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Expansion Planning of Power System for Optimal Sizing of Energy Storage Systems

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Abstract: *One solution to confront the intermittent nature of renewable energies is to utilize energy storage systems (ESSs) in microgrids (MGs). This paper studies an expansion planning problem to report the optimal size of the storage system. The objective function includes the investment cost of the storage system and the operating cost. Adding a storage system to an MG not only can be considered as the investment cost, but also it benefits the system in reducing the operating cost***.** *Therefore, the main target is to minimize the sum of the later items. To ensure the practical capability of solutions, storage management systems (SMS) are used for modeling the storage system. The mixed-integer programming (MIP) method is also employed to formulate the expansion planning problem. The storage system cooperates with thermal units to maximize the obtained economic benefits and minimize the costs. Numerical analysis is performed and a mathematical model is proposed to evaluate an optimal size of the storage system. The numerical results show that a larger storage system does not necessarily mean gaining more economic benefits. There is an optimal condition based on which the storage system is designed and installed. It is found that selecting larger sizes of the storage system imposes higher expansion costs on the MG.*

Keywords: Storage system, expansion planning, microgrid, renewable energy source, mixed-integer programming, storage management systems.

1. INTRODUCTION

The microgrid (MG) technology has created appropriate infrastructures for improving energy consumption efficiency. An MG consists of generators, storage systems, and control devices that operate in traditional centralized networks in either grid-connected or islanded modes under normal operating conditions. The load in the MG is normally supplied by micro sources, such as photovoltaic, wind, fuel cell, and other systems [1]. A central controller provides the connection between the main grid and the MG, and optimizes the operation of the MG. There are many operation challenges caused by the distinctive characteristics of micro sources exposed to intermittency and uncertainty [2]. One potential solution to overcome to these challenges is to establish electrical energy storage systems. Energy storage sources (ESSs) play a pivotal role in the operation of MGs. Storage systems have a fast response, and this adds more flexibility to the control the system of MG, providing numerous benefits in terms of security and costs. Storage systems can also eliminate fast changes of the power and frequency in renewable sources, and hence solve the oscillation and intermittency problem associated with these generation sources. Additionally, the ESS has the potential to store the energy and use it at the desirable period, leading to a good number of economic benefits to the MG [1, 2].

A new approach relying on the net present value (NPV) is introduced in [3] to find the optimal placement of the ESS in an MG; besides, analyzing the economic aspects of using the ESS. The authors also developed a self-adaptive bee swarm optimization (SBSO) algorithm, which was adopted to obtain the optimal size of the ESS to maximize the NPV. Alharbi et al. [4] introduced a model for operation planning for several years; the optimal power and size of battery of ESS was evaluated by the authors. In addition, the optimal power and energy ratings of the ESS were evaluated to minimize the operating cost of the MG [3]. A fuzzy expert system is also exploited to set the power output of the ESS. In another study [5], it was suggested that a novel method based on cost analysis can be employed to approach the optimal sizing of a battery of the ESS. The Authors found that operating and overall costs of the MG can be reduced [4]. Recently, Majidi and Nojavan [6] investigated the optimal sizing of an ESS in an MG; the demand side program (DRP) and reliability indices were taken into account by the authors. Moreover, the authors attempted to reduce the total expenses and operating costs. The optimal size of a battery ESS is found in [7] through analyzing the schedule and cost benefits of MG expansion planning for islanded and grid-connected operation modes of the MG. To improve the operation of distribution systems containing distributed generation and energy storage units, the optimal sizes of photovoltaic systems and ESSs were evaluated in [8]. The proposed operation strategy for ESSs relies on changes in the load and generation during the day. Sayfutdinov et al. [9] suggested the most proper state-of-the-art technologies and designed the best size of the ESS. The paper generalized the adopted approaches for finding the optimal size of ESSs by using self-discharge effects. The operational lifespan of the ESS was chosen as a variable in this study [8]. It was observed that operational lifespan plays a significant role on obtaining the optimal size of ESSs and selecting the most suitable technology. The generation and load data of a building equipped with a PV system for several years was investigated in literature [9] to shape the operating profile of the ESS. The authors attempted to make a balance between power generation and demand sides in the MG system. Recently, a new indicator of the optimal size of the ESS was constructed by scholars [10] to preserve a balance between the source, the storage, and the load sides. To find the optimal size of the ESS, various constraints were utilized along with the investment cost indicator to provide a suitable model. In another study [11], the researchers formulated a capacity planning problem to obtained the optimal size of a PV system combined with a battery energy storage system (BESS) for Nano-grids that are expected to manage distributed RESs. A novel multi-objective problem was proposed and solved in [12] to obtain the optimal size of a BESS for a microgrid, containing several RESs and a BESS, connected to the grid.

