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From "Mechanical Hydraulic" to "Digital Brain": A Review of Gas Turbine Electronic Control System Architecture and Protection Mechanisms

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Abstract. The electronic control system of a gas turbine is the core component that determines the unit's safety, economy, and reliability. From the perspective of electronic and electrical engineering, this paper systematically reviews the four-layer engineering framework of modern heavy-duty gas turbine control systems: sensing and instrumentation, embedded control, power electronics and actuation, and protection and communication. It focuses on the analysis of signal chain design (4–20 mA current loop, 2-out-of-3 voting, TMR redundancy), DPU architecture, PID and cascade control strategies, hardwired protection mechanisms (separation of TPS and control layer), and synchronization and grid connection logic. On this basis, this paper reviews the autonomous development path of China's heavy-duty gas turbine control systems. The research shows that advancements in control technology, from mechanical hydraulics to fully digital control and the industrial adoption of FADEC concepts, continuously expand the performance boundaries of gas turbines, meanwhile, signal integrity, protection independence, and system redundancy are critical issues that cannot be ignored in engineering implementation.

Keywords: Gas turbine, Electronic control, FADEC, PID, DPU

1. Introduction

The working principle of a gas turbine can be summarized as the Brayton cycle: air is compressed by the compressor and enters the combustion chamber, where it mixes with fuel and combusts to produce high-temperature, high-pressure gas that drives the turbine to rotate. The turbine then drives the compressor and the generator (or propeller). This process involves complex coupling of thermodynamics, fluid mechanics, and rotor dynamics.

However, gas turbines face multiple challenges during operation: excessive rotor speed may lead to fracture, excessively high turbine inlet temperature can burn blades, mismatch between intake flow and fuel supply can cause surge or even flameout, and sudden changes in external load may destabilize the system. The time scales of these problems are often at the level of seconds to milliseconds, making manual intervention impossible. Therefore, modern gas turbines must be equipped with electronic control systems that collect state parameters in real time, calculate control variables, and drive actuators to ensure safe and efficient operation under various operating

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conditions. The mechanical design of a gas turbine determines its performance ceiling, while the electronic control system determines to what extent this ceiling can be safely utilized. Understanding this system requires placing thermodynamics, automatic control, electronic circuits, and industrial communication technology within the same engineering framework.

Current literature mostly focuses on thermal performance modeling or overall control strategies, lacking systematic work from the perspective of electronic and electrical engineering that addresses the full signal chain of "physical quantity → electrical signal → digital computation → actuator drive," redundancy voting mechanisms, and protection independence. This paper reviews the hardware architecture, control strategies, protection mechanisms, and domestic autonomous engineering development of gas turbine electronic control systems. It analyzes core key technologies from the three dimensions of signal integrity, real-time performance, and fail-safety, and summarizes the autonomous technology iteration and verification path of heavy-duty gas turbine control systems in light of recent domestic key engineering applications, thereby addressing the shortcomings of single-perspective and incomplete technical system reviews.

2. Electronic control system

2.1. Sensing layer

The sensing layer consists of various sensors, acting as the "senses" of the system. Among them, speed sensors measure the rotational speed of the compressor and power turbine via magnetoelectric or photoelectric methods, providing core feedback for closed-loop control. Temperature sensors use thermocouples or RTDs to measure exhaust temperature, turbine inlet temperature, and ambient temperature, used for temperature protection and power correction. Pressure sensors monitor compressor outlet pressure, combustion chamber pressure, and lubricating oil pressure, participating in anti-surge control and condition diagnosis. Vibration sensors installed on bearing housings detect rotor imbalance or rubbing faults. Position sensors feed back the actual opening of throttle levers, guide vanes, and valves, forming valve position closed loops.

2.2. Decision layer

The decision layer is the "brain" of the system, usually undertaken by a Programmable Logic Controller (PLC) or a dedicated gas turbine controller (such as GE Mark V, Mark VI series). In the aviation field, this function is performed by the Full Authority Digital Engine Control (FADEC) system. The controller executes the following operations cyclically at a period of 10–100 ms: acquiring sensor signals, comparing them with setpoints to obtain deviations, calculating output based on control algorithms, and sending commands to actuators. At the same time, the controller is responsible for sequence control (startup, acceleration, grid connection, shutdown) and fault protection logic. For improved reliability, redundant designs are implemented in key control modules. An example is the 2-out-of-3 voting structure, where three channels carry out independent calculations, and the result validated by at least two channels is taken as the final output.

