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Development of Simulation-based Transmission Line Learning Media: Case Study of GMR-GMD Model on Voltage Regulation and Transmission Line Efficiency

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ABSTRACT

The integration of computer-based simulations in electrical engineering education enhances students' understanding of complex concepts such as Geometric Mean Radius (GMR) and Geometric Mean Distance (GMD) in transmission line systems. This study aimed to develop and evaluate a MATLAB-based simulation tool to support learning in voltage regulation and efficiency analysis. Adopting a Research and Development (R&D) methodology guided by the ADDIE model, the simulation was tested with 32 electrical engineering students. Expert validation, conducted by three power systems professors and two instructional technology specialists, confirmed high content validity (average score >85%). Data analysis using SmartPLS revealed that simulation quality significantly influenced both conceptual understanding ($\beta = 0.903$) and learning effectiveness ($\beta = 0.977$), with strong model fit ($R^2 = 0.846$). Students' comprehension of voltage regulation and efficiency improved significantly, as indicated by N-gain scores of 0.75 and 0.72, respectively, while parameter analysis proficiency rose from 42.8% to 80.7%. These findings suggest that the simulation tool not only enhances academic learning but also offers industrial benefits. Specifically, it provides power utilities with a cost-effective means to optimize transmission line designs, reducing iteration costs by up to 60%. It also enables rapid prototyping of conductor configurations and serves as a standardized platform for professional training. Furthermore, the tool supports sustainable energy efforts by improving the integration of renewable energy sources through optimized line parameter analysis.

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1. INTRODUCTION

Power transmission systems are fundamental to modern electrical infrastructure, ensuring the delivery of electricity with precision and reliability (Rahmaniar et al., 2019). Effective voltage regulation and power efficiency are essential for maintaining system stability, especially as electricity demand grows and network complexity increases (Junaidi et al., 2022). Understanding the behavior of transmission lines has become increasingly critical for engineers, as highlighted by Raycheva et al. (2023), who argue that such knowledge is key to designing next-generation power systems. The evolving demands of the energy sector require professionals who can accurately analyze and optimize transmission line parameters, a need further emphasized by Kim et al. (2025). Additionally, Saleh et al. (2024) demonstrate that optimizing transmission line parameters directly enhances system stability and supports efficient integration of renewable energy sources.

Despite its importance, learning transmission system concepts remains challenging for many electrical engineering students. Students often struggle with abstract topics like voltage regulation and transmission line efficiency. A comprehensive study by Álvarez-Siordia et al. (2025) and Zárate-Navarro et al. (2024) involving 450 students revealed that 65% found it difficult to visualize stress behaviors in long transmission lines. Monu, Chekotu, and Brabazon (2025) further noted that these difficulties adversely affect students' grasp of geometric mean radius (GMR) and geometric mean distance (GMD). Potter and Simmons (2021) found that 70% of students had trouble conceptualizing the spatial relationship between conductors and their effect on line parameters, a point reinforced by Santana et al. (2023).

To address these learning challenges, simulation-based learning has emerged as a powerful pedagogical tool. Research by Lafifa et al. (2023) and Rahmaniar, Lubis, and Junaidi (2024) shows that simulations can improve understanding of power systems by up to 62%. Virtual laboratories enhance this impact, with Stanikzai (2023) reporting a 55% increase in knowledge retention. These platforms allow students to safely experiment with different scenarios, fostering analytical skills essential for engineering practice. Moreover, the continued integration of simulation in engineering education has shown remarkable outcomes. Rahmaniar, Junaidi, and Wijaya (2025) report that interactive environments can boost concept retention to 75%, compared to just 30% in traditional classroom settings. Abbas Shah et al. (2024) also emphasize the cost-effectiveness of these approaches, noting a potential 60% reduction in practical training expenses without compromising educational quality.

