Research on Optimization of Residual Natural Gas Distribution for Combined Cycle Unit Shutdown Process

An-ping WAN\(^{1,2,*}\), Jian-hong CHEN\(^3\) and Yang-jian JI\(^{1,2}\)

\(^{1}\)State Key Laboratory of Fluid Power and Mechatronic Systems, College of Mechanical Engineering, Zhejiang University, Hangzhou, 310027, China

\(^{2}\)Key Laboratory of Advanced Manufacturing Technology of Zhejiang Province, College of Mechanical Engineering, Zhejiang University, Hangzhou, 310027, China

\(^{3}\)Institute of Thermal Science and Power System, Zhejiang University, China

\(*\)Corresponding author

Keywords: Residual gas distribution, Shutdown process optimization, Combined cycle gas turbine, Gas consumption.

Abstract. Although combined cycle gas turbine (CCGT) has been utilized and studied intensively, little attention was paid on optimizing its shutdown process. Under limited residual natural gas, the optimization of shutdown process of CCGT becomes a problem needed to be solved, and no research has been conducted on solving this particular problem. In this study, the overall performance and characteristics of the shutdown process of CCGT were analyzed and modeled. This model was proposed to allocate gas consumption during shutdown process for creating maximum power generation and maximum economic benefit. Based on the shutdown process model, optimal shutdown scheme was proposed and proved, and optimizing algorithms were developed to facilitate the decision making procedure. The calculations of different load-up rates and load-off rates of CCGT showed that the total power generation is more relevant with the load-off rates rather than the load-up rates. When the residual natural gas volume assumed to be \(10^5\) m\(^3\), the shutdown optimization could generate an extra power of 28.41 MW\(\cdot\)h and an extra profit of 4.79 million Yuan annually. This program was applied on three CCGTs in a power plant in Zhejiang Province, China, as a case study. The testing results proved that the obtained optimization scheme is technically stable and effective in the real working condition. Thus, the model and the optimization algorithms were also valid and feasible for potential applications.

Introduction

Optimization of start-stop process in power generating unit can be defined as: under the premise of safety and other constraints, the procedure of selecting appropriate working units and deciding start/stop points to achieve the minimum gas consumption without compromise desirable power generation during the studied period. For improving China's power transmission capabilities, the construction of large-scale smart power grid is included in the 12\(^{th}\) Five-Year Plan (2011~2015). A smart power grid is a modernized electricity network that delivers electricity from suppliers to consumers reliably in a more economic and environmental-friendly way [1]. The construction of such smart power grid creates a strong demand of acquiring reliable high-capacity power unit for peak load regulation. CCGT is a combination of two technologies: the gas turbine and the steam turbine, as the heat of the exhaust gas from the gas turbine is used to raise steam in the heat recovery boiler for the steam turbine [2, 3]. CCGT is a highly competitive technology which suites for the demand of smart power grid [2, 4]. For CCGT is characterized by high efficiency, high flexibility, fast response, low capital costs, low emissions, shorter construction time and smaller space requirement than that for equivalent coal or nuclear power generating units, CCGT plants provide a more and more sustainable form of electrical energy and its extensive applications are continuously increasing during past decades.
A reasonable scheduling scheme of CCGT can reduce gas consumption and emissions, extend its service time, and bring great economic benefit [3]. Since the increasing application of CCGT worldwide and its distinguishable characteristics compared to traditional power generators, optimizing scheduling scheme of CCGT propose a difficult challenge and has drawn a lot of attentions during past twenty years. Bertini et al [5] applied Fuzzy-logic and evolutionary soft computation to optimize the start-up phase of a combined cycle power plant. Their approach reduced the computational load of simulation running significantly while obtained a better schedule. Besides intensive studies conducted on the startup process of CCGT mention above, genetic algorithms [6, 7], linear programming [8], and non-linear programming [9] were applied on optimizing the scheduling of CCGT or combined cycle power plants (CCPP).

Existing literatures on scheduling optimization of CCGT are mostly focused on optimization of startup process or load distribution, as little attention has been paid on modeling or optimizing its shutdown process. However, the shutdown process is as important as the startup process [10, 11]. Improper shutdown process is costly, harmful and dangerous [11, 12], and the gas used in CCGT is related to the performance and the service time of such combined cycle units [13]. Only a few technologies developed for shutdown process [14], but one of them is focusing on scheduling optimization. This study originally focuses on optimizing the shutdown process of CCGT under limited residual natural gas, with the purpose of achieving maximum power generation and minimum gas consumption. In this study, the characteristics of the shutdown process were analyzed and the shutdown process was modeled. Based on the model, optimal shutdown scheme was proved, and algorithms were proposed for single-unit and multi-units shutdown optimization. A computer program based on the model and the algorithms was developed, then was applied on three combined cycle units in a power plant in Zhejiang, China. The case study results proved the effective and efficiency of the proposed methodology.

