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DigSILENT PowerFactory Software's Potential for Analyzing Electrical Power Systems/Potencial do Software DigSILENT PowerFactory para a Análise de Sistemas Elétricos de Potência

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Trabalho de Conclusão de Curso apresentado ao curso de Engenharia Elétrica, Escola de Engenharia Elétrica, Mecânica e de Computação (EMC), da Universidade Federal de Goiás (UFG), como requisito para obtenção do título de bacharel em Engenharia Elétrica.
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ATA DE DEFESA DE TRABALHO DE CONCLUSÃO DE CURSO

Aos trinta dias do mês de junho do ano de 2025, iniciou-se a sessão pública de defesa do Trabalho de Conclusão de Curso (TCC) intitulado "**DigSILENT PowerFactory Software's Potential for Analyzing Electrical Power Systems/Potencial do Software DigSILENT PowerFactory para a Análise de Sistemas Elétricos de Potência**", de autoria de Anna Beatriz Fernandes Amaral, do curso de Engenharia Elétrica, da Escola de Engenharia Elétrica, Mecânica e de Computação da UFG. Os trabalhos foram instalados pela Profa. Dra. Lina Paola Garces Negrete - Orientadora (EMC/UFG) com a participação dos demais membros da Banca Examinadora: Prof. Dr. Gelson Antônio Andrêa Brigatto (EMC/UFG) e Prof. Dr. Igor Kopcak (EMC/UFG). Após a apresentação, a banca examinadora realizou a arguição do(a) estudante. Posteriormente, de forma reservada, a Banca Examinadora atribuiu a nota final de 9,5 (nove vírgula cinco) , tendo sido o TCC considerado APROVADO.

Proclamados os resultados, os trabalhos foram encerrados e, para constar, lavrou-se a presente ata que segue assinada pelos Membros da Banca Examinadora.

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DigSILENT PowerFactory Software's Potential for Analyzing Electrical Power Systems

Anna Beatriz Fernandes Amaral and Lina Paola Garcés Negrete (Adviser)
Escola de Engenharia Elétrica, Mecânica e de Computação - UFG

***Resumo*—Os sistemas elétricos de potência modernos exigem análises rigorosas para atender critérios operativos de estabilidade, eficiência e conformidade com os padrões operacionais. Esta pesquisa investiga a análise de fluxo de carga em regime permanente utilizando o software DigSILENT PowerFactory, empregando três estudos de caso para simular o fluxo de potência através do método Newton-Raphson. Os principais resultados avaliados correspondem às magnitudes de tensão, ângulos de fase e a distribuição de potência ativa e reativa, identificando desvios de tensão em relação aos padrões de tensão do American National Standards Institute (ANSI C84.1-2020). Testes realizados nos sistemas IEEE 14-bus e Sistema Elétrico Nacio-nal Interligado do Peru (SEIN), permitiram a obtenção de resultados que demonstram convergência eficiente em poucas iterações, validando a robustez do algoritmo para redes de pequeno e grande porte, além de ter sido confirmada sua precisão computacional por meio de análise comparativa com simulações no MATLAB. As ferramentas integradas de visualização e relatórios automatizados do software destacam sua utilidade para análise de perfis de tensão e de fluxos de potência, enquanto enfatizam a importância de estratégias de regulação de tensão e gerenciamento de potência reativa para satisfazer restrições operacionais. Além do estudo teórico, a pesquisa estendeu-se para a simulação do Sistema Elétrico Nacional Interligado do Peru (SEIN), demonstrando a capacidade do PowerFactory para simulações em larga escala que, neste caso, revelou desafios críticos, como sobretensões em barras específicas e perdas na transmissão, reforçando a necessidade de otimizações no planejamento e operação de redes elétricas complexas.**

***Palavras Chave*—Fluxo de carga, Método de Newton-Raphson, Normas ANSI, Regulação de tensão, Sistemas Elétricos de Potência.**

Modern power systems require rigorous analysis to meet operational criteria of stability, efficiency, and compliance with operational standards. This research investigates steady-state load flow analysis using DigSILENT PowerFactory software, employing two case studies to simulate power flow through the Newton-Raphson method. The main results evaluated correspond to voltage magnitudes, phase angles, and active/reactive power distribution, identifying voltage deviations from the American National Standards Institute (ANSI C84.1-2020) voltage standards. Tests performed on the IEEE 14-bus system and Peru's National Interconnected Electric System (SEIN) yielded results demonstrating efficient convergence in few iterations, validating the algorithm's robustness for both small and large-scale networks, while its computational accuracy was confirmed through comparative analysis with MATLAB simulations. The software's integrated visualization tools and automated reporting features highlight its usefulness for analyzing voltage profiles and power flows, while emphasizing the importance of voltage regulation strategies and reactive power management to fulfill operational constraints. Beyond the theoretical study, the research extended to simulating Peru's National Interconnected Electric System (SEIN), demonstrating PowerFactory's capability for large-scale simulations that, in this case, revealed critical challenges such as overvoltages at specific buses and transmission losses, reinforcing the need for optimizations in planning and operating complex power networks.

***Index Terms*—ANSI standards, Electrical power systems, Load flow, Newton-Raphson method, Voltage regulation.**

I. INTRODUCTION

Modern electrical power systems require rigorous analysis to ensure stability, efficiency, and compliance with operational standards. Load flow studies, a cornerstone of power system engineering, provide critical insights into steady-state behavior by calculating voltage magnitudes, phase angles, and power flows across networks [1]. These analyses are indispensable for both operational planning—such as devising control strategies during emergencies—and long-term infrastructure development, where future network expansions must be evaluated against existing configurations [2].

The growing complexity of power systems has necessitated advanced computational tools capable of integrating diverse analysis functions. *DigSILENT PowerFactory* has emerged as a leading software solution, combining robust algorithms like the Newton-Raphson method with user-friendly interfaces for modeling AC/DC systems [3]. Its ability to simulate meshed networks and optimize power flow under varying conditions makes it a vital tool for addressing challenges such as voltage regulation, grid losses, and equipment compatibility [1]

Voltage regulation remains a critical concern, with standards, like *American National Standards Institute* (ANSI C84.1-2020), for Electric Power Systems and Equipment operating in 60HZ frequency, defining permissible ranges (e.g., 90%–110% of nominal voltage for medium-voltage systems) to safeguard equipment and ensure reliable operation [4]. PowerFactory's precision in identifying deviations, such as overvoltage scenarios, aligns with these standards, enabling engineers to implement corrective measures like tap adjustments or reactive compensation.

This study evaluates *DigSILENT PowerFactory*'s capabilities through a detailed case study of a 14-bus system with balanced and unbalanced loads, utilizing its power flow analysis tools to assess voltage profiles, grid losses, and generator performance. Comparative validation with MATLAB simulations further underscores the software's computational reliability [3]. Following the 14-bus system evaluation, the study extends the analysis to Peru's National Interconnected Electric System (SEIN), demonstrating *DigSILENT PowerFactory*'s robust capacity for large-scale power system simulations. By bridging theoretical rigor with practical application, this work highlights PowerFactory's role in advancing power system analysis, while identifying opportunities for future research in renewable energy integration.

II. FUNDAMENTAL THEORY

A. Power flow

Power flow calculation is a steady-state analysis of electrical power system to calculate the voltage magnitude and angle at all busbars and power flow in all branches. Load flow analysis is an essential tool in the process of planning, designing, and operation of power systems under different operating conditions and equipment configuration. Based on load flow calculations, different results can be predicted, such as line losses, transformer loading, power exchange between two or more grids, and required voltage control range of transformers and generators[1].

Load flow analysis is conducted for two main purposes: operation and planning. On the one hand, operation may refer to know the state of the system to establish control strategies during emergency situations, or perform economic and security analysis.On the other hand, when speaking about planning, it may refer to know how future expansions of the network will affect the existing infrastructure, among other aspects[2].

The Power flow analysis function of PowerFactory allows the accurate representation of any combination of meshed 1-, 2-, and 3-phase AC and/or DC systems. PowerFactory uses the Newton-Raphson method as its non-linear equation solver. For large transmission systems, especially when heavily loaded, the standard Newton-Raphson algorithm using the "Power Equations" formulation usually converges best[3].

The end objective of the load-fow study is not always to arrive at hard, numerical performance parameters. Often the objective is to gain insight into how the system performs over a range of operating conditions[5].

B. Voltage Range

ANSI C84.1-2020 establishes two critical voltage ranges for power systems: Range A (normal operating conditions) and Range B (temporary variations). For any nominal system voltage, actual voltages across the network must remain within the tabulated limits to ensure equipment compatibility. These ranges specifically govern sustained voltage levels, excluding momentary excursions from switching transients or motor starting. The standard mandates coordination between system design and equipment specifications to maintain voltages within both service (supply) and utilization (equipment) tolerances throughout normal operation.

For medium-voltage systems (2.4–13.8 kV), ANSI C84.1 Range B utilization limits (90%–110% of nominal) are derived from standard motor voltage tolerances, with minor deviations accounting for distribution line drops[4].

Procedimentos de Distribuição de Energia Elétrica no Sistema Elétrico Nacional (PRODIST), translated as Electricity Distribution Procedures in the National Electric System, is a document consisting of 11 modules that regulate and standardize technical activities related to the operation and performance of electrical energy systems. Module 8 establishes the procedures concerning the quality of electricity supply in distribution, covering product quality, service quality, and commercial quality. Among these procedures is the calculation of Voltage Unbalance, a phenomenon characterized by any difference in the amplitudes between the three phase voltages of a three-phase system or by an angular deviation from the 120° electrical difference between the phase voltages of the same system.

The Voltage Unbalance to be compared with the limits is VUF95%, as shown in Table 21, which represents the Voltage Unbalance Factor (VUF%) value. [6]

C. Previous work with DigSILENT PowerFactory

The operation and planning of complex energy systems requires in-depth engineering studies to understand the possible causes of threats to targeted steady-state and dynamic performance criteria, as well as to devise prospective solutions, from both operational and control viewpoints. In view of this, sophisticated software packages, such as DIgSILENT PowerFactory, have emerged to integrate state-of-the-art scientific approaches, which assist power engineers in both academic and industry-oriented research endeavors[1].

III. DIGSILENT POWERFACTORY

The calculation program PowerFactory from DigSILENT, is a computer-aided engineering tool for the analysis of transmission, distribution, and industrial electrical power systems. It has been designed as an advanced integrated and interactive software package dedicated to electrical power system and control analysis in order to achieve the main objectives of planning and operation optimisation.

"DigSILENT" is an acronym for "Digital SImuLation of Electrical NeTworks". DigSILENT Version 7 was the world's first power system analysis software with an integrated graphical single-line interface. That interactive single-line diagram included drawing functions, editing capabilities and all relevant static and dynamic calculation features [3].

It should be noted that this study utilized an academic license of DigSILENT PowerFactory, as the software requires formal licensing for all professional and research applications.

A. Software Introduction

The program has an extensive list of simulation functions, where the following can be highlighted:

- Load Flow Analysis;
- Short-Circuit Analysis;
- Contingency Analysis;
- Quasi-Dynamic simulation;
- Protection Analysis;
- Reliability Analysis;
- Power Quality and Harmonics Analysis;
- Cable Analysis;

- Transmission Network Tools;
- Distribution Network Tools;
- Optimal Power Flow;
- Economic analysis Tools; and
- State Estimation.

