Dean&Francis
ISSN 2959-6157

The importance of Gas Turbines on Combined Cycle Power Plants

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Abstract:
Combined cycle power plant is a highly efficiency power generation facility that improves energy utilization efficiency by integrating two or more different thermal cycle processes. Generally speaking, The steam turbine is the most significant part of a combined cycle power plant. Gas turbines, as thermal engines, can convert the thermal energy generated by fuel combustion into mechanical energy. This paper systematically analyzes various types of gas turbines applied in combined cycle power plants. It details the structural features, working principles, and the respective advantages and disadvantages of heavy-duty, aviation-derived and micro gas turbines. Additionally, it explores optimization methods covering thermodynamic cycle, system integration, and control strategies, as well as the impact of component structure, materials, and fuels on performance. The role of AI in enhancing gas turbine operation, including fault prediction, parameter optimization, and design assistance, is also discussed. The study concludes that diverse gas turbines serve different energy demands, and continuous optimization and AI integration will drive their more efficient and sustainable development.

Keywords: Gas turbines; Combined cycle power plants; optimization.

1. Introduction

The earliest notices of heat engines are found in the “Pneumatics” of Hero of Alexandria, which dates from the year 200 B.C [1]. One of the steam or motive power engines there mentioned is the Æolipiles, a steam reaction engine consisting of a spherical boiler pivoted on a central axis beneath which is placed a flame. The steam escapes by bent pipes facing tangentially in opposite directions at opposite ends of a diameter perpendicular to the axis [2].

The gas turbine is a crucial component in a combined cycle power plant. It has an efficient working process and can provide high-temperature and high-pressure exhaust gas for the entire combined cycle during operation [3]. This high-temperature and high-pressure exhaust gas will enter the waste heat boiler, where steam is generated. The generated steam can drive the steam turbine for secondary power generation. In this way, gas turbines have greatly improved the effi-

ISSN 2959-6157

ciency of energy utilization.

In the book “The History of Gas Turbine Development”, it is mentioned that aero gas turbines began to emerge in the late 1970s. Their models include WP6G, WP6G1, etc. These aero gas turbines have been put into use in oilfield areas such as Daqing, Zhongyuan, and Shengli. They are used for power generation, water injection, heating, and can also perform mechanical drive and other tasks It has played a certain role in ensuring the normal production of the oilfield [4]. By the 1990s, there were some representative gas turbine products, such as QD70, QD128 and QD168 gas turbines. Compared with the more advanced gas turbines in the world, the differences between them were not significant [5]. In the field of heavy-duty gas turbines, there were some representative enterprises. Such as GE, Alstom, Siemens, Mitsubishi Heavy Industries, CIS, etc. The mainstream products of these enterprises are E-type and F-type units. Among them, GE holds a 60% share in the global heavy-duty gas turbine market, while the remaining 40% is shared by four other companies. This is achieved by maintaining foreign units such as the 9E and conducting subcontracting cooperation with companies like GE, RR, and SNECMA. We have established a heavy-duty gas turbine manufacturing platform.

2. Advantages and Disadvantages of Each Type of Gas Turbines

2.1 Heavy-Duty Gas Turbine

Heavy-duty gas turbines are a relatively common type of gas turbine in combined cycle power plants. Generally, they are composed of a compressor, a combustion chamber, and a turbine [6]. The function of the compressor is to compress the air, increase its pressure, and then send the compressed air to the combustion chamber. After that, at the combustion chamber, Compressed air will mix with fuel and burn, thus generating high-temperature and high-pressure gas [7]. These high-temperature and high-pressure gases will then enter the turbine, driving the turbine blades to rotate and converting thermal energy into mechanical energy. During the combined cycle, the high-temperature exhaust gas produced by the heavy-duty gas turbine will enter the heat recovery steam generator, where the heat contained in the exhaust gas is utilized to generate steam, which then drives the steam turbine for the second generation of electricity.

2.1.1 Advantages

In terms of high-power output, its single-unit power can reach several hundred megawatts, which can meet the large-scale power generation demands of large-scale combined cycle power plants. The high efficiency is reflected in the fact that the efficiency of combined cycle power generation can reach over 60%, and it operates stably and reliably [8]. This equipment is very suitable for long-term continuous power generation.

