Study on dynamic characteristics of micro gas turbine with load mutation of pulse generator

Jiaxing Liu and Xin Fu

College of Energy and Power Engineering, Nanjing University of Aeronautics and Astronautics, Nanjing, Jiangsu, 210016, China.

Email: 530938366@qq.com

Abstract. Because of the sudden load phenomenon of the pulse generator, it is required that the gas turbine, as the primary energy source of the pulse generator, not only has certain stability, but also has good dynamic performance. In this paper, based on AMESim, the dual rotor micro gas turbine pulse generator set is modeled, calculated and studied the dynamic characteristics of the micro gas turbine in the case of sudden change of fuel quantity, and the effects of fuel increasing speed on the dynamic characteristics of gas turbine are studied with three different fuel supply strategies (a), (b) and (c).

1. Introduction

For the requirements of modern war on weapons and equipment, all developed countries in the world have begun to explore new weapon systems, in which the new concept of kinetic energy weapons is particularly respected by all countries. Different from the traditional weapons, the electromagnetic orbital gun uses Lorentz force to accelerate the projectile, which breaks through the theoretical limit of traditional chemical energy to launch the projectile and makes its speed far exceed the muzzle speed of the traditional gun. In recent years, it has been vigorously developed by various military powers [1].

For the weapon system of electromagnetic railgun, high-power pulse power supply is one of its important components. The development progress of high-power pulse power supply is closely related to the further development of electromagnetic railgun and its application in actual combat. Pulse generator is a new type of small pulse power supply which can provide repetitive pulse. In the pulse generator, energy storage and conversion are integrated, and the link between power input and power output of weapon load is reduced [2]. Because of the good power density and energy density of the pulse generator, it has become the key to the actual operation of the electromagnetic rail gun and the first choice of the pulse power supply.

Micro gas turbine generator has been widely used in both military and civil fields because of its small size, light weight, simple structure and only rotating motion in its working process. The output power of micro gas turbine is in the range of 20 kW to 500 kW, which is developing towards 1 MW.
The simple cycle thermal efficiency of micro gas turbine with regeneration can reach 30% - 33% [4]. Considering that the rotor moment of inertia of the pulse generator is large, when the gas turbine is connected with the rotor of the pulse generator, the moment of inertia of the gas turbine will be increased obviously. It is hopeful to solve the primary power supply technology of the micro gas turbine pulse generator set by adopting the dual rotor gas turbine with the artery impulse generator.

In the process of using the micro gas turbine pulse generator, in addition to the good steady-state characteristics and stability of the whole system, it is also required to have fast dynamic response characteristics. The dynamic characteristics of gas turbine will directly affect the stability of the whole unit and the performance of the system. The dynamic characteristic is the unstable transition condition that the unit experiences in the process of starting, stopping, sudden increase and decrease of load from one stable condition to another.

In this paper, the micro gas turbine with regenerator is taken as the research object, the simulation model of the system is established based on AMESim, and the change rule of the internal aerodynamic parameters of the gas turbine is analyzed when the load changes suddenly.

![Figure 1. Micro gas turbine system block diagram.](image)

2. Modeling

In this paper, based on the idea of modularization, AMESim is used to build the gas turbine model. As a system modeling and simulation software based on intuitive graphical interface, AMESim has provided a rich model base in hydraulic, mechanical and other aspects and has been widely used, and now AMESim has Gas Turbine library, which can be used in gas turbine simulation.

Based on AMESim gas turbine system simulation model, the biggest feature is fast development speed and model graphics input, and it has the advantages of high simulation accuracy for the transient change process of fluid, especially for the details of pressure, temperature fluctuation and so on [5].

2.1. Modeling method of gas turbine

In the process of gas turbine operation, it is necessary to calculate the aerodynamic thermodynamic parameters of each component. In the calculation process, the position parameters of each component
are solved according to the common working equation of the engine. In this paper, the chamber method considering the volume dynamic effect is used to solve the problem. This method can eliminate the iterative process in the calculation, shorten the calculation time and ensure the accuracy of the calculation [6].

In the gas turbine model, the pneumatic connection of compressor, combustion chamber, gas turbine, power turbine and other components can be regarded as series connection. Among these components, there is a certain volume of cavity. In the dynamic process of gas turbine, the flow is no longer always balanced, and the pressure in the cavity changes with the flow.