Power Factory is designed to be used and operated in a graphical environment. Data is entered by drawing the network elements, using the drawing tool illustrated in Figure 1, and then editing and assigning data to these objects[3].

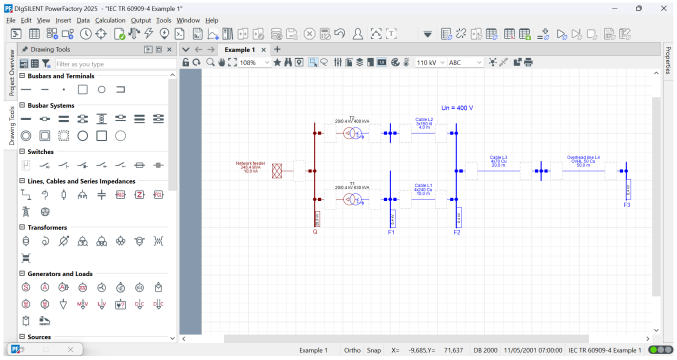


Figure 1: PowerFactory Graphical User Interface (GUI). Source: DigSILENT GmbH. (2025)

To begin, a new project must be created in the software by navigating to File > New > Project. This will open an empty grid, labeled "Grid" by default, with a nominal frequency of 50 Hz (both settings can be modified). Once the project is created, enable the Drawing Tools Bar by clicking the padlock symbol. This allows the user to add electrical components—such as buses (recommended as the first element), transformers, lines, loads, synchronous machines, external grids, and shunts—by dragging their symbols onto the grid.

After placing the desired elements, the user must assign a 'type' to each component. These types can be selected from the DigSILENT library or custom-defined by the user, thereby specifying the nominal characteristics of the elements. After defining the types of all elements and completing the network, a simulation can be perform. This is done by creating study cases and running different scenarios to evaluate the network's behavior under various conditions.

Rather than building a new project from scratch, DigSILENT provides multiple example projects that can be used and modified. These templates include predefined elements with already configured types, from the PowerFactory library, the following examples can be highlighted:

- LV Distribution Network;
- MV Distribution Network;
- Transmission Network;
- Industrial Network;
- 9 Bus System;
- 14 Bus System;
- 39 Bus System;
- CIGRE 604 HVDC-MMC;
- IEC 60909; and
- IEEE Std.399-1997.

For this paper, simulations were conducted using the "14 Bus System" as a case study to evaluate PowerFactory's reliability when applied to real-world energy systems.

IV. TEST AND RESULTS

A. Case Study: 14 Bus System

The power flow analysis was performed using a 14 Bus System provided by the software. The network consists of 14 buses, 5 generators, 11 loads, 16 lines, 5 transformers and one shunt. From the 5 transformers, 3 of them are used to represent one single 3-winding transformer [7].

The network is shown, schematically, in Figure 2.

The network combines data from [8] with additional nominal values:

- Bus 1 - Bus 5: 132 kV;
- Bus 6, Bus 9 - Bus 14: 33 kV;
- Bus 7: 1 kV; and
- Bus 8: 11 kV.

The complete system parameters, from [8] and [7], are presented in Tables 1 to 6:

- Table 1 present the load power demands (active P and reactive Q) at each bus;
- Tables 2–3 specify generator operating points, including slack bus settings, PV bus voltage controls, and capability limits (N.D stands for no data) ;
- Table 4 details transformer parameters, including winding configurations, tap ratios, and short-circuit reactances;
- While tables 5–6 provide transmission line impedance characteristics (R, X, and charging susceptance B) in both per-unit and physical units.

Table 1: Load demand

Load	Bus	P in MW	Q in Mvar
Load_0002	Bus_0002	21.7	12.7
Load_0003	Bus_0003	94.2	19.0
Load_0004	Bus_0004	47.8	-3.9
Load_0005	Bus_0005	7.6	1.6
Load_0006	Bus_0006	11.2	7.5
Load_0009	Bus_0009	29.5	16.6
Load_0010	Bus_0010	9.0	5.8
Load_0011	Bus_0011	3.5	1.8
Load_0012	Bus_0012	6.1	1.6
Load_0013	Bus_0013	13.5	5.8
Load_0014	Bus_0014	14.9	5.0

Source: DigSILENT GmbH. (2025)

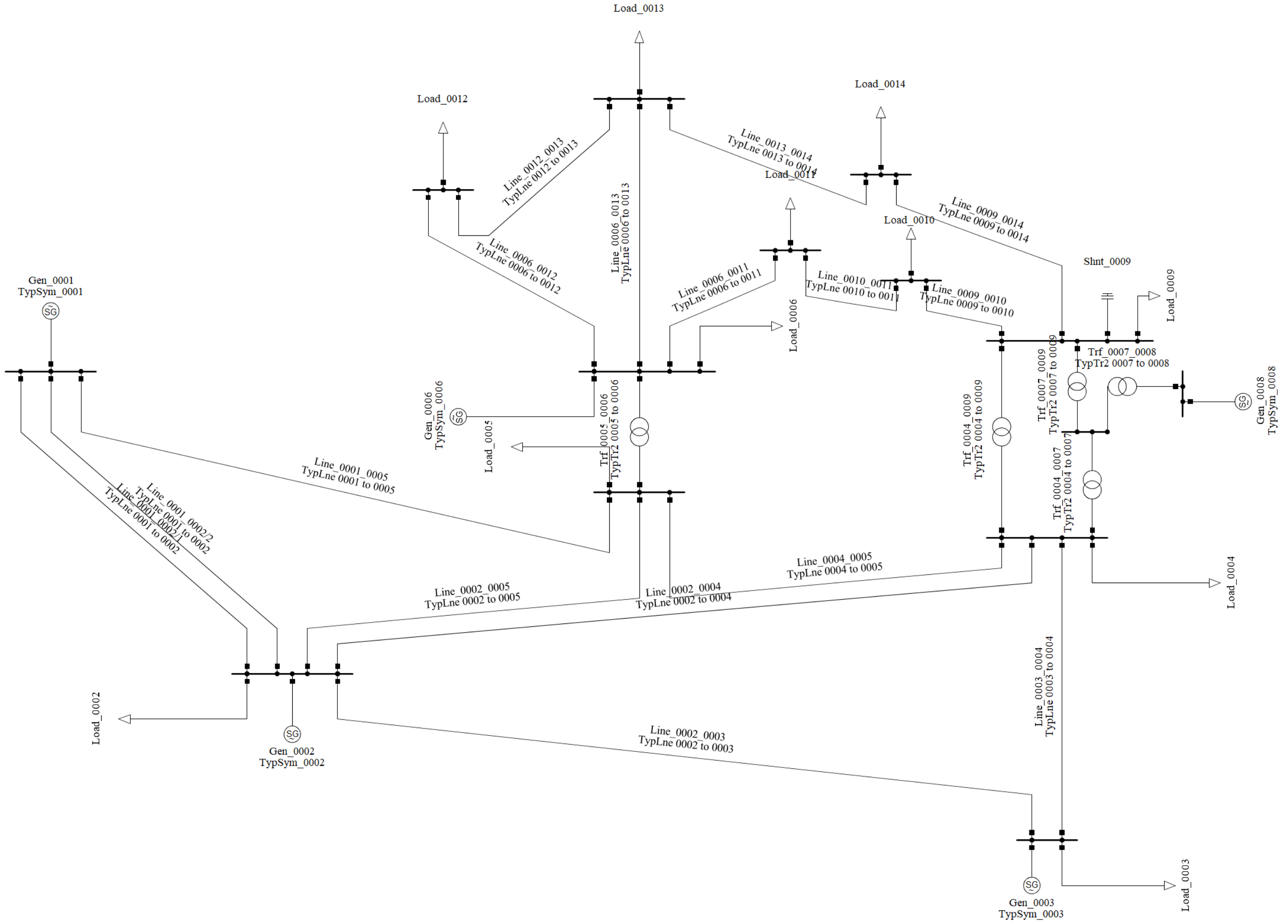


Figure 2: 14 Bus network diagram. Source: DigSILENT. (2025)

Table 2: Generator dispatch

Generator	Bus	P in MW	Q in Mvar
Gen_0001	Bus_0001	N.D	N.D
Gen_0002	Bus_0002	40.0	N.D
Gen_0003	Bus_0003	0.0	N.D
Gen_0006	Bus_0006	0.0	N.D
Gen_0008	Bus_0008	0.0	N.D

Source: DigSILENT GmbH. (2025)

Table 3: Generator controller settings

Generator	Bus Type	Voltage in P.U.	Min Capability in MVA	Max Capability in MVA
Gen_0001	Slack	1.060	N.D	N.D
Gen_0002	PV	1.045	-40.0	50.0
Gen_0003	PV	1.010	0.0	40.0
Gen_0006	PV	1.070	-6.0	24.0
Gen_0008	PV	1.090	-6.0	24.0

Source: DigSILENT GmbH. (2025)

Table 4: Data of Transformers given in [8] based on 100MVA with rated voltages added in the PowerFactory model

Transformer	From_To Bus	Ur HV in kV	Ur LV in kV	x in p.u.	Transformer final turns ratio
Trf_0004_0007	4_7	132.0	1.0	0.20912	0.978
Trf_0004_0009	4_9	132.0	33.0	0.55618	0.969
Trf_0005_0006	5_6	132.0	33.0	0.25202	0.932
Trf_0007_0008	7_8	11.0	1.0	0.17615	0.000
Trf_0007_0009	7_9	33.0	1.0	0.11001	0.000

Source: DigSILENT GmbH. (2025)

Table 5: Data of Lines given in [8] based on 100 MVA

From_to Bus	r in p.u.	x in p.u.	$q_c/2$ in p.u.	B in p.u.
1_2	0.01938	0.05917	0.0264	0.0528
1_5	0.05403	0.22304	0.0246	0.0492
2_3	0.04699	0.19797	0.0219	0.0438
2_4	0.05811	0.17632	0.0187	0.0374
2_5	0.05695	0.17388	0.0170	0.0340
3_4	0.06701	0.17103	0.0173	0.0346
4_5	0.01335	0.04211	0.0064	0.0128
6_11	0.09498	0.19890	0.0000	0.0000
6_12	0.12291	0.25581	0.0000	0.0000
6_13	0.06615	0.13027	0.0000	0.0000
9_10	0.03181	0.08450	0.0000	0.0000
9_14	0.12711	0.27038	0.0000	0.0000
10_11	0.08205	0.19207	0.0000	0.0000
12_13	0.22092	0.19988	0.0000	0.0000
13_14	0.17093	0.34802	0.0000	0.0000

Source: DigSILENT GmbH. (2025)

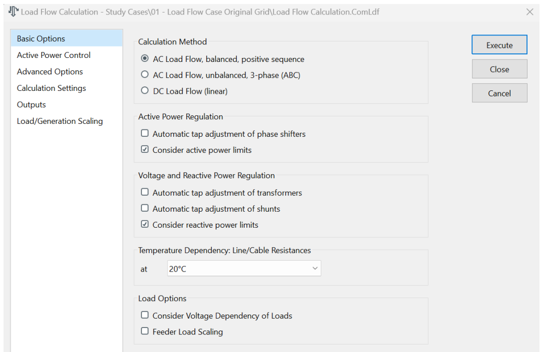
Table 6: Data of Lines in the PowerFactory model

Line	From_To Bus	Un in kV	R in Ω	X in ω	B in μS
0001_0002/1	1_2	132.0	6.75354	20.61956	151.515
0001_0002/2	1_2	132.0	6.75354	20.61956	151.515
0001_0005	1_5	132.0	9.41419	38.862499	282.369
0002_0003	2_3	132.0	8.18754	34.49428	251.377
0002_0004	2_4	132.0	10.12509	30.72200	214.646
0002_0005	2_5	132.0	9.92297	30.29685	195.133
0003_0004	3_4	132.0	11.67582	29.80027	198.577
0004_0005	4_5	132.0	2.32610	7.33725	73.462
0006_0011	6_11	33.0	1.03433	2.16602	0.000
0006_0012	6_12	33.0	1.338490	2.785771	0.000
0006_0013	6_13	33.0	0.720374	1.418640	0.000
0009_0010	9_10	33.0	0.346411	0.920205	0.000
0009_0014	9_14	33.0	1.384228	2.944439	0.000
0010_0011	10_11	33.0	0.893524	2.091643	0.000
0012_0013	12_13	33.0	2.405819	2.176693	0.000
0013_0014	13_14	33.0	1.861428	3.789938	0.000

Source: DigSILENT GmbH. (2025)

1) First scenario: Balanced system

The load flow analysis was performed using the initial system configuration by executing the simulation (Ctrl+F10) and confirming execution through the calculation dialog interface, show in the Figure[3].



