Design and Implementation of Dual Core Network in Digital Workshop

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Abstract: With the in-depth integration of informatization and industrialization, as well as the rapid development of the Internet of Things (IoT), the deployment methods and communication protocols of workshop-level industrial control systems have become increasingly complex. Constructing dedicated industrial control system networks to integrate different devices and systems has raised higher requirements for the real-time performance, accuracy, and stability of information transmission in digital workshop network systems. This paper, based on the requirements for integration and interconnection of digital workshops, designs a dual-core redundant "ring + star" hybrid network topology structure. By independently designing the production control network and the production management network, it meets the business requirements of different industrial control systems and production management systems, effectively reduces the failure rate of workshop networks, enhances the reliability of information transmission between devices and systems, and lays a foundation for the stable operation of various businesses in digital workshops.

Keywords: Digital Workshop; Automatic Control; Star Network; Dual-Core Redundancy

1. Introduction

In the construction process of digital workshops, to execute task processing at the basic layer of digital workshops and achieve communication between control devices and field devices, network communication methods such as field buses, industrial Ethernet communications, and wireless communications can be adopted. The stability and reliability of workshop-level industrial control network systems are the foundation for the stable operation of production lines. With the development of computer and network technologies—particularly the integration of new-generation information technologies and advanced manufacturing technologies—the deployment methods and communication protocols of workshop-level industrial control systems have become increasingly complex. Constructing dedicated industrial control system networks that can adapt to on-site requirements (e.g., equipment from different manufacturers, varying protocols, and diverse production environments) and coordinate equipment to complete production, manufacturing, and information management and control has become particularly important [1]. Based on the differing requirements of various business functions for network systems, this paper designs a hybrid network topology structure comprising two components: the production control network and the production management network. The production control network is primarily used for network connections between PLC control systems, between PLC control systems and centralized monitoring systems, and between PLC control systems and engineer stations. The production management network serves as the main interface device between the workshop and external networks. It connects to the factory local area network (LAN), interfaces with enterprise-level systems such as Manufacturing Execution Systems (MES) and Enterprise Resource Planning (ERP), facilitates the issuance of data (e.g., production work orders, process routes, process parameters, and maintenance plans), and enables the feedback of various production-related information in digital workshops. This structure provides workshop management information services for enterprises' production, quality inspection, process, and logistics departments [2].

2. Current Situation Analysis

In accordance with the relevant requirements of the network capability sub-domain in the smart manufacturing capability maturity model, digital workshops should establish a highly efficient, secure, and fully interconnected network environment to meet the operational needs of internal networks, external networks, wired networks, wireless networks, production information networks, industrial control networks, and office networks related to workshop production. By fully considering network redundancy design, boundary isolation between networks, access control, and other conditions, visualized management of the network environment is achieved through network device monitoring and network platform management. Therefore, building a highly reliable network architecture is the foundation for ensuring stable production and manufacturing in workshops. However, delays or jitter in workshop-level industrial control network systems caused by the lack of systematic design have significant impacts on the production environment, even leading to phenomena such as production shutdowns or material supply interruptions. In summary, the stability of industrial control networks and the redundancy of network architectures are fundamental requirements for the network design of digital workshops [3]. The design of workshop-level industrial control networks is evolving toward a digital, networked, open, and integrated industrial internet direction. Industrial control networks are responsible for network communication of production control systems such as PLCs, DCS, and SCADA, while production management networks handle network communication for management systems such as production operation management systems, quality systems, and equipment operation and maintenance management systems. Different functional networks adopt distinct design methods, following industrial network design standards and traditional TCP/IP Ethernet design standards to achieve interconnection and interoperability between devices, systems, and businesses [4].

3. Design of Industrial Network in Digital Workshops

Currently, most core switches in digital workshops adopt high-performance industrial switches with Layer 3 routing capabilities. However, due to the large number of terminals connected to core switches, operators often only enable the Layer 2 functionality of these switches for easier management and maintenance [5]. During network communication peaks, this setup can instantly cause switching delays, resulting in low network communication efficiency and a large number of packet losses. To meet the stability and redundancy requirements of digital workshops for interconnected networks, this paper designs a hybrid ring + star network topology. By combining two single topology structures, the advantages of both are leveraged to form the physical connection method of the topology.

Based on the process control requirements, workshop layout, and control/information application needs of digital workshops, the overall topology diagram of the workshop network system is designed as follows: Horizontally, it is divided into the production control network and the production information network. Vertically, it is structured into three layers: the workshop convergence layer (L2), the workshop main access layer (L1), and the workshop field access layer (L0) [6]. As shown in the figure 1.

