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Study on Abnormal Action Analysis and Optimization Scheme of Gas Turbine Emergency Shut-Off Valve (ESV)

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Abstract: Gas turbines serve as primary peak-shaving equipment in power grids. The emergency shut-off valve (ESV), the main fuel isolation valve, determines unit start/stop safety and response capability via its opening/closing speed. In a heavy-duty gas turbine series, hydraulic-driven ESVs experienced batch failures including delayed opening and overdue emergency closure. Investigation attributed slow opening to low-temperature oil viscosity increase, and closure delay after long open-hold to trapped oil between the trip solenoid and cartridge valve. Two optimizations were adopted: controller logic upgrade with manual exercising, and a 0.8 mm throttling drain orifice in the cartridge cover to eliminate trapped oil. Field tests verified that opening time was within 2 s, and total emergency closing time after static hold was below 300 ms, meeting design specifications. This solution is applicable to all models, offering an engineering reference for hydraulic ESV reliability and unit maintenance.

1. Introduction

Against the background of new power system construction, large-scale grid integration of wind and solar renewables leads to increased grid output fluctuations and widened peak-shaving gaps. Gas turbines, featuring fast start-up, wide load regulation range, and low start/stop losses, have become the core equipment for deep peak shaving and grid stability support [1]. The fuel supply system is the critical barrier for gas turbine safe operation. The emergency shut-off valve (ESV), as the main natural gas shut-off valve, performs dual safety functions: fuel supply for start-up and fuel cut-off for trip/shutdown. The industry standard design specification requires: ESV opening time from full-close to full-open ≤ 2 s; total closing time from emergency trip command to valve fully closed ≤ 300 ms, with valve action time ≤ 250 ms.

A domestic equipment manufacturer uniformly equips its large-F and small-F series gas turbines with hydraulic actuators to drive the ESV. Compared with electric or pneumatic solutions, hydraulic actuation offers high output torque, fast response, and low operational impact, making it suitable for millisecond-level protection requirements of gas turbines. However, from units commissioned in 2015 to factory-tested units in 2026, multiple units at various sites have successively exposed two common defects: first, ESV opening timeout during the first start-up after winter shutdown, causing ignition failure and flame-out protection; second, static fast-closure test delay significantly exceeding the limit after long-term open-hold. These faults not only delay new unit commissioning and reduce peaking response capability, but also pose major safety hazards such as deflagration and turbine hot-section damage due to delayed fuel cut-off under extreme conditions.

Existing literature [2-5] mainly focuses on flow characteristics of gas turbine control valves, hydraulic system leakage and jamming failures, but rarely provides systematic analysis and complete retrofit solutions for trapped-oil during long-term ESV hold and start-up failure under low-temperature viscosity coupling. Based on field fault data and hydraulic bench comparative tests, this paper progressively isolates the influencing factors, identifies the root causes, proposes coordinated software-logic and hardware-structure optimization measures, and completes engineering verification and promotion feasibility analysis.

2. ESV System Composition, Working Principle, and Fault Statistics

2.1. Fuel Valve System Configuration and Hydraulic Actuator Principle

The fuel circuit adopts a three-stage valve configuration: ESV main shut-off valve, premix fuel control valve, and pilot fuel control valve. The core components of the ESV hydraulic drive unit include trip solenoid valve MBX70AA001, cartridge valve MBX70AA051, opening solenoid valve MBX70AA031, single-acting hydraulic cylinder, and integrated manifold cover plate. Figure 1 shows the P&ID of the ESV hydraulic actuator. The hydraulic control principle is as follows:

