Optimal Sizing of Smart Grid Storage Management System in a Microgrid

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***Abstract*—Development of microgrid (MG) technology is growing in low voltage networks, improving the power supply reliability and energy efficiency. Energy storage system (ESS) plays an important role in operation of MG to achieve higher flexibility and reliability. This paper presents a model for determining the optimal size of an ESS in MG. An expansion planning problem is proposed to consider the investment cost of ESS, as well as operating cost of the microgrid. By increasing the size of the storage system the investment cost linearly increases while the operating cost exponentially reduces. The objective is to find the optimal size of ESS in which the summation of storage system investment cost and MG operating cost is minimized. A practical model for ESS is utilized, which uses rectangular charging and trapezoidal discharging profiles. The optimal storage sizing problem is formulated as a mixed-integer programming (MIP) problem. Illustrative examples of a six-bus system are presented to show the efficiency of the proposed method.**

***Index Terms*— Expansion planning, Microgrid, Storage system**

NOMENCLATURE

C_t	Electricity price.
CIF_S	Capital investment funds for storage system.
DR_i	Ramp down rate limit of unit *i*.
$E_S^{\max}$	System emission limit.
F_{ci}	Production cost function of unit *i*.
F_{fi}	Fuel consumption function of unit *i*.
F_{ei}	Emission function of unit *i*.
$F_{FT}^{\min}$	Minimum fuel consumption.
$F_{FT}^{\max}$	Maximum fuel consumption.
FT	Index for fuel type.
i	Index for unit.
I_{it}	Commitment state of unit *i* at time *t*.
IC	Total investment cost of microgrid
IC_S	Capital investment cost of storage system
k	Depth of discharge.
MC	Total maintenance cost of microgrid.
NG	Number of units.
NT	Number of time periods.
OC	Total operating cost of microgrid.
OM_S	Fixed operation and maintenance cost of storage system.
$P_{D,t}$	System demand at time *t*.
$P_{M,t}$	Power imported (exported) from (to) the main grid at time *t*.
$P_M^{\max}$	Maximum possible power import (exported) from (to) the main grid.
$P_{S,t}$	Power generated (consumed) by the storage system at time *t*.
P_S^R	Rated power of storage system.
P_{it}	Generation of unit *i* at time *t*.
$P_i^{\min}$	Minimum power generation of unit *i*.
$P_i^{\max}$	Maximum power generation of unit *i*.
R_t	System reserve requirement at time *t*.
$SD_{f,it}$	Shutdown fuel consumption of unit *i* at time *t*.
$SD_{e,it}$	Shutdown emission of unit *i* at time *t*.
SD_{it}	Shutdown cost of unit *i* at time *t*.
$SU_{f,it}$	Startup fuel consumption of unit *i* at time *t*.
$SU_{e,it}$	Startup emission of unit *i* at time *t*.
SU_{it}	Startup cost of unit *i* at time *t*.
t	Index for time.
T_i^{off}	Minimum down time of unit *i*.
T_i^{on}	Minimum up time of unit *i*.
UR_i	Ramp up rate limit of unit *i*.
X_{it}^{off}	OFF time of unit *i* at time *t*.
X_{it}^{on}	ON time of unit *i* at time *t*.

I. INTRODUCTION

MICROGRID technology provides an opportunity and a desirable infrastructure for improving the efficiency of energy consumption. MG is an integration of generators, load, storage, and control devices that normally operate connected to or isolated from traditional centralized grid. In MG load is

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usually served by micro resources such as photovoltaic, wind turbine, fuel cell. A central controller is the interface between main grid and MG which coordinates and optimizes the operation of MG. However, there are many challenges and difficulties in implementing and operating MG that need to be addressed. One of the operational challenges is due to distinct characteristic of micro resources which are subject to large fluctuations and uncertainties. A potential solution to this problem is energy storage investment.

ESS has a major role in the operation of MG. Storage systems are fast response devices which add flexibility to the control of the MG, and would provide security and economical benefits for the microgrid. Storage systems can mitigate the frequent and rapid power changes of renewable resources and therefore solve the volatility and intermittency problems associated with renewable resources. Additionally, they can store energy at times of low electricity prices and use the stored energy at times of high electricity prices, hence producing economical benefits for the microgrid. Furthermore, they might be used for load following, voltage and frequency stability, peak load management, power quality improvement, and deferral of upgrade investments. However, the storage system has to be accurately modeled and optimally sized in order to prevent over or underutilization [1], [2].

