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ORIGINAL PAPER

Mixed integer programming based battery sizing

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Abstract In this paper, mixed integer programming (MIP) formulations are proposed to obtain the optimal capacity of the battery energy storage system (BESS) in a power system. Two optimization problems will be investigated: (1) When the BESS is owned by a utility, the operation cost of generators and cost of battery will be minimized. Generator on/off states, dispatch level and battery power dispatch level will be determined for a 24-h period. (2) When the BESS is owned by a community for peak shaving, the objective function will have a penalty component for the deviation of the imported power from the scheduled imported power. The battery sizing parameters, power limit and energy limit, are treated as decision variables in the optimization problems. In both cases, switchable loads are considered. Further, constrains of switchable loads are included in the optimization problem to show their impact on battery sizing. MIP problems are solved by CPLEX. The simulation results present the effect of switchable load penetration level on battery sizing parameters.

Keywords Battery energy storage system · Switchable loads · Mixed integer programming

1 Introduction

Advanced energy storage systems range from flywheel based energy storage to batteries (Lithium Ion, Nickel Metal Hydride, etc.). Large-scale battery storage is now attracting considerable interest. For example, Duke Energy installed a 36 MW battery storage system at the 153 MW Notrees wind power project near Kermit Texas [1]. The

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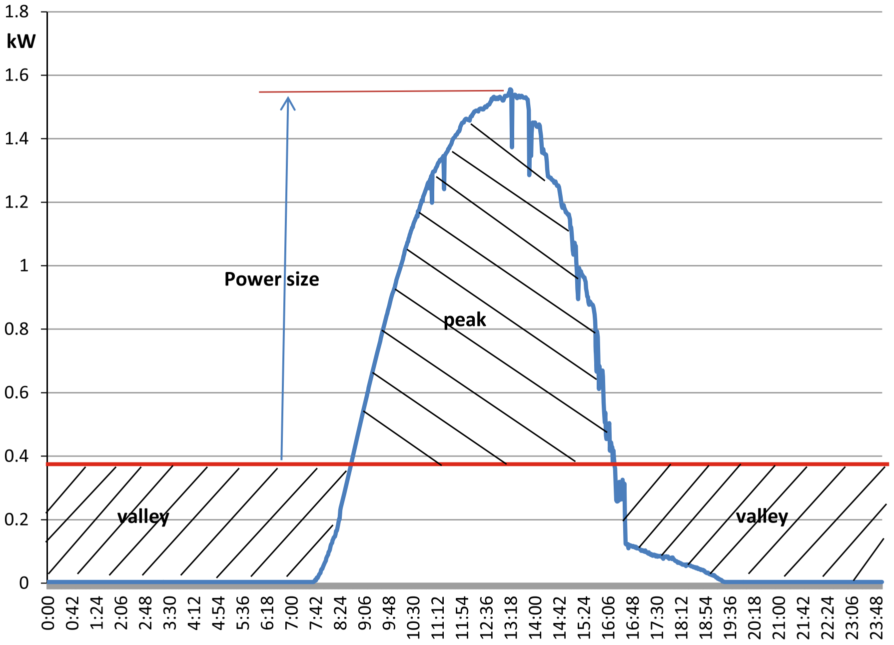

Fig. 1 Peak and valley periods for a battery sited with a 1.6 kW PV panel

important role of a battery energy storage system (BESS) is listed as follows [2,3]. (1) A BESS can help eliminate the need for a peak generator. A peak generator is very expensive and is only used when the demand is at its highest. (2) A BESS can be integrated with a renewable source to solve the intermittent issue and to form a remote area power supply. (3) A BESS can also provide backup energy when a blackout occurs by pumping the grid with stored electrical energy.

The size of a BESS is determined by both the power limit (C_b) and the energy limit (E_b). To determine the size of a BESS, there are couple of ways.

In [4], a battery is sited along with a 1.6 kW Photovoltaic (PV) to generate constant output power. The mean value of the PV is first found for a 24-h period. The power size of the battery is then determined by the difference between the maximum PV output or the minimum PV output versus the mean value. The energy size of the battery is determined by integrating the expected battery discharging power over the valley period or the charging power over the peak period. Figure 1 gives an illustration diagram to show the valley period and the peak period.

Oudalov et al. [5] presents a sizing methodology based on peak shaving similar as the industry practice illustrated in Fig. 1. In [6], Monte Carlo simulation methods are used to find the suitable size for a BESS while meeting the demand and considering outages of generators. Computational simulations were used in [7] to estimate battery capacity for suppression of a PV power plant output fluctuations.

Optimization problems related to a battery energy storage system (BESS) operation have been formulated for BESS operations. For example, in [8], a mixed integer linear programming was introduced to find the optimal operation scheduling of a BESS in order to reduce the effect of intermittence of the renewable generation units. The size of the battery is assumed known and the objective function does not include battery cost. An optimization problem to find a 24-h dispatch pattern for a flow battery is presented in [9]. The flow battery is used for peak shaving and the objective function is the sum of the power deviation between the net load profile and the scheduled power. The optimization program considers battery constraints but does not consider other decision variables.

Variety of other optimization methods can also be found in the literature. In [10, 11], dynamic programming was used to find the optimal capacity of the BESS in a power system. In [12], linear programming was used to optimize the energy storage dispatch schedule. Particle swarm optimization was used in [13] to solve the optimal operating schedule of a BESS for an industrial time-of-use rate user with wind turbine generators. In [14], a method combining the genetic algorithm with linear program to determine the best capacity and operating status of the energy storage system was presented.

