DESIGN OF CONTROL NETWORKS FOR CHINA INITIATIVE ACCELERATOR DRIVEN SYSTEM

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Abstract

In this paper, we report the conceptual design of control networks used in the control system for China initiative accelerator driven sub-critical (ADS) facility which consists of two accelerator injectors, a main accelerator, a spallation target and a reactor. Because different applications have varied expectations on reliability, latency, jitter and bandwidth, the following networks have been designed for the control systems, i.e. a central operation network for the operation of accelerators, target, and reactor; a reactor protection network for preventing the release of radioactivity to the environment; a personnel protection network for protecting personnel against unnecessary exposure to hazards; a machine protection network for protecting the machines in the ADS system; a time communication network for providing timing and synchronization for three accelerators; and a data archiving network for recording important measurement results from accelerators, target and reactor. Finally, we discuss the application of high-performance Ethernet technologies, such as Ethernet ring protection protocol, in these control networks for CIADS.

INTRODUCTION

China is the world's most populous country with a fast-growing economy that has led it to become the largest energy consumer in the world in 2010. In China, nuclear power accounts for relatively small shares (nearly 1%) of the country's total energy consumption in 2011. China is actively promoting nuclear power as a clean, efficient, and reliable source of electricity generation. Driven by the national demand for safe disposal of nuclear waste as well as the potentials for advanced power generation, the Chinese Academy of Sciences initiated an accelerator driven sub-critical (ADS) program in 2011 under the frame of "Strategic Priority Research Program"[1]. The ultimate goal of the China ADS program is to build an industrial demo facility for ADS technology.

In an ADS system, a heavy metal spallation target located at the centre of a sub-critical core is bombarded by the high-energy protons from an accelerator. Figure 1 shows a drawing of China ADS facility which consists of an accelerator, a spallation target and a sub-critical reactor. As shown in Figure 1, a LINAC accelerator which includes two injectors, a medium energy beam transport line (MEBT), several spokes, and a high energy beam transport line (HEBT) is used in China ADS facility. In this paper, we report the conceptual design of control networks used in China ADS facility.

NETWORKS IN CHINA ADS FACILITY

Because different applications have varied expectations on reliability, latency, jitter and bandwidth, several networks have been used in ITER (International Thermonuclear Experimental Reactor) (e.g. [2]-[3]). The China ADS system includes two totally different facilities, accelerator and reactor. To successfully integrate the two different facilities into one system, several networks are required in the control system for China ADS system, while some networks are designed especially for accelerator and other networks are used especially for reactor.

Central Operation System and Network

Control systems in ADS may include a central control system and several local control systems. The central control system is used to control the overall ADS facility, in particular, to exactly couple the high-energy beam from the accelerator to the spallation target located at the centre of the reactor core. The central operation network (CON) used in the central control system provides interface between the operation system in the central control room and various controller and sensors in the system.

Reactor Protection System and Network

To guarantee the integrity of the reactor and to avoid an undue risk to the public health and safety, the plant design incorporates a reactor protection system (RPS). The overall purpose of the RPS is to prevent the release of radioactivity to the environment. To meet this objective, this system is capable of supplying reactor and component trip signals if safe operating limits are exceeded, and initiates the engineered safety features actuation(s) if an accident occurs.

The RPS contains two complete and independent trains of monitoring systems. If a monitoring system detects an unsafe event, signals are transmitted via the reactor protection network (RPN) to the RPS. The RPS determines whether the coincidence for a reactor trip function is satisfied. If so, the protection system opens the reactor trip breakers. Opening these breakers removes power from the control rod drive mechanisms, allowing the rods to fall into the reactor core. If an accident occurs and an engineered safety features actuation is required, the protection system actuates the appropriate safety equipment.

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This work is supported by Strategic Priority Research Program of Chinese Academy of Sciences (XDA03010000).

