Proceedings of the 42nd Chinese Control Conference
July 24-26, 2023, Tianjin, China

Design of Digital Twin Circuit Principle Experiment System Based on NCSLab

Yu-Zhong Li[1,2], Guo-Ping Liu[*2], Yi Yu[2]

1. School of Computer Science and Engineering, Huizhou University, Huizhou, 516007, China

[*]2. School of System Design and Intelligence Manufacture, Southern University of Science and Technology, Shenzhen, 518055, China
E-mail: liugp@sustech.edu.cn

Abstract: This paper is concerned with the requirements of current distance learning of circuit principle experiment of automation specialty, automatic fault detection of experimental equipment, automatic fault isolation, uninterrupted experiment in case of fault, and maintaining the number of available equipment. Specifically, based on the networked control system laboratory (NCSLab) architecture, digital twin, remote control technology and circuit design, aiming at the circuit experiment principle course, the digital twin are realized by Simulink, and a digital twin circuit principle experiment system(DT-CPES) is designed and implemented. The designed system shows that the system can realize the sharing of experimental equipment, the digital twin can predict, and can also verify with the actual measurement data of the circuit experiment. Through the digital twin fault isolation controller(DT-FIC), the fault diagnosis, fault isolation and replacement output of the experimental equipment can be realized. Therefore, the developed system reduces the overall risk and cost of installation and maintenance of large-scale circuit experiments, and provides fault-tolerant redundancy for the experimental system with low computational burden and high reliability.

Key Words: Distance learning; digital twin; remote control; circuit principle; experiment system

1 Introduction

In recent years, due to the impact of the epidemic and the rapid development of distance learning [1], the demand for distance experimental equipment has increased sharply, especially in the fields of power systems, industrial manufacturing systems and industrial electronic applications. Remote equipment provides students with the opportunity to apply theory to practice. Traditional laboratories are limited due to geographical reasons [2]. In addition, for students majoring in automation, experimental equipment is expensive and resources are scarce. With the progress of computer, communication and other technologies, there are remote laboratories [3] and virtual laboratories [4], which realize the sharing of experimental resources from a distance. The network laboratory (Netlab) of Zhejiang University is a comprehensive remote laboratory of electronics and control specialty [5]. It has designed a remote measurement and control system for boilers and created a 3-D scenario-based interactive interface suitable for industrial remote monitoring. The Networked Control System Laboratory (NCSLab) developed jointly by the University of South Wales and the Institute of Automation of the Chinese Academy of Sciences [6-7] can complete the automatic control experiment only through a web browser. Wuhan University developed NCSLab 3D [8-11] on the basis of NCSLab, which enhanced virtual reality and 3D collaborative display. There are other well-known remote laboratories abroad, such as VNLab [12], MIT iLab [13], eComLab [14] and WebLab [15-16], which have good engineering teaching significance. Recently, networked laboratories have also developed in the direction of digital twinning, and many digital twinning laboratories have emerged, such as electrical laboratory [17,18], robot laboratory [19], mechanical, thermal, turbomachinery laboratory [20] and intelligent manufacturing laboratory [21]. However, at present, there is little work on fault prediction and fault isolation of experimental equipment with digital twin. The main work of this paper is to do the following work based on the NCSLab virtual remote online experiment platform: First, the digital twin circuit principle experiment system (DT-CPES) is designed, including four circuit principle experiments such as superposition theorem, and the control expression is given. Second, the circuit design uses analog switch chip, enabling the system to realize circuit switching, LED light indication, current measurement and voltage measurement functions; Thirdly, the digital twin fault isolation controller (DT-FIC) is designed to realize real-time self-inspection. In case of failure, the experimental circuit and instrument access are automatically cut off, the output is replaced by the twin, and the fault is reported in the background, and automatically reconnected after the repair is completed; Through the above system design, the circuit experiment system based on NCSLab realizes remote experiment, equipment sharing, and automatic verification between virtual and real; Analog switch switches improve reliability, reuse instruments and reduce the cost of experimental equipment; Enhance the ability of unattended and convenient maintenance of equipment. System fault self-detection, maintain the number of available experimental equipment, protect equipment from secondary damage and other functions.

[*]This work is supported by SUST-HZU youth visiting teacher project.

