Cryogenic System Simulation based on EcosimPro and EPICS

Qiang Yu

University of Science and Technology of China

Supervisor: Matthias Clausen, DESY

07. Sept. 2016

Abstract

Large scale cryogenic systems are complex industrial processes with large number of correlated variables on wide operation ranges, a dynamic simulator is required to obtain the virtual commissioning for the cryogenic plants, it provides a computer aided design platform for developing and testing new control program. This report presents a cryogenic simulator based on EcosimPro and EPICS, the communication and control architecture are detailed and explained, a dynamic simulation for helium cryogenic system during a complete cool-down phase have been implemented. The cryogenic simulation system will be used at DESY for operator training and process optimization in the future.

Contents

1. Introduction 3

2. Process and control simulation architecture 3

2.1. EcosimPro 3

2.2. EPICS 4

2.3. Simulation architecture 5

3. Cryogenic simulation experiment 6

3.1. Cryogenic model 6

3.2. IOC records configuration 7

3.3. CSS configuration 8

4. Simulation results 9

5. Conclusions and future work 10

1. Introduction

Large scale helium cryogenic plants is a basic subsystem for the physical experiment facility that apply the superconducting technology, such as superconducting nuclear fusion tokamak and particle accelerator, the superconducting magnets are generally cooled under 4.5K. The European X-ray Free Electron Laser (XFEL) linear accelerator constructed at DESY aim to produce pulsed electron beam with the energy of 17.5 GeV, which consists of 800 superconducting 1.3 GHz radio frequency cavities in the 100 cryomodules are cooled in a liquid heliumIIcooling bath at 2K [1].

Cryogenic systems provide the required cooling capacity consisting of helium refrigerators and distribution box are extremely complex continuous industrial processes, the large number of correlated variables include temperature, pressure, flow, liquid level should be controlled to follow the setpoint and keep within permissible range, combined with the control for critical equipment such as compressors and turbines are the mission of control system. MKS-2 take charge of the XFEL cryogenic process control system based on EPICS, I/O components include various of sensors and actors communicate with EPICS through PROFIBUS, the number of PROFIBUS nodes of XFEL cryogenic control system adds up to 540 and results in 12700 EPICS records[2].

The purpose of dynamic simulation for cryogenic system is realizing virtual commissioning of the system, the cryogenic process model was used to replace the real cryogenic plants which connected to the existing control system and then constitute a dynamic simulator, from the view of control engineers and operators, the simulator remains extreme similarity to real system but runs faster, therefore it can be used to help the engineers develop or tune new control strategies and train the operators without influencing the real cryogenic system. In our work, the EcosimPro was selected to modelling cryogenic plants and a multilayer server/client structure was applied to perform the data communication between the model and OPI (Operator Interface).

2. Process and control simulation architecture

2.1. EcosimPro

EcosimPro is a very powerful continuous-discrete simulation tool based on the object oriented modelling paradigm [3], it provides an intuitive graphics environment to create models based on schematic views. There are varieties of library have already been developed for several different domains such as: Cryogenics, Power, Space, Thermal, Control, etc. CRYOLIB is an EcosimPro library for simulating cryogenic systems and provides the user with a large palette of cryogenic components [4].

OPC (OLE for Process Control) is an Interoperability Standard, communication is performed through the client/server architecture and the server represents any device that is able to attend requests from the clients for supplying real-time data [5]. The purpose of the EcosimPro OPC Toolbox is to make conversion of a simulation model into an OPC server and exposing the data in the model to external clients, the connection architecture for the simulation systems is built finally by the OPC protocol. An OPC Server is generated from a Deck in EcosimPro, Deck is an encapsulated EcosimPro simulation model generated for running as a black box, the variables to be exposed by the OPC Server should be select when create the Deck. Through the process shown in Figure 1, an OPC Server corresponding to the simulation represented by the deck is generated finally.

