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Design and Performance Analysis of the Distributed Generation System Based on a Diesel Engine and Compressed Air Energy Storage

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Abstract

The distributed generation system coupled with the energy storage system could perform a ‘peak shaving’ function for maintaining a required power output. As a result it decreased the core engine power rating and increased integrated system’s efficiency. In this study a hybrid power generation system integrated with a Compressed Air Energy Storage (DE-CAES) system was proposed. To carry out a technical analysis the design flow chart was designed and process models were developed. The simulation results were also validated by the experiment. The results revealed that integrated system’s efficiency and fuel saving ratio could be increased by 6.5% and 14.4%, respectively.

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Key words: Distributed generation; DE only; Hybrid DE-CAES system; Fuel saving

1. Introduction

Distributed generation (CCHP - combined cooling, heating and power) is being extensively developed with respect to its merits such as high efficiency, low Greenhouse Gas (GHG) emissions and reliability which is more suitable for remote areas than conventional generation plants [1, 2]. A typical distributed generation, as shown in Figure 1 is composed of a diesel engine (DE), an absorption chiller and the waste heat recovery system. Basically, daily demand loads are fluctuated stochastically. Thus the power output from the core engine has to be adjusted to adapt these changes, resulting in an efficiency reduction during the partial rating power period [3,4]. Considering as an effective solution to deal with this problem [5, 6] energy storage could play an important role in “peak shaving” [7]. As one of energy storage technologies, Compressed Air Energy Storage (CAES) can store excessive shaft power through compressed air, and recover the waste heat from the process during the off peak time. During the peak period stored energy is released to generate power, heat and cool. As downgraded the core engine power size, the system integrated with CAES keeps the engine working stably with high efficiency and reduces the fuel consumption [8].

Energy storage is an emerging technology which is attracting much attention from both academic and industrial communities [7, 9]. The CAES technology along with the thermal energy storage technology are considered as the most promising and affordable alternative. Many researchers have been engagingwith the

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electricity "peak shaving", large scale renewable power generation and distributed generation in order to improve the energy efficiency and decrease the GHG emissions [5, 7, 10]. Although the DE integrated with energy storage has been studied numerically, the modelling of the system components are not accurate enough to reveal the system's characteristics, and the dynamic characteristics of the CAES system are not considered.

In this study, the CAES technology is integrated into a diesel engine based distributed generation system. Both DE and CAES systems are modelled and simulated. The CAES modelling is based on the research of a 1.5MW CAES system in Institute of Engineering Thermophysics (IET), Chinese Academy of Sciences. The hybrid system's performance is also compared with the experimental results

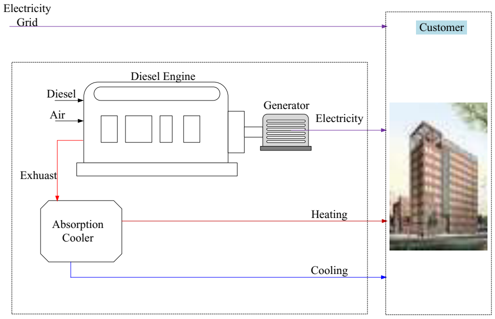

Fig. 1. A typical DG system

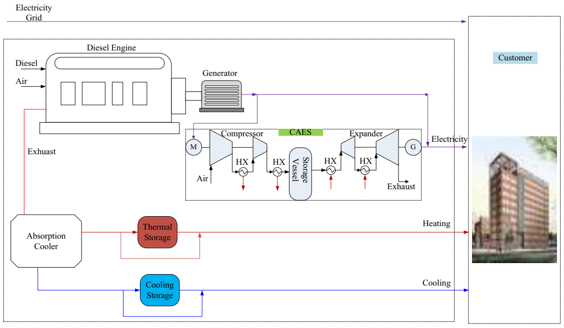

Fig. 2 A DE-CAES generation system

2. System description

The proposed system is illustrated in figure 2. The DE, fueled by diesel to generate power is designed to work at its rated power. The excessive electricity is stored by the CAES system via compressed air during off-peak time. Recovered waste heat (exhaust, coolant water) is stored and then used to heat up the air temperature of the expander in the CAES system during its energy releasing process. Meanwhile stored heat is split to an absorption chiller for generating cooling energy. The rest thermal energy is supplied to customers for hot water or space heating. The cooling and thermal energy storage systems as shown in figure 2 are used to store the abundant cooling and heat of the hybrid system for later use. As a result, it will not be necessary to equip the DE to a community according to the maximum power demand.