2 DT-CPES NCSLab

NCSLab is the networked control system laboratory. Since its establishment in 2006, latest version of the Web browser-malab server, the center Web server-region server-experiment platform. DT-CPES NCSLab adds a digital twin module to the Simulink program, which is compiled on the MATLAB region server and downloaded to the raspberry pie (Rasp.) for execution. The circuit is switched through RS485 bus control relay.

2.1 Architecture of DT-EPCS NCSLab

DT-EPCS NCSLab adopts the latest architecture of NCSLab, as shown in Fig. 1. Users transfer data from the cloud to the center server through Http in the form of web pages, and Administrator also manage the center server through Http. NCSLab provides users with a completely web-based rapid development solution for remote control and networked control. Most of the work in the real laboratory can be completed only through a web browser. The center server connects to the region server through LAN or WAN. The region server includes Matlab server and web server. The web server transmits user data and configuration information to the Matab server and automatically configures it to the digital twin program. The Matlab server downloads it to Rasp. through TCP, and the Raspberry controller control relay switching through RS-485.

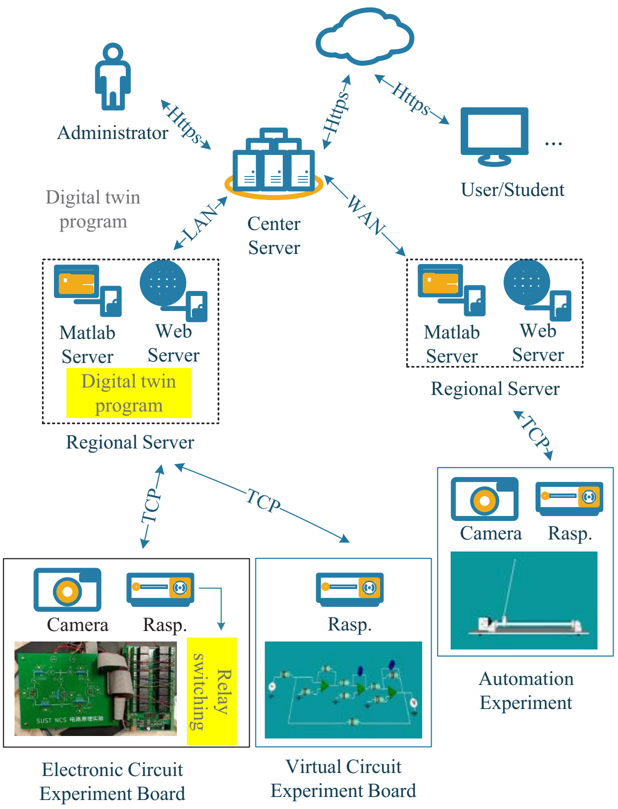


Fig. 1: The architecture of DT-CPES NCSLab

2.2 Data Flow of DT-CPES NCSLab

Fig. 2 shows the data flow of DT-CPES NCSLab. The user sets the experiment and algorithm through the NCSLab GUI on the web browser, and reaches the web server through https. The region server receives the experiment program, configures the user data in the digital twin program, and compiles the program combining experiment prog and digital twin prog with simulink compiler. The executable file is downloaded to the S-Function Model in the controller using TCP protocol and executed. The controller communicates with the physical device (circuit principle experimental board) data exchange through serial port/GPIO. The executable programs of experience prog and digital twin program form a small closed loop in the controller to verify and monitor the operation of the equipment. In the event of a fault, the circuit will be cut off through switch execute, and the replacement data will be uploaded to the server. The real-time input returned by the controller is uploaded to the real-time data module of the server for collection, and finally returned to the NCS Lab GUI of the web browser.