Today, different types of ESS technologies with different characteristics are being developed of which some are available commercially while others are still in the development stage. There are several criteria for comparing and selecting EES technology. [3] compares their characteristics including their advantages and disadvantages. The power and discharge rate of different storage technologies and their applications can be seen in Figure 1.

When considering the storage system in a microgrid an optimal storage system sizing should be performed. The small storage systems may not provide economical benefits and desired flexibility in power generation of other units for the microgrid as much as expected. On the other hand, large storage systems impose higher investment and maintenance costs to the microgrid. Therefore, an optimal size for the storage system should be found where the produced reduction in operating cost due to addition of the storage system is larger than the installation costs imposed by storage. Figure 2 depicts the optimal size of a storage system regarding investment, maintenance and operating costs.

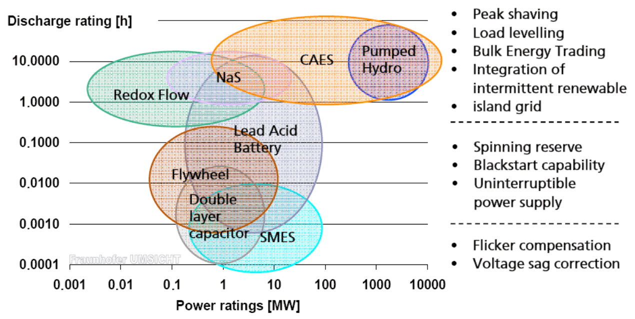

Fig. 1: Storage technology comparison [3]

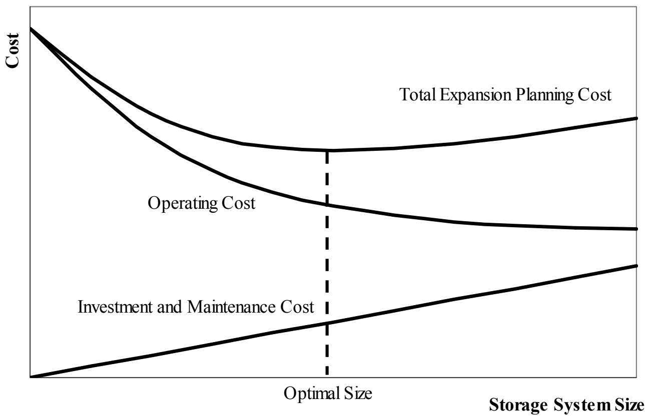

Fig. 2 Optimal sizing of storage system

In this paper a power system expansion planning problem is proposed to find the optimal size of the storage system. The objective of the problem includes the capital cost of the storage system and operating cost of the system. Adding the storage system to the microgrid requires capital cost payments, while on the other hand helps system to reduce the operating costs. Therefore, the objective would be to minimize the summation of these two terms. To ensure the practicality of the solutions, commercially-available storage management systems (SMS) are used for storage system modeling. Mixed integer programming (MIP) is used to formulate the expansion planning problem. The goal of this paper is to find the optimal size of the storage system in a microgrid, incorporating thermal units, in order to obtain maximum economical benefits and minimum payments. In this regard, the renewable resources are ignored in this work and will be discussed in a future paper.

The paper is organized as follows: Section II presents the expansion planning problem formulation and in detail discusses the modeling of the storage system. Section III presents the numerical simulations on a six-bus system. Sections IV and V respectively provide observations and conclusions on the proposed model.