The CAES system is composed of a compression unit, heat exchangers, thermal energy storage, compressed air vessel, expanders, motor and generator. The compression unit which consists of 5-stage compressors delivers an air pressure around 10MPa with equal pressure ratio of each stage. The heat produced by compressors is also recovered and stored. The expansion unit which is composed of of 4-stage expanders is operated at 7MPa with an equal pressure ratio for each stage. The inlet air of each stage is heated up by the DE flue gas before expansion.

3. Methodology

3.1. Design flow of the DE-CAES system

The design flow chart of distributed generation integrated with energy storage systems is illustrated in figure 3. the fluctuated load from users is introduced and its initial basic load is calculated with respect to energy storage and energy release processes. Initial energy storage power and energy release power profiles are first calculated based on their models constructed. Energy balance and stored air pressure are compared. If the difference between stored air pressure and release pressure is negative as shown in figure 3, the initial base load is increased by a small step. As result the energy storage and releasing profiles will be recalculated. After converging into zero, the base load rating power, energy storage and release rating powers (*Psr*, *Prr*) are obtained. Once the energy storage and release power (*Ps*, *Pr*) at certain hours are small and unsuitable for compressors and expanders, the base load engine will be adjusted to adapt the requirement. The load factors, α and β are estimated to be 30%. Thus, the power profiles of the core engine, energy storage and release power are obtained and the system's performance will be calculated.

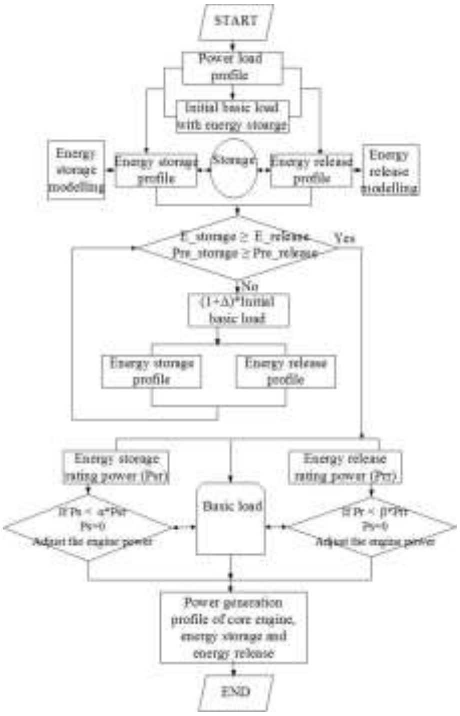

Fig. 3 Design flow chart of the DE-CAES system

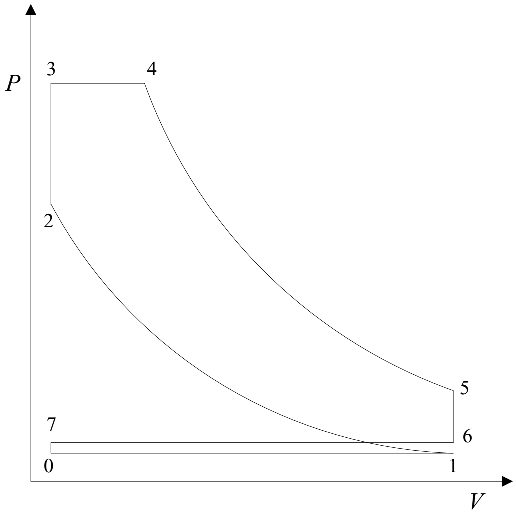

Fig. 4 *P*-*V* diagram of the DE system

3.2. System modelling

3.2.1 Diesel engine

The engine model is developed in terms of dual cycles (limited- and constant-pressure cycle) [11] as shown in figure 4. The ambient air is breathed in the cylinder (0-1) and compressed adiabatically (1-2). It is assumed that diesel is injected into the cylinder which starts to burn at point 2. The fuel combustion first takes place isochorically, raising the pressure (2-3) and then isobarically to a certain temperature (3-4). The combustion gas in the cylinder will drive the piston (4-5) to generate power. Finally, combustion gases are released isochorically (5-6) and then isobarically (6-7) with some residue in the cylinder to start next cycle. The volume ratio (r_{v12}) is set to be 18, and the maximum combustion temperature is around 2200 K. The pressure ratio of point 3 to point 2 (r_{23}) is set by 1.7 at rated power condition. The combustion efficiency and friction coefficient are set by 90% and 0.78 respectively. The heat release coefficient is estimated to be 10% from the working volume surface [11]. The value of r_{23} which changes under part load conditions is calculated according to the experiment results in reference [12]. It is assumed that the pressure at point 6 is 0.5 times higher than that of the ambience. At a part load condition, the engine maitains the same speed in order to maintain the electricity frequency constant. The friction power and heat release are considered as same as the designed condition. Some other thermodynamic equations are also used in the modelling.

