INTERNATIONAL BURCH UNIVERSITY

FACULTY OF ENGINEERING, NATURAL AND MEDICAL SCIENCES

DEPARTMENT OF ELECTRICAL AND ELECTRONICS ENGINEERING

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DISTRIBUTION SYSTEMS

Distribution System Analysis in DIgSILENT PowerFactory

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ABSTRACT

This report presents a detailed analysis of a modeled electrical network using DIgSILENT PowerFactory. This covers various aspects of power system engineering, including network modeling, power flow analysis, and short circuit analysis. Integration of renewable energy sources and optimal capacitor placement strategies are performed to improve network efficiency and stability. A total of 10 Labs are going to be examined in this complete lab report.

Additionally, the report dives into protection schemes and harmonic analysis to ensure robust system performance. The findings provide valuable insights for the design and optimization of modern electrical power systems. DIgSILENT is a software company that specializes in providing power system simulation and analysis tools. Their main product, PowerFactory, is a software solution used for the analysis, planning, and optimization of electrical power systems.

Keywords: DIgSILENT PowerFactory, distribution system, distribution network, power system, power flow analysis, short circuit analysis, renewable energy sources, compensation, optimal capacitor placement, protection schemes, network efficiency, network stability, harmonics

INTRODUCTION

DIgSILENT PowerFactory allows us to cover various aspects of power system engineering. Initially, Load Flow Analysis gives us information about calculation method for Power Flow, special conditions if they are set, and the Maximum Acceptable Load Flow Error. Power flow analysis is performed using Newton-Raphson and Gauss-Seidel Methods. The task is described. The modelled network is shown. Finally, the results of power flow analysis are to be obtained and discussed commenting aspects like power generation, consumption and losses.

Short circuit analysis in the network provided valuable insights into its behavior under various fault conditions. By simulating different types of faults at different locations in the network, we observed significant variations in current magnitude rises and voltage drops, showing the impact of each fault type. Comprehensive understanding of the network's response to various fault scenarios is essential for ensuring its reliability and safety in real-world operations.

PV systems produce electricity during the periods of high demand, especially during daylight hours. This helps reduce the stress on the grid during peak usage hours. PV systems inject power at distribution voltages, helping to stabilize voltage levels and improve overall grid reliability. Distributed PV systems decentralize power generation, offering backup power during outages and disruptions. Integration of PV systems can lead to savings for both utilities and consumers.

Hosting capacity has the main goal of evaluating how much solar energy our network can handle, both without a PV system and with five of them integrated. The concept of hosting capacity revolves around how well the electrical infrastructure can cope with the fluctuations of renewable energy generation. While traditional grids were built for one-way power flow, the rise of PV systems and other DERs means power can now flow in both directions, complicating the grid.

Strategically placing capacitors within the network busses improves the voltage profile. By conducting load flow analysis before and after compensation, we observed significant improvements in voltage profiles and certain reductions in both active (MW) and reactive (Mvar) power losses. All of this is called Optimal Capacitor Placement.

Through simulations, various disturbances such as voltage sags, swells, harmonics, and transients, each with its unique characteristics and effects on electrical systems are explored in detail. These disturbances can have significant impacts, causing equipment malfunctions and disrupting sensitive electronics and control systems. By studying these phenomena, insights into the complexities of power systems and the importance of being in quality electrical supply are gained.

Harmonics are additional frequencies generated when a periodic waveform deviates from its ideal form, often occurring as multiples of the fundamental frequency. They arise due to nonlinear operations or distortion in a signal, enriching its tonal characteristics. Overall, harmonic analysis is crucial for assessing power quality and ensuring efficient operation of electrical systems.

Protective relays play a crucial role in protecting distribution networks by monitoring for abnormalities like overcurrent, overvoltage, or underfrequency. Positioned strategically at substations and along feeders, these relays detect irregular conditions and activate measures to isolate faulty sections, preventing further damage. Simply put, this process involves setting up an overcurrent relay. The plots can be generated from the relay setups.

Electric vehicles (EVs) have become a promising solution for tackling environmental issues and reducing our dependency on traditional fossil fuels. However, integrating EVs into the power distribution network introduces both opportunities and challenges for managing the power system. A critical factor to consider is the impact of EVs on harmonic voltages within the network.

LAB 2 – POWER FLOW ANALYSIS (POWERFACTORY)

1. Problem Statement

For Lab 2, we had to model a Part of the Distribution Network "Gračanica" in DIgSILENT PowerFactory. Firstly, we modelled external 35 kV grid, 35 kV bus, 35/10 kV transformer, 10 kV bus and part of 10 kV network with 10/0,4 kV transformers and 0,4 kV busses and loads.

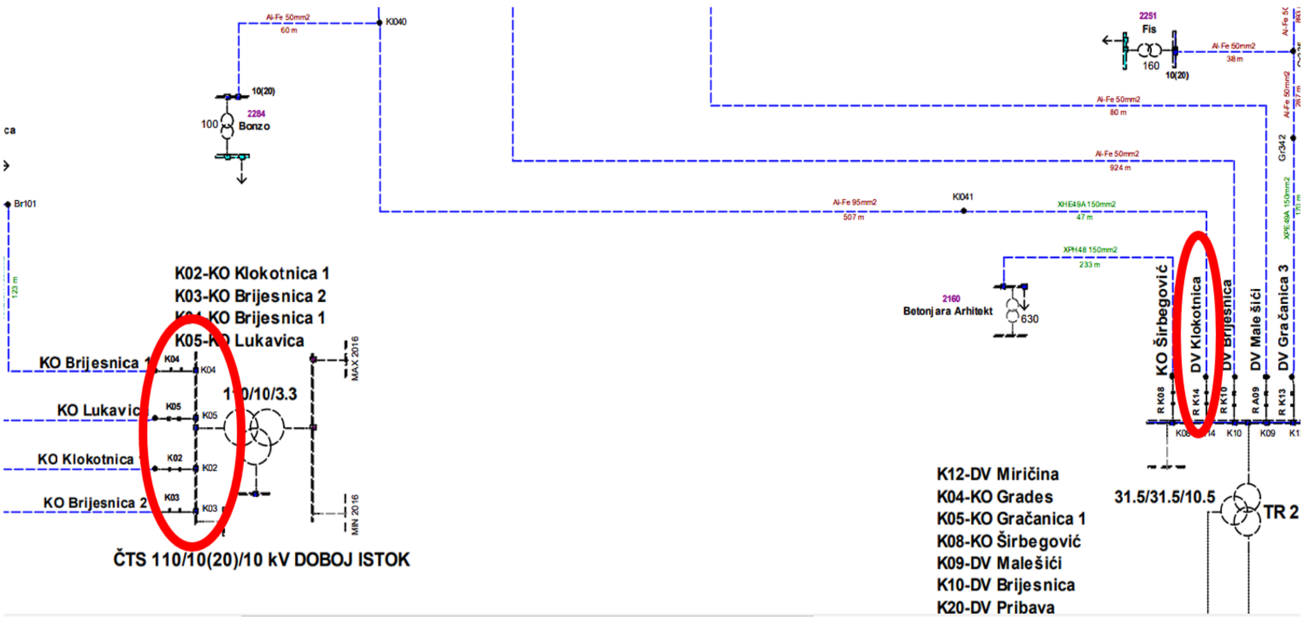

Figure 1. The Starting and Ending Points for the Network

Since we are limited to model the maximum of 50 busses, I had to model only a part of the 10 kV network, starting from DV Klokotnica. This took me all the way to ČTS Doboj Istok - Čvor Transformatorske Stanice, where the ending point of my project is. It took approximately 50 busses/nodes to get to this point of the network.

After modelling the network, power flow analysis was to be performed. Besides this, reports were generated as well.

