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Laboratory Scale Modeling of Short Transmission Lines Based on 150 kV Line Parameters Using DIgSILENT PowerFactory Simulation

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Abstract – This study presents the development of a laboratory-scale simulator for a short transmission line based on a 150 kV system, intended as a learning medium for power system education. The model is scaled down to 380 V. A multi-stage validation approach is applied, consisting of system-level modeling in DIgSILENT PowerFactory, component-level verification using Proteus, and hardware implementation. The performance of the developed simulator is evaluated by analyzing voltage drop under various loading conditions, including different loading levels and both balanced and unbalanced configurations. To enable consistent comparison between simulation and hardware results, all data are normalized using the per-unit system. The results show that under balanced load conditions, the simulator demonstrates high accuracy with an average relative error of 2.3% compared to the real-scale model. Under unbalanced conditions, the average error increases to 9.7%, mainly due to differences in neutral modeling between simulation and hardware. Overall, the proposed simulator is able to reasonably replicate the voltage characteristics of a real transmission line and can be used as an effective tool for studying transmission system operation in a laboratory environment.

Keywords – transmission line, laboratory scale, simulator, voltage drop, DIgSILENT PowerFactory.

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I. INTRODUCTION

Economic growth, industrial expansion, and population growth are driving an increase in demand for electricity in Indonesia [1], [2]. Electricity has become an essential need, not only for daily activities but also as a strategic commodity that supports national development [3]. In the industrial sector, electricity plays a vital role in ensuring the continuity of production processes and operations, as well as promoting job creation and sustainable economic growth [4], [5].

Power systems mainly consist of three main systems: generation, transmission, and distribution. Electricity is generated at power plants, then transmitted through transmission lines to various regions, and finally distributed to consumers [4]. The design of the transmission system must consider reliability, efficiency, and safety to ensure good and stable power quality [6]. One of the main challenges is power loss, which causes not all energy to reach the load point [7].

Understanding the concepts of power system is essential for university students' learning to grasp the principles of power system design and operation. Laboratory education bridges theoretical concepts and real-world applications, and its importance in power systems learning has long been recognized [8]. However, it remains a significant challenge to study and comprehend large-scale transmission systems directly within a classroom or laboratory environment. The limited use of real hardware in power system education is primarily due to the complexity and high cost of establishing a realistic power system setup within a laboratory environment [8]. Consequently, learning activities are often limited to computer simulation-based analyses [9].

In the context of vocational education, mastering technical skills is a top priority. Practical activities play a crucial role in bridging theory and practice and encourage students to understand real-world issues in the field [10]. To support the vocational learning process, a laboratory-scale learning media such as power system simulators are required [11]. Learning thorough simulators that are based on real models enables students to understand the characteristics of real-scale power systems.

One component of the power system that can be studied using a simulator is the transmission line. In transmission lines, several phenomena can be observed for educational purposes, including balanced and unbalanced loading effect, voltage drop, and the Ferranti effect. Pratama et al. emphasized the importance of simulator media as a practical learning tool for students to understand real-world conditions of transmission as well as distribution systems and enhance students' understanding and technical skills [12].

Previous studies have been conducted on the development of electrical engineering learning media. The scaled-down method is widely used to represent high-voltage systems on a laboratory scale. Yamashika and Kamil employed this approach to scale down a 150 kV 100 A transmission system to 15 V 5 A laboratory scale system by scaling down the impedance [13]. Similarly, Murali et al. developed a per-unit-based scaled-down laboratory model that preserved the X/R ratio of the real line [14]. The performance was validated through simulation and experimental testing, showing that the scaled-down model can closely emulate the real transmission line's behavior.

A study done by Ahlawat and Nagarajan discusses the design and testing of a laboratory-scale power cable for educational use [15]. The system was scaled down from a 30 km, 500 kV line to operate at 230 V and 20 A. The system was modeled using a six-section π-equivalent in MATLAB/Simulink and validated through hardware testing. However, the study did not address any specific transmission line phenomena. On the other hand, Foqha et al. captured the Ferranti effect on a lightly loaded transmission line system to design a reactive power compensator [16]. The presence of Ferranti effect causes overvoltage issues at the receiving end. Shunt reactors were designed in software simulation environment and validated through hardware simulation.

The main contribution of this research is the development of a laboratory-scale simulator based on a 150 kV transmission system, scaled down to a standard 380 V three-phase system. In addition, the study evaluates the simulator by analyzing voltage drop under various operating conditions, including different loading levels as well as balanced and unbalanced loads. By incorporating these variations, the simulator can be used to study a range of operating conditions that commonly occur in real transmission lines, making it suitable for learning purposes.