Apart from the aforementioned, the ESS technology can be utilized for load following, the frequency and voltage stability, the peak load management, the power quality improvement, and the capital return. Nonetheless, storage systems requires to be modeled accurately and sized optimally to prevent its surplus or deficient generation [13]. So far, different types of technologies were proposed for ESS; some are commercially available, while others are still in the examination stage [13], in which the advantages and demerits of each technology were explained in details in the literature [15]. Charge and discharge rates of different storage technologies and the applications of such technologies are summarized in Fig. 1. Proposing the small storage systems may also fail to meet acceptable economic benefits and expected flexibility in power generation for the rest of the units available in the MG. Fig. 2 illustrates the optimal size of a storage system considering the costs of investment, repair and maintenance, and operation.

Based on a brief literature review presented above, designing an optimal size or capacity of the storage system is very critical and the capacity of the system should be based on the total expenses, comprising investment and operating costs to satisfy our requirement. In this study, the authors introduce a mathematical model for expansion planning problem with the optimal size and capacity of the storage system. Adding a storage system to the MG necessitates not only satisfy the investment and maintenance expenses, but it reduces the operating cost. Hence, the main aim is minimizing the sum of these two costs.

To better understand the practical capability of the solutions, the storage management system (SMS) method is used to model the storage system. The mixed-integer programming (MIP) method was employed in to formulate the expansion planning problem. The study aims to find the optimal size of the storage system in the MG. The storage system cooperates with thermal units to maximize the obtained economic benefits and minimize the costs.

The paper is structured as follows: after a brief literature review and introduction in section 1, section 2 presents the formulation of the expansion planning of the storage system modeling in details. Section 3 provides the numerical simulations for a 6-bus test system. The results are presented and discussed in sections 4, and finally in section 5 the conclusions will be presented.

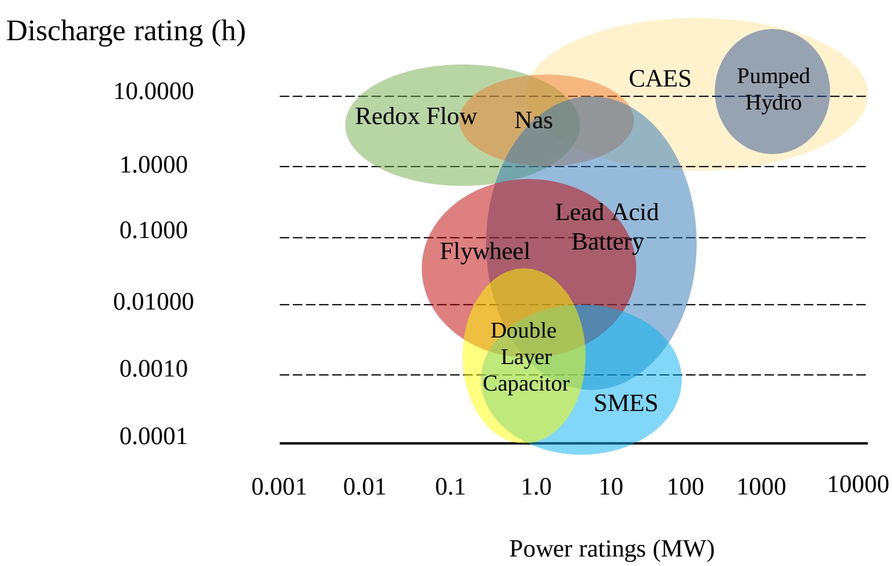

Fig. 1. Comparison between different storage technologies (reproduced from [14]).