2.1.2 Disadvantages

Huge equipment and high investment costs. Long start-up time: It may take several hours from cold start to full-load operation, making it unsuitable for working conditions that require frequent start-stop operations.

2.2 Aviation-Derived Gas Turbine

Aviation-derived gas turbines are a type of machine developed on the basis of aviation gas turbines. Their structural composition is quite similar to that of aviation gas turbines, mainly consisting of high-pressure compressors, high-pressure combustion chambers, high-pressure turbines, and low-pressure turbines [9]. Air is compressed through multiple stages of compressors The compressed air is mixed with fuel in the combustion chamber and then burns. The high-temperature gas will then successively drive the high-pressure turbine to work, and then drive the low-pressure turbine to work. In the combined cycle system, the exhaust gas produced by the aero-derived gas turbine will also enter the waste heat boiler and participate in the steam generation process, thus achieving the utilization of secondary energy.

2.2.1 Advantages

The start-up speed is very fast: it can reach full-load operation within a relatively short period of time and respond quickly to changes in grid load. It is particularly suitable for use as a peak shaving unit. The efficiency is relatively high: it inherits the advanced technology of aviation gas turbines, has a high thermal efficiency, and is relatively small in size. The space it occupies is not very large.

2.2.2 Disadvantages

Relatively lower single-unit power compared to heavy-duty gas turbines, generally around tens of megawatts, making it difficult to meet the full power demand of large power plants. Higher requirements for fuel quality and relatively higher maintenance costs.

2.3 Micro Gas Turbine

The structure of a micro gas turbine is very compact. Generally, it is composed of a centrifugal compressor, a regenerator, a combustion chamber, and a radial turbine. After the air is compressed by the compressor, it is first preheated in the regenerator and then enters the combustion chamber, where it burns together with the fuel [10].

The high-temperature gas produced by the combustion can drive the turbine to do work. In a combined cycle system, the exhaust gas and waste heat produced by micro gas turbines can be used to heat water used in daily life or in small steam systems. This way, cogeneration of heat and power can be achieved, and the overall energy utilization efficiency can also be improved.

2.3.1 Advantages

Small size, light weight, and flexible installation, applicable to distributed energy systems such as CHP for small commercial buildings and communities. Rapid start-up, minimal environmental impact, and low emissions.

2.3.2 Disadvantages

Low power output, typically ranging from hundreds of kilowatts to several megawatts, unable to meet large-scale centralized power supply demands. Relatively lower efficiency, especially when operating alone, though the overall energy utilization efficiency improves in combined cycle CHP mode.

3. Optimization of Gas Turbines

In terms of optimizing the thermodynamic cycle, if one wants to enhance the thermal efficiency of gas turbines, modifying the parameters of the Brayton cycle is a feasible approach. Raising the initial gas temperature is a crucial measure. A higher initial gas temperature will create a greater temperature difference within the cycle, thereby significantly improving the conversion efficiency from thermal energy to mechanical energy. In addition, by reasonably adjusting the pressure ratio of the compressor and optimizing the regeneration cycle, energy loss can be suppressed, and ultimately the overall cycle efficiency can be improved.

System integration optimization refers to the strategy of conducting collaborative optimization for components such as gas turbines, heat recovery boilers, and steam turbines in a combined cycle system. It is necessary to carefully match the parameters of each device so that the waste heat boiler can make the most of the high-temperature exhaust gas emitted by the gas turbine. Once the waste heat boiler has fully utilized these high-temperature exhaust gases, This way, higher-quality steam can be produced, and this high-quality steam can drive the power turbine to generate electricity. In this way, efficient and stepwise utilization of energy can be achieved.

In terms of control strategy optimization, this paper will employ advanced control algorithms such as model predictive control to monitor and adjust the parameters during the operation of gas turbines. This paper will take into account factors such as grid load demand, ambient temperature, and fuel characteristics to make dynamic and fine-tuning adjustments to the turbine's rotational speed, fuel supply, and intake conditions. By doing so, this paper ensures that the gas turbine can operate efficiently and stably under various working conditions, and also reduces the energy consumption and emissions of the gas turbine.

