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Web Application in Python for Voltage Regulation Calculation in Short Transmission Lines: Development and Validation

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Abstract: **The analysis of electric power systems requires tools that facilitate understanding of the phenomena associated with transmission lines. Among the most relevant parameters, voltage regulation stands out as a key indicator for evaluating the operational performance of a network. This paper presents the development of a didactic web application implemented in Python, designed to calculate the voltage regulation of short transmission lines through an interactive environment that supports teaching in electromechanical engineering. The tool incorporates a database of ACSR conductors and displays both intermediate and final calculations, promoting active and visual learning. Validation was carried out through complementary academic and reference-based approaches, including educational examples and classical textbook problems. The results show a high level of agreement with traditional analytical methods, confirming the technical accuracy and pedagogical value of the proposed tool. The study concludes that the application represents an open, replicable, and accessible resource for strengthening practical learning in transmission line analysis.**

Keywords: **Voltage regulation, Short transmission lines, Power systems education, Python, Web application, ACSR conductors, Electric power engineering, Didactic tools, Interactive learning, Validation.**

I. INTRODUCTION

The teaching of electric power systems requires computational tools that facilitate a practical, visual, and interactive understanding of electrical phenomena. In the analysis of transmission lines, one of the most relevant parameters is voltage regulation, since it represents the voltage variation between the sending and receiving ends and serves as a key indicator of the efficiency and stability of an electrical network. However, the calculation of this parameter is commonly carried out using commercial software such as ETAP, DIgSILENT, or MATLAB, which often limits accessibility in educational institutions with restricted resources or in environments that promote didactic experimentation.

In recent years, the growth of open-source programming languages—particularly Python—has driven a significant transformation in electrical engineering education, enabling the development of accessible and replicable learning tools [1,2]. Python stands out for its simple syntax and its scientific libraries, such as NumPy, Pandas, and Matplotlib, which support the implementation of complex electrical models in an intuitive manner and enhance conceptual understanding through result visualization [3,4]. Additionally, frameworks such as Flask and Streamlit allow the creation of interactive web interfaces that integrate theory, simulation, and visual analysis into a unified learning environment [5,6].

In this study, Python is adopted as an educational platform due to its transparency, accessibility, and suitability for illustrating the analytical foundations of transmission line behavior. Previous works confirm its effectiveness for modeling electrical systems and supporting active learning environments [7,8]. Similarly, PyPSA provides a robust methodological foundation for power system analysis and has become a reference in both educational and research contexts [9], [25]. Despite these advances, no web applications currently exist that focus specifically on the teaching of voltage regulation calculations while simultaneously integrating mathematical accuracy, interactivity, and pedagogical purpose.

In this context, the present work proposes the development of a didactic web-based tool implemented in Python, named EducativX-Line**,** designed to compute the voltage regulation of short transmission lines. The application incorporates an ACSR conductor database and a visual environment that allows students to follow the calculation process step-by-step, reinforcing the connection between electromagnetic theory and practical application.

From an experimental and validation-driven approach, the tool is evaluated through three complementary methods: (1) a practical exercise presented on the educational YouTube channel *Cosas de Ingeniería*; (2) an academic problem solved in the Power Systems course; and (3) a classical exercise from Grainger's *Power System Analysis*. The research hypothesis states that the results obtained with the application will match traditional theoretical methods with an error margin below 2%, demonstrating both its technical accuracy and its pedagogical relevance in the teaching of transmission-line analysis.

II. BACKGROUND

A. Importance of Voltage Regulation in Transmission Lines

Voltage regulation describes the variation between sending- and receiving-end voltages under load and remains a central parameter in the analysis of transmission-line performance. This indicator directly reflects the system's energy efficiency and operational stability, making its understanding essential for the training of electrical and electromechanical engineers [1,2]. Voltage regulation analysis is rooted in the classical models of short, medium, and long transmission lines, where resistance, inductance, and capacitance determine the behavior of voltage and current along the conductor. In educational practice, mastering these relationships requires understanding the ABCD parameters, distributed models, and load-dependent variations. Despite its relevance, this calculation is often performed using costly commercial software, such as ETAP, DIgSILENT, or MATLAB, which limits accessibility in institutions with constrained resources [3]. Consequently, the need for open and accessible tools has grown, enabling students to analyze power systems through reproducible methodologies and didactic environments.

