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*— Expansion planning, Microgrid, Energy storage system.**

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 (exported) 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.

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.

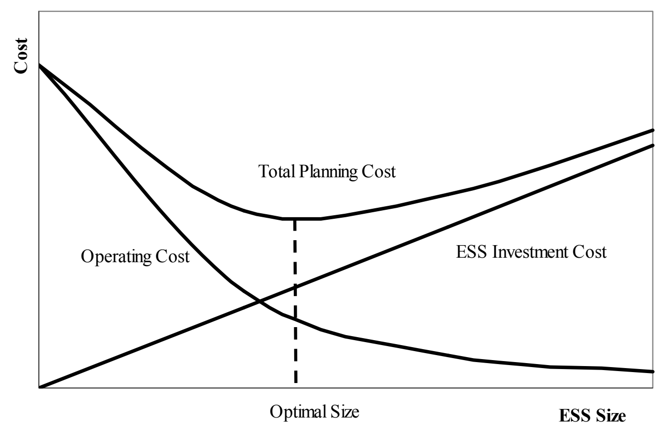

Fig. 1 Optimal ESS sizing

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 study period. This probabilistic reliability index serves as an accurate and consistent basis for assessing reliability of power systems. The significant computational burden of calculating reliability index along with the power system planning mandates a decomposition approach to separate the planning and reliability problems [20]. However, due to smaller size of the planning problems in a microgrid, an efficient model would permit incorporation of the reliability constraints in the planning problem, as proposed in this paper. A simulation method based on Monte Carlo simulation (MCS) is employed to account for random uncertainties along with the optimization scheme and to calculate the microgrid reliability. Random numbers are generated based on the microgrid components forced outage rate and appropriate probability distribution functions, which are used to determine the state of each component and output of each renewable energy resource. A very large number of system operating states are generated to simulate the operation of the microgrid at a particular sampled state. It is subsequently determined if the energy demand can be met with the simulated component states and load levels. In this method, each possible system state is represented by a scenario, which would result in a large number of scenarios and accordingly augment the computational burden. So, a scenario reduction technique is applied to reduce the number of scenarios. Each reduced scenario is assigned a weight that would reflect the probability of the occurrence of the scenario. The Monte-Carlo simulation method is well-suited for such an application as the number of samples is independent of system size for a given accuracy level. A detailed formulation of Monte-Carlo approach for creating scenarios in power system operation with uncertainties can be found in [21]. The effect of transmission network in microgrid operation and reliability calculations is ignored. However, the proposed model could be simply extended to consider the transmission network constraints.

III. Problem Formulation

The objective of the optimal ESS sizing problem for one year is proposed as in (1).

$$Min\, IC + OC \tag{1}$$

$$IC = ICP_B P_B^R + ICE_B C_B^{\max} \tag{2}$$

$$OC = \sum_{s=1}^{NS} p_s \sum_{t=1}^{NT}\sum_{h=1}^{NH}\sum_{i=1}^{NG}[F_i(P_{ith}^s)I_{ith}^s + SU_{ith}^s + SD_{ith}^s] + \sum_{s=1}^{NS}\sum_{t=1}^{NT}\sum_{h=1}^{NH} p_s \rho_{th} P_{M,th}^s \tag{3}$$

The objective includes the ESS investment cost and the microgrid expected operating cost. The ESS investment cost incorporates the power rating investment cost (including the power rating initial cost, the power conversion system initial cost, and the disposal cost) and energy rating investment cost (i.e., the energy rating initial cost) (2). The fixed and variable O&M costs are added to the power rating investment cost. The initial costs are normalized on an annual basis, i.e., distributed over the lifespan of the respective ESS technologies. Using this method, once the ESS has been installed the storage operation cost would be zero [12].

