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Research Article

Design and Application of Virtual Flexible Simulation Experiment Teaching Platform for Relay Protection

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Received: 31 October 2022; **Revised:** 12 December 2022; **Accepted:** 19 December 2022

Abstract: Power system relay protection (PSRP) is a comprehensive course in electrical engineering undergraduate stage, which has a very strong engineering application. However, due to the influence of many factors, such as the power system security, high experimental cost, limited course hours, insufficient open conditions, and so on, traditional experimental teaching combined with hardware is difficult to meet the needs of students in various scenarios anytime and anywhere. Therefore, a low-cost virtual flexible simulation experiment teaching platform (VFSETP) is developed. The platform uses Simulink to build the simulation model of power system primary system and uses graphical user interface (GUI) to design the human-computer interaction interface. Through the communication between GUI and Simulink model, the protection experiments in various scenarios are successfully simulated. The VFSETP has many advantages such as simple interface, good visualization effect, and simple operation. The teachers can easily use it for classroom demonstration, and the students can use it for verification, analysis, expansion, and exploration of experiments in a variety of application scenarios without relying on the laboratory environment. This experimental mode is very conducive to the understanding of knowledge and the cultivation of practical innovation ability. The results of the student survey show that the design method and application mode of the platform can provide a reference for similar courses.

Keywords**:** relay protection, virtual flexible simulation, Simulink, GUI, experimental teaching

1. Introduction

The relay protection is an important branch of power system operation and control, which is directly related to the safe and stable operation of system [1-5]. Therefore, power system relay protection (PSRP) is an important major course of electrical engineering undergraduate stage [6, 7]. The course is characterized by many contents, strong theory, and practice. Students generally feel that the concept and the principle are difficult to understand [8]. In order to solve this problem, it is necessary to set up sufficient experiments as a supplement to theoretical teaching in the course of learning. However, there are still some difficulties in the experimental teaching: (1) Limited by the total class hours of the course, more emphasis is placed on the theoretical course, and the experimental class hours are less. Only a few experiments are difficult to meet the good teaching effect. (2) The power system has the characteristics of high voltage, large current, and various kinds of equipment. The traditional experiment platform is mainly hardware experiments, most of the functions are customized, and few reserved expansion functions. Moreover, due to the system security and cost factors,

DOI: https://doi.org/10.37256/rrcs.2120232119

it is difficult to meet the experimental needs of students in a variety of scenarios. (3) It is difficult to open the laboratory at any time because the scale of the laboratory is small and the number of experimental teachers is limited. When the students have fantastic ideas, there is no condition to put these ideas into practice. In this way, it is not conducive to the cultivation of students' creativity. To sum up, the traditional experimental teaching method of PSRP cannot meet the current educational needs of China.

Based on the demand for electrical professional training and the analysis of the current situation of practical teaching of relay protection courses, it is necessary to build a low-cost virtual flexible simulation experiment teaching platform (VFSETP) to provide better support for the development of relay protection experimental teaching. The virtual simulation experiment teaching of many basic experiments and comprehensive experiments can be completed through this platform. Moreover, teachers can bring the relay protection experiment project into the classroom for demonstration by this platform, which can not only make the theoretical knowledge more vivid, but also solve the problem of insufficient experimental class hours. In addition, students can use the platform to conduct experiments at any time and from anywhere, as well as independently develop and expand experiments, so that students' practical ability, innovation ability, and problem-solving ability can also be well exercised.

For the practical teaching improvement of PSRP, there are mainly two teaching schemes: hardware [9-17] and software [18-23]. The hardware mode needs to rely on certain physical equipment or platform to complete the relay protection experiment. For example, a hardware experiment teaching scheme is provided in [13]. Relays are set using a personal computer, application software, and a communication processor. In a laboratory environment, students are able to set and test digital relays, select current and voltage transformers, determine relays and transformer taps, conduct research, and test their protection design schemes in a laboratory environment. On the original relay protection experimental platform, [14] provides a relay protection experimental platform of process bus, and preliminarily realizes 9-1 sampled value (SAV), tripping, reclosing, and other important generic object-oriented system-wide event (GOOSE) functions. In [16], a relay laboratory was designed, including four modern microprocessor-based relays for the protection of ultra-high voltage transmission lines, portable relay protection experimental devices, substation power transformers, and distribution feeders. However, these hardware platforms cannot allow students to experiment at any time, from any place, and in any scenario. In order to improve the shortage of hardware laboratory experiments, a remote relay protection experiment using IEC 61850, the internet, and other communication technologies were proposed [9, 10, 12]. Although the scheme can realize remote protection at any time, it is still dependent on the fixed physical relay protection equipment and is limited by the hardware conditions, so it is difficult to meet the experimental requirements of various scenarios. In view of the limitations of the current hardware platform, some teachers developed various experimental teaching platforms by using softwares. This kind of experimental scheme does not depend on a particular laboratory setup, or on a particular manufacturer or supplier. For example, some researchers have developed experimental platforms based on Power Systems Computer Aided Design (PSCAD) [19-21] and Laboratory Virtual Instrument Engineering Workbench (LABVIEW) [22, 23]. Indeed, these platforms based on PSCAD and LABVIEW need to have a good foundation, but in many colleges and universities in China, undergraduate students often do not learn PSCAD and LABVIEW. Therefore, it is difficult for most students to apply these two kinds of software platforms. Because the Matrix Laboratory (MATLAB) software has the characteristics of simple programming, wide application, visualization, and strong ability of numerical calculation and system modeling, it is also used in the construction of relay protection virtual simulation platform [24, 25]. However, these platforms are limited to specific scenarios, lacking a variety of protection types and universality of experimental teaching. Based on the convenience of the MATLAB software, a new low-cost VFSETP for relay protection is designed. The platform overcomes the shortcomings of traditional hardware experiments, which can simulate various relay protection methods in many scenarios. Using this platform, teachers can carry out classroom demonstrations, and students can freely carry out experimental simulations, analysis, and exploration according to their interests anytime and anywhere. This kind of teaching mode greatly stimulates students' enthusiasm and engineering practice ability.