The focus of this work is to adopt mixed linear integer programming to solve a battery sizing problem. Due to the availability of commercial solver such as CPLEX, optimization problems with a large dimension of decision variables can be solved in a fast way. Therefore, using mixed linear integer programming, we can make decision for a comprehensive problem. In this work, two types of applications will be investigated: utility application and demand side application. For each type of application, optimal size for a BESS will be decided. For the utility side applications, the main objective is to minimize the total operating cost of the utility considering switchable loads. For the demand side applications, a community with a 24-h load profile is considered. The community purchases scheduled power from the utility and pays penalty if the imported power deviates from the scheduled imported power.

The contribution of this work is twofold:

1. The studied BESS sizing problem is comprehensive and of practice value. This research considers a BESS, generators, controllable loads, and dynamic pricing. Two practical operation problems are formulated based on the utility's point of view to save cost and based on the consumer's point of view for peak shaving.
2. Mixed integer programming models for BESS sizing are developed and solved. Compared to many other model formulations [15,16], where a BESS's size (power and energy) is treated as parameters and a battery's cost is not included in optimization model, in this work, battery's power size and energy size are treated as decision variables. Using the developed models, utilities can make decision to choose a suitable energy and power size for a battery system to save operation cost while considering cost of battery itself.

The paper is organized as follows. The optimization model for the utility application is presented in Sect. 2. The optimization model for the demand application is presented in Sect. 3. Case studies and numerical examples are shown in Sect. 4. The conclusion of the paper is presented in Sect. 5.

2 Utility applications: minimizing operation cost with a BESS and switchable loads

2.1 Objective function

The objective function is to minimize the total cost over a horizon N, including the cost of the dispatched power from the generators (P_i), the cost of the imported power from other areas (P_{im}), and the installation cost of the battery. The battery cost includes cost related to its converter (power size) and the cost of its storage unit (energy size) [17]. Therefore, the battery cost is expressed as

$$\beta_1 C_b + \beta_2 E_b$$

where

β_1 refers to the cost of 1 kW rating of the BESS;
β_2 refers to the cost of 1 kWh rating of the BESS.

In this research, we choose $\beta_1 = \$.20$/kW, while $\beta_2 = \$.25$/kWh.

The switchable loads are assumed to have the same size and there are N_s of them. Status of the k-th switchable load at j-th hour is notated as

$$W_{lk,j} = \begin{cases} 1 & \text{offline} \\ 0 & \text{online} \end{cases} \tag{1}$$

The decision variables for the optimization problem are listed as follows.

- $P_{i,j}$ refers to the dispatched power from the i-th generator at the j-th hour.
- $P_{b,j}$ refers to the power discharged from or charged to the battery energy system at the j-th hour.
- $P_{im,j}$ refers to the imported power at the j-th hour.
- C_b refers to the power rate of the battery energy system.
- E_b refers to the energy rate of the battery energy system.
- $W_{gi,j}$ refers to the binary variable that is equal to 1 if the i-th generator is online and 0 otherwise.
- $W_{lk,j}$ refers to the binary variable that is equal to 1 if the k-th switchable load is offline and 0 otherwise.

where i, j, k are indices.

The objective function is as follows.

$$\min_{\substack{P_{i,j},\, P_{b,j},\, W_{gi,j} \\ W_{lk,j},\, C_b,\, E_b,\, P_{im,j}}} \sum_{j=1}^{N} \left(\sum_{i=1}^{N_g} C_i(P_{i,j}) + \lambda_j P_{im,j} + \left(\sum_{k=1}^{Ns} \alpha W_{lk,j} \right) \right) + \beta_1 C_b + \beta_2 E_b \tag{2}$$

where:
Indices
N_g refers to the number of generator.
N_s refers to the number of switchable loads.
N refers to the number of hours.

Function
C_i refers to the quadratic function of the production cost of the i-th generator.

Parameters
λ_j refers to the price of the imported power at the j-th hour,
α refers to the penalty for switching switchable loads off.

In this research, the size of a switchable load is 3 kW. The penalty of turning off 3 kW switchable load (α) is given as \$0.33/kWh. This value is based on the evaluation of the average value of the electricity and also based on trying different penalty. Given the average electricity is 0.25 cent/kWh, we choose the penalty to be \$1 to turn off a 3 kW switchable load for each hour.

2.2 Constraints

The optimization problem is subject to the following constraints:

1. Power balance

$$\sum_{i=1}^{N_g} P_{i,j} + P_{b,j} + P_{im,j} = D_j - \sum_{k=1}^{N_s} L_s W_{lk,j} \tag{3}$$

   where L_s is the power demand of each switchable load.
2. Generators Limits

$$\underline{P}_i W_{gi,j} \leq P_{i,j} \leq \overline{P}_i W_{gi,j}, \tag{4}$$

   where $\underline{P}_i$ and $\overline{P}_i$ refer to the minimum and the maximum power output of the i-th generator respectively.
3. Ramping Constraints The generators output power is constrained by ramp-up and ramp-down rates. They also are constrained by startup ramp rates and shutdown ramp rates.

$$P_{i,j} - P_{i,j-1} \leq RU_i W_{gi,j-1} + SU_i (W_{gi,j} - W_{gi,j-1}) + \overline{P}_i (1 - W_{gi,j-1})$$
$$P_{i,j} \leq \overline{P}_i W_{gi,j+1} + SD_i (W_{gi,j} - W_{gi,j+1})$$
$$P_{i,j-1} - P_{i,j} \leq RD_i W_{gi,j} + SD_i (W_{gi,j-1} - W_{gi,j}) + \overline{P}_i (1 - W_{gi,j-1}).$$

   where

   RU_i refers to the ramp-up rate.
   RD_i refers to the ramp-down rate.

