Control system for the FFAG complex at KURRI

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Abstract

A simple and convenient control system has been developed for the 150 MeV proton FFAG accelerator complex at Research Reactor Institute, Kyoto University. This control system is designed as a distributed control scheme and developed with simple and versatile tools, such as PLCs, LabVIEW and an IP based network, expecting applications in small accelerators, which are often operated by non-specialists in computer programming or in control systems. The control system for the FFAG accelerator complex has actually been developed by non-specialists, and the developed control system was successfully used for commissioning the FFAG complex.

Key words: Control system, Programmable logic controller, LabVIEW
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1. Introduction

The Kumatori accelerator-driven reactor test (KART) project[1] originated in a proposal for a neutron factory project at Research Reactor Institute, Kyoto University (KURRI)[2]. The KART project was approved by the Ministry of Education, Culture, Sports, Science and Technology, Japan and started in fiscal year 2002. The main purposes of this project are to develop a combined system of the existing nuclear fuel assembly and the accelerator as a proton driver, and to study the feasibility of an accelerator-driven subcritical system (ADS). In our project, a practical fixed field alternating gradient (FFAG) accelerator complex has been chosen as the proton driver, based on successes in proof-of-principle FFAG accelerators at KEK[3, 4, 5].

The accelerator complex consists of one FFAG with induction acceleration as the injector, and two FFAG with RF as the booster and main accelerators[6]. The layout of these accelerators in the accelerator room is shown in Fig. 1. Basic specifications for this FFAG complex are summarized in Table 1.

In designing an accelerator, the control system is an important part, because the simplicity and stability of operation largely depend on the control system. Distributed control architectures have become common and successful as the accelerator control scheme, because of their numerous advantages, such as flexibility, scalability and a reduction of hardwiring. Especially in the case of larger accelerators, like those of GeV-class, the control systems are often constructed based on the Experimental Physics and Industrial Control System (EPICS)[7], which is known as an open-source environment to create distributed soft real-time control systems for scientific instruments, such as particle accelerators and telescopes.

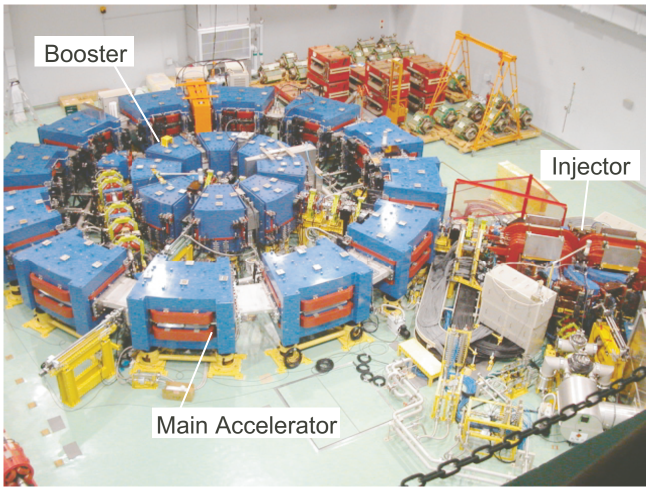

Figure 1: FFAG complex at KURRI. This accelerator complex consists of one FFAG with induction acceleration as the injector, and two FFAG with RF as the booster and main accelerators. The extracted beam from the main accelerator is transported over a distance of about 50 meters to the fuel assembly in an adjacent building.

Table 1: Specification of the FFAG complex at KURRI in the original design.

Beam Energy	25 - 150 MeV
Maximum Average Beam Current	1 μA
Repetition Rate	up to 120 Hz

While the successes of distributed-control systems in larger accelerators are well known, there are few applications to small accelerators, such as cyclotrons with energies of up to 100 ∼

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200 MeV. The control systems for such small accelerators are usually developed in custom specifications defined and maintained by their accelerator suppliers, or in the central control scheme with the legacy hardwiring scheme. In such systems, their users often have to accept less flexibility, more expensive support costs, and less compatibility towards the future, owing to its closed environment or fixed configuration of hardwiring.