2. Design idea of VFSETP

The design of VFSETP should not only meet the requirements of course content and experiment teaching, but also meet the requirements of flexibility, reliability, simplicity, practicability, and scalability. Considering the convenient graphical user interface (GUI) design and Simulink powerful model simulation tool, the design idea of VFSETP is planned.

(1) According to different relay protection principles, the Simulink simulation model of primary power system relay protection is established and optimized.

(2) The user-friendly interface of the VFSETP is established by arranging the controls reasonably. The designed GUI mainly includes the main interface, basic experiment module interface, and sub-module interface.

(3) According to the function of the experimental platform, the callback function (M function) of each control in GUI is written to realize the specific function. It mainly includes the setting of experimental scenarios, the input of model parameters, the data transmission between different interfaces, and the display of results. We can complete the communication function between GUI and Simulink by using the M function to perform the corresponding experimental functions. For example, the value of the GUI "text box" can be read by "get ()" function, the value of file box can be set by "set ()" function, and the data in GUI can be transferred to Simulink system model by assigning ().

(4) The simulation results are displayed graphically on the dynamic interface of human-computer interaction.

The specific design process flow chart is shown in Figure 1.

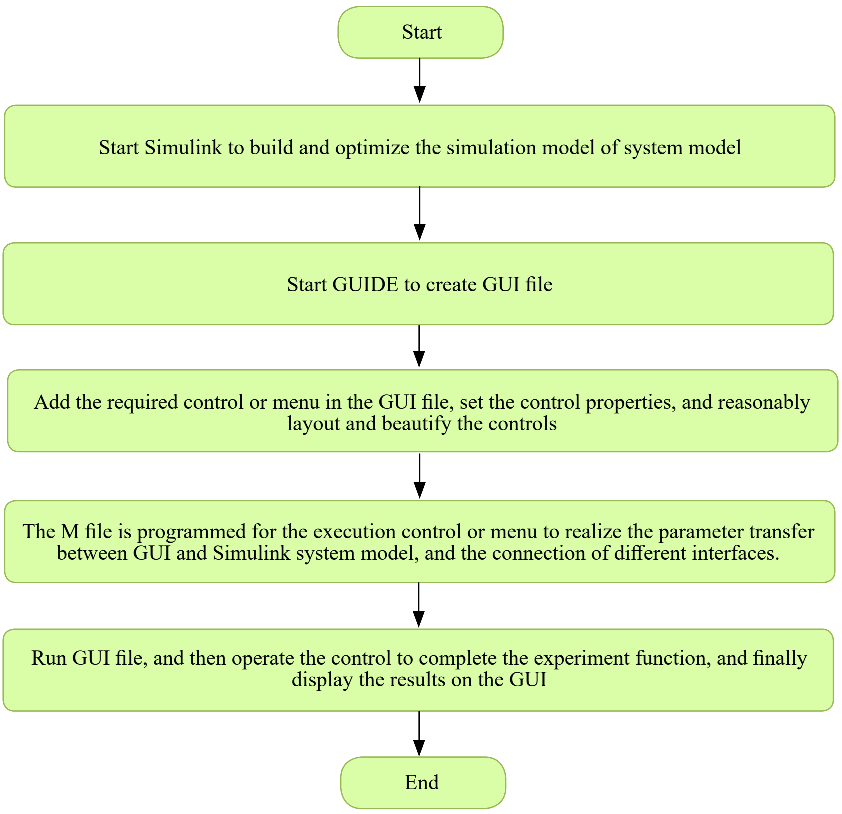


Figure 1. Design process flow chart of virtual experiment platform

3. Structure of VFSETP

The structure of VFSETP adopts modular and hierarchical design ideas. Each module corresponds to a basic experimental project, and each basic module can be decomposed into several sub-modules, which can be further decomposed according to the function. The idea of layered design can be realized by calling GUIs at different levels. The experimental project of the simulation platform is designed based on the content of the PSRP course, which mainly includes four basic experimental modules: single power supply current protection, dual power supply current protection, current longitudinal differential protection, and transformer differential protection. The four basic modules cover the conventional methods of PSRP. Each basic module contains several sub-modules, which correspond to the relay protection of different simulation scenarios. The specific function diagram of the simulation experiment platform is shown in Figure 2.