SU_i refers to the startup ramp rate.
SD_i refers to the shutdown ramp rate.

4. Minimum up and down time Constraints:

$$\sum_{n=j}^{j+UT_i-1} W_{gi,n} \geq UT_i \left[W_{gi,j} - W_{gi,j-1}\right].$$

$$\sum_{n=j}^{j+DT_i-1} [1 - W_{gi,n}] \geq DT_i \left[W_{gi,j-1} - W_{gi,j}\right]$$

where

UT_i refers to minimum up time of the i-th generator;
DT_i refers to minimum down time of the i-th generator.

5. Power rating limits of the battery energy system

$$-C_b \leq P_{b,j} \leq C_b \;\; (j = 1, \ldots, N) \tag{5}$$

6. Energy rating of the battery energy system

$$\underline{E} \leq E_0 + \sum_{j=1}^{n} P_{b,j} \leq \overline{E}, \;\; (n = 1, \ldots, N-1) \tag{6}$$

where $\underline{E}$ and $\overline{E}$ refer to the minimum and the maximum energy limit of the battery unit respectively; E_0 refers to the initial energy stored in the battery. $\overline{E}$ is equal to the decision variable E_b, storage size of the battery. $\underline{E}$ is 0.

7. Imported power limits

$$\underline{P}_{im} \leq P_{im,j} \leq \overline{P}_{im}, \;\; (j = 1, \ldots, N) \tag{7}$$

where $\underline{P}_{im}$ and $\overline{P}_{im}$ refer to the minimum and the maximum imported respectively. For utility applications, the imported power is limited to 15 kW. The minimum imported power is zero kW. For the demand side applications, no limit will be imposed.

8. Integer and binary variables

$$W_{gi,j}, W_{lk,j} \in [0, 1] \tag{8}$$

where $W_{gi,j}$ and $W_{lk,j}$ take either 0 or 1 value.

3 Demand side application: peak shaving

In this scenario we assume that the BESS is owned by a community. The main purpose of BESS is peak shaving or to keep the imported power constant. We assume that the community has no other energy sources but a BESS and switchable loads. The optimization problem is formulated to minimize the cost of power purchasing and penalize any deviation from the scheduled power. The scheduled power is assumed to be the average load for 24 h.

3.1 Decision variables

In this optimization problem the vector of the decisions variables is as follows:

$$X = [\cdots P_{im,j} \;\; P_{b,j} \;\; C_b \;\; E_b \cdots]^T \tag{9}$$

where:

j	refer to j-th hour and $N = 24$.
$P_{b,j}$	refers to the discharged from or charged to the battery energy system at the j-th hour.
$P_{im,j}$	refers to the imported power at the j-th hour.
C_b	refers to the rating power of the battery energy system.
E_b	refers to the rating energy of the battery energy system.

3.2 Objective function

The objective function is to minimize the total cost which is the sum of the cost of imported power, and the cost of the BESS and the penalty due to imported power deviation from the scheduled power.

$$\min_{P_{im,j}, C_b, E_b} \sum_{j=1}^{N} \left(\lambda_j P_{im,j} + F_P (P_{im,j} - P_{sch})^2 \right) + \beta_1 C_b + \beta_2 E_b \tag{10}$$

where:

P_{sch}	refers to the scheduled power to be purchased by the community.
F_P	refers to the penalty for the deviation from the scheduled power.

3.3 Constraints

The optimization problem is subject to the following constraints:

1. Power balance

$$P_{b,j} + P_{im,j} = D_j, \; (j = 1, \ldots, N) \tag{11}$$

2. Power rating limits of battery energy system

$$-C_b \leq P_{b,j} \leq \; C_b, \;\; (j = 1, \ldots, N) \tag{12}$$

3. Energy rating of the battery energy system

$$\underline{E} \leq E_0 + \sum_{j=1}^{n} P_{b,j} \leq \overline{E}, \; (n = 1, \ldots, N-1) \tag{13}$$

   where $\underline{E}$ and $\overline{E}$ refer to the minimum and the maximum energy limit of the battery unit respectively. $\underline{E} = 0$ and $\overline{E} = E_b$.
4. Imported power limits

$$\underline{P}_{im} \leq P_{im,j} \leq \overline{P}_{im}, \; (j = 1, \ldots, N) \tag{14}$$

   where $\underline{P}_{im}$ and $\overline{P}_{im}$ refer to the minimum and the maximum imported respectively.

For the demand side applications, the imported power has no upper limit. The lower limit is zero.

4 Case studies and numerical examples

4.1 BESS applications in utility side

The study system is shown in Fig. 2. BESS applications in utility side and demand side are presented in two different cases. To investigate the BESS application in utility side, the utility owns the BESS. The utility also owns generators. In addition, the utility has interconnections with the external grid to have power imported. Dynamic price for the imported power is give (Fig. 4). The objective of the utility is to minimize the operating cost and meet the load demands (Fig. 3). For the demand side applications, the BESS is owned by the community and the community purchases and imports power from the utility at a dynamic price (Fig. 4). The load profile is shown in Fig. 3. The community, however, does not own any generators.