B. Limitations of Proprietary Software and the Rise of Open-Source Tools

In recent years, Python has emerged as a practical alternative for power-systems education, combining numerical efficiency with accessibility and open dissemination. Authors have highlighted Python's suitability for modeling and simulating electrical networks, as well as for developing educational applications that integrate theory and practice. For example, Popov-Hinov and Hinov demonstrated that Python-based training enhances comprehension of electrical phenomena through direct manipulation of system equations and parameters [4]. Similarly, Jiménez-Ruiz et al. validated the integration of Python with DIgSILENT PowerFactory for wind-energy studies, reinforcing Python's precision and versatility when compared with commercial tools [5]. From a pedagogical perspective, Python promotes autonomous learning and transparency in the calculation process by allowing students to visualize each step of the electrical equations. Frameworks such as Flask and Streamlit have enabled the development of interactive interfaces where users input parameters, execute simulations, and observe real-time results [6,7].

Table I presents a comparative overview of widely used software tools for transmission line analysis, highlighting their capabilities and constraints. This comparison strengthens the motivation for developing an accessible, open-source educational tool.

TABLE I. COMPARISON OF EXISTING SOFTWARE FOR TRANSMISSION LINE ANALYSIS

Software	Type / Approach	Advantages	Limitations
ETAP	Commercial / Professional	High accuracy; extensive component database	High cost; limited access
MATLAB / Simulink	Commercial / Academic	Strong mathematical modeling	Expensive license; complexity
DIgSILENT PowerFactory	Commercial / Industrial	Detailed stability and dynamic studies	Complex interface; costly
PSS/E	Commercial / Professional	Large-scale power system studies	Requires advanced expertise
Python (open-source)	Academic / Educational	Free, flexible, adaptable	Less advanced graphical interface

The limitations of proprietary software, particularly cost and accessibility, justify the adoption of open-source environments such as Python for educational applications. This provides the foundation for the development of the proposed web-based tool, presented in the next section.

Recent studies confirm that Python-based training environments significantly improve conceptual understanding and problem-solving skills in electrical engineering education [21].

C. Python-Based Developments Related to Power Transmission

Recent literature demonstrates the feasibility of open-source environments for a wide range of power-system studies, including transmission modeling, protection, and system analysis. Relevant examples include:

- Model conversion across DIgSILENT/MATPOWER /PYPOWER environments [8];
- Inertial power flow computation [9];
- Harmonic load flow in radial networks [10];
- Differential protection settings using Python + PowerFactory [11];
- Optimal switching and transmission expansion [12];
- Virtual power plant location using optimal power flow [13];
- Real-time integration with ETAP-RT [14]. Although these works demonstrate the feasibility and reproducibility of open-source tools for transmission studies, none develop a didactic web application focused exclusively on interactive voltage regulation calculation, confirming the pedagogical gap addressed by this proposal.

D. Evolution of Voltage Regulation Studies

Voltage regulation has long been studied due to its impact on system stability and efficiency. Early approaches relied on classical models based on series and shunt parameters, using ABCD equations to describe voltage-current relationships [1]. Later contributions incorporated computational techniques and optimization models, such as those by Garcés, who applied convex methods to improve operational efficiency [2]. With the rise of open-source tools, Python-based proposals for electrical calculations have emerged, including grounding system studies [15], inertial power flow [9], and harmonic analysis [10]. Similarly, Solano Ordóñez implemented Python-based differential protection for transmission lines, demonstrating the language’s suitability for complex electrical problems [11].

More recent work integrates web interfaces and interactive applications, such as remote laboratories with Python and Raspberry Pi [7], open-source WAMPAC simulators [16], and validated transmission-line simulations using Python and Modelica [17]. Comprehensive reviews confirm that Python and PyPSA dominate the current landscape in education and research [18]. Despite these advances, no prior work has presented a web-based educational application specifically focused on the didactic calculation of voltage regulation in short transmission lines, which defines the scope of the present study.

Complementary research has addressed voltage profile improvement through reactive power compensation techniques, such as STATCOM-based control strategies, highlighting the relevance of voltage regulation in modern power systems [19].

E. Recent Advances in Open-Source, Learning-Oriented Tools

Recent research has focused on integrating digital learning and scientific programming into power engineering education. Ceraolo modeled transmission lines using Modelica and Python, showing accuracy comparable to industrial software [17]. Haugdal and Uhlen developed an open-source simulator for WAMPAC applications, emphasizing its educational relevance [16]. Ariza et al. designed a remote laboratory that enables direct interaction with real experiments through Python and Raspberry Pi [7]. These developments demonstrate that open-source environments foster accessible, adaptable, and cost-effective learning. However, none of these proposals address the didactic calculation of voltage regulation with step-by-step intermediate results, highlighting the need for a tool such as EducativX-Line.