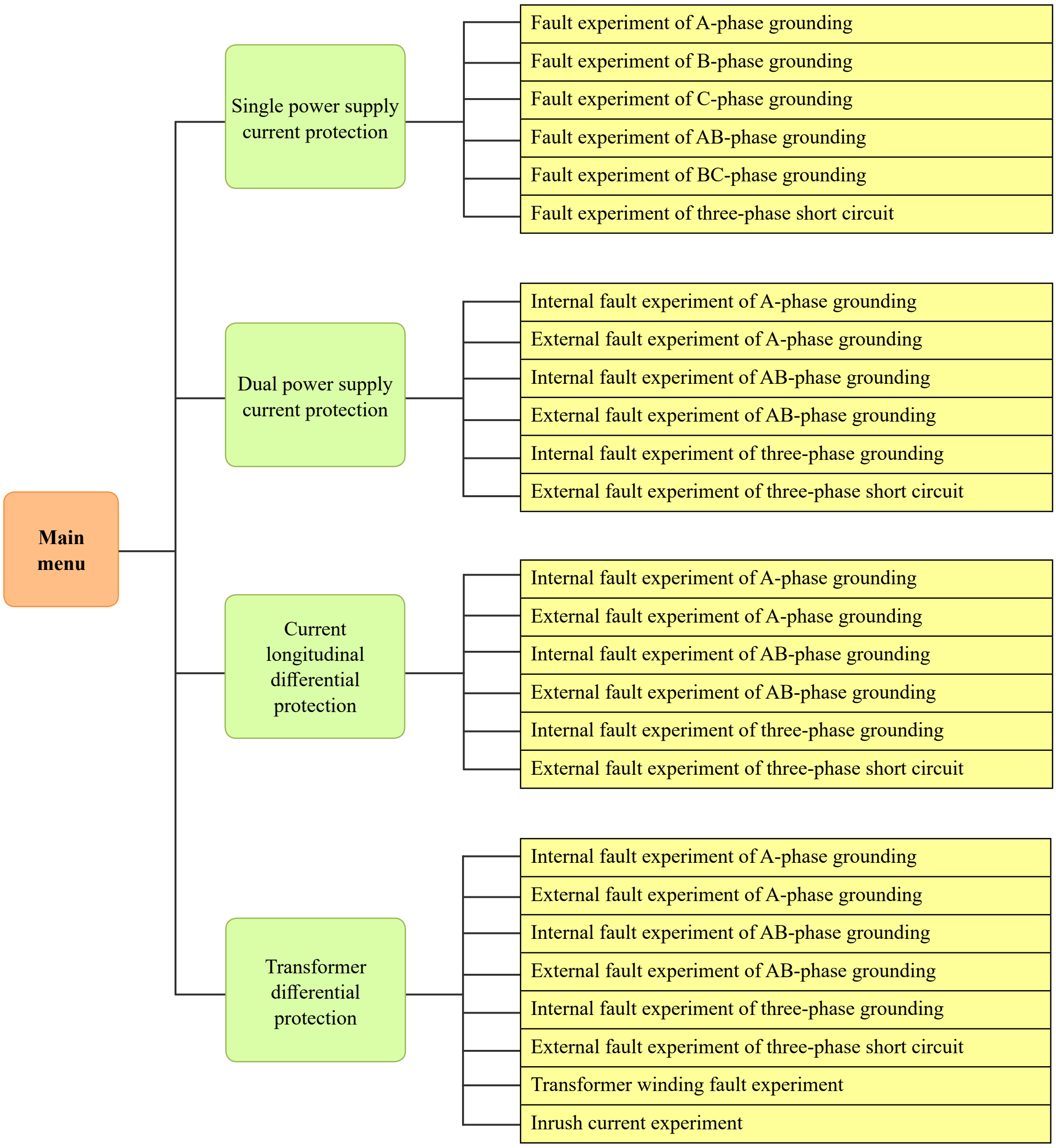


Figure 2. The function diagram of VFSETP

4. Design and implementation of VFSETP

4.1 *Design of the main interface*

According to the system structure and the GUI design method, the main interface and the basic module interfaces can be designed. The main interface is responsible for the management and execution of the overall experimental project. According to the overall design and functional analysis of the experimental platform, the main interface mainly includes the platform name, user manual, experimental project instruction, selection of experimental modules, etc. For the convenience of users, the interface design principle of the experimental platform is simple and intuitive. Based on this principle, some controls such as pop-up menu, pushbutton, static text, uipanel, and axes are firstly added to the new blank interface, and then the controls are reasonably arranged and their properties are set. Finally, we saved the file as MAIN_GUI.fig. In the interface, the static text control is used to display the platform topic and guide the experiment, the pop-up menu is used to select the basic experimental module, the pushbutton control is used to view the experimental platform manual and experimental guidebook, and confirm whether to enter the experiment, the axes control is used to add pictures to beautify the main interface, and the uipanel is responsible for many control management. After the main interface is designed, the callback function (M file) is written for human-computer interaction, which can enter the basic module interface, and then the basic module interface realizes different task functions.

Taking the interface design of transformer differential protection as an example, Figures 3 and 4 show the main interface and basic module interface of the platform, respectively. In the main interface, when you click the【user's manual】and【experimental instruction】buttons, respectively, you can open the platform operation manual and experimental guidebook for the reference of the experimenter. If you click the drop-down menu, you can select the experimental items. When you click the【confirm】and【exit】buttons, respectively, you can choose whether to carry out the experiment or not. For example, select the drop-down menu of transformer differential protection in the main simulation interface, and then click the【confirm】button to enter the basic module experimental interface of transformer differential protection in Figure 4.

