Digital regulation of gas turbine engine on start modes

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Abstract. A gas turbine engine (GTE) with a free power turbine driven by an electric generator is considered. The GTE has an automatic computerized control system (ACS). The fuel for the gas turbine engine is natural gas. The fuel dosage is managed by computer in the moment of ignition, during the start and the idle operation of gas turbine engine.

Keywords. gas turbine engine, free power turbine, fuel dosage, proportional control.

1. Introduction

Gas turbine engines (GTE) are widely used as autonomous gas turbine power generation plants [1, 2] as well as drive engines or primary engines for combined power and heat generation (as cogenerative gas turbine units) or combined cooling, heat and power (CCHP) as trigeneration [3, 4] or integrated energy plants (IEP) [3, 4]. They found a widespread application in stationary and transport [5, 6]. Fuel efficiency for gas turbines [1], diesel engines/gas engines [7, 8] falls with raising temperature at the inlet port. GTE are the most sensitive to inlet/ suction conditions [1]: a specific fuel consumption increases by 0.4 to 1.0 g/(kWh) for each 1 °C rise suction air temperature.

The air cooling technologies are designed to enhance engine output at stabilized temperature level [9, 10]. The most used engine cyclic air cooling systems are based on exhaust heat use [15, 16]. A lot of environment friendly waste heat conversing innovations might be applied in EIAC including based on water-fuel emulsions [17, 18], their afterburning and low temperature condensing [19, 20].

The methods of thermodynamic and statistic analysis of variation of different inlet air cooling techniques and thermal loading are proposed [21, 22]. Such methods as ANSIS [23-25] might be used for manufacture of exhaust heat recovery equipment and simulation of the thermophysical processes of deep exhaust heat utilization.

All the exhaust heat utilization technologies including TIAC enables to prolong a duration of efficient operation of GTE [1, 2, 21, 22] and require precise turbine load regulation.

The use of digital technology to control and regulate a GTE is well known. Control and regulation are highly dependent on the used hardware base and the structure of the digital means. Issues of regulation of a GTE using an IBM compatible computer complex are considered in this study. A number of recommendations have been proposed, the implementation of which in the control and regulation algorithms will significantly improve the quality of the power plant operation. The control system worked for eight years. During this time, there were no hardware failures of the control system units and no damage was caused to the equipment of the power plant.
2. Materials and Methods

The gas turbine engine uses as fuel natural gas and drives an electric generator in an autonomous power plant. A digital regulator differs from an analog regulator in that it can relatively easily move from one characteristic to another. A regulator based on an IBM compatible computer makes it relatively easy to form a nonlinear or piecewise linear characteristic. It is important that an IBM compatible regulator can implement fuel restrictions using a complex non-linear algorithm that takes into account data received from the automatic control system sensors (ACS). For example, when the outside air temperature changes, the control system recalculates the fuel supply restrictions by the Mach number, using the similarity of gas-dynamic processes. One of the authors observed how in two hours the outside air temperature changed from -5 to -30 degrees Celsius. When using controllers as a hardware base, you can also solve the above issues, but this will not be so fast. The ability to operate motors in parallel or with the mains requires a proportional control (external) characteristic. The digital regulator can implement any external (regulatory) characteristic. The characteristic for a motor driven by an electric generator is shown in Fig. 1. The speed of operation of modern dosing and measuring devices makes it possible to obtain the required characteristics without artificial methods.

![Diagram](image)

**Fig 1.** Regulatory characteristic of the power plant gas turbine engine.

In Fig. 1 line "a-b-e" corresponds to the idle run of the generator. The rotation speed at point "e" corresponds to the mains frequency. This frequency is close to 50Hz, and for a free power turbine, the rotation speed is usually about 3000 rpm. Line "a-c-d" corresponds to the maximum power mode. The "S" line is the load line. The load on the engine is determined by the operator control setting. The slope of the characteristic (regulator stiffness) is determined by the value \( \Delta \). For power plants, the value \( \Delta = 0.04 \) which corresponds to the required 4%. The slope is needed for multiple machines to work together and to work with a network. The engine-regulator system is has a delay time. The delay time is a combination of a number of factors. These factors are the time of measurements, the time of command execution and the time of acceleration or deceleration of the gas generator. The expression for the maximum permissible delay time is known

\[
\tau_e < \Delta \cdot T_{ct}
\]

where \( \tau_e \) is the delay time;

\( T_{ct} \) - time constant of the complex "power turbine - rotor of an electric generator".

The time constant is a value of the order of 3 - 5 s.

The magnitude \( \Delta = 0.04 \).

Then \( \tau_e < 0.12...0.2 \) s.