2. The Modelled Network

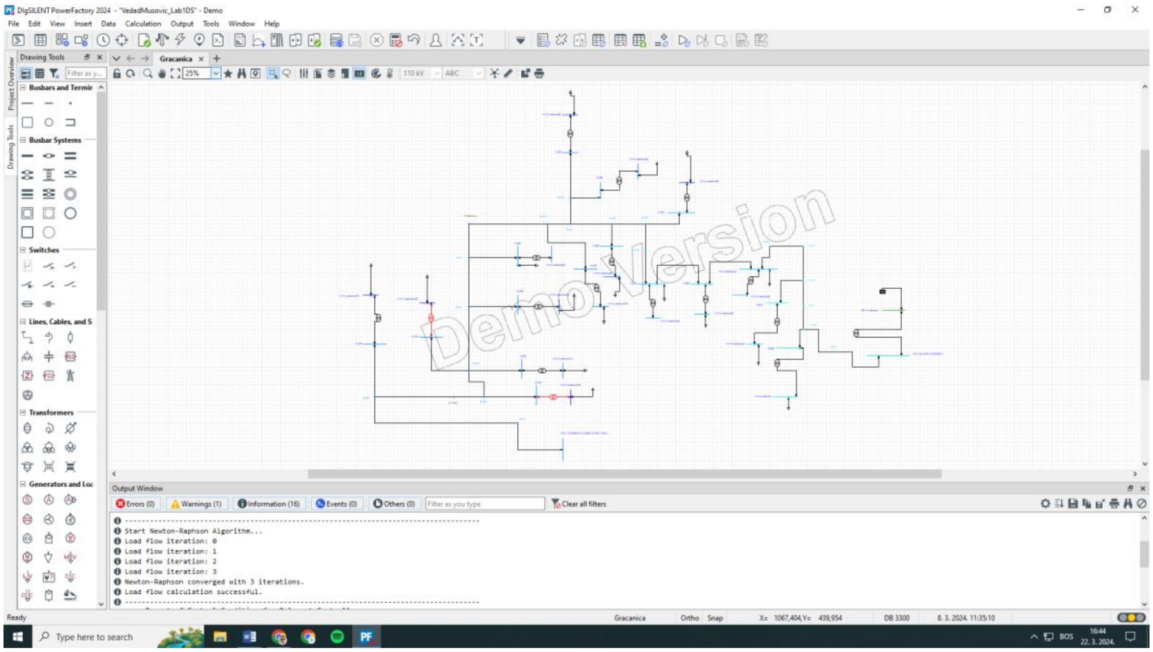

Figure 2. The Modelled Network – A View of the entire Network

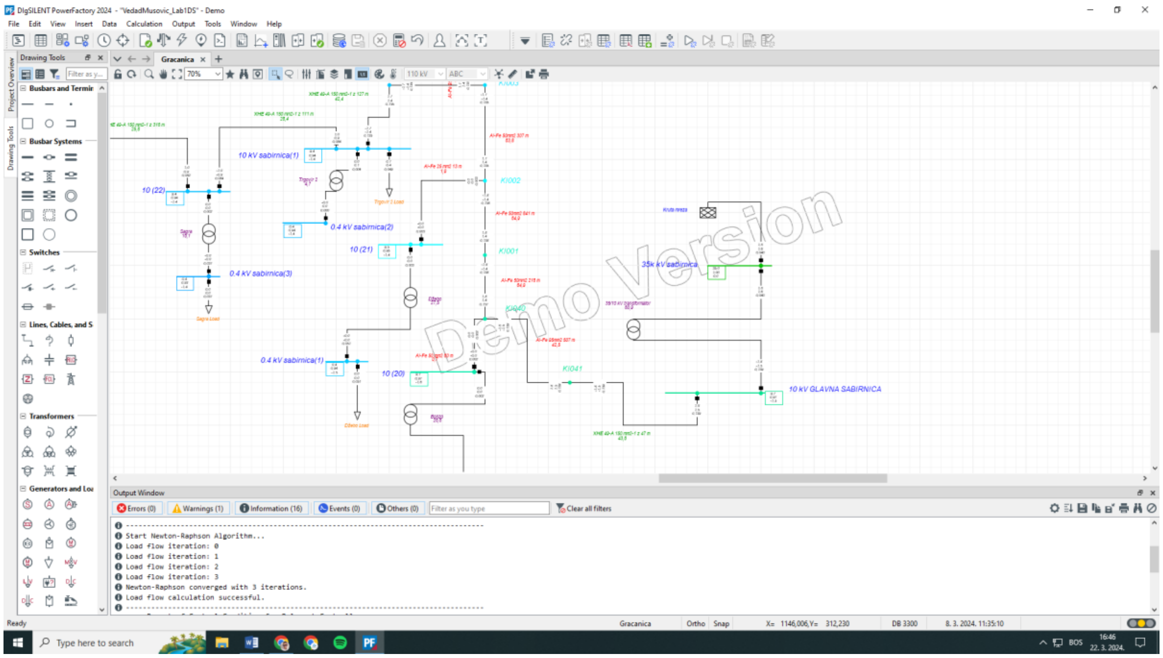

Figure 3. The External 35 kV Grid – The Starting Point

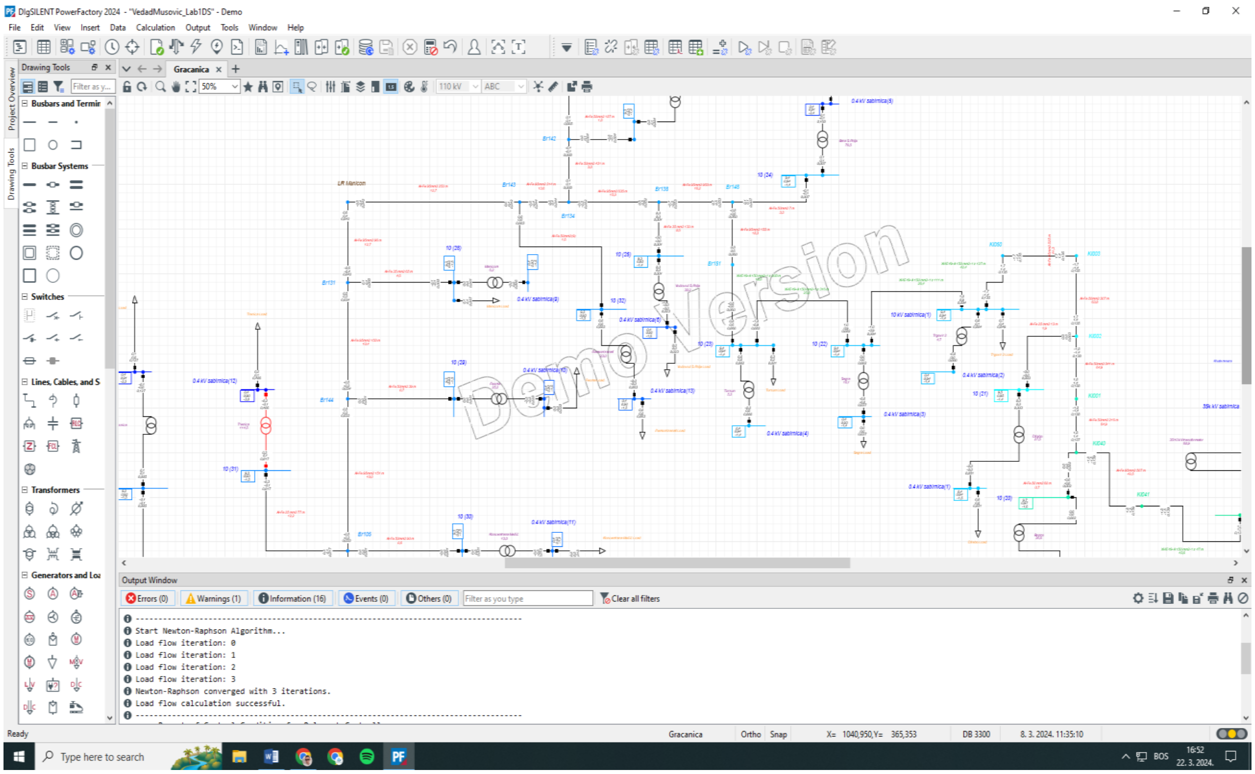

Figure 4. The Modelled Network

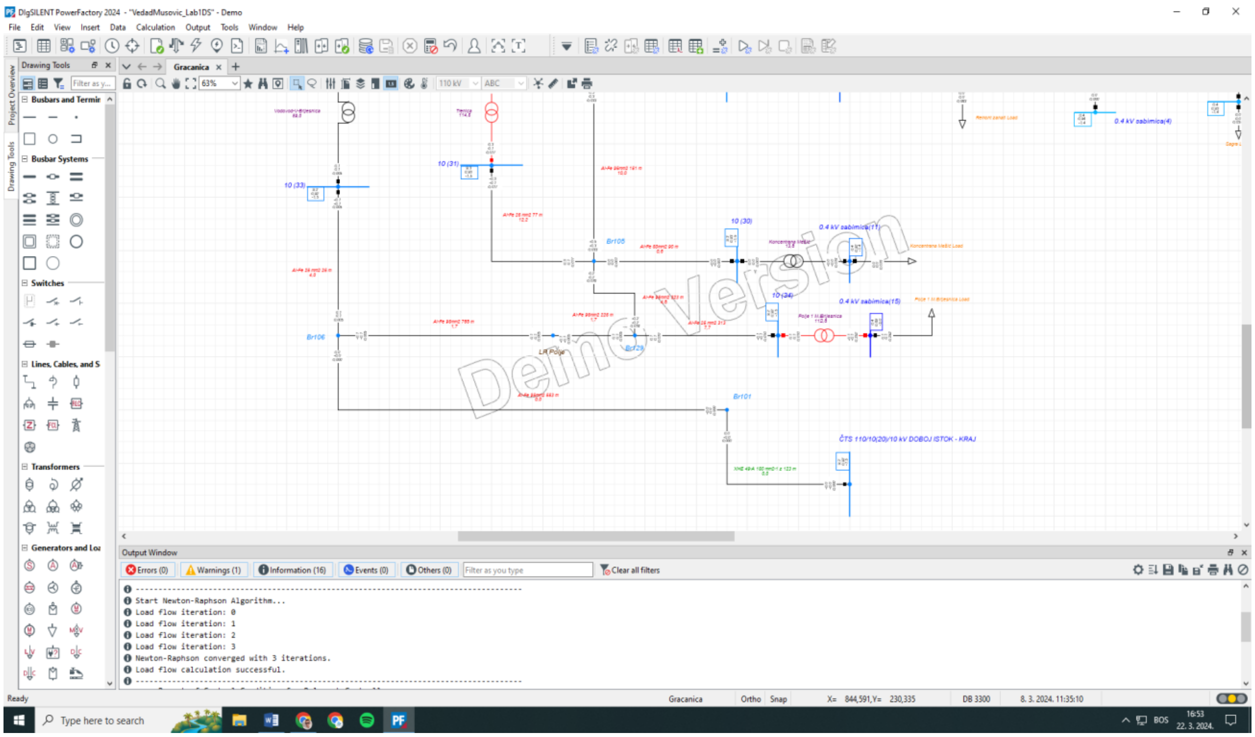

Figure 5. The End of the Network

The data from Excel tables was used to define busses, loads, transformers, cables and transmission lines. Nodes were also placed. They are also counted as a bus by DIgSILENT PowerFactory.