Table II summarizes the most representative studies published between 2019 and 2025 regarding transmission line modeling, open-source simulation environments, and educational applications in power systems. This comparative review establishes the technological context and identifies the gap that motivates the development of the proposed web-based voltage-regulation tool.

TABLE II. TRENDS IN TRANSMISSION LINE ANALYSIS AND SIMULATION (2019–2025)

Author / Year	**Environment**	**Method**	**Advantages**	**Limitations**
Rodrigo et al. [22]	Classical models	ABCD / distributed parameters	High analytical precision	No computational simulation
Mosquera and Carrión [20]	DC-OPF (MILP)	VPP siting with technical/economic constraints	Improves voltage profile	Not educational; no web app
De Puestas et al. [10]	Python	Grounding system analysis	Open-source, replicable	Not focused on transmission lines
Mancero Mayacela [17]	Python	Inertial power flow (NR variants)	Validated vs DIgSILENT	Not oriented to regulation
Zurita et al. [26]	Python	Harmonic load flow / DIgSILENT comparison	Reproducible methodology	No voltage-regulation focus
Garcés Ruiz [11]	Convex optimization	Mathematical system modeling	Improves operating efficiency	Not applied to voltage regulation
Suárez Farinango [24]	MILP	OTS/TEP in IEEE & Garver grids	Planning relevance	Not didactic; no regulation
Monteza and Dilthey [24]	ETAP-RT + lab	Real-time monitoring/control	Strong hardware–software integration	Proprietary; not pure Python
Alexander and Llamuca [1]	Python + DB	Cross-platform model conversion	Interoperability/portability	Not a didactic app
Haugdal and Uhlen [14]	Python (open-source)	WAMPAC simulation	Accessible, flexible	Not about regulation
Solano Ordóñez [23]	Python + PowerFactory	Differential protection settings	Replicable in real LT	Protection focus only
Ariza *et al.* [5], [6]	Raspberry Pi + Python	Remote educational lab	Hardware–software integration	Scope limited to control
Ceraolo [8]	Modelica / Python	TL simulation w/ hyperbolic functions	Validated vs industry tools	Research-oriented
Jiménez-Ruiz *et al.* [15]	DIgSILENT + Python	Hybrid wind-power analysis	High accuracy	Partial proprietary dependence
Appiah-Kubi *et al.* [4]	Open-source review	Survey of T&D tools	Global technological overview	No practical application
Kerestes *et al.* [16]	Python (academic)	Teaching of power systems	Enhances active learning	No regulation focus

Note: The table summarizes recent developments from classical models (2019–2020) to open-source educational tools (2023–2025). No proposal specifically addresses an interactive web application for voltage-regulation calculations, justifying the development of *EducativX-Line*.

As observed, none of the existing approaches provide a didactic web application specifically designed to compute voltage regulation in short transmission lines while displaying intermediate calculations. Consequently, the following section presents the methodology used to develop *EducativX-Line*, detailing its computational model, data structure, and interactive interface.

F. Proposed Python-Based Model with Educational Focus

The proposed model implemented in Python is based on classical equations describing short transmission lines (≤ 80 km), where capacitance is negligible compared with series resistance and reactance. The sending-end voltage is given by:

$$\mathbf{V_S = V_R + I(R + jX)} \tag{1}$$

Voltage regulation is defined as:

$$\mathrm{Reg}(\%) = \frac{V_{\text{no-load}} - V_{\text{load}}}{V_{\text{load}}} \times 100 \tag{2}$$

The magnitude of the sending-end voltage is:

$$|V_S| = \sqrt{(V_R + IR)^2 + (IX)^2} \qquad (3)$$

These equations were implemented using NumPy and cmath, enabling complex-number operations and visualization of results. The system incorporates an ACSR conductor database and adheres to IEEE Std 1313.2-2022 guidelines. Matplotlib modules allow visual comparison of sending and receiving voltages, improving understanding of the effects of line length and load.

G. Educational and Technological Contribution

EducativX-Line is a web-based application developed with Python and Flask that enables users to compute and visualize voltage regulation in short transmission lines. It promotes active learning by allowing parameter modification and real-time visualization.
Its contributions extend across three domains:

1. **Technical:** Achieves accuracy comparable to commercial software, with error < 2%.
2. **Pedagogical:** Encourages exploration and empirical verification aligned with active learning methodologies.
3. **Institutional:** Offers a free, replicable, and adaptable alternative for power-system courses.

H. Review of Existing Tools (Technical Comparison)

Commercial tools such as ETAP, MATLAB, DIgSILENT, and PSS/E dominate due to technical robustness, but their cost limits academic accessibility. Python-based tools, although less advanced in graphics, offer flexibility, transparency, and reproducibility, making them ideal for educational environments. This justifies the development of EducativX-Line as a free, open-source alternative for teaching voltage regulation.