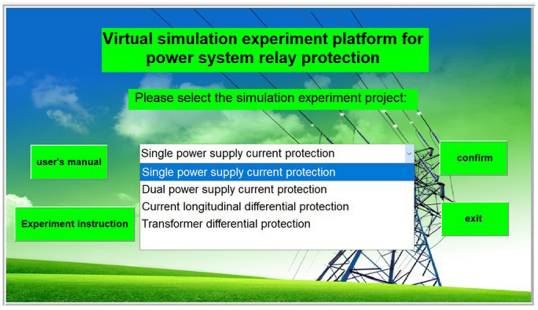


Figure 3. The main interface of VFSETP

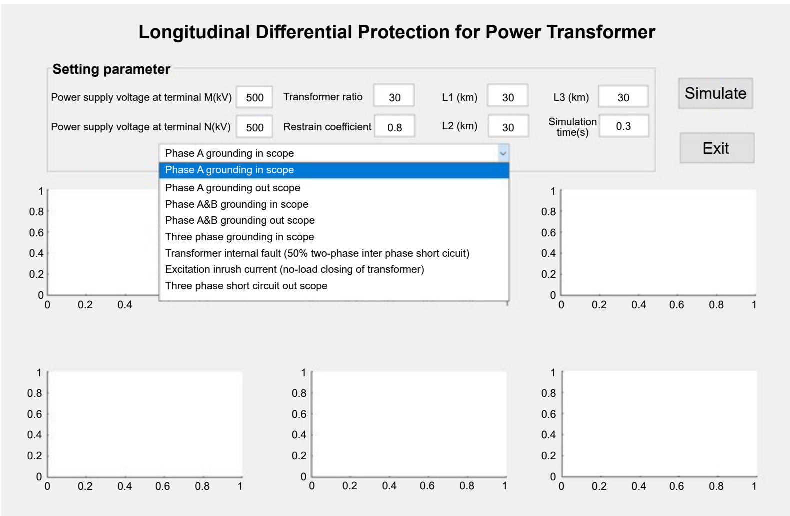


Figure 4. Basic module interface of transformer differential protection

4.2 *Design of the basic experiment module*

The design of the basic experiment module takes the experiment of current longitudinal differential protection module as an example. The design mainly includes the establishment of system simulation model to realize the protection function and the design of a human-computer interface to communicate with it.

(1) Establishment of the primary system simulation model

Simulink is a dynamic system simulation platform provided by MATLAB. It contains many model source libraries and provides powerful system modeling, analysis, and simulation functions. Therefore, this experimental project uses Simulink to build a model to realize the protection function. It includes a circuit breaker module, current measurement module, fault module, relay module, Fourier module, and so on. At the same time, to keep the primary system simple, we need to build a current differential protection subsystem model. In the current differential protection subsystem, the collection and comparison of differential current and braking current are completed, and the breaker in the main system model is controlled for switching operation. Two systems cooperate with each other to form a Simulink model of longitudinal differential protection. Among them, the two models can communicate with the GUI, so that they can freely set the internal and external faults. The differential protection subsystem compares the differential current with the braking current. When there is no fault or external fault, the line operates normally. When there is an internal fault, the differential protection module starts and sends a signal to disconnect the circuit breakers at both ends of the line. The corresponding main and sub-system model are shown in Figures 5 and 6.

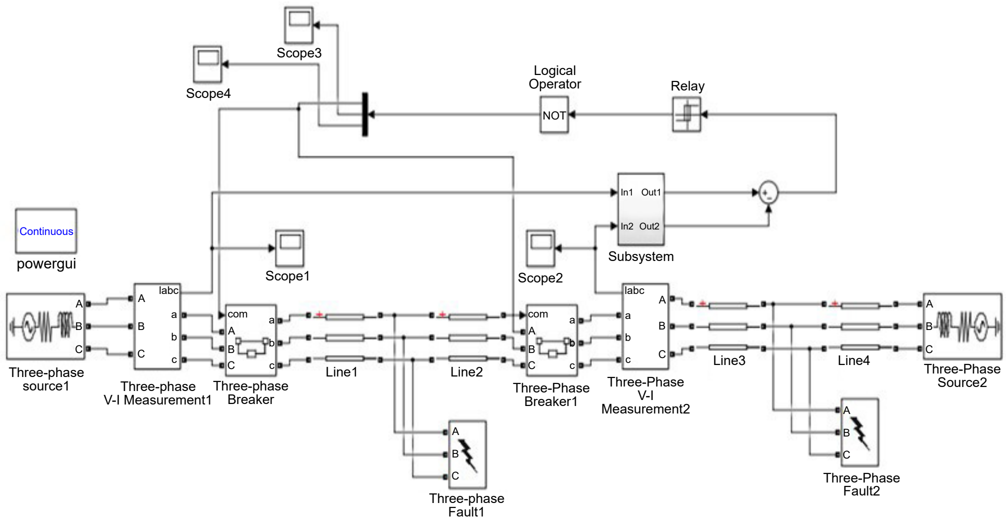


Figure 5. Primary system model of current longitudinal differential protection

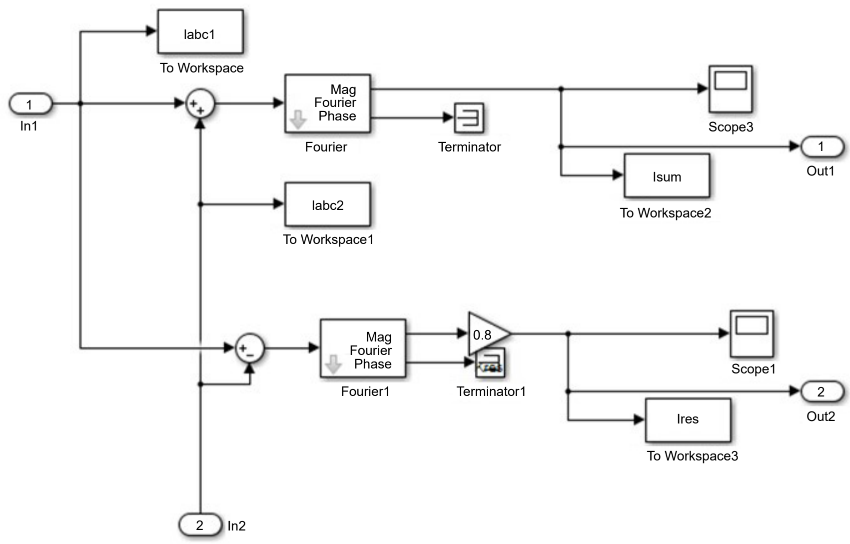


Figure 6. Sub-system model of current longitudinal differential protection

(2) Design of the basic module interface

The design method of the basic module interface is similar to that of the main interface. The interface completes the human-computer interaction function of the experimental project, which should include the input of various parameters, such as the power supply voltage of M and N sides, line length, braking coefficient, simulation time, etc. At the same time, it also needs the selection of fault type, the current display, and simulation process control. In order to realize these functions, the communication between GUI and Simulink is established by compiling M file. According to the specific function analysis, the experimental interface of current longitudinal differential protection module is shown in Figure 7. In the GUI, the experiment parameters and simulation time can be set and changed freely by editing the text control, and the fault type can be selected by the pop-up drop-down menu. The axis control is used to display the experimental results, and the button control is used to select whether to carry out the experiment.

