Design Optimization of Nuclear Power Plant Time Synchronization System (Postprint)

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Abstract

Nuclear power plants feature extensive premises, with numerous time synchronization systems that are widely distributed and have varying accuracy requirements and interface types. Consequently, multiple independent time synchronization systems currently coexist within nuclear power plants, precluding the sharing of clock signals. To address the issues of mutually independent clocks among various systems and redundant configuration of time synchronization systems, this paper analyzes the time synchronization methods, accuracy requirements, and transmission channels of equipment within nuclear power plants, and subsequently adopts a plant-wide unified clock source time synchronization network architecture. This synchronization network is configured with high-precision, high-reliability master clock systems and GPS/BeiDou dual-mode antennas, substantially enhancing system availability; master clocks and secondary clocks are connected via optical fiber cables, with transmission delays configured to improve secondary clock accuracy. Analysis results demonstrate that this synchronization network achieves significant improvements in both reliability and time synchronization accuracy, realizing a unified optimization of technical and economic considerations.

Full Text

Preamble

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Abstract

The devices requiring time synchronization in nuclear power stations are numerous and widely distributed, with varying precision requirements and interface modes. Consequently, multiple independent time synchronization systems currently coexist, preventing clock signal sharing. To address the problems of isolated clocks and redundant system configuration, this paper analyzes equipment timing methods, precision requirements, and transmission channels in nuclear power stations, and proposes an optimized timing network with a unified clock source for the entire plant. This network employs high-precision, high-reliability master clock systems and GPS/BeiDou dual-mode antennas, significantly improving system availability. Optical fiber connections between master and slave clocks, with configured transmission delay compensation, enhance secondary clock precision. Analysis results demonstrate substantial improvements in both reliability and timing precision, achieving technical and economic optimization.

Keywords: Nuclear power station, time synchronizing network, time synchronizing precision, transmission delay
Classification: TM73

1 Introduction

With increasing automation and intelligence of electrical and control systems in nuclear power stations, equipment functionality increasingly depends on accurate, secure, and reliable clocks. Devices such as relay protection equipment, automation devices, security and stability control systems, production information management systems, and Digital Control Systems (DCS) all require a unified time reference. This ensures time consistency for sequence-of-events recording, fault waveform recording, and real-time data acquisition, while guaranteeing accuracy in line fault location, phasor and power angle dynamic monitoring, and unit parameter verification—ultimately improving power plant operational efficiency and reliability [1]. Nuclear power stations cover large areas with numerous systems and devices requiring time synchronization across the nuclear island, conventional island, and Balance of Plant (BOP) buildings. Currently, most systems operate with independent timing systems, preventing clock signal sharing. This fragmented approach leads to technical inconsistency and economic waste.

2 Timing Methods and Transmission Channels

2.1 Timing Methods

Automation equipment in power plants and substations primarily employs four timing methods: pulse timing, serial interface timing, encoding timing, and network timing.

Pulse Timing: Also called hard timing, this method uses the accurate edge of a pulse to calibrate the device. Pulse timing includes Pulse Per Second (PPS), Pulse Per Minute (PPM), and Pulse Per Hour (PPH).

Serial Interface Timing: This method typically involves the clock source sending timing messages to the device via serial interface. The serial interface outputs one frame of time information per second, commonly at 9,600 bit/s. Message content includes year, month, day, hour, minute, and second, and may also contain user-specified information such as GPS satellite count and alarm signals.

Encoding Timing: The IRIG time code sequence, proposed by the Inter-Range Instrumentation Group (IRIG), is widely used for time information transmission. The sequence includes six encoding formats: G, A, B, E, H, and D. IRIG-B code, one of these formats, contains complete time information including year, month, day, hour, minute, and second. As an internationally standardized time code with simple timing circuits and complete absolute time information, IRIG-B is extensively applied in industrial control, power systems, and military fields.

Network Timing: Based on Network Time Protocol (NTP) and Precision Time Protocol (PTP), network timing uses a monitoring clock or GPS clock as the master clock, transmitting timing information in data frames to each slave device. Upon receiving the message, the slave device parses the frame to obtain current time information and corrects its own clock to achieve synchronization. Since network message round-trip time can be estimated, compensation algorithms enable precise timing, with accuracy depending on synchronization source and network path characteristics. The Simple Network Time Protocol (SNTP) recommended by the IEC 61850 standard is a simplified NTP variant that provides comprehensive access to national time and frequency dissemination services, organizing timing subnetworks and adjusting local clocks at each participating node.

2.2 Timing Signal Transmission Channels

Transmission channels should ensure that time signals from the master clock meet quality requirements at user devices. The following channel types are generally available [2]:

- **Coaxial Cable:** Used for high-quality transmission of TTL-level signals such as PPS, PPM, PPH, and IRIG-B (DC) code, with transmission distance not exceeding 10 m.
- **Shielded Twisted Pair:** Used for transmitting RS-232 interface signals within protection rooms (distance 15 m) and RS-422/RS-485 or 20 mA current loop interface signals (distance 150 m).
- **Audio Communication Cable:** Used for transmitting IRIG-B (AC) signals, with transmission distance not exceeding 1,000 m.
- **Fiber Optic:** Used for long-distance transmission of various time signals, with distance depending on fiber type. Generally, multi-mode fiber distance 2,000 m, while single-mode fiber distance is unlimited.

