

Design and Application of a PLC-Based FSSS System for Gas-Fired Boiler

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Abstract

Based on a 260 t/h ultra-high-temperature subcritical gas-fired boiler power generation project at a steel plant, this paper designs a Boiler Furnace Safety Supervision System (FSSS) utilizing Siemens TIA Portal configuration software, WinCC monitoring software, and S7-1500 PLC hardware. The system incorporates key functional modules such as the Main Fuel Trip (MFT), furnace purging, first-out fault memory, and boiler ignition control. Actual unit operation has verified the comprehensive functionality of this FSSS system, providing valuable design and operational reference experience for similar boiler safety monitoring applications.

Keywords

Gas-fired Boiler; Furnace Safety Supervision; PLC; MFT.

1. Introduction

Currently, small and medium-sized gas-fired boilers are widely utilized in comprehensive energy utilization projects within industries such as petrochemicals and metallurgy. The gas-fired boiler power generation model primarily involves the combustion treatment of low-calorific-value gas: steel and metallurgical enterprises can fully utilize blast furnace gas—a byproduct of ironmaking—by feeding it into boilers for combustion. The working fluid is heated to the required state and then fed into steam turbines to drive generators. This approach maximizes the utilization of waste resources, aligning with national energy conservation and carbon reduction policies.

The Furnace Safety Supervisory System (FSSS) ensures the safe startup, shutdown, switching, and operation of all equipment within the boiler combustion system according to specified sequences. Crucially, it rapidly cuts off all fuel entering the boiler furnace under critical conditions, acting as a safety protection and control system to prevent boiler explosions [1,2]. The high degree of automation, efficiency, and reliability of FSSS make it an indispensable safety protection and burner management system for boilers.

This paper details the design and application of an FSSS system using the example of an 80 MW ultra-high-temperature subcritical generating unit at a steel plant in Handan. This project successfully achieved grid connection in August 2024. Its 260 t/h gas-fired boiler FSSS system underwent debugging, configuration, and optimization, smoothly passing the 168-hour full-load operation test. The system operates stably and reliably, providing a guarantee for the safe operation of the boiler.

2. Process Overview

This project employs a 260 t/h ultra-high-temperature subcritical natural circulation boiler with balanced ventilation and single reheat. The main burner fuel is blast furnace gas. Two layers of burners are installed, comprising four high-efficiency low-NO_x burners on the front wall and four on the rear wall, utilizing an opposed firing configuration. The boiler uses acetylene ignition with a

secondary ignition method (acetylene gas is first ignited by a high-energy igniter, which then ignites the main burner). The main design parameters of the boiler are listed in Table 1.

Table 1. Main Design Parameters of the Boiler

Numble	Item	BMCR
1	Superheated Steam Flow (t·h ⁻¹)	260
2	Superheater Outlet Steam Pressure (MPa)	17.4
3	Superheated Steam Temperature (°C)	571
4	Reheated Steam Flow (t·h ⁻¹)	187.9
5	Reheated Steam Inlet/Outlet Pressure (MPa)	3.94/3.76
6	Reheated Steam Inlet/Outlet Temperature (°C)	363/569
7	Boiler Flue Gas Temperature (°C)	140

During the ignition startup process, blast furnace gas and hot secondary air enter the furnace, creating a mixed combustion environment. The ignition guns are equipped with high-energy igniters and advance/retract mechanisms, enabling manual or automatic ignition. Quick-closing valves are installed on the blast furnace gas main header and individual burner branch pipes. This mechanism ensures rapid fuel supply cut-off during abnormal operating conditions (e.g., furnace Fireout, excessive furnace pressure), preventing furnace explosions caused by continued blast furnace gas supply. The boiler combustion system is illustrated in Fig. 1.