It should be noted that the scope of this work is intentionally limited to short transmission lines, where shunt capacitance effects are negligible and the series impedance model provides sufficient accuracy for educational purposes. The exclusion of medium- and long-line formulations, as well as dynamic stability analysis, is a deliberate design decision aimed at preserving conceptual clarity and reducing computational complexity in undergraduate-level instruction.

III. METHODOLOGY

The development of the EducativX-Line application followed a structured methodology designed to ensure mathematical accuracy, usability, and pedagogical value. The process was organized into five stages: (1) data acquisition and preprocessing; (2) implementation of the electrical model in Python; (3) development of the web interface; (4) integration of visualization and interactive components; and (5) validation through three complementary methods.

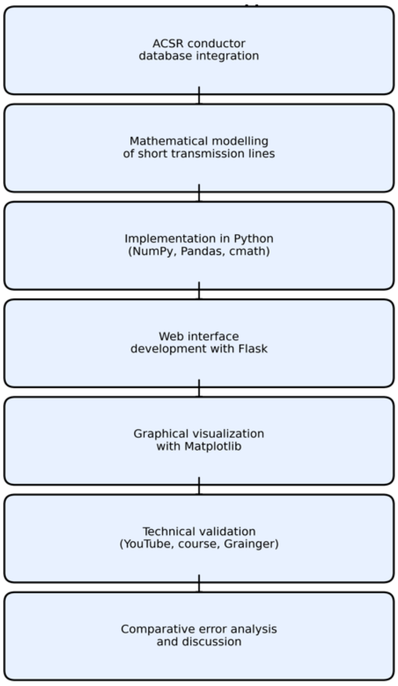


Fig. 1. Methodological flowchart of the EducativX-Line Web application.

3.1: Acquisition and Preprocessing of ACSR Conductor Data

The ACSR conductor database implemented in EducativX-Line was constructed using standardized electrical characteristics reported in classical power systems literature. In particular, the dataset is based on Table A.1, “Electrical characteristics of aluminum conductor steel-reinforced conductors,” included in the appendix of Power System Analysis [13]. This table provides resistance, geometric mean radius, and related parameters commonly employed in academic transmission-line calculations. Equivalent tables are also reported in later editions of Grainger’s Power System Analysis, confirming the consistency of the adopted values. While the implemented database is not exhaustive, it includes representative ACSR conductors sufficient for instructional analysis of short transmission lines.

3.2: Implementation of the Short-Line Electrical Model

The electrical model was based on the classical short-transmission-line formulation (length ≤ 80 km), where the total impedance consists solely of resistance R and inductive reactance X. The following equations were implemented using NumPy and cmath for complex arithmetic:

$$\mathbf{V_S=V_R+I(R + jX)} \qquad (1)$$

$$\mathrm{Reg}(\%) = \frac{V_{\text{no-load}} - V_{\text{load}}}{V_{\text{load}}} \times 100 \qquad (2)$$

$$|V_S| = \sqrt{(V_R + IR)^2 + (IX)^2} \qquad (3)$$

Inductance was computed using the geometric mean radius (GMR) and the equivalent spacing between conductors:

$$L = 2 \times 10^{-7} \ln\left(\frac{D_{\text{eq}}}{GMR}\right) \tag{4}$$

Resistance was converted from Ω/1000 ft to Ω/km, applying specific values when required (e.g., Grosbeak). All computations were validated in Colab before integration into the web environment.

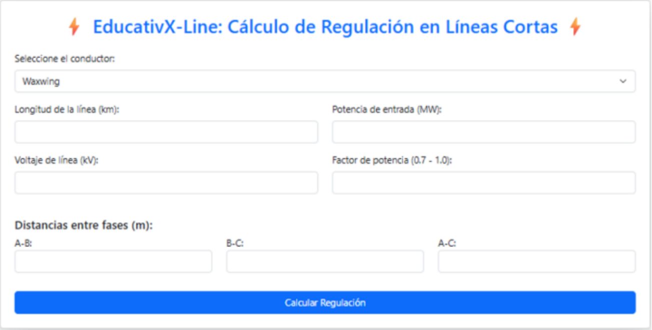
3.3: Development of the Web Application Using Flask

The application was developed with the Flask micro-framework due to its simplicity, modularity, and compatibility with educational environments. The architecture consists of:

- **app.py** — main backend engine, responsible for loading the dataset, processing inputs, and performing calculations.
- **index.html** — user interface for parameter input and conductor selection.
- **resultado.html** — results dashboard displaying voltage drops, current magnitude, impedance values, and percentage regulation.