Calculation Method
● AC Load Flow, balanced, positive sequence
○ AC Load Flow, unbalanced, 3-phase (ABC)
○ DC Load Flow (linear)

Active Power Regulation
☐ Automatic tap adjustment of phase shifters
☑ Consider active power limits

Voltage and Reactive Power Regulation
☐ Automatic tap adjustment of transformers
☐ Automatic tap adjustment of shunts
☑ Consider reactive power limits

Temperature Dependency: Line/Cable Resistances
at 20°C

Load Options
☐ Consider Voltage Dependency of Loads
☐ Feeder Load Scaling

Figure 3: Load Flow calculation Interface. Source: Author. (2025)

The software performed a classical Newton-Raphson algorithm using power equations that converged in 3 iterations. The simulation results are shown in Table [7], which presents the bus voltages comparing nominal and power flow values, and in Table [9], which shows the active and reactive power at each bus bar.

Table 7: Bus Voltage Results

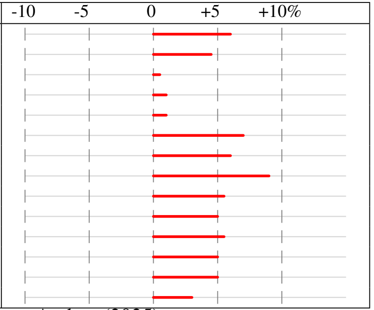
Nominal		Actual	
Bus Name	V (kV)	V_{LL} (kV)	Angle (deg)
Bus_0001	132.00	139.92	0.00
Bus_0002	132.00	137.94	-4.98
Bus_0003	132.00	133.32	-12.72
Bus_0004	132.00	134.46	-10.32
Bus_0005	132.00	134.67	-8.78
Bus_0006	33.00	35.31	-14.22
Bus_0007	1.00	1.06	-13.37
Bus_0008	11.00	11.99	-13.37
Bus_0009	33.00	34.86	-14.95
Bus_0010	33.00	34.69	-15.10
Bus_0011	33.00	34.88	-14.80
Bus_0012	33.00	34.82	-15.08
Bus_0013	33.00	34.66	-15.16
Bus_0014	33.00	34.18	-16.04

Source: DigSILENT GmbH. (2025)

From the Table [8], Bus 8 operates at 1.090 p.u. (11.99 kV against a nominal 11.00 kV), representing a $+9\%$overvoltage that significantly exceeds ANSI C84.1's $\pm5\%$ normal operating range[4],even thought this overvoltage, the Bus 8 is a PV bus, with a controlled voltage at 1.090 p.u. While remaining within the standard's -10% to $+10\%$ emergency utilization limits, this sustained overvoltage (1) approaches the upper threshold for distribution equipment tolerance and (2) suggests potential voltage regulation issues in this network segment, possibly requiring proper voltage adjustment for generators.

Table 8: Voltage Deviation

Bus Name	**Voltage (p.u.)**	-10 -5 0 +5 +10%
Bus_0001	1.060	
Bus_0002	1.045	
Bus_0003	1.010	
Bus_0004	1.019	
Bus_0005	1.020	
Bus_0006	1.070	
Bus_0007	1.062	
Bus_0008	1.090	
Bus_0009	1.056	
Bus_0010	1.051	
Bus_0011	1.057	
Bus_0012	1.055	
Bus_0013	1.050	
Bus_0014	1.036	



Source: Author (2025)

Besides the Bus 8, Buses 1, 6, 7, 9, 10, 11, 12, and 13 also operate outside standard limits—though with less severe deviations.

Table 9: Bus Total Active and Reactive Power results

Bus	P (MW)	Q (Mvar)	Qsh (Mvar)
Bus_0001	232.39	-16.89	0.00
Bus_0002	18.30	29.70	0.00
Bus_0003	-94.20	4.39	0.00
Bus_0004	-47.80	3.90	0.00
Bus_0005	-7.60	11.22	0.00
Bus_0006	-11.20	4.74	0.00
Bus_0007	0.00	0.00	0.00
Bus_0008	0.00	17.36	0.00
Bus_0009	-29.50	-16.60	21.20
Bus_0010	-9.00	-5.80	0.00
Bus_0011	-3.50	-1.80	0.00
Bus_0012	-6.10	-1.60	0.00
Bus_0013	-13.50	-5.80	0.00
Bus_0014	-14.90	-5.00	0.00

Source: DigSILENT GmbH. (2025)

In addition to tabular data, the 14 Bus System network diagram, from Figure [2] provides an intuitive post-power-flow visualization interface, enabling users to interactively analyze simulation results through a dynamic graphical representation, show in Figure [4].The accompanying legend in Figure [5] enables interpretation of the color-coded graphical representation by defining per-unit voltage ranges, and loading level.

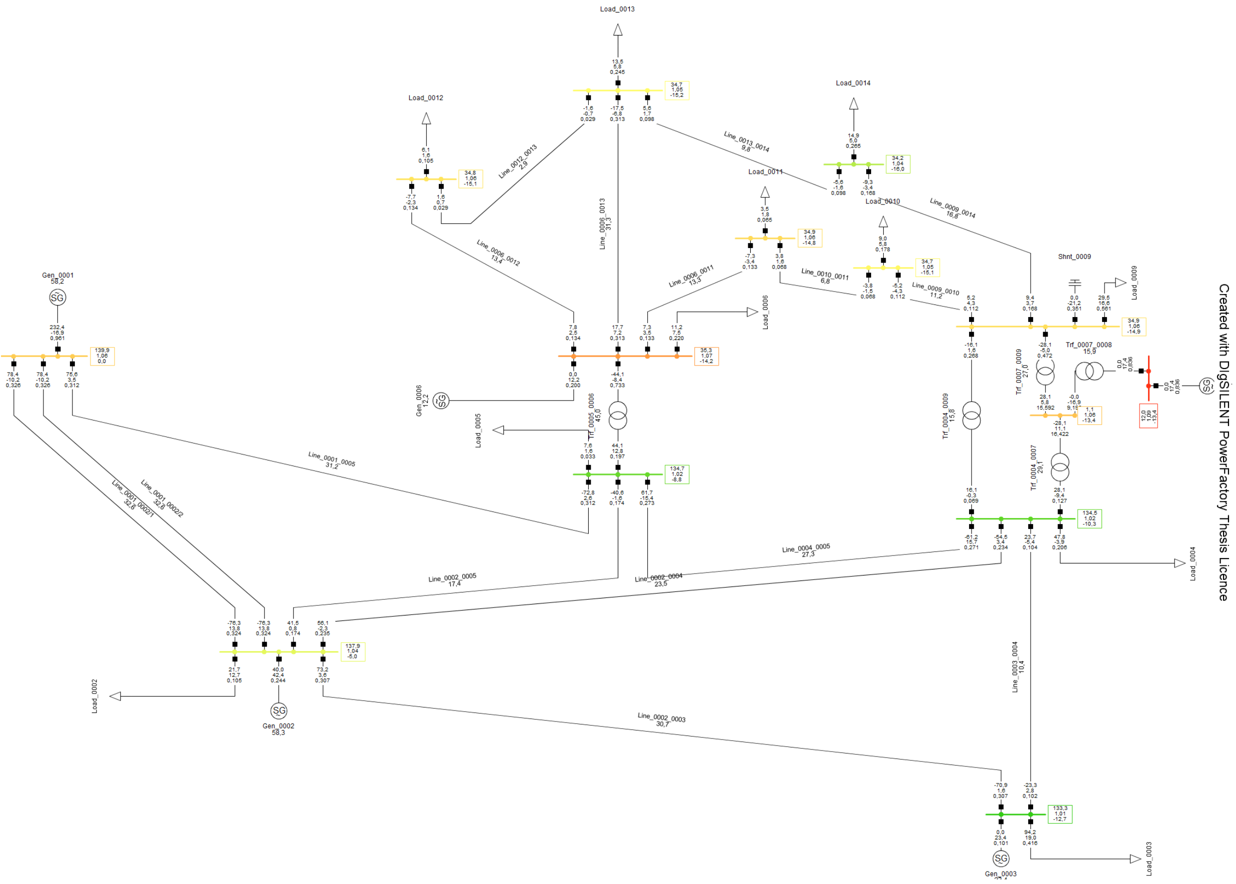


Figure 4: 14 Bus System post-power-flow. Source: DigSILENT. (2025)

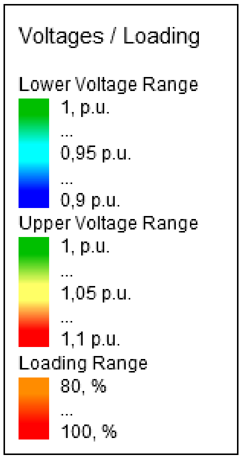


Figure 5: Voltages/Loading Legend. Source: DigSILENT. (2025)

The information from the Figure 4, can be read as Tabular form too, and this representations can be view in the following Tables 10 to 13:

- Table 10 presents the result for the Loads;
- Table 11 presents the result for the generators;
- Table 12 presents the result for the Lines; and
- Table 14 presents the result for the transformers.

Table 10: Load Power Flow Results

Name	P (MW)	Q (Mvar)	PF (-)	I (kA)	I (p.u.)
Load_0002	21.70	12.70	0.86	0.105	0.957
Load_0003	94.20	19.00	0.98	0.416	0.990
Load_0004	47.80	-3.90	1.00	0.206	0.982
Load_0005	7.60	1.60	0.98	0.033	0.980
Load_0006	11.20	7.50	0.83	0.220	0.935
Load_0009	29.50	16.60	0.87	0.561	0.947
Load_0010	9.00	5.80	0.84	0.178	0.951
Load_0011	3.50	1.80	0.89	0.065	0.946
Load_0012	6.10	1.60	0.97	0.105	0.948
Load_0013	13.50	5.80	0.92	0.245	0.952
Load_0014	14.90	5.00	0.95	0.265	0.965

Source: DigSILENT GmbH. (2025)

From Table 10 the power factors for the all the loads range from 0.83 to 0.98, confirming their inductive nature.

