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A Virtual Electric Power Transmission Line Lab*

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The design and implementation of a Virtual Electric Power Transmission Line Lab for undergraduate curricula is introduced in this paper. The aim of the virtual laboratory is to enhance learning and teach students the basis and characteristics of the power transmission line model under different conditions in a virtual interface before entering the field. The user can realize various tests, such as short circuit, no-load, load and fault tests, to develop an understanding of the model behaviors, effects of changes in the model parameters, load and connections. The proposed Virtual Electric Power Transmission Line Lab is developed in the MATLAB graphical user interface (GUI) environment. The proposed virtual lab has been implemented in the Power Systems Lab taught at the Department of Electrical and Electronics Engineering at Karadeniz Technical University as part of the undergraduate curriculum. A survey of the students who took the lab course has been conducted, and the responses are included in this paper.

Keywords: transmission line; computer aided education; virtual laboratory

1. Introduction

Changes and developments in technological advances, fragile financial support for education, and the demands of international university accreditation foundations necessitate a reconsideration of the education curriculums and models [1–3]. For the last few decades, education strategies have changed direction from a traditional education system to modern and flexible education systems to improve knowledge and skills students and provide better education [4]. It is especially important for engineering and science students to acquire theoretical knowledge in the classroom, and laboratories are an effective means of providing practical knowledge and experience [5]. Laboratories offer students such opportunities as the design of experiments and systems; data collection, analysis and interpretation; the development of teamwork and social skills: feeling of realism; and efficient learning [5, 6]. Currently, students' laboratory experiences are negatively affected by many problems, including the following: limited laboratory equipment and time; a lack of available space; a high number of students, which burdens departments and reduces students' opportunities to conduct experiments alone; and an inadequate number of educators [7, 8]. These difficulties impede students' learning processes and generate poor learning outcomes in laboratory courses [5, 9, 10]. Until these difficulties are overcome, students will continue to receive insufficient practical experience with experiments, graduating without inexperience and sufficient scientific knowledge and skills.

In computer-aided education (CAE) systems, classroom and laboratory sections use computers as auxiliary equipment and teaching tools. CAE systems improve the effectiveness and quality of lessons and laboratory work, decrease education costs, reduce the time demands on academic staff, and increase visual perception skills relative to traditional education systems and hands-on labs [11]. In computer-aided education, computer-based virtual lab software is effective educational tool that helps students improve their comprehension of the experimental and theoretical aspects of their courses. As a result, students become active player in their learning process [12]. The virtual laboratory learning environment possesses outstanding features, such as flexibility in the time and location of learning, the realization of different experiments with various scenarios and safety and reduced cost, the opportunity to conduct complex and extensive experiments alone and improved self-learning ability [5, 11]. Many universities, institutions, and colleges have utilized virtual laboratories to provide students with an opportunity to combine both physical experiments and numerical simulations for effective learning [13–15]. MATLAB is one of the software platforms used to design and develop virtual laboratories [16]. Students can employ MATLAB and its toolboxes for development, simulation, analysis, and visualization exercises [17].

Electrical power is an important tool for building new technology, satisfying human demand, providing economic stability, and ensuring sustainability while allowing a high quality in life. Generation, transmission and distribution, the main components of electrical power utilization, must be modeled, analyzed and designed effectively. In the Department of Electrical and Electronics Engineering at Karadeniz Technical University, Turkey, the modeling, analysis and design of electrical power

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system components are taught in a course called Power Distribution Systems, and a set of electrical power line experiments are included in the Power Systems Lab. A Virtual Electric Power Transmission Line Lab (VEPTLL) is developed and made available to students for use in the undergraduate curriculum.

The MATLAB GUI environment is used to develop the Virtual Electric Power Transmission Line Lab introduced in this paper. The Virtual Electric Power Transmission Line Lab allows students to gain an understanding of the characteristics of power transmission line models under different operation conditions. The proposed virtual lab has been used in the Power Systems laboratory course taught in the Department of Electrical and Electronics Engineering at Karadeniz Technical University, Turkey, and the responses to surveys administered to students in the course are evaluated.

2. System architecture

The Virtual Electric Power Transmission Line Lab (VEPTLL) is designed as an auxiliary virtual learning environment support to supplement the actual Electric Power Transmission Line Lab. The combination of these virtual and actual labs can ensure student outcomes required by ABET in its A-K engineering education criteria [18]. The general objectives of the VEPTLL are to ensure that students:

- Get familiar with the system, system parts and principles of system operations.
- Gain experience in preparation of system modules.
- Demonstrate performance of the system with different operation conditions.
- Manipulate the experiment parameters and explore its change.
- Collect data for variable scenarios.
- Analyze and interpret the data and results to build their own judgements and conclusions.
- Understand of the relationship between the system parameters.
- Evaluate the different factors that affect the system characteristics.
- Design and optimize the parameters of system components.