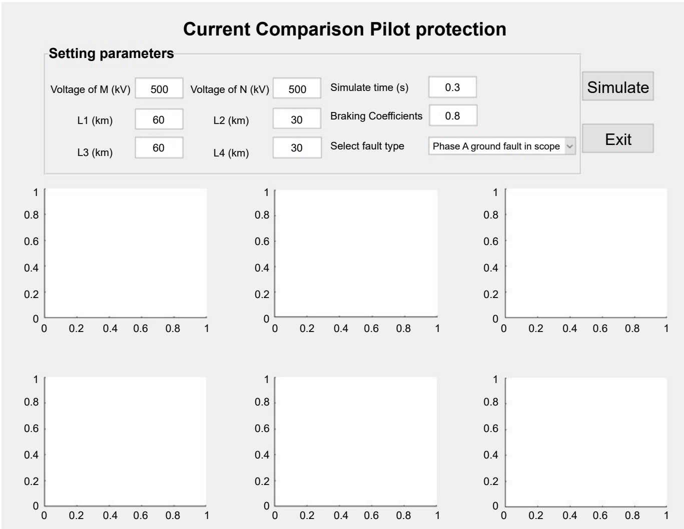


Figure 7. GUI of current longitudinal differential protection

5. Simulation results and analysis

In order to verify the effectiveness of the simulation platform design, the current longitudinal differential protection experiment is taken as an example to analyze the simulation results. As we all know, the types of current longitudinal differential protection mainly include internal fault and external fault. The principle of longitudinal current differential protection is to detect the current at both ends of the line. Then, both ends of the protection device communicate with each other and calculate the differential current and braking current, respectively. The general differential current and braking current are calculated as: $\dot{I}_M + \dot{I}_N, \frac{1}{2}(\dot{I}_M - \dot{I}_N)$. The condition of relay protection action is: $\dot{I}_M + \dot{I}_N > \frac{1}{2}(\dot{I}_M - \dot{I}_N)$. When an internal fault occurs anywhere along the line, the differential current will be far greater than the braking current, which will cause the relay to act, drive the circuit breaker to trip, and isolate the fault. When faults occur outside the line, the braking current will be greater than the differential current, the relay will not act, and the line will continue to operate. The specific external fault and internal fault simulation and results are as follows.

5.1 *External fault*

The external fault types in this platform mainly include three kinds of fault conditions: any phase single-phase grounding, any two-phase grounding, and three-phase grounding. In the GUI, the parameters of different phase grounding short are set, respectively, and the corresponding fault occurs in 0.1 s. The operation results are shown in Figures 8 to 10.