Figure 1. The generation process of the OPC Server in EcosimPro

2.2. EPICS

The Experimental Physics and Industrial Control System (EPICS) is a set of software tools and applications which provide a software infrastructure for Application Developers to create distributed control systems. EPICS uses a client/server model with Channel Access (CA) network protocol for passing data, as shown in the figure 2, Channel Access is the 'backbone' of EPICS make a client can communicate with a number of servers. CA clients are applications that usually runs in the workstation/PC, typical generic clients are operator control screens, alarm panels, and data archive/retrieval tools [6]. IOC (Input Output Controller) run the CA Server task are a fundamental part of an EPICS control system, real heart of IOC is the database loaded into IOC memory, database is a collection of various types of EPICS records that appear as function-blocks to create applications implementing such as data reading and writing, scaling, filtering, alarm detection, calculations, control loops and so on. Channel Access provides network access to IOC databases and Device Support driver allows records to interact with hardware inputs and outputs (I/O), the Sequencer runs finite state machines on the IOC can be used to sequence complex operations that connect to the database through Channel Access also [7]. Figure 3 shows the IOC software components, based on these, the IOC transfer process variables and define their behavior by real-time control algorithms.

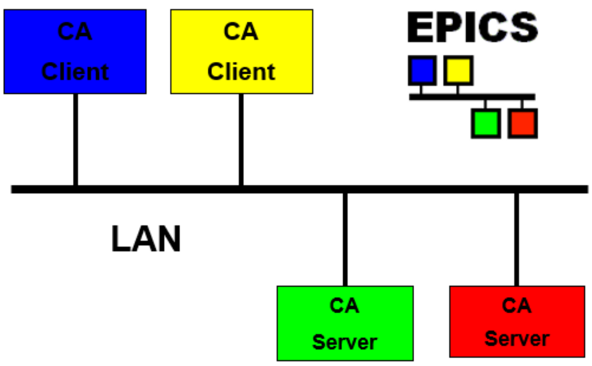


Figure 2. EPICS Channel Access

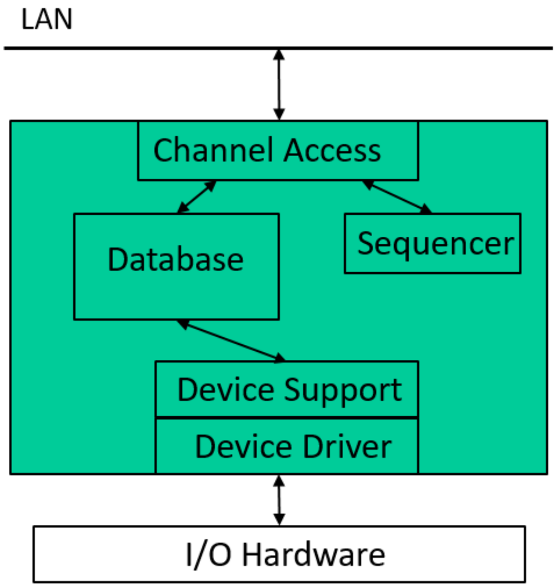


Figure 3. IOC software components

EPICS IOC can run in a variety of computers that running different operating systems such as: VME based, running vxWorks or RTEMS, PC running Windows, Linux, RTEMS, Apple running OSX.

2.3. Simulation architecture

The control architecture for a simple application instance of EPICS normally comprises three layers: OPI layer, IOC layer and field device layer, OPI and IOC run in different computers. Particularly, the computer run IOC software called "IOC Core" is typically built from VME/VXI hardware crates, CPU boards, and I/O boards. The I/O boards drive the hardware plant directly or through a variety of standard field buses and then establish the connection between IOC and field device layer.

Comparing to the real control framework of EPICS, our cryogenic simulation system also have a three-layer architecture, see in Figure 4. The field device layer is integrated into the cryogenic process model in where the cryogenic plant is modeled with Ecosimpro, and then converted into the OPC Server with a set of I/O variables were exposed to IOC. The IOC layer is implemented by soft IOC which is an instance of IOC Core running as a process on a "non-dedicated" computer and without real I/O hardware, soft IOC runs with the EPICS IOC shell that is used to interpret startup scripts (st.cmd) and to execute commands entered at the console terminal as a simple command interpreter [7]. In OPI layer, Control System Studio (CSS) is selected as the CA client application, CSS is an Eclipse-based collection of tools to monitor and operate large scale control systems [8], which provides integrated environment tool for engineering, configuration and operation, it's very convenient for us to configure process values (PVs), alarm PVs, synaptic displays and trend plotting, etc.