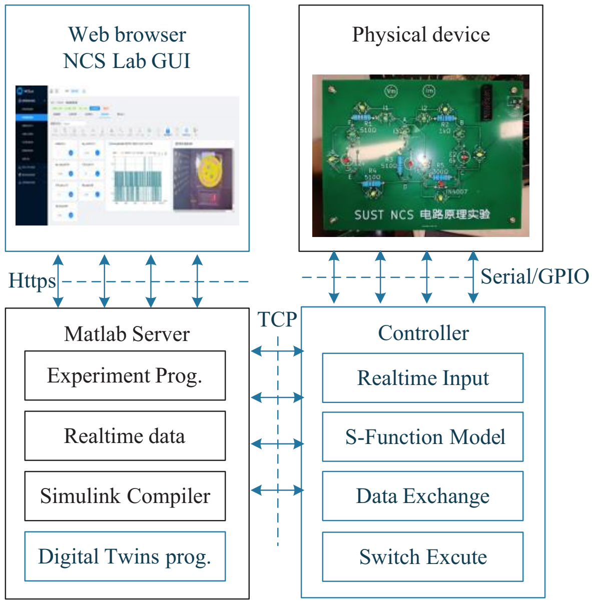


Fig. 2: NCSLab Data Flow

3 Digital Twin Circuit Principle Experiment System

The digital twin circuit principle experiment system (DT-CPES) is a model representation of actual circuit principle experiment equipment. The digital twin background simulation operation can record the current experimental equipment status and the historical data related to the equipment, and can also refine the control, optimize the equipment operation, predict abnormalities, fault isolation and replace the output. So as to reduce risks and equipment costs and improve operation efficiency.

3.1 Design of Digital Twin Circuit Principle Experiment System

The digital twin circuit principle experiment system is mainly composed of circuit experiment module and digital twin module, and the other modules include main power switch, logic gate, isolating switch control, experiment input, verification & fault detection and experimental output module. Fig. 3 is the schematic diagram of the digital twin experiment equipment system. The main switch is responsible for receiving the equipment request signal and opening the equipment. The circuit experiment module controls the real circuit through serial port/GPIO. There are two isolating switches on the input side and output side of the circuit experiment module. The circuit experiment module runs in parallel with the digital twin module. The circuit experiment module is sent to the Verification and fault detection module, through the isolation switch on the output side and the output of the digital twin. Digital twin fault isolation controller(DT-FIC) consists of Logic OR, Isolating switch control and Verification & fault detection.

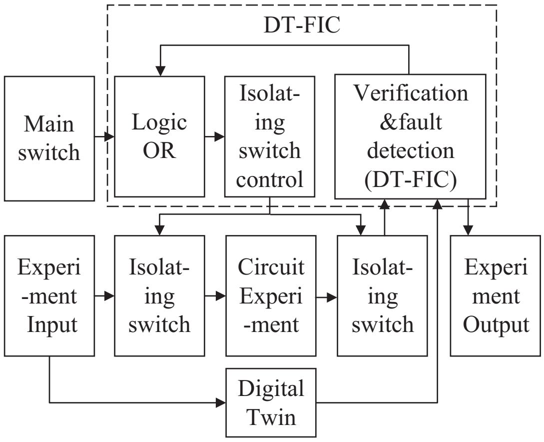


Fig. 3: Digital twin circuit principle experimental system

When the circuit experimental system is normal, the actual experimental output is obtained through the DT-FIC. Fig. 4 is the Simulink diagram of the digital twin circuit principle experimental system. When the circuit experiment module fails, the real output of the module will be compared with the virtual (predicted) output of the digital twin module. When the absolute value of the real output is greater than three times the absolute value of the virtual output, it is considered that there is a fault. At this time, the fault signal will be sent to the logic gate OR, and the DT-FIC will be controlled to disconnect the isolating switch, so that the circuit experiment module is isolated, and the virtual output will replace the original output.

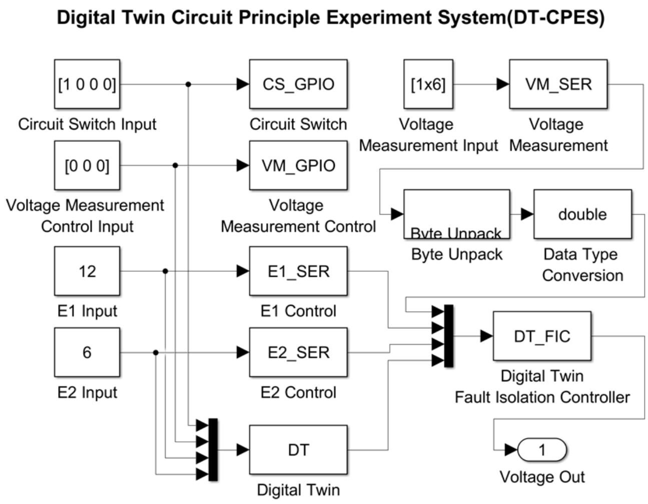


Fig. 4: Simulink for DT- CPES

Although it is a virtual output at this time, the experiment will not be interrupted due to equipment failure, and fault isolation will ensure safety and prevent equipment damage from expanding. We use the following method to solve the synchronization problem, based on timestamp, the digital twin module inputs the signal first. After calculating and obtaining the output result, the input signal is then sent to the circuit experimental module. Both the digital twin module and the circuit experimental module receive output signals, they are input to DT-FIC for detection and processing.