The microgrid expected operating cost (3) includes fuel costs for producing electric power by the units inside the microgrid, startup and shut down costs of the units, and cost of importing (or exporting) electricity from (or to) the main grid. The real-time electricity price, i.e. ρ_t, is the electricity price at the point of connection to the main grid. The objective is subject to the following constraints:

A. Microgrid and Unit Constraints

The microgrid constraints include power balance (4), power transfer limit (5) and load curtailment limit (6).

$$\sum_{i=1}^{NG} P_{ith}^s I_{ith}^s + \sum_{i=1}^{NR} P_{rth}^s + P_{B,th}^s + P_{M,th}^s + LS_{th}^s = P_{D,th}^s \tag{4}$$

$$\left|P_{M,th}^s\right| \le P_M^{\max} UY_{M,th}^s \tag{5}$$

$$0 \le LS_{th}^s \le P_{D,th}^s \tag{6}$$

The power balance equation ensures that the power generated from local units, power generated (consumed) by ESS, and the power imported (exported) from (to) the main grid would meet the hourly microgrid load. A load shedding variable is added to the power balance equation if the available generation from the microgrid units and the main grid could not supply the load. The ESS power, $P^s_{B,th}$, is positive when the storage is discharging, negative when charging, and zero when ESS is in idle mode. The main grid power, $P^s_{M,th}$, is positive when the power is imported from the main grid, negative when the power is exported to the main grid, and zero when the microgrid operates in islanded mode. The load is obtained using load forecasting techniques and is considered fixed in each scenario. The power imported (exported) from (to) the main grid is limited by (5), where the associated contingency state is included in this constraint to represent the state of the line connected to the main grid in each scenario. The load shedding is limited by the microgrid hourly load in each scenario (6). Constraints on thermal unit i for every scenario s at day t at hour h are proposed as follows:

$$P_i^{\min} I_{ith}^s UX_{ith}^s \le P_{ith}^s \le P_i^{\max} I_{ith}^s UX_{ith}^s \tag{7}$$

$$P_{ith}^s - P_{it(h-1)}^s \le UR_i(1 - y_{ith}^s) + P_i^{\min} y_{ith}^s \tag{8}$$

$$P_{it(h-1)}^s - P_{ith}^s \le DR_i(1 - z_{ith}^s) + P_i^{\min} z_{ith}^s \tag{9}$$

$$\sum_{k=h}^{h+UT_i-1} I_{ith}^s \ge UT_i\ y_{ith}^s \tag{10}$$

$$\sum_{k=h}^{h+DT_i-1} (1 - I_{ith}^s) \ge DT_i\ z_{ith}^s \tag{11}$$

The minimum and maximum generation of a unit is limited by (7), which is based on physical limitations of unit power generation. Unit contingency states are added to this constraint to consider the availability of the unit in each scenario. Using (7), the generation output of a unit will be zero when the unit is not committed or is on outage. Ramping up and down limits are formulated by (8) and (9), respectively, which would limit the generation increase/decrease between two successive hours. The unit minimum up and down time constraints are defined by (10) and (11), respectively. Using minimum up time limit, the unit cannot be turned off for specific number of hours after it is turned on. Similarly using minimum down time limit, the unit cannot be committed and turned on for specific number of hours after it is turned off.

Constraints (8)-(11) are defined based on the unit startup and shut down indicators, i.e., y and z, respectively. These indicators are obtained based on the unit commitment as in (12)-(13). y is one when the unit is started up and is zero otherwise. z is one when the unit is shut down and is zero otherwise.

$$y_{ith}^{s} - z_{ith}^{s} = I_{ith}^{s} - I_{it(h-1)}^{s} \tag{12}$$

$$y_{ith}^{s} + z_{ith}^{s} \le 1 \tag{13}$$

In addition to these typical constraints, fuel and emission constraints could be considered for each thermal unit as well as the microgrid. The proposed unit constraints include hourly operation of units and in detail consider the inter-temporal constraints of each thermal unit.

