Teaching Design of Integrated Energy Control Based on Event-Driven AOE Network

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***Abstract*—There are a lot of control problems in the field of comprehensive energy control. In view of the problems of single experimental environment and difficult programming in the traditional control experiment teaching, the control principle research itself is out of focus. In this paper, a semi-physical simulation experiment teaching method is designed, which combines the low code controller developed by ourselves with Simulink simulation model to carry out the hardware-in-the-loop simulation of the control target and complete the verification and analysis of the control principle or the designed strategy. Taking photovoltaic maximum power tracking control for typical application of integrated energy system as an example, this paper explains how to guide students to understand the experiment objective, design event-driven AOE (Activity on edge network) network control strategy, configuration file, operation simulation and analysis. This method has been applied to the course "Design and Practice of New Energy Electric Power System" in Zhejiang University, which greatly reduces the requirements of strategy development on students' programming ability, makes them focus on the principle and strategy design itself, have a deeper understanding of comprehensive energy control, and help the national energy and electric power field talent training and the development of comprehensive energy digital technology.**

***Keywords*—integrated energy system control platform, Integrated energy digital technology, Hardware-in-the-loop simulation, Experimental teaching, Low code**

I. Introduction

As the key of theoretical research and engineering application, the design, realization and analysis of the control strategy of system operation or equipment is the core topic in the field of comprehensive energy, and also the key link of talents training in universities and laboratories. As an important link in teaching and scientific research practice, the research and development of experimental platforms related to integrated energy has always been a focus of attention: Wang Mengxue et al. sorted out, summarized and projected ten representative simulation planning platforms of integrated energy system [1]. Yuan Xiaoping et al. developed a comprehensive demonstration platform for new energy utilization based on seven energy conversion subsystems, such as photoelectric conversion and wind power conversion, to promote experimental teaching and scientific research of energy and electrical related majors in colleges and universities in the utilization of new energy [2]. Shi Yanlei et al. built a hardware-in-the-loop virtual simulation experiment platform for intelligent connected vehicles based on hardware-in-the-loop and computer numerical simulation technology [3].

From the current widely used experimental environment, physical test has problems such as unstable equipment, high cost and long verification cycle, while pure virtual experiment is easy to make students lose the sense of experiment operation and experience, which is not conducive to the accumulation of engineering experience. From the perspective of commonly used controllers, PLC, DSP and other controllers have high requirements for students' knowledge of related hardware and software and programming ability [4]. Their development threshold is high, and debugging and maintenance is difficult. As a result, students spend too much time on programming and debugging, and neglect the understanding of control principles and strategy design and analysis. It is easy to copy the case code and only pay attention to the verification of a single instruction [5], which is not conducive to the cultivation of students' independent exploration thinking and engineering practice ability.

To solve the above problems, this paper proposes a new teaching design of comprehensive energy control experiment. Based on the event-driven control strategy design, hardware-in-the-loop simulation experiment is carried out by combining the low code controller with Simulink model, and a control strategy design and verification experiment platform without complex programming development is constructed. Combined with photovoltaic maximum power tracking control as an example, the experimental model and teaching process are explained. Hardware in the loop is a real-time engineering semi-physical simulation technology in which the controlled object is a real-time mathematical model simulation and connected to a real controller, which can give full play to the complementary advantages of hardware and software [6,7].

This method has been applied to the experimental course "Design and Practice of New Energy Electric Power System" of Electrical engineering major of Zhejiang University. In class, teachers and students complete the micro-grid black start control experiment based on this platform. The platform highly restores the actual operation scenario of new energy, enabling students to deepen their understanding of the micro-grid black start

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control scheme and realize the power distribution control of gas turbine after the micro-grid black start and operation.

The experimental platform involved saves the heavy phase of unfamiliar controller entry and programming debugging, reduces students' unnecessary learning pressure and improves experiment efficiency. At the same time, the lightweight equipment allows students to carry out experiments and independent expansion more flexibly and freely, making the smooth and smooth transition of students from control principle learning, strategy design to verification and analysis, which is conducive to stimulating their interest in learning, maintaining their enthusiasm for experiments, improving their innovation ability, and deepening their understanding of comprehensive energy control principle and design. It is a powerful practice of personnel training in response to the construction and development of national new electric power system.

