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Backpressure adjustable gas turbine combined cycle: A method to improve part-load efficiency

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ABSTRACT

Nowadays, power demand and supply of the power grid fluctuate constantly for the increasing proportion of the renewable energy. Improving the operation performance of the gas turbine combined cycle (GTCC) power plant at part-load conditions is becoming a very critical problem. An innovative combined cycle solution, called backpressure adjustable gas turbine combined cycle (BAGTCC) with corresponding operation strategies, is proposed in this paper to improve off-design performance by adjusting turbine backpressure. The off-design calculation models of the combined cycle are built and their reliability is verified. The feasibility of this scheme is analyzed with the Mach number of the gas flow in turbine. Then, the part-load operation characteristics of the topping cycle, bottoming cycle and combined cycle of the GTCC and BAGTCC, operating with two different operation strategies respectively, are analyzed and compared. The simulation results show that, the proposed BAGTCC can broaden the load range, where turbine inlet temperature (TIT) maintains its design value, from 100–82.4% to 100–63.7%. The combined cycle efficiency has been improved significantly in that load range, up by 0–0.52 and 0–1.76 percentage points over the two conventional operation strategies respectively. Furthermore, this solution has the ability to adjust the power distribution of topping and bottoming cycle, which means that the heat-to-electric ratio can be adjusted when the bottoming cycle is involved in heating. The energy saving potential of BAGTCC can be increased by broadening the compressor flow adjustment range. In conclusion, backpressure regulating is an efficient method to improve the part-load efficiency of the GTCC.

1. Introduction

Due to the factors of environment and technology, the electricity market is gradually absorbing a large number of renewable energy sources, including solar energy, wind energy, hydropower, biomass energy and other forms of power generation that always follow the load variations on the intra-day, intra-week and seasonal timescales [1,2]. Therefore, there will be a large load fluctuation in the power systems, which will cause fossil-fueled power plants to undergo frequent load change and long-term part-load operation to supply fluctuating back-up power [3–5] and to deteriorate their efficiency [6] and emissions [7]. Compared with coal-fired power plant, gas-fired power plants have higher efficiency, faster load change ability and lower level of pollutant emissions. However, their efficiency decreases faster with the load reduction and their load range is narrower [8]. Therefore, in the future with higher renewables, gas turbine should improve its operating efficiency at part-load conditions to bear peak-shaving tasks frequently [9]. Thus, predicting the operating characteristics and optimizing the operation of the GTCC under part-load conditions are of great significance.

Much theoretical research has been done to simulate the operating characteristics of GTCC power plant components under part-load conditions. Stage stacking [10,11] is a method commonly used for predicting the performance of compressor. Kim et al. [12] proposed an improved method to calculate the specific operating conditions of multistage axial flow compressor using stage performance curves, which can analyze the effect of the inlet and outlet boundary conditions and the inlet guide vane (IGV) angle on operation characteristics effectively. Haglind and Elmegaard [13] employed component maps and turbine constants to predict the part-load performance of the gas turbine respectively. Lee et al. [14] developed a general-purpose gas turbine performance prediction program adopting compressor stage-

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Nomenclature

A	area [m^2]
c	absolute velocity of the flow [m/s]
c_p	specific heat capacity [kJ/(kg·K)]
G	mass flow rate [kg/s]
h	enthalpy [kJ/kg]
h_0^*	stage inlet stagnation enthalpy [kJ/kg]
Δh_S^*	stage isentropic enthalpy drop [kJ/kg]
k_g	thermal conductivity of the gas [W/(m·K)]
L_0	theoretical air quantity [kg/kg fuel]
M_r	average relative molecular mass [g/mol]
m	mass flow of the gas [kg/s]
m_s	mass flow of the steam [kg/s]
n	rotate speed [r/s]
p	pressure [Pa]
P	power [MW]
p_4^*	turbine exhaust stagnation pressure [Pa]
Δp	total pressure of the fan [Pa]
$Q_{ar,net,p}$	lower heating value [kJ/kg]
q_V	volume flow rate [m^3/s]
R	gas constant
T	temperature [K]
T_3^*	turbine inlet stagnation temperature [K]
T_4^*	turbine exhaust stagnation temperature [K]
u	circumferential velocity [m/s]
U	heat transfer coefficient [W/(m^2·K)]
w	relative velocity of the flow in rotor blade [m/s]