3 Timing Requirements Analysis

3.1 Equipment Requiring Time Synchronization

Time synchronization equipment in nuclear power stations is primarily distributed in the 500 kV switchyard, 220 kV auxiliary substation, nuclear island electrical building, and conventional island building. Equipment in the 500 kV switchyard, 220 kV auxiliary substation, and conventional island mainly includes power system protection, measurement and control, fault recording, Power Management Unit (PMU), fault location, and energy acquisition devices, primarily using IRIG-B code. Equipment in the nuclear island electrical building includes nuclear power plant radiation monitoring, data acquisition, instrumentation, DCS systems, and some electrical protection and control devices, using NTP, serial messages, and IRIG-B code. Additionally, digital clock systems distributed throughout various plant buildings also require timing via IRIG-B code.

3.2 Timing Precision Requirements

Power automation equipment (systems) have different time synchronization accuracy requirements—not necessarily "the higher the better," as improved precision entails corresponding costs. Therefore, 盲目 pursuit of high precision is unnecessary; the principle is to meet the minimum resolution required by the synchronized device. Reference [1] studied accuracy requirements for power system equipment, identifying four categories with accuracies of 1 s, 1 ms, 10 ms, and 1 s. Corresponding requirements for nuclear power station equipment are:

- **Accuracy 1 s:** Line traveling wave fault location and PMU.
- **Accuracy 1 ms:** Power system relay protection, measurement and control, fault recording, and nuclear power plant monitoring, data acquisition, instrumentation, and DCS systems.
- **Accuracy 1 s:** Energy acquisition and digital clock systems.

3.3 Impact of Timing Precision on System Function

Line traveling wave fault location and PMU are the two systems with the highest timing precision requirements in nuclear power stations. Traveling wave fault location relies on recording the arrival time of current or voltage traveling waves at both line ends. With traveling wave propagation speed approximating the speed of light (300 km/ s), a 1 s timing error corresponds to approximately 150 m of location error. To ensure fault location accuracy within several hundred meters, timing system errors must be controlled within a few microseconds.

PMU requires synchronized sampling of voltage and current at different power system nodes under a unified time reference to analyze power system status on a common time coordinate. While timing precision has minimal impact on amplitude measurement, it significantly affects phase angle measurement. For 50

Hz voltage and current signals, a 1 s timing error corresponds to a 0.018° phase angle error. Reference [3] analyzes the impact of timing errors from various PMU system components on system performance and provides solutions.

4 Optimized Timing Network Design

4.1 Network Architecture

Time synchronization systems can be configured in several ways, with typical forms including basic, master-slave, and master-standby configurations. Large power plants, 500 kV substations, and similar critical applications should adopt master-standby configurations to improve reliability [4]. Given the large number of widely distributed devices requiring time synchronization and the high reliability requirements in nuclear power stations, this paper proposes a plant-wide unified, high-reliability, high-precision timing network, with architecture shown below.

[FIGURE:N]

Fig. Network architecture of time synchronization system in nuclear power station

Independent master clock systems are installed in both the 500 kV switchyard and 220 kV auxiliary substation to meet timing requirements for electrical equipment in these buildings. Each master clock system comprises two master clocks that mutually synchronize via IRIG-B code. A slave clock is installed in the nuclear island electrical building, receiving timing signals from both master clock systems. All timing extension devices and slave clocks receive reference signals from these two independent clock systems, ensuring highly reliable clock sources. Additionally, optical transceivers in the 220 kV auxiliary substation convert IRIG-B electrical signals to optical signals, distributing timing to plant-wide digital clocks through a tree-shaped fiber network.

4.2 Master Clock

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

Equipped with a high-precision phase-locked loop tracking the active time reference, the master clock achieves timing accuracy better than 1 s. Output signal types include IRIG-B code, pulse signals, and serial messages; interface types include TTL level, RS-422/RS-485, Ethernet, and fiber optic.

4.3 Slave Clock

The slave clock has the same characteristics and working principle as the master clock but does not include an antenna, receiving only IRIG-B code signals from the master clock as its time reference.

4.4 Reliability

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

Timing extension devices and slave clocks can obtain time references from both independent master clock systems. As shown in the network architecture, each synchronized device can receive timing signals from four master clocks. Loss of satellite signal or failure of any single master clock cabinet does not compromise network reliability. Even if both master clocks in one system lose power, plant-wide equipment continues to receive reliable timing signals from the other system.

4.5 Network Delay

Timing system precision depends primarily on satellite signal accuracy and processing delays in timing devices and networks. From an engineering perspective, this paper does not analyze satellite signal precision but focuses on network delay impact.

Network delay refers to the time required from when the master clock receives the satellite time signal until it reaches the synchronized device, comprising delays from electronic device processing and forwarding. For the former, master and slave clocks have compensation mechanisms; for the latter, compensation must be based on transmission channel length. When master and slave clocks communicate via optical fiber, channel delay can be calculated by the following formula:

$= L$

where C is the speed of light; L is the transmission distance; n1 is the refractive index of the fiber core, with a typical value of 1.48.

From this, the transmission delay of optical signals in fiber is calculated to be approximately 4.9 s per kilometer. In one nuclear power station, timing fiber lengths reach 3 km, corresponding to a network delay of 15 s. Therefore, to ensure timing network precision, channel delay compensation must be implemented at slave clocks based on each fiber’ s length.

Conclusion

This paper systematically analyzes timing requirements in nuclear power stations, presents common timing solutions and channel requirements, and proposes a high-reliability, high-precision, plant-wide unified timing network structure that meets nuclear power station requirements. This network achieves technical and economic optimization by eliminating redundant clock systems and facilitates network expansion for different construction schedules. The proposed solution also provides valuable reference for timing networks in conventional power plants.

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Note: Figure translations are in progress. See original paper for figures.