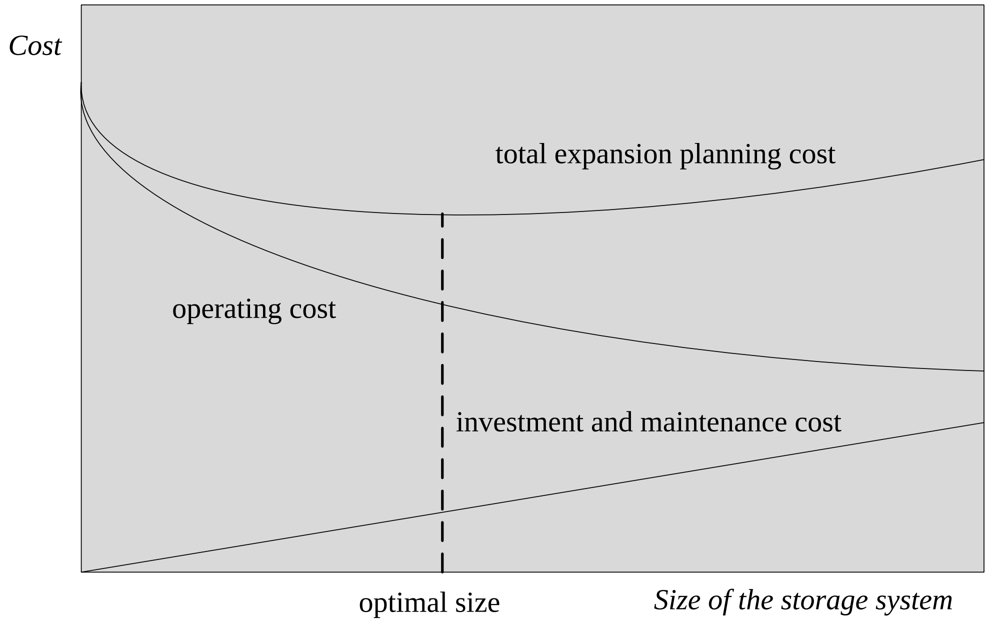

Fig. 2. Optimal sizing of a storage system [15].

2. PROBLEM FORMULATION

The objective of the expansion planning problem is to minimize the total cost of the system that includes the costs of investment, repair and maintenance, and operation in the ESS. The objective function is formulated as follows:

$$Min\ IC + MC + OC = Total\ Cost \tag{1}$$

where *IC* represents the investment cost of the new storage system that is a linear function of the rated storage power defined in equation (2). *MC* stands for the repair and maintenance cost of the storage system and includes fixed and variable costs associated in equation (3). The fixed repair and maintenance cost is a function of the rated power. However, this variable cost itself is a function of the total energy generated in the planning horizon. Also, *OC* is the operating cost of the MG that includes fuel costs for power generation by units within the MG and the electricity purchase (or sell) price from (or to) the main grid, which is formulated in (4). The electricity price at the connection point to the main grid will be determined through the price prediction.

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

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

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

As mentioned above, the main objective of this study is to determine the optimal solution considering the constraints of the system and the unit [16-22].

2.1. Constraints of the system

Constraints of the system ensure the safe and reliable operation of the system and provide the connection between the operation of the MG equipment and the main grid. Constraints of the system are expressed as follows:

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

$$\sum_{i=1}^{NG} P_i^{max} I_{it} + \; P_M^{max} \; \geq P_{D,t} + R_t \quad (t = 1, \dots, NT) \tag{6}$$

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

$$\sum_{i=1}^{NG} \sum_{t=1}^{NT} \left[F_{ci}(P_{it}) I_{it} + SU_{c,it} + SD_{c,it} \right] \leq E_S^{max} \tag{8}$$

The power balance equation (5) guarantees that the sum of power generated by local sources, the storage system, and the main grid supply the load demand at each hour. The storage system power, $P_{s,t}$, is positive (negative) when the battery is operating in the discharge (charging) mode, and is zero when the storage system is assumed ideal. The power of the main grid, $P_{M,\,t}$, is positive (negative) when the power flows from (into) the main grid, and is zero when the MG operates in the islanded mode. The load is fixed, and is determined using load prediction methods. By employing formula (6), we secure that a sufficient number of units participate in meeting the required reserve for the system. Different methods have been suggested for determining the amount of required reserve; the most conventional ones include the load percentage and maximum capacity of the unit in the system.

