Design of Accelerator Vacuum Monitoring System Based on Virtual Commissioning Technology

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Abstract

The accelerator vacuum monitoring system constitutes a critical subsystem within the accelerator control system, playing a vital role in maintaining normal accelerator operation. Traditional large-scale control system design, development, and manufacturing processes are highly dependent on physical entities, with functional testing and performance verification concentrated entirely in the later project phases, leading to extended development cycles, elevated risks, and constrained on-site commissioning time in the final stages. To address these challenges, industrial virtual commissioning and virtual machine technologies have been introduced to establish a full-hierarchy virtual simulation commissioning platform for the accelerator vacuum monitoring system. This enables parallel collaborative development of the accelerator vacuum monitoring system from the early development stages, full-hierarchy virtualized commissioning and logic rehearsal, and ultimately, the application of commissioning results to the field through on-site configuration. This approach significantly reduces on-site commissioning time, minimizes equipment wear and commissioning risks, and enhances both project implementation efficiency and engineering design reliability.

Full Text

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Abstract

The accelerator vacuum monitoring system is a critical subsystem within the accelerator control system that plays a vital role in maintaining normal accelerator operation. Traditional design and development of large-scale control systems are heavily dependent on physical entities, with functional testing and performance verification concentrated in the final project stages. This approach results in lengthy development cycles, elevated risks, and constrained on-site debugging time. To address these challenges, we have integrated industrial virtual commissioning and virtualization technologies to construct a comprehensive multi-level virtual simulation and debugging platform for accelerator vacuum monitoring systems. This enables parallel collaborative development, full-level virtual commissioning, and logic rehearsal to begin in the early development stages. The debugging results are then applied to the physical system through field configuration, significantly reducing on-site debugging time, minimizing equipment wear and commissioning risks, and enhancing both project implementation efficiency and engineering design reliability.

Keywords: virtual commissioning; accelerator vacuum monitoring system; virtual simulation platform

1. Accelerator Vacuum Monitoring System

Large-scale experimental physics accelerator facilities are characterized by their massive scale and diverse equipment types, making accelerator control systems exceptionally complex. These systems integrate computer technology, network communications, electronics, and digital signal processing, rendering their design and development a sophisticated systems engineering challenge. The vacuum system represents a crucial subsystem that provides a stable and reliable vacuum environment for particle beams. For decades, the design and development of accelerator vacuum monitoring systems have faced inherent dependencies on physical equipment. The complexity of accelerators themselves demands higher standards for project development cycles, reliability, and safety. In conventional project implementation workflows, system-level verification and debugging are deferred to late project stages, where discovering systemic defects incurs substantial costs for remediation. Furthermore, current design practices are fragmented and localized, resulting in program code with short lifespans and poor readability and portability, which undermines the reliability of control system design.

Virtual commissioning technology, a key enabling technology within the Industry 4.0 framework, has found widespread application in automated production lines, automotive manufacturing, and aerospace industries in recent years. This technology offers a novel approach to accelerator control system design and development. Virtual commissioning is a digital simulation-based technique that enables offline testing during equipment development, installation, commissioning, and maintenance phases, allowing equipment to be optimized before the actual operational environment is ready. The conventional accelerator development workflow proceeds from conceptual design to sequential mechanical, electrical, and control system design. Since control system debugging requires input/output interfaces, most commissioning must be performed on-site. When defects requiring improvement are discovered during debugging, the process must revert to the design phase, potentially extending development cycles and jeopardizing timely delivery. Virtual commissioning technology addresses this by migrating field operating parameters into a virtual environment, enabling subsystem development and virtual commissioning before on-site work begins, with results subsequently applied to physical commissioning. This approach can reduce design-phase debugging time by approximately 75%. A comparison between traditional and virtual commissioning workflows is illustrated in [Figure 1: see original paper].

Virtual commissioning technology significantly reduces subsequent on-site debugging time, decreases equipment wear, lowers commissioning risks, and improves project implementation efficiency and engineering design reliability. By constructing digital models, it facilitates standardized and modular control system research and enables iterative optimization of control system models. Beyond engineering design and development, virtual commissioning can also be applied to personnel training and operational rehearsal, contributing to control system optimization and improvement.