II. PROBLEM FORMULATION

The objective of expansion planning problem is to minimize the total cost of the system which includes the investment cost, maintenance cost, and system operating cost of the storage system. This objective function is formulated as follow:

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

Where the first term represents the investment cost of new storage system which is a linear function of the storage rated power as presented in (2). The second term is the maintenance cost of the storage system, which includes fixed and variable maintenance costs (3). Fixed maintenance cost is a function of the rated power, however variable maintenance cost is a function of total energy produced in the planning horizon. The last term is the operating cost of the microgrid, incorporating fuel costs for producing electric power by the units inside the microgrid as well as cost of buying (or selling) electricity from (or to) the main grid (4). The electricity price at the point of connection to the main grid, C_t, is determined through price forecasting for the study period.

$$IC = IC_S P_S^R \tag{2}$$

$$MC = OM_S P_S^R \tag{3}$$

$$OC = \sum_{t=1}^{NT} \sum_{i=1}^{NG} F_{ci}(P_{it}) I_{it} + \sum_{t=1}^{NT} C_t P_{M,t} \tag{4}$$

As mentioned, the objective is to determine the optimum solution subject to unit and system constraints [4]-[10]:

A. System Constraints

System constraints guarantee operational reliability and system security, also provide coupling between operation of MG devices and main network. The system constraints are presented as follow:

$$\sum_{i=1}^{NG} P_{it} I_{it} + P_{S,t} + P_{M,t} = P_{D,t} \qquad (t = 1,\ldots,NT) \tag{5}$$

$$\sum_{i=1}^{NG} P_i^{\max} I_{it} + P_M^{\max} \ge P_{D,t} + R_t \qquad (t = 1,\ldots,NT) \tag{6}$$

$$F_{FT}^{\min} \le \sum_{i \in FT} \sum_{t=1}^{NT} [F_{fi}(P_{it}) I_{it} + SU_{f,it} + SD_{f,it}] \le F_{FT}^{\max} \tag{7}$$

$$\sum_{i=1}^{NG} \sum_{t=1}^{NT} [F_{ei}(P_{it}) I_{it} + SU_{e,it} + SD_{e,it}] \le E_S^{\max} \tag{8}$$

The power balance equation (5) guarantees that the summation of power generated from local resources, the power from (or to) the storage system, and the power from (or to) the main grid satisfy the load in each hour. The power of the storage system, $P_{S,t}$, is positive when the battery is discharging, negative when the battery is charging, and zero when the storage system is idle. The main grid power, $P_{M,t}$, 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 fixed and obtained using load forecasting techniques.

Using (6), it is ensured that a sufficient number of units is committed to satisfy the reserve requirement. A variety of approaches has been proposed to determine the amount of reserve required by a system. The most common approaches are percentage of the load and largest unit capacity in the system.

Fuel limit (7) restricts the total amount of the fuel to be consumed by the thermal units in a microgrid in the scheduling horizon. This limit shows the interdependency of the electricity to the fuels (mostly fossil fuels) used to generate power. The total emission produced by the units in a microgrid is restricted by (8).

B. Unit Constraints

Unit constraints include (9)-(13).

$$P_{i,\min} I_{it} \le P_{it} \le P_{i,\max} I_{it} \qquad (t = 1,\ldots,NT)(i = 1,\ldots,NG) \tag{9}$$

$$\begin{aligned} P_{it} - P_{i(t-1)} \le UR_i[1 - I_{it}(1 - I_{i(t-1)})] + P_{i,\min}[I_{it}(1 - I_{i(t-1)})] \\ (t = 1,\ldots,NT)(i = 1,\ldots,NG) \end{aligned} \tag{10}$$

$$\begin{aligned} P_{i(t-1)} - P_{it} \le DR_i[1 - I_{i(t-1)}(1 - I_{it})] + P_{i,\min}[I_{i(t-1)}(1 - I_{it})] \\ (t = 1,\ldots,NT)(i = 1,\ldots,NG) \end{aligned} \tag{11}$$

$$[X_{i(t-1)}^{on} - T_i^{on}][I_{i(t-1)} - I_{it}] \ge 0 \;\; (t = 1,\ldots,NT)(i = 1,\ldots,NG) \tag{12}$$

$$[X_{i(t-1)}^{off} - T_i^{off}][I_{it} - I_{i(t-1)}] \ge 0 \;\; (t = 1,\ldots,NT)(i = 1,\ldots,NG) \tag{13}$$

The minimum and maximum generation of a unit is limited by (9), which is based on physical limitations of unit energy power generation. Ramping up and down limits are formulated by (10) and (11), respectively. Using these limits, the unit cannot increase its generation between two successive hours more than its ramp up limit allows. Similarly, the unit cannot decrease its generation between two successive hours less than its ramp down limit allows. The unit minimum up and down time constraints are defined by (12) and (13), 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. Furthermore, individual fuel constraint could be considered for each thermal unit.