Inequality (7) evaluates the limitation of the total fuel consumed by thermal units of the MG during the considered planning horizon. This constraint specifies the interdependency between the electricity and the fuel (most of the fossil fuels) for the power generation. The total amount of emissions in the MG is, therefore, constrained according to formula (8).

2.2. Constrains of the units

Constraints of the units are formulated in (9) to (13). It is worth noting that in the following inequalities the "t" index varies from $t \;= 1, \dots, NT$ and the "i" index changes from $i = 1, \dots,$ to NG.

$$P_{i,min} I_{it} \leq P_{it} \leq P_{i,max} I_{it} \tag{9}$$

$$P_{it} - P_{i(t-1)} \leq UR_i \left[1 - I_{it} \left(1 - I_{i(t-1)} \right) \right] + P_{i,min} \left[I_{it} \left(1 - I_{i(t-1)} \right) \right] \tag{10}$$

$$P_{i(t-1)} - P_{it} \leq DR_i \left[1 - I_{i(t-1)} (1 - I_{it}) \right] + P_{i,min} \left[I_{i(t-1)} (1 - I_{it}) \right] \tag{11}$$

$$\left[X_{i(t-1)}^{on} - T_i^{on} \right] \left[I_{i(t-1)} - I_{it} \right] \geq 0 \tag{12}$$

$$\left[X_{i(t-1)}^{off} - T_i^{off} \right] \left[I_{it} - I_{i(t-1)} \right] \geq 0 \tag{13}$$

The minimum and the maximum power generation of the units are constrained by (9). These limitations are determined according to the physical limitations of energy generation by the unit. Inequalities (10) and (11) evaluate the limiting values of increasing and decreasing ramps. Using these values highlights that the considered unit cannot increase its generation beyond the acceptable limitation value within two consecutive hours. The maximum and minimum time constrains of the units are also defined by equations (12) and (13). Using the maximum value of the minimum time, the unit cannot be switched off for a specific number of hours once it is switched on. Similarly, using the minimum value of the minimum time, the unit cannot participate in power generation, and cannot be switched on for a given number of hours once it is switched off. Additionally, the exclusive constraint of fuel can be considered for each thermal unit.

2.3. Constraints of the storage system

In this paper, the battery has been assumed as an option for energy storage. The corresponding constraints of the storage system include charge, discharge, and ideal modes as shown in Fig. 3. Storage system charging has conventionally a rectangular shape, meaning that the system can start charging once it received the charging command from the controller and the charging process is performed at a constant power level. Contrary to charging, battery discharging can follow default discharge profiles. Discharge profiles have practically a trapezoidal shape. As a result, the power generated by the storage system is changed based on a gradual increase or decrease of the generated power under the conditions that the power changes between zero and a discharge value and/or vice versa. Using the trapezoidal profile, the amount of energy accessible from each discharge period can be maximized [22]. Discharge profiles in terms of the shape, time duration, and the number of discharge periods are different. Fig. 3 shows one type of real discharge profile.

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

$$-P_S^R v_t \leq P_{S,t} \leq k P_S^R u_t \quad (t = 1, \dots, NT) \tag{15}$$

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

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

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

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

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

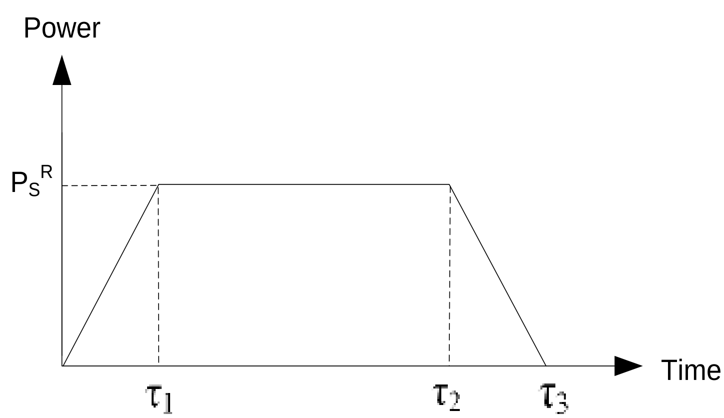

Fig. 3. Real discharge trend for an energy storage system.