The production control network's convergence layer (L2) and main access layer (L1) primarily adopt a ring network topology, while the field access network (L0) uses a star network topology. The convergence layer (L2) employs two high-performance Layer 3 industrial switches to form a redundant ring. Redundant 10G single-mode fiber optic modules are configured to reserve interfaces for the upper-level plant network. The main access layer (L1) utilizes four Gigabit fiber optic ring networks, specifically: the A-line main ring network, B-line main ring network, C-line main ring network, and Geng-line main ring network. Each main ring network uplinks to the convergence switches of the L2 convergence layer through two switches on the ring, forming inter-ring redundant coupling with the convergence layer ring network. The field access network (L0) adopts a star topology to connect to the main network. Each PLC is equipped with two network interface cards (NICs): one connects upward to the production control main network, and the other connects downward to the PLC control subnet, linking distributed I/O substations, frequency converters, electronic scales, moisture meters, and other control devices within the segment.

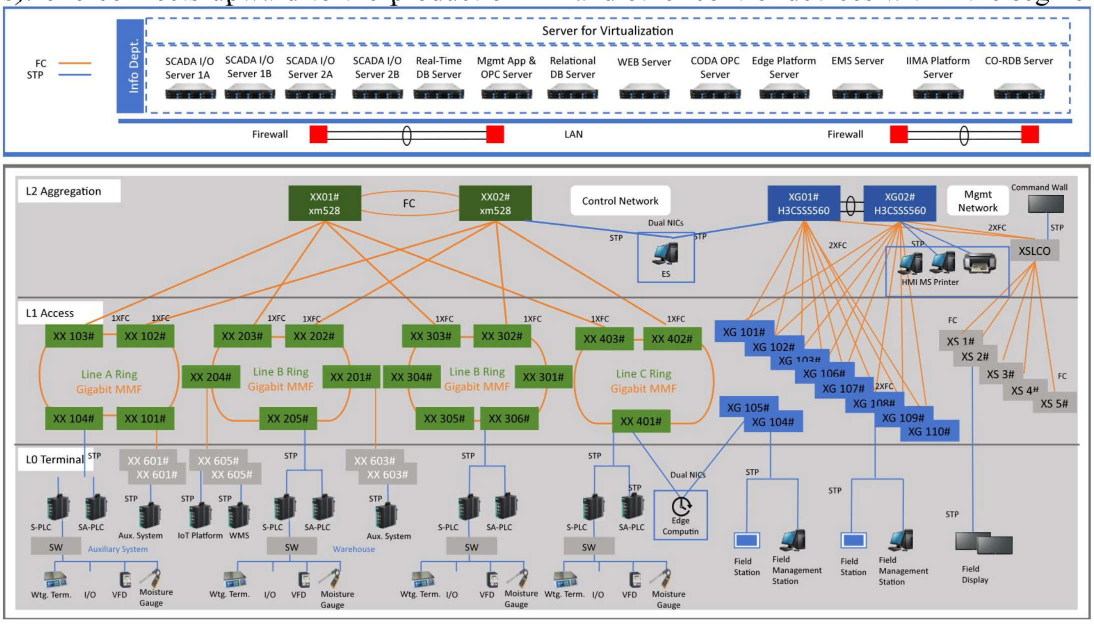

Figure 1 Workshop Dual-Core Redundant Network Architecture

The production management network's convergence layer (L2), main access layer (L1), and field access network (L0) all adopt a star network topology. The convergence layer (L2) uses two three-layer high-performance commercial switches to form a redundant ring, with redundant 10G single-mode fiber optic modules configured to reserve interfaces for the upper-level plant network. The main access layer (L1) employs a star topology, where each main access switch redundantly connects to the L2 convergence switches via two Gigabit fiber optic links. The field access layer (L0) connects to the main network using a star topology. Notably, the on-site industrial display systems form a separate network before connecting to the information network's convergence L2 switches. Both the production control network and the production management network are configured with 10G single-mode optical interfaces at their respective convergence switches. These interfaces uplink to the plant-level network, achieving network connectivity with the virtualized server platform of the information center [7].

3.1 Communication Protocols of the Workshop Network System

Based on process control requirements, workshop layout, and control/information application needs, the workshop network system is designed into a production control network and a production management network, with vertical stratification into a workshop convergence layer, a workshop main access layer, and a workshop field access layer. According to the communication requirements of the production control network, network communication within the control system can be categorized from bottom to top into industrial bus Ethernet communication and standard industrial Ethernet communication. The production management network adopts standard Ethernet communication. Industrial bus Ethernet includes 50ms-level industrial bus network communication between PLCs in each control segment and their local distributed I/O substations, frequency converters, intelligent detection instruments, intelligent control units, etc. Standard industrial Ethernet includes 100ms-level standard industrial Ethernet communication between PLCs across segments, as well as between SCADA I/O servers and controllers (PLCs), and between engineer stations and controllers (PLCs). Standard Ethernet covers communication between database servers, Web servers, OPC servers, and SCADA I/O servers; between management terminals, engineer stations, monitoring PCs, and servers; and between Web servers, OPC servers, and the plant-level network [8]. As shown in the figure 2.