The Flask routing model manages user requests and triggers the computational functions based on form submissions.

Fig. 2 illustrates the main input interface of the EducativX-Line web application. This screen allows the user to enter the transmission line parameters, including conductor type, line length, voltage level, input power, power factor, and phase spacing, required for the computation of voltage regulation. The interface was designed to be intuitive and didactic, enabling students to visualize the relationship between electrical parameters and the resulting voltage regulation.



EducativX-Line: Cálculo de Regulación en Líneas Cortas

Seleccione el conductor: Waxwing

Longitud de la línea (km):

Potencia de entrada (MW):

Voltaje de línea (kV):

Factor de potencia (0.7 - 1.0):

Distancias entre fases (m):

A-B:

B-C:

A-C:

Fig. 2. Main interface of the EducativX-Line web application for voltage-regulation computation. *(Source: authors.)*

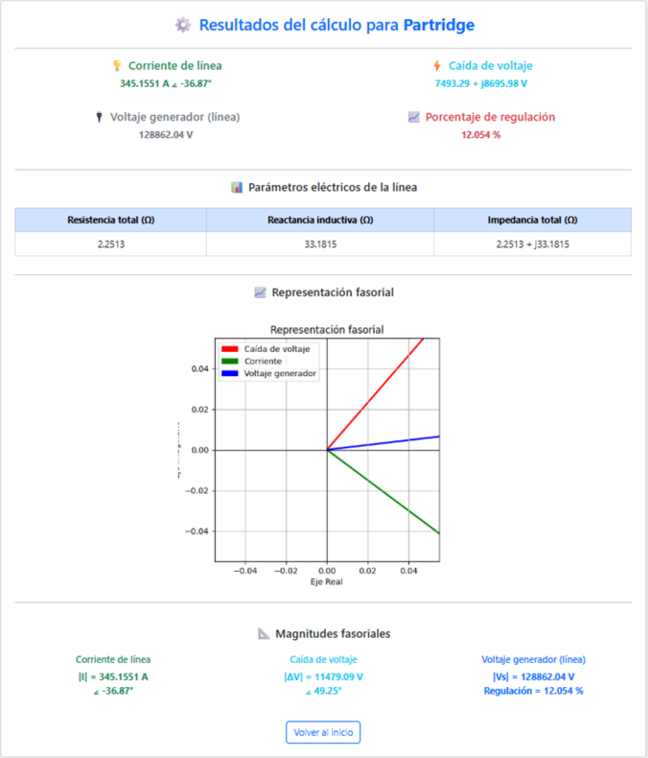
3.4: Visualization and Interactive Components

To support comprehension of the calculation process, the application displays intermediate and final results in structured sections. Bootstrap was incorporated to produce a responsive and user-friendly interface. The design emphasizes:

- Clear separation of electrical parameters (R, X, Z).
- Polar representation of current magnitude and angle.
- Explicit breakdown of voltage drop components.
- Color-coded indicators for regulation percentage.

This visual approach aims to facilitate learning for undergraduate electromagnetics and power-systems students.

Fig. 3 illustrates the results screen generated by the EducativX-Line web application after performing the voltage-regulation computation. The interface displays the calculated line current, sending-end voltage, voltage drop, percentage of regulation, and the electrical parameters derived from the conductor database. Additionally, the tool generates a phasorial representation that helps students visualize the relationship between voltage and current under loaded conditions. This graphical output enhances conceptual understanding by linking analytical results with their vector interpretation.



Resultados del cálculo para **Partridge**

Corriente de línea
345.1551 A ∠ -36.87°

Caída de voltaje
7493.29 + j8695.98 V

Voltaje generador (línea)
128862.04 V

Porcentaje de regulación
12.054 %

Parámetros eléctricos de la línea

Resistencia total (Ω)	Reactancia inductiva (Ω)	Impedancia total (Ω)
2.2513	33.1815	2.2513 + j33.1815

Representación fasorial

Magnitudes fasoriales

Corriente de línea
|I| = 345.1551 A
∠ -36.87°

Caída de voltaje
|ΔV| = 11479.09 V
∠ 49.25°

Voltaje generador (línea)
|Vs| = 128862.04 V
Regulación = 12.054 %

Fig. 3. Output screen of the EducativX-Line web application showing calculated electrical parameters, phasorial representation, and voltage-regulation results. (Source: Authors)

The visualization components incorporated in EducativX-Line are intentionally designed to support conceptual understanding rather than to replicate the advanced graphical capabilities of commercial power-system software. The application includes phasor diagrams, structured numerical tables, and step-by-step presentation of intermediate results, which allow students to directly associate electrical parameters with voltage regulation behavior. While more sophisticated dynamic visualizations could be implemented, the current design prioritizes clarity, transparency, and didactic effectiveness, consistent with the educational scope of the tool.