3.2.2 CAES system modelling

There are mainly compression, expansion, air storage and heat exchange processes of CAES system. In this study, a 5-stage piston compressor with inter-coolers is used. It is estimated that the power which is proportional to the air flow rate will not be changed when the outlet pressure is changed [13]. A 4-stage turbine expander with inter-heaters is designed for power production. To keep the power frequency constant, the expander is designed to rotate at a constant speed with a sliding pressure mode to adjust power generation. The compressed air is stored in a steel vessel with constant volume and its heat exchange coefficient is assumed based on an experiment results (K_v=34.4W/m^{2}K). The storage models are constructed based on references [13, 14].

3.2.3 System integration

The evaluation indicators are presented below. They are DE efficiency, CAES efficiency without and with consideration of the waste heat reuse, hybrid DE-CAES system efficiency and fuel saving ratio.

$$\eta_{tDE} = \sum Po_{DE} * t \Big/ \left(\sum m_f * LHV \right) \tag{18}$$

$$\eta_{CAES1} = \sum Po_{\mathrm{ex}} * t \Big/ \left(\sum Po_{cp} * t \right) \tag{19}$$

$$\eta_{CAES2} = \sum Po_{\mathrm{ex}} * t \Big/ \left(\sum Po_{cp} * t + \sum Ex_{hex} \right) \tag{20}$$

$$\eta_{DECAES} = \left(\sum Po_{demand} * t \right) \Big/ \left(\sum m_f * LHV \right) \tag{21}$$

$$\xi_{fs} = \left(\sum m_{fDE} - \sum m_{fDECAES} \right) \Big/ \left(\sum m_{fDE} \right) \tag{22}$$

3.3 Experiment of the CAES expander

A 4-stage air expander experiment system with inter-heaters is constructed and tested in IET, China. The generated power is measured by a hydraulic dynamometer. The expander's performance has been tested under various inlet pressures.

4. Results and Discussion

4.1. Comparison of Experiment and Simulation

Figure 5 shows both measured and simulated results of the expander. The first one presents the power generation as a function of the inlet pressure, and the second one illustrates the ratio of the pressure ratio to rated values of each stage as a function of inlet pressure. It could be seen that the simulated results were in good agreement with the experimental results, which indicated that the expander modelling was consistent and acceptable.

4.2. Simulation Results and discussion

Figure 6 shows a load profile of a school. It could be seen that each type of the load (power, cooling, heating) was fluctuated very much diurnally and nocturnally. If the core engine was selected according to the maximum value, most of the time it would work under partial load with relatively low efficiency. The rating power was obtained through the design flow chart of figure 3, and parameters of the proposed system was given in table 1. One could see that the power rating of the core engine was downgraded by 35.3%.

The load profile of each sub-system is shown in figure 7. It could be seen that the diesel engine operated stably in a whole day. The compressor mainly worked during the night time (off-peak time) while the expander performed mainly during the daily time (peak time) to consume the stored energy by compressor. Since the expander of the CAES system generated power according to the demand, it had to work with various inlet pressure (sliding pressure mode). The power generation and pressure ratio of each stage is shown in figures 8 and 9. The power generation of first 3 stages changed synchronically, while the fourth stage was slightly different. It could be explained in figure 11 that the pressure ratio of the first 3 stages did not change much, while the fourth stage changed apparently.