Table 11: Generator and Shunt Power Flow Results

Name	P (MW)	Q (Mvar)	PF (-)	I (kA)	I (p.u.)	Loading (%)
Gen_0001	232.39	-16.89	1.00	0.961	0.550	58.25
Gen_0002	40.00	42.40	0.69	0.244	0.558	58.29
Gen_0003	0.00	23.39	0.00	0.101	0.232	23.39
Gen_0006	0.00	12.24	0.00	0.200	0.114	12.24
Gen_0008	0.00	17.36	0.00	0.836	0.159	17.36
Shnt_0009	0.00	-21.20	0.00	0.351	1.056	00.00

Source: DigSILENT GmbH. (2025)

In table 11, generators 3, 6 and 8 all show 0.00 MW of active power generation but provide positive reactive power, which implies they are operating as synchronous condensers or as reactive power compensation equipment.

Table 12: Line Power Flow Results

Name	Bus	P (MW)	Q (Mvar)	PF (-)	Loading (%)
Line_0001_0002/1	1_2	78.42	-10.20	0.99	32.63
Line_0001_0002/1	2_1	-76.27	13.83	-0.98	32.63
Line_0001_0005	1_5	75.55	3.50	1.00	31.22
Line_0001_0005	5_1	-72.79	2.58	-1.00	31.22
Line_0002_0003	2_3	73.19	3.57	1.00	30.70
Line_0002_0003	3_2	-70.87	1.58	-1.00	30.70
Line_0002_0004	2_4	56.14	-2.29	1.00	23.52
Line_0002_0004	4_2	-54.46	3.39	-1.00	23.52
Line_0002_0005	2_5	41.51	0.76	1.00	17.42
Line_0002_0005	5_2	-40.61	-1.63	-1.00	17.42
Line_0003_0004	3_4	-23.33	2.81	-0.99	10.44
Line_0003_0004	4_3	23.70	-5.42	0.97	10.44
Line_0004_0005	4_5	61.74	-15.37	0.97	27.27
Line_0004_0005	5_4	-61.22	15.67	-0.97	27.27
Line_0006_0011	6_11	-7.29	-3.36	-0.91	13.28
Line_0006_0011	11_6	7.34	3.47	0.90	13.28
Line_0006_0012	6_12	7.78	2.49	0.95	13.36
Line_0006_0012	12_6	-7.71	-2.34	-0.96	13.36
Line_0006_0013	6_13	-17.53	-6.75	-0.93	31.29
Line_0006_0013	13_6	17.74	7.17	0.93	31.29
Line_0009_0010	9_10	5.24	4.31	0.77	11.23
Line_0009_0010	10_9	-5.23	-4.27	-0.77	11.23
Line_0009_0014	9_14	-9.32	-3.42	-0.94	16.77
Line_0009_0014	14_9	9.44	3.67	0.93	16.77
Line_0010_0011	10_11	-3.77	-1.53	-0.93	6.78
Line_0010_0011	11_10	3.79	1.56	0.92	6.78
Line_0012_0013	12_13	1.61	0.74	0.91	2.94
Line_0012_0013	13_12	-1.60	-0.74	-0.91	2.94
Line_0013_0014	13_14	5.63	1.69	0.96	9.79
Line_0013_0014	14_13	-5.58	-1.58	-0.96	9.79

Source: DigSILENT GmbH. (2025)

Table 12 provides direct bidirectional power flow data for each line segment,directly illustrating the power flow direction and the losses occurring within the lines. For example, a flow from Bus 1 to Bus 2 shows P=78.42 MW, while the flow from Bus 2 to Bus 1 shows P=-76.27 MW, indicating 2.15 MW of active power losses along that segment.

The losses for all the lines are shown in Table 13,with a total active power losses of 11.24 MW and a total reactive power losses of 13.89 Mvar.

Table 13: Line Power Losses

Line Name	P Loss (MW)	Q Loss (Mvar)
Line_0001_0002/1	2.15	3.63
Line_0001_0005	2.76	6.08
Line_0002_0003	2.32	5.15
Line_0002_0004	1.68	1.10
Line_0002_0005	0.90	-0.87
Line_0003_0004	0.37	-2.61
Line_0004_0005	0.52	0.30
Line_0006_0011	0.05	0.11
Line_0006_0012	0.07	0.15
Line_0006_0013	0.21	0.42
Line_0009_0010	0.01	0.04
Line_0009_0014	0.12	0.25
Line_0010_0011	0.02	0.03
Line_0012_0013	0.01	0.00
Line_0013_0014	0.05	0.11

Source: Author. (2025)

Table 14 reveals the most significant finding: the symmetry between both directions, where the active power flowing into one side nearly matches the magnitude flowing out of the other side, demonstrating that the internal resistances of the transformers are being neglected.

Table 14: Transformer Power Flow Results

Name	Bus	P (MW)	Q (Mvar)	PF (-)	Loading (%)
Trf_0004_0007	4_7	28.09	-9.42	0.95	29.08
Trf_0004_0007	7_4	-28.09	11.11	-0.93	29.08
Trf_0004_0009	4_9	16.09	-0.32	1.00	15.80
Trf_0004_0009	9_4	-16.09	1.63	-0.99	15.80
Trf_0005_0006	5_6	44.06	12.82	0.96	44.98
Trf_0005_0006	6_5	-44.06	-8.40	-0.98	44.98
Trf_0007_0008	7_8	0.00	17.36	0.00	15.92
Trf_0007_0008	8_7	-0.00	-16.91	-0.00	15.92
Trf_0007_0009	7_9	-28.09	-5.00	-0.98	27.01
Trf_0007_0009	9_7	28.09	5.80	0.98	27.01

Source: DigSILENT GmbH. (2025)

The system summary in Table 15 confirms balanced operation under initial conditions, with 272.39 MW generation supplying 259.00 MW load at 0.96 power factor. Grid losses totaled 13.39 MW (4.91% of generation), while maintaining 130.61 MW spinning reserve from the 700 MW installed capacity, with reactive power support provided by -21.20 Mvar capacitor compensation.

Table 15: Balanced System Summary

System Components			
Substations	0	2-w Transformers	5
Busbars	14	3-w Transformers	0
Terminals	0	Synchronous Machines	5
Lines	16	Asynchronous Machines	0
Loads	11	Shunts/Filters	1
Power Summary			
Category	P (MW)	Q (Mvar)	S (MVA)
Generation	272.39	78.50	283.47
External Infeed	0.00	0.00	0.00
Load P(U)	259.00	73.50	269.23
Motor Load	0.00	0.00	0.00
Losses and Compensation			
Grid Losses	13.39	26.20	-
Line Charging	-	-28.30	-
Capacitor Compensation	-	-21.20	-
Capacity Metrics			
Installed Capacity	700.00 MW		
Spinning Reserve	130.61 MW		
Power Factors			
Generation	0.96		
Load/Motor	0.96 / 0.00		

Source: Author. (2025)

To validate the usage, potential, and reliability of PowerFactory software, a comparative power flow analysis was performed in MATLAB using the 14-bus system data with the Newton-Raphson method. The results are presented in Table 16, demonstrating close agreement between both computational approaches.

Table 16: Line Power Flow Results in MATLAB

Name	Bus	P (MW)	Q (Mvar)
Line_0001_0002	1_2	78.41	-10.21
Line_0001_0002	2_1	-76.26	13.85
Line_0001_0005	1_5	75.58	3.52
Line_0001_0005	5_1	-72.81	2.57
Line_0002_0003	2_3	73.18	3.57
Line_0002_0003	3_2	-70.86	1.58
Line_0002_0004	2_4	56.14	-2.25
Line_0002_0004	4_2	-54.46	3.36
Line_0002_0005	2_5	41.50	0.79
Line_0002_0005	5_2	-40.60	-1.66
Line_0003_0004	3_4	-23.34	2.85
Line_0003_0004	4_3	23.71	-5.46
Line_0004_0005	4_5	-61.24	15.63
Line_0004_0005	5_4	61.75	-15.33
Line_0006_0011	6_11	7.34	3.45
Line_0006_0011	11_6	-7.28	-3.34
Line_0006_0012	6_12	7.78	2.49
Line_0006_0012	12_6	-7.71	-2.34
Line_0006_0013	6_13	17.74	7.16
Line_0006_0013	13_6	-17.52	-6.74
Line_0009_0010	9_10	5.24	4.33
Line_0009_0010	10_9	-5.23	-4.29
Line_0009_0014	9_14	9.44	3.68
Line_0009_0014	14_9	-9.33	-3.43
Line_0010_0011	10_11	-3.77	-1.51
Line_0010_0011	11_10	3.78	1.54
Line_0012_0013	12_13	1.61	0.74
Line_0012_0013	13_12	-1.60	-0.73
Line_0013_0014	13_14	5.63	1.68
Line_0013_0014	14_13	-5.57	-1.57

Source: Author. (2025)

However, PowerFactory distinguishes itself through practicality, offering:

- Integrated visualization tools: Real-time color-coded network diagrams;
- Streamlined workflow: Automated report generation and one-click Power Flow analysis,and
- User-friendly interface: Drag-and-drop component libraries and interactive result tables.

To validate the consistency between both software solutions, a percentage error analysis was conducted using MATLAB results as the reference. The error for each line was calculated as:

$$\text{Erro\%} = \left(\frac{X_{\text{PowerFactory}} - X_{\text{MATLAB}}}{X_{\text{MATLAB}}} \right) \times 100 \qquad (1)$$

where X represents either active (P) or reactive (Q) power flow. Table 17 summarizes the percentage errors for all transmission lines in the system, revealing that Only 3 out of 30 lines (10% of cases) show active power errors exceeding 1%

This comparison demonstrates excellent agreement in active power calculations while highlighting potential differences in reactive power modeling approaches between the software packages.

Table 17: Percentage Errors in Line Power Flow (PowerFactory vs MATLAB)

Line Name	Bus	P Error (%)	Q Error (%)
Line_0001_0002	1_2	0.013	-0.09
Line_0001_0002	2_1	0.013	-0.14
Line_0001_0005	1_5	-0.040	-0.57
Line_0001_0005	5_1	-0.027	0.39
Line_0002_0003	2_3	0.014	0.00
Line_0002_0003	3_2	0.014	0.00
Line_0002_0004	2_4	0.000	1.78
Line_0002_0004	4_2	0.000	0.89
Line_0002_0005	2_5	0.024	-3.80
Line_0002_0005	5_2	0.025	-1.81
Line_0003_0004	3_4	-0.043	-1.40
Line_0003_0004	4_3	-0.042	-0.73
Line_0004_0005	4_5	0.817	-1.66
Line_0004_0005	5_4	-0.033	0.26
Line_0006_0011	6_11	-0.68	-2.61
Line_0006_0011	11_6	0.82	3.89
Line_0006_0012	6_12	0.00	0.00
Line_0006_0012	12_6	0.00	0.00
Line_0006_0013	6_13	-1.18	-5.73
Line_0006_0013	13_6	1.26	6.38
Line_0009_0010	9_10	0.00	-0.46
Line_0009_0010	10_9	0.00	-0.47
Line_0009_0014	9_14	-1.27	-7.07
Line_0009_0014	14_9	0.00	-0.27
Line_0010_0011	10_11	0.00	1.32
Line_0010_0011	11_10	0.26	1.30
Line_0012_0013	12_13	0.00	0.00
Line_0012_0013	13_12	0.00	1.37
Line_0013_0014	13_14	0.00	0.60
Line_0013_0014	14_13	0.18	0.64

Source: Author (2025)

The analysis for the First Scenario (Balanced System under Initial Conditions) confirms PowerFactory's solution accuracy. This establishes a reliable baseline for subsequent scenarios, like with Unbalanced system, PV Generator Replacement and real power transmissions networks.