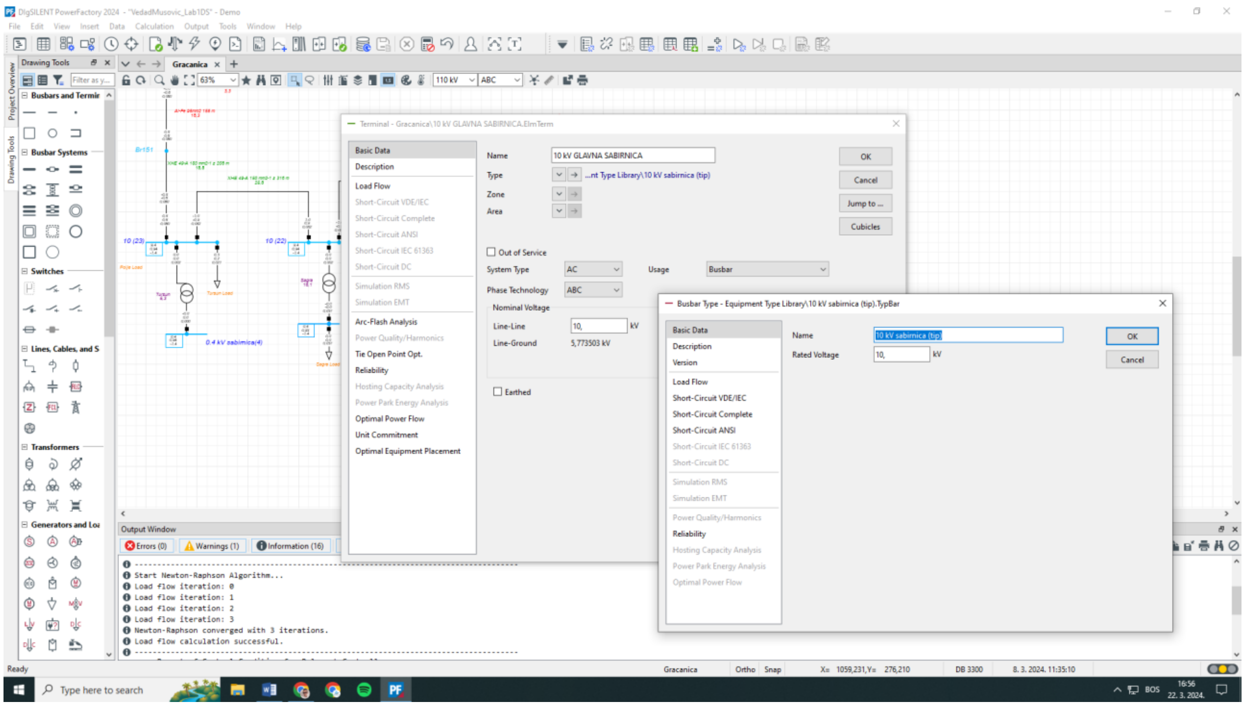

Figure 6. Example of how a Bus is modelled

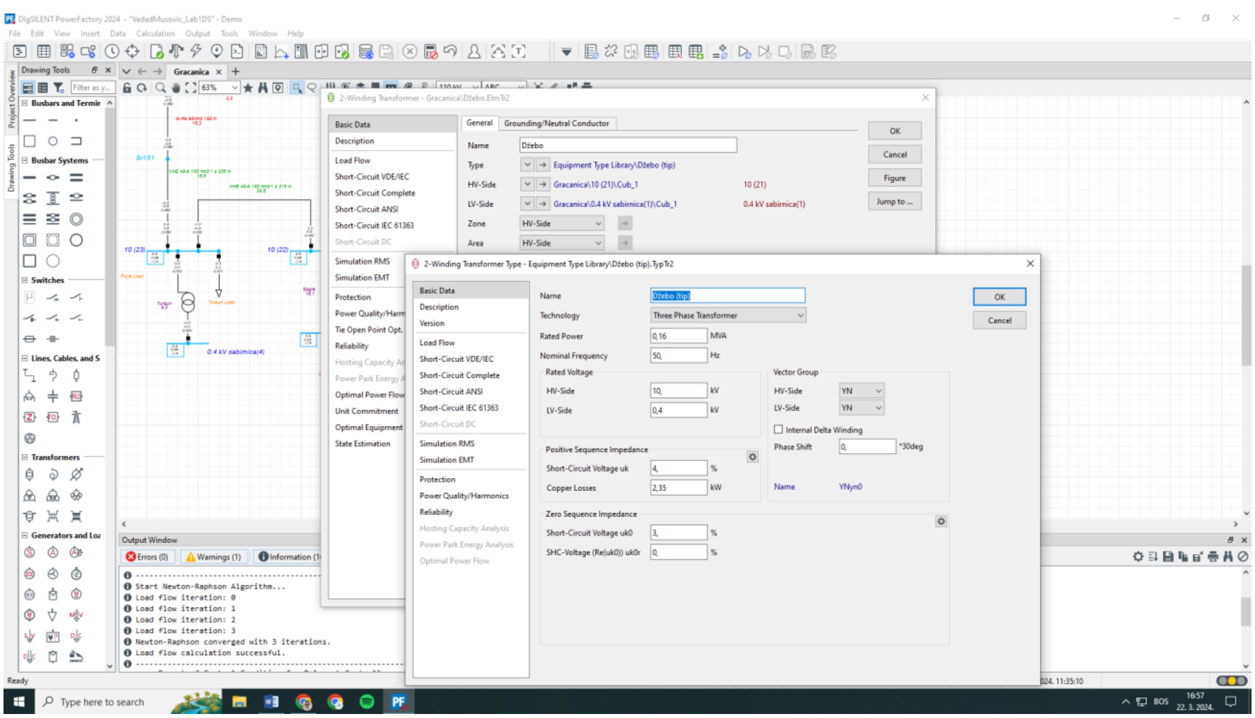

Figure 7. Example of how a Transformer is modelled

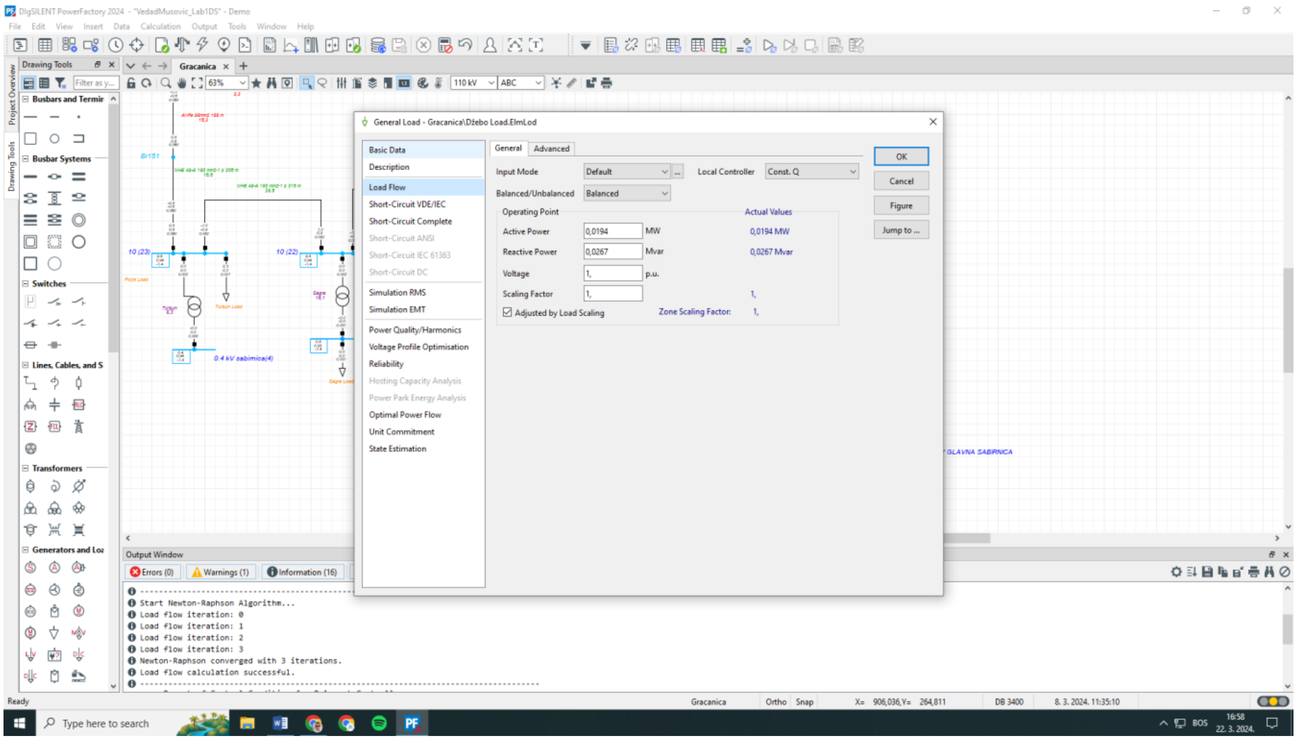

Figure 8. Example of how a Load is modelled

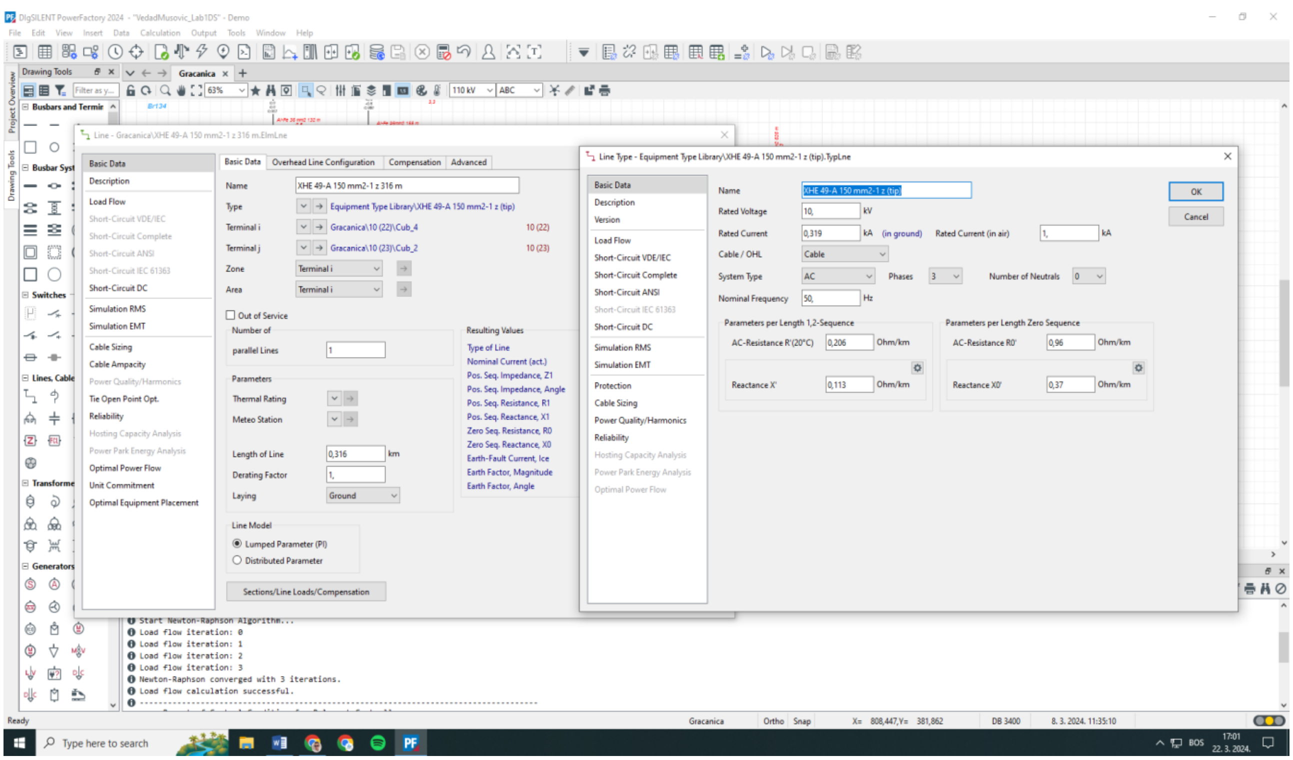

Figure 9. Example of how a Cable is modelled

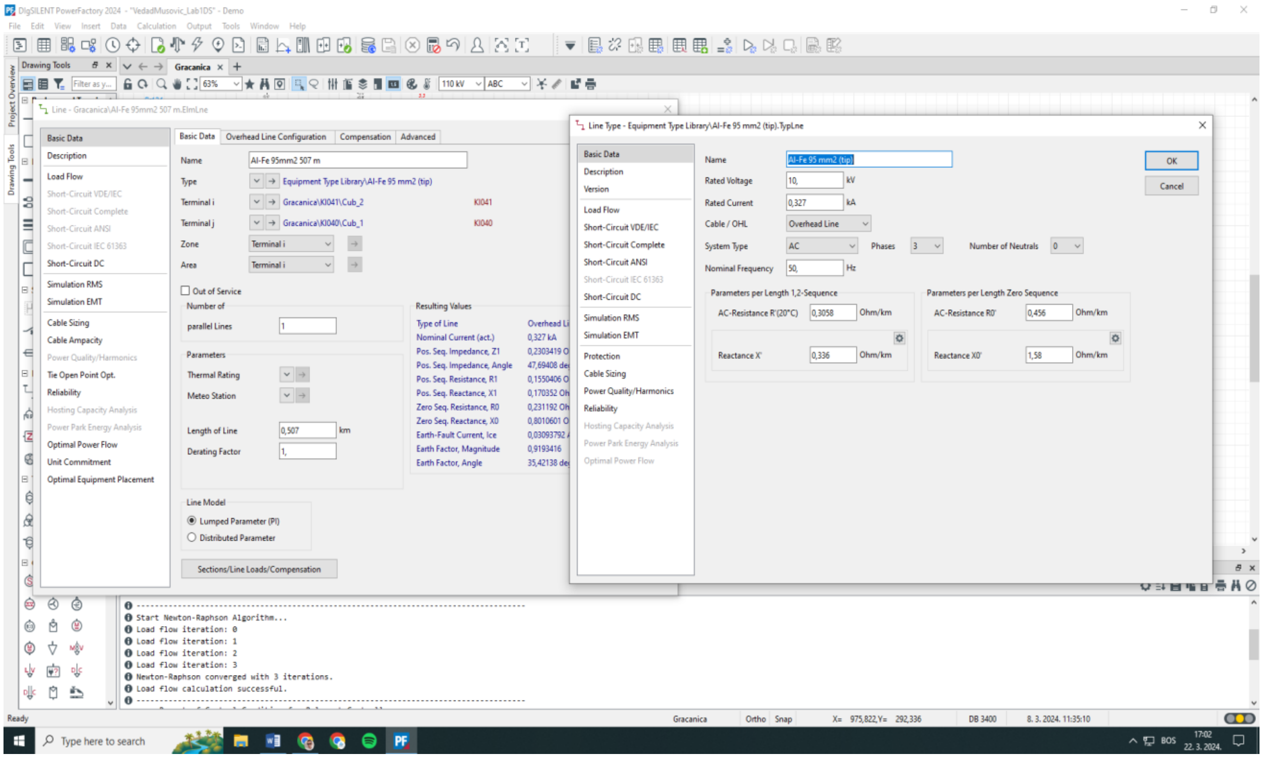

Figure 10. Example of how a Transmission Line is modelled

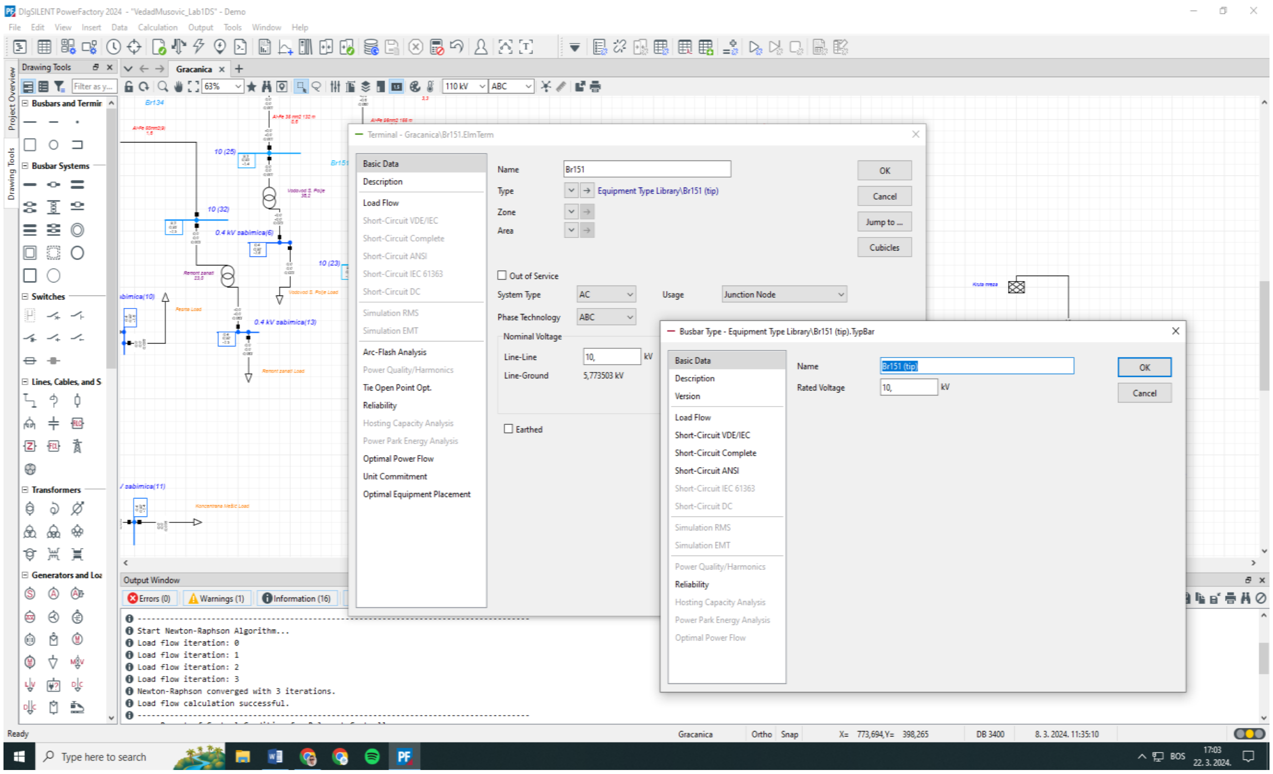

Figure 11. Example of how a Junction Node is modelled

When modelling busses, we need to make sure that the voltages are carefully put and do not differ from each. Transformers need to have their power defined in MVA, while our Excel data is in kVA. Short circuit voltage and copper losses are entered as well. The most important thing is to correctly set high voltage and low voltage sides for transformers. Also, for example, when connecting them to the circuit, we need to make sure that 10 kV side is connected to the 10 kV bus and 0.4 kV side to the 0.4 kV bus.

For Cable, the Cable/OHL is set to cable. The length is defined alongside resistance R, reactance X and conductance B in units/per length. They are defined for positive and negative sequences as one set of values, and for the zero-sequence as the other values.

For Transmission Line, the Cable/OHL is set to Overhead Line. Like for cables, the length is defined alongside resistance R, reactance X and conductance B in units/per length. Material of the transmission lines can also be changed. They are defined for positive and negative sequences as one set of values, and for the zero-sequence as the other values.

For Load, active and reactive power need to be specified, alongside the per unit voltage. It is the percentage difference between the first two voltages in “Potrosaci” Excel table.

Sabirnice	U_n [kV]	U [kV]	dU [%]

3. Power Flow Analysis

By pressing CTRL+F10, or by pressing the three arrows at the top menu, we perform Load Flow Analysis. AC Load Flow, Balanced, positive sequence is performed. The analysis succeeded, meaning that the Network was correctly modelled. The square windows of every component in the network had a values displayed in it, as shown in Figures from 2. The Modelled Network.

Additionally, in the output window, we get crucial info about the Load Flow Analysis. The Newton – Raphson algorithm was used to get the correct calculations. **Newton – Raphson method converged in 3 iterations.** This method takes more time per iteration, compared to Gauss – Seidel, but it converges in much less iterations. Control conditions for all controllers are successful.