Fig. 1 shows the main window of the VEPTLL. The VEPTLL consists of four modules, which are described in the text below:

1. Short circuit test
2. No-load test
3. Load test
4. Earth fault test

2.1 Module 1: Short circuit test

A power transmission line is modeled with a pi model in the VEPTLL. This module helps students understand the effects of a short circuit on the pi transmission line. The voltage, current and power values and the waveforms of the voltage and current can be observed in Module 1. The user interface window for Module 1 is shown in Fig. 2. The source voltage (VR, VS, VT), source frequency (f), source resistance (RR, RS, RT), source inductance (LR, LS, LT), pi model resistance (R), pi model mutual capacitance (C), and pi model earth capacitance (Cj) are the main inputs for the transmission line model short circuit test. Students are able to change the source and the line model parameters and thereby obtain the voltage and current waveforms and values for the current, voltage and power levels for different conditions.

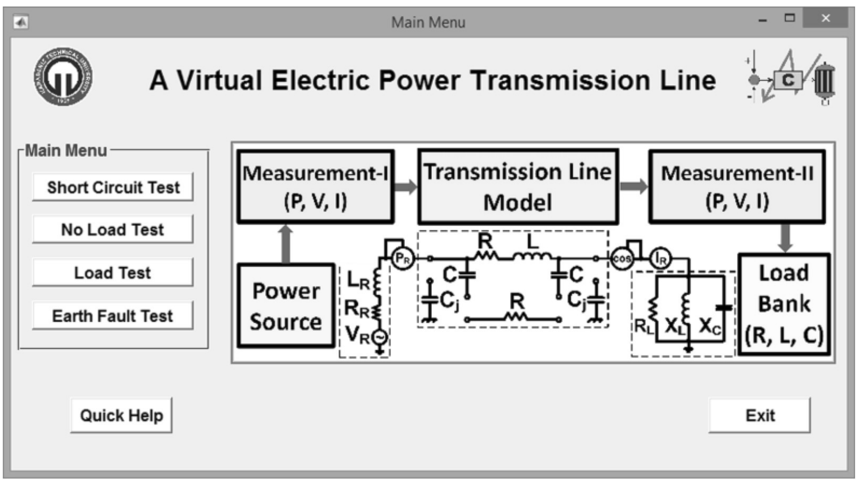

Fig. 1. The main menu of VEPTLL.

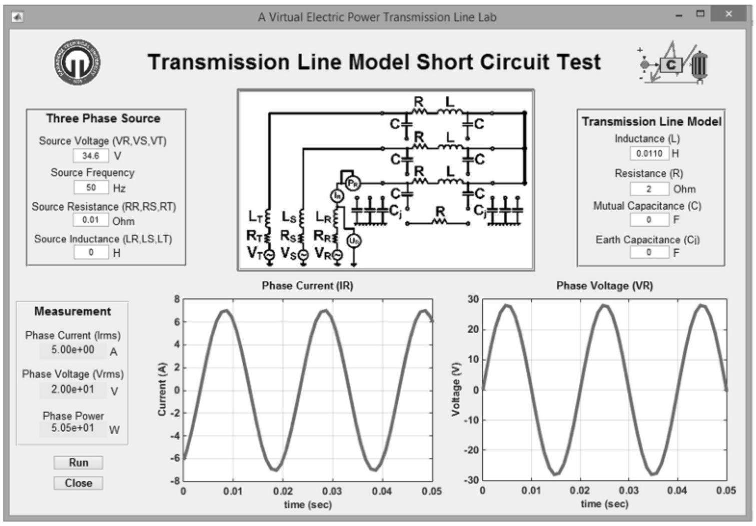

Fig. 2. The short circuit test interface.

The student should be able to state the relationship between the system parameters. For instance, he might state that the pi model inductance (L) is inversely proportional to the short circuit current and power, the pi model resistance (R) is directly and inversely proportional to the short circuit power and current, respectively, or the pi model mutual capacitance (C), and earth capacitance (Cj) are independent of the short circuit outputs. On the other hand, the source frequency (f) is inversely proportional to the short circuit current and power, but directly proportional to the pi model inductance (L) and independent of the pi model resistance (R). The student can design simple experiments to test scenarios, law or hypotheses. For instance, increasing source voltage increases current on the module configuration, which is based on Ohm's law. The system parameters related to source and line sides can be manipulated and output measurements are recorded for variable conditions. Thus the error or uncertainty in test result, danger faced during experimental lab will be minimized. The students can graph and analyze the data and interpret the curve or results of data analysis as fulfilling or not the expected or law or hypotheses

2.2 Module 2: No load test

The interface for Module 2 is shown in Fig. 3. The main inputs for Module 2 are the same as those for Module 1. This module shows how the changes in the connection of the pi model transmission line