2) *Second scenario:* Unbalanced system

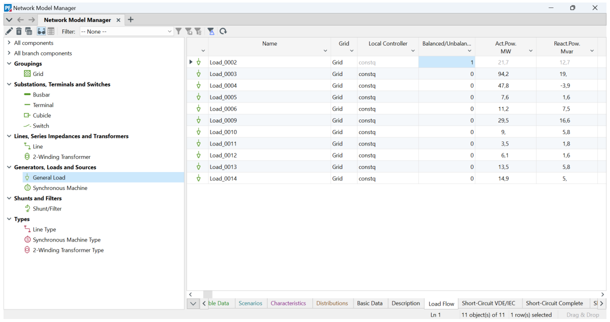
For this scenario, a Load Flow analysis was performed on an unbalanced system where the 11 loads, from Table 1, in the 14-bus system had their active and reactive power distributed according to Table 18

Table 18: Unbalanced Load Distribution

Name	**Phase 1**		**Phase 2**		**Phase 3**	
	P (MW)	**Q (Mvar)**	**P (MW)**	**Q (Mvar)**	**P (MW)**	**Q (Mvar)**
Load_0002	17.0	5.0	4.0	6.0	0.7	1.7
Load_0003	11.0	8.0	49.0	6.0	34.2	5.0
Load_0004	6.0	-2.0	28.0	-0.3	13.8	-1.6
Load_0005	2.0	0.2	1.0	1.0	4.6	0.4
Load_0006	2.0	2.0	3.0	2.0	6.2	3.5
Load_0009	19.0	13.0	2.0	1.0	8.5	2.6
Load_0010	5.0	4.0	3.0	1.0	1.0	0.8
Load_0011	1.0	0.6	2.0	0.9	0.5	0.3
Load_0012	2.0	0.6	1.1	0.2	3.0	0.8
Load_0013	3.5	1.3	4.5	1.2	5.5	3.3
Load_0014	4.8	1.3	4.4	1.7	5.3	2.0

Source: Author (2025)

This distribution was implemented using the "Network Model Manager" page in the software, as shown in Figure 6. First, in the "Balanced/Unbalanced" column, the value "0" (representing balanced load) was changed to "1" (representing unbalanced load). Then, the load characteristics were entered according to the specifications in Table 18.



Name	Grid	Local Controller	Balanced/Unbalan...	Act.Pow. MW	React.Pow. Mvar
Load_0002	Grid	constq	1	21,7	12,7
Load_0003	Grid	constq	0	94,2	19,
Load_0004	Grid	constq	0	47,8	-3,9
Load_0005	Grid	constq	0	7,6	1,6
Load_0006	Grid	constq	0	11,2	7,5
Load_0009	Grid	constq	0	29,5	16,6
Load_0010	Grid	constq	0	9,	5,8
Load_0011	Grid	constq	0	3,5	1,8
Load_0012	Grid	constq	0	6,1	1,6
Load_0013	Grid	constq	0	13,5	5,8
Load_0014	Grid	constq	0	14,9	5,

Figure 6: "Network model manager" page. Source: DIGSILENT. (2025)

After implementing the load distribution, an unbalaced Power Flow was simulated by changing the calculation method, from "AC Load Flow, balanced, positive sequence" to "AC Load Flow, unbalanced, 3-Phase (ABC)", as show in the Figure 3

Table 19: Bus Voltage Unbalanced Power Flow Results

Bus Name	Phase	V_{LN} (kV)	Angle (deg)	V_{LL} (kV)
Bus_0001	A	80.72	0.10	139.81
	B	80.94	-120.01	140.19
	C	80.69	119.91	139.76
Bus_0002	A	79.63	-4.81	137.92
	B	79.84	-125.05	138.29
	C	79.45	114.94	137.61
Bus_0003	A	75.96	-11.51	131.57
	B	78.87	-132.65	136.61
	C	76.12	106.01	131.84
Bus_0004	A	77.04	-9.81	133.44
	B	78.50	-130.19	135.97
	C	77.33	109.06	133.94
Bus_0005	A	77.25	-8.45	133.80
	B	78.37	-128.61	135.74
	C	77.63	110.75	134.46
Bus_0006	A	20.24	-14.35	35.06
	B	20.41	-133.77	35.35
	C	20.51	105.52	35.52
Bus_0007	A	0.61	-13.87	1.06
	B	0.61	-132.81	1.06
	C	0.62	106.63	1.07
Bus_0008	A	6.90	-13.62	11.95
	B	6.90	-133.07	11.95
	C	6.96	106.64	12.06
Bus_0009	A	20.01	-16.14	34.66
	B	19.81	-134.03	34.31
	C	20.54	105.40	35.58
Bus_0010	A	19.93	-16.24	34.52
	B	19.73	-134.24	34.17
	C	20.42	105.24	35.37
Bus_0011	A	20.03	-15.41	34.69
	B	20.00	-134.19	34.64
	C	20.38	105.29	35.30
Bus_0012	A	19.89	-15.25	34.45
	B	20.15	-134.42	34.90
	C	20.27	104.52	35.11
Bus_0013	A	19.82	-15.31	34.33
	B	20.06	-134.56	34.74
	C	20.16	104.49	34.92
Bus_0014	A	19.58	-16.76	33.91
	B	19.58	-135.20	33.91
	C	20.04	104.02	34.71

Source: Author. (2025)

The simulation results are presented in Tables 19 to 25, where Table 19 displays the bus voltages, including both line-to-neutral (V_{LN}) and line-to-line (V_{LL}) values.

Using the voltage line-to-line values, a study of the Voltage Unbalance Factor (VUF%) was performed using the CIGRE Method [9]. The calculation uses the following equations:

$$VUF\% = \sqrt{\frac{1-\sqrt{3-6\beta}}{1+\sqrt{3-6\beta}}} \cdot 100 \tag{2}$$

$$\beta = \frac{V_{ab}^4 + V_{bc}^4 + V_{ca}^4}{(V_{ab}^2 + V_{bc}^2 + V_{ca}^2)^2} \tag{3}$$

Where V_{ab}, V_{bc}, and V_{ca} represent the magnitudes of the line voltages (V_{LL}).

The result of the VUF are show in Table 20:

Table 20: Voltage Unbalance Factor (VUF%)

Bus Name	VUF%
Bus_0001	0.19
Bus_0002	0.28
Bus_0003	2.47
Bus_0004	1.15
Bus_0005	0.85
Bus_0006	0.77
Bus_0007	1.08
Bus_0008	0.57
Bus_0009	2.18
Bus_0010	2.07
Bus_0011	1.22
Bus_0012	1.12
Bus_0013	1.01
Bus_0014	1.56

Source: Author calculations (2025)

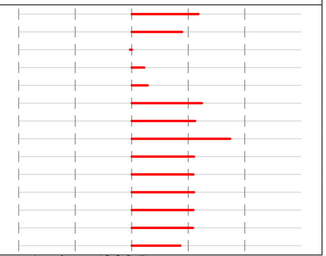
Using the unbalanced voltage limits specified in Table 21 according to PRODIST standards, was observed that while Buses 0003, 0009, and 0010 slightly exceed the 2% limit, they remain below the 2% threshold. Therefore, the results indicate that the system maintains balanced voltages overall.

Table 21: Nominal Voltage Limits for Unbalance Indicator[6]

Indicator	Nominal Voltage	
	Vn $\leq$ 1.0 kV	1 kV $<$ Vn $<$ 230 kV
VUF%	3.0%	2.0%

As shown in Table 8 from the first scenario, Buses 10, 12, and 13 exhibited voltage deviations exceeding ANSI C84.1 limits. However, Table 22 demonstrates improved performance for these same buses, with all operating within the 5% range. Notably, Bus 8 remains in critical operation. Overall, most buses showed slight decreases in their voltage deviation values.

Table 22: Unbalanced Voltage Deviation

Bus Name	**Voltage (p.u.)**	-10 -5 0 +5 +10%
Bus_0001	1.059	
Bus_0002	1.045	
Bus_0003	0.997	
Bus_0004	1.011	
Bus_0005	1.014	
Bus_0006	1.062	
Bus_0007	1.056	
Bus_0008	1.087	
Bus_0009	1.050	
Bus_0010	1.046	
Bus_0011	1.051	
Bus_0012	1.044	
Bus_0013	1.040	
Bus_0014	1.028	

Source: Author (2025)

The complete numerical results of the three-phase unbalanced power flow simulation are presented in Tables 21 through 24 below:

- Table 23 presents the result for the Loads;
- Table 24 presents the result for the generators;
- Table 26 presents the result for the Lines; and
- Table 25 presents the result for the transformers.

Table 23: Load Unbalanced Power Flow Results

Name	P (MW)	Q (Mvar)	PF (-)	I (kA)	I (p.u.)
Load_0002	21.70	12.70	0.86	0.105	0.955
Load_0003	94.20	19.00	0.98	0.417	0.993
Load_0004	47.80	-3.90	1.00	0.205	0.980
Load_0005	7.60	1.60	0.98	0.033	0.983
Load_0006	11.20	7.50	0.83	0.221	0.935
Load_0009	29.50	16.60	0.87	0.567	0.957
Load_0010	9.00	5.80	0.84	0.179	0.958
Load_0011	3.50	1.80	0.89	0.065	0.945
Load_0012	6.10	1.60	0.97	0.105	0.950
Load_0013	13.50	5.80	0.92	0.244	0.951
Load_0014	14.50	5.00	0.95	0.259	0.965

Source: DigSILENT GmbH. (2025)

Table 24: Generator and Shunt Unbalanced Power Flow Results

Name	P (MW)	Q (Mvar)	PF (-)	I (kA)	I (p.u.)	Loading (%)
Gen_0001	232.15	-16.829	1.00	0.960	0.549	58.19
Gen_0002	40.00	42.434	0.69	0.244	0.558	58.31
Gen_0003	0.00	23.947	0.00	0.105	0.240	23.95
Gen_0006	0.00	12.443	0.00	0.204	0.117	12.44
Gen_0008	0.00	17.502	0.00	0.844	0.161	17.50
Shnt_0009	0.00	-21.191	0.00	0.351	1.056	0.00

Source: DigSILENT GmbH. (2025)

Table 25: Transformer Unbalanced Power Flow Results

Name	Bus	P (MW)	Q (Mvar)	PF (-)	Loading (%)
Trf_0004_0007	4_7	27.950	-9.263	0.95	37.81
Trf_0004_0007	7_4	-27.950	11.107	-0.93	37.81
Trf_0004_0009	4_9	16.002	-0.197	1.00	21.48
Trf_0004_0009	9_4	-16.002	1.665	-0.99	21.48
Trf_0005_0006	5_6	43.940	12.805	0.96	48.31
Trf_0005_0006	6_5	-43.940	-8.369	-0.98	48.31
Trf_0007_0008	7_8	0.000	17.502	0.00	17.85
Trf_0007_0008	8_7	-0.000	-17.031	-0.00	17.85
Trf_0007_0009	7_9	-27.9500	-4.982	-0.98	38.19
Trf_0007_0009	9_7	27.9500	5.924	0.98	38.19