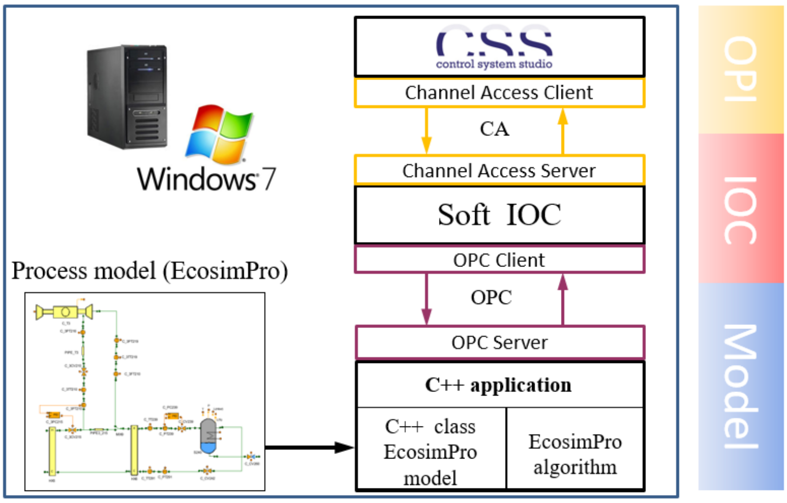


Figure 4. Simulation architecture

The whole cryogenic simulation system run in one computer running Windows, two kinds of communication protocol based on the Client/Server model are applied for the data transport between neighboring layers, one is the Channel Access for CSS and IOC, another is the OPC for IOC and underlying model. The IOC appear revealing dual role can be regarded as either CA Server in term of CSS or OPC client in term of the cryogenic process model.

3. Cryogenic simulation experiment

3.1. Cryogenic model

A helium refrigerator modeled in EcosimPro combine a compressor station and a coldbox, all the cryogenic components come from the CRYOLIB, includes a compressor and a gas tank in the compressor station, two turbines, four heat exchangers and a phase separator in the coldbox, a number of pipes are used to connect different components, valves and sensors are integrated in model as the I/O devices. Through compression, helium with high pressure (13bar) and high temperature (300K) is generated in the compressor station and then enter into the coldbox, a part of helium flow through turbines, the temperature come down with decrease of pressure after expansion, then return to the compressor station from the LP (low pressure) stream of heat exchangers; Another part of helium flow through the HP (high pressure) stream of heat exchangers and is cooled by heat transfer with the cold helium in the LP stream. At first, the helium in the HP stream flow through a bypass valve and joins the helium in the LP stream, the opening of the bypass valve is controlled to decreased with the cool down process, when the temperature in the cold end of heat exchangers fall to 7K, the bypass valve will be closed and all the helium in the HP stream flow through the throttle valve and enter into the phase separator, the temperature fall to 4.5K further and the liquid helium will be generated.

48 process variables in the cryogenic model was selected to be exposed by the OPC

server, 15 of these can be write by the IOC and then receive the control quantity outputs from the records.

3.2. IOC records configuration

There are 86 IOC records in total configured in the database for the cryogenic simulation, table 1 show its constituents. What a record does depends upon its type and the values in its fields, different records can transmit data each other, implement specific application in cooperation.

Table1. Constituents of database for the cryogenic simulation

Record Type	Quantity	Application
ai	38	Analog Input, read PVs from OPC Server
ao	18	Analog output, write control quantity to OPC Server
bi	6	Binary Input, read binary values from OPC Server
bo	6	Binary output, write command to OPC Server
pid	10	PID controller, implement PID algorithm
calc	6	Calculation, calculate setpoint and control quantity
seq	2	Sequence, trigger the processing and send values to those records

The control block diagram for the inlet valve CV210 of turbines set shown in Figure 5 illustrate how the records work together. Two turbines connect in series in the model, the input pressure of each turbine and the temperature at the outlet of the second turbine are three variables interact each other, the turbine set can be regarded as a delay block. Three PID loops applied in this SIMO system to control the CV210, the minimum output of the three controllers was selected as the opening input of CV210 that avoid the overshoot of the three controlled variables, this function is performed by the MIN( ) configured in CALC field of the calculation record.