II. COMPOSITION AND APPLICATION OF THE INTEGRATED ENERGY CONTROL EXPERIMENTAL TEACHING PLATFORM

A. Composition and function of experimental teaching platform

Simulink is used to build the virtual model of the controlled object and abstract the controlled object and its environment. With the low code controller as the physical controller, the control strategy can be realized and run by combining the model, and the experiment of control principle analysis, strategy design and verification can be realized. The block diagram of the experimental platform is shown in Figure 1.

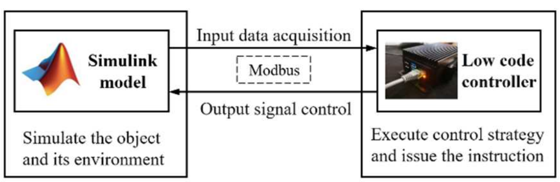

Fig. 1. The block diagram of the experimental platform

B. Principle and use of low code controller

The author developed a low code controller device based on event-driven technology. The controller part shown in Figure 1 has the functions of existing programmable controller such as logic operation, sequence control, timing, counting and arithmetic operation. It also supports the function of solving equations and mathematical optimization model, and has wide adaptability to the solution of various control problems. In the experiment, the low-code controller communicates with Simulink model through Modbus protocol, collects the measurement point information of the model as input, executes the set control strategy and outputs instructions to the model, thus completing the hardware-in-the-loop simulation control process. In Simulink, S-function is used to realize the communication between model and controller, and as a control module in the model, the acquisition input and control instruction output signals are connected.

By expressing the designed control strategy as AOE network structure, the user can fill in the standard configuration file in EXCEL format based on this and import it to the controller, and run the model and controller to observe and measure the control results, thus realizing the simulation object control without writing code. The standard profile consists of three profiles: a measurement point property configuration to describe the controller collection point or a custom calculation point, an AOE configuration to set up the AOE network to implement the desired control policy, and a communication configuration to describe the communication implementation.

C. The control strategy is expressed by event-driven AOE network

Event-driven [8,9], as a strategy expression paradigm, shows that the control flow is composed of events and actions according to a certain logical relationship. The event is used to describe the state of the controlled object and can be used as the condition of the execution of the action or the mark of the completion of the action. Actions are used to express the specific instructions that the controller executes, such as assigning values to variables and performing optimization calculations. In low code controller, AOE network [10], a directed acyclic graph, is used to visualize control strategy. The schematic diagram of AOE network is shown in Figure 2. Corresponding to the event-driven paradigm, nodes of AOE network represent events, edges represent actions, i.e. responses and operations to events, and the direction of edges represents the progressive and migration relationship between events represented by nodes.

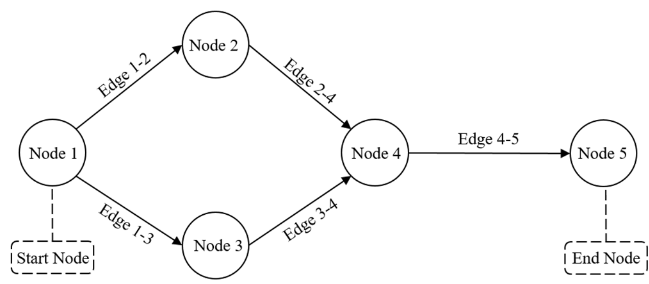

Fig. 2. AOE network composition diagram

The theoretical basis for the design and implementation of the control strategy based on event-driven and AOE network structure is that the control strategy can be abstracted as a mathematical model, and the actual control process can be reflected as the response of the controller to the controlled object or the change of environmental state and other events, and all have a certain implementation process. Therefore, the use of event-driven AOE network can describe the actual control process. In theory, only the user to the variable control mathematical model part of the form of close to mathematical formula configuration, you can realize the control function, without complex programming.

Using AOE network to present event-driven control strategy can transform text form into a combination of text and text, making the control process more clear and intuitive and adding more convenient modification. Event-driven paradigm is easier to understand and grasp, and it is also convenient for students to check their own design, modify details or compare and analyze other schemes.

