DISTRIBUTED CONTROL OF LARGE-SCALE MAGNET POWER SUPPLIES FOR HALF*

Fang Li[1], Ke Xuan[†,1], Chuan Li[1], Liuguo Chen[1], Qun Liu[1], Gongfa Liu[1]

[1]National Synchrotron Radiation Laboratory, University of Science and Technology of China, Hefei, China

Abstract

Fourth-generation synchrotron radiation sources, characterized by ultra-high brightness and nanometer-scale spatial resolution, have become core facilities for cutting-edge scientific research. The Hefei Advanced Light Source comprises nearly 2,000 magnet power supplies that require remote online adjustment and synchronized current setting to meet the beam-physics requirements. This paper proposes a distributed control system architecture to address the control requirements of large-scale magnet power supplies. At the hardware level, server clusters are built and virtualization technology is leveraged to provide highly available system services. At the network level, a star-topology Ethernet network and a synchronized timing network are constructed. At the software level, a custom communication protocol enables remote monitoring and control of the magnet power supplies. In addition, data security and efficient deployment are also addressed. The proposed distributed control system provides a scalable solution for large-scale magnet power-supply management in fourth-generation light sources.

INTRODUCTION

The Hefei Advanced Light Source (HALF) is a fourth-generation synchrotron radiation light source operating in the low-energy regime, based on a diffraction-limited storage ring (DLSR) [1, 2]. The HALF accelerator complex comprises an injector and an electron storage ring. The injector, consisting of a full-energy linear accelerator (linac) and a beam transport line, generates high-energy electron beams. The storage ring operates at 2.2 GeV and achieves a horizontal natural emittance of 86 pm·rad. This diffraction-limited storage ring, characterized by its ultra-low emittance, is pivotal for realizing high-performance synchrotron radiation. The storage ring utilizes a modified hybrid 6-Bend Achromat (6BA) lattice structure, which incorporates numerous dipole, quadrupole, sextupole, and octupole magnets, as well as fast orbit correctors [3]. Consequently, a large number of power supplies is required to energize these magnets and coils.

Magnet power supplies modulate the magnetic field strength by regulating the output current, thereby controlling the particle beam trajectories. Remote control of the injector and storage-ring power supplies includes current setting and readback, status monitoring, fault detection, and alarm handling. Effective control of these magnet power supplies is critical to the stability and quality of the synchrotron radiation. Specifically, HALF uses 1,998 power supplies to provide stable current for magnets distributed along the 366-m-long injector and the 480-m-circumference storage ring. Given the large number of devices and their wide spatial distribution, a distributed control architecture is essential for reliable online adjustment and monitoring [4, 5].

Previous studies have reported control-system architectures for light sources and accelerator facilities, as well as software frameworks and EPICS-based implementations [6, 7, 8]. Building on these developments, this paper presents a magnet power-supply control system for HALF with a focus on system-level implementation, including distributed architecture design, a custom communication protocol, scalable IOC deployment, and secure access control. These elements, together with batch-configurable control software, enable distributed control of large numbers of magnet power supplies.

DESIGN AND IMPLEMENTATION

Architecture

The architecture of the power supply control system is illustrated in Fig. 1. The distributed control is implemented via a network infrastructure, providing Ethernet communication as the channel for data exchange between the power supplies and the upper-level control software. To achieve effective monitoring and control of the power supplies, which are distributed across various equipment rooms, dedicated network switches are deployed to provide network access. The control system network is logically divided into multiple Virtual Local Area Networks (VLANs) to improve network efficiency and enhance security.

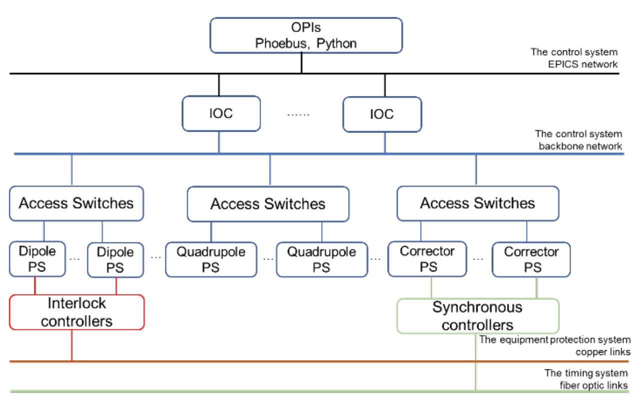

Figure 1: The system architecture.