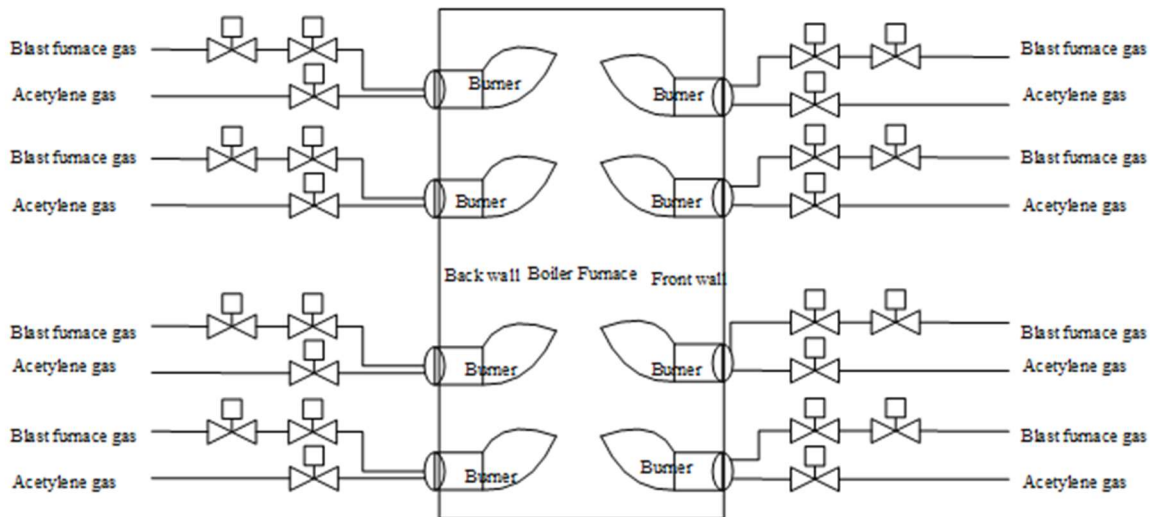


Fig. 1 Boiler Combustion System Diagram

3. Composition of the Furnace Safety Supervision System

The FSSS system for this project is PLC-centric, comprising the FSSS control cabinet, Fire detection control cabinet, process valves, instrumentation, and other controlled equipment. It forms a three-tier architecture (supervisory layer, control layer, and field device layer) to achieve process monitoring of field equipment, dynamic data display and recording, parameter setting, and management. The entire system features manual operation, self-diagnosis, alarm, and interlocking functions. The control system structure is shown in Fig. 2.

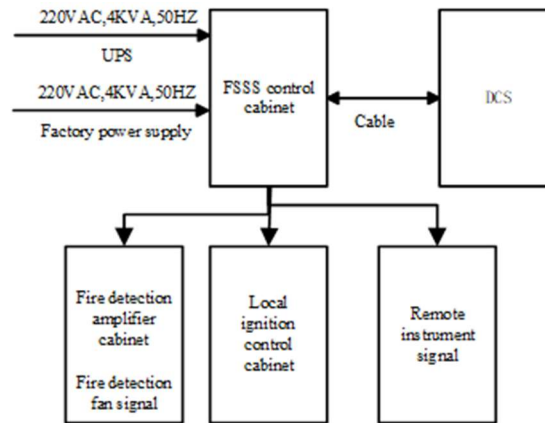


Fig. 2 Diagram Control System Structure Diagram

The system includes the following components:

- 1) FSSS Control Cabinet: 1 unit, housing the PLC controller and modules, circuit breakers, contactors, trip relays, and other components, providing robust control functionality.
- 2) Fire Detection Amplifier Cabinet: 1 unit. Signals from Fire detector probes for all burners and ignition guns are routed through this cabinet into the FSSS system, enabling monitoring of each burner and ignition gun status. Fire detectors provide feedback signals to the PLC indicating Fire presence, Fire intensity, and faults.
- 3) Local Ignition Cabinets: 4 units. These control the advance/retract of the 8 ignition guns (2 layers), the firing of high-energy igniters, and the opening/closing of quick-closing valves on the blast furnace gas pipelines.
- 4) Process Instrumentation: Detects signals such as boiler furnace pressure, forced/induced draft fan operation status, and blast furnace gas pressure. Controls actions like main fuel system valve opening/closing and ignition gun advance/retract.
- 5) DCS Interlock Signals: The boiler Distributed Control System (DCS) provides signal interfaces to the FSSS system. Interlock signals include boiler drum level signals, forced draft fan (FD) / induced draft fan (ID) status signals, and total air flow signals. These signals are transmitted to the FSSS system via hardwired connections for logic-based protection.