![Diagram](image)

**Figure 2.** Schematic diagram of chamber method.

Suppose that the pressure in the cavity is uniform, expressed as $P$. The working gas is an ideal gas, and the thermal inertia is ignored. The mass conservation should be satisfied in the cavity:

$$V \frac{d\rho}{dt} = W_{in} - W_{out} \tag{1}$$

Where $\rho$ is the density of the gas in the cavity, $V$ is the volume of the cavity, and $W_{in}$ and $W_{out}$ are the mass flow of the ideal gas flowing into and out of the inlet and outlet sections of the cavity, respectively.

And ideal gas should follow:

$$\rho = \frac{p}{R_g T} \tag{2}$$

Formula (1) can be rewritten as:

$$\frac{\partial \rho}{\partial V} \frac{dP}{dt} + \frac{\partial \rho}{\partial T} \frac{dT}{dt} = \frac{W_{in} - W_{out}}{V} \tag{3}$$

Finally, we can get:

$$\frac{dP}{dt} = \frac{R_g T}{V} (W_{in} - W_{out}) \tag{4}$$

In the formula, $P$, $T$, $W_{in}$ and $W_{out}$ are respectively the pressure, temperature and mass flow of the working medium at the inlet and outlet of the chamber, and $R_g$ is the gas constant.

2.2. **Modeling based on AMESim**
The regenerator model includes convection heat transfer module, hot wire conduction module and heat capacity module. The convection heat exchange module represents the heat convection between the gas and the pipe wall, and the heat conduction module represents the heat conduction between the two solid parts of the pipe. In the heat capacity module, the temperature of the material output at each port is the same:

\[
\frac{dT}{dt} = \frac{\sum_{i=1}^{4} \Delta h_i}{m \cdot C_p}
\]  

(5)

And the energy storage in the heat capacity is expressed as:

\[
s_e = m \cdot (h_{spe} - h_{spe0}) - s_{e0}
\]  

(6)

Where \(\Delta h_i\) is the input heat flow of port \(i\), \(C_p\) is the constant pressure heat capacity of the material, \(s_e\) is the energy stored in the heat capacity, \(h_{spe}\) is the specific enthalpy of the current temperature, and \(h_{spe0}\) and \(s_{e0}\) are the energy and specific enthalpy stored in the heat capacity at zero time respectively.

Figure 3. Regenerator model.

Figure 4. gas turbine system model.
2% air leakage is set behind the compressor, which is mixed with the main stream before the gas turbine and after the combustion chamber.

When the gas turbine generator unit operates stably, the following four criteria shall be guaranteed:
(1) The mass air flow through the whole system is constant.
(2) The compressor speed is equal to the gas turbine speed.
(3) The power consumed by the compressor shall be equal to the power produced by the turbine.
(4) The power produced by the power turbine is equal to the power consumed by the load.

2.3. System dynamic characteristic analysis

In the power shaft section of the system, the rotor balance equation shall be met:

$$\frac{dn}{dt} = \frac{900}{J^* n^n} (N_{out} - N_{load})$$

Where $n$ is the output speed of the power shaft; $N_{out}$ is the output power of the power turbine; $N_{load}$ is the power consumed by the load; $J$ is the moment of inertia of the power shaft.

In the dynamic process of sudden decrease of power consumed by load, $\frac{dn}{dt} > 0$, in order to make the shaft speed $n$ return to stability as soon as possible, it is necessary to reduce the output power immediately. The best way to reduce the output power is to reduce the total enthalpy of gas working medium rapidly. There are two ways to reduce the total enthalpy of the working medium, one is to set a vent valve behind the compressor to reduce the mass air flow through the gas turbine, the other is to reduce the amount of fuel in the combustion chamber. In the process of changing the amount of fuel, it should be ensured that lean flameout will not occur.