II. METHODOLOGY

A. Short Transmission Line Model

Based on the length, transmission lines are classified into three main categories: short, medium, and long transmission lines. A transmission line shorter than 80 km is classified as short transmission [17]. In short transmission lines, the capacitive effect between lines is generally very small and thus neglected while resistance and inductor are lumped [18]. The equivalent circuit of short transmission line is as represented in Figure 1.

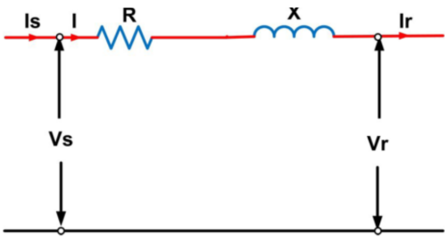

Figure 1. Short transmission line model

In short transmission lines, the sending-end voltage (Vs) can be represented by the vector sum of the receiving-end voltage (Vr), the voltage drops across the line resistance R, and the voltage drop across the line reactance X. Using phasor notation, this relationship is expressed in (1)-(2). The difference between sending end voltage and receiving end voltage is called voltage drop.

$$V_s = V_r + IR + jIX \quad (1)$$

$$V_r = V_s - I(R + jX) \quad (2)$$

Furthermore, the voltage drops along the transmission line becomes more pronounced as the distance between the sending and receiving ends increases. Since the total series impedance is proportional to line length, a longer line results in a larger voltage drop [19]. Consequently, the receiving-end voltage will be noticeably lower than the sending-end voltage. In addition, higher load currents amplify the effect of the voltage drop [20], as illustrated in Figure 2.

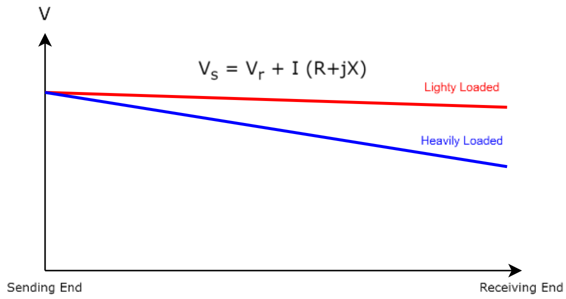

Figure 2. Voltage through transmission line

B. Research Workflow

The research workflow is illustrated in Figure 3. This study employs a multi-stage validation workflow—progressing from real-scale system modeling in DIgSILENT PowerFactory and electronic-scale simulation in Proteus to final hardware prototyping. The first stage involves modeling a transmission line in DIgSILENT PowerFactory to establish baseline data. Power flow simulations are conducted across balanced and unbalanced loading levels to generate per-unit (p.u.) value for voltage drop. This stage provides the theoretical standard against which all subsequent scaled models are compared.

The simulation in Proteus 8 Professional was used during the validation stage to assist in determining the sizing of components, namely resistors, inductors, and capacitors, in the scaled-down model. These components were then evaluated to assess whether they could produce voltage drops that reasonably represent the behavior of the corresponding transmission model developed in DIgSILENT PowerFactory.

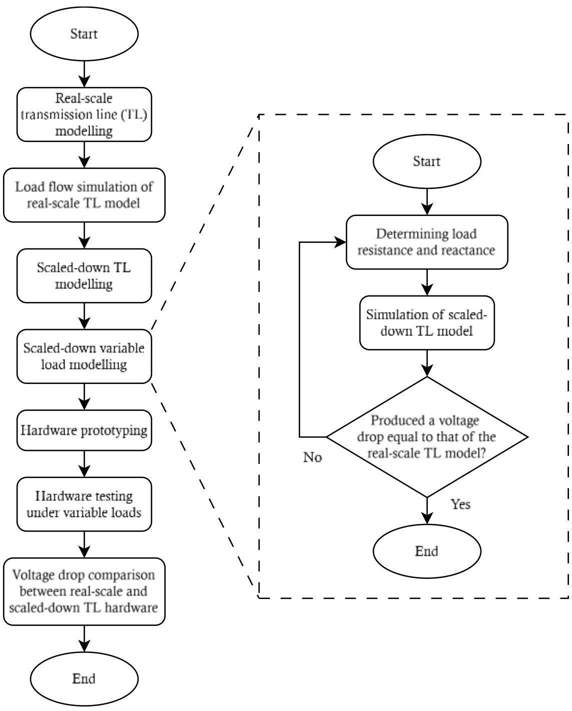

Figure 3. Research workflow

Following the determination of the scaled-down model parameters, a hardware prototype was developed. In the final stage, a comparative analysis was carried out between the hardware measurements and the simulation results. To enable a consistent comparison across different voltage levels, all data were normalized using the per-unit system, allowing for a more balanced evaluation of how well the simulator represents the behavior of the real-scale transmission system.