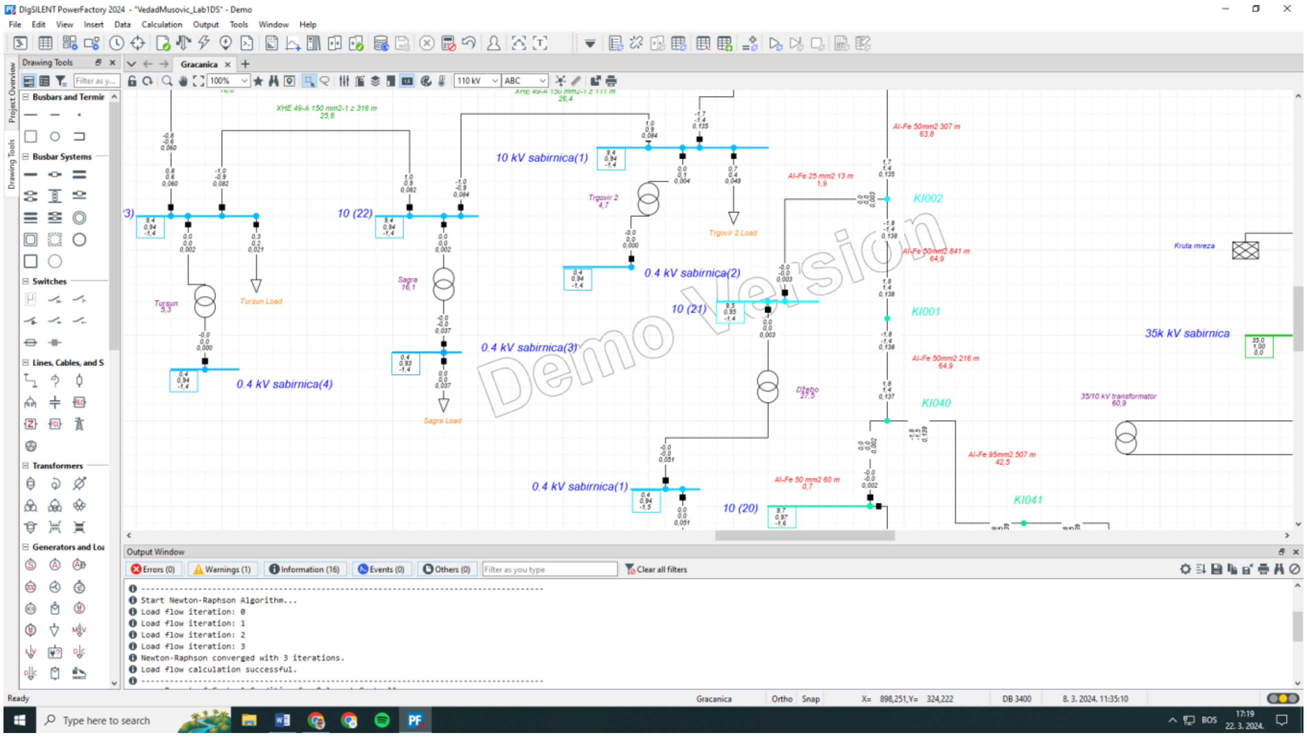

Figure 12. A closer View of the Values in Load Flow Analysis

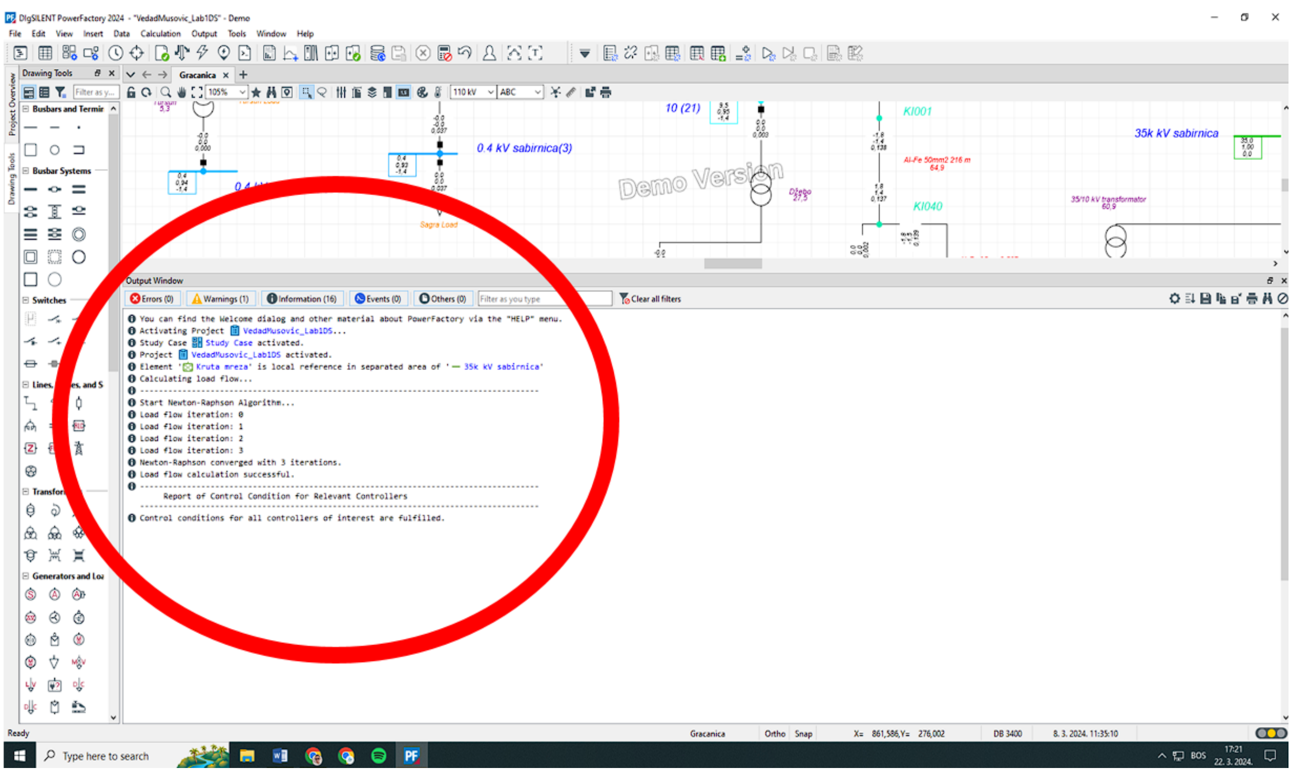

Figure 13. The Output Window

4. The Reports

22. 3. 2024.

Load Flow Calculation			
Calculation Method	AC Load Flow, balanced, positive sequence	Active Power Control	as Dispatched
Automatic tap adjustment of transformers	No	Balancing	by reference machine
Automatic tap adjustment of shunts	No	Load Flow Method	Newton-Raphson (Power Equations, classical)
Automatic tap adjustment of phase shifters	No	Max. Acceptable Load Flow Error:	
Consider active power limits	No	Bus Equations (HV)	1,0 kVA
Consider reactive power limits	No	Bus Equations (MV)	1,0 kVA
Temperature Dependency at	20°C	Bus Equations (LV)	0,0 kVA
Consider Voltage Dependency of Loads	No	Model Equations	0,1 %
Feeder Load Scaling	No		

Figure 14. Load Flow Report

22. 3. 2024.

Losses, Active Power (no load) MW	Losses, Reactive Power (no load) Mvar	
0,0	0,3	
External Networks, Active Power MW	External Networks, Reactive Power Mvar	External Networks, Apparent Power MVA
1,8	1,6	2,4

2.3 Additional Power Summary

Compensation, L Mvar	Compensation, C Mvar	
0,0	0,0	
Generators, Power Factor -	Loads, Power Factor -	Motor Loads, Power Factor -
0,000	0,834	0,000

2.4 Maximum/Minimum Summary

Maximum voltage of all terminals p.u.	Minimum voltage of all terminals p.u.	
1,000	0,887	
Maximum Loading %		
114,5		

2.5 Interchange Power Flow Summary

Interchange Power Flow To Other Grids	**Interchange Flow, Active Power MW**	**Interchange Flow, Reactive Power Mvar**
Total	0,0	0,0

Figure 15. Grid Summary Report

22. 3. 2024.

2 Gracanica

2.1 Overview

Number of Voltage Levels	Number of Connected Grids	No. of Substations	No. of Busbars	No. of Terminals	No. of Lines
3	0	0	35	20	37
No. of 2-w Trfs.	No. of 3-w Trfs.	No. of 4-w Trfs.	No. of syn. Machines	No. of asyn. Machines	No. of Static Generators
17	0	0	0	0	0
No. of PV Systems	No. of Loads	No. of SVS	No. of Shunts/Filters	No. of Other Elements	No. of Isolated Areas
0	16	0	0	1	1
No. of Unsupplied Isolated Areas					
0					

2.2 Power Summary

Generators, Active Power MW	Generators, Reactive Power Mvar	Generators, Apparent Power MVA
0,0	0,0	0,0
Generators, Nominal Active Power MW	Generators, Nominal Reactive Power Mvar	Generators, Nominal Apparent Power MVA
0,0	0,0	0,0
Generators, difference between maximum and actual active power MW	Generators, difference between maximum and actual reactive power Mvar	
0,0	0,0	