Greek letters

α	absolute flow angle
α_a	excess air coefficient
α_k	outlet flow angle when the Mach number is 1.0
β	relative flow angle
γ	adiabatic exponent
δ	yaw angle
η_c	combustion efficiency
η_{IDF}	efficiency of the induced draft fan
η_{tm}	efficiency of transmission equipment
λ	reduced velocity
μ	flow coefficient
μ_g	dynamic viscosity of the gas
ξ	kinetic energy utilization coefficient
π	relative pressure
ρ	density of the gas
φ	velocity coefficient of stator blade
ψ	velocity coefficient of rotor blade
ω	total pressure loss coefficient
Ω	reaction degree

Subscripts/superscripts

a	air
f	fuel
g	gas
in	inlet parameters
out	outlet parameters
r	rotor blade
s	stator blade
T	gas turbine
t_0	ambient condition
t_2	compressor outlet condition
t_3	combustion chamber outlet condition
1	inlet of the blade
2	outlet of the blade
0	design value
*	stagnation value

Acronyms

BAGTCC	backpressure adjustable gas turbine combined cycle
CHP	combined heat and power
GTCC	gas turbine combined cycle
HRSG	heat recovery steam generator
IGV	inlet guide vane
LHV	lower heating value
TET	turbine exhaust temperature
TIT	turbine inlet temperature
VAN	variable area nozzle
VIGV	variable inlet guide vane

stacking method and turbine stage-by-stage model with blade cooling. Alobaid et al. [15] built a simulation model of combined cycle with a triple-pressure heat recovery steam generator (HRSG) using Aspen Plus Dynamics and Apros and verified the accuracy of the results. Zhang et al. [16] analyzed the off-design performance of the bottoming cycle with a triple-pressure HRSG using the method proposed by Ganapathy [17], in which the overall heat transfer coefficients of individual heating surfaces are estimated considering thermodynamic design parameters of HRSG and part-load gas parameters. Haglind [18] built the heat transfer model of heat exchangers, in which the relationship between the overall heat transfer coefficient and the heat transfer coefficient of the gas (steam, water) side and the method to correct the transfer coefficient under off-design conditions for each heating surface were presented. Steam turbine off-design predicting models are often built by the method of Stodola [18,19].

Much work exists for improving the performance of the GTCC power plant at design condition. Recuperated (partial recuperation and fully-recuperation) [20,21] and intercooled gas turbine cycle [22] are the normal methods of thermal system integration aiming to optimize the performance. Gogoi [23] analyzed the performance of an air and fuel recuperated GTCC and the proposed cycle improved the performance compared with non-recuperated GTCC. Several GTCC systems working with partial recuperation are analyzed and optimized in Ref. [21]; the optimal recuperative mass fraction is located at roughly 90%. Kumari and Sanjay [22] compared and analyzed the influence of different operating parameters, compressor pressure ratio, TIT, air-fuel equivalent ratio and residence time on the conventional gas turbine cycle and intercooled gas turbine cycle, and the results show that intercooled cycles are superior to conventional cycles in thermodynamics and emission performance.

The optimizations, aiming to achieve higher operation performance under part-load conditions, mainly focus on compressor variable inlet guide vane (VIGV), turbine variable area nozzle (VAN) and other operation strategies. Kim and Hwang [24] analyzed the operation strategies including fuel flow control, variable speed control and IGV control for single-shaft recuperated gas turbine as well as fuel flow control and VAN control for two-shaft recuperated gas turbine. As the results, variable speed control and VAN control give the best performance characteristics under part-load conditions, respectively. Haglind [18,25] evaluated the effects of the IGV and VAN on gas turbines and combined cycles' part-load performance. As his research, variable geometry generally deteriorates the part-load performance of the gas turbine; however, that of the combined cycle is usually enhanced. Mehrpanahi and Payganeh [26] utilized multi-objective genetic