The proposed MIP model is tested using TOMLAB/CPLEX Package. The studied system shown in Fig. 2 consists of six generators, a BESS, and load demands with profile shown in Fig.3. Price of the imported power from the external is presented in Fig. 4. This price profile is obtained from Ameren Corporation website [18] for a winter day. The specifications of the generators are presented in Tables 1 and 2.

Fuel cost of the generators are calculated using following equation:

$$C_i(P_i) = a_i P_i^2 + b_i P_i + c_i. \tag{15}$$

In this case, firstly we present the base scenario where no switchable loads are presented. Then, two scenarios are considered to investigate the impact of the switchable loads on the BESS. In the first scenario, penalty is imposed on switching off any

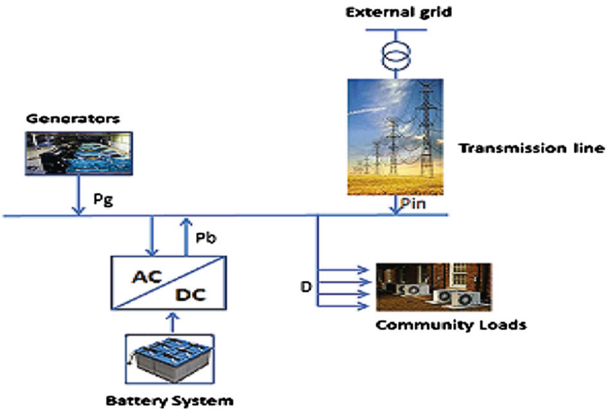

Fig. 2 The study system

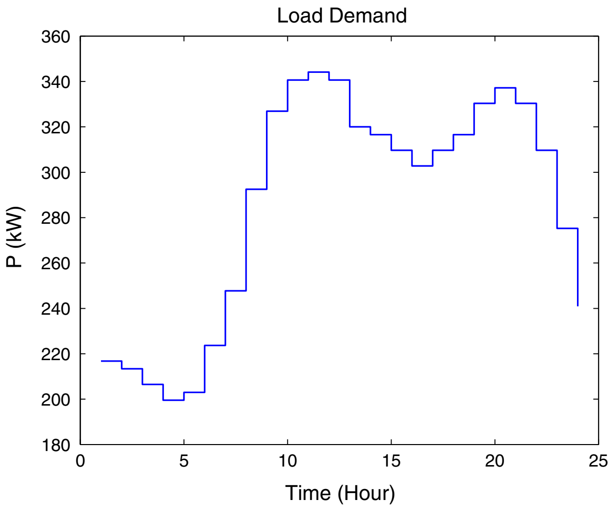

Fig. 3 Load profile for a day

switchable load without considering any other constraints. In the second scenario, other constraints are imposed on the switchable loads: (1) any switchable load must run for at least 19 h each day; (2) Once the switchable load is on, it must continue being on for 6 h consecutively. We assume that each switchable load is represented by 3 kW.

Therefore, the following constraints must be added to the model:

$$\sum_{n=j}^{j+DT_k-1} [1 - W_{lk,n}] \geq DT_k[W_{lk,j-1} - W_{lk,j}], (j = 1, \ldots, N).$$

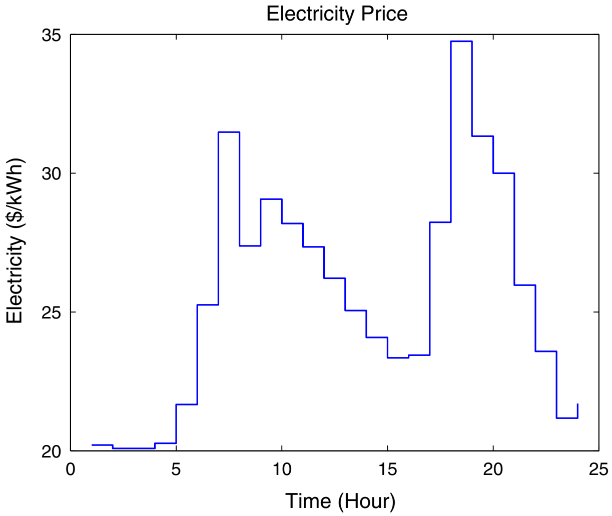

Fig. 4 Electricity price for a day

Table 1 Specifications of the generators

Unit	a_i $\left(\frac{\$}{(\mathrm{kW})^2\mathrm{h}}\right)$	b_i $\left(\frac{\$}{\mathrm{kWh}}\right)$	c_i $\left(\frac{\$}{\mathrm{h}}\right)$	$\underline{P}_i$ (kW)	$\overline{P}_i$ (kW)
1	0.01433	27.8893	118.8206	5	20
2	0.01261	24.6637	118.1083	5	20
3	0.00812	18.1000	218.3350	5	50
4	0.00463	10.6940	142.7348	30	70
5	0.00143	10.6616	176.0575	50	100
6	0.00199	7.6121	313.9102	30	120

Table 2 Specifications of the generators

Unit	UT (h)	DT (h)	SU (kW)	SD (kW)	RU (kW)	RD (kW)
1	8	6	5	10	5	5
2	8	6	5	10	5	5
3	8	6	10	15	5	10
4	8	6	20	15	10	10
5	8	6	30	20	15	15
6	8	6	30	20	20	20

where DT_k refers to minimum up time of the k-th switchable load once it is switched on. In this case study, $DT_k = 6$ h. The constraint can understood as: if at j-th hour, the k-th load is switched on (its status is changed from 1 to 0), the for the next 6 h, the sum of the compliment of the binary variable should be ≥ 6.