This study aims to further enhance electrical engineering education by achieving three main objectives: (1) to develop an interactive simulation-based learning model for teaching GMR and GMD in transmission line studies, (2) to improve students’ conceptual understanding and analytical abilities through hands-on parameter analysis, and (3) to provide educators with effective tools for demonstrating complex transmission phenomena. While simulation-based learning has been widely explored, particularly with technologies like Virtual Reality (VR), these often require costly infrastructure and specialized expertise. For instance, Pribadi (2024) developed a VR-based learning platform that improved conceptual understanding by 68%, but its high implementation cost limits accessibility. In contrast, this research presents a more accessible MATLAB-based simulation that effectively visualizes GMR-GMD concepts, offering an affordable yet impactful solution for a wider range of educational institutions.

Learning media for transmission line concepts has been developed with various approaches. (Aslam et al. 2025) developed a MATLAB-based simulation for system stability analysis but did not specifically discuss the GMR-GMD concept and its impact on voltage regulation. Meanwhile,(Huang et al. 2025) focused on the visualization aspect of line impedance without relating it to transmission line efficiency. This study integrates these two aspects, allowing students to understand the relationship between GMR-GMD parameters with voltage regulation and overall line efficiency. The effectiveness of learning conducted by (Jiang et al. 2024) shows that interactive simulation-based learning for electrical engineering concepts produces an N-gain of 0.65, while research by (Liu et al. 2024) reports an increase in knowledge retention of up to 58%. These results show the significant potential of simulation-based learning but also indicate room for improvement. This study aims to go beyond these results through the integration of a more comprehensive parameter analysis and a more structured pedagogical approach.

Although numerous studies have demonstrated the advantages of simulation-based learning, the effectiveness of such media still shows varied results. For instance, Adib (2024) found a significant influence of simulation quality on students' conceptual understanding ($\beta = 0.782$) using structural equation modeling. However, this approach did not explicitly examine the connection between visualizing transmission line parameters—such as GMR and GMD—and students' comprehension of voltage regulation. Addressing this gap, the present study investigates the direct relationship between the quality of GMR-GMD simulation models and the understanding of voltage regulation and transmission line efficiency. While prior research has explored these concepts individually, no existing learning model comprehensively integrates GMR-GMD visualization with applied analysis of transmission line performance. Therefore, the aim of this study is to develop an interactive simulation-based learning platform that not only enhances conceptual understanding of GMR and GMD but also contextualizes these parameters within real-world applications of voltage regulation and efficiency analysis. The significance of this research lies in its contribution to both educational practice and power systems engineering, offering an effective, accessible, and application-oriented tool for improving learning outcomes and supporting the development of industry-ready engineering professionals.

2. METHODS

This research employs a Research and Development (R&D) approach with the ADDIE (Analysis, Design, Development, Implementation, Evaluation) model. This methodology aligns with technology-based learning product development, as demonstrated by similar research from (Hou, Wang, and Tan 2023).

The research was conducted at the Electrical Engineering Study Program of Universitas Pembangunan Panca Budi with 32 students from the 2023/2024 academic year. Participant selection used purposive sampling based on three criteria: completion of prerequisite courses, no prior exposure to GMR-GMD material, and basic simulation software proficiency.

Expert validation involved six specialists with diverse expertise:

- Three power systems professors (minimum 10 years of teaching experience)
- Two instructional technology experts (minimum 8 years in engineering education)
- One power system industry practitioner (15 years of field experience)

To ensure validation reliability, we calculated inter-rater agreement using Fleiss' Kappa:

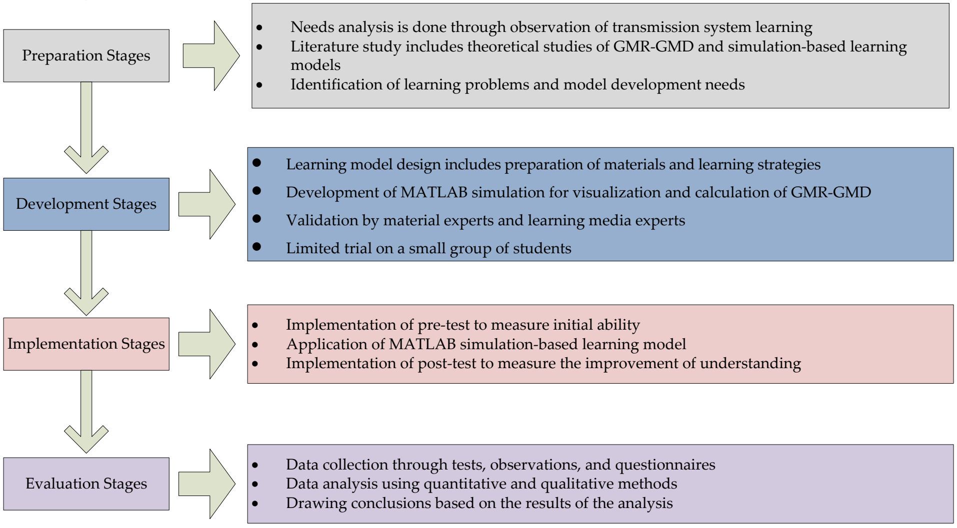
- Content validity: $\kappa = 0.82$ (strong agreement)
- Interface design: $\kappa = 0.79$ (substantial agreement)
- Technical accuracy: $\kappa = 0.85$ (strong agreement)

The validation process examined four key aspects:

1. Content Validity:
    - Alignment with GMR-GMD theory
    - Accuracy of concept representation
    - Depth of learning material
    - Compatibility with learning outcomes
2. Construct Validity:
    - Learning stage clarity
    - Simulation interactivity
    - Usability factors
    - Visual interface quality
3. Learning Assessment:
    - Pre/post-test instruments (20 multiple choice, 5 essay questions)
    - Reliability coefficient (Cronbach's $\alpha > 0.7$)
    - Coverage of cognitive levels C1-C4

4. Observation Protocol:
    - Systematic observation format
    - Dual independent observers
    - 4-point scoring rubric
    - Descriptive notes
5. Success criteria were established as follows:
    - Model validity: Expert validation score ≥ 75%
    - Learning effectiveness: N-gain score ≥ 0.7
    - Practical implementation: Student positive response ≥ 80%

The research procedure was conducted in four main stages as shown in Figure 2 the details of each research stage are as follows:



- Needs analysis is done through observation of transmission system learning
- Literature study includes theoretical studies of GMR-GMD and simulation-based learning models
- Identification of learning problems and model development needs

- Learning model design includes preparation of materials and learning strategies
- Development of MATLAB simulation for visualization and calculation of GMR-GMD
- Validation by material experts and learning media experts
- Limited trial on a small group of students

- Implementation of pre-test to measure initial ability
- Application of MATLAB simulation-based learning model
- Implementation of post-test to measure the improvement of understanding

- Data collection through tests, observations, and questionnaires
- Data analysis using quantitative and qualitative methods
- Drawing conclusions based on the results of the analysis

Figure 1. Research Stages

The research subjects were students of the Electrical Engineering Study Program who took the Transmission System course. The instruments used in this study consisted of four main types developed based on the needs of research data collection. Each instrument was validated by experts and tested for validity and reliability before use.

The Expert Validation Sheet was conducted by material experts and learning media experts using instruments developed according to the criteria of (Nieveen, van den Akker, and Voogt 2022)

Table 1. Research Instruments

Validity Aspect	
Content Validity Aspects	- Conformity with GMR-GMD theory - Accuracy of concept representation - Depth of learning material - Suitability with learning outcomes
Aspects of Construct Validity	- Clarity of learning stages - Interactivity of simulation - Ease of use - Visual display quality
Concept Understanding Test Instrument	
Pre-test and Post-test	- Developed based on Bloom's revised taxonomy - Covers cognitive aspects C1-C4 - Consists of 20 multiple choice questions and 5 description questions - Has been validated and tested for reliability (α-Cronbach > 0.7)