The error in determining the permissible delay time goes into reserve, but taking into account the transient process time of the gas generator, which is 0.1 ... 0.3 s, a fast-acting regulator should be used. During operation, the gas turbine engine is in different operating modes. The automatic control system (ACS) must track the transition of the GTE from one mode to another.

In marine gas turbine engines, which are used in the power industry, the starter drive is connected and disconnected from the turbocharger shaft using an overrunning clutch. This type of clutch does not respond instantly to engagement. The starter drive rotates without load and picking up speed during cluch
use. When the clutch is turned on, transient processes can occur, in which the half-couplings can open, and the springs can engage the overrunning clutch at low speed to avoid damage.

When using an AC drive, it makes sense to use a frequency control of an induction motor. It makes sense to use a converter with the ability to work on a five-point characteristic. It is important that the asynchronous electric motor does not go over to the non-working part of its characteristic. For this purpose, the automatic control system must form a task for the converter based on the measured speed of rotation of the circuits.

In the case of using a DC drive, it makes sense to use a regulated independent excitation and regulated power supply. This is not difficult to do at present.

Fuel is ignited and supplied when the high pressure compressor rotation speed required for ignition is reached (this speed is set by the engine designers). The ignition system is turned on and the igniter start gas valve is controlled. After a time specified by the developer, an ignition dose of fuel is supplied. It is impossible to supply a lot of gas, because engines, as a rule, have emergency pressure protection (first throw protection). If low quantity of gas is supplied, then the combustion may stop due to the effect of the emergency protection.

The parameters of the metering valves at low fuel rate are not very repeatable from valve to valve. Therefore, the position of the dispenser during ignition must be selected experimentally. In this case, it is important to record the temperature of stable combustion and the temperature of the outside air. When the outside temperature changes, the ignition dose of the fuel gas must be changed. You can offer a formula to determine it

$$ T_{\text{stable}} = T_0 \cdot \frac{T}{T_0} - 1 $$

where $T_{\text{stable}}$ is the temperature of stable combustion during ignition;

$T_0$ - standard outside temperature;

$T$ - the ratio of the actual outdoor temperature to the standard outdoor temperature.

From the above formula, it follows that with a decrease in the air temperature at the inlet, the ignition dose of gas should be increased.

3. Results and Discussion

When accelerating the gas generator in the mode of support using starters, the fuel supply is gradually, depending on the time, increased until the starters are turned off. As the rotation speed increases, the torque of the starters decreases. In addition, the strength limitations of electrical machines must be taken into account. Therefore, the escort stage is limited.

The transition of the gas generator to the warm-up mode does not require sharp maneuvers and its timing is not critical. Abrupt changes in fuel delivery are not desirable due to the risk of a current break in the compressors. At low speeds, the efficiency of the turbomachines is low. Therefore, a sharp increase in fuel supply is dangerous. It is advisable to set the regulator to a large value (see Fig. 1) and gradually increase the set rotation speed. In Fig. 2 shows the start time variation for the parameters of the gas turbine engine.

![Fig. 2. Starting the gas turbine engine](image-url)
In Fig 2 shows the time dependences for:

- $n_2$ - rotation speed of the high-pressure compressor;
- $n_1$ - rotation speed of a free power turbine;
- $t$ - temperature behind the high-pressure turbine;
- $P$ - pressure in front of the nozzles;
- $h$ - position of the fuel dispenser.

The graphs in Fig. 2, the first pressure surge is clearly visible (40th second); disconnection of starters (120th second). The warm-up mode is entered from the second minute and ends in the fourth minute. The warm-up time and the speed $n_2$ at which this mode is performed is specified by the engine manufacturer.

**Fig. 3. Transition to BAC with closure of ABT**

After the end of the warm-up mode, the gas generator is further accelerated until the rotation speed of the power turbine $n_3$ approaches the synchronous speed of the generator by a predetermined value. In Fig. 3 shows the process of transition to the beginning of automatic control of the power turbine speed $n_1$.

In Fig.3 shows the same parameters as in Fig.2. In the first minute of the graph in Fig.3. Warm-up mode ends. At about the second and a half minute, the air bypass tape (ABT) closes. Closing the ABT is accompanied by a decrease in temperature, but due to the fact that the regulator is not set rigidly, there are no abrupt changes in fuel supply. In Fig.4 shows the transition to BAC at different $n_3$.

**Fig. 4. Transition to BAC from 2800 rpm and from 2950 rpm**
In Fig. 4 shows the transitions to the BAC from 2800 rpm and from 2950 rpm. The expediency of switching from 2950 rpm is obvious. When approaching the synchronous frequency, it is necessary to change the regulation parameter (switch from regulation \( n_1 \) to regulation \( n_2 \)) and regulate harder \(( \Delta = 0.04 \)). The requirement to switch to BAC from 2800 rpm is dictated by the use of analog hydraulic regulators. For electronic regulators, we recommend switching from a 2950 rpm power turbine. It should be noted that the ones shown in Fig. 2 - Fig. 4 graphs were obtained experimentally in an autonomous power plant. No data processing was undertaken when generating the graphs. This also applies to temperature. The graphs show the measured temperature, which differs from the actual one.