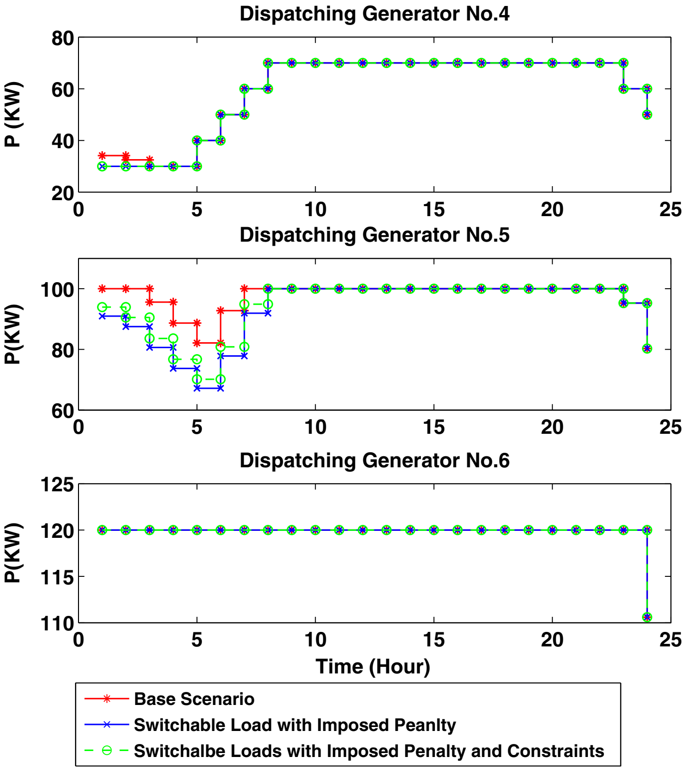

Fig. 5 Generator dispatch level. Five switchable loads are considered. Penalty of switching off: \$1 for 3 kW

$$\sum_{j=0}^{j=24} [1 - W_{lk,j}] \geq M_{on}, (k = 1, \ldots, N_s).$$

where M_{on} refers to the minimum number of hours which any switchable load should be on in a 24-h period. In this case study, $M_{on} = 19$ h.

4.1.1 Simulation results

The three scenarios are compared.

- Base scenario without switchable loads
- With switchable loads and imposed penalty. Five switchable loads are considered.
- With switchable loads, imposed penalty and switchable load constraints. Five switchable loads are considered.

Figure 5 shows the optimal dispatch of each generator for the three scenarios. While three generators are not committed, it can be seen that all of the other three generators are committed to dispatch their maximum limits at the time of the peak loads.

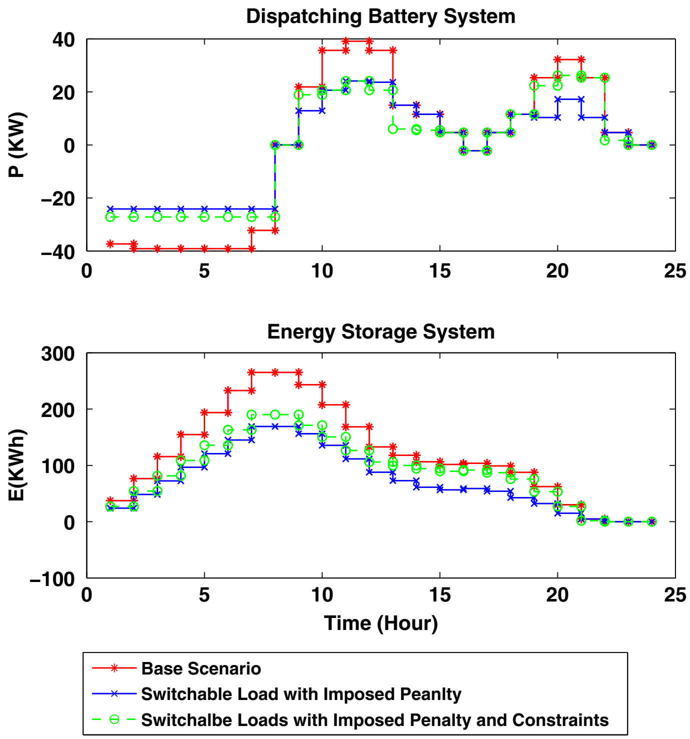

Fig. 6 BESS power and energy level. Five switchable loads are considered. Penalty of switching off: $1 for 3 kW

Figures 6 and 7 present the battery power dispatch level and energy level for 24 h. Positive power means the battery is discharging while negative power means charging. Comparing the price and load profiles, we can find that during light load and low price periods, the BESS will get charged while during peak load and high price periods, the BESS discharges. In addition, with switchable loads, the charge and discharge levels of the BESS are less than those without switchable loads. In turn, the energy capacity required for the BESS is much less. Therefore, presence of switchable loads reduces the size of the battery.

Comparing the case of five switchable loads and ten switchable loads, we can find that with higher penetration of switchable loads, the size of BESS will be reduced even more.