**Objective Function of Shutdown Process**

The optimization of shutdown process of CCGT under limited residual natural gas can be defined as: under the constraint that the volume of residual natural gas is constant, determination of shutdown scheme for every involving combined cycle unit via analysis and calculation of all characteristics of those combined cycle units. The purpose of shutdown process optimization is to achieve the maximum power generation and the greatest economic benefit under the premise of safety.

The objective function of shutdown optimization is expressed by the following equation:

$$\max \ E = \sum_{i=1}^{N} \int_{0}^{T_i} P_i(t)dt$$

(1)

The constraints are listed in the following express set:

$$\begin{align*}
F = \sum_{i=1}^{N} \int_{0}^{T_i} f(P_i(t))dt & \leq F_s - F_m \\
\lim_{\Delta t \to 0} \frac{P_i(t+\Delta t) - P_i(t)}{\Delta t} & \geq S_{\text{down}} \\
\lim_{\Delta t \to 0} \frac{P_i(t+\Delta t) - P_i(t)}{\Delta t} & \leq S_{\text{up}} \\
\Delta t & \leq \max_{P_i(t)} \\
p_i \text{min} & \leq P_i(t) \leq P_i \text{max}
\end{align*}$$

(2)

$$f(P_i(t))$$ can be described in quadratic form as shown in the following equation:

$$f(P_i(t)) = a_i P_i^2(t) + b_i P_i(t) + c_i$$

(3)

Decision procedure of optimizing the shutdown process of CCGT with limited residual natural gas can be described as follows: 1. A safe margin natural gas volume is obtained based on the limited residual gas volume; 2. The natural gas volume required for shutdown process is calculated; 3. Whether the optimization is performed or not is based on the obtained required gas volume;
According to requirements of power grid, the shutdown optimization is not appropriate for the unit when the residual gas amount is comparatively large. The key factor in the decision making procedure is to decide whether the residual natural gas volume is suitable for the shutdown optimization application or not. In this study, the upper limit of natural gas volume \(F_{\text{max}}\) is defined as the total natural gas consumption in all CCGTs during the load-up and load-off processes. The lower limit of gas volume \(F_{\text{min}}\) is defined as the total gas volume consumed by all working units during the immediate shutdown process (shutdown from current load). Base load \(P\) is a corrected value based on the designed base load. It is corrected according to temperature, pressure, other environmental factors and running hours under current load in real working condition. The maximum load \(P_{\text{max}}\) is defined as the largest load can be reached in the load-up process based on residual natural gas under the premise of safety. The maximum load equals to the base load if there is sufficient residual natural gas.

The gas consumption characteristic curve can be deduced from shutdown curves. The curve is quite different from traditional steam turbine characteristic curve which is a continuous quadratic function [15]. When the total load of the CCGT is in the range of 130 MW to 240 MW, the load and the gas consumption of the gas turbine remain constant. Since the gas consumption characteristic curve is quite distinguishable, the curve can be expressed in the following set of equations:

\[
\begin{align*}
  f(P_i(t)) = & \begin{cases} 
    a_i P_i^2(t) + b_i P_i(t) + c_i & (P_i(t) \leq P_{\text{SteamStop}}) \\
    C_i & (P_{\text{SteamStop}} < P_i(t) < P_{\text{SteamStart}}) \\
    a_2 P_i^2(t) + b_2 P_i(t) + c_2 & (P_{\text{SteamStart}} \leq P_i(t) \leq P_b)
  \end{cases}
\end{align*}
\]

(4)

**Shutdown Optimization**

**Optimization of Single-Unit Shutdown**

Previous literatures [3] show a positive correlation between power and efficiency of CCGT. When CCGT is running at its base load, the maximum efficiency has reached. To generate more power by using residual natural gas, the following "optimal" scheme is proposed: the current load of the CCGT is firstly increased at the maximum load-up rate till its base load reached, then the unit is running at its base load for a while, and finally it is running down at the maximum load-off rate.

**Optimization of Multi-units Shutdown**

Under the influences of environmental and other factors, the performance of each CCGT in a CCPP is always different [3]. If the natural gas consumed by the less efficient unit can be used by the more efficient unit, the overall efficiency will certainly be improved. Suppose there are \(N\) CCGTs running in a CCPP, a generic optimizing algorithm was proposed and described as the following three steps:

1. **Simulation**: the optimal scheme of “increasing load - keeping base load - reducing load” is assumed to be applied on shutting down every CCGT;

2. **Calculation**: to calculate and to compare their power generation during the optimal shutdown procedure, as performance indexes;

3. **Decision**: the optimal scheme of “increasing load - keeping base load - reducing load” is applied to the CCGT which has the maximum power generation, while the other units have to shut down immediately.

A more detailed optimizing algorithm is described in Fig.1.

At first, the proposed algorithm obtains performance indexes and gas consumption characteristic curves of all involving units by optimal scheme simulations. Necessary operation-relating data is obtained in PI database from SIS system, such as heating value, current load, and running hours.