Loads, Active Power MW	Loads, Reactive Power Mvar	Loads, Apparent Power MVA
1,7	1,1	2,1
Loads, Nominal Active Power MW	Loads, Nominal Reactive Power Mvar	Loads, Nominal Apparent Power MVA
1,7	1,1	2,1
Loads, difference between nominal and actual active power MW	Loads, difference between nominal and actual reactive power Mvar	
0,0	0,0	
Motor Loads, Active Power MW	Motor Loads, Reactive Power Mvar	Motor Loads, Apparent Power MVA
0,0	0,0	0,0
Losses, Active Power MW	Losses, Reactive Power Mvar	
0,1	0,4	
Losses, Active Power (load) MW	Losses, Reactive Power (load) Mvar	
0,1	0,2	

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Figure 16. Grid Summary Report

In the following figures, Busbar/Terminals Report is presented to give us the network overview.

PF 22. 3. 2024.

Busbars/Terminals

1 Parameters

Lower Limit of Terminal Voltage p.u.	Upper Limit of Terminal Voltage p.u.	Lower Limit of Connected Elements Active Power MW	Upper Limit of Connected Elements Active Power MW	Show Connected Elements without Active Power	Minimum Loading of Connected Elements %
0,9	1,1	-10000	10000	Yes	30

2 Grids

2.1 Gracanica

Gracanica

2.1.1 Terminals

Terminals

Terminal	Nominal Line-Line Voltage kV	Voltage, Magnitude p.u.		Line-Line Voltage, Magnitude kV		Voltage, Angle deg	
0.4 kV sabirnica	0,4	0,957		0,4		-1,7	
	Name	Element type	Active Power MW	Reactive Power Mvar	Power Factor -	Current, Magnitude kA	Loading %
	Bonzo Load	General Load	0,0	0,0	0,778	0,031	
Terminal	Nominal Line-Line Voltage kV	Voltage, Magnitude p.u.		Line-Line Voltage, Magnitude kV		Voltage, Angle deg	
10 (34)	10,0	0,925		9,2		-1,5	
	Name	Element type	Active Power MW	Reactive Power Mvar	Power Factor -	Current, Magnitude kA	Loading %
	Polje 1 M.Brijesnica	2-Winding Transformer	0,1	0,1	0,786	0,010	112,8
Terminal	Nominal Line-Line Voltage kV	Voltage, Magnitude p.u.		Line-Line Voltage, Magnitude kV		Voltage, Angle deg	
10 kV GLAVNA SABIRNICA	10,0	0,972		9,7		-1,5	
	Name	Element type	Active Power MW	Reactive Power Mvar	Power Factor -	Current, Magnitude kA	Loading %
	35/10 kV transformator	2-Winding Transformer	-1,8	-1,5	-0,780	0,139	60,9
	XHE 49-A 150 mm2-1 z 47 m	Line	1,8	1,5	0,780	0,139	43,6
Terminal	Nominal Line-Line Voltage kV	Voltage, Magnitude p.u.		Line-Line Voltage, Magnitude kV		Voltage, Angle deg	
10 kV sabirnica(1)	10,0	0,938		9,4		-1,4	
	Name	Element type	Active Power MW	Reactive Power Mvar	Power Factor -	Current, Magnitude kA	Loading %

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Figure 17. Busbar/Terminals Report

PF 22. 3. 2024.

