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Performance analysis of absorption thermal energy storage for distributed energy systems

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Abstract

In recent years, distributed energy systems (DES) have attracted worldwide attention. Distributed generation unit (DG) in DES usually works under part load during night, which results in low efficiency and the waste heat of DG cannot be fully utilized. This study proposes a novel absorption thermal energy storage system together with electric energy storage for distributed energy systems. The proposed absorption thermal energy storage system which is a combination of absorption chiller and liquid storage tanks, has a higher energy storage density. During off-peak hours, the extra electricity of DG can be used by electric chillers (EC) and the extra waste heat of DG is stored by the proposed absorption thermal energy storage system. The stored thermal energy is released in peak hours to meet the cooling loads of buildings. A case study of DES in a campus under cooling-dominated climate is conducted to evaluate the performance of the proposed system. The results in a typical summer day indicate that the DG utilization rate increases from 80% to 92.9%, meanwhile the required capacities of electric chillers can be obviously reduced. The operating cost of DES also reduces by 12.9% compared with the DES without energy storage. Through appropriate operation strategy, off-the-grid operation for DES can be achieved without energy waste by applying the proposed energy storage method.

Keywords: absorption thermal energy storage; waste heat; distributed energy system; peak load shifting; self-sufficient micro grid

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1. Introduction

Nowadays, building energy is mainly supplied by centralized energy systems (CES) which utilize centralized power plants and individual thermal energy systems. As worldwide energy demand increases rapidly, it becomes a big challenge to utility grid. Besides, the efficiency of CES is also low from the perspective of primary energy consumption. In the last decade, distributed energy systems (DES) are becoming a more attractive energy supply option worldwide. Compared with CES, DES can employ renewable energy and waste heat, achieve the cascade utilization of energy, which make DES has the advantages of high efficiency, cost saving and low greenhouse (GHG) emissions. A typical DES consists of distributed generation unit (DG), boilers, absorption chillers (AC) and electric chillers (EC). Performance of DES has been evaluated by many researchers from the perspectives of energy, economy and environment [1-3]. The optimization design and operation optimization of DES were developed to reduce operating costs, economic costs and carbon emissions [4, 5].

For the distributed energy systems, it's hard to simultaneously match the cooling, heating and power loads in buildings as they usually vary with time. As a result, the DES especially DG either designed with oversized capacity and works under part load, result in low efficiency as the waste heat of DG cannot be fully utilized, or the DES still needs to import electricity from utility grid. Energy storage can balance the energy demand and supply, achieve peak load shifting and reduce system capacity. Although the thermal energy storage (TES) using chilled water storage for DES has been investigated and considered as a feasible method to address the abovementioned problems of DES [5], energy storage density of chilled water storage is very low (9.5 kWh/m^3 under 5 ^oC / 13 ^oC), which limits its application to DES.

Absorption thermal energy storage (ATES) surpasses other types of TES in many aspects, which including much higher energy storage density, negligible heat lass, using solar energy or waste heat as heat sources. It attracts increasing interests in recent years. Both experimental and simulation studies were conducted for ATES [6-9]. The absorption chiller integrated with absorption thermal energy storage has been proved to be feasible [9, 10]. Applying ATES to distributed energy systems is a very promising option, however there is a lack of research on it by far. This paper investigates the potential of ATES applying to DES. To achieve a better performance, the ATES is proposed together with electric power storage for DES. The performance of the proposed energy storage method is evaluated by a case study of campus buildings. The performance of the DES with energy storage is compared with the DES without energy storage by DG utilization rate, operating cost and import feature from power grid.

2. Proposed energy storage for distributed energy systems

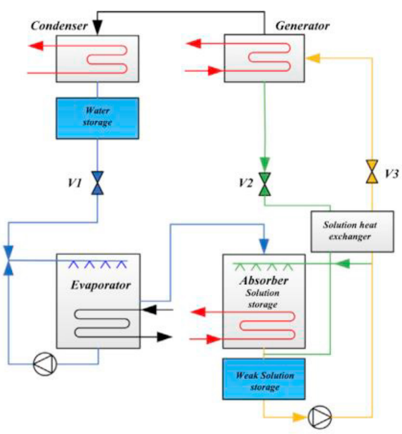

Fig. 1. Schematic of ATES integrated with absorption chiller [6]