Constraints (14) and (15) determine the operation mode of the storage system. Inequality (14) guarantees the storage system cannot operate in the charge and discharge modes simultaneously, and constraint (15) determines the limiting values of the storage power level at each hour. The set equation (16) states three sections of the trapezoidal profile of the discharge in a mathematical form. In the ramp section of the power generated by the storage system, i.e. sections 1 and 3 (triangular shapes in Fig. 3), the accessible energy generated is consumed between the current and the previous hours. The symbol of TD_t is the number of continuous discharge hours at time t, and it is evaluated by inequalities (17) and (18). It should be noted that in the daily unit commitment problem, when the storage system is not in the discharge mode, i.e. when $u_t = 0$, the discharge counter becomes zero. On the other hand, when the storage system operates in the discharge mode, i.e. $u_t = 1$, the discharge counter becomes equal to the discharge counter in the previous hour plus one. However, the charging is limited based on the rated power and the state of charge (SOC). The SOC is obtained from (19) and at each hour it is equal to the SOC of one hour. Therefore, it is assumed that $\Delta t = 1$.

Constraint (20) limits the value of SOC for the storage system to prevent over-charging. It should be considered that the discharge profile given by the manufacturer is determined based on the power required by the operator. The default discharge profile, therefore, cannot be changed arbitrarily or be increased because it affects the battery temperature [23].

The general mathematical model for constraints is given in this section. The formulation of the MIP problem for these constraints is given in [21].

Another important constraint related to the installation of the storage system is investment costs limitation, which is formulated as follow:

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

Using this constraint, the investment cost for installing a storage system is limited. Based on this inequality, the size or capacity of the storage system is constrained.

3. NUMERICAL SIMULATION

A 6-bus test system, as shown in Fig. 4, is used to illustrate the performance of the proposed method. The method is implemented on a 2.4 GHz PC using CPLEX 11.0 software [24].

The characteristics of the generators and energy storage system are listed in Tables 1 and 2. The maximum amount of power imported to the grid can meet the required reserve in the MG. The planning horizon is set five years. In this study, four test cases are considered as follow:

a) Test case 1: Choosing a base case;

b) Test case 2: Adding a storage system to Case 1;

c) Test case 3: Determining the optimal size of the storage system in Case 2;

d) Test case 4: Analyzing sensitivity.

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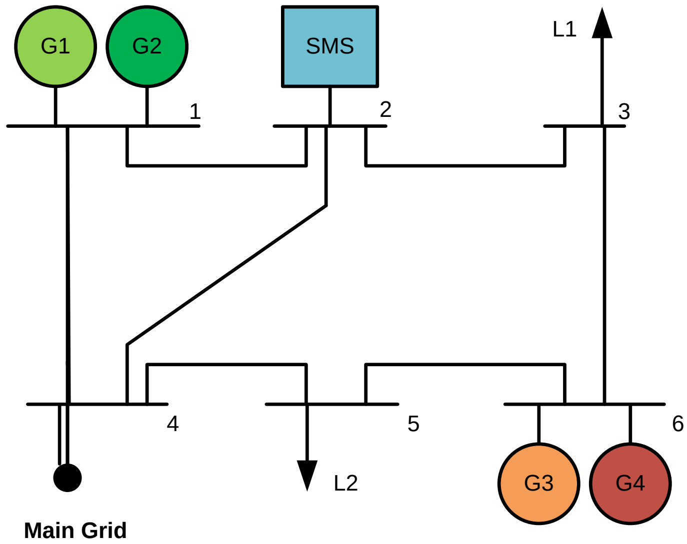

Fig. 4. The 6-bus test system.