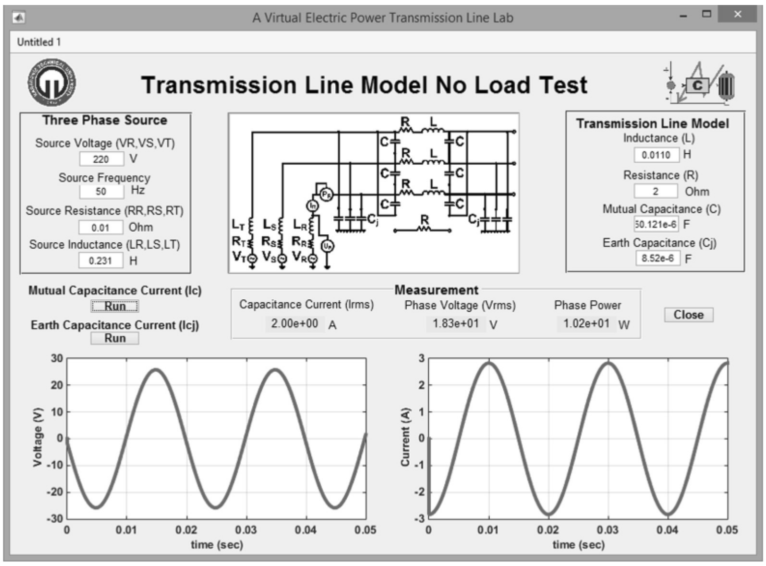

Fig. 3. The no load test interface.

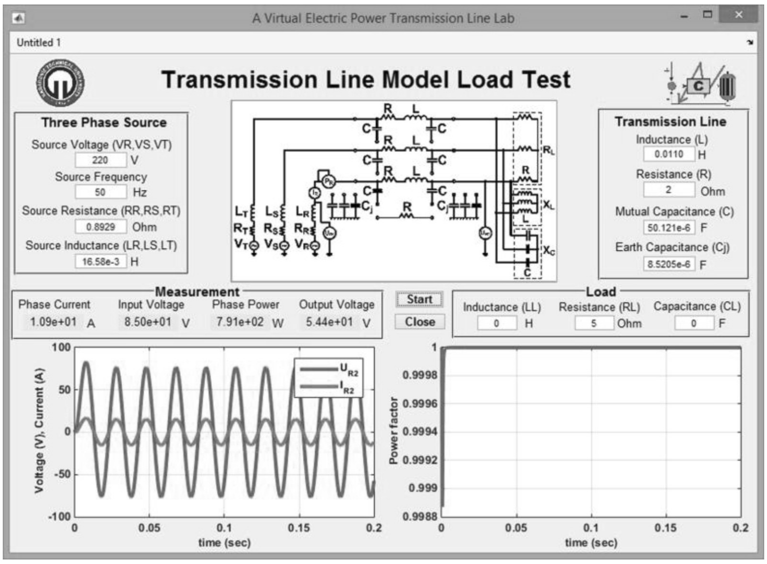

Fig. 4. The load test interface.

affect the current and voltage of the system. The mutual and earth capacitance currents, phase voltage and power levels as well as the current and voltage waveforms are obtained for a given scheme of the transmission line connections.

It should be comprehended that the source frequency (f), the pi model mutual capacitance (C) and earth capacitance (Cj) are inversely proportional to the mutual capacitance current and phase voltage and power, and the earth capacitance current (Icj) is simply related to earth capacitance (Cj) and independent of the mutual capacitance (C).

2.3 Module 3: Load test

This module analyzes the characteristics of the power transmission line connected with loads (resistive, inductive and capacitive). Fig. 4 shows the user interface screen for Module 3. The input and output voltage, current and active power values are measured, and the related current and voltage characteristics are obtained after running the module. The module also provides opportunities to observe the power factor waveform and the differences between the input and output voltage values.

The student might specify that the output voltage and current magnitudes and power factor values are dependent of the load characteristics consisting of inductance (LL), resistance (RL) and capacitance (CL). Thus, the student might be able to observe and interpret the outputs. For instance, increasing load resistance (RL) decreases current on the module configuration, which is based on Ohm's law, or as the load is only resistive, the voltage and current are in same phase and power factor is one, or when the transmission line only connects to inductive load (RL and LL), power factor will be less than one and the current waveform is lagging behind the voltage waveform.

2.4 Module 4: Fault test

A fault on a power transmission line can damage the system apparatus. The effects of faults on the system can be observed. Different types of fault occur in a power transmission line, including a single line-to-earth fault. The fault effects can be reduced using a Petersen coil, which improves the security and reliability of the power network in the power system. This module shows how the Petersen coil affects the system output during the single line-to-earth fault on the transmission line. The interface for Module 4 is shown in Fig. 5.

It might be pointed out that the output voltage peak value during the fault is dependent of the inductance value of Petersen coil (Lp), so that the peak value can be decreased by means of higher inductance (Lp) used in.