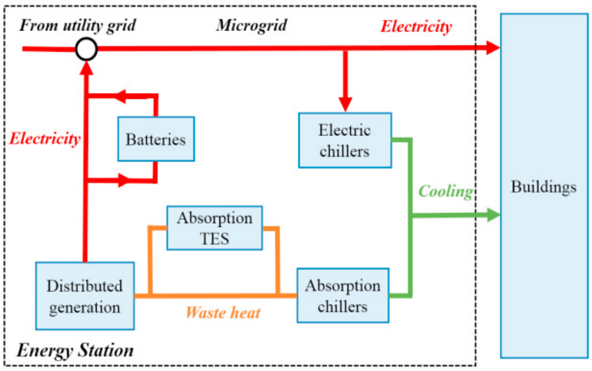

Fig. 2. Schematic of DES with proposed energy storage

The schematic of the ATES which is integrated with absorption chiller is shown in Fig.1. Its working principle is similar to absorption chiller, while a solution storage tank and a water storage tank are added. LiBr/H_2O is adopted as the working fluids in this study. During charging, the water of dilute solution in generator is vaporized by the heat sources like solar energy and waste heat, then the concentrated solution is pumped to solution tank. Energy is stored by the concentrated solution in solution tank. During discharging, the concentrated solution in solution tank is pumped into absorber and absorbs water vapor from evaporator and turns to dilute solution. Cooling energy is released in the evaporator. When there is no thermal energy storage, the system also can serve as an absorption chiller. The energy storage density (ESD) of the ATES is proportional to the concentration difference of the LiBr solution during charging and discharging processes (ΔX), which can be calculated by Eq. (1) [11]. Where Q_e is stored thermal energy, $V_{solution}$ and V_{water} are tank volumes of LiBr solution and water, respectively, X is solution concentration, ρ is density, r is latent heat of water vaporization, s and w represent dilute solution and water, respectively.

$$\mathrm{ESD} = \frac{Q_e}{V_{\mathrm{solution}} + V_{\mathrm{water}}} = \frac{r}{\frac{X_s}{\Delta X \rho_s} + \frac{1}{\rho_s} + \frac{1}{\rho_w}} \tag{1}$$

Fig. 2 shows the schematic of DES with proposed energy storage. The proposed energy storage consists of the absorption thermal energy storage and the electrical energy storage. The battery banks can be used for electrical energy storage. During off-peak hours, the extra electricity generated by DG is stored by the batteries while the waste heat of DG is utilized by the ATES and stored in the solution tank. During peak hours, the stored thermal energy and electricity are released to meet the peak loads of cooling and electricity. Then the energy demand and supply can be balanced and peak load shifting can be also achieved. The performance of energy storage and release of the proposed system in each moment (one hour in this study) can be calculated by the Eqs. (2)-(4). Where C is cooling energy, E is electricity. When E_{grid}=0 in each moment, it means the DES with proposed energy storage can achieve off-the-grid operation. Other detailed formulas of DES can be found in literature [12].

$$C_{\mathrm{total}} = C_{\mathrm{AC}} + C_{\mathrm{EC}} + C_{\mathrm{ATES}} \tag{2}$$

$$E_{\mathrm{grid}} = E_{\mathrm{consumption}} - (E_{\mathrm{generation}} + E_{\mathrm{release}} - E_{\mathrm{storage}}) \tag{3}$$

$$\sum_{k=1}^{24} E_{\mathrm{storage}} = \sum_{k=1}^{24} E_{\mathrm{release}} \ , \quad \sum_{k=1}^{24} C_{\mathrm{storage}} = \sum_{k=1}^{24} C_{\mathrm{release}} \tag{4}$$

3. Case description

To evaluate the performance of the DES with proposed energy storage, a case study is conducted. The case study is conducted by comparing with a referenced DES which serves a group of campus buildings in the Hong Kong Polytechnic University. The campus map is shown in Fig. 3(a). The total floor area of the campus buildings is 252,901 m^2. The schematic of the referenced DES is shown in Fig. 3(b). It is a typical DES which includes distributed generation units, absorption chillers and electric chillers. The capacities of this referenced DES can be found in Table 1. More details of this campus and DES are available in [12]. It can be found in Fig. 3(c) that it still needs to import massive electricity (up to 5000 kW) from utility grid during peak load by employing the referenced DES, which imposes much pressure to the grid.

In the DES with proposed energy storage, the “Hoppecke” battery bank is selected. Each string in parallel consists of 24 batteries. Other details of the battery bank are available in [13]. The concentration difference of the LiBr solution during charging and discharging processes (ΔX) is set as 12% [14], and the energy storage density of the ATES is 151.1 kWh/m^3 which is calculated by Eq. (1). In this case study, the performance of the DES with proposed energy storage will be compared with that of the referenced DES without energy storage in a typical summer day in August 2015. The operation strategy of the DES with proposed energy storage is as follows: During off-peak hours (23:00-08:00), cooling load is supplied only by EC. During peak hours (08:00-23:00), cooling load is supplied by EC, AC and stored absorption thermal energy. The energy storages follow the electricity load of the buildings. The design and operation strategy for the DES with proposed energy storage target the condition of off-the-grid operation meanwhile without energy waste.