The gas consumption \(F_i\) and \(F_{\text{j}}\) in load-up and load-off processes of each unit, the total gas consumption \(F_i\) in immediate shutdown process and the gas volume \(N F_{\text{m}}\) needed for \(N\) units splitting safely from system are then calculated. If the given volume of total residual gas \(F_S\) is greater than the sum of \(F_1, F_3, F_i\) and \(N F_{\text{m}}\), then this CCGT can be shutdown using the optimal scheme of “increasing
load - keeping base load - reducing load” which shown in Fig.4. $F_3 - F_1 - F_r - N F_m$ is the volume of natural gas required to sustain running in base load. The power generation in this stage is calculated afterwards. If the given volume of total residual gas $F_3$ is less than the sum of $F_1$, $F_r$, and $N F_m$, then this CCGT cannot reach its base load and can only perform the scheme of “increasing load - reducing load”. The maximum load can be reached in the increasing process is calculated using interpolating method. At the same time, its power generation during load-up and load-off process is calculated.

Figure 1. Detailed algorithm for optimizing multiple-units shutdown.

After calculating and comparing the power generation of all units, the CCGT which has maximum power generation and best comprehensive performance indexes can be found, and then it can perform the optimal shutdown scheme of “increasing load - keeping base load - reducing load” as shown in Fig.3. The other units should perform safe shutdown process immediately from current load. Finally, the power generation, the operating time, the gas consumption and the load of each unit in each period of its shutdown procedure are calculated and plotted.

**Case Study**

The shutdown optimization method proposed has been applied in three CCGTs in a CCPP. In this plant, the operation-relating parameters were set or obtained from PI database as follows:

- $S_{Maxup} = 600$ MW h$^{-1}$; $S_{Maxdown} = 540$ MW h$^{-1}$;
- $LHV_B = 67864.93$ kJ kg$^{-1}$; $LHV = 64817.39$ kJ kg$^{-1}$;
- Surrounding temperature is $20^\circ$C; Pressure is 101.01kPa; Running hour is 2000h, Current loads of three unit are 270 MW, 350 MW and 300 MW respectively.

According to the data shown above and previous literatures [16,17], the base load is correctly from 389 MW to 378 MW. The corrected gas consumption characteristic curve is expressed in the following equation:
Based on the above parameters and equation, when the residual natural gas volume is set at $10^5 \text{ m}^3$, the CCGT#2 has the maximum power generation. Thus, the unit #2 should perform the optimal shutdown scheme of “increasing load - keeping base load - reducing load” shown in Fig.5 while unit #1 and unit #3 should stop immediately.

The relationships between power generation and load-up, load-off rates are plotted in Fig.2 and Fig.3. According to Fig.2, with the increase of load-up rate, the total power generation of unit #2 increases slightly while the total power generation of unit #1 and #3 remain the same since they shutdown immediately at current load.

![Figure 2. Power generation against load-up rates.](image1)

![Figure 3. Power generation against load-off rates.](image2)

Fig.3 shows that with the increase of load-off rate, the total power generation of unit #1 and unit #3 suffer a linear decrease while total power generation of unit #2 has a linear increase. Among different load-off rates, the maximum growth of total power generation is 28.41 MW$\cdot$h. It means that the power generation in the maximum load-off rate is 28.41 MW more than that in minimum load-off rate. Assuming there are 250 shutdowns annually, it will generate more than 7102.25 MW$\cdot$h a year. The current price of electricity is 674 Yuan per MW$\cdot$h in China, thus there will be an annual additional profit of 4.79 million for this CCPP.

Conclusions

This study focuses on optimizing shutdown process of CCGT for maximizing power generation under limited residual natural gas volume. The work itself is original and unprecedented. The following marks are achieved:

1. A shutdown process model for natural gas consumption was proposed based on analyzing performance of CCGT. The purpose of this model is allocating natural gas consumption more efficiently and obtaining the greatest economic benefits with the maximum power generation. This model is designed for one or more combined cycle units, and is corrected according to operation-data in real working condition.

2. Based on the model, an optimal shutdown scheme is proposed: the current load of the CCGT is firstly increased at the maximum load-up rate till its base load reached, then the unit is running at its base load for a while, and finally it is running down at the maximum load-off rate. The optimal scheme was proved mathematically, and algorithms were developed based on the optimal shutdown scheme for dealing with multi-units CCPP.

3. A computer program was developed to realize the shutdown optimization using the developed algorithms. The residual gas volume $F_S$ is identified and used as the decisive factor to perform the
shutdown optimization. Different shutdown processes were illustrated in the shutdown optimizing algorithm of the computer program.

4. The computer program was applied to a CCPP with three CCGTs in Zhejiang. The results show that the total power generation is more relevant with the change of load-off rate rather than load-up rate. Assuming the residual natural gas volume is $10^3$ m$^3$, the new scheme could produce an extra power generation as much as 28.41 MW·h and an extra economic profit as much as 4.79 million Yuan annually.

Acknowledgments

This research is financially supported by the Postdoctoral Science Foundation of Zhejiang Province (BSH1602126), National Key Technology Research and Development Program of the Ministry of Science and Technology of China (2015BAF32B04), National Natural Science Foundation of China (51705455).

References