3. Simulation results

This section gives the results from the virtual experiments conducted to test the proposed VEPTLL. The main parameters related to interfaces are given in Appendix.

3.1 Short circuit test

The user interface window of Module 1 shown in Fig. 2 is used to test the model under short circuit conditions. The system is simulated for different transmission line model configurations under a constant three phase source level. The configuration parameters and corresponding results are given in Table 1 for a sample case study.

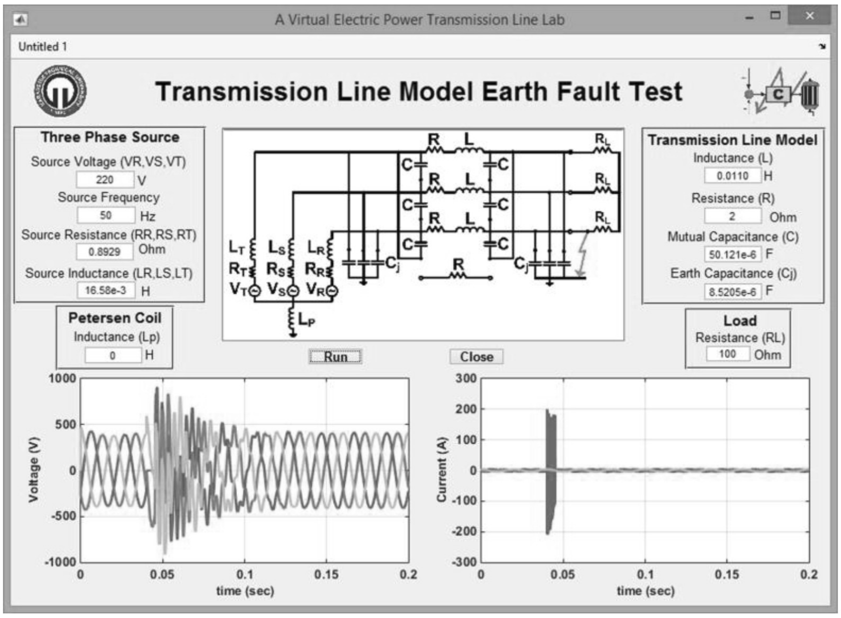

Fig. 5. The earth fault test interface.

Table 1. The transmission line short circuit test parameters and outputs

(a) The transmission line phase current (I_R).

		R (Ω)			
		1.00	**2.00**	**3.00**	**4.00**
L (H)	**0.01**	6.06	5.37	4.60	3.93
	0.02	3.14	3.03	2.87	2,68
	0.03	2.11	2.07	2.02	1,95
	0.04	1.59	1.57	1.55	1.52

(b) The transmission line phase power (P_R).

		R (Ω)			
		1.00	**2.00**	**3.00**	**4.00**
L (H)	**0.01**	20.00	20.00	20.00	20.00
	0.02	20.00	20.00	20,00	20.00
	0.03	20.00	20.00	20.00	20.00
	0.04	20.00	20.00	20.00	20.00

Table 2. The transmission line short circuit test parameters and outputs

(a) The transmission line phase current (I_R).

		R (Ω)			
		1.00	**2.00**	**3.00**	**4.00**
L (H)	**0.01**	2.00	2,00	2.01	2.01
	0.02	1.97	1.97	1.97	1.98
	0.03	1.94	1.94	1.94	1.94
	0.04	1.89	1.89	1.90	1.90

(b) The transmission line phase power (P_R).

		R (Ω)			
		1.00	**2.00**	**3.00**	**4.00**
L (H)	**0.01**	18.4	18.5	18.6	18.8
	0.02	16.1	16.2	16.4	16.7
	0.03	13.5	13.6	13.9	14.3
	0.04	10.4	10.6	11.1	11.6

Table 3. The transmission line load test parameters and outputs

IR (A)	UR1 (V)	PR (W)	UR2 (V)	PF
Case I (LL=0 H, RL=5 Ω, CL= 0 F)				
10.9	85.4	758	54.7	1
Case II (LL=0.001 H, RL=5 Ω, CL= 0 F)				
11.4	72.2	378	28.5	0.5327
Case III (LL=0 H, RL=5 Ω, CL= 0.001 F)				
16.4	61.2	901	44.2	0.5371
Case IV (LL=0.01 H, RL=5 Ω, CL= 0.001 F)				
11.1	83.7	772	52.4	0.9998

3.2 No load test

The system is simulated using the user interface window of Module 2 shown in Fig. 3 for different configurations under a constant three phase source level. The configuration parameters and corresponding results are given in Table 2 for a sample case study.