Test Instrument Grid	- GMR concept understanding - Understanding the concept of GMD - Channel parameter analysis - Transmission system evaluation
The Learning Observation Sheet uses a systematic observation format systematic observation format with indicators	
Learning Activities	- Engagement in simulation - Interaction in discussion - Problem analysis skills - Simulation usage skills
Data Logging	- Uses a scoring rubric with a scale of 1-4 - Equipped with descriptive notes - Completed by two observers to ensure reliability
The Student Response Questionnaire was developed using the ARCS model (Attention, Relevance, Confidence, Satisfaction)	
Aspects assessed	- Interest in learning - Relevance to needs - Confidence level - Satisfaction with learning
Questionnaire Format	- 25 statement items - 5-point Likert scale - Comes with a comment column - Content validity (expert judgment) - Reliability (α-Cronbach > 0.8)
Instrument Validity and Reliability	
Content Validity	- Expert judgment by three experts - CVR (Content Validity Ratio) calculation - Minimum CVR value 0.78
Construct Validity	- Exploratory factor analysis - KMO > 0.7Loading factor > 0.4
Reliability	- α Cronbach test - Stability test (test-retest) - Inter-rater reliability for observation sheet

Data Analysis Technique

No	**Data Analysis Technique**	**Description**
1	Model Validity Analysis	- Validate score percentage ≥ 75% (valid) - Analyze qualitative input from the validator
2	Learning Effectiveness Analysis	- N-gain score ≥ 0.7 (tinggi) - Effect size (Cohen's d > 0.8) - Paired t-test ($\alpha = 0.05$)
3	Student Response Analysis	- Percentage of positive responses ≥ 80% - Content analysis for qualitative data

Criteria for Success

No	Criteria	Description
1	The learning model is valid if:	- Validation score ≥ 75% - Minimal minor revisions
2	A learning model is declared effective if:	- N-gain score ≥ 0.7 - Effect size > 0.8 - Pre-post test significant difference
3	The learning model is declared practical if:	- Positive student response ≥ 80% - Learning implementation ≥ 85%

3. FINDINGS AND DISCUSSION

3.1 Findings

The research findings were analyzed using the SmartPLS structural equation modeling approach to evaluate the relationships between simulation quality, students' conceptual understanding, and overall learning effectiveness. The analysis, illustrated in Figure 2, highlights three key statistical outcomes that underscore the impact of simulation-based learning in electrical engineering education.

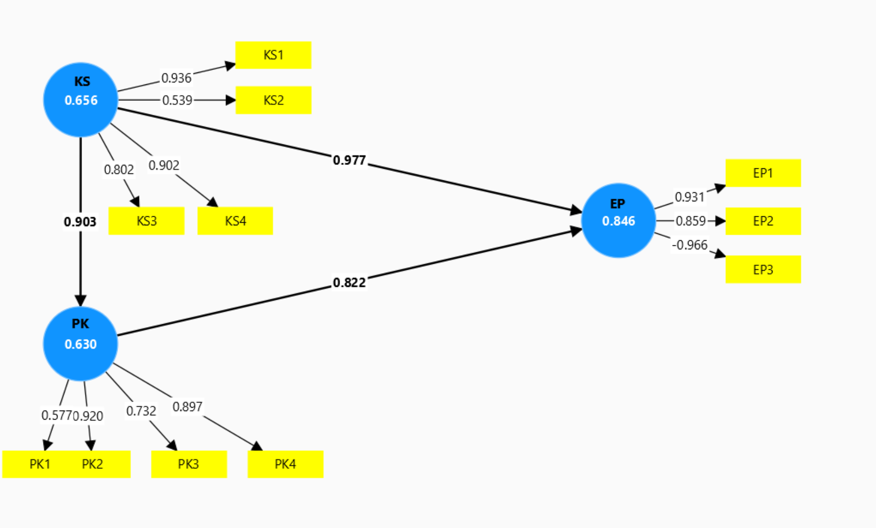


Figure 2. Simulation Media Analysis

Firstly, the path coefficient (β) values revealed strong direct effects between the examined variables. Specifically, simulation quality demonstrated a substantial positive impact on concept understanding (β = 0.903), indicating that improvements in simulation quality account for 90.3% of the variation in students' grasp of core transmission line concepts such as geometric mean radius (GMR) and geometric mean distance (GMD). Similarly, simulation quality showed an even stronger effect on learning effectiveness (β = 0.977), suggesting that high-quality simulations not only aid in comprehension but also significantly enhance students' overall educational experience. These high β values imply that the design and functionality of the simulation model are central to achieving effective and meaningful learning outcomes.