2.3. Actuation layer

The actuation layer receives controller commands and acts on the gas turbine. The fuel metering valve regulates the fuel flow into the combustion chamber and is the most important control means. The Inlet Guide Vane (IGV) adjusts the compressor inlet angle, affecting flow and pressure ratio.

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The anti-surge bleed valve opens at low speed or during transient conditions to prevent compressor surge. The ignition system ignites the mixture during the startup phase. On the generator side, actuators rely on the excitation system to regulate terminal voltage and reactive power, accepting coordination control from the gas turbine and electrical systems.

The entire system forms a closed loop: sensor acquires status → controller calculates deviation → actuator adjusts → status changes → sensor acquires again, continuously cycling.

2.4. Signal chain: from "physical world" to "digital world"

Gas turbine control is essentially a signal chain: physical quantity (temperature/pressure/speed) → sensor → electrical signal (mV/mA/V/pulse) → signal conditioning → A/D conversion → controller (digital computation) → D/A or digital output → actuator (valve, servo, relay).

Industrial gas turbine control systems adopt several standard signal types with distinct characteristics and application scenarios. The 4–20 mA current signal features outstanding anti-interference performance, as its measurement accuracy is immune to wire resistance changes, and it supports real-time wire breakage detection. The 0–10 V voltage signal boasts simple wiring structures but suffers from poor anti-interference ability, making it unsuitable for long-distance signal transmission. Thermocouple millivoltage signals, primarily generated by K-type and N-type thermocouples, are widely applied to measure the exhaust temperature of gas turbines. In addition, magnetoelectric and eddy current pulse signals are the mainstream choices for rotational speed and shaft displacement detection in turbine systems.

Inside the controller, signal conditioning must first be performed: amplification, filtering, cold junction compensation, isolation, and then ADC converts it into a digital quantity. Upon output, DAC or PWM drives electro-hydraulic servo valves and IGV servo mechanisms.

2.5. Controller hardware: DPU, PLC, and real-time systems

Heavy-duty gas turbines usually use Distributed Processing Units (DPU) or industrial PLC/DCS as the core control equipment, equipped with 32-bit or multi-core industrial processors. The control cycle can reach 10 ms or even shorter. Real-time operating systems such as VxWorks are used to ensure control timeliness. Various functional modules can be inserted into the equipment cabinet, including power boards, CPU boards, analog input boards, analog output boards, digital input boards, digital output boards, and communication boards. The system includes typical functional modules: the AI (Analog Input) module mainly receives field analog signals such as temperature, pressure, and flow, the AO (Analog Output) module outputs 4–20 mA command signals to control actuators such as fuel valves, the DI (Digital Input) module collects switch signals such as ignition feedback, oil pump status, and protection relay status, the DO (Digital Output) module is used for switch control functions such as oil pump start/stop, fault alarm, and trip relay triggering. In the direction of autonomous control, the Longyou Class E unit has already used the "Huadian Ruilan" autonomous DPU to achieve gas turbine control [1]. The operation of large-capacity F-class units (such as Tongnan 550 MW) provides conditions for engineering verification of autonomous control systems on larger-capacity platforms. The retrofit application of systems such as GE Mark VIe also confirms the engineering feasibility of the DPU architecture in gas-driven units [2].

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2.6. Communication network: industrial ethernet, fieldbus, and three-layer network

The gas turbine control system is not a single microcontroller but a hierarchical network. The enterprise plant-level network is responsible for data exchange with DCS, SCADA, and plant-level databases. The control-level network mainly realizes data transmission between controllers, generally adopting a redundant industrial Ethernet architecture. The I/O-level network undertakes communication between controllers and various I/O modules, with mainstream methods including IONET, Profibus, Modbus TCP, etc. Commonly used communication protocols include Modbus TCP/RTU, PROFIBUS-DP, Profinet, and OPC UA. In engineering applications, strict requirements are imposed on control network construction: shielded twisted-pair cables or optical fibers, industrial switches, and redundant ring networks must be deployed. Otherwise, electromagnetic interference in complex field environments can easily cause signal distortion, leading to misjudgment by the gas turbine system, resulting in false overtemperature or false overspeed alarms, and affecting stable unit operation.