In addition to thermal units, the renewable units are considered in the model. A long-term forecast would determine the generation pattern of each renewable unit, which would be considered as a constant in the load balance equation. A deterministic method (based on historical data) or simulation approach could be used to forecast the input behavior of the generation source, which will further be combined with the power curve of the renewable source to produce the generation pattern [22]. As an example, the wind speed distribution could be modeled by the Weibull probability distribution function. Various methods for estimating Weibull's parameters are available [23]-[25]. The power output of a wind turbine is given as

$$P_{wth}^{s} = \begin{cases} 0 & v_{ht}^{s} < v_{CI} \; or \; v_{ht}^{s} \ge v_{CO} \\ P_{w}^{\max} \dfrac{v_{ht}^{s} - v_{CI}}{v_{R} - v_{CI}} & v_{CI} \le v_{ht}^{s} < v_{R} \\ P_{w}^{\max} & v_{R} \le v_{ht}^{s} < v_{CO} \end{cases} \tag{14}$$

Where P_w^{max} represents the wind rated power, and v_{CI}, v_R and v_{CO} are cut-in speed, rated speed and cutout speeds, respectively. v^s_{ht} is the wind speed at day t at hour h in scenario s.

The integration of intermittent renewable sources would challenge the reliability of the microgrid when the renewable source size is comparable with the microgrid size, so the additional resources and ESS must guarantee a reliable supply of energy to loads [26].

B. ESS Constraints

The ESS is modeled by (15)-(20).

$$-P_{B}^{R} \le P_{B,th}^{s} \le kP_{B}^{R} \tag{15}$$

$$C_{th}^{s} = C_{t(h-1)}^{s} - P_{B,th}^{s} \Delta t \tag{16}$$

$$0 \le C_{th}^{s} \le C^{\max} \tag{17}$$

$$C_{t1}^{s} = C^{0} \tag{18}$$

$$C_{th}^{s} = C^{end} \qquad (h = NH) \tag{19}$$

$$ICP_{B} P_{B}^{R} + ICC_{B} C_{B}^{\max} \le CIF_{B} \tag{20}$$

The ESS has three operation modes of charging, discharging and idle. Constraint (15) defines the limits on ESS power as it can violate charging and discharging rated powers. The ESS state of charge is calculated by (16) and constrained by (17). State of charge at every hour is equal to state of charge at the previous hour plus the energy stored at the current hour. Note that in the day-ahead unit commitment the time interval is 1 hour, therefore we consider $\Delta t = 1$. If ESS is charging, P_B^R is negative and the state of charge will increase. If ESS is discharging, P_B^R is positive and the state of charge will decrease. Using (17) ESS overcharging is prevented. The ESS state of charge at the start and end of each day is obtained by (18)-(19). The capital investment fund on ESS installation is limited (20) which accordingly restricts the ESS size.

The minimum charging and discharging time constraints might also be considered as ESS constraints. So, when the storage starts charging is should be maintained in charging mode for at least minimum charging time. Similarly, when the storage starts discharging is should be maintained in discharging mode for at least minimum discharging time. The ESS charging and discharging could be subjected to predefined charge/discharge profiles [4]. The charging of the ESS usually has a rectangular shape, so that the storage would start charging as soon as the charging command is sent by the controller and charging occurs at a constant power level. Unlike charging, the discharging of a battery would follow predefined discharging profiles. The discharging profiles typically have a trapezoidal shape, so the ESS goes through a gradual increase and decrease in power production when transitioning between zero and discharging rated power or vice versa. Using such trapezoidal profile, the amount of energy available from each discharge period could be maximized. The discharge profiles vary in shape, duration, and number of discharge periods. Note that the discharge profile is predefined by manufacturer based on the operator's need for power. The predefined discharge profile cannot be arbitrarily modified or expanded since it impacts the battery temperature [27].