Source: DigSILENT GmbH. (2025)

Table 26: Line Unbalanced Power Flow Results

Name	Bus	P (MW)	Q (Mvar)	PF (-)	Loading (%)
Line_0001_0002/1	1_2	78.345	-10.181	0.99	33.04
Line_0001_0002/1	2_1	-76.202	13.802	-0.98	33.04
Line_0001_0002/2	1_2	78.345	-10.181	0.99	33.04
Line_0001_0002/2	2_1	-76.202	13.802	-0.98	33.04
Line_0001_0005	1_5	75.460	3.533	1.00	32.45
Line_0001_0005	5_1	-72.698	2.545	-1.00	32.45
Line_0002_0003	2_3	73.201	3.537	1.00	35.37
Line_0002_0003	3_2	-70.822	1.856	-1.00	35.37
Line_0002_0004	2_4	56.055	-2.214	1.00	25.71
Line_0002_0004	4_2	-54.368	3.354	-1.00	25.71
Line_0002_0005	2_5	41.447	0.808	1.00	18.86
Line_0002_0005	5_2	-40.539	-1.662	-1.00	18.86
Line_0003_0004	3_4	-23.378	3.092	-0.99	13.37
Line_0003_0004	4_3	23.788	-5.604	0.97	13.37
Line_0004_0005	4_5	61.697	-15.288	0.97	30.02
Line_0004_0005	5_4	-61.173	15.611	-0.97	30.02
Line_0006_0011	6_11	-7.291	-3.430	-0.90	18.51
Line_0006_0011	11_6	7.363	3.581	0.90	18.51
Line_0006_0012	6_12	7.755	2.513	0.95	15.22
Line_0006_0012	12_6	-7.682	-2.360	-0.96	15.22
Line_0006_0013	6_13	-17.410	-6.802	-0.93	33.57
Line_0006_0013	13_6	17.621	7.219	0.93	33.57
Line_0009_0010	9_10	5.252	4.275	0.78	13.36
Line_0009_0010	10_9	-5.238	-4.239	-0.78	13.46
Line_0009_0014	9_14	-9.079	-3.375	-0.94	21.43
Line_0009_0014	14_9	9.201	3.633	0.93	21.43
Line_0010_0011	10_11	-3.762	-1.561	-0.92	13.54
Line_0010_0011	11_10	3.791	1.630	0.92	13.54
Line_0012_0013	12_13	1.582	0.760	0.90	3.41
Line_0012_0013	13_12	-1.575	-0.754	-0.90	3.41
Line_0013_0014	13_14	5.485	1.756	0.95	13.08
Line_0013_0014	14_13	-5.421	-1.624	-0.96	13.08

Source: DigSILENT GmbH. (2025)

The losses for all the lines are shown in Table 27,with a total active power losses of 11.41 MW and a total reactive power losses of 14.41 Mvar. Values slight higher than the Balanced system, in Table 13.

Table 27: Line Unbalanced Power Losses

Line Name	P (MW)	Q (Mvar)
Line_0001_0002/1	2.143	3.621
Line_0001_0005	2.762	6.078
Line_0002_0003	2.379	5.393
Line_0002_0004	1.687	1.140
Line_0002_0005	0.908	-0.854
Line_0003_0004	0.410	-2.512
Line_0004_0005	0.524	0.323
Line_0006_0011	0.072	0.151
Line_0006_0012	0.073	0.153
Line_0006_0013	0.211	0.417
Line_0009_0010	0.014	0.036
Line_0009_0014	0.122	0.258
Line_0010_0011	0.029	0.069
Line_0012_0013	0.007	0.006
Line_0013_0014	0.064	0.132

Source: Author. (2025)

The unbalanced power flow results are summarized in Table 28, with 272.15 MW generation supplying 258.60 MW load at 0.96 power factor, and with 13.55 MW of grid losses(4.98% of generation). Notably, the system exhibits 27.19 Mvar of reactive losses, partially offset by 28.30 Mvar of line charging and 21.19 Mvar of capacitor compensation, with an installed capacity of 700 MW and 130.85 MW spinning reserve.

Table 28: Unbalanced System Summary

System Components			
Substations	0	2-w Transformers	5
Busbars	14	3-w Transformers	0
Terminals	0	Synchronous Machines	5
Lines	16	Asynchronous Machines	0
Loads	11	Shunts/Filters	1
Power Summary			
Category	P (MW)	Q (Mvar)	S (MVA)
Generation	272.15	79.50	283.52
External Infeed	0.00	0.00	0.00
Load P(U)	258.60	73.50	268.84
Motor Load	0.00	0.00	0.00
Losses and Compensation			
Grid Losses	13.55	27.19	-
Line Charging	-	-28.30	-
Capacitor Compensation	-	-21.19	-
Capacity Metrics			
Installed Capacity	700.00 MW		
Spinning Reserve	130.85 MW		
Power Factors			
Generation	0.96		
Load/Motor	0.96 / 0.00		

Source: DigSILENT GmbH. (2025)

In this case, the differences between the balanced and unbalanced power flow analyses, as shown in Tables 15 and 28, are relatively small. The most significant disparity is in the reactive power component of grid losses. However, when evaluating the complete system, this difference is not significant, as both power flow analyses show grid losses representing approximately 4.9% of total generation.

B. Case Study: Peru's National Interconnected Electric System (SEIN)

After the hypothetical 14-bus case study, which examined the reliability and versatility of DIgSILENT PowerFactory, a real energy transmission system was simulated using the software.

The power flow analysis was conducted on Peru's National Interconnected Electric System (SEIN), which can be observed in the Figure 7. The data was sourced from the official website of the Comité de Operación Económica del Sistema (COES) [10], alreadly in the Powerfactory's native format.

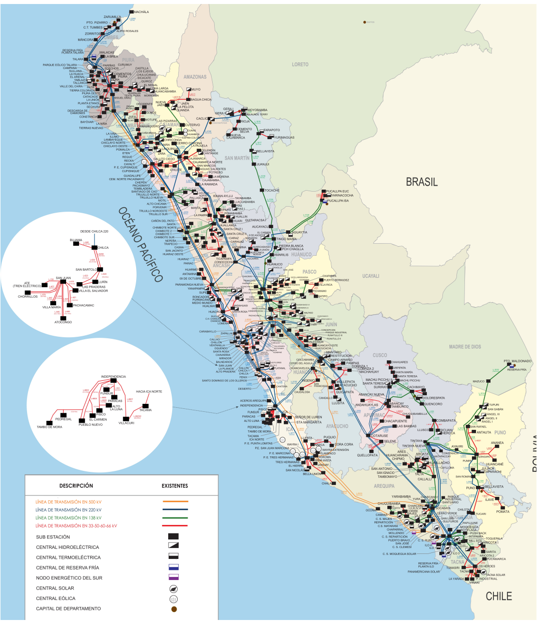


Figure 7: Existing lines in SEIN in 2025 Source:COES. (2025)

Due to the system's large scale, it's divided into several areas: Centro 1, Centro 2, Norte, Sur Este, Sur Oeste, and Tocache-Bellavista.

The following tables present the power flow simulation results.

Table 29 provides a overview of the Area Centro 1 electrical system, detailing its core components and power balance. It is evident that this area features is a complex network, with 117 substations and a substantial 660 busbars and 2599 terminals. The power summary reveals a significant generation capacity of 5095.61 MW, supplying a load of 3811.54 MW. The positive Inter Grid Flow of 1090.47 MW suggests Area Centro 1 is a net exporter of power to connected regions.

Furthermore, the substantial negative (-)capacitive Grid Losses in Q (-2545.79 Mvar) coupled with large positive (+)inductive compensation (3019.48 Mvar) highlight reactive power management within the system.

Both generation and load operate at high power factors, near unity (1.00 and 0.99 respectively), indicating efficient real power utilization.

Table 29: Area Centro 1 - Balanced System Summary

Area Centro 1 System Components			
Substations	117	2-w Transformers	148
Busbars	660	3-w Transformers	87
Terminals	2599	Synchronous Machines	81
Lines	418	Asynchronous Machines	0
Loads	186	Shunts/Filters	56
Power Summary			
Category	P (MW)	Q (Mvar)	S (MVA)
Generation	5095.61	411.73	5112.22
External Infeed	0.00	0.00	0.00
Inter Grid Flow	1090.47	-127.19	-
Load P(U)	3811.54	646.73	3866.02
Motor Load	0.00	0.00	0.00
Losses and Compensation			
Grid Losses	193.59	-2545.79	-
Line Charging	-	-4524.14	-
Compensation ind.	-	3019.48	-
Compensation cap.	-	-581.49	-
Capacity Metrics			
Installed Capacity	6030.36 MW		
Spinning Reserve	519.42 MW		
Power Factors			
Generation	1.00		
Load/Motor	0.99 / 0.00		

Source: DigSILENT GmbH. (2025)

The Table 30,details the inter-grid power flows from Area Centro 1, confirming this area's significant role as a power source within the interconnected system.

Table 30: Area Centro 1 - Inter Grid Flow Details

Area Centro 1 Interconnections		
Destination	P (MW)	Q (Mvar)
Area Sur Este	-29.78	-47.43
Area Norte	-169.79	6.94
Area Sur Oeste	832.10	-22.27
Tocache-Bellavista	270.96	-42.20
Area Centro 2	-221.88	53.72
Enlace Norte-Centro	126.30	-51.24
Enlace Centro-Sur	282.56	-24.71
Total	1090.47	-127.19

Source: Author. (2025)

Table 31 summarizes the Area Centro 2 system, revealing its relatively smaller scale compared to Area Centro 1, with only 8 substations and 242 busbars. This area maintains a robust power exporter with 932.50 MW of local generation serving a load of 570.75 MW while experiencing 52.81 MW in losses. The system exhibits excellent generation power factor (1.00), though the slightly lower load power factor (0.94) indicates significant reactive power demand.

Table 31: Area Centro 2 - Balanced System Summary

Area Centro 2 System Components			
Substations	8	2-w Transformers	48
Busbars	242	3-w Transformers	36
Terminals	174	Synchronous Machines	45
Lines	141	Asynchronous Machines	0
Loads	88	Shunts/Filters	20
Power Summary			
Category	P (MW)	Q (Mvar)	S (MVA)
Generation	932.50	63.07	934.63
External Infeed	0.00	0.00	0.00
Inter Grid Flow	308.94	-67.86	-
Load P(U)	570.75	209.70	608.05
Motor Load	0.00	0.00	0.00
Losses and Compensation			
Grid Losses	52.81	158.59	-
Line Charging	-	-299.45	-
Compensation ind.	-	19.01	-
Compensation cap.	-	-256.38	-
Capacity Metrics			
Installed Capacity	998.30 MW		
Spinning Reserve	87.15 MW		
Power Factors			
Generation	1.00		
Load/Motor	0.94 / 0.00		

Source: DigSILENT GmbH. (2025)

The Inter Grid Flow, shown in Table 32, indicates that Area Centro 2 is also a net power exporter, but at a smaller scale.

