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## Article

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## Active regulation for improving the off-design conditions of distributed combined cooling, heat and power system

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### Abstract

This paper briefly introduces the characteristics of Distributed Combined Cooling, Heating and Power (CCHP) System, and indicates that the off-design conditions are the root cause of the performance reduction of system. An active regulation method based on system performance improvement is proposed in this paper, including component regulation method at the unit equipment level and unit equipment regulation method at system level. In addition, the study focusing on the impact of energy storage active regulation at system level on system performance is performed on the 100 kW experimental platform. The experimental results show that: the active regulation method in all conditions of system, compared with conventional generation system, has a primary energy saving rate of 76%, and a relative energy saving rate of 29.5%, and the system performance is significantly improved.

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**Keywords:** Distributed energy system; Combined cooling; Heating and power (CCHP); Off-design conditions; Active regulation; Energy storage / cool storage

### 1. Introduction

Distributed energy system is a kind of energy supply method close to the users. It emerged in western developed countries in the 1970s. Due to advantages of energy saving, environmental protection, economy, reliability, flexibility and intelligent operation, all countries around the world are promoting the construction of the distributed energy system [1–5]. Distributed energy system is mainly in the form of combined cooling, heating and power (CCHP), which, as a new generation energy supply mode, is an important supplement to the traditional centralized large-scale energy supply mode. It has the following four main features: (1) Direct energy supply to users nearby. According to

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the user's demand, the energy supply system is built in the vicinity of the user, which simplifies the system energy transmission links, thereby reducing the energy loss during the transmission process and also the transmission cost, and improving the safety of the energy supply to users; (2) Small scale. It is mainly designed to meet the needs of local energy users, so the system has medium and small capacity compared with the traditional centralized energy supply system; (3) Multi-energy output of cooling, heating and electricity can meet the various energy needs of users at the same time; (4) CCHP system is in line with the "suitable temperature, cascade utilization" principle of integrated energy system, various grades of energy in the system will realize cascade utilization.

As one of the future energy development trends, the promotion of CCHP system can greatly alleviate many problems encountered in energy generation and utilization, such as environmental protection, safety, energy conservation, etc. However, as a complex system consisting of multiple subsystems, it is still in a stage of rapid development. The integration of different subsystems such as power, cold, heat and electric control, off-design conditions and how to meet building requirements still require further researches [6–11]. In addition, the distributed system has low single-unit capacity and low single-unit efficiency, and its off-design conditions will also lead to system performance reduction. The working state of a gas turbine is not only related to the characteristics of its components, but also to characteristics of the load it drives. The distributed CCHP system is a direct user-oriented energy supply system, which is mainly used in the field of energy supply for buildings. In a building, cooling and heating load takes up a considerable proportion of the total building energy consumption, and the requirements for cooling and heating loads have close relation with the type, location, cycle and ambient temperature of the user's life and work. Buildings with different functions or in different regions require different cooling and heating loads. Even for the same building, the load required in different months, at different times of the day is different. It can be seen that the typical load curves of various buildings vary widely, as shown in Fig. 1 [12]. If these "unsteady demand" cannot be carefully analysed, and a plan corresponding to the energy supply system load variation is not made out separately, it will result in "undersupply" or increased energy consumption instead of energy saving. In the past ten years, the research team has undertaken the national "973" projects, projects of National Natural Science Foundation of China and provincial and municipal research projects on the integration of distributed energy systems and improvement of off-design conditions, and made some fruitful progress. This paper studies the active regulation of distributed CCHP system, in order to improve the performance of the system in all conditions.

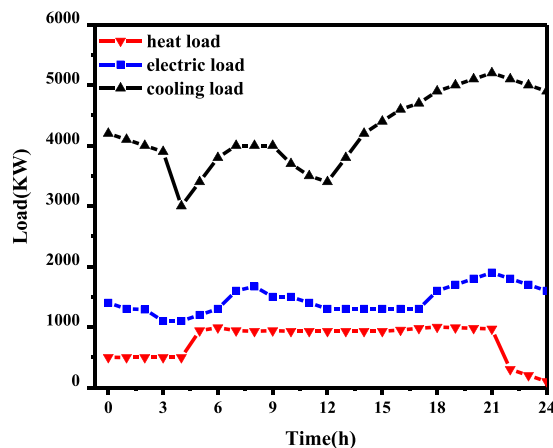


Fig. 1. Thermoelectric load demand of a summer typical daily user.