The reason for this kind of situation in small accelerators is that available distributed-control schemes are often designed and developed to pursue higher operation performances by using sufficient budget and manpower, which is usually allowed in larger accelerators.

Meanwhile, the applications of the small accelerators become expanding beyond fundamental science, e.g., applications in engineering, biology and medicine. The control systems for small accelerators are now required to be sufficiently flexible and reliable to adopt such applications, and to be opened for users, who are not specialized to accelerators, to customize them to be suitable for their uses.

Therefore, an open-based environment for a distributed-control system with proper size and simplicity for a small accelerator is required to realize a reduction of the costs on maintenance, developments and operations, and the acquirement of higher flexibility and better usability at the same time.

The FFAG accelerator complex in the KART project is regarded as being one of the typical cases of such expanding applications of small accelerators. The constructed FFAG accelerator complex will be operated with collaboration of the fuel assembly, and reactor physicists are expected to be typical users of this FFAG accelerator complex in this project.

In this paper, we report on the development and current status of our control system for the FFAG accelerator complex.

2. Design concept and system architecture

2.1. Design concept

In designing of the present control system, the characteristics of small accelerators and the institutes that own small accelerators were considered. In small accelerators, the high performance required in larger accelerators is not necessarily achieved, while the severer requirements concerning the cost in the construction and in the maintenance should be taken into account. Due to the limitation in human resources, the development and maintenance should be performed by the staff with less training on the development environment. Therefore, we set several attainment targets in the present development, as follows:

- A GUI based environment should be realized for developers with fewer skills in programming language so as to minimize efforts on education for the development environment.

- A simple distributed system should be intended for both scalability and robustness.

- Cheap, common hardware from the industrial world should be the primary platform for the system to achieve the minimized cost and sufficient compatibility of the control system.

- The protocols used in the control system should follow the common industry standards for compatibility towards the future.

2.2. System architecture

The architecture of the present control system is shown in Fig. 2. In this architecture, devices and instruments, such as power supplies and motor drivers, are governed by respective PLC modules to perform low-level controls, e.g., autonomous operations and the status monitor. These PLCs are connected to an IP-based network to communicate with remote PCs.

Each PLC serves a database of connected instruments and devices on the network by using the capability of memory operations over the network. All requests and the status readout of connected instruments and devices are performed by writing to, or reading from, this database. Remote PCs are responsible for higher level of controls, such as the man-machine interface (MMI) and the integrated sequences, which involve multiple devices connected to different PLCs.

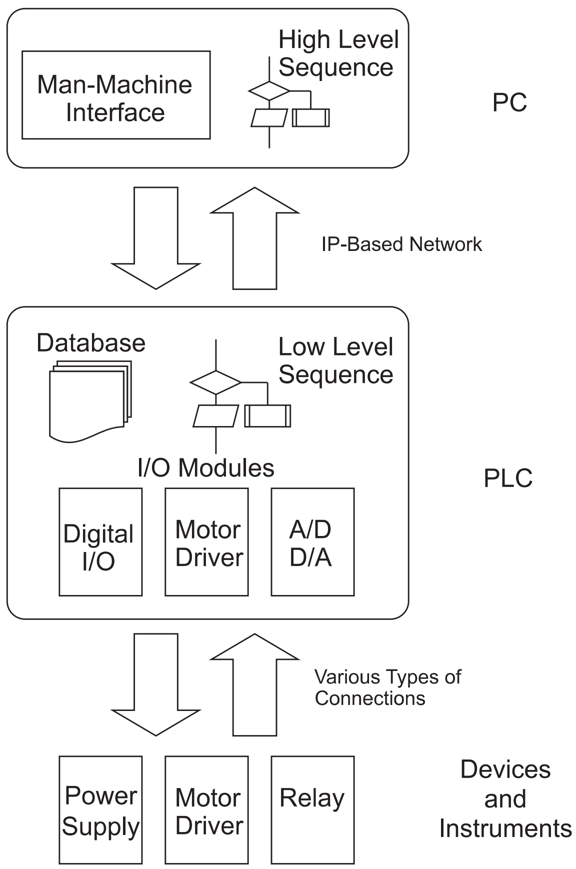

Figure 2: Architecture of the present control system.