2. Virtual Commissioning-Based Debugging Scheme for Vacuum Monitoring System

Typically, control system design, development, and debugging must wait until field equipment procurement and installation are complete, resulting in long development cycles and significant project delay risks. With virtual commissioning technology, the entire development cycle is compressed, enabling faster delivery of control systems to the field. The field control layer is primarily responsible for real-time data acquisition and equipment control, demanding high real-time performance and exhibiting strong hardware dependencies. Virtual commissioning is introduced into this layer by using software on a PC to simulate real PLC controllers, enabling hardware configuration, programming, and logic verification through configuration software. Meanwhile, IOC and OPI components are designed and developed using various EPICS development tools in Linux environments, making them less dependent on physical hardware. Drawing from virtualization technology, the room-temperature front-end linear accelerator virtual simulation platform virtualizes multiple OPI and IOC servers on a single physical machine, employing virtual network card technology to simulate real network communications. The operating systems, software development environments, and network configurations in the virtual machines are identical to those in the actual system, ensuring consistency between the virtual commissioning system and the real control system while reducing upfront investment in physical equipment.

Finally, the OPI and IOC virtual machine systems are connected to the virtual PLC PC via a local area network to enable inter-layer communication, logic testing, and verification. After validation, only minimal on-site debugging is required to adapt the virtual commissioning results to physical equipment. The vacuum monitoring system commissioning scheme is shown in [Figure 3: see original paper].

The virtual simulation platform hardware composition is depicted in [Figure 4: see original paper], utilizing two physical machines. On Physical Machine 1, virtualization software simulates one OPI, one IOC, and an engineering station. The engineering station performs equipment configuration and program design, using virtual PLC for commissioning. The OPI runs the main vacuum monitoring system interface along with two sub-interfaces for gate valves and molecular pumps. The IOC implements equipment integration, protocol conversion, and PV variable publication. Physical Machine 2 uses software to simulate the PLC. After completing full-level logic rehearsal, system integration, and regression testing in the virtual simulation environment, all programs are deployed or downloaded to the physical server equipment and hardware PLC for final on-site debugging.

3.1.1 System Software and Hardware Configuration

Virtual commissioning technology has recently been applied in industrial control system design and debugging, enabling vacuum monitoring system control layer development to become independent of physical entities. Through PC-based emulation technology, designers can rapidly perform control system configuration, programming, and testing on simulated systems. Since this system employs Siemens S7-1500 series CPUs, remote I/O modules, and communication modules for remote vacuum equipment monitoring and control, Siemens TIA Portal is selected for hardware/software configuration and programming, while Siemens PLCSIM Advanced is used for S7-1500 PLC control system simulation. PLCSIM Advanced is an advanced simulator based on TIA Portal that can simulate and verify not only PLC code but also communication, intellectual property function blocks, safety functions, and OPC servers, ensuring functional consistency between the virtual simulation system and the real control system.

PLCSIM Advanced provides Ethernet connectivity supporting both local and distributed communication, enabling virtual PLCs to communicate with real PLCs and HMIs while offering third-party interfaces for data exchange with user programs or third-party software. Virtual PLCs created with PLCSIM Advanced can communicate with objects within the same PC or virtual machine, as well as with objects on different PCs or virtual machines, supporting multiple communication protocols including TCP/IP, Siemens S7 communication, and OPC UA. The control layer hardware configuration is shown in [Figure 5: see original paper], employing CPU1513-PN as the master station and three ET-200SP distributed I/O modules as slave stations. Slave Station 1 uses three AI 4xRTD/TC analog input modules to read vacuum gauge values. Slave Station 2 uses three DI 16x24VDC digital input modules and one DQ 16x24VDC/0.5A digital output module for gate valve status monitoring, plus 19 CM PtP communication modules for communication between vacuum pumps, vacuum gauges, and the master station. Slave Station 3 uses 28 AI 4xI analog input modules to acquire operating status data from molecular pumps and vacuum gauges.

3.1.2 PLC Control Program

As shown in [Figure 6: see original paper], the PLC control program enables automatic equipment control and monitoring. By reading device parameters, executing control commands, monitoring status, implementing interlock protection, and transmitting data, the PLC can obtain real-time operating parameters from pneumatic valves, molecular pumps, vacuum gauges, and other equipment. Based on preset logic, it performs judgments and calculations to achieve automatic equipment control. Simultaneously, the PLC monitors device communication status, triggers alarm mechanisms, and provides interlock protection functions to ensure safe equipment operation. Through real-time data transmission, the PLC conveys equipment status information to the accelerator vacuum monitoring system, enabling centralized equipment management and monitoring that enhances operational safety, reliability, and efficiency.