## 2. System off-design conditions analysis and active regulation strategy and technology

Off-design conditions result in reduced power system efficiency (including diesel and gas turbines), as shown in Fig. 2. The main causes for the performance reduction of the gas turbine system are as follows: (1) The temperature of the turbine inlet decreases in off-design conditions, causing the thermal energy grade at the source to decrease and the system cascade utilization to deteriorate; (2) There is a large energy grade difference between the internal medium temperature flue gas grade of the gas turbine CCHP system and the thermal energy grade required by

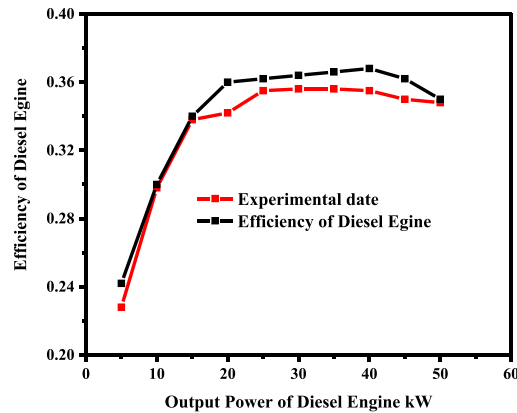


Fig. 2. Change of diesel engine efficiency with output power.

the LiBr absorption refrigerator, that is, the cyclic coupling between the Brayton cycle of the gas turbine and the absorption refrigeration cycle is not appropriate; (3) the gas turbine power generation efficiency decreases in off-design conditions, resulting in system performance reduction; (4) The cooling and heating loads of the system do not match the user's load. When the output is too large, energy is wasted. When the output is too small, additional heat is required or electricity is input from the grid.

To solve the performance deterioration problem caused by the off-design conditions of gas turbine distributed CCHP system, a combined active regulation idea is proposed to try two active regulation methods for improving the off-design conditions of the system: First, the component regulation at the unit equipment level, i.e., compressor inlet air control (turbine air flow regulation) and gas turbine flue gas reinjection control (by increasing compressor inlet temperature); second, unit equipment regulation at system level, that is, to add the energy storage system in the system, as shown in Figs. 3 and 4. This paper focuses on the improvement of system performance by active energy storage regulation, and discusses the effect of active energy storage regulation on the performance enhancement of distributed CCHP system in all conditions.

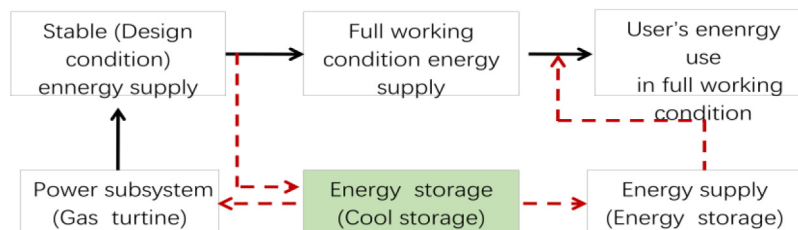


Fig. 3. CCHP system of active regulation with storage energies.

### 2.1. Characteristics of system off-design conditions

The off-design conditions of gas turbines can lead to a significant performance reduction in distributed CHP systems [11–16]. The working state of a gas turbine is not only related to the characteristics of its components, but also to the characteristics of load it drives. The distributed CCHP system is a user-oriented energy supply system, which is mainly used in the field of energy supply for buildings. In a building, cooling and heating load takes up a considerable proportion of the total building energy consumption, and the requirements for cooling and heating loads have close relations with the type, location, cycle and ambient temperature of the user's life and work. Buildings with different functions or in different regions require different cooling and heating loads. Even for the same building, the load required in different months, at different times of the day is different. It can be seen that the typical load curves of various buildings vary widely. If these “unsteady demand” cannot be carefully analysed, and

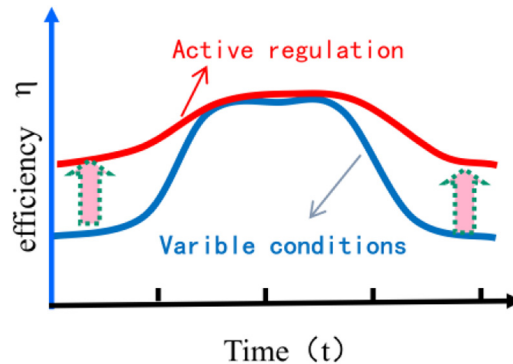


Fig. 4. Performance change curve of active energy storage control system.