C. Storage System Constraints

In this paper battery is considered as an alternative solution to store energy. Constraints on the storage system model the charging, discharging and idle states of storage system operation. The charging of the storage system usually has a rectangular shape. It means that the storage can 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 can follow predefined discharging profiles. The discharging profiles typically have a trapezoidal shape, so the storage system 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 [10]. The discharge profiles vary in shape, duration, and number of discharge periods. Fig. 3 depicts a typical discharge profile.

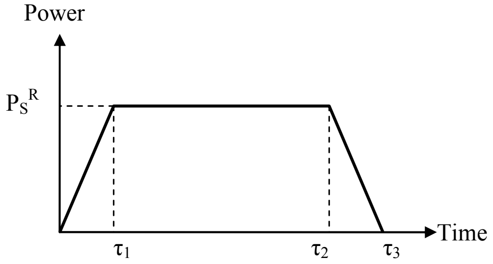

Fig. 3 Typical discharge profile of a storage system

The storage system is modeled by (14)-(20).

$$u_t + v_t \le 1 \qquad (t = 1,\ldots,NT) \tag{14}$$

$$-P_S^R v_t \le P_{S,t} \le kP_S^R u_t \qquad (t = 1,\ldots,NT) \tag{15}$$

$$P_{S,t} = \begin{cases} \alpha(TD_t - 0.5)kP_S^R, & 1 \le TD_t \le \tau_1 \\ kP_S^R, & \tau_1 + 1 \le TD_t \le \tau_2 \\ \alpha(\tau_3 - TD_t + 0.5)kP_S^R, & \tau_2 + 1 \le TD_t \le \tau_3 \end{cases} \tag{16}$$

$$0 \le TD_t \le \tau_3 u_t \tag{17}$$

$$1 - (\tau_3 + 1)(1 - u_t) \le TD_t - TD_{t-1} \le 1 \tag{18}$$

$$SOC_t = SOC_{t-1} - P_{S,t}\Delta t \tag{19}$$

$$0 \le SOC_t \le SOC^{\max} \tag{20}$$

Constraints (14) and (15) define the operating mode of the storage system, where (14) ensures that the storage system cannot be at the charging and discharging mode at the same time and (15) defines the limits on storage power level for every hour.

Constraint (16) formulates three segments of the trapezoidal discharge profile. In production ramping of the storage system, i.e. segments 1 and 3, the average energy production between the current hour and previous hour is used. TD_t counts the number of continuous discharging hours at hour t and is obtained by (17) and (18). Using (17) and (18), when the storage system is not in discharging mode, i.e. $u_t = 0$, the discharge counter is set to zero. On the other hand, when the storage is discharging, i.e. u_t=1, the discharging counter would be equal to the discharging counter at the previous hour plus one. However, the charging is limited by the rated power and state of charge (SOC). SOC is obtained using (19). SOC at every hour is equal to SOC 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 Δt = 1. Constraint (20) limits SOC of the storage system to prevent overcharging.

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 [11].

The general mathematical model of constraints is provided here. However, the MIP formulation of these constraints can be found in the literature [9].

Another important constraint related to the installation of the storage system is the limit on capital investment funds, where

$$(IC_S + OM_S)P_S^{rated} \le CIF_S \tag{21}$$

Using this constraint, the capital fund on storage system installation is limited, and accordingly the storage system size is restricted.

III. NUMERICAL SIMULATION

A six-bus system, as shown in Fig. 4, is analyzed to illustrate the performance of the proposed method. The proposed method was implemented on a 2.4-GHz personal computer using CPLEX 11.0 [12].

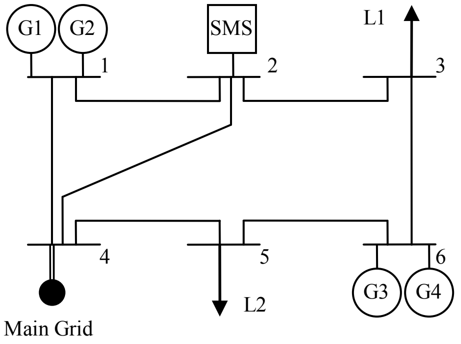

Fig. 4. Six-bus system

The objective is to find the optimal size of the storage system which minimizes the total expansion planning cost. The characteristics of generators are given in Table II. The maximum possible power import to the grid is considered large enough to satisfy any reserve requirements in the microgrid. A scheduling horizon of five years is considered.