Table 1. Characteristics of generation 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)	Maximum 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 2. Characteristics of the energy storage system.

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

a) Test case 1

In the base case, the storage system is not added to the scheme. The main aim is to minimize the total operating costs on the planning horizon, by applying the unit commitment problem to the whole planning horizon. The total operating cost, in this case, is $36,361,650. Unit 1 operates as the base unit during all operating hours, while other units operate when the load demand is not responded by merely unit 1, and higher electricity prices in the market do not allow the MG to import electricity from the main grid. At the time the price of electricity is low, the power of imported from the main grid to the MG, while at the times the price is higher, thermal units within the MG are switched on to meet the demand. The generated surplus power is returned to the grid once again.

b) Test case 2

A 2000 kW storage system, in this case, is added to the design. The storage system can be charged up to 10 MWh to the maximum limit of SOC within 5 hours. A trapezoidal discharge profile is considered, which determines that the storage system is discharged within 7 hours with a power discharge rate of 1.66 MW. From the start of discharging it takes 1 hour for the power to reach the rated discharge power, 5 hours to continue discharging under the rated discharge power, and 1 hour for the output power to reach zero. By adding the storage system, the total operating cost of the system drops to $35,396,496, which shows a 2.65% reduction. Nevertheless, considering the investment cost equal to 480 $/kW for the storage system, $960000 is added to the overall costs of the system. The storage system is mostly charged at off-peak hours when the electricity price is low. The system is again discharged at peak hours when the electricity price is high. The discharge power of the storage system during peak hours is used for demand response in the MG under heavy loading conditions or for selling power to the main grid, leading to increased economic benefits to the MG.

c) Test case 3

In this case, the rated power of the storage system is considered as a problem variable. Charging and discharging profiles are similar to those in Case 2, i.e. 5 hours for the rectangular charging and 7 hours for the trapezoidal discharging. Using the proposed method for determining the size of the storage system, the optimal size of the storage system is 950 kW. The total cost of expansion planning is $36,356,860 which includes $35,881,860 as of the total operating cost, $456,000 as of the investment cost of the storage system, and $19,000 as of the fixed costs of repair and maintenance. Identical to Case 2, the storage system is mostly charged during off-peak hours when the electricity price is low, and is discharged during peak hours when the electricity price is high.

d) Test case 4

The sensitivity of the total costs to the size of the storage system is analyzed in this section. The size of the storage system is increased from 0 to 2000 kW with steps of 100 kW, where 0 means that no storage system is used. Fig. 5 shows the total costs of investment and repair and maintenance for the ESS as a function of the size of the storage system. As the size of the storage system increases, the total cost of investment and maintenance increases linearly. The cost of repair and maintenance is considered in the five-year planning horizon. Fig. 6 shows the operating cost of the system in terms of the size of the storage system. It is observed that the operating cost decreases as the size of the storage system increases. The larger size of the storage system might mean more energy storage during off-peak hours and higher energy generation during peak hours, leading to more economic benefits for the system. The total expansion planning cost of the system consists of the sum of the maintenance and investment costs of the storage system, plus the operating cost of the system, as shown in Fig. 7.

As the size of the storage system is increased from 0 to 900 kW, the total cost of expansion planning is reduced, meaning that a larger storage system is more beneficial to the MG. However, for sizes larger than 900 kW, a larger storage system means more cost of expansion planning. It is evident from Fig. 6 that in the 5-year expansion planning horizon, ESSs with rated power greater than 1200 kW are not economical. In this case, the reduction in the operating cost of the MG caused by installing the storage system is less than the costs of maintenance and investment in the storage system. Hence, it will not be reasonable to install this system.

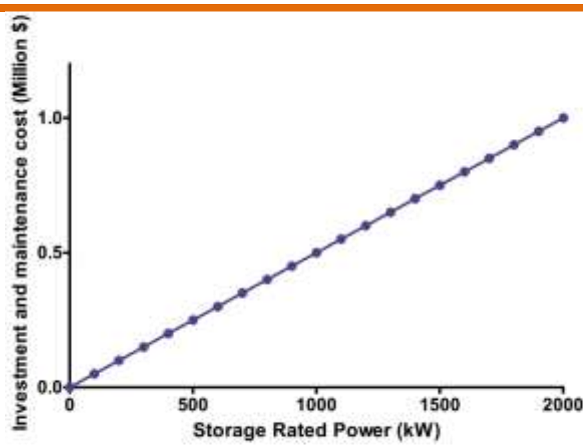

Fig. 5. Investment and maintenance cost of the storage system.