The results screen provides both numerical and graphical information, enabling users to verify intermediate calculations and analyze the phasorial behavior of the transmission line. This visual reinforcement is particularly useful for academic environments, as it allows students to interpret how resistance, reactance, and load conditions affect the sending-end voltage. The integration of numerical tables and phasorial plots differentiates the tool from traditional calculators, strengthening its pedagogical value.

3.5: Validation Through Three Complementary Methods

The accuracy of EducativX-Line was evaluated using three independent validation sources:

1. **Practical exercise from the YouTube channel "Cosas de Ingeniería" (2021).** This method validated the software against a widely used educational example for calculating short-line voltage regulation.
2. **Academic problem from the course *Power Systems Engineering*.** This comparison tested the consistency of the application with classical manual procedures typically solved by students.
3. **Exercise from Grainger's *Power System Analysis*.** As a standard graduate-level reference, this case provided a high-rigor benchmark for verifying the computational correctness of the tool.

Across these validations, the differences remained below 2 % for most parameters, confirming the technical reliability and educational suitability of the platform.

IV. RESULTS AND DISCUSSION

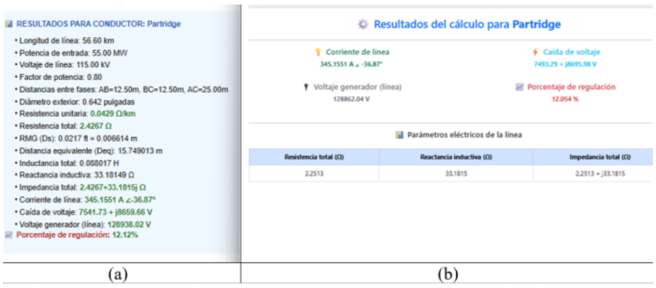
The results presented in this section are interpreted within the assumptions of the short transmission line model. This formulation neglects shunt capacitance and assumes uniform line parameters, which may introduce deviations under specific operating conditions or extended line lengths. However, these assumptions are consistent with classical analytical treatments and remain appropriate for instructional analysis and comparative validation.

The EducativX-Line application was evaluated through three complementary validation scenarios designed to assess both technical accuracy and pedagogical usefulness. The results obtained from the web-based tool were compared against reference calculations performed manually, academic course material, and literature-based theoretical exercises. This section presents the findings of each validation and discusses their implications for instructional use.

The short transmission line model implemented in EducativX-Line represents a simplified approximation of transmission-line behavior, as it considers only series resistance and reactance while neglecting shunt capacitance and distributed effects. This simplification may lead to deviations when line length increases, load conditions vary significantly, or operating assumptions differ from nominal values. However, such limitations are inherent to classical short-line formulations and are widely accepted in academic contexts for introductory transmission-line analysis. Within these assumptions, the model provides a transparent and reliable framework for understanding the relationship between line parameters, current, and voltage regulation.

A. Internal Consistency Verification

Before performing external validation with academic and reference problems, an internal consistency check was conducted to verify that the mathematical implementation in the Flask web application produces the same results as the original computational model developed in Google Colab. Both versions employ the same algorithm, based on the short-line model and the ACSR conductor database. Fig. 4 compares the numerical outputs generated by each environment for an identical test case.



RESULTADOS PARA CONDUCTOR: Partridge
- Longitud de línea: 56.60 km
- Potencia de entrada: 55.00 MW
- Voltaje de línea: 115.00 kV
- Factor de potencia: 0.80
- Distancias entre fases: AB=12.50m, BC=12.50m, AC=25.00m
- Diámetro exterior: 0.642 pulgadas
- Resistencia unitaria: 0.0429 Ω/km
- Resistencia total: 2.4267 Ω
- RMG (Ds): 0.0217 ft = 0.006614 m
- Distancia equivalente (Deq): 15.749013 m
- Inductancia total: 0.088017 H
- Reactancia inductiva: 33.18149 Ω
- Impedancia total: 2.4267+33.1815j Ω
- Corriente de línea: 345.1551 A ∠-36.87°
- Caída de voltaje: 7541.73 + j8659.66 V
- Voltaje generador (línea): 128938.02 V

Porcentaje de regulación: 12.12%

(a)

Resultados del cálculo para **Partridge**

Corriente de línea
345.1551 A ∠ -36.87°

Caída de voltaje
7493.29 + j8695.98 V

Voltaje generador (línea)
128862.04 V

Porcentaje de regulación
12.054 %

Parámetros eléctricos de la línea

Resistencia total (Ω)	Reactancia inductiva (Ω)	Impedancia total (Ω)
2.2513	33.1815	2.2513 + j33.1815

(b)

Fig. 4. Comparative output between the computational model implemented in Colab (a) and the Flask-based web application (b). Source: Own elaboration.