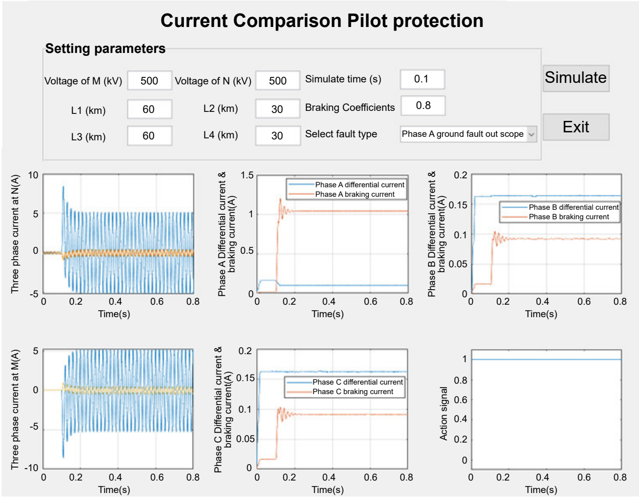


Figure 8. Simulation results of external A-phase grounding short circuit fault

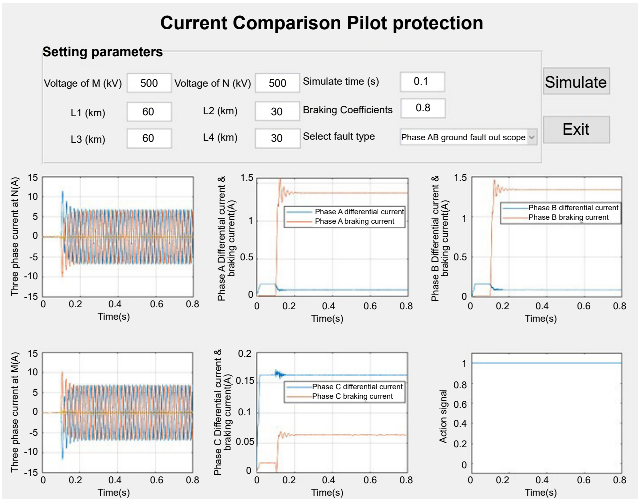


Figure 9. Simulation results of external AB-phase grounding short circuit fault

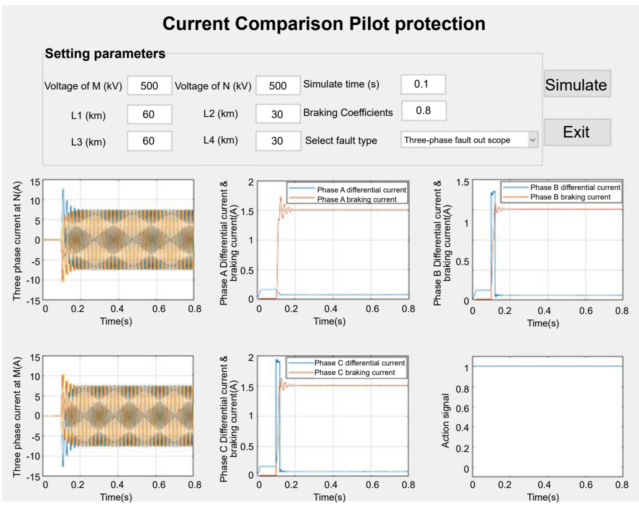


Figure 10. Simulation results of external three-phase grounding short circuit fault

It can also be seen from Figures 8 to 10 that when the time is 0.1 s and a short circuit of A-phase grounding, AB-phase grounding or three-phase grounding occurs outside the area, the fault module acts under three conditions and the system fails. At this time, the protection device installed at M and N points detects that the corresponding fault phase current suddenly increases in the opposite direction with the same values under various conditions. Therefore, the differential current in the corresponding phase protection device is less than the braking current, and the longitudinal current differential protection device does not operate. The simulation results show that the function of longitudinal differential protection is realized by the simulation software.

5.2 *Internal fault*

The internal fault types in this platform experiment also primarily include three kinds of fault conditions: single-phase grounding, two-phase grounding, and three-phase grounding. In the GUI, the parameters of various faults are set, respectively, and the corresponding short fault is also set to 0.1 s. The operation results are shown in Figures 11 to 13.

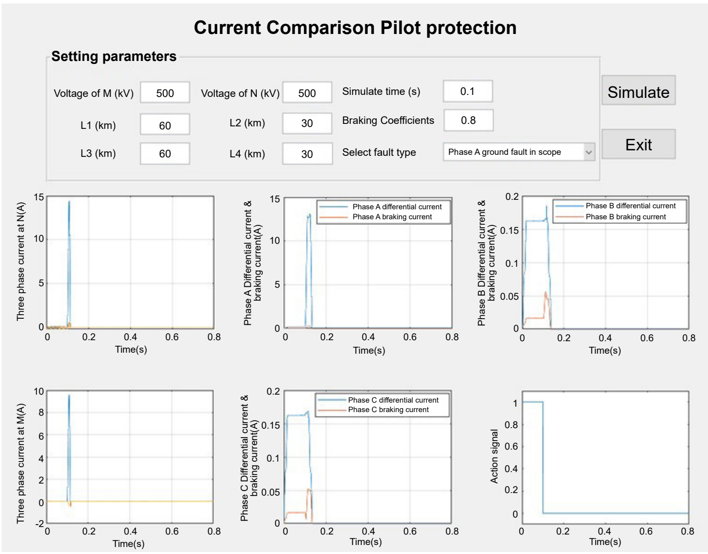


Figure 11. Simulation results of internal A-phase grounding short circuit fault

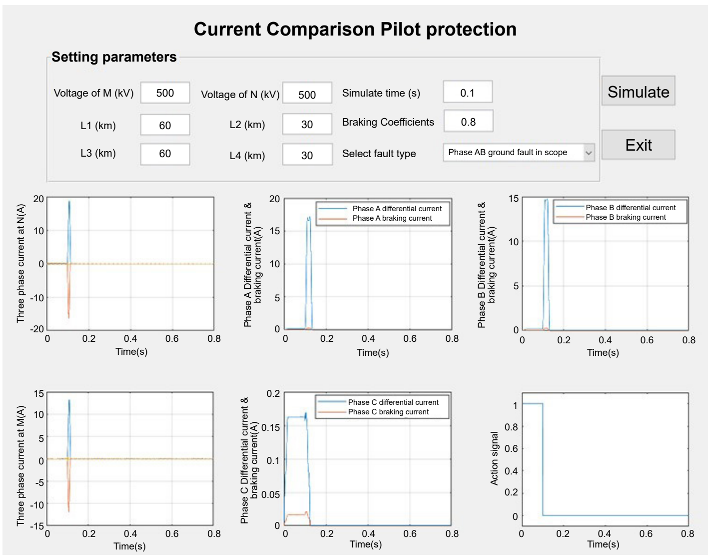


Figure 12. Simulation results of internal AB-phase grounding short circuit fault

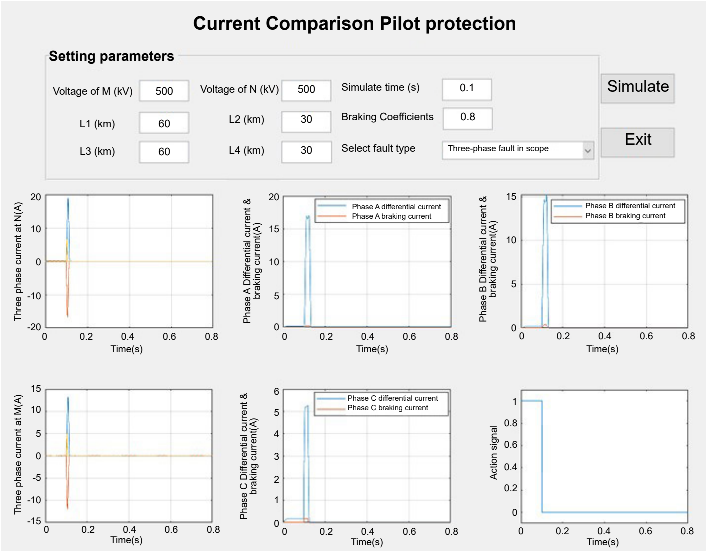


Figure 13. Simulation results of internal three-phase grounding short circuit fault