	XHE 49-A 150 mm2-1 z 127 m	Line	-1,7	-1,4	-0,785	0,135	42,4
	Trgovir 2 Load	General Load	0,7	0,4	0,860	0,049	
Terminal	**Nominal Line-Line Voltage kV**	**Voltage, Magnitude p.u.**		**Line-Line Voltage, Magnitude kV**		**Voltage, Angle deg**	
35k kV sabirnica	35,0	1,000		35,0		0,0	
	Name	**Element type**	**Active Power MW**	**Reactive Power Mvar**	**Power Factor -**	**Current, Magnitude kA**	**Loading %**
	35/10 kV transformator	2-Winding Transformer	1,8	1,6	0,756	0,040	60,9
	Kruta mreza	External Grid	1,8	1,6	0,756	0,040	
Terminal	**Nominal Line-Line Voltage kV**	**Voltage, Magnitude p.u.**		**Line-Line Voltage, Magnitude kV**		**Voltage, Angle deg**	
Br101	10,0	0,925		9,2		-1,5	
	Name	**Element type**	**Active Power MW**	**Reactive Power Mvar**	**Power Factor -**	**Current, Magnitude kA**	**Loading %**
Terminal	**Nominal Line-Line Voltage kV**	**Voltage, Magnitude p.u.**		**Line-Line Voltage, Magnitude kV**		**Voltage, Angle deg**	
Br105	10,0	0,926		9,3		-1,5	
	Name	**Element type**	**Active Power MW**	**Reactive Power Mvar**	**Power Factor -**	**Current, Magnitude kA**	**Loading %**
Terminal	**Nominal Line-Line Voltage kV**	**Voltage, Magnitude p.u.**		**Line-Line Voltage, Magnitude kV**		**Voltage, Angle deg**	
Br106	10,0	0,925		9,2		-1,5	
	Name	**Element type**	**Active Power MW**	**Reactive Power Mvar**	**Power Factor -**	**Current, Magnitude kA**	**Loading %**
Terminal	**Nominal Line-Line Voltage kV**	**Voltage, Magnitude p.u.**		**Line-Line Voltage, Magnitude kV**		**Voltage, Angle deg**	
Br129	10,0	0,925		9,3		-1,5	
	Name	**Element type**	**Active Power MW**	**Reactive Power Mvar**	**Power Factor -**	**Current, Magnitude kA**	**Loading %**
Terminal	**Nominal Line-Line Voltage kV**	**Voltage, Magnitude p.u.**		**Line-Line Voltage, Magnitude kV**		**Voltage, Angle deg**	
Br131	10,0	0,927		9,3		-1,5	
	Name	**Element type**	**Active Power MW**	**Reactive Power Mvar**	**Power Factor -**	**Current, Magnitude kA**	**Loading %**
Terminal	**Nominal Line-Line Voltage kV**	**Voltage, Magnitude p.u.**		**Line-Line Voltage, Magnitude kV**		**Voltage, Angle deg**	
Br134	10,0	0,929		9,3		-1,5	

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Figure 18. Busbar/Terminals Report

PF 22. 3. 2024.

	Name	Element type	Active Power MW	Reactive Power Mvar	Power Factor -	Current, Magnitude kA	Loading %
Terminal	Nominal Line-Line Voltage kV	Voltage, Magnitude p.u.		Line-Line Voltage, Magnitude kV		Voltage, Angle deg	
Br138	10,0	0,931		9,3		-1,4	
	Name	Element type	Active Power MW	Reactive Power Mvar	Power Factor -	Current, Magnitude kA	Loading %
Terminal	Nominal Line-Line Voltage kV	Voltage, Magnitude p.u.		Line-Line Voltage, Magnitude kV		Voltage, Angle deg	
Br142	10,0	0,928		9,3		-1,5	
	Name	Element type	Active Power MW	Reactive Power Mvar	Power Factor -	Current, Magnitude kA	Loading %
Terminal	Nominal Line-Line Voltage kV	Voltage, Magnitude p.u.		Line-Line Voltage, Magnitude kV		Voltage, Angle deg	
Br143	10,0	0,928		9,3		-1,5	
	Name	Element type	Active Power MW	Reactive Power Mvar	Power Factor -	Current, Magnitude kA	Loading %
Terminal	Nominal Line-Line Voltage kV	Voltage, Magnitude p.u.		Line-Line Voltage, Magnitude kV		Voltage, Angle deg	
Br144	10,0	0,926		9,3		-1,5	
	Name	Element type	Active Power MW	Reactive Power Mvar	Power Factor -	Current, Magnitude kA	Loading %
Terminal	Nominal Line-Line Voltage kV	Voltage, Magnitude p.u.		Line-Line Voltage, Magnitude kV		Voltage, Angle deg	
Br148	10,0	0,935		9,4		-1,4	
	Name	Element type	Active Power MW	Reactive Power Mvar	Power Factor -	Current, Magnitude kA	Loading %
Terminal	Nominal Line-Line Voltage kV	Voltage, Magnitude p.u.		Line-Line Voltage, Magnitude kV		Voltage, Angle deg	
Br151	10,0	0,936		9,4		-1,4	
	Name	Element type	Active Power MW	Reactive Power Mvar	Power Factor -	Current, Magnitude kA	Loading %
Terminal	Nominal Line-Line Voltage kV	Voltage, Magnitude p.u.		Line-Line Voltage, Magnitude kV		Voltage, Angle deg	
KI001	10,0	0,963		9,6		-1,5	
	Name	Element type	Active Power MW	Reactive Power Mvar	Power Factor -	Current, Magnitude kA	Loading %
	Al-Fe 50mm2 841 m	Line	1,8	1,4	0,782	0,138	64,9

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Figure 19. Busbar/Terminals Report

	Al-Fe 50mm2 216 m	Line	-1,8	-1,4	-0,782	0,138	64,9
Terminal	**Nominal Line-Line Voltage kV**	**Voltage, Magnitude p.u.**		**Line-Line Voltage, Magnitude kV**		**Voltage, Angle deg**	
KI002	10,0	0,949		9,5		-1,4	
	Name	**Element type**	**Active Power MW**	**Reactive Power Mvar**	**Power Factor -**	**Current, Magnitude kA**	**Loading %**
	Al-Fe 50mm2 841 m	Line	-1,8	-1,4	-0,780	0,138	64,9
	Al-Fe 50mm2 307 m	Line	1,7	1,4	0,785	0,135	63,8
Terminal	**Nominal Line-Line Voltage kV**	**Voltage, Magnitude p.u.**		**Line-Line Voltage, Magnitude kV**		**Voltage, Angle deg**	
KI003	10,0	0,944		9,4		-1,4	
	Name	**Element type**	**Active Power MW**	**Reactive Power Mvar**	**Power Factor -**	**Current, Magnitude kA**	**Loading %**
	Al-Fe 50mm2 307 m	Line	-1,7	-1,4	-0,784	0,135	63,8
	Al-Fe 95mm2 525 m	Line	1,7	1,4	0,784	0,135	41,3
Terminal	**Nominal Line-Line Voltage kV**	**Voltage, Magnitude p.u.**		**Line-Line Voltage, Magnitude kV**		**Voltage, Angle deg**	
KI040	10,0	0,966		9,7		-1,6	
	Name	**Element type**	**Active Power MW**	**Reactive Power Mvar**	**Power Factor -**	**Current, Magnitude kA**	**Loading %**
	Al-Fe 50mm2 216 m	Line	1,8	1,4	0,782	0,137	64,9
	Al-Fe 95mm2 507 m	Line	-1,8	-1,5	-0,781	0,139	42,5
Terminal	**Nominal Line-Line Voltage kV**	**Voltage, Magnitude p.u.**		**Line-Line Voltage, Magnitude kV**		**Voltage, Angle deg**	
KI041	10,0	0,972		9,7		-1,5	
	Name	**Element type**	**Active Power MW**	**Reactive Power Mvar**	**Power Factor -**	**Current, Magnitude kA**	**Loading %**
	XHE 49-A 150 mm2-1 z 47 m	Line	-1,8	-1,5	-0,780	0,139	43,6
	Al-Fe 95mm2 507 m	Line	1,8	1,5	0,780	0,139	42,5
Terminal	**Nominal Line-Line Voltage kV**	**Voltage, Magnitude p.u.**		**Line-Line Voltage, Magnitude kV**		**Voltage, Angle deg**	
KI050	10,0	0,939		9,4		-1,4	
	Name	**Element type**	**Active Power MW**	**Reactive Power Mvar**	**Power Factor -**	**Current, Magnitude kA**	**Loading %**
	XHE 49-A 150 mm2-1 z 127 m	Line	1,7	1,4	0,785	0,135	42,4