When the power consumed by the load suddenly increases, $\frac{dn}{dt} < 0$, the output speed of the power shaft decreases, it is necessary to immediately increase the amount of fuel injected into the combustion chamber and increase the total enthalpy of the working medium, so as to increase the output power of the power turbine and make the speed return to stability. In the process of increasing the fuel quantity, first of all, it is necessary to prevent the fuel rich flameout caused by the rapid increase of fuel. More importantly, it is necessary to prevent the over temperature protection triggered by the high temperature after the combustion chamber from stopping, or even damaging the turbine blades.

3. Dynamic characteristics of micro gas turbine

In this paper, two examples are given to show the dynamic performance of gas turbine system, including the influence of sudden increase and decrease of fuel quantity on gas turbine. In these two cases, the dynamic process of the key aerodynamic thermodynamic parameters of gas turbine with the sudden change of fuel quantity is studied. In addition, three different fuel supply strategies (a), (b) and (c) are used to study the effect of fuel increase speed on the dynamic characteristics of gas turbine.

3.1. Instantly increase the fuel supply

The dynamic change process of gas turbine is simulated when the fuel supply suddenly increases by 30% in standard condition. The change rule of fuel is shown in Figure 5. Figure 6-9 shows the changes
of gas turbine speed, mass air flow (W), turbine front temperature (T4), power turbine exhaust temperature (TET) and power turbine output power (Nout) with the sudden increase of fuel. The whole system returned to stability in about 2s after fuel sudden increase.

Figure 6 and figure 7 respectively show the change of gas turbine speed and air mass flow with time. When the fuel mass flow suddenly increases, the output power of gas turbine increases, which makes the power generated by gas turbine greater than that consumed by compressor. These extra power is used to increase the speed of main shaft, while the speed increases, more air enters the gas turbine, and the mass air flow also increases.

![Figure 5. Variation of fuel mass flow vs. Time.](image1)

![Figure 6. Variation of Gas turbine speed vs. Time.](image2)
Figure 7. Variation of mass air flow vs. Time.

Figure 8. Variation of T4 and TET vs. Time.
Figure 8 shows the change of gas turbine pre turbine temperature and power turbine exhaust temperature with time. In the process of fuel increase, the gas turbine pre turbine temperature and power turbine exhaust temperature should be increased. However, it is worth noting that in the process of fuel sudden increase, both of them are increased first, then decreased, and finally returned to stability. This is because the speed of fuel increase is very large, and the increase of gas turbine speed is very slow compared with the increase of fuel. The sharp increase of fuel-air ratio in this process causes the temperature to rise very fast. With the gradual increase of gas turbine speed, the air mass flow increases, the fuel-air ratio decreases, and the temperature in front of gas turbine and the exhaust temperature of power turbine decreases. Finally, the whole system returns to stability.

In this example, the initial temperature of the gas turbine is 1177K, the stable temperature is 1285.5K when the fuel quantity increases, and the maximum temperature reached in the process of first rising and then falling is 1372.4K, which is 86.9K more than the stable temperature, about 80% of the temperature rise. The initial temperature of the exhaust gas of the dynamic turbine is 781.5K, the stable temperature is 819.3K, and the maximum temperature reached is 901K.

Figure 9 shows the change of power output of power turbine with time. In the process of sudden increase of fuel quantity, with the instantaneous increase of exhaust temperature of gas turbine, the instantaneous increase of inlet temperature of power turbine makes the output power of power turbine reach a stable state after a step increase, and finally after about 2s.

3.2. Instantly decrease the fuel supply
Assuming that the fuel mass flow suddenly decreases by 30% under standard conditions, the fuel mass flow changes with time as shown in Figure 10. Because the change rule of the system parameters is similar to that of the previous fuel increase process, it will not be further described in this section.

With the decrease of fuel supply, the decrease of power from gas turbine makes the main shaft speed of gas turbine decrease, which leads to the decrease of mass air flow and power output of power turbine. The initial exhaust temperature of gas turbine and power turbine is 1177K and 781.5K.
respectively, and the lowest process temperature is 981K and 653.6K respectively. Finally, the exhaust temperature is stable at 1087K and 782.6K.

**Figure 10.** Variation of fuel mass flow vs. Time.

**Figure 11.** Variation of Gas turbine speed vs. Time.
Figure 12. Variation of mass air flow vs. Time.

Figure 13. Variation of T4 and TET vs. Time.