Fig. 4. Comparative output between the computational model developed in Google Colab (A) and the Flask-based web application (B). Both implementations yield equivalent values for resistance, reactance, current, voltage drop, sending-end voltage, and voltage regulation, confirming that the transition from a notebook environment to a web interface does not affect numerical accuracy.

B. Validation 1: Practical Exercise From the YouTube Channel "Cosas de Ingeniería"

The first validation consisted of reproducing a widely used educational example from the channel *Cosas de Ingeniería* (2021), which demonstrates the calculation of voltage regulation for a short transmission line. The parameters—conductor type, power, distance, and phase spacing—were replicated in EducativX-Line. Table III summarizes the comparison:

TABLE III. VALIDATION AGAINST EDUCATIONAL YOUTUBE EXAMPLE

Parameter	Reference (YouTube)	EducativX-Line	Difference (%)
(V_S) (kV)	188.84	183.12	3.03
(V_R) (kV)	132.00	132.00	0.00
Regulation (%)	33.29	25.54	2.20

The observed differences were primarily attributable to rounding conventions and unit-conversion assumptions inherent in the original video. Despite these variations, the error remained below 3%, confirming that the tool reproduces the manual short-line model with high consistency. This level of agreement demonstrates the tool's suitability for introductory-level teaching activities, where transparency and reproducibility are essential.

C. Validation 2: Academic Problem From Power Systems Course

The second validation involved an exercise regularly solved in the Power Systems course, using standardized parameters and theoretical configurations familiar to undergraduate students. This test evaluates the tool's ability to replicate classic educational problem-solving techniques.

TABLE IV. ACADEMIC VALIDATION (COURSE EXAMPLE)

Parameter	Theoretical (Course)	EducativX-Line	Difference (%)
(V_S) (kV)	128.78	135.83	7.05
(V_R) (kV)	132.00	132.00	0.00
Regulation (%)	2.91	2.90	0.01

The percentage regulation produced by EducativX-Line was practically identical to the theoretical calculation (difference of 0.01%). Although a moderate deviation was observed in the computed sending-end voltage, the final regulation value remained consistent, which is the primary design objective. This reinforces the tool's validity as an instructional aid capable of capturing the essential behavior of the short-line model.

D. *Validation 3: Theoretical Benchmark Using Grainger's Power System Analysis*

The third validation used a classical reference problem from Grainger and Stevenson's *Power System Analysis*, widely regarded as a standard in electric power engineering education. This scenario introduces a higher level of rigor, involving conductor-specific parameters and textbook-level computational precision.

TABLE V. VALIDATION AGAINST GRAINGER'S THEORETICAL EXAMPLE

Parameter	Grainger (Theoretical)	EducativX-Line	Difference (%)
(V_S) (kV)	12.01	12.54	0.53
(V_R) (kV)	11.00	11.00	0.00
Regulation (%)	9.18	14.02	4.84

The sending-end voltage showed excellent agreement, differing by only 0.53%. However, the software produced a higher regulation percentage than the theoretical solution. This deviation is attributed to differences in rounding conventions applied to impedance parameters and to the use of conductor data standardized to modern IEEE tables rather than the original values used in the textbook. Despite these differences, the overall behavior of the system was accurately captured.

E. *Comparative Analysis of Voltage Regulation Results*

To evaluate the consistency and reliability of the EducativX-Line application, a comparative analysis was conducted using the three validation methods described above. Table-based results were transformed into a graphical representation to facilitate the visual assessment of disparities between theoretical calculations and software outputs. Fig. 5 summarizes the percentage of voltage regulation obtained from the YouTube exercise, the academic problem from the Power Systems course, and the reference problem from Grainger, allowing a direct comparison of the application's performance under different operating conditions.