The control network adopts a standard hierarchical structure, comprising the access layer, the aggregation layer,

* Work supported by the University of Science and Technology of China under Grant No. KY2310000064
† xuanke@ustc.edu.cn

and the core layer. Access switches are installed in the power supply equipment rooms and are directly connected to the power supplies via network cables. Aggregation switches are deployed in the control equipment rooms and communicate with the access switches via optical fibers. The core switches, serving as the backbone of the control network, utilize a redundant configuration and are located in a Class-B data center server room equipped with reliable power supply and environmental controls.

In addition to network-based control, a subset of power supplies requires pulse-based synchronous control. Since the corrector magnets in the storage ring need to modulate their magnetic fields synchronously to achieve global beam orbit correction, synchronous controllers for the power supplies have been deployed. The controller receives trigger signals from the local stations of the timing system [9], fans them out, and transmits them via optical fibers to all power supplies requiring synchronization. Upon receiving the signal, the power supplies immediately adjust their output currents according to pre-configured setpoints.

For the machine protection of the injector and the storage ring, the status of the dipole magnets is a critical monitoring target. Consequently, the status signals from these power supplies must also be hardwired into the facility's Interlock Protection System. Once a fault or abnormal condition is detected by the interlock controller, the beam will be immediately terminated.

Timing Network

The slow feedback of the beam trajectory requires that the power supplies for the slow correction magnets synchronously adjust their current setpoints. The synchronization signals for the power supplies are generated by local timing stations distributed across different equipment rooms. Fan-out modules in the 10 power supply halls receive the synchronization signals from the local timing stations and distribute them to all slow-correction magnet power supplies that require synchronization. Optical fiber is used as the signal transmission medium to ensure immunity to electromagnetic interference in the environment. The timing structure of the power supplies is shown in Fig. 2.

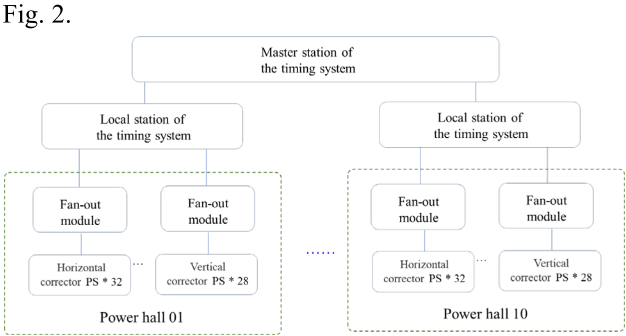

Figure 2: The timing structure.

Communication Protocol

The remote control of HALF power supplies is implemented via RJ45 network interfaces using TCP/IP communication. The remote-control functions defined in the protocol primarily include: setting and reading back the power status, setting and reading back current values, pre-loading current setpoints for synchronized triggering, acquiring power supply status and threshold settings, and resetting faults.

Communication adopts a command-response mode, where the digital control card of the power supply functions as the server and the control software acts as the client. Control commands are ASCII-based strings, initiated by the start character '@' and terminated by the end character '#'. The control commands are categorized into read and write operations, following the format: "@ + W/R + Control Code + Setpoint + Checksum + #". The control code designates specific functions, such as powering the supply on/off or setting current values. The checksum is calculated as the arithmetic sum of all bytes in the command frame. Both the control codes and checksums are represented in hexadecimal characters. An example of communication between the power supply and the control system is shown in Fig. 3.

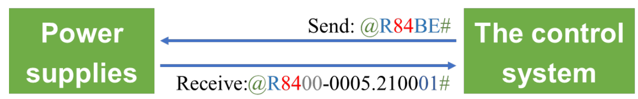

Figure 3: Example of Data Communication.

Read and write operations on the power supplies are implemented by defining distinct control codes. For instance, 'W81' designates switching the power supply on or off, while 'R81' designates reading the status of the power switch. For current read/write operations, 'W82' sets the current value, 'R82' reads the set current value, and 'R84' reads the current output value. Regarding the response code returned by the power supply, a value of 0x00 indicates normal operation, whereas other values denote errors. The power supply status is represented by two bytes, with each bit corresponding to a specific fault type, including cooling water failure, DCCT failure, output over-current, output over-voltage, etc.