3.3 Load test

The power transmission line with different load types (resistive, inductive and capacitive) is discussed in Module 3, which is shown in Fig. 4. The configuration parameters and corresponding results

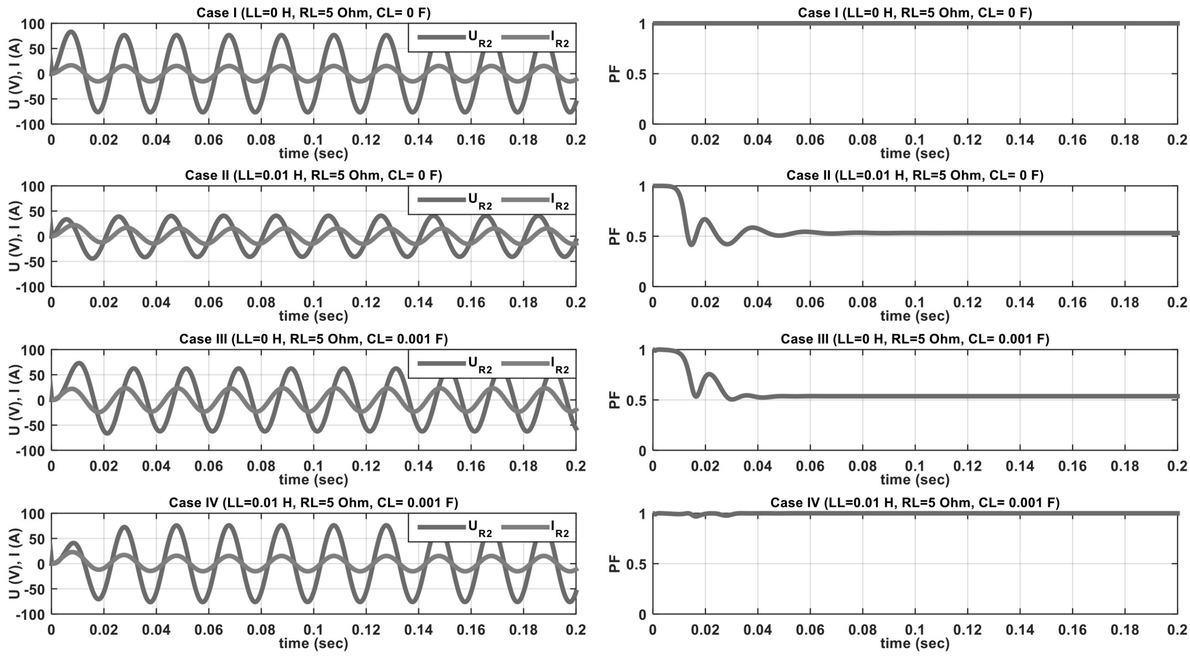

Fig. 6. The results for the load tests.

are given in Table 3 and shown in Fig. 6 for sample case studies.

3.4 Fault test

The effects of a single line-to-earth fault at the transmission line is observed in Module 4, as shown in Fig. 5. The voltage and current waveforms for a sample case study are shown in Fig. 7.

4. Student assessment and evaluation

The number of registered students for the lab class was 47 for the academic year. In the laboratory, students were working in groups of two or three. The lab report and questionnaire are used to reveal the effectiveness of learning in the Virtual Electric Power Transmission Line Lab. The experiment report prepared in the GUI environment was detailed in the laboratory experiment handout. The students who worked in the same group prepared the lab report. The lab report must include following headings: summary, introduction, theory, experiment procedure, results and conclusions. The lab reports are marked by the course lecturer based on different angles such as quality level in report organization, correctness of diagrams, figures and formatting, data analysis and discussion, interpretation of the gathered results, etc.

Questionnaires are a useful means of observing and evaluating students' reactions to and percep-

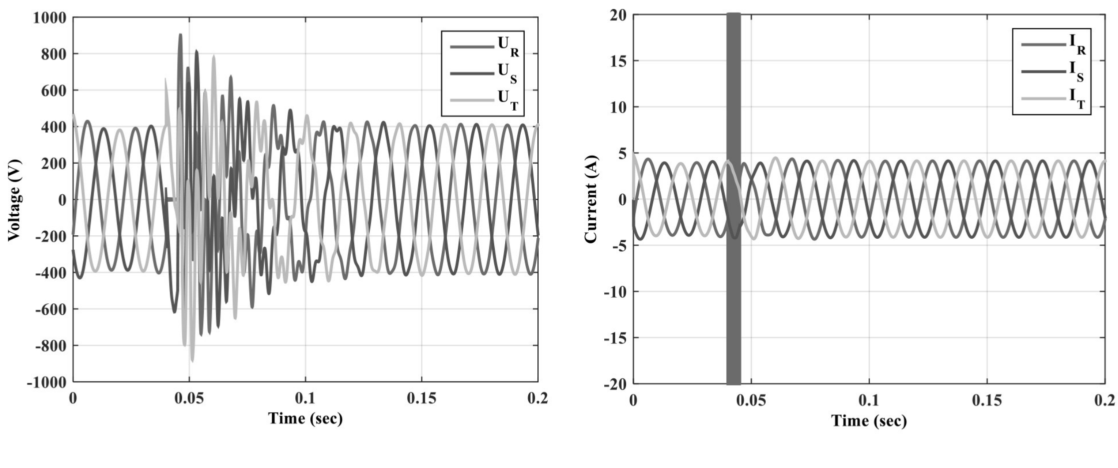

Fig. 7. The results for the fault tests: Voltage and current waveforms.