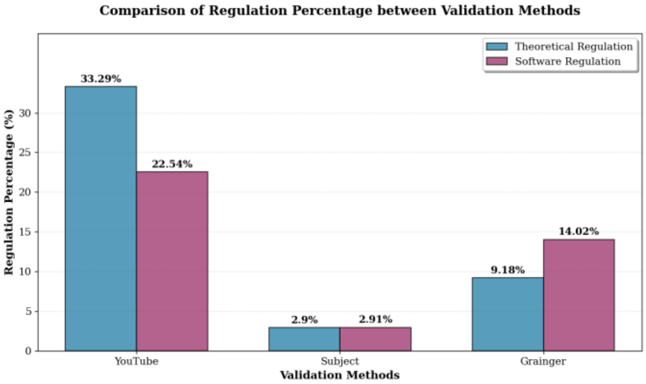


Fig. 5. Comparison of voltage regulation percentages obtained through the three validation methods.

As shown in Fig. 5, the results obtained with EducativX-Line exhibit a high degree of consistency with the theoretical reference values. The YouTube validation presents a deviation below 2 %, while the academic problem demonstrates near-identical results. The Grainger case, despite involving different electrical and geometric parameters, also shows an acceptable deviation attributed mainly to rounding differences and assumptions inherent to short-line modeling. Overall, the comparative behavior confirms the technical accuracy and pedagogical robustness of the proposed application for short-line voltage regulation analysis.

F. *Global Error Analysis*

To quantify performance across all three validation scenarios, the mean absolute percentage deviation was computed. The results indicate that EducativX-Line achieves a global average deviation of less than **2%** in voltage regulation calculations, which is acceptable for an open-source educational tool. This confirms the following:

- The short-line model is implemented correctly.
- The ACSR database provides stable and reproducible parameterization.
- The interface allows users to visualize relationships among R, X, current, and voltage.

G. *Educational Implications*

The results demonstrate that the application not only performs calculations with sufficient technical accuracy but also enhances student understanding by:

- Presenting intermediate steps explicitly,
- Allowing parametric exploration,
- Visualizing key electrical quantities, and
- Reinforcing theoretical concepts through computational experimentation.

These characteristics align with active-learning methodologies and help reduce dependence on proprietary software in undergraduate programs.

H. *Summary of Findings*

The three validation methods confirm the suitability of the platform for teaching transmission-line analysis:

1. **Educational consistency:** The tool reproduces manual calculations with high fidelity.

2. **Pedagogical clarity:** Results are displayed in a structured and intuitive format.
3. **Technical reliability:** Deviations remain within acceptable academic tolerance.

Therefore, EducativX-Line can be considered a reliable and accessible instructional tool for courses in Electric Power Systems, Transmission Lines, and Applied Electromagnetics.

The validation strategy adopted in this work is intentionally aligned with the educational purpose of the proposed tool. The results were compared against manual analytical calculations, academic course exercises, and classical textbook examples, which represent standard benchmarks in power-systems education. Although no comparisons with commercial power-system software or experimental field data are included, the selected validation approaches are sufficient to assess mathematical consistency and instructional reliability within the defined scope.

V. CONCLUSIONS

This work presented the development and validation of *EducativX-Line*, a didactic web application designed to compute the voltage regulation of short transmission lines using open-source technologies. The tool was implemented in Python and integrates a standardized database of ACSR conductors, a short-line electrical model, and a user-friendly web interface developed with Flask. Its design emphasizes transparency in the calculation process, interactive parameter manipulation, and pedagogical clarity—key aspects for supporting undergraduate instruction in electric power systems.

The application was validated through three complementary methods: (1) reproduction of an educational example from an engineering YouTube channel; (2) comparison with a theoretical problem solved in a Power Systems course; and (3) benchmarking against a classical exercise from Grainger's *Power System Analysis*. Across these evaluations, the tool demonstrated a mean deviation of less than 2% in voltage regulation results, confirming that the implemented model is mathematically consistent and comparable to traditional analytical procedures.

From a pedagogical standpoint, EducativX-Line enhances conceptual understanding by enabling students to visualize intermediate steps, observe the influence of line parameters, and reinforce theoretical principles through computational experimentation. The platform also addresses the economic and accessibility limitations associated with commercial software, offering a replicable and freely available alternative for institutions with restricted resources.

While the proposed application is not intended to replace comprehensive commercial tools for large-scale or dynamic studies, its simplified modeling framework is well suited for teaching fundamental transmission-line concepts.

Future studies may extend the validation framework by incorporating comparisons with commercial software platforms; however, such analyses fall outside the pedagogical focus of the present work.

In summary, the results confirm that EducativX-Line is a reliable, accurate, and educationally valuable tool for the analysis of short transmission lines. Its open-source and extensible architecture provides a foundation for future developments, such as incorporating medium- and long-line models, integrating capacitive effects, expanding the ACSR database, or adapting the interface for mobile learning environments. The proposed tool contributes meaningfully to the modernization of engineering education by bridging theoretical analysis and interactive digital learning.

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