When the constraints for switchable loads are imposed, the requirement for battery power and energy size will go slightly up. In terms of optimization problem, imposing additional constraints is equivalent to reducing the feasible region. Therefore, for minimization problem, the cost will go up. This additional cost is also manifested in the requirement of increasing battery size. Figure 7 present the comparison of battery sizes for the three scenarios when ten switchable loads are considered. With ten switchable loads, cost can be further reduced.

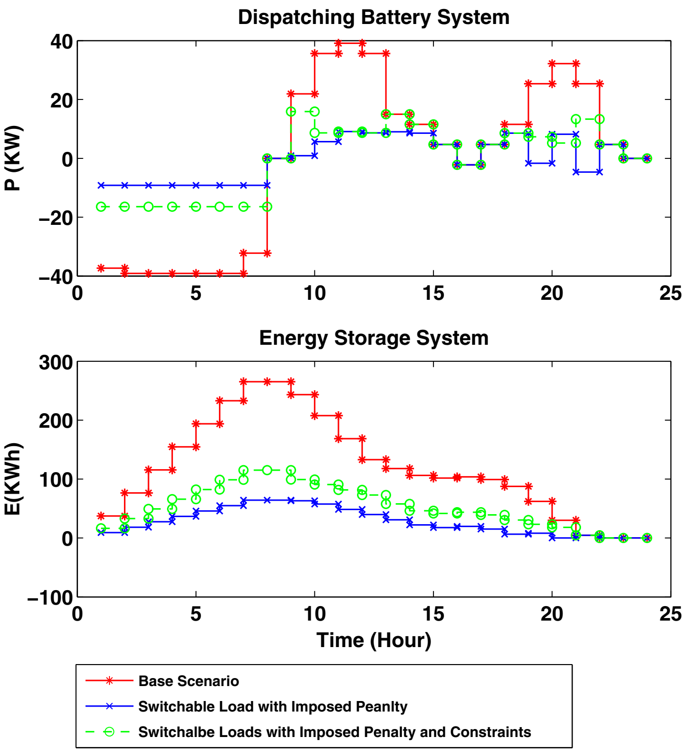

Fig. 7 BESS power and energy level. Ten switchable loads are considered. Penalty of switching off: $1 for 3 kW

Figures 8 and 9 show the impact of the switchable loads on the load profile. Both figures demonstrate that switchable loads are effective to shave peak demand. Figure 9 shows that the higher the penetration of switchable load, the flatter the load profile becomes.

Figure 10 presents the switching status of the five loads. It can be observed that without the minimum on time constraints, there is more flexibility for switchable loads and more loads are switched off during Hour 20 when the demand is at its second peak. With the minimum on time constraint imposed, at Hour 20, there are less loads switched off.

Table 3 shows the results of different scenarios to investigate the impact of the switchable loads. It can be found that increasing the number of switchable loads can help reduce the size the BESS. For example, with five switchable loads, the energy size and the power size can be reduced by 1/3. With more switchable loads, we see more reduction in size. With constraints imposed, the requirement for the energy size and the power size is higher.

It is found that for the system studied, with 5 % penetration of switchable loads ($N_s = 5$, each switchable load 3 kW), the size of energy storage can be cut down 30 %.

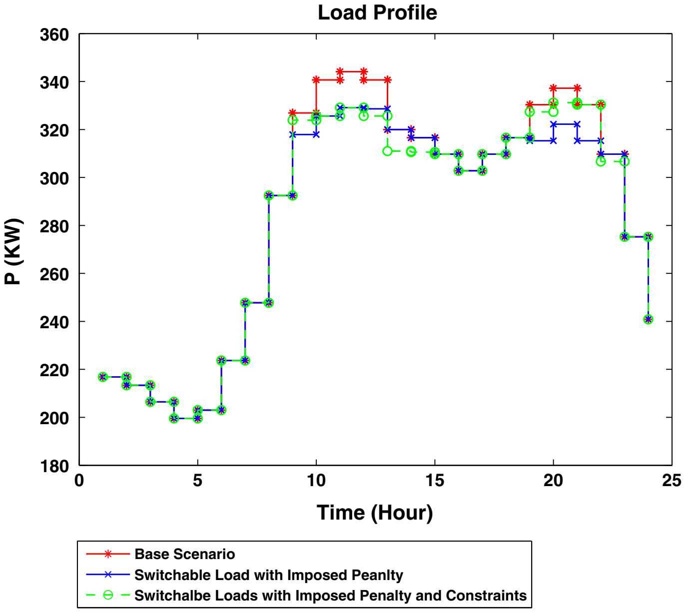

Fig. 8 Switchable load effect on load profile. Five switchable loads are considered