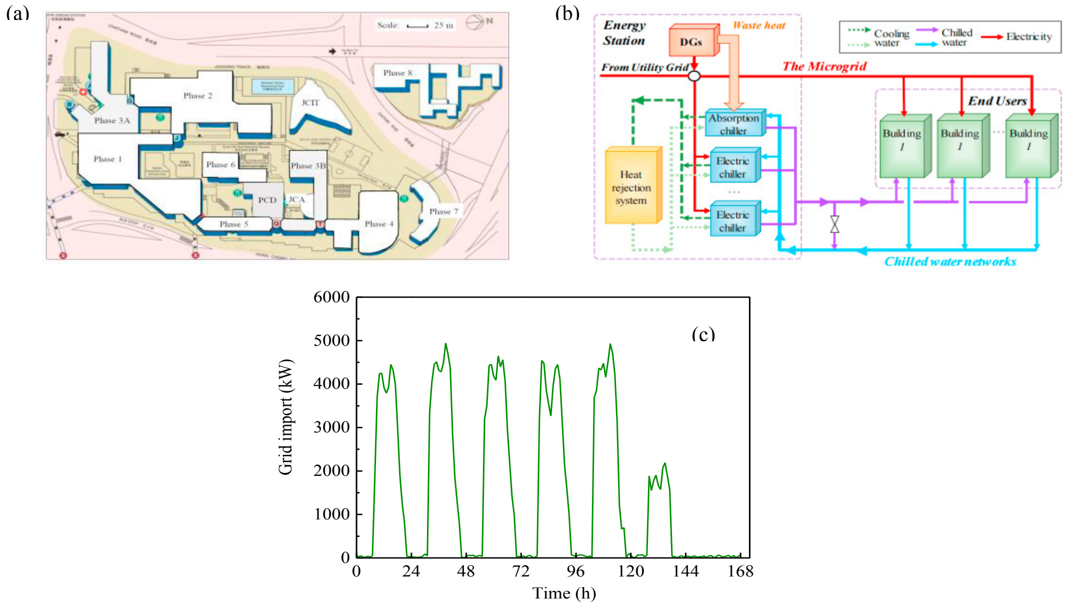

Fig. 3. (a) Campus map; (b) Schematic of DES in [12]; (c) Grid import feature in a typical summer week [12]

4. Results and discussion

Based on the design and operation strategy mentioned in the above sections, the designed capacities of the DES with proposed energy storage are determined to meet the cooling and electricity loads of the campus buildings, which are listed in Table 1. The proposed DES includes the same 2 distributed generation units, 3 less electric chillers and 4 more absorption chillers than the referenced DES, and total installed capacity of the chillers in the proposed DES is 10.3% (3724 kW) less than that of the referenced DES. Besides, the proposed DES includes 10 storage tanks (each is 63 m^3 consisting of LiBr solution and water) and 279 strings of battery bank for energy storage.

Table 1. Capacities of referenced DES and DES with proposed energy storage.

	DG (kW)	EC (kW)	AC (kW)	ATES tank (m^3)	Battery bank (strings)
Referenced DES	5900×2	3980×6	2054×6	0	0
DES with energy storage	5900×2	3980×3	2054×10	63×10	279

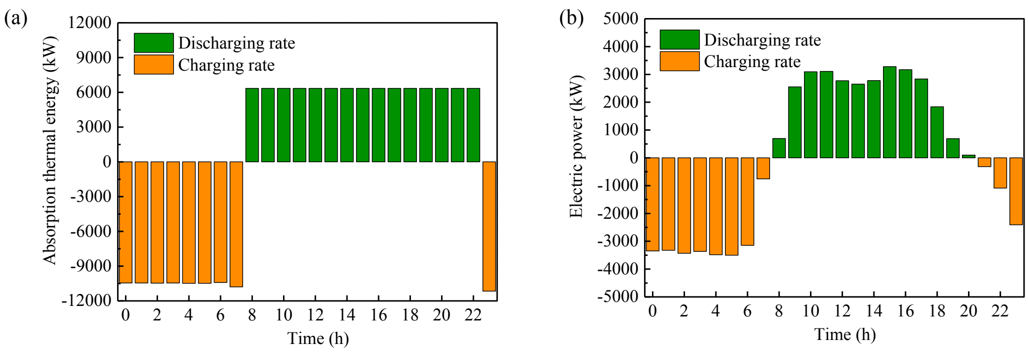

Fig. 4. Charging/discharging profiles of (a) absorption thermal energy, (b) electric power in the DES with proposed energy storage