Control Software

The control software for the magnet power supplies is based on EPICS 7 and runs on the Debian 12 operating system. The Input/Output Controller (IOC) application software utilizes StreamDevice and asynDriver [10] modules as data communication drivers, acquiring parameters and status from each power supply via periodic polling. The architecture of the control software is illustrated in Fig. 4. The HALF magnet power supply system employs a total of 30 IOCs, the majority of which are hosted on virtual machines. However, to ensure operational efficiency, the IOCs for the corrector magnets of the storage ring are hosted on physical servers.

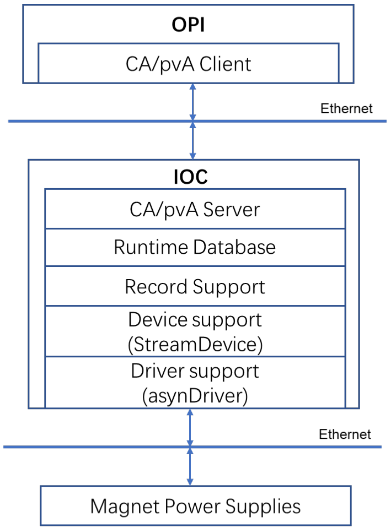

Figure 4: Architecture of the control software.

Efficient deployment is critical because a single IOC typically controls dozens of power supplies. Techniques such as templates and macro substitution are employed to facilitate the rapid configuration and deployment of the IOCs. Furthermore, a Python-based tool has been developed to generate mapping lists correlating power supply names with their IP addresses and ports, thereby enabling the efficient generation of template files.

The system operator interface (OPI) is developed based on the Phoebus platform [11]. This interface encompasses control functionalities for both the injector and storage ring power supplies. Additionally, multiple Python scripts have been integrated to facilitate functions such as the configuration of polling intervals, one-click startup and shutdown operations, and parameter setting based on predefined data.

Data Access Security

To further enhance system security, the Lightweight Directory Access Protocol (LDAP) [12, 13] is utilized in the development and operation of the IOCs. LDAP provides unified authentication and access policy management, ensuring both the security of access to control data and management efficiency. LDAP accounts are categorized into three groups: the 'DEFAULT' group comprises all login-enabled users without specific designation; 'csusers' consists of all staff members in the controls department; and the 'csexperts' group includes IOC developers and operational accounts.

Access security management is implemented within the IOC environment. Access control is enforced by configuring the Access Security Group (ASG) field for individual records within the IOC database files. Concurrently, an Access Security Configuration (.acf) file is created to define read and write privileges for distinct user groups, and this file is referenced in the IOC start-up script. Specifically, read access to power supply records remains unrestricted, whereas write access is governed by three distinct security levels: Level 1 permits write operations by all users; Level 2 restricts write access exclusively to members of the 'csexperts' group; and Level 3 grants write privileges to members of both the 'csusers' and 'csexperts' groups. The integration of LDAP account management with these access protocols significantly enhances the security of the power supply control system.

Performance Evaluation

Although standard operations, such as switching power supplies on/off or writing target current values, have low timing stringency, minimizing latency is critical for the synchronous triggering of corrector magnets to ensure synchronized beam orbit correction. Two comparative experiments were conducted to evaluate performance. In the first experiment, current setpoints were written sequentially to the Process Variables (PVs) of twenty corrector magnet power supplies. In the second experiment, target current values for synchronous triggering were first pre-loaded into all power supplies; subsequently, a timing device was used to fan out a pulse serving as the trigger signal. Upon receiving this trigger, the power supplies immediately ramped their output according to the pre-stored target values. An oscilloscope was employed to capture the current profiles of the first and last power supplies and to measure the time delay between their respective rise times. The results indicate that the conventional sequential setting method resulted in a delay of 424 ms. In contrast, the synchronous trigger method achieved a delay of only 440 μs, as shown in Fig. 5. Consequently, the synchronous control scheme ensures that all power supplies achieve synchronized output changes within 1 ms, demonstrating superior real-time performance.