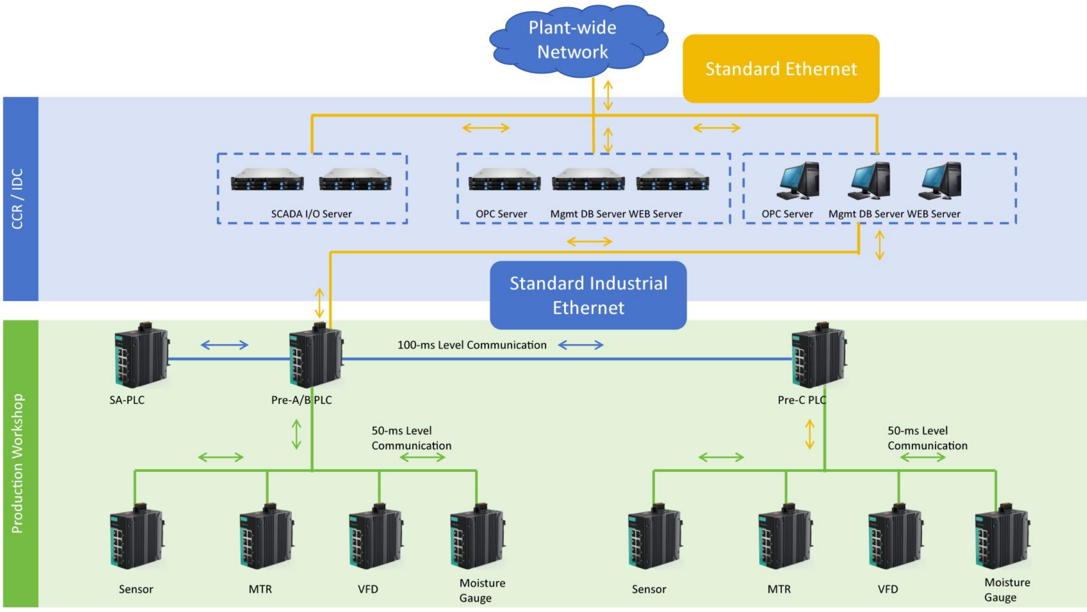

Figure 2 Communication Protocol for Workshop Dual-Core Redundant Network

3.2 Requirements for Workshop Network Design

In the construction of digital workshops, it is necessary to achieve interconnection and interoperability of all factory business terminals (PLCs, SCADA, MES), while comprehensively considering requirements such as physical link redundancy, industrial real-time data switches, bandwidth, latency, packet loss rate, broadcast storm isolation, and rapid self-healing and reconstruction of the network. After the completion of the workshop control network deployment, the design will be carried out from the following aspects:

(1) Appropriate Link Redundancy and Rapid Recovery: Industrial networks achieve appropriate physical link redundancy through industrial redundancy protocol technologies such as ring networks, ring cutting, and inter-ring coupling. Meanwhile, they ensure millisecond-level rapid network convergence and recovery.

(2) Hierarchical Flow Control and Bandwidth Reservation: A hierarchical design is implemented for real-time and non-real-time communication at the lower layer. Combined with industrial redundant Layer 2 protocol control, this guides the rational flow of data streams from all terminals, provides different bandwidth reservations between layers, and achieves optimal network performance design.

(3) Redundancy of Network Devices and Terminals: Dual redundancy of routers and terminals is achieved through designs based on VRRP (Virtual Router Redundancy Protocol) and terminal dual network cards.

(4) Network Quality of Service (QoS) Control: The quality of service of industrial switches ensures low latency for industrial real-time data communication, providing guarantees to meet the needs of industrial communication.

3.3 Security Requirements for Workshop Industrial Networks

In accordance with the Guidelines for Information Security Protection of Industrial Control Systems and specific information security requirements of certain industries, the construction of workshop control networks necessitates the division of security domains and logical isolation. Monitoring of network status and auditing of operational log behaviors are required for the workshop backbone network. Considering the technical characteristics of industrial Ethernet applications, necessary optimizations to the traditional control system network architecture are needed to adapt to the stability of automated control on workshop processing lines. Additionally, through boundary isolation of workshop control systems, zonal protection, monitoring and auditing of abnormal internal network communications, and unified monitoring and management of security devices within the system, a security management system is formulated to ensure the secure operation of the system.