3. Hardware

3.1. Selection of PLC - FA-M3R series

The FA-M3R series PLC [8] available from Yokogawa Electric Corporation was chosen as the local processors for our control system. The FA-M3R series has several features, as follows:

- All maintenance of FA-M3R over the network, including the whole restore of ladder sequences, is realized. Therefore, the arrangement of modules has much more flexibility than other PLC series, which often requires some serial connections for maintenance.
- A self-recovery system of ladder sequence is implemented. A complete copy of ladder sequences is made, and a check-sum for both codes is continuously performed whenever FA-M3R PLC is powered on. A damaged block in the ladder sequence is recovered from another copy as soon as a check-sum error is found.
- A built-in backup battery maintains the data on the memory for ten years without an external power supply.
- No special programming for remote I/O is required by the bus extension feature. The bus in the backplane can be extended by a high-speed (10 Mbps) full-duplex link over optical fiber, and remote modules are treated as if they are a part of one PLC unit, regardless of their physical place.

3.2. Configuration of the hardware in this control system

The standard hardware configuration of the current control system is shown in Fig. 3.

A so called “master-slave” scheme based on the bus extension feature of FA-M3R series is introduced in the current configuration of PLCs. Each master module block, which usually consists of one CPU and an Ethernet module for TCP/IP connection, has several slave module blocks, each of which consists of several I/O modules for connected instruments and devices, connected by using the bus extension feature. With this scheme, the master and slave module blocks are treated as if they consisted of one large PLC module block. Additionally, a higher communication speed of 10 Mbps and reliability can be also achieved, comparing to the ordinary remote I/O process (typically several hundreds kbps) based on the conventional serial communication protocol.

Master module blocks are usually placed at a lower radiation area so as to prevent the memory and CPUs of PLC from radiation damages mainly by neutrons induced by the proton beam. Slave module blocks are often implemented in instruments and devices, such as power supplies, when sufficient space is available, and they are used in the same way as remote I/Os in a conventional PLC system. A typical implementation of a slave module block is shown in Fig. 4.

All of the instruments and devices are organized in several groups based on the hardware configuration in the accelerator complex, such as an “ion source” or a “booster”. One CPU of PLC is usually assigned to each group, and all of the controls of connected instruments and devices in the group are managed by this CPU. Currently, all of this FFAG complex is organized into ten such groups with one additional CPU for the beam line between the FFAG complex and the fuel assembly. The actual configuration of the hardware devices is shown in Fig. 5.

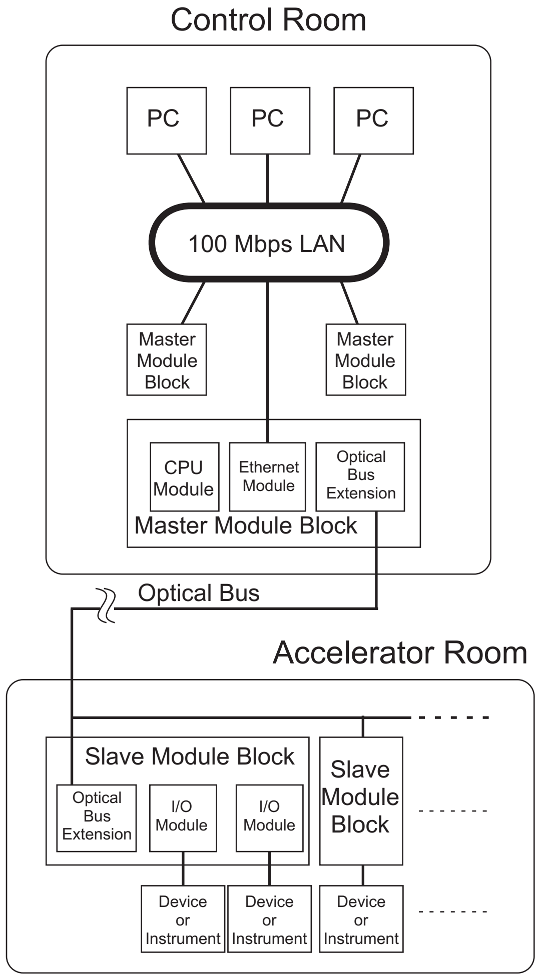

Figure 3: Hardware configuration of the present control system.

