Nuclear Power Plant Time Synchronization System Design Optimization Postprint

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Abstract

Nuclear power plant sites are extensive, with numerous time-synchronization systems that are widely distributed, each having different precision requirements and interface formats. Consequently, multiple independent time-synchronization systems currently exist within nuclear power plants, preventing the sharing of clock signals. To address the issues of independent clocks among various systems and redundant configuration of time-synchronization systems, this paper analyzes the time-synchronization methods, precision requirements, and transmission channels of equipment within nuclear power plants, and subsequently proposes a plant-wide unified clock source time-synchronization network architecture. This network is configured with a high-precision, high-reliability master clock system and GPS/BeiDou dual-mode antennas, which significantly enhances system availability; the master clock and secondary clocks are connected via optical fiber cables, and the precision of the secondary clocks is improved by configuring the transmission delay of the optical fiber cables. Analysis results demonstrate that this time-synchronization network achieves substantial improvements in both reliability and time-synchronization precision, realizing a unified optimization of technical and economic considerations.

Full Text

Preamble

Title: Design and Optimization of Time Synchronization System in Nuclear Power Stations
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Abstract

The devices requiring time synchronization in nuclear power stations are numerous and broadly distributed, with varying precision requirements and interface types. Consequently, multiple independent time synchronization systems currently coexist, preventing clock signal sharing. To address the problems of isolated clocks and redundant system configurations, this paper analyzes equipment timing methods, precision requirements, and transmission channels in nuclear power stations, and proposes a unified, plant-wide timing network structure with a single clock source. This system significantly enhances availability through its high-precision, high-reliability master clock system and GPS/BeiDou dual-mode antenna. Optical fiber connections between master and slave clocks, with configured transmission delay compensation, improve secondary clock precision. Analysis results demonstrate that the optimized timing network substantially improves both reliability and synchronization precision, achieving technical and economic optimization.

Keywords: Nuclear power station, time synchronizing network, time synchronizing precision, transmission delay

1 Introduction

With increasing automation and intelligence of electrical and control systems in nuclear power stations, more device functions depend on accurate, secure, and reliable clocks. Equipment including relay protection devices, automation systems, security and stability control systems, production information management systems, and Digital Control Systems (DCS) all require a unified time reference to meet time consistency requirements for sequence-of-events recording, fault waveform recording, and real-time data acquisition. This ensures accurate line fault location, dynamic monitoring of phasors and power angles, unit parameter verification, and stable control levels, thereby improving plant operational efficiency and reliability. Nuclear power plants have large footprints with numerous systems and devices requiring synchronization across nuclear islands, conventional islands, and Balance of Plant (BOP) buildings. Currently, most systems are equipped with dedicated timing systems, preventing clock signal sharing among different systems. This fragmented approach creates technical inconsistencies and economic waste, and some systems have overly simplistic configurations that fail to meet required precision and reliability standards. To address these issues, this paper proposes a unified, plant-wide timing network with high precision and reliability.

2.1 Time Synchronization Methods

Timing methods for power plant and substation automation equipment primarily include four types: pulse timing, serial interface timing, coded timing, and network timing.

(1) Pulse Timing. Also known as hard timing, this method uses the accurate edge of a pulse to calibrate the device being synchronized. Pulse timing includes Pulse Per Second (PPS), Pulse Per Minute (PPM), and Pulse Per Hour (PPH) signals.

(2) Serial Interface Timing. This method typically involves the clock source sending timing messages to the device being synchronized via a serial interface. Serial interface time information outputs one frame per second, with common data transmission rates of 9,600 bit/s. The serial timing message content includes year, month, day, hour, minute, and second, and may also include other user-specified information such as the number of GPS satellites received and alarm signals.

(3) Coded Timing. The IRIG time code sequence was proposed by the Inter-Range Instrumentation Group (IRIG) and is widely used in time information transmission systems. The code sequence is divided into six encoding formats: G, A, B, E, H, and D. IRIG-B code is one of these formats, containing complete time information including year, month, day, hour, minute, and second. As an internationally recognized time code, IRIG-B features simple timing circuits and complete absolute time-scale information, making it widely applied in industrial control, power systems, and military fields.