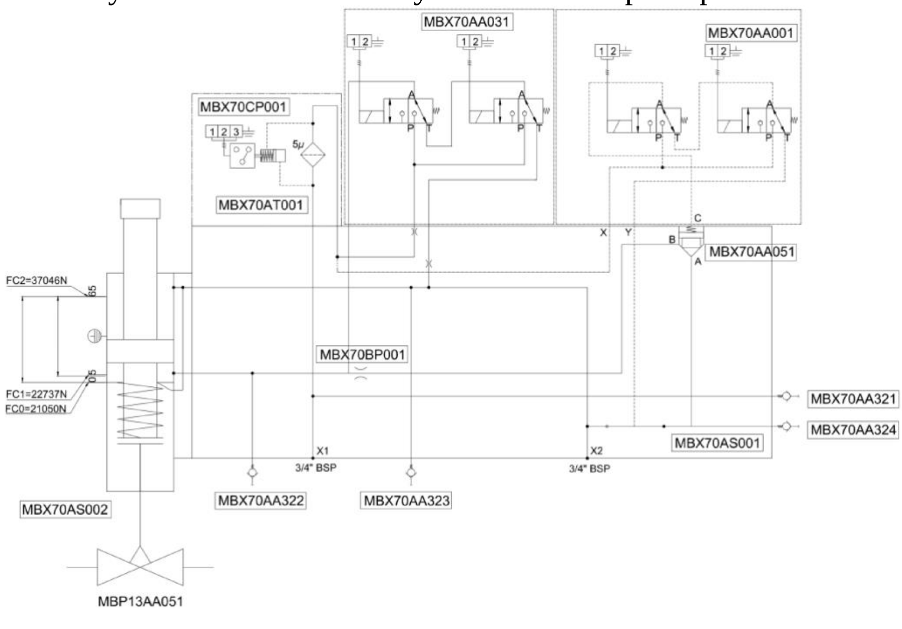

Figure 1: P&ID of the ESV actuator

- Start-up/hold-open condition: The trip solenoid valve is energized, pressure oil seals the upper control chamber of the cartridge valve, and the main passage B of the cartridge valve is blocked from return oil A. Simultaneously, the opening solenoid valve is energized, pressure oil enters the lower chamber of the hydraulic cylinder, overcoming spring force to drive the valve stem upward, thus opening the ESV.
- Emergency fast-closure condition: The trip solenoid valve is de-energized, control oil in the cartridge valve upper chamber returns to the tank through the solenoid valve, the cartridge valve opens rapidly, enabling large-flow drainage from port B to return port A. At the same time, the opening solenoid valve is de-energized, providing secondary drainage from the lower cylinder

chamber. The dual-path ensures rapid valve closure; even if the opening solenoid valve power supply fails, the independent de-energization of the trip solenoid valve can still complete the safety shut-off, providing redundant protection.

2.2. Basic Information Summary of Faulty Units

Multiple units simultaneously experienced ESV abnormal action, covering both long-term operated units and factory-tested units. Detailed conditions are listed in Table 1.

For units under commissioning or already in operation, multiple users have reported slow ESV action during gas turbine start-up, leading to ignition failure and inability to start. Meanwhile, other users reported slow fast-closure time during static ESV tests. Since many projects are involved, this paper describes the events using two typical projects as examples.

Table 1: Basic information and defect types of faulty units.

Power Plant	Commissioning/Testing Status	Faulty Component	Defect Mode
Site 1	Commissioned 2023-12	Fuel valve hydraulic actuator	ESV slow opening
Site 2	Commissioned 2015-05	Fuel valve hydraulic actuator	ESV slow fast-closure after long open-hold
Site 3	Commissioned 2020-05	Fuel valve hydraulic actuator	ESV slow opening
Site 4	Factory commissioning stage	Fuel valve hydraulic actuator	ESV slow fast-closure after long open-hold

2.3. Typical Fault Phenomena and Test Data

2.3.1. Site 1- ESV Slow Opening Fault

During winter low-temperature conditions in December 2023, the first ignition test of the gas turbine at Site A triggered flame-out protection twice in succession. The unit sequence curve showed that the time from ignition command to ESV fully-open feedback exceeded 5 s, far beyond the 2 s design threshold. When the operation was repeated for a second ignition, the valve opening time returned to acceptable values. The fault pattern showed distinct characteristics: ①it occurred only during the first start-up after prolonged cold shutdown; ②lower ambient temperature correlated with higher fault probability; ③after one action cycle, the second start/stop performance automatically recovered. The entire actuator was enclosed in a housing without heat tracing, so the oil temperature equalled ambient temperature.