ISBN 978-3-95450-148-9

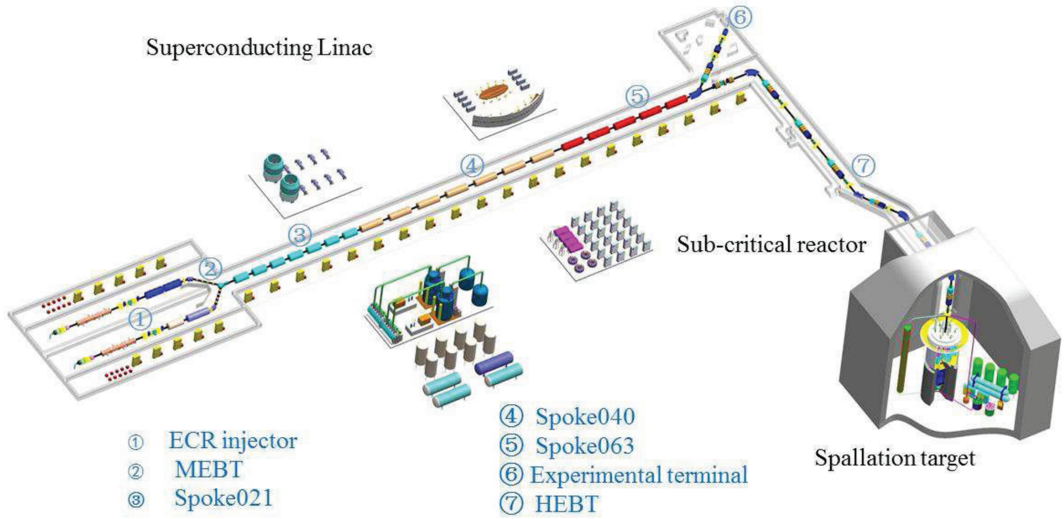

Figure 1: Layout of main systems in China ADS facility.

The RPS is designed to be independent of all process control systems. However, in certain applications, some control signals and other nonprotective functions are derived from individual protection channels through isolation amplifiers. These control signals are transmitted via the operation network to the main control room.

Personnel Protection System and Network

The personnel protection system (PPS) will protect personnel against unnecessary exposure to hazards from the machine, including radioactivity and electromagnetic radiation, electrical shock, and other dangerous phenomena, such as faulty ventilation, helium release, or oxygen deficiency hazards.

The PPS contains some sensors and controllers in the ADS facility, a network and the operation system in the central control system. If a sensor in the monitoring system detects an unsafe event, signals are transmitted via the personnel protection network (PPN) to operator's safety desk in the central control room. If an accident occurs, the personnel protection system actuates the appropriate safety equipment. The PPS safety functions will be defined and designed in advance, by performing a complete set of hazard and risk analysis for accelerator, spallation target and reactor.

Machine Protection System and Network

The machine protection system (MPS) will protect the machine's equipment in the accelerator from damage induced by beam losses and/or malfunctioning equipment. Protection will be achieved by initiating an emergency shutdown upon detection of critical and non-nominal conditions. The machine protection network provides communication between the machine protection system and the sensors or controllers. If a sensor in the monitoring system detects a non-nominal event, signals are transmitted via the machine protection network to the machine protection system. The machine protection system determines whether an emergency shutdown should be initiated.

In an accelerator driven sub-critical system, an emergency shutdown of the accelerator will result in the shutdown of the reactor. Therefore, the protection functions in MPS will be defined and designed very carefully in advance, by performing a complete set of analysis for accelerator, spallation target and reactor.

Time Communication Network

Time Communication Network (TCN) provides timing and synchronization with an accuracy of 10 ns RMS. The official project time used in China ADS system is UTC. Only plant system I&C requiring high accuracy time synchronization shall be connected to TCN. Plant system I&C may have multiple TCN network interfaces.

IEEE-1588, also called Precision Time Protocol (PTP), will be selected for the Time Communication Network (TCN). The N.I. PXI-6683 board may be used as the timing and synchronization board for fast controllers. The NI PXI-6683 and PXI-6683H timing and synchronization modules synchronize PXI and PXI Express systems using GPS, IEEE 1588, and IRIG-B to perform synchronous events. The PXI-6683 can generate events and clock signals at specified synchronized future times and timestamp input events with the synchronized system time. The PXI-6683 features an onboard TCXO that can be disciplined to GPS, IEEE 1588, and IRIG-B for long-term stability. These modules support the 2008 version of IEEE 1588, also known as IEC 61588:2009.

Data Archiving System and Network

As a research facility, acquiring, managing and archiving its data is an essential task for China ADS facility. All the data produced during the operation of ADS system needs to be stored and managed. The archive's main responsibility is to store multiple copies of

ISBN 978-3-95450-148-9

all digital objects and to be able to recall them on request. These digital objects grow in capacity over the years as the accumulated data grow. The stored data is expected to be investigated by researchers during the operation and beyond. Data archiving network is a scalable communication channel which allows the scientific data to be transferred from the sensors and controllers into the Data Archiving system. The data archiving network may be deployed using a dedicated high-throughput Ethernet communication network.