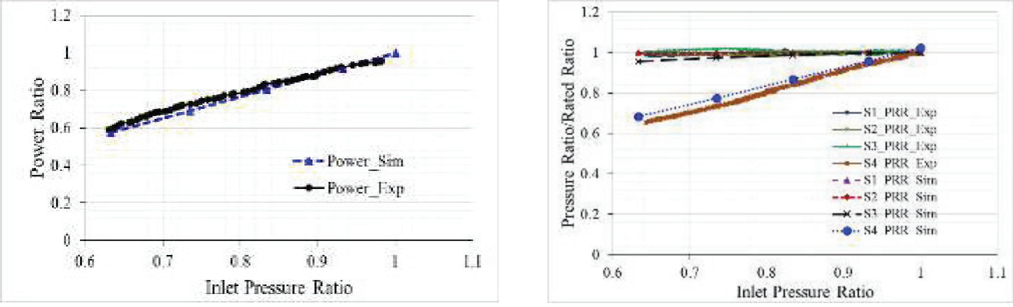

Fig. 5 Experiment and simulation comparison of the expander

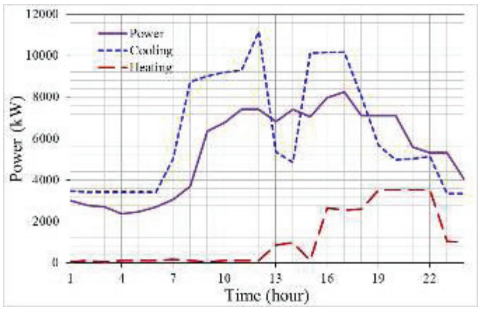

Fig. 6 Load profile of a school

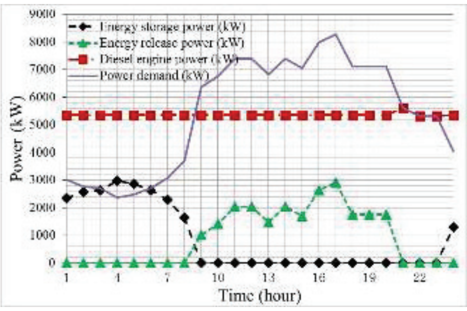

Fig. 7 Power output of each unit of the hybrid system

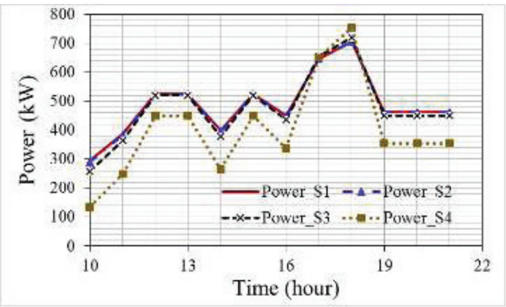

Fig. 8 Power output of each stage of the CAES expander

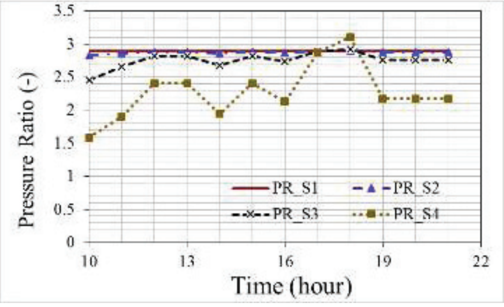

Fig. 9 Pressure ratio of each stage of the CAES expander

Table 1. Parameters of the DE only system and proposed hybrid DE-CAES system

DE only system	DE	Rating power / kW	8266
		Efficiency	44.7%
		Rotation speed / rpm	1000
Hybrid system	DE	DE rating power / kW	5347.3
		Efficiency	44.7%
		Rotation speed / rpm	1000
	CAES	Energy storage rating power / kW	2977.34
		Energy release rating power / kW	2918.66
		Design pressure ratio	70
		Inlet temperature / K	700
		Compressor efficiency	85%

Expander efficiency	85% (1, 2 stages), 86% (3, 4 stages)
Air storage vessel volume / m^3	4975

Table 2 reveals the performance of both DE only and hybrid DE-CAES systems based on a diurnal cycle of 24 hours. The total efficiency of the DE only system was 38.67% (integrated system 1) which was much lower than its rated efficiency (44.7%). For the hybrid DE-CAES system, the core engine efficiency was around its rated efficiency of 44.7%. The efficiency of the CAES without and with consideration of the waste energy utilization from the DE exhaust were 106% and 64.2%, respectively. The integrated exergy efficiency of the hybrid DE-CAES system was 45.18% (integrated system) which was higher than the DE rated efficiency. The fuel saving ratio of the hybrid system was 14.41%. If the cooling and heating demand was taken into account, this would be 12.7%, while the cooling power was generated by the electricity with COP of 4.5 and the fuel-to-electricity efficiency was estimated by 44.7%.

Table 2. Performance of the DE only system and proposed hybrid DE-CAES system

Mode	DE only	DE in hybrid system	CAES		Integrated system	Fuel Saving Ratio 1	Fuel Saving Ratio 2
			I	II			
Efficiency	38.67%	44.7%	1.06	64.2%	45.18%	14.41%	12.7%

5. Conclusion

A design methodology of distributed generation combined with compressed air energy storage was developed and a case study was carried out. In the hybrid DE-CAES system, the CAES expander could work in a sliding pressure mode to fulfill the power demand of the customer. The modelling of the expander was also verified by the IET expander platform. Based on the results from technical and experimental analyses the following conclusions can be drawn.

(1) When introducing energy storage system, the power rating of the core engine of the distributed generation system can be downgraded by 35.3% and the system can be operated stably with high/rated efficiency.
(2) The efficiency of hybrid DE-CAES will be improved by 6.5% which is more efficient than the DE only system. Furthermore, the fuel saving ratio can be increased by 14.41%.

Acknowledgements

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Biography

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