4. Conclusion and Recommendations

The graphs show that the proportional control method works satisfactorily as part of a turbine generator. The ignition dose of fuel (natural gas), determined according to the above formula, ensures stable engine operation at the beginning of start-up.

The transition to the beginning of automatic operation must be performed being as close as possible to the synchronous speed mode of the power turbine. In robotic modes, before the start of automatic regulation, the controller needs to be adjusted not rigidly.

In the mode of maintaining the frequency of the power turbine, the regulator must have a rigid characteristic with an S-shaped section.

The requirement to switch to BAC from 2800 rpm is dictated by the use of analog hydraulic regulators. For electronic regulators, we recommend switching from a 2950 rpm power turbine.

References

[1] Farouk, N.; Sheng, L.; Hayat, Q. Effect of Ambient Temperature on the Performance of Gas Turbines Power Plant. In: International Journal of Computer Science 2013, 10, 1(3), 439–442.
[2] Radchenko, A., Trushliakov, E., Kosowski, K., Mikielewicz, D., Radchenko, M. Innovative turbine intake air cooling systems and their rational designing. Energies 13(23), 6201 (2020), doi:10.3390/en13236201
[3] Kalhori, S.B.; Rabiei, H.; Mansoori, Z. Mashad trigeneration potential – An opportunity for CO2 abatement in Iran. Energy Conversion and Management 2012, 60, 106–114
[4] Radchenko, A., Stachel, A., Forduy, S., Portnoi, B., Rizun, O.: Analysis of the Efficiency of Engine Inlet Air Chilling Unit with Cooling Towers. In: Ivanov V., et al. (eds): Advances in Design, Simulation and Manufacturing III (DSMIE 2020), Lecture Notes in Mechanical Engineering, pp. 322-331. Springer, Cham (2020) https://doi.org/10.1007/978-3-030-50491-5_31
[5] Cherednichenko, O.; Mitienkova, V. Analysis of the Impact of Thermochemical Recuperation of Waste Heat on the Energy Efficiency of Gas Carriers. J. Marine. Sci. Appl. 2020, https://doi.org/10.1007/s11804-020-00127-5
[6] Konovalov, D., Kobalava, H., Radchenko, M., Scurtu, I.C., Radchenko, R.: Determination of hydraulic resistance of the aerothermopressor for gas turbine cyclic air cooling. In: TE-RE-9D 2020, EJS Web of Conferences, 180, 010131 (2020) https://doi.org/10.1051/e3sconf/20201801012
[7] Trushliakov, E., Radchenko, A., Forduy, S., Zubarev, A., Hrych, A.: Increasing the Operation Efficiency of Air Conditioning System for Integrated Power Plant on the Base of Its Monitoring. In: Nechyporuk M., Pavlikov V., Kritskiy D. (eds) ICTM 2019, AISC, vol. 1113, 351-360. Springer, Cham (2020) https://doi.org/10.1007/978-3-030-37618-5_30
[8] Forduy, S., Radchenko, A., Kuczynski, W., Zubarev, A., Konovalov, D.: Enhancing the fuel efficiency of gas engines in integrated energy system by chilling cyclic air. In: Tonkonogyi V. et al. (eds.) Grabchenko’s International Conference on Advanced Manufacturing Processes. InterPartner-2019. Lecture Notes in Mechanical Engineering. Springer, Cham, pp. 500–509 (2020).
[9] Trushliakov, E., Radchenko, A., Radchenko, M., Kantor, S., Zielikov, O.: The Efficiency of refrigeration capacity regulation in the ambient air conditioning systems. In: Ivanov V., et al. (eds.) Advances in Design, Simulation and Manufacturing III (DSMIE 2020). LNME, pp. 343-353. Springer, Cham (2020) https://doi.org/10.1007/978-3-030-50491-5_33
[10] Radchenko, A., Trushliakov, E., Tkachenko, V., Portnoi, B., Prjadko, O.: Improvement of the refrigeration capacity utilizing for the Ambient Air Conditioning System. In: Tonkonogyi, V. et al. (eds.) Advanced Manufacturing Processes II. InterPartner 2020. Lecture Notes in Mechanical Engineering, pp. 714-723. Springer, Cham (2021).
[11] Konovalov, D., Kobalava, H., Maksymov, V., Radchenko, R., Avdeev, M.: Experimental Research of the Excessive Water Injection Effect on Resistances in the Flow Part of a Low-Flow Aerothermopressor. In: Ivanov V., et al. (eds.) Advances in Design, Simulation and Manufacturing III (DSMIE 2020). Lecture Notes in Mechanical Engineering, pp. 292-301. Springer, Cham (2020).
[12] Radchenko, R., Pyrysunko, M., Radchenko, A., Andreev, A., Kornienko, V.: Ship engine intake air cooling by ejector chiller using recirculation gas heat. In: Tonkonogyi, V. et al. (eds.) AMP, InterPartner-2020. LNME, pp. 734-743. Springer, Cham (2021). https://doi.org/10.1007/978-3-030-68014-5\_71