(4) Network Timing. Network timing is based on the Network Time Protocol (NTP) and Precision Time Protocol (PTP), using a monitoring clock or GPS clock as the master clock to transmit timing information in data frames to each synchronized device. Upon receiving the message, the synchronized device parses the frame to obtain current time information and adjusts its own time to achieve synchronization with the master clock. The round-trip time of messages in the network can be estimated, enabling precise synchronization through compensation algorithms. The timing accuracy depends on characteristics of the synchronization source and network path. The Simple Network Time Protocol (SNTP) recommended by the IEC 61850 standard is a type of network timing that simplifies NTP server and client strategies, providing comprehensive access to national time and frequency dissemination services, organizing time synchronization subnets, and enabling each local clock in the subnet to adjust its time.

2.2 Time Signal Transmission Channels

Time signal transmission channels should ensure that time signals from the master clock meet the quality requirements of user equipment when transmitted to them. The following channel types are generally available for selection:

(1) Coaxial Cable. Used for high-quality transmission of TTL-level signals such as PPS, PPM, PPH, and IRIG-B (DC) code TTL-level signals, with transmission distances not exceeding 10 meters.

(2) Shielded Twisted Pair. Used for transmitting RS-232 interface signals within protection rooms, with transmission distances not exceeding 15 meters; also used for transmitting RS-422/RS-485 and 20mA current loop interface signals within protection rooms, with transmission distances not exceeding 150 meters.

(3) Audio Communication Cable. Used for transmitting IRIG-B (AC) signals, with transmission distances not exceeding 1,000 meters.

(4) Optical Fiber. Used for long-distance transmission of various time signals, with transmission distances depending on fiber type. Generally, multi-mode fiber transmission distances do not exceed 2,000 meters, while single-mode fiber transmission distances are not limited.

3.1 Equipment Requiring Time Synchronization

Equipment requiring time synchronization in nuclear power stations is primarily distributed in the 500kV switchyard, 220kV auxiliary substation, nuclear island electrical building, and conventional island building. Equipment in the 500kV switchyard, 220kV auxiliary substation, and conventional island building mainly includes power system protection, measurement and control, fault recording, Power Management Unit (PMU), fault location, and energy acquisition devices, with IRIG-B code as the primary timing signal type. Equipment in the nuclear island electrical building requiring synchronization mainly includes nuclear power plant radiation monitoring, data acquisition, instrumentation, and DCS systems, as well as some electrical protection and measurement and control devices located in the nuclear island, using timing signal types including NTP, serial messages, and IRIG-B code. Additionally, digital clock systems distributed throughout various nuclear power plant facilities also require synchronization using IRIG-B code interfaces.

3.2 Time Synchronization Accuracy

Power automation equipment and systems have different accuracy requirements for time synchronization, rather than simply pursuing higher precision as commonly assumed. Improved timing precision comes at corresponding costs. Therefore, it is unnecessary to blindly pursue high precision; the principle is to meet the minimum resolution requirements of the synchronized device itself. Reference [1] studied the time synchronization accuracy requirements for power system equipment, broadly dividing them into four categories with accuracies no greater than 1 s, 1ms, 10ms, and 1s. The accuracy requirements for equipment in nuclear power stations are as follows:

(1) Time synchronization accuracy no greater than 1 s: Line traveling wave fault location and PMU.

(2) Time synchronization accuracy no greater than 1ms: Power system relay protection, measurement and control, fault recording devices, and nuclear power plant monitoring, data acquisition, instrumentation, and DCS systems.

(3) Time synchronization accuracy no greater than 1s: Energy acquisition and digital clock systems.

3.3 Impact of Time Synchronization Accuracy on System Function

Line traveling wave fault location and PMU are the two systems with the highest clock precision requirements in nuclear power stations, and their function implementation depends on timing accuracy. The key to traveling wave fault location is recording the arrival time of current or voltage traveling waves at both ends of the line. The traveling wave propagation speed is approximately the speed of light at 300 km/ s, meaning a 1 s timing error corresponds to a location error of approximately 150 meters. To ensure fault location accuracy within a few hundred meters, the timing system error must be controlled within a few microseconds.

PMU requires synchronized sampling of voltage and current at different nodes of the power system under a unified time scale to generate synchronous samples for system state analysis on a unified time coordinate. Timing system precision has minimal impact on amplitude measurement but significant impact on phase angle measurement. For 50Hz voltage and current signals, a 1 s time error corresponds to a phase angle error of 0.018°. Reference [3] analyzed the impact of time errors generated in various stages of the PMU system on system performance and provided solutions.