C. Reliability Constraint

The reliability is defined in terms of LOLE. Equation (21) finds the times and scenarios in which the load is curtailed. In case of load curtailment w^s_{th} would be equal to 1. Using this curtailment indicator, the probability of curtailment scenarios is considered in LOLE (22). The obtained LOLE at each year should be less than its predefined targeted value (23).

$$0 \le LS_{th}^{s} \le Mw_{th}^{s} \tag{21}$$

$$LOLE = \sum_{s=1}^{NS} p_{s} \sum_{t=1}^{NT} \sum_{h=1}^{NH} w_{th}^{s} \tag{22}$$

$$LOLE \le LOLE^{Target} \tag{23}$$

IV. Numerical Simulation

A microgrid is analyzed to illustrate the performance of the proposed method. The characteristics of microgrid generators, including 4 thermal units and 1 wind unit, are shown in Table I. The considered ESS for installation in the microgrid has annualized power and energy investment costs of 40 \$/kW/year and 11 \$/kWh/year, respectively. The capacity of the line connecting the microgrid to the grid is 10 MW, which limits the power transfer between the grid and microgrid. The wind speed distribution is modeled by a Weibull probability distribution function with a mean speed of 5.5 m/s and a shape parameter of 2. To model component outages as well as wind speed, 500 scenarios are generated. The scenario reduction is applied which reduces the number of scenarios to 5 as shown in Table II. It is assumed that the microgrid load will not increase in future years, so a one year scheduling horizon is considered. The reliability criterion is 0.1 day/year. The proposed method was implemented on a 2.4-GHz personal computer using CPLEX 11.0 [28].

TABLE I
CHARACTERISTICS OF GENERATING UNITS

Unit No.	Bus No.	Cost Coefficient (\$/MWh)	Min. Capacity (MW)	Max. Capacity (MW)
1	Gas	27.7	1	5
2	Gas	39.1	1	5
3	Gas	61.3	0.8	3
4	Gas	65.6	0.8	3
5	Wind	0	0	1
Unit No.	Min. Up Time (h)	Min. Down Time (h)	Ramp Up (MW/h)	Ramp Down (MW/h)
1	3	3	2.5	2.5
2	3	3	2.5	2.5
3	1	1	3	3
4	1	1	3	3
5	-	-	-	-

TABLE II
PROBABILITIES OF REDUCED SCENARIOS

Scenario	1	2	3	4	5
Probability	0.714	0.121	0.075	0.039	0.051

The following cases are considered:
Case 1: Base case
Case 2: Adding a ESS to Case 1
Case 3: Optimal sizing of the ESS in Case 2
Case 4: Islanding mode

Case 1: the total microgrid cost is \$2,159,003. The total generation cost is \$3,806,540 and the total cost of imported power is \$552,353. However, power is sold back to the main grid at times of excess power, providing economical benefits of \$2,199,890 for the microgrid. Unit 1 acts as the base unit at all the operating hours, while other units are committed whenever the load cannot be supplied by unit 1 individually and the higher market prices do not justify power import to the microgrid. When the electricity price is low, power is imported from the main grid to the microgrid, while at times of higher market prices thermal units inside the microgrid are turned on to satisfy the load and excessive generated power is sold back to the main grid. The LOLE of 0.1 day/year is satisfied in this case and the expected energy not supplied is 374.06 MWh.

Case 2: in this case, a 10 MWh ESS with rated power of 2 MW is added to the microgrid. The storage can be charged in 5 hours to reach the maximum SOC. By adding the ESS, the total generation cost and total cost of power import are \$3,790,482 and \$558,938, respectively. The payment to the microgrid by selling power to the grid is \$2,388,150. In addition the investment cost of the ESS is added to the objective, which is \$190,000. Considering these values, the total operating cost of the microgrid would be \$2,151,270, which is 0.34% reduced compared to Case 1. This reduction is mostly due to the reduction in generation cost and increase in power export provided by ESS. ESS is mostly charged at the off-peak hours, when the price of electricity is low, and is discharged at peak hours, when the price of electricity is high. The discharged power of storage at peak hours is used for satisfying the load in microgrid when the load is high or to sell power to the main grid and increase economic benefits. The reliability criterion is satisfied in this case as the LOLE of 0.1 day/year is obtained.