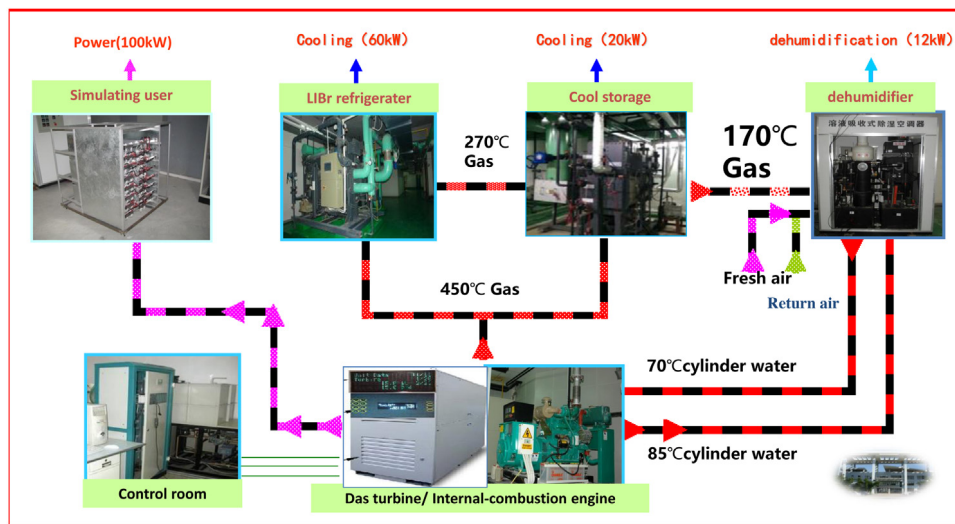


Fig. 5. 100 kW level experimental system with active regulation of energy storage.

a plan corresponding to the energy supply system load is not made out separately, it will result in “undersupply” or increased energy consumption instead of energy saving.

## 2.2. System-level regulation strategies based on system performance improvement

The off-design conditions of distributed energy systems are the direct cause of system performance reduction. To solve this problem, we have studied the active regulation strategy and mechanism of all conditions of the system through system energy storage, in order to improve the regulation potential of the energy supply side to the system’s off-design conditions. On the basis of studying the real-time nature of the user load and its impact on the performance of the power subsystem in all conditions, the energy storage subsystem is added to the energy supply system. Through the use of active energy storage control means, the performance of the distributed system is expected to be improved. The 100 kW experimental research platform with energy storage subsystem designed and constructed by ourselves has components as follows : a power system comprising of 30 kW gas turbine (CAPSTONE30) and 50 kW internal combustion engine (CWDR50-85 /70), 60 kW flue gas complementary combustion type LiBr absorption refrigeration unit, 12 kW absorption refrigeration cylinder liner hot water dehumidifier (homemade), 100 kW Diesel engine simulation load (electric hot water boiler) , 20 kW phase change energy storage (cold storage) device and so on, as shown in Fig. 5.

Experimental results show that: after the active energy storage regulation is applied to the system, the COP of absorption refrigeration (heat pump) driven by residual heat reaches 0.672, and its energy efficiency is increased by 19%–30% compared with the traditional method, and the energy utilization rate of the flue gas is increased by about 10%, achieving efficient and full utilization of the waste heat; compared with the conventional generation system, the primary energy utilization rate of the combined system with active energy storage regulation is 76%, and the relative energy saving rate is 29.5%. It can be seen that the energy storage system can effectively alleviate the problem caused by the mismatch between energy supply and user demand in the CCHP system. Through the coordination of the power subsystem and the energy storage subsystem, it can be ensured that the power subsystem always operates under high-efficiency condition to obtain stable power output, and the extra energy is stored in the energy storage device. At peak load, the energy storage device releases stored energy so that the unit does not need to be overloaded.

### 3. Results

Compressor inlet air regulation, that is, turbine air flow regulation. A throttle valve is installed at the air inlet. After the air is throttled, the density becomes smaller, the pressure is lowered, the exhaust gas temperature of the gas turbine is increased, and the residual heat grade is improved, which is convenient for the waste heat utilization in the downstream of the CCHP system. Under partial load, the energy conservation of the system is significantly improved, and the range of operating conditions for energy-saving operation of the system is expanded. As to regulation of the gas turbine flue gas reinjection, part of gas turbine exhaust is mixed with compressor inlet air, resulting in the increased compressor inlet temperature and the turbine exhaust gas temperature, and higher waste heat grade, thus to facilitate waste heat utilization in the downstream of CCHP system. The relative energy saving rate has been improved, and the off-design condition range for energy-saving operation of the system has also been expanded.

The active energy storage regulation at system level, through the coordination of the power subsystem and the energy storage subsystem, can ensure that the power subsystem always runs under high-efficiency conditions to obtain stable power output, and the extra energy is stored in the energy storage device. At peak load, the energy storage device releases stored energy so that the unit does not need to be overloaded. Theoretical research shows that compared with the traditional regulation methods, the active regulation method can significantly improve the energy-saving performance of the CCHP system in off-design conditions. For distributed CCHP system, off-design condition is an important feature, and also is the root cause of system performance reduction. The research shows that the active regulation method can significantly improve the performance of the CCHP system, and greatly increase the primary energy utilization rate and relative energy-saving rate. The waste heat of flue gas is used for refrigeration, and the waste heat of medium- and low-temperature flue gas and the hot water of cylinder liner are used for dehumidification, implementing the energy use principle of “suitable temperature, cascade utilization”, which improves the primary energy utilization rate and the relative energy saving rate of the system.

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