2.3.2. Site 2- ESV Fast-Closure Delay Fault

In March 2024, static characteristic comparison tests were performed on the original hydraulic actuator test bench, simulating unit trip power-off conditions. Figures 2 and Figures 3 show two sets of comparative test data:

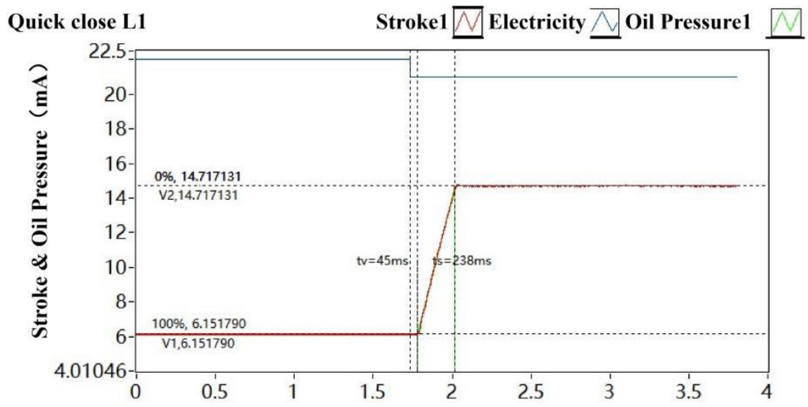

Figure 2: ESV fast-closure time (immediate close after opening)

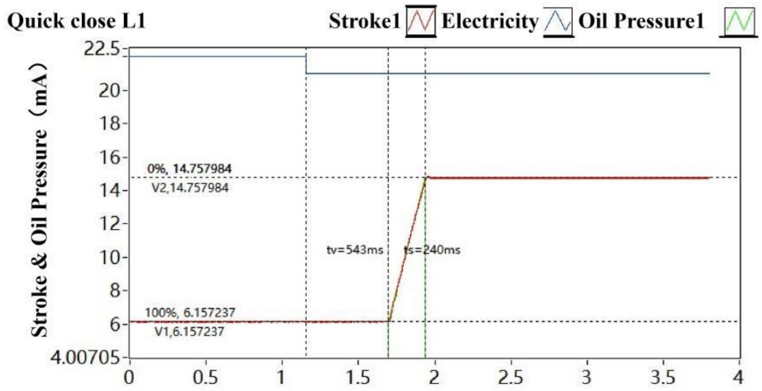

Figure 3: ESV fast-closure time (close after 8 min open-hold)

1) ESV fully opened and immediately de-energizing the trip solenoid valve: delay time tv = 45 ms, valve action time ts = 238 ms, total closing time = 283 ms;
2) ESV held fully open for 8 minutes then de-energizing: tv = 543 ms, ts = 240 ms, total closing time = 783 ms

The data prove that the static hold time only affects the response delay segment, while the mechanical valve action speed remains basically unchanged. Under long-term hold, the total closing time exceeded the 300 ms safety limit, and Site D replicated exactly the same test results.

3. Root Cause Analysis Step by Step

3.1. Cause Analysis of ESV Slow Opening

The dynamic viscosity of hydraulic oil increases exponentially as temperature decreases. After cold shutdown, oil fluidity deteriorates significantly. The ESV actuator has no pre-heating circuit or heat tracing. After prolonged winter static conditions, oil viscosity is extremely high, the filling rate of pressure oil into the lower cylinder chamber decreases, and the pressure build-up speed for valve stem drive slows down, directly prolonging the full-open response time.

During the first switching action, the hydraulic oil continuously circulates, and frictional heat rapidly raises local oil temperature and reduces viscosity. Therefore, the second start-up action returns to normal performance. This mechanism perfectly matches all field characteristics: "cold-first-start fault, self-healing on second attempt, and high incidence in winter."

3.2. Cause Analysis of ESV Fast-Closure Delay after Long-Term Open-Hold

As shown in Figure1 (P&ID of the ESV hydraulic actuator), when the gas turbine is ready to start, the trip solenoid valve MBX70AA001 is energized, and the cartridge valve MBX70AA051 is kept closed under hydraulic oil pressure, blocking port B from return port A. When the opening solenoid valve MBX70AA031 is energized, hydraulic oil enters the lower cylinder chamber and the ESV opens.