TABLE I
CHARACTERISTICS OF GENERATING UNITS

Unit No.	Bus No.	Cost Coefficient ($/MWh)	Minimum Capacity (MW)	Maximum Capacity (MW)	Startup Cost ($)
1	1	27.7	1	5	40
2	1	39.1	1	5	40
3	6	61.3	0.8	3	10
4	6	65.6	0.8	3	10

Unit No.	Shutdown Cost ($)	Minimum Up Time (h)	Minimum Down Time (h)	Ramp Up Rate (MW/h)	Ramp Down Rate (MW/h)
1	0	3	3	2.5	2.5
2	0	3	3	2.5	2.5
3	0	1	1	3	3
4	0	1	1	3	3

TABLE II
CHARACTERISTICS OF STORAGE SYSTEM

	Bus No.	Investment Cost ($/kW)	Fixed O&M Cost ($/kW-year)	Charging Duration (h)	Discharging Duration (h)
Storage System	2	480	4	5	7

The following cases are considered:
Case 1: Base case
Case 2: Adding a storage system to Case 1
Case 3: Optimal sizing of the storage system in Case 2
Case 4: Sensitivity analysis

Case 1: in base case the storage system is not added to the system. The objective is to minimize the total operating cost over the scheduling horizon, i.e. performing UC for the entire scheduling horizon. The total operating cost in this case is $36,361,650. Unit 1 acts as the base unit at all the operating hours, while other units are used whenever the load cannot be satisfied by unit 1 individually and the higher market prices doesn't allow 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.

Case 2: in this case, a 2000 kW storage is added to the system. The storage can be charged in 5 hours to reach the maximum SOC of 10 MWh. A trapezoidal discharge profile is considered, which discharges the storage in 7 hours with the rated discharge power of 1.66 MW. From the start time of discharging, it takes 1 hour to reach the rated discharge power, 5 hours to discharge at the rated discharge power, and 1 hour to reach zero power output.

By adding this storage system, the total operating cost of the system is dropped to $35,396,496 which shows 2.65% reduction. However, considering the investment cost of $500/kW for the storage system, $1,000,000 will be added to the total cost of the system. Storage system 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 economical benefits.

Case 3: in this case the rated power of the storage system is considered as the problem variable. The charge and discharge profiles are as proposed in Case 2, i.e. 5 hour rectangular charging and 7 hour trapezoidal discharging. Using the proposed optimal storage sizing approach, the optimal size of 950 kW is found for the storage system. The total expansion planning cost is $36,356,860, which is composed of $35,881,860 total operating cost, $456,000 storage investment cost and $19,000 storage fixed O&M cost.

Similar to Case 2, storage system 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.

Case 4: the sensitivity of the total costs to the storage system is analyzed in this case. The storage system size is increased from 0 to 2000 kW, with steps of 100 kW, where 0 means that no storage system is installed in the system. Fig. 5 shows the summation of investment and maintenance costs of the storage system as a function of the storage size. By increasing the storage size the summation of investment and maintenance costs is linearly increased. The maintenance cost is considered in the five-year expansion planning horizon. Fig. 6 shows the operating cost of the system with respect to storage system size. By increasing the storage size the operating cost of the system is reduced. A higher size of the storage system can store more energy at off-peak hours and thus produce more energy at peak hours, which provides higher economical benefits for the system. The summation of storage system investment and maintenance cost, and the system operating cost provides the total system expansion planning cost, as depicted in Fig. 7.

By increasing the storage size from 0 to 900 kW the total expansion planning cost is reduced, which means that a larger storage system is more beneficial for the microgrid. However, for the values larger than 900 kW a larger storage system leads to higher expansion planning costs.

It can be derived from Fig. 6 that for the five-year planning horizon, the storage systems with rated power of more than 1200 kW are not economical. In this case, the reductions in the operating cost of the microgrid caused by installation of storage system are less than the investment and maintenance costs of the storage system, hence making this installation unreasonable.