3.3. Network and PCs

As for the network, a conventional 100 Mbps LAN is prepared as the network for PLCs and remote PCs. As introduced above, this LAN is also used for the maintenance of PLC. Wi-Fi access points are prepared at most places in the accelerator facility building for remote PCs, which enable on-site test operations anywhere in the Wi-Fi area.

Conventional laptop and desktop PCs are used as remote PCs for MMI and higher level controls. The required specifications for remote PCs are not very high, i.e., just required to have a conventional network capability and to meet the hardware specifications for LabVIEW[9], which is the environment for developing MMIs and the higher level of controls as described in the latter section. Some PDAs are also possible candidates as remote PCs with proper adjustments of the performance of MMI.

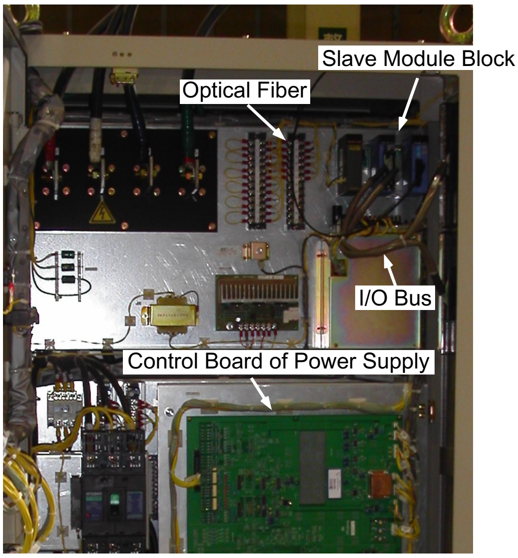

Figure 4: Typical implementation of a slave module block. In this case, a slave module block is implemented into the d.c. power supply for "F-magnets" of the main ring. This slave module block is connected to its master module block by a high-speed (10 Mbps) full-duplex link over optical fiber, and serves for the digital I/O connection with the control board of this power supply.

Several laptop PCs and PDAs with a Wi-Fi capability are actually prepared as wireless controllers for on-site test operations.

3.4. Compatibility with other PLC series

Sometimes our control system is required to accept the instruments in which a different series of PLC is already implemented. This will cause an incompatibility in communication with remote PCs. This time we are determined to use FL-net[10] to overcome such a problem[11]. FL-net, which is also known as OPCN-2, is an open network, defined and standardized by the Japan Electrical Manufacturer's Association(JEMA), the compatibility is guaranteed as long as the equipment is certificated by JEMA. Almost all of the current PLC series available in Japan are in accordance with FL-net. A CPU of FA-M3R PLC is prepared in our control system side, and a cyclic data-transfer protocol supported by FL-net is used for the synchronizing the memory blocks of FA-M3R and the PLC implemented in the instrument to share the status and command between them. With this scheme, remote MMI PCs are not required to adopt communication with any PLC series other than FA-M3R.

4. Software

4.1. Architecture

There are three main layers in our software architecture, i.e., a low-level layer, an MMI layer and a communication layer connecting between the first two layers (Fig. 6).

The low-level layer consists of sequences required for autonomous operations, including protection routines against hardware failures. Routine tasks that are frequently used, e.g., the initialization of a magnet or the start/stop of a vacuum pump, are also implemented in this layer. These sequences were developed with the ladder logic language supplied as part of "WideField 2", the default environment for the development of the FA-M3R series.

The MMI layer consists of MMI software and other high-level sequences running on remote PCs. MMI software is basically developed as a virtual instrument (VI) of LabVIEW. LabVIEW is known for its user friendly GUI environment, thus less training in development is expected with LabVIEW. Another advantage in LabVIEW is continuous support by National Instruments for various operating systems, such as Windows, Mac OS or Unix. With this policy, we expect the developed software to still be working on platforms in the future.

The communication layer is software that governs the communication between PCs and PLCs in the present control system. This part is also developed as a LabVIEW VI, namely "communication VI", and is implemented into all PCs as the standard communication environment of the present control system.