When an emergency trip is required, the trip solenoid valve MBX70AA001 is immediately de-energized, the hydraulic oil on the cartridge valve MBX70AA051 flows back to the tank through the trip solenoid valve, the cartridge valve opens, rapidly connecting port B to return port A for large-flow drainage, and the hydraulic shut-off valve closes quickly to prevent further damage to the gas turbine. Simultaneously, the opening solenoid valve MBX70AA031 also de-energizes upon receiving the emergency trip signal, connecting the lower cylinder chamber to the return line, accelerating the ESV fast-closure time. Even if the opening solenoid valve is not de-energized, de-energizing the trip solenoid valve alone is sufficient to achieve the fast-closure function.Under the energized hold-open condition of the trip solenoid valve, pressure oil from port P to port A keeps the cartridge valve closed, isolating the main oil passage B from the return ports X2(Y). A closed dead chamber exists between the solenoid valve port P and the cartridge valve control chamber C, i.e., the "trapped-oil" zone. Under normal instantaneous open/close conditions, the trapped-oil pressure is not significantly unbalanced, and drainage is unobstructed. However, when the valve remains open for several minutes or longer, the oil in the trapped zone is static without circulation, and the pressure state deviates from dynamic equilibrium. At the moment the trip solenoid valve is de-energized, the trapped oil cannot be rapidly relieved, delaying the pressure release of the cartridge valve control chamber, which in turn delays the cartridge valve opening sequence, macroscopically manifesting as a significantly increased fast-closure delay. The longer the static hold time, the greater the trapped-oil pressure imbalance and the more pronounced the delay. This structural design defect is common to all models in the series.

4. Optimization Retrofit Schemes and Test Verification

Two sets of measures-software logic optimization and hardware oil-circuit structural modification-were respectively developed for the two independent faults, and implemented stepwise on the test bench and in actual units.

4.1. Structural Modification Design

Without compromising the cartridge valve’s hold-open sealing capability, a micro-circulation pressure relief for the trapped-oil zone was achieved. An internal oil passage was machined inside the original manifold cover plate, connecting the trip solenoid valve port A to the return port Y, with a precision orifice of 0.8 mm diameter installed in the middle. The tiny throttling cross-section only allows continuous micro-drainage to balance trapped-oil pressure; the flow rate is insufficient to offset the solenoid valve’s hold-open pressure, thus not affecting the cartridge valve’s sealing performance. This fundamentally eliminates static trapped-oil pressure accumulation. In the original cartridge valve cover plate of the ESV hydraulic actuator, an additional passage from the solenoid valve inlet port A to the return port Y was added. Only the cover plate was replaced with the optimized version; all other components (solenoid valves, cartridge valve, hydraulic cylinder) were reused. Figure 4 illustrates the modification.

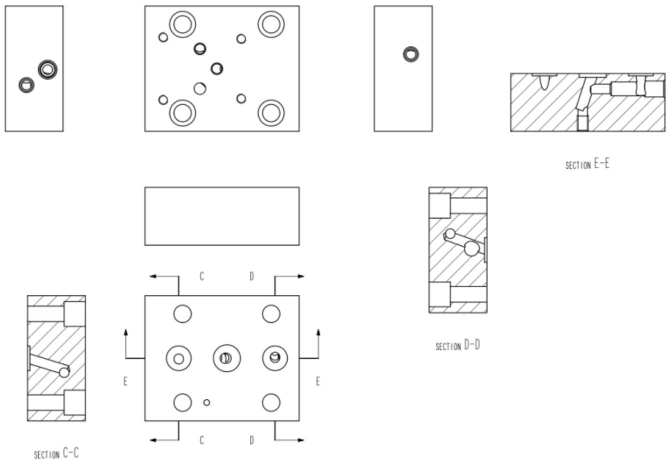

Figure 4: Optimized cartridge valve cover plate

4.2. Bench and Field Verification Results

The original hydraulic test bench replicated the 8-minute long-term open-hold condition of the Site B unit. Comparative tests after installing the optimized cover plate are shown in Figure 5 and Figure 6:

- Immediate fast-closure after full open: tv = 42 ms, ts = 235 ms, total time = 277 ms;
- Fast-closure after 8 min open-hold: tv = 45 ms, ts = 236 ms, total time = 281 ms.