D. Standard file configuration for low code controllers

1) Measuring point configuration: The value includes the serial number, name, properties, default value, and remarks of the measurement point.

2) AOE configuration: AOE configuration is used to describe the event driven type AOE network, is a code controller is designed to achieve the core of the control strategy, its configuration is divided into AOE overall configuration and node configuration and configuration, each module content as shown in the Table 1 below.

TABLE I. LOW-CODE CONTROLLER AOE CONFIGURATION FILE CONTENT

Module Name	Module Content
AOE Network	Describe the number of AOE networks, the overall information, define the initial value of variables
AOE Node	Define the ID, name, type, timeout period, and event expression of each node
AOE Edge	Define the ID of each side, first and last node, failure mode, type, and action parameters

3) Communication configuration: Communication file configuration includes communication mode configuration and measuring point register configuration.The communication mode configuration contains different information depending on the type of communication protocol used. The low code controller supports communication protocols such as Modbus.Measuring point register configuration is used to give the address information of storing measuring point data, including serial number, register type, starting address, data type, etc.

III. EXPERIMENTAL TEACHING MODEL

A. Design of experimental teaching model

For control principle and implementation courses, the experimental teaching process based on the combination of low code controller and Simulink is shown in Figure 3.The whole system is divided into three stages: experimental preparation, student independent experiment and expansion and progression, which are interlinked and progressive, taking into account the two dimensions of consolidating the foundation and stimulating innovation. While ensuring that all students meet the basic experimental requirements, it also provides complete and free experiment opportunities for some students who have the need for innovation and exploration.

In the first step of the independent experiment -- guiding students to design the control strategy of event-driven paradigm on the basis of understanding the control principle, students can choose to complete the whole control process by themselves, or teachers can build the overall AOE network framework and leave some key events and actions blank for students to fill in independently. It can make the experimental teaching plan more flexible, standardized and efficient, and strong pertinence.

In the extension stage, students can be guided to carry out independent innovation design and verification practice. Lightweight experimental platform also provides conditions for students to get out of the laboratory, for the need for physical testing, by replacing the Simulink model with a physical object, modify the communication configuration, can also achieve the same control strategy, for students in the use of extracurricular activities such as competition, research and development to provide help.

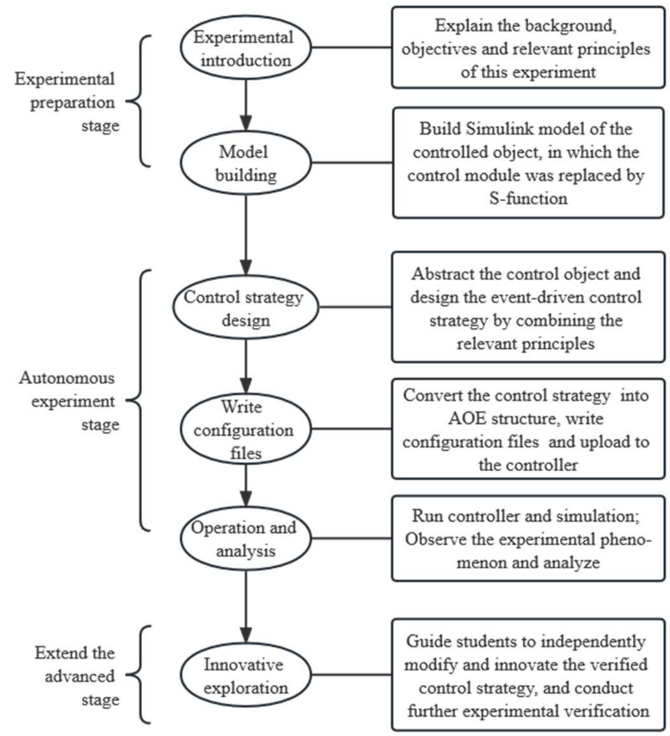

Fig. 3. Experimental teaching flow chart

B. Contrast with traditional teaching mode

For Due to the large difference between the hardware used in model simulation and programming and the weak connectivity, traditional control courses often need to go both ways. Moreover, the controllers used in previous practice are mostly programming, requiring students to learn the hardware structure, command system and other characteristic knowledge, and then develop and debug the hardware and the underlying code by themselves. Its development threshold is high, occupies a lot of time and energy of students and has little correlation with the actual control algorithm itself.