4. Influence of Components and Role of AI in Optimization

Reasonable design of component structure can reduce the resistance encountered by the airflow and improve the efficiency of energy conversion. Take optimizing the flow channel structure of compressors and turbines as an example. Doing so can minimize the vortex and separation of the airflow, thereby reducing the loss of airflow during the flow process. The structural design of the combustion chamber directly affects the mixing of fuel and air as well as the combustion situation. If the structure of the combustion chamber is optimized, it can ensure the complete combustion of fuel and improve the combustion efficiency. The compact structural design can also play a role in reducing the floor space occupied by gas turbines, and at the same time, it can lower the costs required for manufacturing and installing gas turbines.

The application of high-performance materials plays a crucial role in the optimization of gas turbines. After the development of high-temperature resistant alloy materials, turbine blades can withstand higher gas temperatures, thereby enhancing the thermal efficiency of gas turbines. Lightweight and high-strength materials like carbon fiber composite materials reduce the weight of compressors and turbines, and also decrease the inertia of rotating components. The response speed and starting performance of gas turbines have been improved. These materials have excellent corrosion resistance and fatigue resistance, which extends the service life of components and reduces maintenance costs.

Different fuel properties have a very significant impact on the performance and emissions of gas turbines. Clean fuels like natural gas produce relatively less pollutants during combustion and can meet stricter environmental requirements. Natural gas has stable combustion characteristics, which is beneficial for efficient combustion. Unlike clean fuels, inferior fuels like heavy oil Although it has certain benefits in terms of cost, during the combustion process, carbon deposition and corrosion are often caused, which will affect the performance and reliability of the gas turbine. It is crucial to select the appropriate fuel based on its characteristics and optimize the combustion system

ISSN 2959-6157

for enhancing the performance of gas turbines. Additionally, developing new fuels characterized by low or zero carbon emissions, such as hydrogen and biofuels, is a key direction for future gas turbines in the field of sustainable energy development.

Artificial intelligence algorithms will analyze a large amount of operational data from gas turbines, including temperature, pressure, vibration and rotational speed, etc. By doing so, a fault prediction model can be established. By comparing real-time monitoring data with the model, potential faults can be detected in advance, and maintenance work can be carried out promptly to prevent faults from actually occurring. This can reduce downtime and also lower maintenance costs. Neural network models based on deep learning can learn the data characteristics of gas turbines during normal operation and failure, and then accurately predict how long components can still be used, providing a scientific basis for maintenance decisions.

AI can optimize the operating parameters in real time based on the working conditions, environmental factors and load requirements of gas turbines. The AI system will use reinforcement learning algorithms to repeatedly test different operation strategies in the simulated environment to learn the best parameter combination, which can ensure relatively high efficiency under all working conditions. Take the situation where there is a significant fluctuation in the power grid load as an example. At this time, the artificial intelligence system can quickly adjust the fuel supply and intake, achieve a rapid response, and make power generation more efficient.

In the design process of gas turbines, artificial intelligence can assist in optimizing components. Generative design algorithms can automatically generate a large number of design schemes based on requirements and constraints, and then evaluate and screen these design schemes to determine the optimal design. Take the design of compressor blades as an example. AI can quickly generate blade models with different shapes and parameters, and evaluate the aerodynamic performance of these blade models through CFD analysis. Doing so can enhance the quality of the design and also significantly shorten the cycle required for the design to a large extent.

5. Conclusion

In summary, each type of gas turbine heavy-duty, aviation-derived, and micro exhibits unique performance characteristics that make them suitable for specific application scenarios in power generation. Heavy-duty gas turbines dominate large-scale power plants with high power output and efficiency but face challenges in terms of high costs and slow start-up. aviation-derived turbines offer rapid response and good efficiency, ideal for grid peak shaving, while micro gas turbines are well-suited for distributed energy systems with their compact size and low emissions.

Future development of gas turbines should focus on further optimizing thermodynamic cycles, improving material performance, and exploring new fuel options to enhance efficiency and reduce environmental impact. The integration of AI technologies holds great promise, enabling more precise control, predictive maintenance, and innovative designs. Continued research and technological advancements in these areas will be crucial for gas turbines to meet the growing global energy demands sustainably and efficiently.

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