Table 4. Student evaluation assessment questions (Section A)

Q1.	Compared to other experiments in this laboratory course, this experiment is				
	very easy (1)	easy (2)	reasonable (3)	difficult (4)	very difficult (5)
Q2.	Compared to other experiments in this laboratory course, the workload of this experiment is				
	too much (1)	much (2)	reasonable (3)	few (4)	too few (5)
Q3.	The experiment realization speed is				
	very fast (1)	fast (2)	reasonable (3)	slow (4)	very slow (5)
Q4.	Overall, this experiment is				
	very good (1)	good (2)	reasonable (3)	inadequate (4)	high inadequate (5)
Q5.	Overall, the experiment instructor is				
	very good (1)	good (2)	reasonable (3)	inadequate (4)	high inadequate (5)

Table 5. Student evaluation assessment questions (Section B)

Q6.	I understood the main idea.
Q7.	The experiment coordination was very poor.
Q8.	The experiment was interesting.
Q9.	The experiment sheet was well organized.
Q10.	I learned something that I will remember in the future.
Q11.	The experiment sheet helped me understand the instructions effectively.
Q12.	The virtual environment was easy to use.
Q13.	Using the virtual environment helped me interpret the experiment results.
Q14.	Using the model developed for the virtual environment enhanced my knowledge and skills.
Q15.	I find the model developed for the virtual environment useful for learning related concepts in the corresponding course.
Q16.	Using the model developed for the virtual environment increased my interest in this subject.
Q17.	The experiment goal was clear and understandable.
Q18.	I was able to fully use the model developed for the virtual environment by following the instructions provided.
Q19.	It was difficult to gather data in this experiment?
Q20.	The instructor provided effective supervision and guidance during the experiment.
Q21.	How experiment was to be conducted was explicitly explained in the experiment sheet.
Q22.	It was easy to follow the instructions because the experiment sheet was well organized.
Q23.	I will need more information to prepare the experiment report.

Note: Strongly agree: 1, Agree: 2, Neither agree nor disagree: 3, Disagree: 4, Strongly disagree: 5.

Table 6. Student evaluation assessment questions (Section C)

Q24.	Instructor was powerful communicator.
Q25.	Instructor was eager to teach.
Q26.	Instructor performance interacted with me.
Q27.	Instructor explanation was explicit and fluent.
Q28.	Instructor explanation complicated taking notes.
Q29.	Instructor provided me concentrate more.
Q30.	Instructor behavior was friendly and pleasant.
Q31.	Instructor was well prepared.
Q32.	Instructor had self-confident.
Q33.	I ask for instructor help for other things.

Note: Strongly agree: 1, Agree: 2, Neither agree nor disagree: 3, Disagree: 4, Strongly disagree: 5

tions of the experiment. Therefore, a questionnaire covering the experiment, the characteristics of the GUI interface and instructor performance during the experiment was completed by the students. The students created a pros-and-cons list for the experiment and interface. The questionnaire consisted of thirty-three questions and was subdivided into three sections (Section A, B and C) listed in Tables 4–6. In Section A, the students provide their general opinions on the experiment and instructor and all questions will be scored along a five-point scale of 1–5 to rate the general point of view about lab and lecturer. The effectiveness of the experiment and instructor is assessed by the students' detailed observations and comments in Sections B and C, respectively. The five-level Likert scale is applied in these sections [19, 20]. A score between 5 (strongly disagree) and 1 (strongly agree) based on the Likert scale is assigned by the students. Radar charts were created with regards to the students' success based on the laboratory report and the students' opinion related to questionnaires (average score) and shown in Figs. 8–11.

According to the responses in Fig. 9, the lowest score (1.70 over 5.00) belongs to the item "Overall, the experiment instructor is" in Section A. It shows that most of the students accept that the lecturer is adequate during the lab session. On the other hand, the highest score (3.15 over 5.00) belongs to the item "Compared to other experiments in this laboratory course, the workload of this experiment is" in Section A. It shows that the students assume that the workload is at a reasonable level. In Section B, the lowest score (1.60 over 5.00) shown in Fig. 10 belongs to the item "The virtual environment was easy to use" so that it is clear that the virtual lab interface is user-friendly educational tool for the students. On the one hand, the highest score (4.00 over 5.00) belongs to the item "The experiment

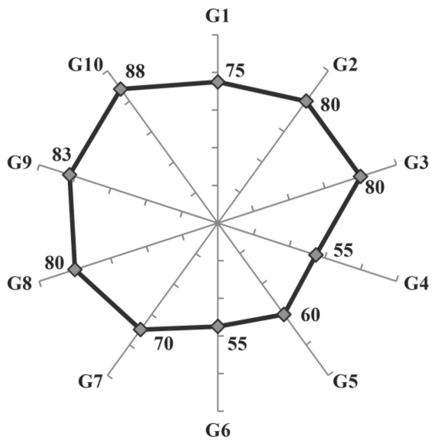

Fig. 8. Group score of laboratory report (10 groups, max score: 100).