It can also be seen from Figures 11 to 13 that when the time is 0.1 s and a short circuit of A-phase grounding, AB-phase grounding or three-phase grounding occurs in the area, the fault module acts under three conditions and the system fails. At this time, the protection device installed at M and N points detects that the corresponding fault phase current suddenly increases in all cases, and the direction is the same. Therefore, the differential current in the corresponding phase protection device is far greater than the braking current, and the longitudinal current differential protection device acts quickly in 0.01 s to cut off the fault line and return the three-phase current to zero. The simulation results of the internal fault also show that the function of longitudinal differential protection is realized by the simulation software. By adjusting the values of L1 and L2, the position of the fault point on the line can be changed. The experiment also shows that for the current differential protection, the protection will operate reliably in case of a fault at any position in the area.

In conclusion, Figures 8 to 13 show that the simulation system can easily observe the current waveform and its change trend after the fault, and can also easily observe the action of the relay by changing the position of the fault point, which fully reflects the principle of current differential protection.

6. Assessment and analysis

After the design of the experimental platform is completed, the traditional hardware experiment is maintained. Making full use of VFSETP, the practice teaching mode has been reformed. The main applications are as follows:

(1) Teacher's classroom demonstration teaching: In order to deepen students' understanding of theoretical knowledge in classroom teaching, some experimental contents are implanted into theoretical teaching in the form of demonstration. This model not only makes the abstract theory more vivid and intuitive but also expands the experimental content and makes up for the lack of traditional experimental hours.

(2) Extracurricular expansion experiments: Students can also choose the projects based on their interests and level during their spare time. The experimental content includes system modeling, interface design, programming, experimental analysis, and so on. The independent experiment mode not only improves the students' programming practice ability but also further deepens the understanding of knowledge.

(3) Inquiry learning: The teaching main body of the traditional PSRP course is the teacher. Most classroom teaching focuses on teachers' speaking and students' listening, which restricts students' initiative and creativity to a certain extent. Through the platform demonstration, more students are attracted and have the desire to explore more scenarios of relay protection experiments by consulting data independently under the inspiration and guidance of teachers. This model not only improves students' enthusiasm for learning knowledge, but also greatly enhances their ability to analyze and solve problems, as well as cultivate their sense of innovation.

This teaching mode based on VFSETP has been used in 1801 and 1802 classes of electrical engineering major at the Shandong University of Technology. In order to evaluate the teaching effect of the experimental platform, at the end of this course, the students answered a questionnaire anonymously to evaluate the learning effect of the PSRP course. The results of the questionnaire are shown in Figure 14. Under the condition of the same grade, the same major, and the same teacher, the effect of the improved teaching mode and the traditional teaching mode is also compared. The traditional teaching mode is implemented for 1803 and 1804 classes. After the examination, the scores of the four classes are compared, and the results are shown in Figure 15.