Table 32: Area Centro 2 - Inter Grid Flow Details

Area Centro 2 Interconnections		
Destination	P (MW)	Q (Mvar)
Area Centro 1	221.88	-53.72
Tocache-Bellavista	-33.17	15.96
Area Norte	120.23	-30.09
Total	308.94	-67.86

Source: Author. (2025)

Table 33 provides an overview of the Area Norte system, showing an infrastructure with 46 substations and 426 busbars. This area exhibits an operational profile with 1070.95 MW of generation attempting to meet a larger load of 1212.22 MW, resulting in a net import indicated by the negative Inter Grid Flow of -254.79 MW. Grid losses of 113.51 MW are observed, and substantial line charging (-1823.55 Mvar) and inductive compensation (1215.20 Mvar) highlight the significant reactive power management required in this region.

Table 33: Area Norte - Balanced System Summary

Area Norte System Components			
Substations	46	2-w Transformers	75
Busbars	426	3-w Transformers	74
Terminals	1071	Synchronous Machines	60
Lines	215	Asynchronous Machines	0
Loads	145	Shunts/Filters	43
Power Summary			
Category	P (MW)	Q (Mvar)	S (MVA)
Generation	1070.95	-14.20	1071.04
External Infeed	0.00	0.00	0.00
Inter Grid Flow	-254.79	82.11	-
Load P(U)	1212.22	180.17	1225.53
Motor Load	0.00	0.00	0.00
Losses and Compensation			
Grid Losses	113.51	-1337.69	-
Line Charging	-	-1823.55	-
Compensation ind.	-	1215.20	-
Compensation cap.	-	-153.98	-
Capacity Metrics			
Installed Capacity	1256.73 MW		
Spinning Reserve	130.44 MW		
Power Factors			
Generation	1.00		
Load/Motor	0.99 / 0.00		

Source: DigSILENT GmbH. (2025)

the Table 34,describes the inter-grid power flows from Area Norte, confirming this area as a net importer of power.

Table 34: Area Norte - Inter Grid Flow Details

Area Norte Interconnections		
Destination	P (MW)	Q (Mvar)
Area Centro 1	169.79	-6.94
Tocache-Bellavista	-191.99	67.19
Enlace Norte-Centro	-112.36	-8.24
Area Centro 2	-120.23	30.09
Total	-254.79	82.11

Source: Author. (2025)

Table 35provides an overview of the Area Sur Este system, showing an infrastructure with 29 substations and 206 busbars, maintains a local generation of 428.10 MW. With a load of 538.80 MW, Area Sur Este is a net importer, reflected by the negative inter-grid flow of -145.05 MW, broken in Table 36. Grid losses are relatively low at 34.36 MW.

Table 35: Area Sur Este - Balanced System Summary

Area Sur Este System Components			
Substations	29	2-w Transformers	42
Busbars	206	3-w Transformers	29
Terminals	349	Synchronous Machines	18
Lines	81	Asynchronous Machines	0
Loads	57	Shunts/Filters	19
Power Summary			
Category	P (MW)	Q (Mvar)	S (MVA)
Generation	428.10	5.84	428.14
External Infeed	0.00	0.00	0.00
Inter Grid Flow	-145.05	76.48	-
Load P(U)	538.80	162.49	562.77
Motor Load	0.00	0.00	0.00
Losses and Compensation			
Grid Losses	34.36	-105.36	-
Line Charging	-	-314.91	-
Compensation ind.	-	18.58	-
Compensation cap.	-	-146.34	-
Capacity Metrics			
Installed Capacity	468.38 MW		
Spinning Reserve	10.92 MW		
Power Factors			
Generation	1.00		
Load/Motor	0.96 / 0.00		

Source: DigSILENT GmbH. (2025)

Table 36: Area Sur Este - Inter Grid Flow Details

Area Sur Este Interconnections		
Destination	P (MW)	Q (Mvar)
Area Sur Oeste	-115.16	21.84
Area Centro 1	29.78	47.43
Enlace SE-SO	-59.68	7.21
Total	-145.05	76.48

Source: Author. (2025)

Table 37 summarize Area Sur Oeste system, with 16 substations and 210 busbars. A Important observation from its power summary is the significantly lower local generation of 112.04 MW compared to its substantial load of 948.90 MW. This difference is primarily covered by a large net power import, evidenced by the -851.56 MW Inter Grid Flow. Grid losses are modest at 14.69 MW, while reactive power compensation plays a role in maintaining system balance. The system exhibits excellent generation power factor (1.00), though the slightly lower load power factor (0.94) indicates significant reactive power demand.

Table 37: Area Sur Oeste - Balanced System Summary

Area Sur Oeste System Components			
Substations	16	2-w Transformers	59
Busbars	210	3-w Transformers	41
Terminals	376	Synchronous Machines	16
Lines	116	Asynchronous Machines	0
Loads	70	Shunts/Filters	30
Power Summary			
Category	P (MW)	Q (Mvar)	S (MVA)
Generation	112.04	-5.05	112.15
External Infeed	0.00	0.00	0.00
Inter Grid Flow	-851.56	-59.84	-
Load P(U)	948.90	344.21	1009.41
Motor Load	0.00	0.00	0.00
Losses and Compensation			
Grid Losses	14.69	-114.95	-
Line Charging	-	-263.89	-
Compensation ind.	-	138.26	-
Compensation cap.	-	-312.74	-
Capacity Metrics			
Installed Capacity	208.25 MW		
Spinning Reserve	93.73 MW		
Power Factors			
Generation	1.00		
Load/Motor	0.94 / 0.00		

Source: DigSILENT GmbH. (2025)

Table 38 confirms the critical role of Area Centro 1 as its primary power source, from which it imports a massive 832.10 MW. The table also confirms the power import characteristics of Area Sur Oeste.

Table 38: Area Sur Oeste - Inter Grid Flow Details

Area Sur Oeste Interconnections		
Destination	P (MW)	Q (Mvar)
Area Sur Este	115.16	-21.84
Enlace SE-SO	60.11	-27.88
Area Centro 1	-832.10	22.27
Tocache-Bellavista	0.08	-0.77
Enlace Centro-Sur	-194.80	-31.61
Total	-851.56	-59.84

Source: Author. (2025)

Table 39 focuses on the Enlace Centro-Sur interconnection, which, as expected for a pure transmission link, shows zero substations, transformers, synchronous machines, generation, and load. Its primary function is to facilitate power transfer through its 4 lines and 8 Busbars. The link consumes power for transmission, with significant reactive power for line charging (-259.47 Mvar).

Table 39: Enlace Centro-Sur - Balanced System Summary

Enlace Centro-Sur System Components			
Substations	0	2-w Transformers	0
Busbars	8	3-w Transformers	0
Terminals	0	Synchronous Machines	0
Lines	4	Asynchronous Machines	0
Loads	0	Shunts/Filters	5
Power Summary			
Category	P (MW)	Q (Mvar)	S (MVA)
Generation	0.00	0.00	0.00
External Infeed	0.00	0.00	0.00
Inter Grid Flow	-14.85	11.36	-
Load P(U)	0.00	0.00	0.00
Motor Load	0.00	0.00	0.00
Losses and Compensation			
Grid Losses	14.85	-116.75	-
Line Charging	-	-259.47	-
Compensation ind.	-	105.39	-
Compensation cap.	-	0.00	-

Source: DigSILENT GmbH. (2025)

The power transfer through Enlace Centro-Sur is further elaborated in Table 40.

Table 40: Enlace Centro-Sur - Inter Grid Flow Details

Enlace Centro-Sur Interconnections		
Destination	P (MW)	Q (Mvar)
Area Centro 1	-282.56	24.71
Area Sur Oeste	194.80	31.61
Tocache-Bellavista	72.92	-44.96
Total	-14.85	11.36

Source: Author. (2025)

Table 41 provides a summary of the Enlace Norte-Centro system. Similar to other "Enlace" sections, it functions purely as a transmission corridor through its 2 lines.

Table 41: Enlace Norte-Centro - Balanced System Summary

Enlace Norte-Centro System Components			
Substations	0	2-w Transformers	0
Busbars	0	3-w Transformers	0
Terminals	0	Synchronous Machines	0
Lines	2	Asynchronous Machines	0
Loads	0	Shunts/Filters	0
Power Summary			
Category	P (MW)	Q (Mvar)	S (MVA)
Generation	0.00	0.00	0.00
External Infeed	0.00	0.00	0.00
Inter Grid Flow	-13.95	59.48	-
Load P(U)	0.00	0.00	0.00
Motor Load	0.00	0.00	0.00
Losses and Compensation			
Grid Losses	13.95	-59.48	-
Line Charging	-	-75.13	-
Compensation ind.	-	0.00	-
Compensation cap.	-	0.00	-

Source: DigSILENT GmbH. (2025)

The power transfer through Enlace Norte-Centro is further elaborated in Table 42.

Table 42: Enlace Norte-Centro - Inter Grid Flow Details

Enlace Norte-Centro Interconnections		
Destination	P (MW)	Q (Mvar)
Area Norte	112.36	8.24
Area Centro 1	-126.30	51.24
Total	-13.95	59.48

Source: Author. (2025)

Table 43 provides a summary of the Enlace SE-SO system, which connects Area Sur Este and Area Sur Oeste. Similar to other link Norte- Centro, it functions purely as a transmission corridor through its 2 lines.

Table 43: Enlace SE-SO - Balanced System Summary

Enlace SE-SO System Components			
Substations	0	2-w Transformers	0
Busbars	0	3-w Transformers	0
Terminals	0	Synchronous Machines	0
Lines	2	Asynchronous Machines	0
Loads	0	Shunts/Filters	0
Power Summary			
Category	P (MW)	Q (Mvar)	S (MVA)
Generation	0.00	0.00	0.00
External Infeed	0.00	0.00	0.00
Inter Grid Flow	-0.43	20.67	-
Load P(U)	0.00	0.00	0.00
Motor Load	0.00	0.00	0.00
Losses and Compensation			
Grid Losses	0.43	-20.67	-
Line Charging	-	-23.52	-
Compensation ind.	-	0.00	-
Compensation cap.	-	0.00	-

Source: DigSILENT GmbH. (2025)

The Table 44 specifies an power export of 60.31 MW to Area Sur Oeste, while it receives 59.68 MW from Area Sur Este. This illustrates the Enlance SE-SO's crucial role as an bidirectional power transfer link.

Table 44: Enlace SE-SO - Inter Grid Flow Details

Enlace SE-SO Interconnections		
Destination	P (MW)	Q (Mvar)
Area Sur Este	59.68	-7.21
Area Sur Oeste	-60.11	27.88
Total	-0.43	20.67

Source: Author. (2025)

Table 45 presents the system summary for Tocache-Bellavista, an area with 5 substations and 69 busbars. Its local generation of 8.00 MW is considerably lower than its load of 122.83 MW, indicating a reliance on external power. The negative Inter Grid Flow of -118.79 MW confirms its status as a significant power importer, this status is confirmed by the Table 46.