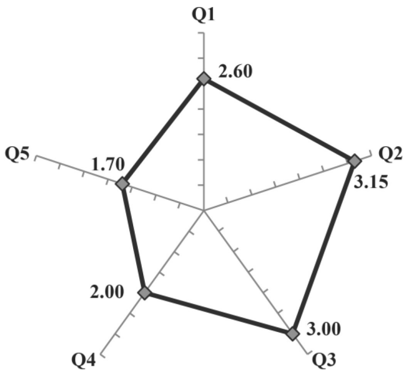

Fig. 9. Summary of responses to the student opinion survey (Mean value) (Sections A).

coordination was very poor". It states explicitly that the students agree on the coordination in the lab session is not inadequate. In Section C, most of the students express that the lab lecturer behaves in a friendly and pleasant way assigned to the lowest score (1.34 over 5.00) and they do not need more help for other things during the lab session allocated to the highest score (4.60 over 5.00) as shown in Fig. 11.

The students assessed that the experiment with virtual lab is not more difficult than the other experiments in the same laboratory (Questions 1 and 2). The duration (total time allocated to finish the virtual lab) was assumed to be reasonable by the students (Question 3). The general impression about the virtual lab session and lecturer were good (Questions 4 and 5). The students comprehended main idea and believed that they would not forget what they learned during the virtual lab (Questions 6 and 10). The students agreed that the virtual lab experiment format based on coordination, clarification and organization level, workload and stay on track is adequate (Questions 7–9, 11, 18,

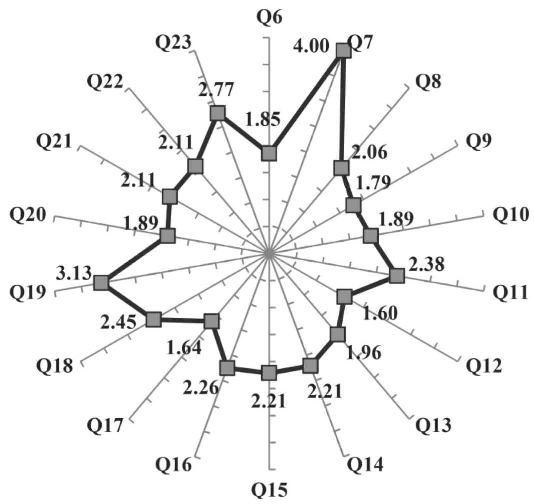

Fig. 10. Summary of responses to the student opinion survey (Mean value) (Sections B).

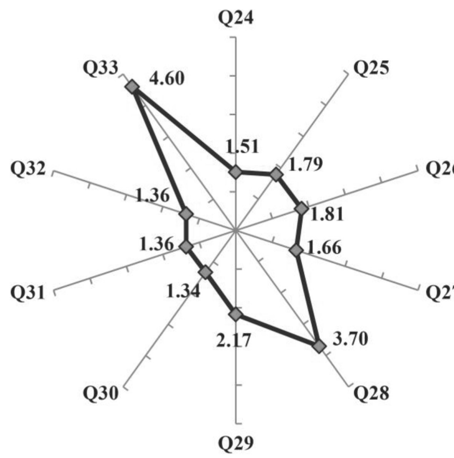

Fig. 11. Summary of responses to the student opinion survey (Mean value) (Sections C).

21 and 22). There were no complaints about difficulty of use of the virtual environment, but rather the virtual environment made easier for the students to comment on experiment's results (Questions 12 and 13). The virtual lab helped the students to enhance their knowledge and understand the material covered in the corresponding lectures better (Questions 14 and 15). The virtual lab attracted the students to be interested in this subject but not too much (Question 16). The majority of students agreed that the goal of experiment was defined explicitly (Question 17). The lecturer was considered to marginally help the students during the experiment (Question 20). They felt unsure about necessities of extra information to complete the experiment report and difficulties of gathering data (Questions 19 and 23). The students assumed

that the lecturer had effective communication behaviors (Question 24), an enthusiasm to the topic (Question 25) and ability to explain and describe effectively (Questions 27 and 28), displayed passion for students (Question 26), motivated their effort and achievement (Question 29), established positive teacher-student relationship (Question 30), became more responsible in carrying out duties as a lecturer to be prepared before a lecture and exhibit self-confidence (Questions 31 and 32) and exhibited caring of student needs for other subjects and problems (Question 31).