C. Real-Scale Transmission Line Modelling

This study proposed a scaled-down model to represent a 50 km 150 kV transmission line. The transmission line considered in the modelling is 150 kV line using ACSR, which is commonly used in Indonesia [21]. The cross-section of the line is 240 mm^2 with a resistance of 0.12 Ω/km and an inductance of 1.26 mH/km. This single line diagram of the system consists of grid, transmission line, and load can be seen in Figure 4.

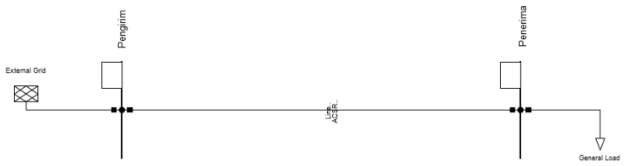

Figure 4. Single-line configuration using DIgSILENT PowerFactory software

D. Laboratory-Scale Transmission Line Modeling

To represent the transmission system on a laboratory scale, technical parameters must be adjusted. These adjustments include voltage, impedance, current, and power, which are derived from an actual transmission network system. Table 1 presents a scale comparison between the parameters of the transmission network system modelled using PowerFactory and the parameters of the system in the laboratory scale. The voltage scaling factor of 1:395 (150 kV to 380 V) was selected to ensure compatibility with industrial laboratory measurement instruments while maintaining safety.

Table 1. Comparison of actual transmission network system parameters and laboratory models

Parameters	Actual	Laboratory	Scale
L-L Voltage (V)	150,000	380	1:395
R (Ω)	6	6	1:1
L (mH)	63	63	1:1

The voltage is scaled down from 150 kV to 380 V, while the line resistance and impedance are maintained adjusted to match the line length of 50 km. To preserve the fundamental electrical characteristics of the 50 km ACSR conductor, the series resistance and inductance (R and L) were maintained at a 1:1 physical ratio. This selection ensures the X/R ratio remains constant, preserving the system's phasor behavior and voltage drop characteristics. The hardware of the transmission line simulator is shown in Figure 5.

Figure 5. Transmission line simulator

E. Variable Load Modelling

In the hardware implementation process, four stages load variations were used: 25%, 50%, 75%, and 100% relative to the maximum loading of the line. Load parameters (R and L) were determined via iterative experiment rather than purely analytical derivation to account for the constraints of discrete commercial component values. Since physical resistors and inductors are manufactured in standard increments, this iterative approach allowed for the identification of component combinations that most closely converged with the target per-unit loading levels defined in the 150 kV reference model. The details of the load configuration are presented in Table 2. In the hardware implementation, the loading of each phase can be independently selected using rotary switches, as shown in Figure 6.

Table 2. Loading variations on the variable load

Loading	Real-Scale Load (MVA)	Resistance (Ω)	Inductance (mH)
25%	37.2	2780.0	604.0
50%	74.0	1530.0	302.0
75%	110.9	930.0	202.0
100%	148.1	600.0	152.0

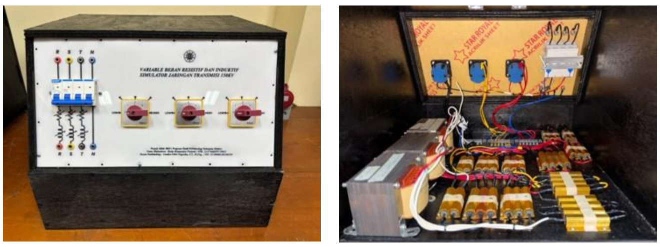

Figure 6. Variable load simulator

F. Hardware Testing Setup

The hardware setup of the laboratory-scale transmission system is shown in Figure 7, while the detailed cable connection is illustrated in Figure 8. The grid is represented by a three-phase source that is connected to the transmission line. The transmission line is then connected to the load, which can be varied using a selector that allows phase-by-phase adjustment. The three-phase configuration used in the testing is Wye-ungrounded.