3.2 Circuit Experiment Module

The circuit experiment module is compiled by Simulink's S-function and downloaded to the underlying embedded controller to realize hardware data interaction. Fig. 5 is the schematic diagram of the circuit experiment module.

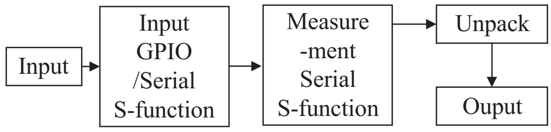


Fig. 5: Circuit Experiment Module

Input first sends input and setting data to Input GPIO/Serial S-function for configuration and input. Through Measurement Serial S-function, it continuously sends requests to underlying instruments based on serial communication, such as voltmeter and ammeter, reads data, unpacks and parses, and finally outputs measurement results.

3.3 Digital Twin Module

The digital twin module is generated by Simulink programming. Fig. 6 is the schematic diagram of the digital twin module.

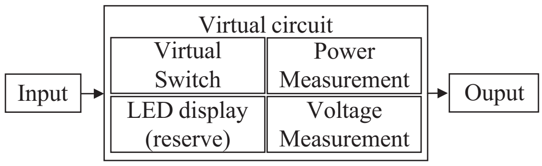


Fig. 6: Digital Twin Module

After the input parameters enters the module, through the virtual circuit, there are virtual switch circuits, power measurement circuits, voltage measurement circuits in the virtual circuit, and LED display circuits are reserved for future AI detection of LED on and off.

4 Experiment Implementation

The schematic diagram of the circuit principle experiment is shown in Fig. 7. The circuit principle experiment is based on the circuit principle experiment published by Wuhan University [8-11], including superposition theorem, Tellegen theorem, superposition theorem and substitution theorem. The circuit consists of DC voltage sources E1 and E2, resistors R1~R5, diode IN4007 and three pairs of SPDT (Single Pole Double Throw) S1~S3 for switching the circuit. Through circuit switching, measure the voltage and current I1~I3 between nodes A, B, C, D, E and F for experiment. The circuit control expression is derived as follows: set the voltage drop on R_1~R_5 as U_1~U_5, and set the input as power E_1, E_2 and E_3, $E_3 = U_{CD}$; Set I_1, I_2 and I_3 for output.

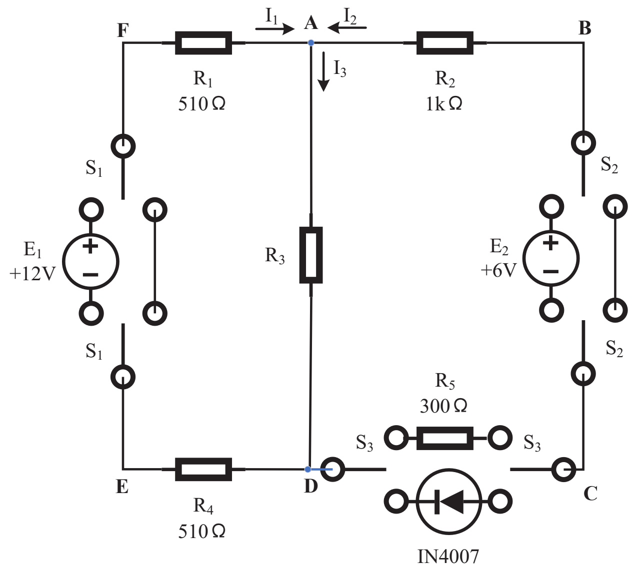


Fig. 7: Circuit Principle Experiment

According to Kirchhoff's current law and voltage law(KCL & KVL), the equation group can be deduced, as shown in equation (1):

$$\begin{cases} E_1 = U_1 + U_4 + U_3 & \text{(KVL)} \\ E_2 = U_2 + U_3 + U_5 & \text{(KVL)} \\ I_3 = I_1 + I_2 & \text{(KCL)} \end{cases} \xrightarrow{\text{Ohm's Law}} \begin{cases} E_1 = I_1 R_1 + I_1 R_4 + I_3 R_3 \\ E_2 = I_2 R_2 + I_3 R_3 + I_2 R_5 \\ E_3 = I_3 R_5 - I_1 R_5 \end{cases} \quad (1)$$