4. Architecture of the Furnace Safety Supervision System

4.1 PLC Main Control System

The FSSS control cabinet is powered by dual 220 VAC sources: one from the UPS and one from the plant emergency power supply. It is equipped with an automatic transfer switch (ATS) and provides internal 24 VDC power. The system employs Siemens S7 series PLCs as the main controllers. The hardware includes: 2 CPU 1515R-2 PN control modules (redundant), 2 PS 25W 24V DC PLC power modules (redundant), 15 DI 16×24VDC ST digital input modules, 8 DQ 16×24VDC/0.5A ST digital output modules, 5 AI 8×I 2-/4-wire BA analog input modules, 1 Engineering Station, 1 Operator Station.

The redundant configuration of the CPU and power modules significantly enhances the safety and reliability of the control system. If one system fails, the other automatically takes over operation to prevent boiler shutdown accidents caused by PLC hardware or software faults. The supervisory monitoring software uses Siemens WinCC V7.5, while the programming software for the PLC is TIA Portal V18. Communication between the supervisory computer (HMI) and the PLC uses Industrial Ethernet. The main control system diagram is shown in Fig. 3.

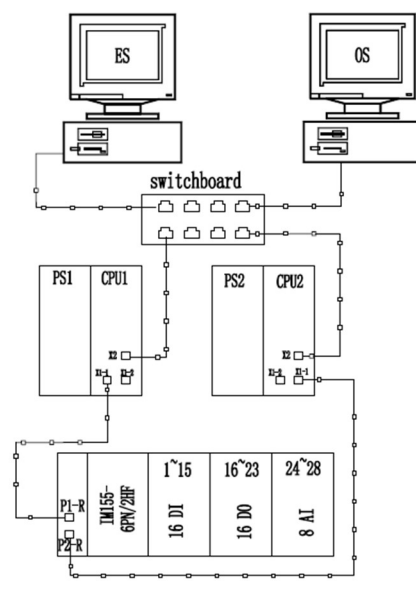


Fig. 3 PLC Main Control System Schematic

4.2 Local Ignition System

One local ignition control cabinet is installed near each corresponding burner. The control objects of the ignition cabinet include the high-energy igniter, the quick-closing valve on the ignition fuel line, the ignition gun, and its actuator. The ignition control system enables local and remote ignition/extinguishing of the ignition guns and controls the opening/closing of the blast furnace gas pipeline quick-closing valves. Upon MFT activation, the system automatically terminates the ignition process in the cabinets and closes the blast furnace gas quick-closing valves, ensuring no further fuel enters the boiler furnace.

4.3 Fire Detection and Cooling Air System

Fire detection equipment is critical within the boiler furnace safety supervision system of thermal power plants for determining the establishment/extinguishment of Fire in the entire furnace or within individual burner units. This equipment triggers alarms and FSSS system interlocks during full furnace Fire loss or burner unit Fire failure [3].

This project employs an explosion-proof ultraviolet (UV) split-type Fire detector (referred to as Fire scanner or FSS). Each burner and each ignition gun is equipped with one Fire scanner probe. The Fire scanner system outputs signals such as scanner fault, Fire intensity, and Fire present/absent to the PLC system. Since the scanner probes are installed in high-temperature zones of the boiler, a dedicated cooling air system, consisting of two redundant fans, is essential for their proper operation. Additionally, two differential pressure transmitters are installed at the outlet of the cooling fans to monitor fan outlet pressure differential. Three pressure transmitters (configured for 2-out-of-3 voting) are installed on the main cooling air duct. An alarm is triggered if the cooling air pressure drops low. If the pressure drops very low (Low-Low) for a sustained period (delayed by 30 minutes), the system generates an MFT signal to prevent the Fire scanner system from being damaged by overheating.

4.4 Process Instrumentation

The remote instrumentation in this section primarily serves interlock protection functions. It includes various critical pressure switches, transmitter signals, etc. The FSSS system also receives signals transmitted from the boiler DCS. When relevant instrument parameters exceed system setpoints, MFT will be triggered.