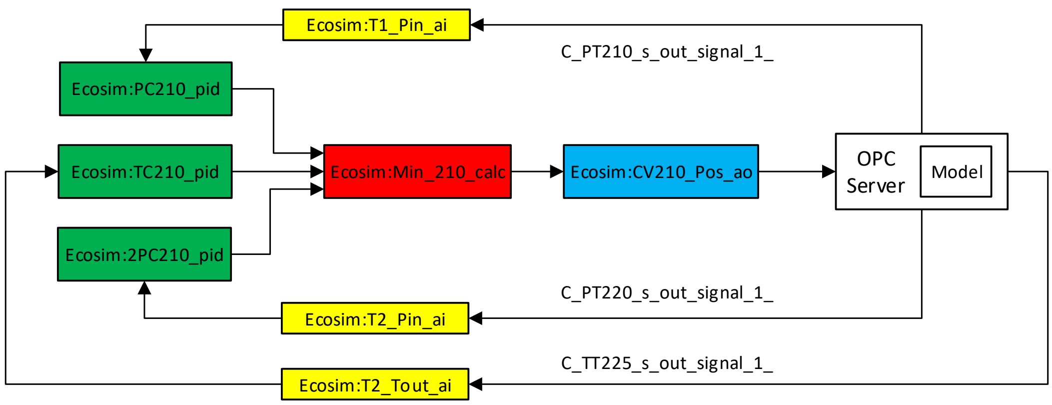


Figure 5. Control block diagram in IOC

The Calculation record can also be configured to implement piecewise function because the C language's question mark operator is supported [9], the format is:

(condition)? True result : False result

This application is used for the set-point management of the turbines revolving speed and the open-loop control for the bypass valve CV208, as the Figure 6 and Figure 7 show, the set-point of revolving speed is assigned according to the turbine inlet temperature, the opening of CV208 depend on the temperature of cold end inlet of the last heat exchanger.

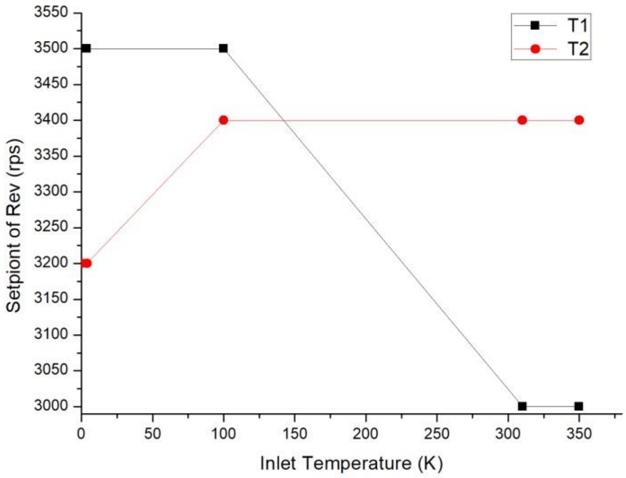


Figure 6. Set-point management of the turbines revolving speed

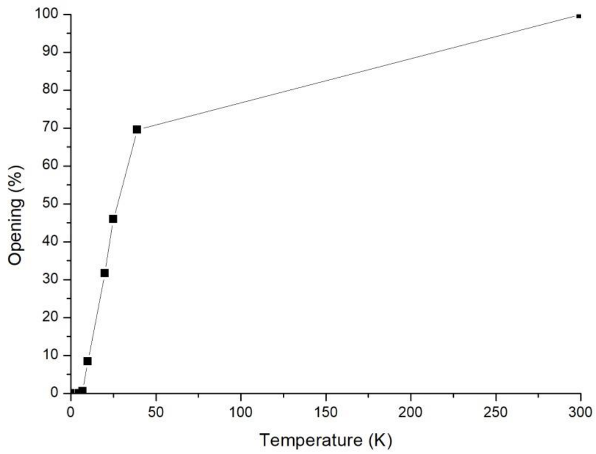


Figure 7. Calculation of the opening of CV208

In order to keep the balance between a smooth running and precision of the simulation, the scanning time for all the ai and bi records are set to 1s, that for ao, bo, seq records are set to "Passive", that for pid and calc are set to 2s.

3.3. CSS configuration

A supervision interface was configured for the cryogenic simulation, as shown in the Figure 8, varieties of plug-in are used to connect with IOC records and read or write filed values. The supervision interface can run as a shell to display process variables and implement some manual operations, history curve of the process variables can be obtained by configure the TrendPlotter. The CSS configuration for cryogenic simulator are same as the real cryogenic control system.