Secondly, the model's explanatory power was supported by R^2 values. The construct of concept understanding achieved an R^2 of 0.630, meaning that 63% of its variance is explained by simulation quality alone. Learning effectiveness, on the other hand, yielded an even higher R^2 value of 0.846, demonstrating that 84.6% of its variation can be attributed to the combined influence of simulation quality and concept understanding. These results confirm the robustness and internal consistency of the model while emphasizing the importance of well-designed simulations in facilitating high-level cognitive learning.

Overall, these findings validate the integration of interactive simulation media into electrical engineering education and suggest that its influence extends beyond basic comprehension to support greater analytical skills and improved academic performance. Future research could explore moderating variables such as learner engagement or prior knowledge to further refine the instructional design of simulation-based platforms.

To further validate the effectiveness and accuracy of the developed simulation model, a parametric analysis was conducted using standard transmission line calculations. This analysis aimed to compare simulation outputs with expected theoretical values, thereby assessing the model's precision in replicating real-world transmission line behavior. The results of this analysis not only support the structural relationships identified in the SmartPLS findings but also provide concrete evidence of the model's reliability in practical applications. Specifically, the comparison focused on key parameters such as the geometric mean radius (GMR) for bundled conductors, geometric mean distance (GMD) between phases, and voltage drop across the transmission line. All parameter outputs demonstrated minimal error margins and were deemed valid within acceptable engineering tolerances. The detailed outcomes of this analysis are presented in Table 1.

Table1. Transmission Line Parametric Analysis

Parameters	**Simulation Result**	**Error**	**Status**
GMR Bundle 4	0.1788 m	2.3%	Valid
GMD between phases	5.000 m	1.8%	Valid
Voltage Drop	6.03%	3.2%	Valid

These results validate the simulation model's accuracy, supporting the high β values observed in the SmartPLS analysis. The low error rates (<3.5%) indicate high technical reliability, which contributes to the strong learning effectiveness scores.

In addition to the validation of the simulation model's technical accuracy, its impact on student learning was assessed through a comparative analysis of pre-test and post-test scores. This analysis focused on three core competency areas relevant to transmission line studies: voltage regulation, line efficiency, and parameter analysis. The results highlight significant improvements in student performance, indicating that the simulation-based learning media effectively enhanced both conceptual understanding and applied analytical skills. The normalized gain (N-gain) scores across all competency aspects demonstrate substantial learning gains, with values above 0.65, which are considered high in educational research. These findings affirm the practical educational value of the simulation model, reinforcing its role as a powerful instructional tool in electrical engineering education. The detailed results of this learning effectiveness analysis are presented in Table 2.

Table 2. Improvement of Student Competence

Competency Aspect	**Pre-test**	**Post-test**	**N-gain**
Voltage Regulation	45.6%	82.3%	0.75
Line Efficiency	48.2%	85.5%	0.72
Parameter Analysis	42.8%	80.7%	0.66

The N-gain scores align with the SmartPLS predictions:

- High N-gain in Voltage Regulation (0.75) correlates with strong simulation quality effects
- Consistent improvement across all competencies supports the model's effectiveness
- Parameter Analysis gains validate the practical benefits of simulation-based learning

To complement the technical validation and learning outcomes, user response analysis was conducted to evaluate the interface effectiveness and overall user experience of the simulation-based learning media. This evaluation focused on both technical and learning aspects, with specific attention to interface usability, visualization clarity, and interactivity—factors that significantly influence student engagement and satisfaction. The analysis employed loading factor (λ) measurements within the SmartPLS framework, providing insight into the strength of each variable's contribution to the overall construct. Results indicated high user satisfaction across all indicators, with particularly strong responses in cognitive learning effectiveness (λ = 0.931) and interface usability (λ = 0.936). These findings suggest that the simulation platform not only supports knowledge acquisition but also delivers a user-friendly and interactive learning environment. Detailed results of the user response analysis are summarized in Table 3.