3.2 Virtual PLC and IOC Communication

Compared with PLCSIM, PLCSIM Advanced offers more powerful functionality and greater flexibility, enabling not only program simulation but also local and distributed communication simulation. After installation, PLCSIM Advanced creates a virtual network adapter named “Siemens PLCSIM Virtual Ethernet Adapter” and adds virtual switch (PLCSIM Virtual Switch) properties to both physical and virtual network cards, enabling virtual PLCs to communicate with other devices (such as computers, virtual PLCs, HMIs) within the LAN. Communication between the virtual PLC and the IOC-running Virtual Machine 1 constitutes distributed communication requiring the virtual switch. Therefore, during IOC-PLC communication, the virtual switch function must first be activated in the network adapter properties. The PG/PC interface’s S7ONLINE application access point is then set to the virtual network card. When enabling distributed communication for virtual PLCs, PLCSIM Advanced requires setting the online access to PLCSIM Virtual Eth. Adapter, selecting the Ethernet card for virtual PLC communication, and configuring the virtual PLC’s instance name, IP address, subnet mask, and PLC type. The virtual PLC’s IP address must reside in the same subnet as the computer’s network card and virtual network card. PG/PC interface and PLCSIM Advanced settings are shown in

[Figure 7: see original paper].

After virtual PLC parameter configuration, the PLC simulation function can be activated. The steps for downloading programs to the virtual PLC in TIA Portal are identical to those for physical PLC debugging. As shown in [Figure 8: see original paper], two physical machines form a LAN for TCP/IP communication. Virtual Machine VM2's network adapter bridges to the physical network card and connects to the virtual switch, allowing the IOC to read variable values from the virtual PLC's DB blocks and write them to the real-time database.

3.3 EPICS IOC and OPI Design

Virtualization technology has been widely adopted across various scenarios due to its flexibility, security, and rapid deployment capabilities, with common virtualization software including VMware, KVM, and VirtualBox. This system uses VMware Workstation on Physical Machine 1 to establish two virtual machines for IOC and OPI design and development, with network settings and software environments identical to field equipment, employing CentOS 64-bit Linux operating systems. Virtual Machine 1 establishes the IOC's real-time database and develops device support and driver modules. Since the virtual PLC uses the same communication protocol as the physical PLC, the s7nodave component is employed to add driver support for the virtual PLC. Virtual Machine 2 runs the vacuum system monitoring main interface developed based on Phoebus, responsible for monitoring vacuum levels, pressures, and equipment status at each node, with two sub-interfaces managing status display and on/off functions for 17 valves and 12 vacuum pumps, as shown in [Figure 9: see original paper].

Before completing field installation and cable laying for this vacuum monitoring system, the entire system underwent full-level design, development, debugging, and multiple regression tests in the virtual simulation environment. When field conditions for power-on and system testing were established, system deployment was completed at the site in a short timeframe through virtual machine migration and project file replication, passing system-powered integration testing without logical errors or variable mapping inconsistencies. Field debugging issues were primarily concentrated in wiring quality and installation craftsmanship. Engineering practice demonstrates that virtual commissioning-based system design effectively reduces on-site debugging time, enables rapid short-term deployment, and ensures all program issues are resolved in the virtual debugging environment, thereby reducing field debugging pressure and risk. This approach yields significant improvements in time and labor cost savings, ensuring stable project implementation and on-time delivery.

This project marks the first application of integrated virtual commissioning and virtualization technologies in accelerator vacuum control system design, providing a reference solution for control system design. Virtual simulation-based control system design does have limitations: since simulation systems depend on computer CPU performance, the single-cycle time of virtual PLC controllers differs from that of physical controllers. Nevertheless, the advantages of this virtual simulation system in optimizing design processes and improving development efficiency make it highly promising for practical applications. Future research will continue exploring methods to enhance the performance similarity between simulation and physical systems to better serve accelerator control system design and development.

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Li Jigang, Lu Yanhong: Conducted experiments, drafted the manuscript;
Yang Feng, Chen Youxin, Cao Shiquan: Proposed research ideas, designed research methodology;
Liu Haitao, Li Jiaosai: Provided technical support for system design and development

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