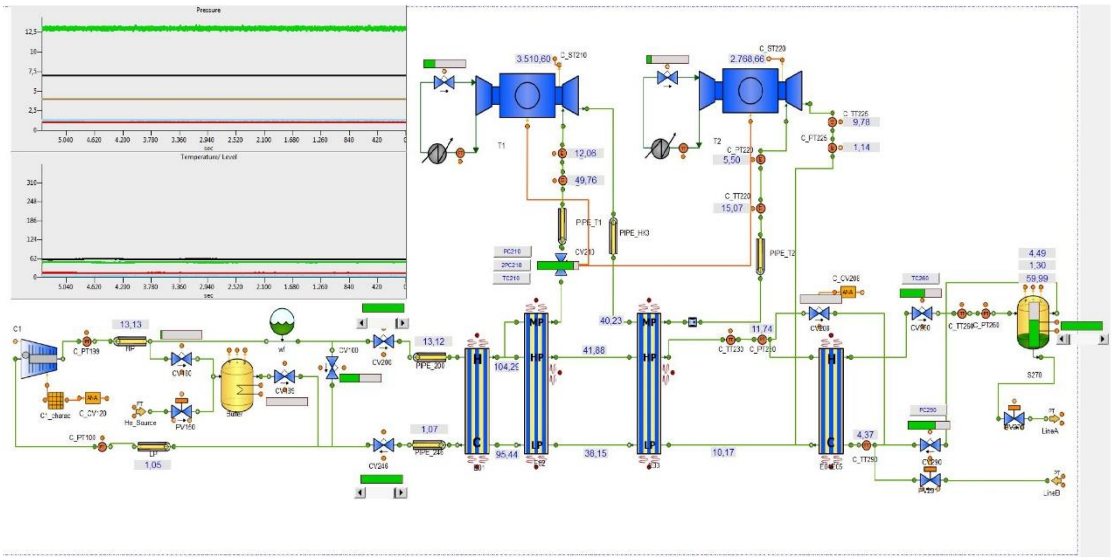
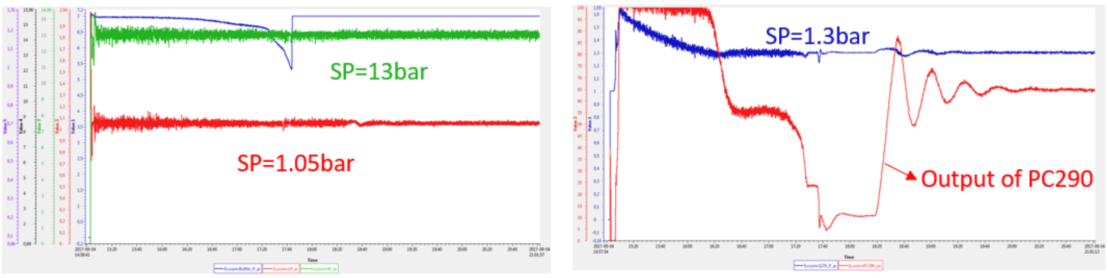


Figure 8. Supervision interface for the cryogenic simulator

4. Simulation results

The simulation process can be accelerated by setting a RealTimeFactor, in this experiment, it is 100 times faster than a real-time simulation and not take us much time to get the simulation result. Figure 9 shows the pressure regulation, it can be seen the control for high pressure and low pressure in the compressor station (left graph) perform well, and the pressure in the phase separator S270 (right graph) follows this set-point with time by the control of PC290.

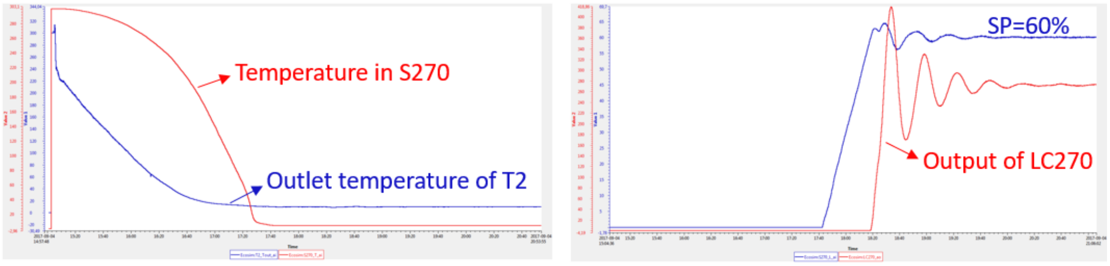


High & Low Pressure regulation

Pressure of Phase separator S270

Figure 9. Pressure regulation in compressor station and coldbox

We can observe the evolution of temperatures at S270 and also at the outlet of second turbine from Figure 10, the temperature at the beginning is 300K and by the end of the cooldown it drops to 4.5K in S270, and in the point the helium begins to liquefy, the liquid level reach the set-ponit after a period of liquidation and regulation.