4.1 Reliability analysis

The reliability of the survey data can be measured by the internal consistency analysis method. Cronbach's alpha is a test technique and provides an estimate of the reliability for a given test [21]. Many surveys have been analyzed to find the value of Cronbach's alpha by this technique [22, 23]. Cronbach's alpha can be defines as given below.

$$\alpha = \frac{n}{n-1}\left(1 - \frac{\sum V_i}{V_{test}}\right) \tag{1}$$

where n is the number of questions, V_i is for the variance of scores on each question and V_{test} is the total variance of overall scores on the entire survey.

The reliability coefficient for Cronbach's alpha technique is normally ranges between 0 and 1. A high value of Cronbach's alpha indicates good internal consistency of the questions and reliability of the survey. The reliability statistics outcomes are given in Table 7. There is an overall reliability in the survey by reason of the high value of Cronbach's alpha given in Table 7.

Although the virtual lab is easier to set up, modify and conduct as mentioned above, but not more realistic, the system configuration can be performed in experimental way as in local case: Selection of transmission line model, selection of load resistors, reactors, capacitors, selection of variable transformer, selection of measurement components (voltmeter, ammeter, wattmeter, power factor and oscilloscope). The experimental study can be applied after the system test setup is finished. It is important to keep in mind that the real laboratory is completely realistic, but it is not easy to use, time-consuming to use and it's set up is cost.

Table 7. Reliability statistics of survey data

Cronbach's alpha	Cronbach's alpha based on standardized items	Total questions
0.861	0.868	33

5. Conclusion

A Virtual Electric Power Transmission Line Lab for undergraduate engineering curricula is designed and implemented in this paper. The Virtual Electric Power Transmission Line Lab introduced in this study helps students understand the characteristics of power transmission line models in a virtual interface. Students can use the VEPTLL with four modules.

Module 1 provides students with an understanding of the effects of short circuits on the pi transmission line. The voltage, current and power waveform and values can be obtained for different conditions. The second module shows the effects of changes in the connection of the transmission line without any load and the parameter values on the system outputs. The power transmission line is analyzed for different loads (resistive, inductive and capacitive) in Module 3. The effects of a single line-to-earth fault on the transmission line can be observed in Module 4.

The proposed VEPTLL has been used in the Power Systems Lab course taught at the Department of Electrical and Electronic Engineering at Karadeniz Technical University as a part of the undergraduate curriculum. A survey of the students who completed the lab has been conducted, and the responses are included in this paper. The survey indicates that the students benefit from the lab. They found is usable, easy, and understandable.

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Appendix

Short Circuit Test			**No Load Test**		
Three phase source			**Three phase source**		
VR, VS, VT	:	34.6 V	VR, VS, VT	:	220 V
f	:	50 Hz	f	:	50 Hz
RR, RS, RT	:	0.01 Ω	RR, RS, RT	:	0.01 Ω
LR, LS, LT	:	0 H	LR, LS, LT	:	0.231 H
Transmission line			**Transmission line**		
L	:	0.0110 H	L	:	0.0110 H
R	:	2 Ω	R	:	2 Ω
C	:	0 F	C	:	50.121x10^{-6} F
Cj	:	0 F	Cj	:	8.52x10^{-6} F

Load Test			**Fault Test**		
Three phase source			**Three phase source**		
VR, VS, VT	:	220 V	VR, VS, VT	:	220 V
f	:	50 Hz	f	:	50 Hz
RR, RS, RT	:	0.8929 Ω	RR, RS, RT	:	0.8929 Ω
LR, LS, LT	:	16.58x10^{-3} H	LR, LS, LT	:	16.58x10^{-3} H
Transmission line			**Transmission line**		
L	:	0.0110 H	L	:	0.0110 H
R	:	2 Ω	R	:	2 Ω
C	:	50.121x10^{-6} F	C	:	50.121x10^{-6} F
Cj	:	8.5205x10^{-6} F	Cj	:	8.5205x10^{-6} F
Load			**Load**		
LL	:	0 H	RL	:	100 Ω
RL	:	5 Ω	**Petersen coil**		
CL	:	0 F	Lp	:	0 H

Nomenclature

VR, VS, VT	:	Source voltage	LL	:	Load inductance
f	:	Source frequency	RL	:	Load resistance
RR, RS, RT	:	Source resistance	CL	:	Load capacitance
LR, LS, LT	:	Source inductance	PR	:	Phase power
R	:	Model resistance	IR	:	Phase current
C	:	Mutual capacitance	UR1	:	Input phase voltage
C_j	:	Earth capacitance	UR2	:	Output phase voltage
PF	:	Power factor			

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