HIGH-PERFORMANCE ETHERNET TECHNOLOGIES

Ethernet IEEE 802.3 is the most widely accepted networking standard for many reasons. It is one of the cheapest solutions for shared media access among computers. Ethernet also provides enough flexibility to operate at varying data rates from 10 Mbit/s to 100 Gbit/s. Another distinct advantage of an Ethernet-based access network is that it can be easily connected to the customer network, due to the prevalent use of Ethernet in corporate and, more recently, residential networks. Ethernet's wide acceptance has also brought wide availability of hardware and support for every computer platform. A typical service provider's network is a collection of switches and routers connected through optical fiber.

The Ethernet topology could be a ring, a tree, a star (hub-and-spoke), or full or partial mesh. Reliability, security, delay or latency, throughput, ease of use, and availability are the main issues while choosing the communication type. In the time communication network or machine protection network, delay should be minimized. A tree or star topology can be considered. In the data archiving network, a dedicated high-throughput Ethernet should be used to maximize the throughput. On the other hand, in the central operation network, the reactor protection network, or the personnel protection network, network reliability is the critical issue while choosing the communication type. Various Ethernet redundancy methods, such as Ethernet ring protection, can be used to improve reliability. Furthermore, both redundant Ethernet and wired lines should be used in the reactor protection network to provide an extremely reliable communication link.

Ethernet Ring Protection Networks

The Ethernet Ring Protection (ERP) protocol, defined in ITU-T G.8032 [4], provides protection for Ethernet traffic in a ring topology, while ensuring that no loops are within the ring at the Ethernet layer. ERP networks have been used in the control systems for accelerator injector I and II in China initiative accelerator driven sub-critical (CIADS) facility. In this section, we discuss the potential application of ERP in the central operation network for CIADS.

ERP builds a logical ring topology while maintaining a loop-free forwarding mechanism by logically blocking a link port in the ring, referred to as Ring Protection Link (RPL) (e.g. [5]-[6]). Once a link fails, the vertices adjacent to the failure block the failed link, and the RPL is unblocked. With this mechanism, an Ethernet ring maintains a logical linear network. Under a single failure condition, a fast protection signal from an ERP protocol message can relocate block positions and provide protection switching times of less than 50 ms, maintaining normal service. In principle, when multiple links fail in a ring an ERP cannot provide protection.

We denote a network topology by a graph $G(V, L)$, where V is the set of vertices and L is the set of links, indexed by v and l, respectively. Figure 2 shows three examples of Ethernet ring network topologies, where there are 22, 37, and 37 vertices in Figure 2(a), (b) and (c), respectively, and 25, 43, and 40 links in Figure 2(a), (b) and (c), respectively.

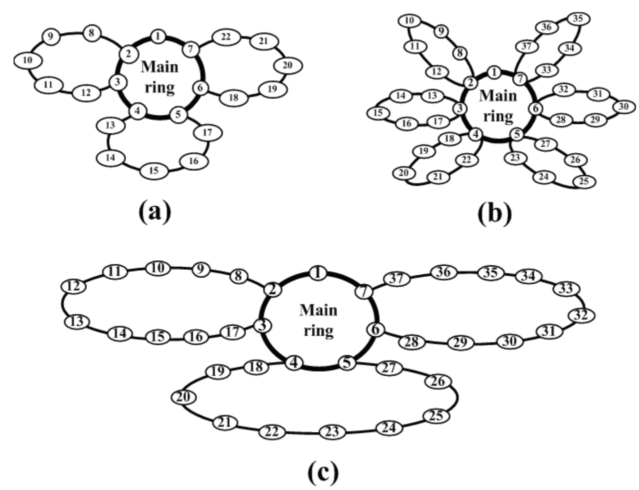

Figure 2: Three examples of Ethernet ring networks. (a) One main ring and three subrings. There are 5 vertices in each subring. (b) One main ring and six subrings. There are 5 vertices in each subring. (c) One main ring and three subrings. There are 10 vertices in each subring.

The set of the simple rings in G is denoted by R. A simple ring is composed of a set of links that form a physical ring/cycle with no straddling links. For example, vertices {1, 2, 3, 4, 5, 6 and 7} in Figure 2 form a simple ring which is used as the main ring.