Table 45: Tocache-Bellavista - Balanced System Summary

Tocache-Bellavista System Components			
Substations	5	2-w Transformers	9
Busbars	69	3-w Transformers	9
Terminals	81	Synchronous Machines	3
Lines	42	Asynchronous Machines	0
Loads	17	Shunts/Filters	4
Power Summary			
Category	P (MW)	Q (Mvar)	S (MVA)
Generation	8.00	-2.00	8.25
External Infeed	0.00	0.00	0.00
Inter Grid Flow	-118.79	4.78	-
Load P(U)	122.83	17.47	124.06
Motor Load	0.00	0.00	0.00
Losses and Compensation			
Grid Losses	3.97	-41.98	-
Line Charging	-	-68.90	-
Compensation ind.	-	25.81	-
Compensation cap.	-	-8.08	-
Capacity Metrics			
Installed Capacity	8.70 MW		
Spinning Reserve	0.03 MW		
Power Factors			
Generation	0.97		
Load/Motor	0.99 / 0.00		

Source: DigSILENT GmbH. (2025)

The most valuable information from the previous table is the Grid losses, which represent 49.62% of the generation in the area.

Another notable result value is the generation power factor of 0.97, different from the previous areas that had an power factor of 1, the value reveals reactive power contribution from local generators.

Table 46: Tocache-Bellavista - Inter Grid Flow Details

Tocache-Bellavista Interconnections		
Destination	P (MW)	Q (Mvar)
Area Centro 1	-270.96	42.20
Area Norte	191.99	-67.19
Area Sur Oeste	-0.08	0.77
Enlace Centro-Sur	-72.92	44.96
Area Centro 2	33.17	-15.96
Total	-118.79	4.78

Source: Author. (2025)

The most significant power transfers are visually highlighted in Figure 8, demonstrating once again the interconnections between areas of the Peruvian energy system.

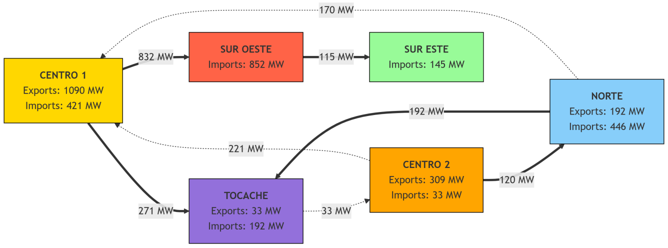


Figure 8: SEIN fluxograma Source:Author(2025)

Following the power flow simulation and analysis of the summarized results presented in the previous tables, a voltage deviation study was conducted for the buses within each area of the system.

Given the large number of buses in each area of the SEIN, Tables 47 through 52 highlight the most significant voltage deviations.

In Table 47, from the 660 busbars of Area Centro 1, 44 exceed +10% deviation while one falls below -10%. Overall, the table shows that 6.67% of buses exceed ANSI C84.1 limits.

Table 47: Area Centro 1 Voltage Deviation

Bus Name	Voltage (p.u.)	-20 -15 -10 0 +10 +15 +20%
CHAVARRIA SVC 4.86	1.160	
MARIATEGUI 60	1.153	
MIRADOR 60	1.153	
IZAGUIRRE 20	1.145	
PachacutecLV1	1.145	
JICAMARCA 60	1.140	
CARHUAC66	1.136	
CB_CALLAO10	1.127	
PAMPILLA2 60	1.127	
CHILLON10_D	1.124	
DCATALINA1	1.123	
DCATALINA2	1.123	
PAMPILLA 60	1.123	
Derv L-ChiCall_1	1.125	
HUAYCOLORO 22.9	1.124	
La Gringa23	1.124	
VILLA EL SALVADOR	1.124	
CHORRILLOS 60	1.118	
MIRADOR 10	1.119	
ZAPALLAL 60	1.119	
GLORIA T1 10	1.117	
GLORIA T2 10	1.117	
ILLAPU 13.8	1.117	
INFANTAS 60	1.116	
ILLAPU 22.9	1.115	
NARANJAL 60	1.114	
MIRADOR10_2do	1.114	
GLORIA 22.9	1.114	
VENTANILLA 60	1.114	
CT OQUENDO 13.8	1.108	
CT OQUENDO 10	1.106	
T1	1.106	
ACER20	1.107	
T2	1.107	
T3	1.107	
OQUENDO 60	1.111	
IZAGUIRRE 10	1.111	
HUAYCOLORO 0.48	1.111	
QUIMPAC 60	1.110	
Derv L-6754_1	1.103	
PACHACAMAC 60	1.104	
PROGRESO 10	1.101	
SanFrancisco66	0.916	
Poroma500Cs2	0.897	

Source: Author (2025)

In Table 48, the overall percentage is 4.95%, where 12 out of 242 busbars exceed the limits. Ten of them are below -10%.

Table 48: Area Centro 2 Voltage Deviation

Bus Name	Voltage (p.u.)	-30 -15 0 +7.5 +15%
Filter Bus_VIZ	1.136	
VIZCARRA SVC 16	1.136	
OROYA NUEVA 138	0.884	
OXAPAMPA 23	0.852	
OXAPAMPA 138	0.851	
FRANCOISE 10.5	0.87	
YAUPI 138B	0.86	
OXAPAMPA 60	0.835	
VILLAR60	0.805	
PBERMUDEZ60	0.766	
PICHA60	0.762	
SATIPO60	0.728	

Source: Author (2025)

Table 49 reveals the most significant busbar voltage deviations, where all listed busbars are below -10%, with two nearing a -30% deviation. These extreme undervoltages suggest load issues or a reactive power deficit, concerns that were previously observed in the Area Norte System Summary (Table 33).

Another significant value is the overall percentage of 1.41%, which represents the lowest deviation among all analyzed SEIN Areas. This percentage corresponds to 6 out of 426 busbars in the Area.

Table 49: Area Norte Voltage Deviation

Bus Name	Voltage (p.u.)	-30 -20 -10 0%
CHULU60	0.875	
Derv L-6657_1	0.865	
MORROPON60	0.864	
LLARGA 60	0.856	
Terminal(10)	0.732	
Terminal(11)	0.732	

Source: Author (2025)

In Table 50, the overall percentage of deviations is 1.94%, which is below 2%, similar to Area Norte. Specifically, 4 out of 206 busbars exceed the ANSI C84.1 limits. Although these deviations are not as large as in the previously discussed area, they are still critically high.

Table 50: Area Sur-Es Voltage Deviation

Bus Name	Voltage (p.u.)	-20 -10 0 +7.5 +15%
TINTAYA 10	1.108	
ANANEA60	0.883	
ANDY60	0.879	
CHILCAYOC60	0.843	

Source: Author (2025)

Table 51, presents the highest overall percentage of 7.62%, but the 16 out of 210 Busbars listed, all of them are below the 10% mark, so they're not critically as the 4 previous areas.

This result is very similar to the Balanced 14-Bus System, where one of the buses is very close to the +10% limit, while the others exceed ANSI's +5% standard (Table 8).

Table 51: Area Sur-Oe Voltage Deviation

Bus Name	Voltage (p.u.)	0 +5 +7.5 +10%
PUCAMARCA 66	1.096	
CAMA10	1.074	
LOS HEROES 10.5B	1.060	
OCOÑA 60kV	1.062	
Ocoña 10kV	1.062	
Ocoña 33kV	1.062	
Derv L-6637_1	1.056	
LOS HEROES 66	1.059	
SOLAR TACNA 0.3A	1.059	
SOLAR TACNA 0.3B	1.059	
SOLAR TACNA 23	1.059	
SOLAR TACNA 66	1.059	
TOMASIRI 66	1.055	
PARQUE INDUSTRIAL	1.052	
CHARCANI VI 33	1.051	
TACNA 66	1.051	

Source: Author (2025)

In the Area Tocache-Bellavista, only two out of 69 buses reveal a small deviation beyond the +5% limit, representing 2.9% of busbars exceeding the standard, as shown in Table 52.

Table 52: Area Tocache Bellavista Voltage Deviation

Bus Name	Voltage (p.u.)	0 +5 +7.5 +10%
CT INDEPENDENCIA 60	1.064	
CT PISCO 60	1.064	

Source: Author (2025)

From the results obtained through the power flow simulation performed in PowerFactory, various improvements can be analyzed for later implementation, primarily aimed at reducing voltage deviations in critical states and control.

V. CONCLUSIONS

This study demonstrates the robust capabilities of DigSILENT PowerFactory for power system analysis, shows its accuracy in load flow simulations through the Newton-Raphson method. The 14-bus case study achieved rapid convergence in just three iterations, with Bus 8 showing a critical +9% overvoltage that exceeded ANSI C84.1 standards. This persistent voltage deviation highlights the need for corrective measures such as voltages adjustments. Comparative analysis with MATLAB confirmed the software's computational reliability, while the measured grid losses of 4.9% (13.39 MW) provided valuable insights into system efficiency.

The unbalanced load flow analysis revealed important operational considerations. While most buses maintained voltages within acceptable limits, Bus 8 remained problematic with its sustained overvoltage condition. Some buses (0003, 0009, and 0010) showed minor voltage unbalance (2.18,2.47 and 2.07% VUF), though within emergency tolerances. These findings emphasize the software's ability to model real-world asymmetric conditions and underscore the importance of dynamic voltage control strategies in unbalanced networks, particularly through targeted reactive power management.

The study's extension to Peru's National Interconnected Electric System (SEIN) demonstrated PowerFactory's exceptional capability in handling complex, real-world power networks. The large-scale simulation revealed critical system-wide challenges, including significant voltage violations across multiple regions, with some buses experiencing extreme deviations beyond ±10% of nominal values. The analysis highlighted substantial power transfer requirements between regions, particularly the heavy dependence of southern areas on northern generation, creating stressed transmission corridors with notable power losses. Voltage regulation emerged as a key concern, with both overvoltage and undervoltage conditions persisting in different parts of the network, indicating potential reactive power management issues. The simulation also exposed important load-generation imbalances, where certain regions relied on imports for over 90% of their demand. These findings collectively underscore the value of PowerFactory in identifying systemic vulnerabilities and optimization opportunities in national-scale power systems, providing utility operators with actionable insights for improving grid reliability and efficiency. The software's robust handling of this complex network, with its numerous buses, generators, and interconnections, confirms its suitability for large-scale power system analysis and planning.

The software's comprehensive visualization tools, including color-coded network diagrams and interactive result tables, proved particularly valuable for interpreting complex system behavior. This functionality significantly enhances its utility for both educational purposes and professional engineering applications. Additionally, the ability to quickly generate detailed technical reports containing all relevant system parameters represents another critical advantage for practical engineering work.

The study concludes that DigSILENT PowerFactory is a reliable, versatile tool for power system analysis.

VI. FUTURE RESEARCH

1) Advanced Contingency Scenarios: Expanding contingency analysis to include multiple simultaneous failures (e.g., N-2 or N-3 contingencies).

2) Short-Circuit Analysis with Renewable Integration: Extend PowerFactory's short-circuit studies to evaluate fault current contributions from inverter-based resources (solar/wind)

3) BESS Implementation for Voltage/Frequency Stability: Optimize BESS sizing and placement using PowerFactory's Optimal Power Flow tool for grid support during contingencies.

4) Transient Stability Studies: Simulate large disturbances to analyze rotor angle stability and critical clearing times.

5) Dynamic Analysis of Hybrid Systems: Combine PowerFactory's RMS and EMT simulations to study interactions between synchronous generators and power electronics (HVDC/BESS).

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