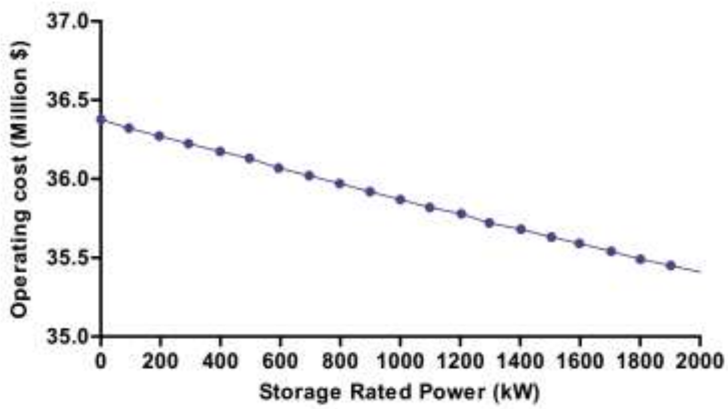

Fig. 6. Operating cost of the MG.

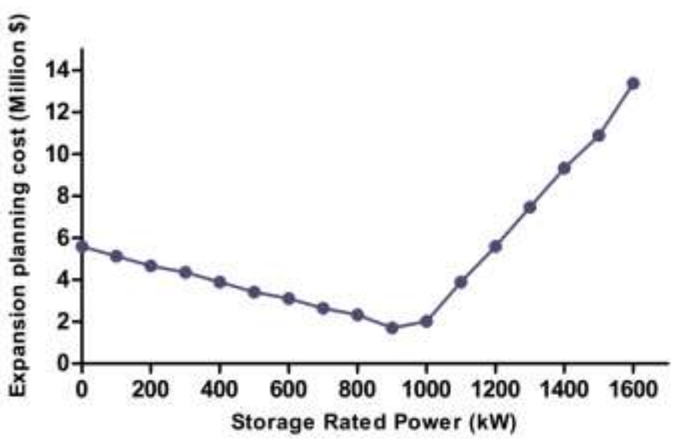

Fig. 7. The overall expansion planning cost.

4. DISCUSIONS

The following items need to be taken into consideration in the problem of determining the optimal size of the storage system:

- In the proposed test cases, the expansion planning horizon is considered for five years. Assuming longer or shorter periods, the planning horizons can influence the results. For instance, a larger storage system in Case 3 may be obtained as the optimal size of the storage system in the MG.
- The present study considers merely the economic benefit of the storage system under the conditions that an MG with thermal units is added. The benefits of the storage system will be significant when RESs are present in the system.
- In numerical studies, the charging and discharging profiles of the storage system are assumed constant. However, the proposed method can consider variable charging and discharging profiles as well and as a result, can find optimal charging and discharging profiles for the storage system.
- The transmission system is discarded in the problem formulation because, in general, in an MG, the transmission system has sufficient capacity for power distribution and emergency conditions will not occur. Yet, constraints of the transmission system can be simply added to the formulation of the proposed problem.
- Since the execution time of the problem is not important, the considered problem is executed in one single shot. To increase the response time and find the final solution in a very short time, the available decomposition methods can be used.

5. CONCLUSIONS

The paper proposed a mathematical model to calculate the optimal size of a storage system. The suggested method employs an expansion planning problem where the capital costs and the repair and maintenance cost of the storage system plus the operating cost of the system are considered together and are optimized simultaneously. An accurate model is used for the storage system where charging and discharging profiles of the storage system are utilized. Numerical studies show that a larger storage system does not necessarily mean supplying more economic benefits. There is an optimal point based on which the storage system is installed. Larger sizes of the storage system may impose higher expansion costs on the MG.

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