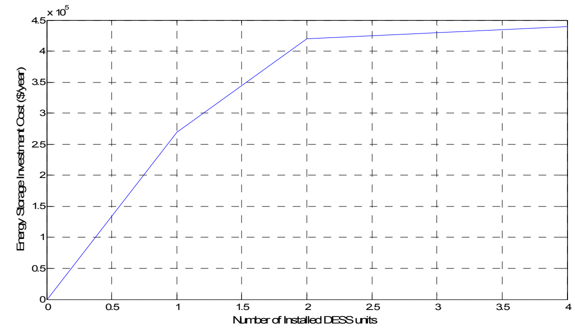

Figure 3. Investment cost with different number of installed DESS

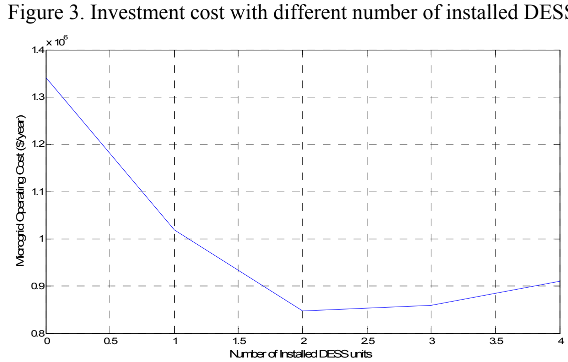

Figure 4. Micogrid operating cost with different number of installed DESS

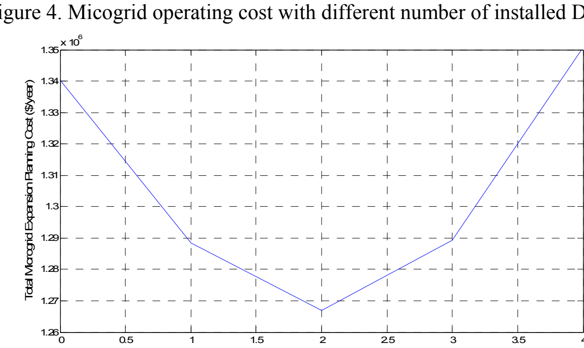

Figure 5. Microgrid total expansion planning cost with different number of installed DESS units

To further investigate the impact of the number of the installed ESS units, different scenarios with various number of ESSs are studied. The results are shown in Figs. 3-5. The investment cost increases with increasing the number of ESS units as shown in Fig. 3. From Fig. 4, it can be seen that the microgrid operation cost decreases as n increases until n reaches 2 and then increases again. Same behavior is observed at the microgrid total expansion planning cost as can be seen in Fig. 5. The minimum total expansion planning cost occurs at $n = 2$ which is similar to the solution obtained by the proposed planning model. This validates the ability of the proposed model to determine both the optimal number and the optimal size of the ESS in the microgrid. Detailed cost analysis for all scenarios is given in Table IV.

TABLE IV
DETAILED COST ANALYSIS FOR DIFFERENT DESSS NUMBER

DESS Number (N)	DESS Investment Cost ($/year)	Generation Cost ($/year)	Profit of Power Exchanged ($/year)	Operation Cost ($/year)	Expansion Planning Cost ($/year)
0	0	2,163,984	823,862	1,340,122	1,340,122
1	270,000	1,815,074	796,585	1,018,489	1,288,489
2	420,000	1,689,341	842,478	846,863	1,266,863
3	430,000	1,719,841	860,563	859,278	1,289,278
4	440,000	1,693,881	783,122	910,759	1,350,759

When CESS configuration is adopted, the optimal ESS power rating and energy rating is found to be 5.85 MW and 13 MWh, respectively. However, the lack of flexibility in CESS configuration, especially when the discharging cycles are limited, prevent the microgrid from taking advantage of the electricity price variations to increase its benefit compared to the DESS configuration. Moreover, it is observed that the cost of local generation is the highest in CESS case while the benefit of exchanging power with the main grid is the lowest. Increasing the discharging cycles limit will enhance the economic viability of CESS configuration but it will also reduce its lifetime. DESS configuration, on the other hand, tends to cope better with price electricity variations while prolonging the ESS lifetime.

IV. CONCLUSION

Adding the ESS into the microgrid reduces its operation cost and at the same time imposes an investment cost to the microgrid. When the total reduction in the operation cost exceeds the investment cost, the integration of the ESS is justifiable. However, both the investment cost and the microgrid operation cost are related to the installed ESS size. The model proposed in this paper not only addressed the question of what the optimal ESS size should be in the microgrid but also how many ESS units should be installed. The latter is important when the real-time electricity price at PCC is used, especially when a charging/discharging cycle limit is imposed on the installed ESS units to prolong their lifetime. Based on the studied microgrid, the minimum total microgrid expansion planning cost was found when two ESSs were installed with different power rating and energy rating. However, changing the characteristics of the studied microgrid or ESS would yield different results. The proposed model could be further used to provide a comprehensive comparison between the aggregated ESS configuration and the distributed ESS configuration to decide which one is more suitable for certain applications. It also can be used to compare between different energy storage technologies, which will be performed in future research.

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