In usual case, each remote PC has one or more MMIs and one or more communication VIs for the communication with PLCs. These VIs run independently, and information is shared as global variables of LabVIEW.

4.2. Communication Layer

4.2.1. Communication VI

In the present control system, the communications between PLCs and PCs are performed by the communication VIs in the communication layer. As shown in Fig. 6, the parameters from devices and instruments, and the manipulations from MMI VIs are initially stored in the D-registers of PLC and global variables in remote PCs, respectively, and communication VIs refer and synchronize global variables and D-registers. All the communications between PLCs and PCs are initiated by the communication VIs, usually every 100 ms. the translations between D-registers and global variables are defined in the allocation tables described later. With this communication scheme, developers of the MMI layer and those of the low-level layer do not have to pay attention to communications between them.

The communication scheme based on this communication VI in the current control system is the major difference compared to similar PC-PLC based systems, such as the AVF cyclotron at Tohoku University[12]. In their case, the communication protocol was not standardized. Therefore, any developers in MMI layers or lower layers have to build their own custom communication protocols over TCP/IP, resulting in a complicated development with less compatibility toward the future.

4.2.2. Allocation table

An allocation table of the parameters in D-registers is given as a text file for each CPU, and referred by communication VIs. This file contains the necessary information for translating data on a PLC and PCs, such as the name of global variables and the assigned addresses on D-registers of PLC. Additionally, other information, such as physical pin assignments of PLC modules, conversion coefficients of parameters and the IP address