The control network must use shielded twisted-pair cables/fiber optics + industrial switches + redundant ring network. Otherwise, electromagnetic interference will make the gas turbine "mistakenly believe it is overtemperature/overspeed."

2.7. Power supply and redundancy

Gas turbine control systems have extremely high requirements for power supply reliability, ensuring that the control system does not lose power first due to power supply failure. The system conventionally uses 220 V AC and 24 V DC from plant power as the main power supply, and key controllers are equipped with dual 24 V DC redundant power supplies to achieve power fault tolerance. In important application scenarios with high reliability requirements, UPS and batteries are also configured to form an uninterruptible power supply system. At the same time, the system has a complete module-level redundancy design covering CPU, power supply, communication, and I/O modules. Through a multi-level redundancy architecture, it comprehensively guarantees the continuous stability of control system power supply and operation, avoiding system shutdown or control failure caused by single-point faults. Safety-critical signals commonly use 2-out-of-3 voting: three speed channels, three temperature/vibration/pressure channels, and three controllers compute independently, and action is taken only when two agree. GE Mark VIe, Mitsubishi DIASYS, and Siemens SPPA-T3000 all adopt TMR or dual-redundant architectures.

3. Control principles

The core of the electronic control system is feedback control. Taking speed control as an example: set the desired speed as N_{ref} , the actual speed as N_{act}, and the deviation $e = N_{ref} - N_{act}$. When the speed is low, fuel supply is increased, when high, it is decreased. This cycle of "measurement → comparison → correction" enables the system to automatically resist disturbances. The most commonly used control in industry is Proportional-Integral-Derivative (PID) control:

$$u(t) = K_p e(t) + K_i \int_0^t e(\tau)d\tau + K_d \frac{de(t)}{dt} \quad (1)$$

Where K_p is the proportional coefficient, K_i is the integral coefficient, K_d is the derivative coefficient. The proportional term makes the correction force larger when the deviation is larger, the integral term eliminates steady-state error but may reduce stability, the derivative term acts in

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advance based on the rate of change to suppress overshoot. Gas turbines often adopt cascade PID: the outer loop controls speed/power, and the inner loop controls fuel flow.

A gas turbine is a multi-input multi-output system: fuel affects speed and temperature, guide vanes affect flow and pressure ratio, and load simultaneously affects speed and exhaust temperature. When power command increases, the controller increases fuel while appropriately opening the guide vanes, satisfying power demand while avoiding overtemperature.

4. Core protection functions

The turbine inlet temperature of heavy-duty gas turbines often reaches above 1300 °C. Overtemperature for tens of seconds can cause blade creep and ablation. The system monitors exhaust temperature and turbine inlet temperature in real time, and takes control measures such as fuel reduction or power limitation when temperature approaches the upper limit. Anti-surge control judges the operating point through pressure ratio and speed, adjusts the inlet guide vanes, and limits unit acceleration to avoid operating conditions crossing the surge line.

Gas turbine overspeed protection adopts multi-stage threshold logic for hierarchical safety control: 103% speed for fuel cutback, 110% speed for electrical trip, and 112% speed for mechanical overspeed bolt action [3, 4]. The first threshold suppresses overspeed by fuel reduction, the second executes fuel cut-off and shutdown, and the mechanical overspeed device serves as the last line of defense. The gas turbine has a complete start-up and shutdown sequence control process, sequentially completing the entire process of turning gear, ignition, acceleration to self-sustaining speed, fuel increment adjustment, synchronization and grid connection, and step-by-step loading. During operation, the system immediately transfers to a protected state. Generator excitation and voltage control rely on AVR to regulate excitation current, stably maintain terminal voltage, achieve reactive power adjustment, and complete voltage, frequency, and phase synchronization matching before grid connection.