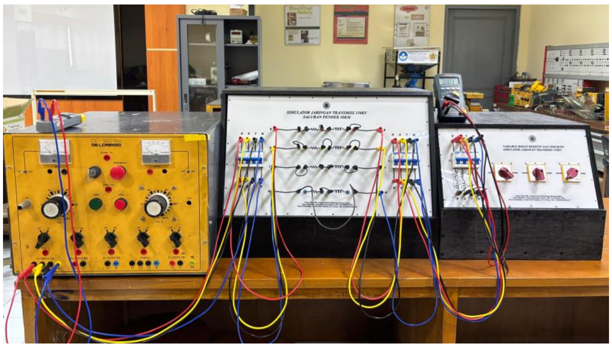

Figure 7. Equipment used in the laboratory testing

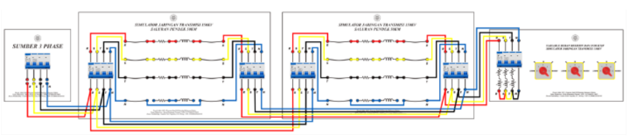

Figure 8. Connection between equipment used in the laboratory testing

III. RESULTS AND DISCUSSION

Voltage drop testing on the laboratory-scale transmission line was conducted by applying various load conditions. In addition to varying the load magnitude, both balanced and unbalanced load conditions were tested. After completing the experiments, the accuracy of the laboratory-scale model was evaluated by comparing its results with those of the real-scale transmission line model.

A. Balanced Load Testing

The simulator's functional accuracy was evaluated by comparing its relative voltage drop against the real-scale 150 kV model across multiple load levels. To ensure a standardized comparison between the 150 kV system and the 380 V laboratory hardware, per-unit (p.u.) normalization was applied to the data presented in Table 3 and Table 4. Vs is the sending end voltage, Vr is the receiving end voltage, and Vd is the voltage drop. Under balanced loading, the system maintains electrical symmetry, allowing Phase R to serve as the representative data point for both the software simulation and hardware prototype

Table 3. Real-scale model transmission line voltage drops with respect to balanced load variation

Loading	V_s (kV)	V_r (kV)	V_d (kV)	V_d (p.u.)
25%	150.00	147.05	2.94	0.020
50%	150.00	143.93	6.06	0.040
75%	150.00	140.99	9.01	0.060
100%	150.00	138.04	11.95	0.080

Table 4. Laboratory-scale tranmission line voltage drop with respect to balanced load variation

Loading	V_s (kV)	V_r (kV)	V_d (kV)	V_d (p.u.)
25%	387.29	380.19	7.10	0.019
50%	387.63	372.04	15.59	0.041
75%	387.63	365.29	22.34	0.059
100%	387.29	356.80	30.48	0.080

Comparative analysis reveals that the simulator accurately replicates the inverse relationship between load magnitude and receiving-end voltage characteristic of short transmission lines. While absolute voltage values differ due to the scaling factor, the per-unit (p.u.) normalization facilitates consistent validation across all loading levels. At 100% load, both the 150 kV model and the 380 V hardware exhibited an identical peak voltage drop of 0.080 p.u. The marginal deviations observed in the p.u. values (typically 0.001 to 0.002) signify a successful replication from a simulation environment to physical hardware

These discrepancies are technically attributed to practical hardware constraints, such as the inherent manufacturing tolerances of the resistors and inductors and the sensitivity limits of the laboratory measurement equipment. The alignment between these measurement data confirms that the simulator is reliability in representing balanced load condition of a real-scale 150 kV transmission line.

B. Unbalanced Load Testing

Unbalanced loading tests were performed across three variations to evaluate phase-specific voltage behavior, with results detailed in Table 5 and Table 6. In both the simulation and hardware environments, the results generally reflect the expected trend where the most significant voltage drop occurs in the phase with the highest load magnitude.

While several per-unit values showed a close correlation, the deviations between the software model and the hardware prototype were more pronounced than those observed in the balanced tests, with absolute errors ranging from 0.001 to 0.016 p.u. These findings suggest that while the simulator effectively replicates the fundamental characteristics of non-uniform loading, the higher discrepancies in specific variations indicate that the current model's accuracy under these conditions requires further investigation

Table 5. Real-scale model tranmission line voltage drops with respect to unbalanced load variation