Case 3: using the proposed approach, the optimal size of 3.6 MW at 18 MWh is found for ESS. The total operating cost of the microgrid is \$2,143,446, which is composed of \$3,758,124 total generation cost, \$610,472 total cost of power import, \$342,000 investment cost of the ESS and \$2,567,150 obtained from exporting power. The total cost is 0.72% dropped compared to that in Base Case. Similar to Case 2, ESS is mostly charged at off-peak hours, when the price of electricity is low, and is discharged at peak hours, when the price of electricity is high. The microgrid reliability criterion is satisfied. Table III summarizes the costs in Cases 1-3. Power export is shown with a negative value to represent this cost as a benefit for the microgrid.

TABLE III
SUMMARY OF SYSTEM COSTS

Case No.	Case 1	Case 2	Case 3
Generation Cost (\$)	3,806,540	3,790,482	3,758,124
Power Import (\$)	552,353	558,938	610,472
Power Export (\$)	-2,199,890	-2,388,150	-2,567,150
Storage Inv. Cost (\$)	0	190,000	342,000
Total Cost (\$)	2,159,003	2,151,270	2,143,446

The obtained optimal ESS size is capable of satisfying tighter limitations on the microgrid reliability index. By considering a reliability criterion of 0.05 day/year, the ESS schedule is slightly changed to satisfy the reliability criterion. The microgrid total cost is increased to \$2,178,723. Therefore, the storage system is a viable option to achieve desired level of reliability in a microgrid.

To further investigate the impact of the ESS size of the microgrid cost and reliability, the problem is solved for a variety of ESS sizes. The results are provided in Figs. 2-4, which depicts the microgrid total cost as a function of ESS rated power and capacity. The ESS rated power is increased from 1 to 5 MW, with a step of 1 MW, and the ESS capacity is changed from 1 to 8 times the rated power. So, the horizontal axis represents the minimum number of hours that ESS can reach its maximum capacity. By increasing the ESS size the investment cost is linearly increased as shown in Fig. 2 and the microgrid operating cost is reduced as shown in Fig. 3. A larger ESS requires higher power import (as well as local generation) in low price hours, thus increasing the cost of power import. On the other hand, a larger ESS increases the power export to the grid at times of high electricity prices and also reduces the units generation cost. Therefore, it would result in reduced operating costs.

The summation of microgrid operating cost and ESS investment cost provides the total microgrid cost, as shown in Fig. 4. By increasing the ESS capacity from 1 to 5 times the rated power, the microgrid total cost is reduced, which means that a larger ESS is more beneficial for the microgrid. However, for larger capacities the microgrid total cost is increased.