The low code controller used in this experiment platform can communicate with Simulink to establish co-simulation, so as to improve the experiment fluency and simplify unnecessary steps. Figure 4 and Figure 5 respectively show the traditional experimental teaching model and the teaching model designed in this paper. It can be seen that the experimental platform is developed in the form of writing related configuration table files directly based on control strategies, without writing codes and debugging, which enables students to focus on the application layer design, control principle and strategy design itself, reduces the experimental pressure of students, improves the experimental efficiency and improves the teaching effect.

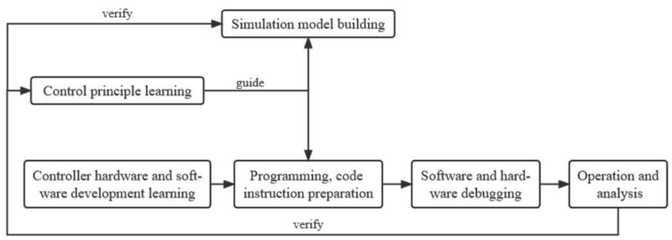

Fig. 4. Teaching mode of traditional experimental courses

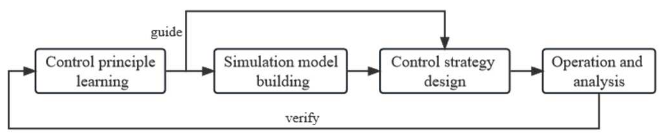

Fig. 5. Teaching mode of the low code way

IV. INTEGRATED ENERGY CONTROL TEACHING CASE REALIZATION

A. Experimental preparation stage

1) Experimental background and objective

New energy is an important force in the development of energy transformation and construction of new power system in our country. Photovoltaic cells, as a promising future energy technology choice, are in a leading position [11]. How to stabilize photovoltaic modules at maximum power point has become the key research object in academic circles. This experiment will take the design and verification of the control strategy of photovoltaic array maximum power tracking as the goal, guide students to master the basic photovoltaic maximum power tracking control method, and further deepen students' understanding and knowledge of new energy, broaden their vision, and cultivate their interest in future study and research.

2) Principle of photovoltaic maximum power tracking control

The P-V curve of the output power characteristics of photovoltaic cells is shown in Figure 6 [12]. The maximum power point tracking (MPPT) is essentially a self-optimizing process, that is, the photovoltaic array can intelligently output the maximum power under various sunshine and temperature environments by controlling the terminal voltage.

There are many methods to study MPPT technology of photovoltaic array based on optimization mathematical model, perturbation and so on [13]. In this experiment, a relatively mature incremental conductance method is selected: the voltage at the operating point is adjusted by calculating incremental changes, so that it gradually approaches the voltage at the maximum power point [14,15].The voltage power curve of photovoltaic array is a single-peak curve. At the point of maximum output power, the derivative of power to voltage is zero. For the expression of power, the derivative of U on both sides of the equation is as follows:

$$\frac{dP}{dU} = \frac{d(UI)}{dU} = I + U\frac{dI}{dU} \qquad (1)$$

When $\frac{dP}{dU} > 0$, U less than the maximum power point voltage Um; When $\frac{dP}{dU} < 0$, U greater than the maximum power point voltage Um; When $\frac{dP}{dU} = 0$, U is equal to the maximum power point voltage Um.