4.1 Network Structure

Time synchronization systems can be configured in various ways, with typical forms including basic, master-slave, and master-standby configurations. Large power plants, 500kV substations, and similar critical applications should adopt master-standby time synchronization systems to improve reliability. Given that nuclear power stations have more equipment requiring synchronization, broader distribution, and higher reliability requirements, this paper proposes a unified, plant-wide timing network with high reliability and precision, as shown in the figure below.

[FIGURE:N] *Network of time synchronizing system in nuclear power station*

Independent master clock systems are installed in the 500kV switchyard and 220kV auxiliary substation to meet the timing requirements of electrical equipment in these buildings. Each master clock system is configured with two master clocks that mutually synchronize via IRIG-B code. A slave clock is installed in the nuclear island electrical building, receiving time reference signals from the master clocks and providing autonomous time reference signals for time signal expansion. All timing expansion devices and slave clocks receive timing reference signals from these two independent clock systems, ensuring high reliability of the clock signal source. Additionally, optical transceivers in the 220kV auxiliary substation convert IRIG-B electrical signals to IRIG-B optical signals, which are distributed to plant-wide digital clocks through a tree-shaped optical fiber network.

4.2 Master Clock

The master clock consists of five components: a power processing unit, GPS/BeiDou satellite signal reception and IRIG-B signal processing unit, central timing processing unit, human-machine interface unit, and expansion signal output unit. The master clock can receive GPS, BeiDou, and IRIG-B code as reference time signals. When any currently active signal experiences performance degradation or loss, the device automatically switches to track the next available reference time signal. If all three reference time signals become unavailable, the master clock maintains high-precision time synchronization signal output through its built-in high-stability crystal oscillator holdover function, with holdover accuracy better than 1 s/hour.

The master clock employs a high-precision phase-locked loop to track the active time reference, achieving timing accuracy better than 1 s. Output signal types include IRIG-B code, pulse signals, and serial messages, with interface types including TTL level, RS-422/RS-485, Ethernet, and optical fiber.

4.3 Slave Clock

The slave clock has the same characteristics and operating principle as the master clock but does not have an antenna and can only receive IRIG-B code signals output from the master clock as its time reference signal.

4.4 Reliability

Each master clock is configured with a GPS/BeiDou dual-mode antenna capable of receiving both GPS and BeiDou time signals. The master clock can be configured to use either GPS or BeiDou as the primary time reference signal, with the other as the backup. Each independent clock system has two master clocks that mutually calibrate time via IRIG-B code, ensuring that loss of one master clock does not affect normal operation of the clock system.

Timing expansion devices and slave clocks can obtain time reference signals from both independent master clock systems. As shown in the network structure diagram, each synchronized device can receive timing signals from four master clocks. Loss of satellite signal or failure of one master clock cabinet does not affect the reliability of the timing network. Even if both master clocks in one clock system fail due to power loss, plant-wide synchronized equipment can still receive reliable timing signals.

4.5 Network Delay

Timing system precision primarily depends on satellite signal accuracy and the processing delay of timing equipment and networks. From an engineering application perspective, this paper does not analyze satellite signal accuracy but briefly discusses the impact of network delay on precision.

Network delay refers to the time required from when the master clock receives the satellite time signal until the time signal is transmitted to the synchronized device, mainly including delays generated by electronic devices processing and forwarding time signals, as well as transmission channel delay. For the former, master and slave clock equipment have corresponding compensation mechanisms; for the latter, compensation must be applied based on signal transmission channel length. When time signals are transmitted between master and slave clocks via optical cable, the channel delay can be calculated by the following formula:

$$! = L$$

where C is the speed of light, L is the transmission distance, and n is the refractive index of the fiber core, with a typical value of 1.48.

From this formula, the transmission delay of optical signals in fiber is approximately 4.9 s per kilometer. In one nuclear power station, the timing optical cable length reaches 3km, corresponding to a network delay of 15 s. This demonstrates that to ensure timing network precision, channel delay compensation must be performed at the slave clock side based on the length of each optical cable.

5 Conclusion

This paper systematically reviews the timing requirements of nuclear power stations, presents common timing solutions and channel requirements, and proposes a unified, plant-wide timing network structure with high reliability and precision that meets the requirements of timing equipment in nuclear power stations. This timing network achieves technical and economic optimization, avoids redundant construction of clock systems, and considers the convenience of network expansion to accommodate timing extensions in buildings with different construction schedules. This solution also provides a valuable reference for timing networks in conventional power plants.

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