5. Functions of the Furnace Safety Supervision System

Several key points must be considered when designing a PLC-based FSSS system:

- 1) An independent hardwired trip circuit separate from the PLC system is essential. This allows operators to manually trip the boiler via a pushbutton, controlling trip relays to trigger MFT if the PLC fails.
- 2) For critical signals, a 2-out-of-3 voting logic is employed. Furthermore, these signals are wired into different PLC input modules via hardwiring to avoid FSSS function loss due to a single module failure.
- 3) This system designs a Sequence of Events (SOE) module specifically for capturing the First-Out cause of an MFT trip. This ensures that after an MFT occurs, the cause of the trip fault is displayed on the operator interface for troubleshooting.

The main functions of the FSSS system in this project include: Furnace Purging, MFT, and Boiler Ignition. The key protection functions are elaborated below.

5.1 Boiler Furnace Purging

Before starting the boiler, technicians must promptly, thoroughly, and systematically clean the internal furnace. The reason is that during shutdown periods, flammable elements may accumulate in locations such as the flue gas passages and the furnace itself. If air mixes with these elements in a certain proportion and encounters an ignition source, explosions can occur. Purging aims to eliminate these flammable elements, preventing accidental combustion within the boiler [4].

To safely execute this purging process, all the following conditions must be satisfied:

- 1) Main Fuel Trip (MFT) is active (tripped).
- 2) No conditions exist that would trigger MFT.
- 3) At least one forced draft (FD) fan is operating normally.
- 4) All quick-closing valves are closed.
- 5) All Fire detection devices indicate "No Fire".
- 6) Total air flow is maintained between 30% and 40%.
- 7) The Over Fire Air (OFA) damper angle is adjusted to the purge position, set to greater than 30%.
- 8) The burner air supply regulating damper angle is set consistently with the OFA damper, at an angle greater than 80%.
- 9) All blast furnace gas leak tightness checks are completed, and the boiler drum water level is adjusted.

The purging procedure is as follows: After MFT is triggered, if all the above conditions are met, the operator can issue a "Start Furnace Purging" command. A timer is then started, set for 600 seconds. If any of the purge permit conditions are violated during this time, the purging process is immediately aborted. Once the timer expires, the PLC system logs "Furnace Purging Complete". Furthermore, the "Furnace Purging Complete" flag can be reset upon receiving a "Reset MFT Command" or if the "Total Air Flow drops below 25% BMCR" (after a 600-second delay).

5.2 Main Fuel Trip Protection

The MFT mechanism is fundamentally safety-oriented-when the boiler cannot operate safely or when combustion conditions deteriorate significantly within the furnace, this mechanism actively cuts off all energy supply to the furnace to prevent potential hazardous situations [5,6,7,8]. The MFT trip logic is shown in Fig. 4. When a Main Fuel Trip occurs, all incoming fuel is cut off, and the boiler ceases operation.