3) Photovoltaic array model construction

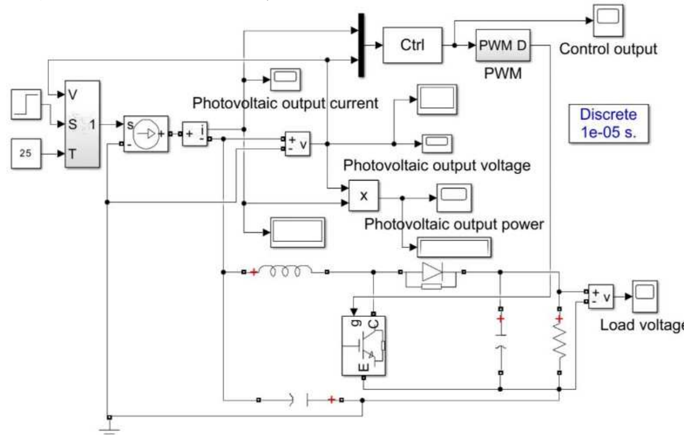

Fig. 6. Simulink model of PV array

Based on the P-U characteristics of photovoltaic cells, the Simulink simulation model of photovoltaic array is built, as shown in Figure 6. Ctrl in the figure is an S-function module, which realizes the communication function between the simulation model and the controller. The controller collects photovoltaic output current and voltage data, sends the control signal to the PWM module, and controls the photovoltaic output voltage by adjusting PWM waveform.

B. Autonomous experiment stage

1) Control strategy AOE topology design

According to the basic principle of incremental conductance method to realize photovoltaic maximum power point tracking, the control strategy is divided into a set of a series of events and actions according to the logical flow. The complete presentation of AOE network form is shown in Figure 7.

2) Fill in the configuration file

According to the AOE diagram of the control strategy in Figure 7, the measuring points, AOE network and communication are configured according to the standard EXCEL file format of the low-code controller, so as to realize the development of the control strategy without programming.

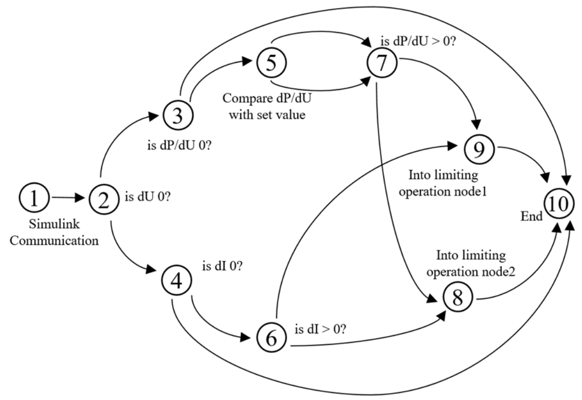

Fig. 7. AOE diagram of control strategy for photovoltaic maximum power point tracking by incremental conductance method

Firstly, the information of the experimental collection point is configured, which is called measuring point. Four measuring points are needed in this experiment, which are respectively photovoltaic output current (I_POINT) collected by the controller, photovoltaic output voltage (U_POINT), voltage set value (Uset_POINT) output by the controller to PWM module in the model, and status point (DoCal_POINT), which are used to judge whether the controller will calculate according to the status of the measuring point. The default value is 0.

Then, the AOE diagram of the control strategy is specifically configured, which is divided into three contents: AOE network overall declaration, node declaration and side declaration. In the overall statement of AOE network, the name of AOE control network is set as photovoltaic MPPT control, the trigger condition is selected as event control, and the initial value of each variable is set. Table 2 shows the configuration of node declaration. Table 3 shows the configuration of edge declaration.

TABLE II. NODE CONFIGURATION OF CONTROL STRATEGY AOE

ID	Node Name	Type	Time-out	Expression
1	Simulink communication event	Condition	10	Do_Cal_POINT > 0.5
2	dU judged 0	Switch	10	Dabs(dU) <= e
…	…	…	…	…
9	Switch to intermediate node 2 of the limiting operation	Condition	10	1
10	End node	Condition	10	Do_Cal_POINT == 0

TABLE III. EDGE CONFIGURATION OF CONTROL STRATEGY AOE

Head-tail node	Action Name	Type	Action Parameter
1; 2	AOE triggers measurement point reset	SetPoints	DoCal_POINTS: 0; dU: U_POINT – Un1; dI: I_POINT – ln1;
2; 3	Store voltage and current values	SetPoints	Un1: U_POINT; In1: I_POINT;
3; 10	Enter the end node	None	/
…	…	…	…
7; 9	Reduce voltage	SetPoints	Uset_POINT: Uset_POINT - Uc;

When the calculation status judgment point DoCal_POINT>0.5, node 1 is triggered and the controller enters the calculation process. Nodes 2-7 Perform logical judgment on the set expression and select one of the two outgoing edges of the node according to the result. Nodes 8 and 9 play a connecting role and enter the end node through the next edge after being triggered. When all calculation steps and signal transmission are completed, enter the end node 10, change the value of DoCal_POINT to 0, and wait for the re-calculation after the next communication. The timeout time is set as 100ms to prevent unnecessary AOE triggering repeatedly in the setting process.