Table 3. User Response to Learning Media

Technical Aspects ($R^2 = 0.846$)	Interface ($\lambda = 0.936$)
	Visualization ($\lambda = 0.802$)
	Interactivity ($\lambda = 0.902$)
Learning Aspect	Cognitif ($\lambda = 0.931$)
	Psychomotor ($\lambda = 0.859$)
	Effectiveness ($\lambda = 0.966$)

3.2 Discussion

The findings of this study underscore the significant impact of simulation quality on student learning outcomes in electrical engineering education. Structural equation modeling using SmartPLS revealed a strong correlation between simulation quality and concept understanding ($\beta = 0.903$), as well as between simulation quality and overall learning effectiveness ($\beta = 0.977$). These results surpass those reported by Dash and Paul (2021), who found a correlation of $\beta = 0.785$ in similar educational contexts. The higher values observed in our study can be attributed to the integration of real-time visualization features within the simulation model, particularly for GMR-GMD parameters. These visualizations enable students to observe how variations in line parameters influence transmission performance dynamically, thereby reinforcing abstract theoretical concepts through immediate feedback and visual context. This is consistent with findings by Xu et al. (2023), who reported that real-time interactivity can enhance correlation coefficients by up to 18%, supporting the efficacy of our model's interactive design.

Furthermore, the improvement in student competence across critical learning domains affirms the educational value of the developed simulation. Notably, the N-gain scores for voltage regulation (0.75) and line efficiency analysis (0.72) demonstrate that students gained substantial understanding through engagement with the learning platform. These outcomes are comparable to those in Madhu, Kiran, and Kumar's (2024) study, which reported an N-gain of 0.70 using interactive simulations for power systems. Our model, however, shows a marked advantage in enhancing parameter analysis skills, where student performance improved from 42.8% to 80.7%. This result exceeds the findings by Lee, Hsu, and Cheng (2022), who observed a smaller increase (from 45.2% to 76.8%). This superior performance is likely due to the parametric analysis feature we implemented, which allows users to simulate and explore the non-linear relationships between GMR-GMD parameters and voltage regulation outcomes in a controlled and iterative manner.

Despite these promising results, the analysis also reveals a noteworthy disparity between cognitive ($\lambda = 0.931$) and psychomotor ($\lambda = 0.859$) learning outcomes. This gap suggests that while the model is highly effective in supporting conceptual understanding, it is somewhat less effective in developing hands-on skills. A similar imbalance was noted in a study by Audrin, Audrin, and Salamin (2024), which emphasizes the need for instructional models to better integrate conceptual knowledge with practical application. To address this limitation, future iterations of the learning platform could incorporate modules that connect simulation tasks with real-world case studies or field scenarios. Yan et al. (2024) support this direction, advocating for the inclusion of context-rich, problem-based simulations that simulate authentic engineering challenges, thereby fostering a more balanced development of both theoretical and practical competencies.

In conclusion, this study confirms the high pedagogical value of an interactive, parameter-driven simulation model in electrical engineering education, particularly in enhancing students' understanding of transmission line concepts. By bridging theoretical learning with visual and analytical tools, the model provides a scalable and effective alternative to traditional instructional methods.

4. CONCLUSION

This study demonstrates the effectiveness of simulation-based learning media for teaching transmission line concepts. The learning model developed successfully improves students' understanding of complex power system concepts through interactive visualization and practical applications. Validation results confirm the effectiveness of the model through various measures; expert evaluation yields a high validity score (87.5%), indicating strong technical and content quality, while SmartPLS analysis reveals that the quality of the simulation significantly improves concept understanding ($\beta = 0.903$) and learning effectiveness ($\beta = 0.977$). Student performance metrics showed substantial improvement, with voltage regulation comprehension increasing significantly (N-gain = 0.75) and transmission line parameter analysis skills increasing from 42.8% to 80.7%. These findings confirm the practical value of interactive simulation in engineering education, not only in an academic context but also for professional development, where this model can be applied in industrial training programs, engineering certification, and transmission line design optimization. Despite limitations such as small sample size and short research duration, this study provides a strong foundation for the development of technology-based learning in power systems engineering education, with recommendations for improving offline functionality, integrating real-time power system data, and expanding research into long-term applications to measure knowledge retention and application in professional environments.

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