Unit synchronization and grid connection need to match corresponding grid frequency parameters: 50 Hz systems correspond to 3000 r/min, 60 Hz systems correspond to 3600 r/min. During grid connection, phase sequence, amplitude, frequency, and phase angle must be verified. The automatic synchronizer determines qualification before executing the closing operation. After grid connection, the speed is locked by the grid, and only active and reactive power can be adjusted. The gas turbine is equipped with an independent hardwired protection system. The electronic overspeed relay can hard-cut fuel at 110% speed. UV/IR flame detection signals are directly connected to the protection circuit. Fault signals such as high vibration and low lubricating oil pressure actuate protection through hard relays. The protection system (TPS) and the control system (TCS) are independent of each other. The core principle in engineering is: "Control can be smart, but protection must be dumb and reliable."

Aero-engines have extremely stringent requirements for weight, reliability, and fuel economy. FADEC is the standard configuration of modern aero-engines, featuring full authority control, integrated optimization, adaptive adjustment, and fault diagnosis capabilities. FADEC autonomously determines all adjustment variables based on the pilot's thrust request, and can complete performance optimization under constraints such as temperature, surge, and life. It automatically corrects control parameters with changes in flight altitude, intake temperature, and pressure, and has health monitoring, channel switching, and degraded operation functions. Industrial heavy-duty gas turbine control is gradually absorbing FADEC design concepts to achieve control capabilities such as full authority scheduling, equipment health management, and fault degraded operation [5].

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5. Development trends

Heavy-duty gas turbine control systems are showing multi-dimensional development trends. The degree of full digitalization and networking continues to increase, and traditional mechanical hydraulic backup solutions are gradually being replaced by fully digital control systems. Control algorithms are becoming increasingly intelligent. Model Predictive Control (MPC) and various data-driven algorithms are gradually being applied to achieve optimized control under multivariable constraints. Digital twin technology is gradually being implemented. Through real-time synchronous operation of virtual simulation models and physical units, it can provide support for control system parameter tuning and unit fault prediction.

The domestic industrialization process continues to accelerate. In May 2021, the first domestically developed autonomous controllable heavy-duty gas turbine control system (TCS) was successfully connected to the grid and put into operation at Huadian Longyou Power Plant, marking that China Huadian took the lead in fully mastering the key technologies of the whole process of heavy-duty gas turbine control systems, including independent design, production, commissioning, and transformation, promoting the domestic development of gas turbines in China [1]. In February 2024, the first prototype of the 300 MW-class F-class heavy-duty gas turbine was assembled and rolled off the line in Lingang, Shanghai, which is an important milestone in the independent innovation and development of heavy-duty gas turbines in China [6]. On March 21, 2026, Unit 1 of the Huadian Chongqing Tongnan Gas Turbine Project, China's first 550 MW F-class gas turbine unit, successfully completed 168 hours of full-load operation and was officially put into commercial operation, marking a new breakthrough in China's application of large-capacity high-efficiency clean energy equipment [7].

System control strategies are gradually adapting to low-carbon development needs. With the continuous development of hydrogen and hydrogen-blended combustion technologies, control systems need to have the ability to adapt to dynamic changes in fuel calorific value.

6. Conclusion

The electronic control system of a gas turbine is an indispensable part of modern power equipment. It senses operating status through sensors, calculates control variables by the controller based on closed-loop algorithms, and drives actuators to adjust parameters such as fuel and guide vanes, realizing functions including speed/power control, temperature protection, anti-surge, and sequential start-stop. From mechanical hydraulics to fully digital control, to FADEC and intelligent algorithms, advancements in control technology continuously expand the performance boundaries and application scope of gas turbines.

The value of studying this topic lies not only in understanding an engineering technology, but also in appreciating the comprehensive application of interdisciplinary knowledge: physical laws describe natural processes, mathematical tools quantify change patterns, electronic and electrical engineering realizes signal acquisition and power drive, and information technology realizes automatic adjustment. A truly advanced machine is not only "powerful," but also "knows what it should do." Through system architecture analysis and control principle derivation, this paper clarifies the core role of electronic control systems in the safe operation of gas turbines. Future work can combine simulation platforms such as MATLAB/Simulink to quantitatively verify PID parameter tuning and multivariable coordinated control.

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