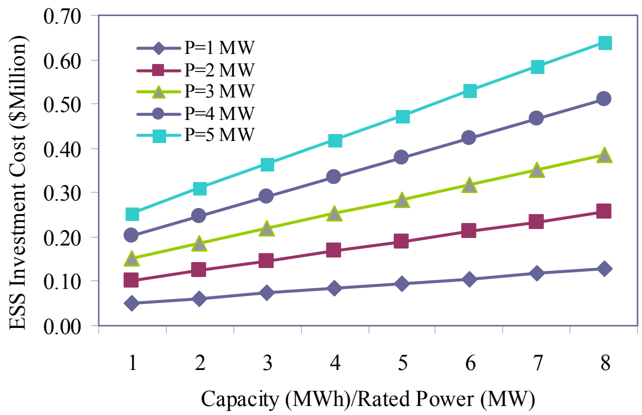

Fig. 2 ESS Investment Cost as a function of ESS size

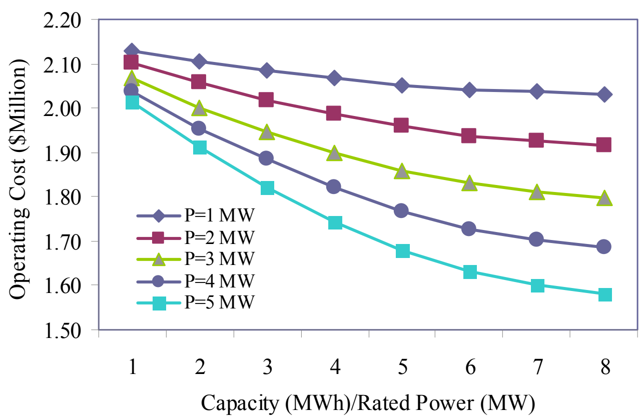

Fig. 3 Microgrid operating cost as a function of ESS size

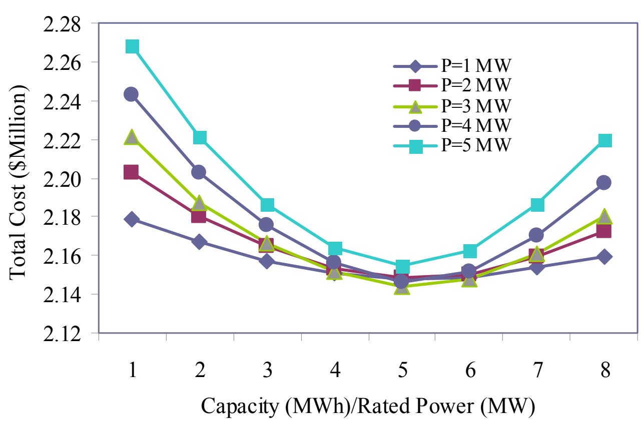

Fig. 4 Microgrid total cost as a function of ESS size

In the proposed model the ESS is installed and optimally sized to increase microgrid reliability and provide economic benefits rather than smoothing out the generation of renewable energy resource. The ESS optimal sizing in a microgrid with only renewable energy resources will be considered in a future work where the ESS handles the volatility and intermittency in generation of renewable energy resources.

V. Discussion

ESS would increase the microgrid reliability by reducing load shedding and improve the microgrid economics by storing energy at low price hours and generating the stored energy at high price hours. It might also help defer the need for additional microgrid investments to meet the microgrid peak load. Specific features of the proposed optimal ESS sizing problem are listed as follows:

- Optimal ESS sizing: The optimal ESS size in a microgrid is found which minimizes the total microgrid cost during the scheduling horizon and satisfies predefined reliability criteria. A planning problem is solved while considering short-term operation constraints. This coordination would offer practical and efficient solutions for the microgrid planning.
- Economic benefits: Despite high capital investments, the ESS provides economic benefits for microgrid. ESS offers low cost power to local loads and reduces the need for local generation or energy import from the main grid.
- Reliability consideration: A stochastic approach is used to calculate the microgrid reliability criterion which employs the Monte Carlo simulation for the modeling of random component outages. The proposed approach considers the microgrid operations in the base case and contingencies. Load curtailment is enabled in the model to ensure the feasibility of the obtained solution and further determine microgrid reliability index. ESS provides a viable opportunity for satisfying desired levels of reliability in a microgrid and could be considered as a quick and efficient solution to the microgrid reliability problems.
- Practical results: The presented results provide an insight on the application of ESS for improving the economics and the reliability of microgrids. A variety of energy sources, such as thermal and renewable units, could be included in the model.
- Computational efficiency: The reliability consideration would add additional binary and continuous variables to the planning problem. An efficient MIP model was proposed to find the solution in a reasonable time.

VI. Conclusion

In this paper an accurate model for calculating the optimal ESS size in a microgrid was proposed. The approach utilized an expansion planning problem, where the ESS investment cost and microgrid operating cost were taken into account. The reliability index of the system was calculated afterwards to ensure reliable operation of the microgrid by satisfying reliability criterion. An MIP formulation was proposed to effectively calculate the reliability criterion within the optimization problem, resulting in accurate reliability assessment of the microgrid. Numerical studies revealed that a larger ESS does not necessarily provide larger economical benefits. There exists an optimal point that the ESS should be installed, where larger ESS sizes might impose higher expansion costs to the microgrid.

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