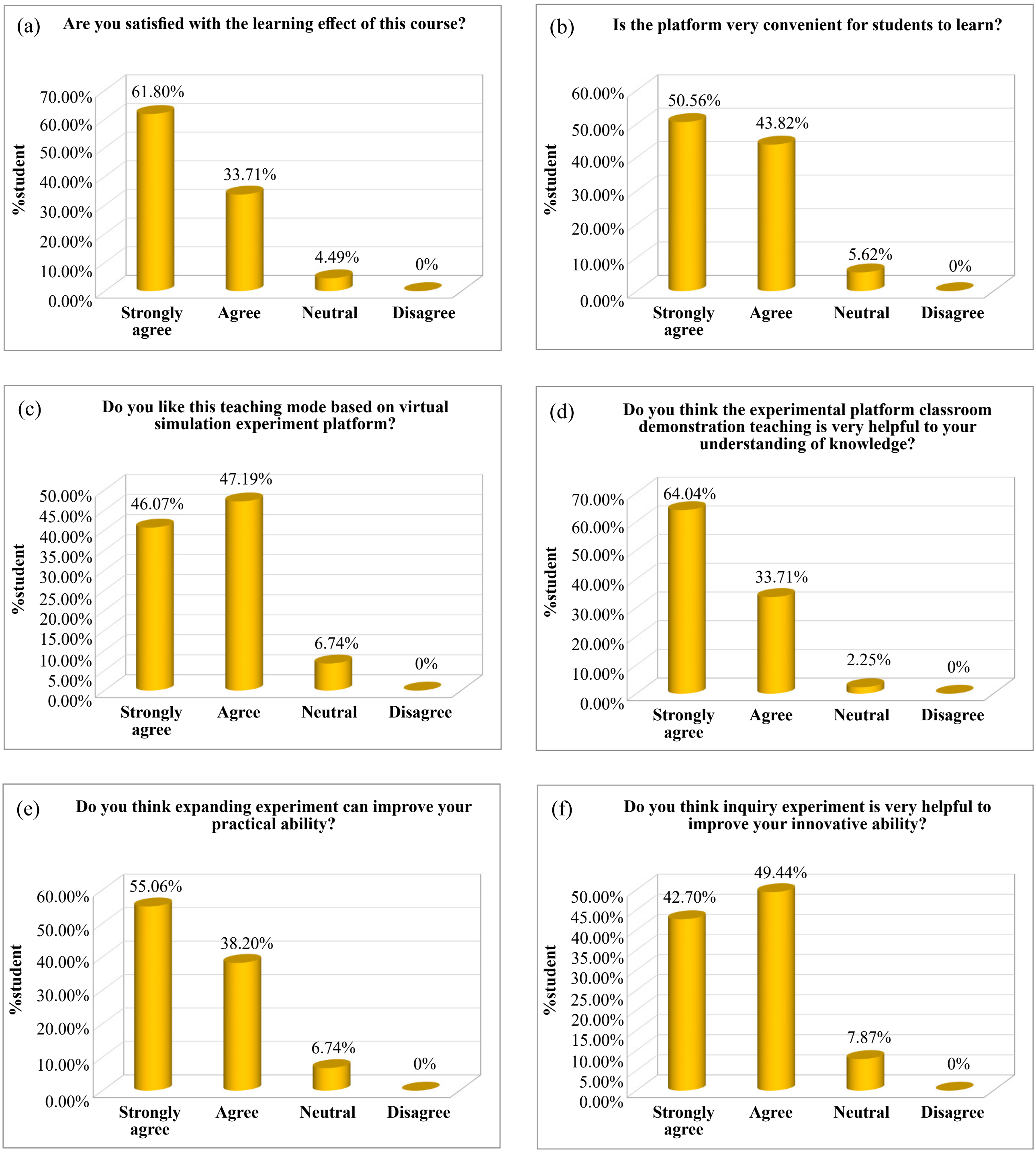
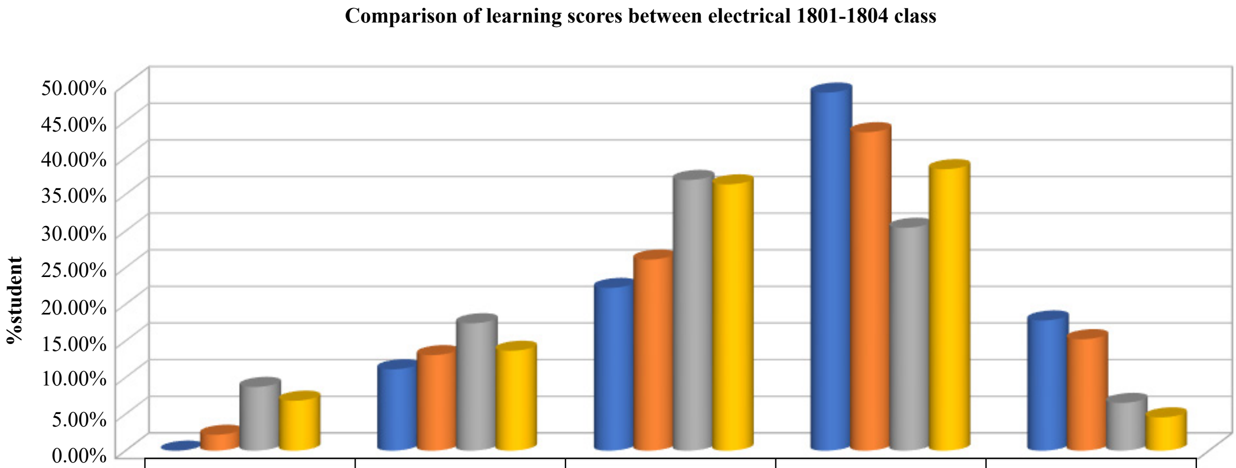


Figure 14. Data obtained from the questionnaire of the course



	< 60	60-70	70-80	80-90	> 90
1801	0.00%	11.11%	22.22%	48.89%	17.778%
1802	2.17%	13.04%	26.09%	43.48%	15.217%
1803	8.70%	17.39%	36.96%	30.43%	6.522%
1804	6.82%	13.64%	36.36%	38.43%	4.545%

Figure 15. The effect of platform teaching mode and traditional teaching mode

From Figures 14 and 15, it can be seen that 95.51% of students are satisfied with the teaching effect of the course, 94.38% of students think that the VFSETP provides convenience for students' learning, 93.26% of students like the improved teaching mode, 97.75% of students feel that classroom demonstration teaching based on VFSETP is helpful to their understanding of knowledge. 93.26% of students think that extended experiments can improve students' practical ability, and 92.14% of students think that exploratory experiments are very helpful to improve students' innovative ability. In general, more than 90% of the students are satisfied with the course from various perspectives. Through the comparison of examination scores, the students of 1801 and 1802 classes (classes adopted improved teaching mode) have higher scores, students who scored above 80 accounted for a large proportion, and their failure rate also decreases significantly as compared with the students of 1803 and 1804 classes (classes adopted traditional teaching mode). Therefore, through the evaluation of the course, it can be concluded that the application of the experimental platform has greatly improved the teaching effect.

7. Conclusion

Aiming at the teaching difficulties of the PSRP course, a low-cost VFSETP is constructed based on the Simulink and GUI of MATLAB. The platform first establishes the primary system simulation model of power system through Simulink, and then designs the human-computer interaction interface through GUI. Finally, the specific experimental functions are completed through the communication between GUI and Simulink model. This platform can not only be used for relay protection model design and simulation analysis, but also can be used for experimental teaching to assist classroom demonstration teaching and students' anytime and anywhere. Given that the platform provides good visualization and is simple to use, makes it convenient to conduct simulation analysis and research on relay protection techniques under different parameters. Moreover, the design method of combining Simulink and GUI interface is very easy to maintain and expand in the later stage. In this way, students can expand and explore various relay protection application scenarios on this platform whenever and wherever, without the need for a laboratory, which is conducive to training students' practical and innovative abilities. Furthermore, the design method and application mode of the platform greatly improve the teaching effect and serve as a model for similar courses. At the same time, it can also provide a tool for further research on power system relay protection.

Conflict of interest

We authors hereby declare that we do not have any conflict of interest with the content of this manuscript.

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