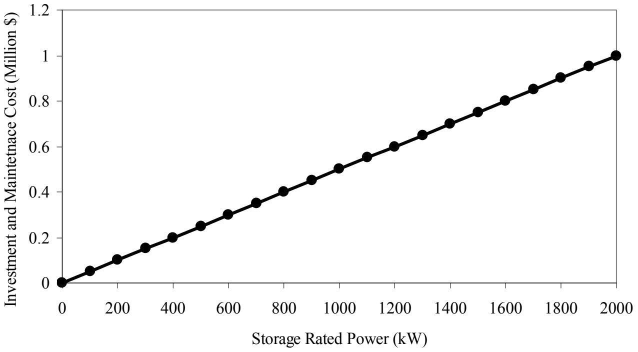

Fig. 5 Investment and maintenance costs of storage system

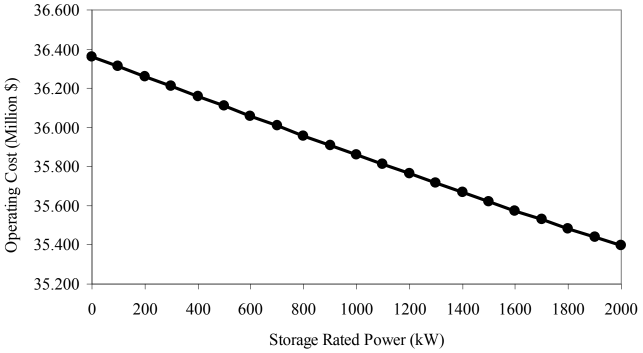

Fig. 6 Operating cost of microgrid

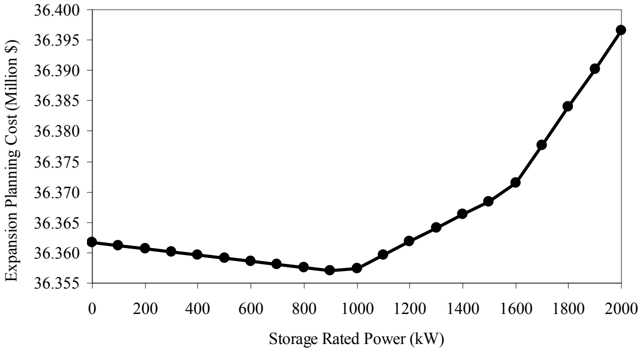

Fig. 7 Total expansion planning cost

IV. OBSERVATIONS

Following issues should be considered in the proposed optimal storage sizing problem.

- In the studied cases a planning horizon of five year is considered. Assuming longer, or shorter, planning horizons might change the obtained results. For instance, a larger storage system in Case 3 might be obtained as the optimal storage size for this microgrid.
- In this paper only the economical benefits of the storage system when added to a microgrid with thermal units is inspected. Apparently, the benefits of the storage system would be much higher when considering renewable resources in the system. In this case the storage system is used for satisfying both economical and security aspects of the microgrid. This topic will be inspected in our future study.
- In the numerical studies, the charging and discharging profiles of the storage system are assumed to be fixed. However, the proposed methodology can handle variable charging and discharging profiles and consequently find the optimal charging and discharging profiles of the storage system.
- Transmission network is not considered in the formulation, since generally in a microgrid the transmission network has enough capacity to handle power flow and congestion is not probable. However, the transmission network constraints can easily be added to the proposed formulation.
- Since the execution time of the problem is not important the problem is solved in one shot. In order to increase the solution speed and find the solution in a much less time, available decomposition approaches can be used.

V. CONCLUSION

In this paper an accurate model for calculating the optimal size of a storage system was proposed. The proposed approach utilized an expansion planning problem, where the installation cost of the storage system, maintenance cost of the storage system and operating cost of the system were considered together and optimized simultaneously. A precise storage system model was used, incorporating charging and discharging profiles of the storage system. Numerical studies revealed that a larger storage system does not necessarily provide larger economical benefits. There was an optimal point that the storage system should be installed based on that. Larger sizes of the storage system might impose higher expansion costs to the microgrid.

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