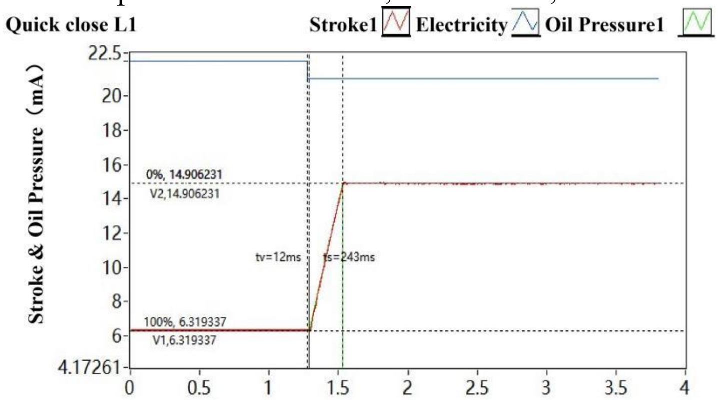

Figure 5: ESV immediate fast-closure (after cartridge cover plate optimization)

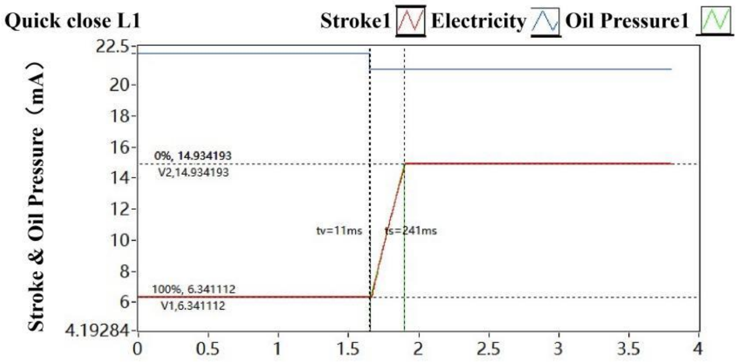

Figure 6: ESV fast-closure after 8 min hold (after cartridge cover plate optimization)

There was almost no difference in delay time between the two conditions, and the total closing time was stably below the 300 ms threshold. After the modified cover plates were batch-installed on Site B units, long-term operational spot-checks of static fast-closure performance remained fully compliant. Site D units were directly pre-equipped with the optimized cover plates during factory assembly, and no fast-closure over-limit issues occurred during commissioning.

5. Promotion Strategy and Full Life-Cycle Quality Improvement Suggestions

5.1. Graded Promotion Path

- New unit manufacturing: all units to be equipped with the optimized cartridge valve cover plate as standard; controllers pre-loaded with upgraded logic; 100% bench testing under both low-temperature and long-term hold conditions at factory to eliminate defects at source.
- In-service unit service: establish fault records; for units with open/close abnormalities or approaching major overhauls, batch retrofits (cover plate replacement and program upgrade) shall be carried out as a standardized value-added service.
- Technical documentation consolidation: incorporate the retrofit parameters, logic code, and cover plate machining drawings into the fuel actuator design specifications and on-site maintenance work instructions.

5.2. Long-Term Reliability Improvement Measures

- Medium adaptation upgrade: select low-temperature, high-viscosity-index anti-wear hydraulic oil to reduce viscosity variation over a wide temperature range, mitigating cold-start negative effects.
- Factory test expansion: add -10 ℃ low-temperature simulated start-up tests and 10-min long-term hold fast-closure endurance tests to expand factory quality inspection boundary conditions.
- Structural iterative optimization: re-check the overall oil circuit layout of the next-generation actuator to comprehensively identify and eliminate potential trapped-oil dead zones.
- Intelligent monitoring enablement: install oil temperature sensors and online ESV open/close time monitoring points; build fault early-warning models to achieve abnormal pre-alarm.

6. Conclusions

The direct cause of slow cold-start first-opening of the gas turbine hydraulic ESV is the increase in hydraulic oil viscosity and reduction in filling rate under low temperatures. The software solution of controller logic upgrade and manual exercising pre-heating before start-up can completely eliminate this fault and is applicable to all series.

The closed trapped-oil zone between the trip solenoid valve and the cartridge valve control chamber is the structural root cause of excessive emergency fast-closure delay after long-term valve open-hold. Adding a 0.8 mm throttling drain orifice in the cartridge valve cover plate can balance the trapped-oil pressure, ensuring that fast-closure performance after long-term static hold consistently meets specifications.

The coordinated software and hardware optimization schemes have been validated through bench tests and long-term operation on multiple actual units. The retrofits are cost-effective and maintain original safety redundancy. They can be proactively applied in new unit production as well as standardized retrofits for in-service units, effectively enhancing the reliability of the gas turbine fuel safety system while expanding revenue opportunities for maintenance services.

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