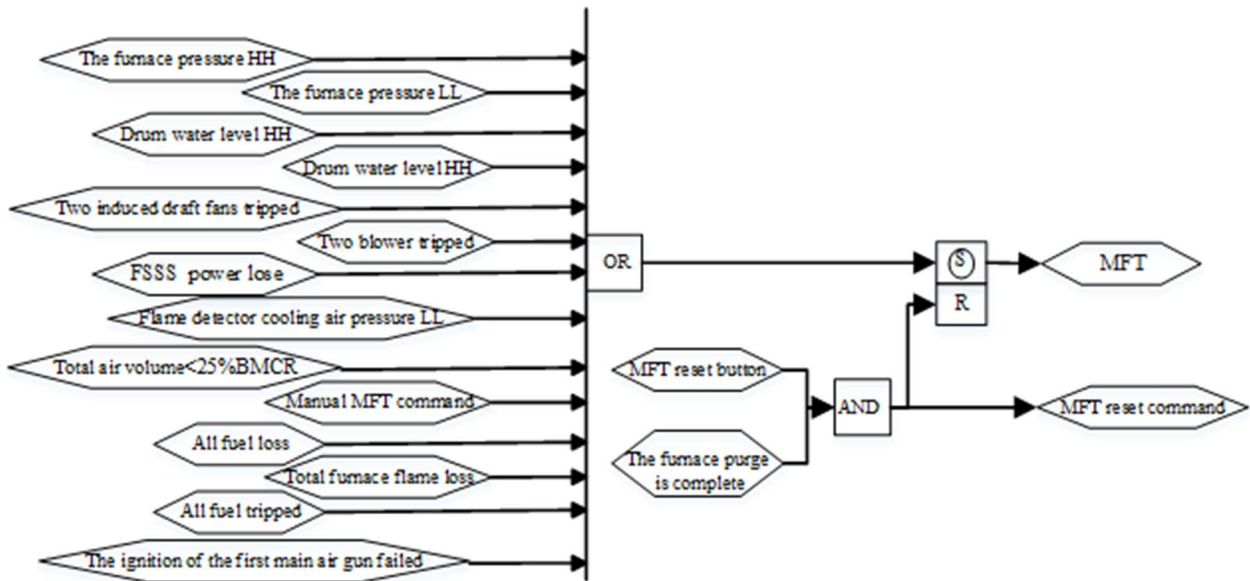


Fig. 4 MFT Trip Logic Diagram

After an MFT protective action is triggered, the FSSS system trips the relevant equipment. The specific protective actions for the boiler MFT in this project are listed in Table 2.

Table 2. MFT Trip Protective Action Devices

Numble	Item	Action Method
1	Close Main Fuel Line Quick-Closing Valve	Hardwired, Soft Logic
2	Close Ignition Fuel Line Quick-Closing Valve	Hardwired, Soft Logic
3	Retract All Ignition Guns	Hardwired, Soft Logic
4	Close Superheater Desuperheating Water Valve	Soft Logic
5	Close Reheater Desuperheating Water Valve	Soft Logic
6	Trip Steam Turbine	Soft Logic
7	Trip Intermittent Blowdown	Soft Logic
8	Interlock Damper Actions	Soft Logic

5.3 Boiler Ignition Logic

To ensure safety, the following conditions must all be satisfied before allowing the startup of the ignition gun sequence control (ignition permissive):

- 1) Control mode is PLC Automatic.
- 2) No ignition gun is signaling "Igniting".
- 3) Ignition gun header inlet quick-closing valve is fully open.
- 4) Ignition gun header pressure is not low.
- 5) Ignition gun header pressure is not high.
- 6) Ignition gun gas inlet quick-closing valve is fully closed.
- 7) "Ignition Gun Stopping" signal does not exist.
- 8) "Ignition Gun Trip" flag does not exist.
- 9) "First Ignition Gun Ignition Failure" flag does not exist.

The ignition control sequence for an ignition gun consists of the following three steps:

Step 1: Advance ignition gun; feedback is "Ignition Gun Advanced". After the advance command is issued, wait 15 seconds, then command ignition gun retraction.

Step 2: Fire the high-energy igniter for the ignition gun; feedback is "Ignition Gun Firing". The firing duration is controlled by the PLC.

Step 3: Open the ignition gun gas inlet quick-closing valve; feedback is "Ignition Gun Gas Valve Open".

If the action and feedback for any step are not achieved, the PLC will set the "Ignition Sequence Control Failed" flag.

The stop control sequence for an ignition gun consists of the following two steps:

Step 1: Close the ignition gun gas inlet quick-closing valve; feedback is "Ignition Gun Gas Valve Closed".

Step 2: Retract the ignition gun; feedback is "Ignition Gun Retracted".

If the action and feedback for any step are not achieved, the PLC will set the "Stop Sequence Control Failed" flag.

6. Summary

During the equipment commissioning phase, the FSSS hardware and software demonstrated safety and reliability, with protective actions strictly executed according to specifications. The PLC-based boiler FSSS system was designed in strict compliance with relevant national standards. Its application in the blast furnace gas-fired boiler power generation project at the steel plant, validated through actual operation, effectively reduces operator workload, enhances boiler safety and stability, and lays a solid foundation for the efficient and economical operation of the steel plant.

Future research will place greater emphasis on enhancing intelligence and automation levels to achieve comprehensive and precise monitoring of the boiler furnace and combustion system. Concurrently, with the continuous development of technologies such as the Internet of Things (IoT) and big data, FSSS systems will be capable of remote monitoring and fault prediction, further improving power plant operational efficiency and safety. Additionally, FSSS systems will focus on reducing energy consumption and emissions, contributing to the green and sustainable development of power plants.

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