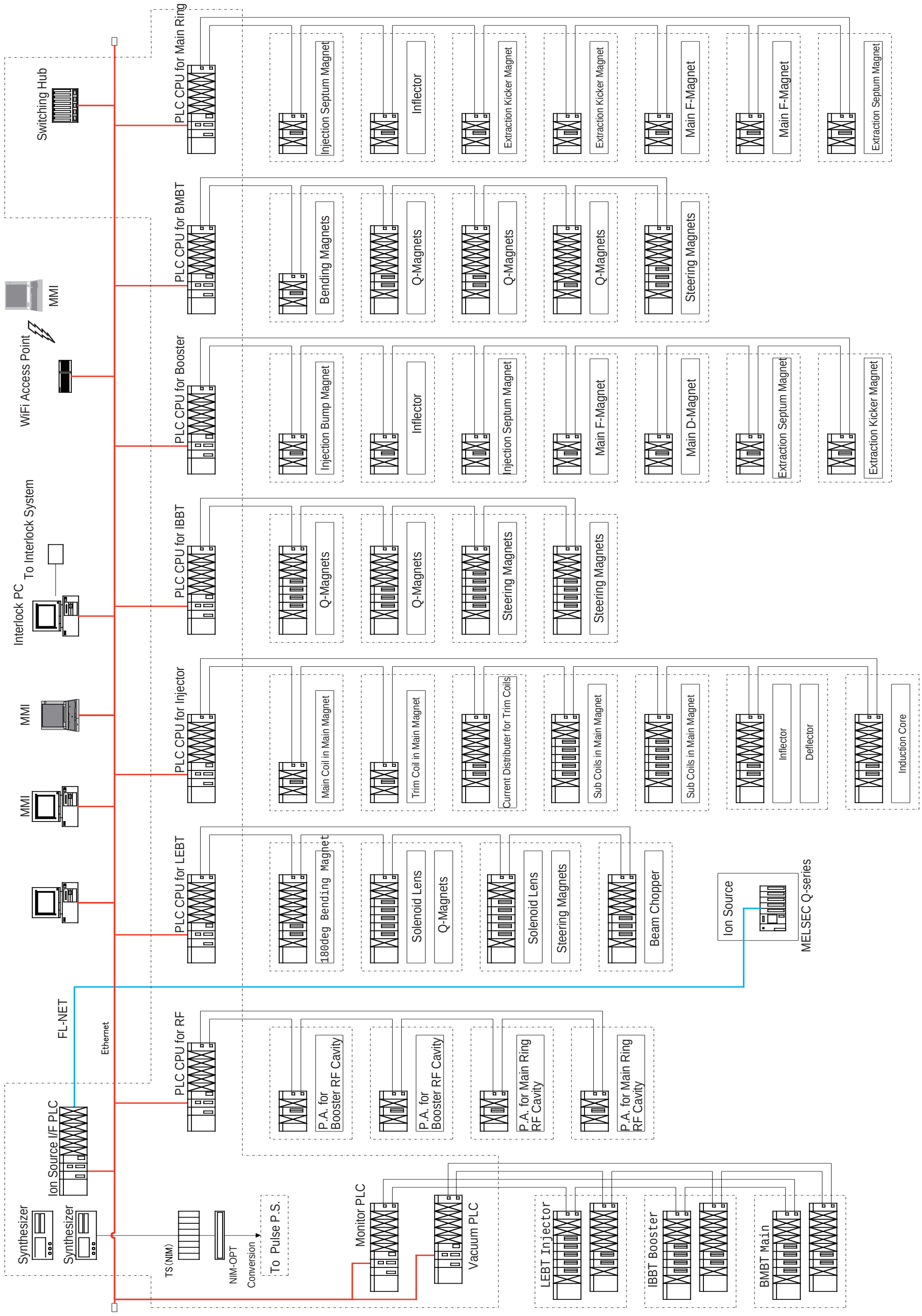

Figure 5: Actual hardware configuration of the current control system. There are ten groups of control devices based on the hardware configuration of the FFAG complex. One CPU usually governs from five to eight slave module blocks. An additional PLC is assigned to control the beam line towards the fuel assembly for an ADS study. These PLCs and PCs for MMI are connected over a 100 Mbps LAN.

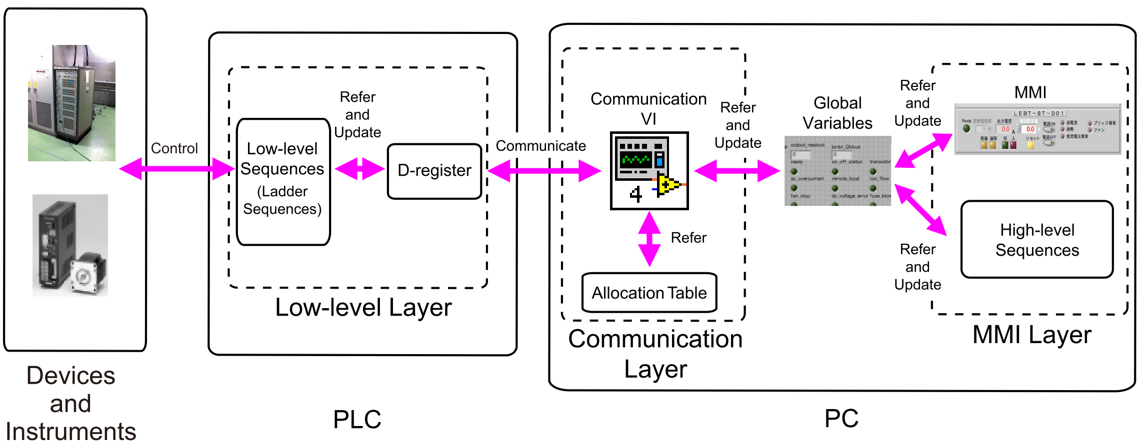

Figure 6: Architecture of software in the control system. The low-level layer and the MMI layer are connected by the communication layer, which is developed as a LabVIEW VI, namely "communication VI". This communication VI performs the communication between PLCs and PCs by synchronizing global variables of LabVIEW in remote PCs and D-registers on PLCs.

of PLC, are also included. In this meaning, the essence of this control system is in these allocation tables. These allocation tables are continuously maintained by a group of technical staff who directly treat PLCs and hardware devices, and referred by all developers working on this control system. These original tables are prepared as Excel files for the convenience of technical staff who may not have sufficient skills on computers. Every time the original Excel files are updated, these files are exported as text files and served to communication VIs.

4.3. *MMI and Low-level layers*

Now that the communication VIs have already managed the communications between PLCs and remote PCs by synchronizing D-registers and global variables, the developers of the MMI software and the ladder sequences can concentrate only within their respective layers.