[13] Popli, S., Rodgers, P., Eveloy, V. Trigeneration scheme for energy efficiency enhancement in a natural gas processing plant through turbine exhaust gas waste heat utilization. Applied Energy 2012, 93, 623–636.

[14] Radchenko, R., Kornienko, V., Pyrysunko, M., Bogdanov, M., Andreev, A. (2020) Enhancing the Efficiency of Marine Diesel Engine by Deep Waste Heat Recovery on the Base of Its Simulation Along the Route Line. In: Nechyporuk M., Pavlikov V., Kritskiy D. (eds) Integrated Computer Technologies in Mechanical Engineering (ICTM 2019). Advances in Intelligent Systems and Computing (2020), vol 1113. Springer, Cham, pp.337-350

[15] Mikielewicz, D.; Kosowski, K.; Tucki, K. et al. Gas Turbine Cycle with External Combustion Chamber for Prosumer and Distributed Energy Systems, Energies 2019, 12, Issue: 18.

[16] Cherednichenko, O.; Havryst, V.; Shebanin, V. et al. Local Green Power Supply Plants Based on Alcohol Regenerative Gas Turbines: Economic and Environmental Aspects. Energies 2020, 13, 2156.

[17] Kornienko, V., Radchenko, R., Mikielewicz, D., Pyrysunko, M., Andreev, A.: Improvement of characteristics of water-fuel rotary cup atomizer in a boiler. In: Tonkonogyi, V. et al. (eds.) AMP, InterPartner-2020. LNME, pp. 664-674. Springer, Cham (2021) https://doi.org/10.1007/978-3-030-68014-5\_64

[18] Kornienko, V., Radchenko, R., Stachel, A., Andreev A., Pyrysunko, M.: Correlations for pollution on condensing surfaces of exhaust gas boilers with water-fuel emulsion combustion. In: Tonkonogyi V. et al. (eds.) Grabchenko’s International Conference on Advanced Manufacturing Processes. InterPartner-2019. Lecture Notes in Mechanical Engineering. Springer, Cham, pp. 530–539 (2020).

[19] Kornienko, V., Radchenko, M., Radchenko, R., Konovalov, D., Andreev, A., Pyrysunko, M.: Improving the efficiency of heat recovery circuits of cogeneration plants with combustion of water-fuel emulsions. Thermal Science 25(1, Part B), 791-800 (2021), doi: 10.2298/TSCI200116154K

[20] Kornienko, V., Radchenko, R., Konovalov, D., Andreev, A., Pyrysunko, M.: Characteristics of the rotary cup atomizer used as afterburning installation in exhaust gas boiler Flue. In: Ivanov V., et al. (eds.) ADSM III (DSMIE 2020). LNME, 302–311. Springer, Cham (2020) https://doi.org/10.1007/978-3-030-50491-5\_29

[21] Dawoud B.; Zurigat Y.H.; Bortnany J. Thermodynamic assessment of power requirements and impact of different gas-turbine inlet air cooling techniques at two different locations in Oman. Applied Thermal Engineering 2005, 25, 1579–1598.

[22] Yang, Ch.; Yang, Z.; Cai, R. Analytical method for evaluation of gas turbine inlet air cooling in combined cycle power plant. Applied Energy 2009, 86, 848–856.

[23] Bohdal Ł, Kukiełka L., Legutko S., Patyk R., Radchenko A.M. Modeling and Experimental Research of Shear-Slitting of AA6111-T4 Aluminum Alloy Sheet. Materials (2020) Manuscript ID: materials-859458

[24] Bohdal L, Kukielska L., Radchenko A.M., Patyk R., Kulakowski M., Chodó r J. Modelling of guillotining process of grain oriented silicon steel using FEM, in AIP Conference Proceeding 2078, 020080 (2019)

[25] Bohdal L, Kukielska L., Świłło S., Radchenko A.M., Kulakowska A. Modelling and experimental analysis of shear-slitting process of light metal alloys using FEM, SPH and vision-based methods, in AIP Conference Proceedings 2078, 020060 (2019)