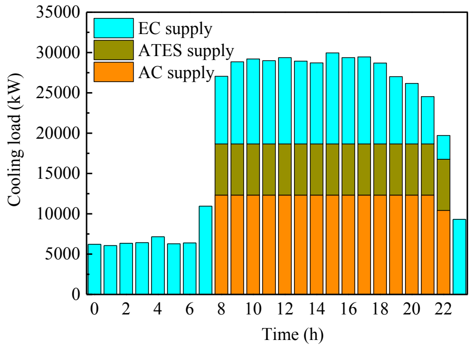

Fig. 5. Cooling load supply by the DES with proposed energy storage

The charging/discharging strategies of the DES with proposed energy storage are shown in Fig. 4. From the charging/discharging profile of absorption thermal energy (Fig. 4(a)) it can be found that 9 hours are used to thermal energy storage and 15 hours are used to release cooling energy. The exhaust heat of the DG has been fully absorbed by the absorption chillers or stored by the ATES during the whole day. While there is a little difference for the charging/discharging profile of electric power (Fig. 4(b)), in which 11 hours are used to electric energy storage and 13 hours are used to release electric energy. This difference is based on the actual electrical load of the campus buildings. The hourly cooling load supply by the proposed DES is shown in Fig. 5. Compared with the referenced DES, the electric chillers in the proposed DES save 17.7% of power consumption due to part of its cooling load is replaced by the ATES during peak hours. Meanwhile, the overall installed capacity of the electric chillers also can be sharply reduced, which has been shown in Table 1.

Generated power of DG in the proposed DES also has obviously increase when compared with the referenced DES, as shown in Fig. 6. The average DG utilization rate increases from 80% to 92.9%, which results in a higher efficiency and eliminating equipment idleness. Compared with the referenced DES, the proposed DES can reduce 12.9% of operating cost. In addition, the proposed DES also can save 3.2% of primary energy consumption and 3.4 % of power consumption than the referenced DES, even though the referenced DES already saved 9.58% of primary energy consumption compared with the centralized energy system [12]. Finally, the grid import profiles of the two systems are compared and shown in Fig. 7. It can be found that imported electricity from grid to the proposed DES is zero in each moment, which means the peak load shifting and even self-sufficient micro grid can be achieved by employing the DES with proposed energy storage. In particular, the self-sufficient micro grid is achieved without any exhaust heat from DG is wasted.

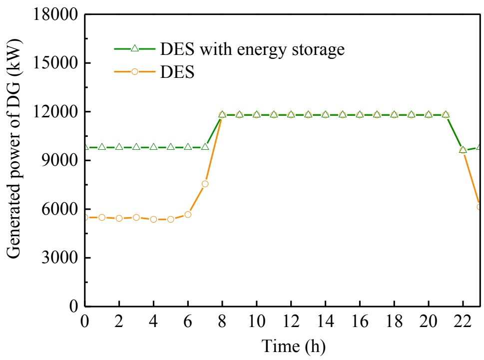

Fig. 6. Comparison of generated power of DG between DES with proposed energy storage and referenced DES

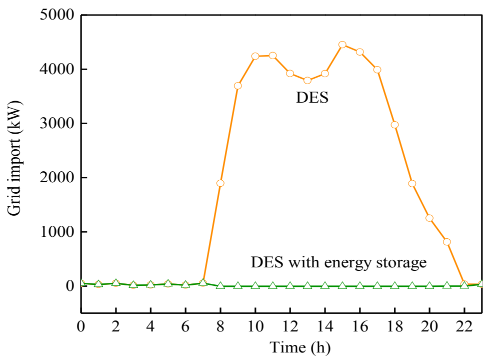

Fig. 7. Comparison of grid import profiles between DES with proposed energy storage and referenced DES

5. Conclusions

An absorption thermal energy storage together with electric energy storage method is proposed for distributed energy system. A case study in a campus is conducted to evaluate the performance of the DES with proposed energy storage. The results indicate that the DES with proposed energy storage has better performance than the referenced DES without energy storage. Conclusions are drawn as follows.

1) The proposed ATES has a much higher energy storage density than chilled water storage. By applying the proposed energy storage, overall capacity of the chillers reduces by 10.3% (3724 kW), power consumption of the electric chillers reduces by 17.7%, comparted with the referenced DES without energy storage.
2) Compared with the referenced DES, the average DG utilization rate of the proposed DES can increase from 80% to 92.9%, operating cost can reduce by 12.9%, and the primary energy consumption as well as overall power consumption can also slightly decrease.
3) Peak load shifting and self-sufficient micro grid can be achieved without energy waste by utilizing the DES with proposed energy storage, which serves as a more efficient and grid-friendly DES.

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