3.4 Key Technologies for Dual-Core Redundant Network Design

OSPF (Open Shortest Path First) is the most commonly used dynamic routing protocol in industrial and IT networks. During configuration, the uniqueness of the Router ID must be ensured to avoid conflicts. Furthermore, route redistribution is used to control the size of the routing table. If the number of subnets remains excessive, dividing the network into areas combined with route redistribution can further limit the routing table size. The advantage of enabling OSPF dynamic routing lies in its simplicity and ease of route learning, though it may pose challenges in controlling the scale of the routing table. Thus, in scenarios with clear routing communication, combining OSPF with static routing can achieve optimal routing implementation.

VRRP (Virtual Router Redundancy Protocol) is designed solely for router redundancy and does not participate in route calculation or routing table formation. The routers involved in VRRP can range from 2 to a maximum of 16, with the virtual redundant router not grouped by physical routers but by VLANs. Through VRRP, dual redundancy backup and load balancing of physical routers can be achieved. VRRP can also be combined with static routing or OSPF in a single network to realize the dual effects of optimal routing, router redundancy, and load balancing [9].

3.5 On-Site Implementation Principles for Workshop Control Networks

(1) Dual redundant power supplies are adopted for the backbone switches of the production control network and production management network. One power supply uses an enterprise-level UPS, and the other uses standard mains power. This ensures network stability if either circuit fails.

(2) All network cables are laid within cable trays or pipelines and must not be exposed. Cable installation complies with relevant national standards, with network cables separated from power cables and control/communication cables to minimize interference with control and communication signals [10].

(3) For Ethernet cabling over long distances or in areas with strong interference sources, optical fibers are selected. Industrial shielded twisted pair cables are used to avoid electromagnetic interference.

(4) During cable tray installation, bending angles exceeding allowable limits that could damage communication lines are avoided. Additionally, network communication cables must be protected from wear, cutting, rolling, moisture, or prolonged exposure to high-temperature environments during installation.

(5) To enhance safety and reliability, all direct connections use dual-link protection, and connected ports are ensured not to reside on the same board.

4 Workshop Network Operation and Maintenance

4.1 Workshop Network Operation and Maintenance Platform

Industrial network management software platforms primarily address the unified management of all network devices (mainly industrial switches and firewalls), including detailed device acquisition, topology visualization, configuration management, and security policy maintenance. This enables timely localization and maintenance of industrial network faults, reducing unplanned network downtime. Equipped with industrial network management software, scanning and configuring IP addresses for newly added switches connected to the control network via the management software can achieve the following information functions.

4.2 Perception of Workshop Network Status

Industrial network management software enables automated network management, presenting network settings, device statuses, and tracking records through a visual interface. It aggregates data collected from terminals, networks, applications, and other levels of the industrial control network to perceive the current network status in real time. By analyzing the results of network status monitoring, network security administrators can understand the overall security posture of the network, target vulnerable assets for reinforcement, and enhance network security and attack resistance.

4.3 Centralized Configuration and Distribution of Workshop Policies

Based on the management platform, batch

unified configuration changes, firmware system management, and policy management for all network devices are achieved. Industrial network management software can perform tasks such as firmware downloads, system backups, and database cleanups for devices, as well as update settings for all devices, specific device types, or individual devices. The system scans and records all devices to check compliance and adjust device settings.

4.4 Timely Early Warning and Handling of Workshop Faults

Industrial network management software provides visual alerts through multiple methods when faults occur in the workshop's industrial control network, facilitating efficient maintenance by personnel. Through this platform, anomalies in the network are promptly reported to managers, accurately locating the detailed position of network faults and improving fault resolution efficiency.

4.5 Centralized Management of Workshop Network Devices

This function enables detailed visualization of all network device information (topology, traffic, device configurations, etc.). The number and appearance of visible devices can be customized for specific users, with logical or physical zone-based configurations to display the topology and status of specific network nodes. For each view, an additional topology display is generated, allowing free arrangement and networking of assigned devices. These created views can then be assigned to required users.

5. Conclusion

Under the dual-core network architecture of digital workshops, VRRP in the industrial control network enables multiple routes to collaborate and back up each other, while OSPF assumes the role of "pruning" redundant lines, preventing broadcast storms, and achieving link load balancing. Redundant network design is essential for improving the reliability and availability of production networks in digital workshops. When any physical link in a ring network port fails, traffic is automatically redirected to other links, realizing link redundancy and reducing the probability of network interruptions from multiple dimensions. For industrial management networks, non-industrial-grade switches can be used for design considering cost-effectiveness and stability. However, unreasonable design or deployment (e.g., topology layering, VLAN division) may still lead to excessive network redundancy, reduced performance, and resource waste. Therefore, thorough preliminary research and scientifically rational resource allocation are critical during network design.

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