Reliability Analysis of ERP Networks

In order to evaluate the reliability of an ERP network, we define the following variables. p^1_{link} and p^0_{link} are the possibilities of single link to be connected or disconnected, respectively. F^1_{ring} and F^0_{ring} are the possibilities of Ethernet ring protection to be successful or fail, respectively. In the simulation, with a given p^0_{link}, the random sampling is used to determine whether the i-th link in the set L is connected or not in each time cycle. Then, all links in each ring (main ring or subring) will be checked. If two or more links fail in a ring, Ethernet ring

ISBN 978-3-95450-148-9

protection is taken as failure in this time cycle. For example, in Figure 2(a), four rings (a main ring and 3 subrings) are checked. If two links in the same ring fail, e.g., the link from vertex 8 to vertex 9 and the link from vertex 10 to vertex 11, ERP in this time cycle is recorded as failure. Finally, the possibilities of ERP failure is calculated as follows, $F_{ring}^{0} = N_{fail} / N$, where N is the total sampling number and N_{fail} is the number of Ethernet ring protection failure.

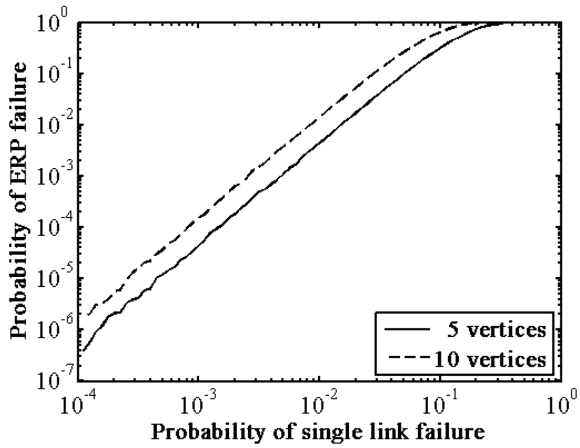

Figure 3: The possibilities of Ethernet ring protection (ERP) failure F_{ring}^{0} as a function of the possibilities p_{link}^{0} of single link failure. Two topologies in Figure 2(a) and Figure 2(c) are compared, where 5 or 10 vertices exist in each subring.

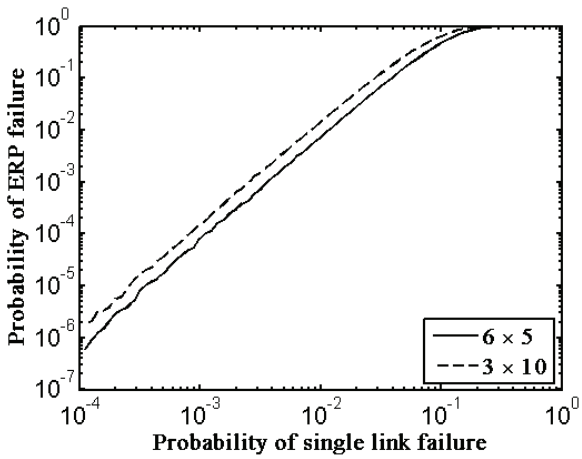

Figure 4: The possibilities of Ethernet ring protection (ERP) failure F_{ring}^{0} as a function of the possibilities p_{link}^{0} of single link failure. Two topologies in Figure 2(b) and Figure 2(c) are compared, where $m \times n$ represents that there are m subrings and there are n vertices in each subring.

Figure 3 shows the possibilities of ERP failure F_{ring}^{0} as a function of the possibilities p_{link}^{0} of single link failure for two topologies in Figure 2(a) and Figure 2(c). The difference between two topologies in Figure 2(a) and Figure 2(c) is that the vertex number in each subring is different. It is shown clearly in Figure 3 that increasing the number of vertices in each ring increases the possibility of ERP failure.

Figure 4 shows the possibilities of ERP failure F_{ring}^{0} as a function of the possibilities p_{link}^{0} of single link failure for two topologies in Figure 2(a) and Figure 2(b). The difference between two topologies in Figure 2(a) and Figure 2(b) is that the number of subrings is different. As shown in Figure 4, for a given total number of vertices, increasing the number of rings improves the reliability of ERP networks.

CONCLUSION

We have reported the conceptual design of control networks for China ADS facility. Six networks have been discussed, i.e. a central operation network, a reactor protection network, a personnel protection network, a machine protection network, a time communication network, and a data archiving network. Finally, we have studied the application of Ethernet ring protection network in CIADS, by evaluating the reliability of three Ethernet topologies with ERP protocol. The simulation results indicate that we should decrease the number of switches in each ring, in order to lower the possibility of ERP failure. If we have to implement many switches in the ERP network, we should increase the number of rings, in order to improve the reliability of ERP networks.

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ISBN 978-3-95450-148-9