The configuration of the edge is one-to-one corresponding to the AOE network shown in Figure 7. For example, the DoCal_POINT is set to 0 on the edge 1-2 to prevent the network from being triggered instantaneously and unnecessarily when the loop ends. Sides 2-3 store voltage and current values; Edge 4-8 adds one step to the initial voltage set value; Sides 8-10 and 9-10 judge whether the voltage exceeds the limit value. If not, output the current voltage value, otherwise output the set voltage value.

Modbus protocol is used to realize the communication between low-code controller and Simulink controlled object. Open the source file of S function in Simulink model, set the number of input signals to 2 and the number of output signals to 1, and set the sampling time to 0.01 (communicate with the controller once every 10ms of simulation).Add the command to establish Modbus communication and the control command to read the current measurement value and voltage measurement value. The communication configuration is shown in Table 4.

TABLE IV. COMMUNICATION CONFIGURATION

Register Type	Starting Address	Data Type	New Request	Polling Cycle	Point ID
Holding	1	EightByte-Float	FALSE	2000	1001
Holding	5	EightByte-Float	FALSE	2000	1002
Holding	9	EightByte-Float	FALSE	2000	1003
Holding	13	TwoByte-IntUnsigned	FALSE	2000	1004

3) Run simulation and analysis results

Then use the network cable to connect the low code controller with the computer, enter the controller configuration interface, import the prepared configuration file and run the controller, Simulink model, then can carry out the hardware in the loop simulation test.

In Figure 8, the horizontal axis is the time and the vertical axis is the output power of the photovoltaic array. It can be seen that after the control, the photovoltaic output power is successfully adjusted to the maximum power point, and the photovoltaic output power can be quickly adjusted to the new maximum power point when the environmental parameters change. This verifies the validity of the control strategy of photovoltaic maximum power tracking by incremental conductivity method in this experiment.

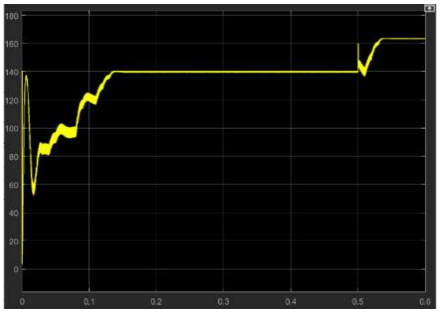

Fig. 8. Photovoltaic output power waveform controlled by incremental conductance method

C. *Autonomous experiment stage*

On the basis of the completion of this experiment, for the students who have the ability to learn, they can be encouraged to design the strategy for more dimensions of evaluation and analysis, expansion, such as: the incremental conductance method of the operation of the response time, overshot and other parameters to measure, try to change the control strategy or adjust the instruction parameters of the Angle of optimization and improvement; Or, learn other photovoltaic maximum power tracking control principles, or even completely independently design new control methods, learn and put into practice.

V. CONCLUSION

It serves the teaching practice of comprehensive energy control and responds to the national construction of "new engineering" based on the new needs of strategic development, the new situation of international competition and the new requirements of moral cultivation. The experiment platform combines the emerging low-code technology to realize the hardware-in-the-loop simulation. The universal equipment has wide adaptability to various kinds of control realization. It breaks away from the cumbersome restrictions of traditional controllers and allows students to focus on the control principles and strategy design of integrated energy systems, integrating theory into practical classroom and advocating innovation in multi-level teaching.

According to the feedback of students in the practical course, the low-code approach reduces about 60% of the time for the development and implementation of the control strategy, and makes the study and design of the principle and strategy itself occupy the main position in the overall experiment, and the teaching effect is significantly improved. The next step is to use the experimental teaching platform to complete the typical control cases of integrated energy system energy storage optimization control, power system operation analysis and so on, improve the platform experience, increase the benefit of students' use, to help the cultivation of energy and power talents.

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