Write it in matrix form and calculate the inverse to get the control expression, see equation (2):

$$\begin{bmatrix} E_1 \\ E_2 \\ E_3 \end{bmatrix} = \begin{bmatrix} R_1 + R_4 & 0 & R_3 \\ 0 & R_2 + R_5 & R_3 \\ -R_5 & 0 & R_5 \end{bmatrix} \begin{bmatrix} I_1 \\ I_2 \\ I_3 \end{bmatrix} \xrightarrow{\text{inv}} \begin{bmatrix} I_1 \\ I_2 \\ I_3 \end{bmatrix} =$$

$$\begin{bmatrix} \frac{1}{R_1 + R_3 + R_4} & 0 & \frac{-R_3}{(R_1R_5 + R_3R_5 + R_4R_5)} \\ -\frac{R_3}{(R_1R_2 + R_2R_3 + R_1R_5 + R_2R_4 + R_3R_5 + R_4R_5)} & \frac{1}{R_2 + R_5} & \frac{R_3(R_1 + R_4)}{(R_1R_5^2 + R_1R_2R_5 + R_3R_5^2 + R_2R_3R_5 + R_4R_5^2 + R_2R_4R_5)} \\ \frac{1}{R_1 + R_3 + R_4} & 0 & \frac{R_1 + R_4}{(R_1R_5 + R_3R_5 + R_4R_5)} \end{bmatrix} \begin{bmatrix} E_1 \\ E_2 \\ E_3 \end{bmatrix}. \quad (2)$$

If the output matrix of the experiment circuit and the digital twin is $\mathbf{I_E}$ and $\mathbf{I_T}$ respectively, and the verification and fault detection signal is S_0={0, 1}, then the output of the digital twin circuit principle experimental system is shown in equation (3):

$$\mathbf{I} = S_0 \mathbf{I_E} + \overline{S_0} \mathbf{I_T} \ . \quad (3)$$

4.1 Design of Electronical Circuit

The system uses KiCAD 6.0 for circuit design. The circuit schematic diagram is shown in Fig. 8. There is no irrelevant wiring and through-hole on the top layer of the camera area of experimental circuit board. Except for the experimental circuit resistance R1-R5, diode DD1, the other LEDs, analog switches, and drive chips are installed on the top layer; In the circuit design, the voltage of each node can be measured, and a voltmeter can be used by switching through the analog switch CD4051.

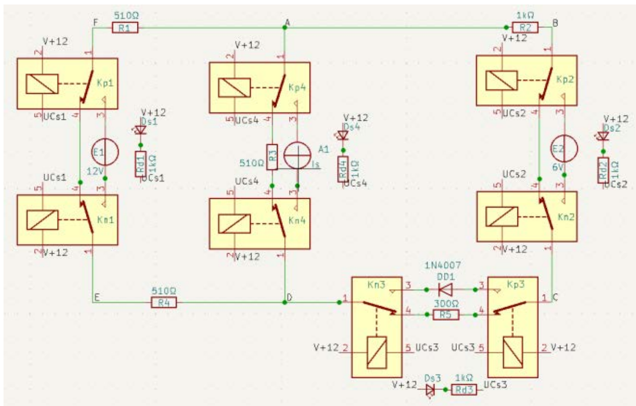


Fig. 8: Circuit Schematic Diagram

For the circuit switching circuit, it is necessary to use the normally open and normally closed functions of the relay. Since the voltage measurement circuit only uses a voltmeter, it uses the CD4051 single ended 8-channel multiplexer switch; The LED display circuit only requires a switch function, connected using relay circuits, and considering the internal resistance of each analog switch, compensation and calculation are carried out in Simulink; Due to the analog voltage range of the circuit being greater than the analog voltage of the chip, the ULN2003 driver circuit is used to increase the load voltage and current to drive the analog switch. The driver and amplifier circuits are shown in Fig. 9; The measurement voltage range is large, with positive and negative electrodes. Therefore, a positive and negative power supply is used to ensure that the range is within the power supply range, and a differential proportional amplifier is used to amplify and buffer the measured voltage. In differential signals, the positive channel is the circuit node voltage in the experiment. Since the voltmeter with serial port can only take positive value, one channel will raise the negative voltage to make the output measurement voltage positive; The use of proportional amplification is because the measured voltage may exceed the power supply voltage, so the purpose of measurement is to reduce the voltage proportionally and then transmit it to Raspberry Pi for calculation and restoration. The circuit board adopts 4-layer wiring. The DT-CPES diagram are shown in Fig. 10. After testing, DT-CPES can conduct four circuit principle experiments, which comply with KVL and KCL. A typical fault is that the chip cannot fully achieve rail to rail. If E1 and E2 exceed the system supply voltage, the circuit will malfunction, and CD4051 will heat up in a few seconds until the chip is damaged.