Variation	Phase	Loading	V_s (kV)	V_r (kV)	V_d (kV)	V_d (p.u.)
1	R-N	25%	86.60	85.05	1.55	0.018
	S-N	50%	86.60	83.08	3.52	0.041
	T-N	75%	86.60	81.02	5.58	0.064
2	R-N	50%	86.60	83.28	3.32	0.038
	S-N	75%	86.60	81.22	5.38	0.062
	T-N	100%	86.60	79.05	7.55	0.087
3	R-N	100%	86.60	78.91	7.69	0.089
	S-N	25%	86.60	85.13	1.47	0.017
	T-N	50%	86.60	83.16	3.44	0.040

Table 6. Laboratory-scale tranmission line voltage drops with respect to unbalanced load variation

Variation	Phase	Loading	V_s (kV)	V_r (kV)	V_d (kV)	V_d (p.u.)
1	R-N	25%	222.10	218.10	4.00	0.018
	S-N	50%	220.40	211.20	9.20	0.042
	T-N	75%	221.30	209.70	11.60	0.053
2	R-N	50%	221.40	212.80	8.60	0.039
	S-N	75%	219.90	205.90	14.00	0.064
	T-N	100%	221.10	205.40	15.70	0.072
3	R-N	100%	221.40	203.50	17.90	0.082
	S-N	25%	220.30	215.70	4.60	0.021
	T-N	50%	220.90	213.00	7.90	0.036

C. Voltage Drop Accuracy

The accuracy of the laboratory-scale simulator in emulating the real-scale 150 kV model is quantified through the relative error metrics in Table 7 and Table 8. Under balanced loading, the trainer demonstrated high fidelity with an average relative error of only 2.3% (ranging from 0.7% to 4.8%), confirming its capacity to accurately represent symmetrical transmission behavior. While the accuracy remained high under balanced conditions, unbalanced loading introduced more significant deviations, with relative errors ranging from 1.9% to a peak of 23.5%. Although this peak error appears numerically high, it corresponds to a minimal absolute deviation of only 0.004 p.u., maintaining an overall average error of 9.7%

The significant relative error observed during unbalanced loading (Table 8) is primarily due to the modeling difference between the simulation and hardware neutral paths. While the PowerFactory model utilizes an ideal Wye-grounded configuration, where the neutral point is fixed at zero potential, the laboratory hardware employs a Wye-ungrounded setup with a physical neutral return cable. In the hardware, the neutral current generated by unbalanced loads flows through the return cable, causing a neutral point displacement that alters the phase-to-neutral voltage readings. This physical phenomenon was not captured by the ideal ground reference in the simulation, thus accounting for the higher deviation in per-unit voltage drop values.

Table 7. Relative error of voltage drops between the real-scale transmission line model and the laboratory-scale trainer under balanced load conditions

Loading	V_d (p.u.)		Relative Error (%)
	Model	**Hardware**	
100%	0.080	0.080	0.7%
75%	0.060	0.059	2.1%
50%	0.040	0.041	1.5%
25%	0.020	0.019	4.8%
Average			**2.3%**

Table 8. Relative error of voltage drops between the real-scale transmission line model and the laboratory-scale trainer under unbalanced load conditions

Variation	Phase	V_d (p.u.)		Relative Error (%)
		Model	**Hardware**	
1	R-N	0.018	0.018	1.9%
	S-N	0.041	0.042	3.2%
	T-N	0.064	0.053	17.9%
2	R-N	0.038	0.039	2.3%
	S-N	0.062	0.064	2.7%
	T-N	0.087	0.072	17.9%
3	R-N	0.089	0.082	8.1%
	S-N	0.017	0.021	23.5%
	T-N	0.040	0.036	9.3%
Average				**9.7%**

IV. CONCLUSION

In this study, a laboratory-scale model of a short 150 kV transmission line was developed as an educational tool. The model was designed to replicate the voltage drop characteristics of a 150 kV transmission line simulated using PowerFactory. The key stage in the development process involved determining the line impedance values that could accurately reproduce the reference voltage drop. Experimental testing was conducted under various loading levels, including both balanced and unbalanced load conditions. The results show that, under balanced load conditions, the average error between the simulation model and the hardware was only 2.3%, indicating a high degree of accuracy. This shows that the developed model can accurately replicates voltage drop characteristics of a short transmission line, especially under balanced load conditions.

Under unbalanced loading, error averaged 9.7% because the simulation's ideal ground reference did not account for the physical neutral return path used in the hardware. In the physical Wye-ungrounded setup, neutral current flows through a cable with an impedance, causing neutral point displacement and additional voltage drops that the ideal software model does not replicate. Future work will focus on incorporating neutral conductor impedance into the simulation to better align its accuracy with physical transmission characteristics

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