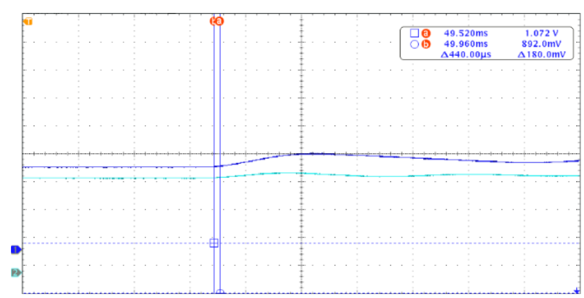

Figure 5: Time delay of current ramping.

CONCLUSION

The magnet power supply control system of HALF employs a distributed control architecture to enable remote operation and monitoring. A customized communication protocol supports the extension of control commands, ensuring system flexibility. Furthermore, the implementation of data access policies has enhanced system security. The timing signal-based synchronous current setting scheme enables the storage ring corrector magnets to modulate their currents simultaneously within an extremely short timeframe. Test results indicate that the latency of current synchronization satisfies application requirements. The system has been developed and will be commissioned in coordination with the HALF facility's construction timeline.

REFERENCES

[1] L. Wang *et al.*, "Hefei Advanced Light Source: A Future Soft X-Ray Diffraction-Limited Storage Ring at NSRL", in *Proc. IPAC'18*, Vancouver, Canada, Apr.-May 2018, pp. 4598-4600. doi: 10.18429/JACoW-IPAC2018-THPMK120

[2] Z. Sun *et al.*, "Construction of Hefei advanced light facility begins", The Innovation, vol. 4, no. 6, p. 100514, Nov. 2023. doi: 10.1016/j.xinn.2023.100514

[3] T. H. Sun *et al.*, "Design of magnets for Hefei advanced light facility", in *Proc. IPAC'23*, Venice, Italy, May 2023, pp. 3677-3679. doi: 10.18429/JACoW-IPAC2023-WEPM053

[4] G. Liu, *et al.*, "Design of the HALF control system", in P*roc. ICALEPCS'23*, Cape Town, South Africa, Oct. 2023, pp. 958-961. doi: 10.18429/JACoW-ICALEPCS2023-WE1BCO03

[5] L. R. Dalesio *et al.*, "EPICS 7 Provides Major Enhancements to the EPICS Toolkit", in *Proc. ICALEPCS'17*, Barcelona, Spain, Oct. 2017, pp. 22-26. doi: 10.18429/JACoW-ICALEPCS2017-MOBPL01

[6] Hoteit H *et al.*, "Modernizing of magnet power supplies at KARA and a transition to EPICS-based control system", in *Proc. IPAC'24*, Nashville, USA, May 2024, pp.3739-3741. doi: 10.18429/JACoW-IPAC2024-THPS08

[7] Cheng Y S *et al.*, "Design and implementation of control system for TPS pulsed magnet power supply". *IEEE Transactions on Applied Superconductivity*, 2016, vol. 26, no. 4, pp.1-5. doi: 10.1109/TASC.2016.2537374

[8] Lu Y *et al.*, "The magnet power supply control system for high energy photon source". *Radiation Detection Technology and Methods*, 2026, vol. 10 no. 1, pp.102-107. doi: 10.1007/s41605-025-00567-z

[9] G. Zhai, *et al.*, "The design of Hefei advanced light facility timing system", *Nucl. Tech.*, vol. 45, no. 12, pp. 120102, 2022. doi: 10.11889/j.0253-3219.2022.hjs.45.120102

[10] M. R. Kraimer *et al.*, "EPICS Asynchronous Driver Support", in *Proc. ICALEPCS'05*, Geneva, Switzerland, Oct. 2005, paper P3_074.

[11] K. Shroff *et al.*, "New Java Frameworks for Building Next Generation EPICS Applications", in *Proc. ICALEPCS'19*, New York, NY, USA, Oct. 2019, pp. 1504. doi: 10.18429/JACoW-ICALEPCS2019-WESH1002

[12] J. Sermersheim, "Lightweight Directory Access Protocol (LDAP): The Protocol", IETF, RFC 4511, Jun. 2006. doi: 10.17487/RFC4511

[13] G. McIntyre *et al.*, "Cyber Secure Experimental Physics and Industrial Control System", in *Proc. ICALEPCS'25*, Chicago, IL, USA, Sep. 2025, pp. 829-837. doi: 10.18429/JACoW-ICALEPCS2025-WEBG005