In the case of MMI software development, placing items like buttons and meters on the front panel window and composing block diagrams by wiring them with respective global variables are the typical tasks (Fig. 7). One can also develop more complicated control sequences exactly in the same way as developing a conventional VI in LabVIEW.

The situation is quite similar in the development of ladder sequences for PLC. In the ladder logic language, referring/setting values on a certain D-register is as easy as treating a conventional digital/analog terminal of a PLC module. Therefore, the development of the ladder sequences implemented as the low-level control layer becomes similar to those of the standalone PLCs.

5. Current status

Currently, our control system has served the beam commissioning of the 150 MeV FFAG accelerator complex together with the development of the control system itself for more than three years[13]. The first beam extraction from the main ring succeeded in October, 2008, and the experiments combined

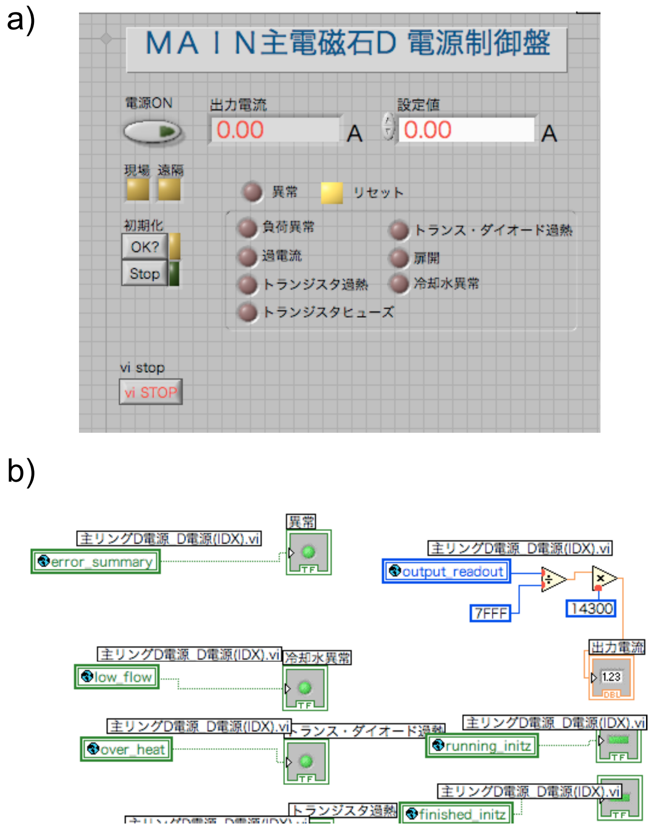

Figure 7: Typical examples of a)a front panel window and b)a block diagram of MMI software developed with LabVIEW. These are developed for the power supply of D-magnets in the main ring.

with the fuel assembly started in March, 2009. No serious interferences to the commissioning and the operations arising from the control system have occurred up to now.

As planned in the beginning, the development of the control system was successfully performed by a small group consisting of two scientists, three technical staff and a graduate student, who are also main members of the construction and the commissioning group. Additionally, many of them had no experience in accelerator operation or construction prior to this project. Specific training was not performed for developing the control system, but just for the conventional usage of LabVIEW and basic knowledge on PLC. The total cost of the control system was also minimized to be as low as 1/10 of a typical control system for a cyclotron of 100 MeV-class developed by typical accelerator manufacturers.

Based on the success of this control system in the FFAG complex, some applications to other facilities in our institute are now in progress.

One such typical example is the pneumatic transportation facilities for neutron irradiation at our institute[14]. This facility manages the transfer of samples to the center region of the 5 MW nuclear reactor at KURRI for neutron activation analysis or radioisotope production. A malfunction of this system can cause an undesirable neutron flux disturbance at the core, resulting in a disturbance to stable reactor operation. The previous control system was based on hard-wiring and custom circuits, intending to ensure reliability rather than flexibility or usability. The control system has now been replaced by a new one developed on the present control architecture to increase the flexibility for better user experience, while maintaining the reliability. The cooperation with MySQL and Apache is also realized for the web-based status monitor and the management system of radioactivity produced with this facility.

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