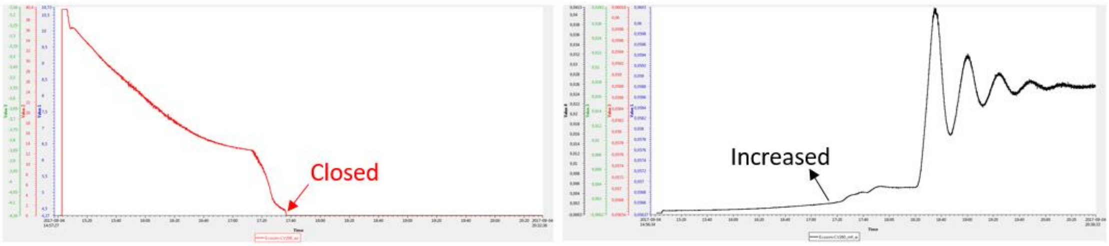


Process of cooldown from 300K-4.5k

Liquid Helium Level

Figure 10. Cooldown and liquidation in the phase separator

The opening of the bypass valve CV208 should be controlled to decreased until closed completely with the cool down process, see the left graph in Figure 11, that can make the mass flow through the turbines increase, it's an important mechanism to increase the refrigeration ability and cool the helium further, after the temperature in the outlet of the second turbine under 15K, the opening of the throttle valve CV60 increase, the same thing with the mass flow through it, see the right graph in Figure 10, that lead to the generation of the liquid helium.



Opening of bypass valve CV208

Mass flow of throttle valve CV260

Figure 11. Evolution of the CV208 opening and the mass flow through CV260

5. Conclusions and future work

A dynamic simulation for helium cryogenic system during a complete cool-down phase can be implemented by the simulator based on EcosimPro and EPISC, a two-Server/Client architecture is applied to establish the communication between CSS and OPC Server running the model, controllers configured in the EPICS IOC have achieved a satisfactory performance after setting reasonable scanning time and tuning. It is possible to accelerate the simulation process, developers will benefit from it when they debug control program use the simulator.

In the future, new IOC records to implement dynamic regulation for PID parameters will be configured and that will make the simulator more automatic; Building the simulator in more than one computers running the three layers respectively and replace the soft IOC by real IOC core also be expected; Last but not least, the cryogenic simulation system will be used at DESY for operator training and process optimization.

Acknowledgements

First of all, I would like to extend my sincere gratitude to my supervisor Matthias Clausen for his instructive advice and useful guidance on my project. I am deeply grateful of her help in the completion of this summer student project. Also, I would like to thank all the members in MKS-2 for their support and time answering my questions in study and life; The DESY summer student organizing team is highly appreciated for coordinating and running this program.

References

[1] Ayvazyan V, Clausen M, Petersen B, et al. RF heat load compensation with electrical heater for XFEL accelerator-measurements at CMTB, AMTF and FLASH[C]//IOP Conference Series: Materials Science and Engineering. IOP Publishing, 2015, 101(1): 012159.

[2] Bacher R, Kumar M, Wilksen T, et al. The large scale European XFEL control system: Overview and status of the commissioning[C]//15th International Conference on Accelerator and Large Experimental Physics Control Systems. Beschleunigerphysik, 2015 (PUBDB-2015-04845).

[3] E. Agrupados. EcosimPro: modeling and simulation software, 2016.

[4] E. Agrupados. CRYOLIB Library v1.2.7 User Manual, 2016.

[5] Zamarreño J M, Mazaeda R, Caminero J A, et al. A new plug-in for the creation of OPC servers based on EcosimPro© simulation software[J]. Simulation Modelling Practice and Theory, 2014, 40: 86-94.

[6] Lewis S A. Overview of the Experimental Physics and Industrial Control System: EPICS[J]. h ttp://csg. lbl. gov/EPICS/OverView. pdf, 2000.

[7] Kraimer M R, Anderson J B, Johnson A N, et al. EPICS application developer's guide[J]. 2010.

[8] http://controlsystemstudio.org

[9] Stanley P, Anderson J, Kraimer M. Record reference manual[J]. 1995.