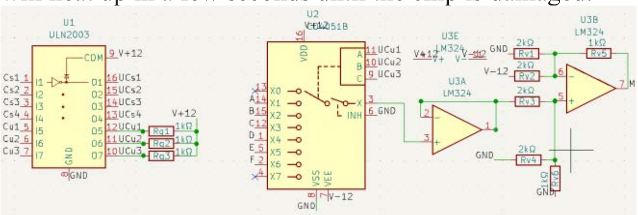


Fig. 9: Drive and Amplifier circuit

Therefore, in the verification and fault detection circuit, when E1 and E2 are close to or even exceed the power limit, the circuit is automatically cut off, replaced by digital twin for output, and uploaded to the NCSLab web. The design has been proven effective through testing.

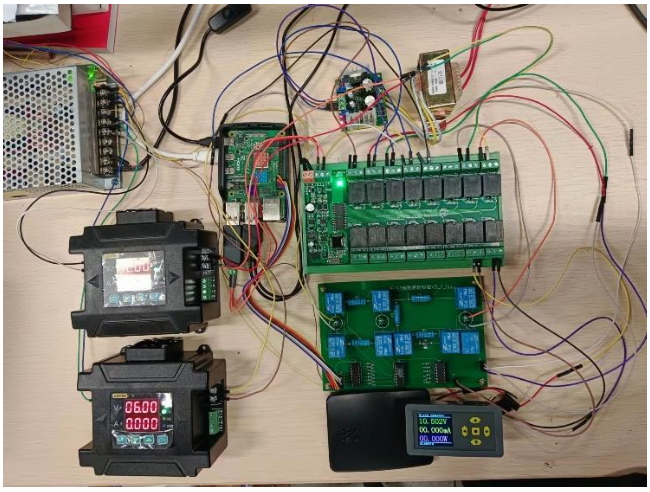
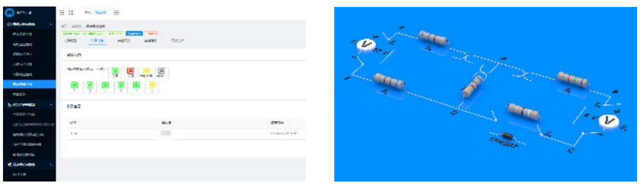


Fig. 10: DT-CPES

4.2 Design of Web System

The design of the web system is based on the NCSLab laboratory of Wuhan University [8-11], adding components and subdirectories. NCSLab front-end uses React framework, written in JavaScript, and creates front-end web interactive applications through DOM scripts, DHTML, AJAX and other technologies. Use 3D-max drawing to realize 3D display of virtual devices. Users can view and interact with 3D scenes by zooming in/out and from any possible angle. Web interface, 3D diagram, as shown in Fig. 11 (a) and (b).



(a) Web interface (b) 3D diagram

Fig. 11: Simulink for digital twin module

5 Conclusion

With the increasing demand of distance learning and distance experiment verification, the design and application of networked laboratory based on digital twin have attracted a great deal of attention. Based on the NCSLab framework of Wuhan University[8-11], this paper designs DT-EPCS, which can carry out three experiments, namely, Kirchhoff's law, Tellegen's theorem, substitution and superposition theorem. The use of analog switches and chip components improves the integration of the circuit; The DT-FIC is used for fault switching isolation and output replacement of the circuit. Therefore, the developed technology enhances the reliability of the experimental equipment, contributes to maintenance of the available quantity of experimental equipment, and avoids its secondary failures. The future research direction is to deduce and calculate the internal resistance of analog switch, increase the measurement accuracy, and use multi-agent networked control theory to solve the communication delay and interference problems of large number of users.

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