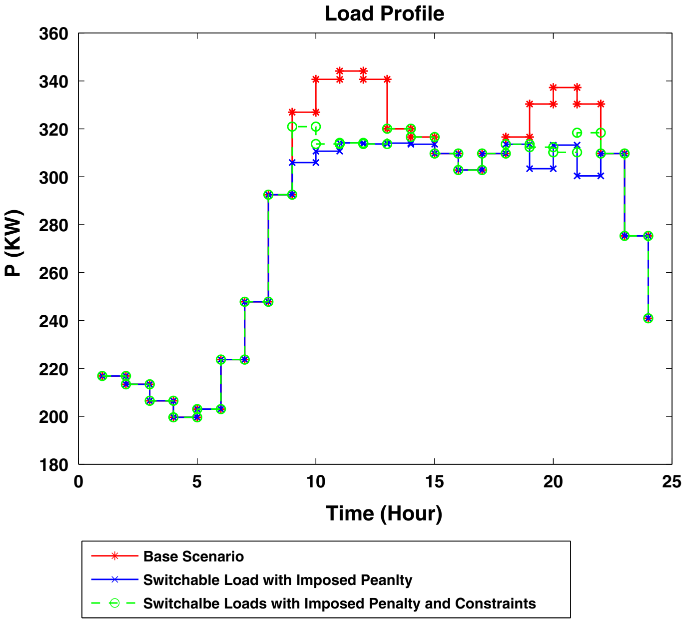

Fig. 9 Switchable load effect on load profile. Ten switchable loads are considered

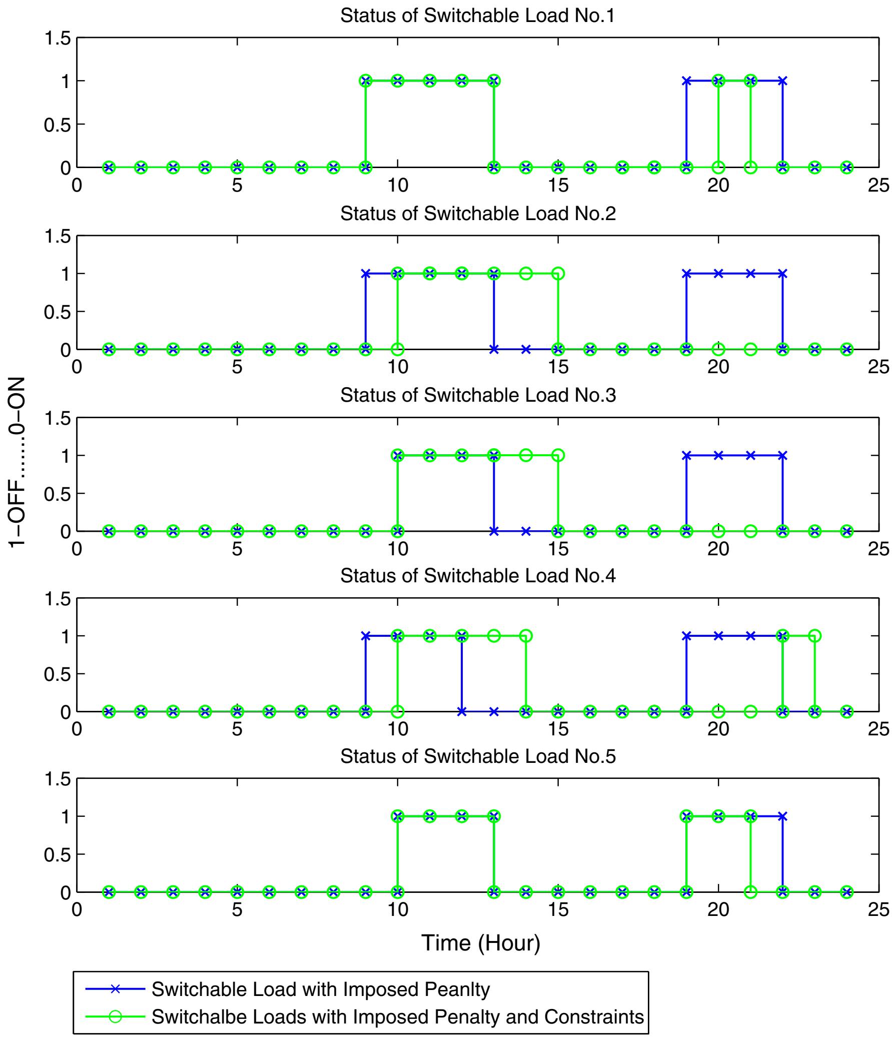

Fig. 10 Switchable load status. Ten switchable loads are considered

Table 3 Summary of BESS applications in the utility side scenarios

Scenario	Ns	C_b kW	E_b kWh
Base	0	39.11	265.130
Penalty imposed	5	24.161	169.130
Penalty imposed	10	9.161	64.130
Penalty imposed	14	3.11	19.130
Constraints imposed	5	27.161	190.130
Constraints imposed	10	16.447	115.130
Constraints imposed	14	7.876	55.130

4.2 BESS applications in demand side

In this application, a community is purchasing power from the utility at dynamic price given in Fig. 4 in order to meet its demands shown in Fig. 3. The community is requested to schedule a constant power from the grid. A penalty would be imposed on any deviation in the scheduled power. The power schedule is usually the average of the daily demand.

The most conservative size for a battery system can be obtained by investigating the load profile for 24 h. The BESS is used to compensate the variation of load and the imported power will be kept constant at the average power level. The power size of the BESS is the maximum difference between load and the average load value over 24 h. The energy size can be found by integrating the power difference over a valley filling period. The computing of power and energy size is demonstrated in the following two equations:

1. Upper bound on energy rating

$$E_b = \int_0^{24} (P_{Dmd} - P_{ave})dt, \quad P_{Dmd} \geq P_{ave} \tag{16}$$

   where P_{Dmd} is the power demand and P_{ave} is the average power.
2. Maximum value of charging or discharging power

$$C_b = max\left\{|P_{ave} - P_{Dmd}(j)|\right\}, \quad (j = 1, \ldots, 24) \tag{17}$$

The computed battery size is 510 kWh for total storage and 88 kW for charging and discharging power.