Figure 14. Variation of power turbine output power vs. Time.
From figure 11 to figure 14, it can be seen that the system is stable about 7s after the change of fuel mass flow, while it only takes about 2s for the system to recover stability in the process of fuel increase. This is because after the decrease of fuel quantity, the power capacity of gas turbine decreases, making the spindle speed change slower than that in the process of fuel increase. Other aerodynamic and thermal parameters of gas turbine are similar to the change rule of gas turbine speed speed.

3.3. Dynamic characteristics of gas turbine at different speed of increasing fuel

In order to study the phenomenon that the temperature in front of the gas turbine rises first, then decreases, and finally reaches a stable state, resulting in a temperature spike. The following three fuel supply strategies (a), (b) and (c) are used to study the temperature change with time before the gas turbine. Scheme (a) is the case of fuel sudden increase of 30%, scheme (b) is that fuel supply increases by 30% from 1s under standard working condition, and scheme (c) is that fuel increase time is 2s. Their fuel mass flow change with time is shown in Figure 15.

![Figure 15. Variation of fuel mass flow in three strategies vs. Time.](image1)

![Figure 16. Variation of T4 in three strategies vs. Time.](image2)
Figure 16 shows the change of temperature in front of gas turbine with time under three fuel supply strategies (a), (b) and (c). With the slowing down of fuel increasing speed, the rise of fuel-air ratio is not so sharp, and the peak of temperature curve in front of gas turbine is also gradually reduced. With the increase of main shaft speed of gas turbine, the air mass flow is gradually increased, and the temperature in front of turbine is stable. But when the peak of temperature curve before gas turbine is eliminated, the stable time of gas turbine will increase. Under the (a) fuel supply strategy, the maximum temperature in front of the gas turbine is 1372.4K, and the stable time of the gas turbine is about 2s. Under the (b) fuel supply strategy, the maximum temperature in front of the gas turbine is 1315.7K, and the stable time of the gas turbine is about 2.5s. Under the (c) fuel supply strategy, the maximum temperature in front of the gas turbine is 1298.7K, and the stable time of the gas turbine is about 3s.

4. Conclusion

Based on AMESim software, the simulation model of micro gas turbine pulse generator set is established. According to the sudden change of gas turbine load, the change of fuel quantity is taken as the solution. The following conclusions are obtained from the simulation calculation of the dynamic process of gas turbine during the change of fuel mass flow:

(1) In the process of sudden increase of fuel quantity, the speed of gas turbine, mass air flow and output power of power turbine all increase immediately, while the temperature before gas turbine and exhaust temperature of power turbine will rise first, then fall down, and finally reach a steady state, resulting in a curve peak process, and the gas turbine unit will reach a stable state after about 2s. In the process of sudden decrease of fuel quantity, the conclusion is similar to the former, except that the stabilization time of the system is longer than that of the case of sudden increase of fuel quantity, and the stabilization time is 7s.

(2) In the process of fuel sudden increase, the temperature in front of the gas turbine increases first and then decreases. Three different fuel supply strategies (a), (b) and (c) are used for simulation. It is found that with the decrease of fuel increasing speed, the peak height will gradually decrease, but at the same time, the stability time of the system will also be longer. In the design of the controller, it should be considered that the peak height will not reach the turbine blade over temperature protection, and at the same time, the stability time of the system should be reduced as much as possible.

Reference

[1] Liu Qing. 2012 Simulation Research on Railgun Load of the Pulse Alternator Harbin Institute of Technology
[2] Ye Caiyong, Yu Kexun, Liu Xiaoxu. 2008 High Voltage Engineering 02 373-6
[3] LI Zheng,WANG De-hui,XUE Ya-li,LI Dong-hai.2005 Chinese Journal of Power Engineering 25 13-7
[4] Zhang Haozhi. Micro Turbine Summary Survey Tsinghua University 2000(6)
[5] REN Xinyu,Guo Yingqing,Yao Huating. 2004 A Simulation of Anti-surge Regulator Performance for the Aero-engine using AMESim Journal of Aerospace Power 19(4)
[6] HU Xiao Chen. 2017 Modeling and Performance Analysis of Power Thermal Management System Based on MATLAB Simulation Platform Nanjing University of Aeronautics and Astronautics