For the optimization problem, the community will try to minimize the total cost of purchasing the power, paying penalty and paying battery. Imposing a penalty on the deviation between the scheduled imported power (288 kW) and the purchased power may have an impact on BESS sizing. To investigate that impact the latter two constraints are added to the mathematical model equations (14)-(18). Different penalties which are \$1, \$10, and \$100 have been considered. Table 4 shows the results of testing each of those penalties. Figures 11 and 12 show that the heavier the penalty imposed, the less deviation between the purchased and scheduled power. They also show that the heavier the penalty imposed, the larger the BESS size is required. With a heavy penalty on imported power deviation, the size of the battery will be close to the most conservative case: 510 kWh and 88 kW.

Table 4 Summary of BESS applications in the demand side scenarios

Scenario	Penalty cost \$	C_b kW	E_b kWh	$Min.P_{im}$ kW	$Max.P_{im}$ kW
Case A	1	76.239	450.295	275.79	293.74
Case B	10	87.010	500.51	286.56	288.6
Case C	100	88.526	506.034	287.98	288.1

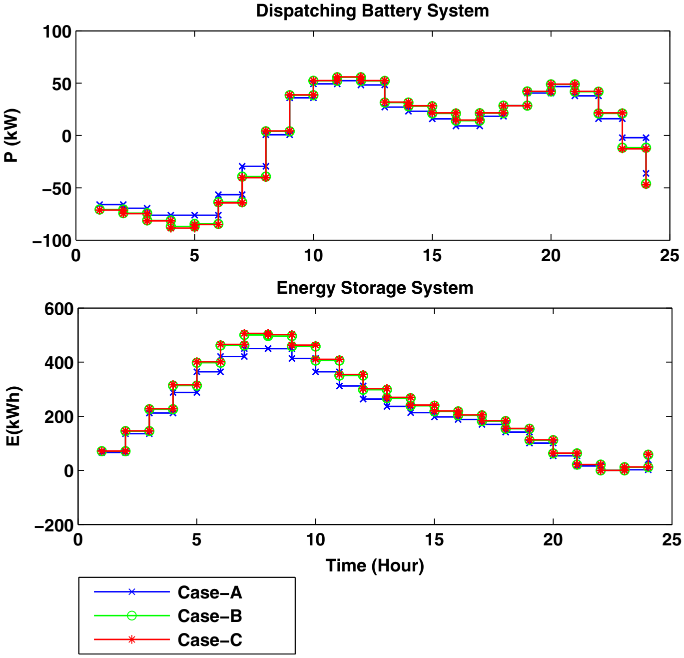

Fig. 11 BESS power and energy level in demand side applications

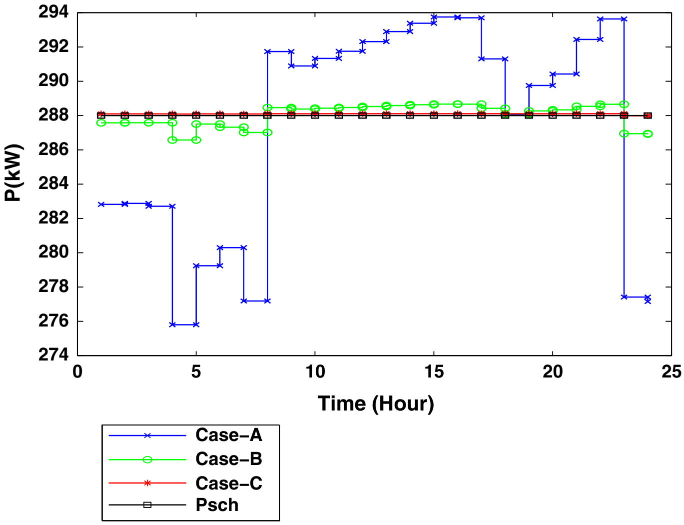

Fig. 12 Purchased power versus the scheduled power in demand side applications

The penalized cost is dependent on the deviation of imported power from the scheduled power. When the penalty is set to $1, the maximum power deviation observed from Fig. 12 is 4 %. The size of the battery is reduced about 10 %.

At \$10 penalty rate, the imported power is already very close to the scheduled power and the deviation is insignificant. At \$100 penalty rate, the deviation is also insignificant. Therefore, the related component on power deviation in the objective function has negligible effect on the total objective function when the penalty rate increases from \$10 to \$100. This makes the battery power size and energy size remain almost the same for \$10 and \$100 penalty.

5 Conclusion

This paper presents MIP problem formulation to find the size of a BESS. The BESS could be owned by a utility to reduce the operation cost or owned by a community for peak shaving. Switchable loads are considered in the problem formulation and unit commitment is also considered. Objective functions, linear constraints for the BESS and switchable load constraints suitable for MIP solving are defined. The optimization problems are solved by commercial tool CPLEX. Case study results demonstrate the impact of switchable load penetration on BESS size. It is found that for the system studied, with 5 % penetration of switchable loads, the size of energy storage can be cut down 30 %. In addition, the size of the energy storage can also be determined based on multiobjective optimization of imported power deviation and battery cost. If we can tolerate 4 % power deviation, we can cut down the size of a BESS by 10 %.

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