Figure 20. Busbar/Terminals Report

	Al-Fe 95mm2 525 m	Line	-1,7	-1,4	-0,785	0,135	41,3
Terminal	**Nominal Line-Line Voltage kV**	**Voltage, Magnitude p.u.**		**Line-Line Voltage, Magnitude kV**		**Voltage, Angle deg**	
LR Manicom	10,0	0,927		9,3		-1,5	
	Name	**Element type**	**Active Power MW**	**Reactive Power Mvar**	**Power Factor -**	**Current, Magnitude kA**	**Loading %**
Terminal	**Nominal Line-Line Voltage kV**	**Voltage, Magnitude p.u.**		**Line-Line Voltage, Magnitude kV**		**Voltage, Angle deg**	
10 (33)	10,0	0,925		9,2		-1,5	
	Name	**Element type**	**Active Power MW**	**Reactive Power Mvar**	**Power Factor -**	**Current, Magnitude kA**	**Loading %**
	Vodovod-V-Brijesnica	2-Winding Transformer	0,1	0,1	0,769	0,005	59,0
Terminal	**Nominal Line-Line Voltage kV**	**Voltage, Magnitude p.u.**		**Line-Line Voltage, Magnitude kV**		**Voltage, Angle deg**	
LR Polje	10,0	0,925		9,3		-1,5	
	Name	**Element type**	**Active Power MW**	**Reactive Power Mvar**	**Power Factor -**	**Current, Magnitude kA**	**Loading %**
Terminal	**Nominal Line-Line Voltage kV**	**Voltage, Magnitude p.u.**		**Line-Line Voltage, Magnitude kV**		**Voltage, Angle deg**	
10 (32)	10,0	0,928		9,3		-1,5	
	Name	**Element type**	**Active Power MW**	**Reactive Power Mvar**	**Power Factor -**	**Current, Magnitude kA**	**Loading %**
Terminal	**Nominal Line-Line Voltage kV**	**Voltage, Magnitude p.u.**		**Line-Line Voltage, Magnitude kV**		**Voltage, Angle deg**	
10 (30)	10,0	0,926		9,3		-1,5	
	Name	**Element type**	**Active Power MW**	**Reactive Power Mvar**	**Power Factor -**	**Current, Magnitude kA**	**Loading %**
Terminal	**Nominal Line-Line Voltage kV**	**Voltage, Magnitude p.u.**		**Line-Line Voltage, Magnitude kV**		**Voltage, Angle deg**	
0.4 kV sabirnica(1)	0,4	0,939		0,4		-1,5	
	Name	**Element type**	**Active Power MW**	**Reactive Power Mvar**	**Power Factor -**	**Current, Magnitude kA**	**Loading %**
	Džebo Load	General Load	0,0	0,0	0,588	0,051	
Terminal	**Nominal Line-Line Voltage kV**	**Voltage, Magnitude p.u.**		**Line-Line Voltage, Magnitude kV**		**Voltage, Angle deg**	
0.4 kV sabirnica(10)	0,4	0,917		0,4		-1,6	

Figure 21. Busbar/Terminals Report

22. 3. 2024.

Terminal	Name	Element type	Active Power MW	Reactive Power Mvar	Power Factor -	Current, Magnitude kA	Loading %
	Fesma Load	General Load	0,0	0,0	0,625	0,028	

Terminal	Nominal Line-Line Voltage kV	Voltage, Magnitude p.u.	Line-Line Voltage, Magnitude kV	Voltage, Angle deg
0.4 kV sabirnica(11)	0,4	0,922	0,4	-1,4

Terminal	Name	Element type	Active Power MW	Reactive Power Mvar	Power Factor -	Current, Magnitude kA	Loading %
0.4 kV sabirnica(11)	Koncentrana Mešić Load	General Load	0,0	0,0	0,141	0,018	

Terminal	Nominal Line-Line Voltage kV	Voltage, Magnitude p.u.	Line-Line Voltage, Magnitude kV	Voltage, Angle deg
0.4 kV sabirnica(13)	0,4	0,919	0,4	-1,5

Terminal	Name	Element type	Active Power MW	Reactive Power Mvar	Power Factor -	Current, Magnitude kA	Loading %
0.4 kV sabirnica(13)	Remont zanati Load	General Load	0,0	0,0	0,486	0,063	

Terminal	Nominal Line-Line Voltage kV	Voltage, Magnitude p.u.	Line-Line Voltage, Magnitude kV	Voltage, Angle deg
0.4 kV sabirnica(14)	0,4	0,905	0,4	-2,3

Terminal	Name	Element type	Active Power MW	Reactive Power Mvar	Power Factor -	Current, Magnitude kA	Loading %
0.4 kV sabirnica(14)	Vodovod-V-Brijesnica	2-Winding Transformer	-0,1	-0,0	-0,827	0,127	59,0
	Vodovod V.Brijesnica Load	General Load	0,1	0,0	0,827	0,127	

Terminal	Nominal Line-Line Voltage kV	Voltage, Magnitude p.u.	Line-Line Voltage, Magnitude kV	Voltage, Angle deg
0.4 kV sabirnica(2)	0,4	0,936	0,4	-1,4

Terminal	Name	Element type	Active Power MW	Reactive Power Mvar	Power Factor -	Current, Magnitude kA	Loading %
0.4 kV sabirnica(2)							

Terminal	Nominal Line-Line Voltage kV	Voltage, Magnitude p.u.	Line-Line Voltage, Magnitude kV	Voltage, Angle deg
0.4 kV sabirnica(3)	0,4	0,932	0,4	-1,4

Terminal	Name	Element type	Active Power MW	Reactive Power Mvar	Power Factor -	Current, Magnitude kA	Loading %
0.4 kV sabirnica(3)	Sagra Load	General Load	0,0	0,0	0,364	0,037	

Terminal	Nominal Line-Line Voltage kV	Voltage, Magnitude p.u.	Line-Line Voltage, Magnitude kV	Voltage, Angle deg
0.4 kV sabirnica(4)	0,4	0,935	0,4	-1,4

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Figure 22. Busbar/Terminals Report

	Name	Element type	Active Power MW	Reactive Power Mvar	Power Factor -	Current, Magnitude kA	Loading %
Terminal	Nominal Line-Line Voltage kV	Voltage, Magnitude p.u.		Line-Line Voltage, Magnitude kV		Voltage, Angle deg	
0.4 kV sabirnica(5)	0,4	0,910		0,4		-2,4	
	Name	Element type	Active Power MW	Reactive Power Mvar	Power Factor -	Current, Magnitude kA	Loading %
	Bare S. Polje	2-Winding Transformer	-0,1	-0,1	-0,842	0,168	76,5
	Bare S. Polje Load	General Load	0,1	0,1	0,842	0,168	
Terminal	Nominal Line-Line Voltage kV	Voltage, Magnitude p.u.		Line-Line Voltage, Magnitude kV		Voltage, Angle deg	
0.4 kV sabirnica(6)	0,4	0,917		0,4		-1,6	
	Name	Element type	Active Power MW	Reactive Power Mvar	Power Factor -	Current, Magnitude kA	Loading %
	Vodovod S. Polje	2-Winding Transformer	-0,0	-0,0	-0,724	0,023	38,2
	Vodovod S. Polje Load	General Load	0,0	0,0	0,724	0,023	
Terminal	Nominal Line-Line Voltage kV	Voltage, Magnitude p.u.		Line-Line Voltage, Magnitude kV		Voltage, Angle deg	
0.4 kV sabirnica(7)	0,4	0,923		0,4		-1,4	
	Name	Element type	Active Power MW	Reactive Power Mvar	Power Factor -	Current, Magnitude kA	Loading %
	Kantić Kompany Load	General Load	0,0	0,0	0,223	0,066	
Terminal	Nominal Line-Line Voltage kV	Voltage, Magnitude p.u.		Line-Line Voltage, Magnitude kV		Voltage, Angle deg	
0.4 kV sabirnica(8)	0,4	0,911		0,4		-2,0	
	Name	Element type	Active Power MW	Reactive Power Mvar	Power Factor -	Current, Magnitude kA	Loading %
	Polje 2 M. Brijesnica	2-Winding Transformer	-0,1	-0,0	-0,802	0,107	50,3
	Polje 2 M. Brijesnica Load	General Load	0,1	0,0	0,802	0,107	
Terminal	Nominal Line-Line Voltage kV	Voltage, Magnitude p.u.		Line-Line Voltage, Magnitude kV		Voltage, Angle deg	
0.4 kV sabirnica(9)	0,4	0,925		0,4		-1,5	
	Name	Element type	Active Power MW	Reactive Power Mvar	Power Factor -	Current, Magnitude kA	Loading %
Terminal	Nominal Line-Line Voltage kV	Voltage, Magnitude p.u.		Line-Line Voltage, Magnitude kV		Voltage, Angle deg	

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Figure 23. Busbar/Terminals Report

10 (20)	10,0	0,966		9,7		-1,6	
	Name	Element type	Active Power MW	Reactive Power Mvar	Power Factor -	Current, Magnitude kA	Loading %
Terminal	Nominal Line-Line Voltage kV	Voltage, Magnitude p.u.		Line-Line Voltage, Magnitude kV		Voltage, Angle deg	
10 (21)	10,0	0,949		9,5		-1,4	
	Name	Element type	Active Power MW	Reactive Power Mvar	Power Factor -	Current, Magnitude kA	Loading %
Terminal	Nominal Line-Line Voltage kV	Voltage, Magnitude p.u.		Line-Line Voltage, Magnitude kV		Voltage, Angle deg	
10 (22)	10,0	0,937		9,4		-1,4	
	Name	Element type	Active Power MW	Reactive Power Mvar	Power Factor -	Current, Magnitude kA	Loading %
Terminal	Nominal Line-Line Voltage kV	Voltage, Magnitude p.u.		Line-Line Voltage, Magnitude kV		Voltage, Angle deg	
10 (23)	10,0	0,936		9,4		-1,4	
	Name	Element type	Active Power MW	Reactive Power Mvar	Power Factor -	Current, Magnitude kA	Loading %
	Tursun Load	General Load	0,3	0,2	0,790	0,021	
Terminal	Nominal Line-Line Voltage kV	Voltage, Magnitude p.u.		Line-Line Voltage, Magnitude kV		Voltage, Angle deg	
10 (24)	10,0	0,935		9,4		-1,4	
	Name	Element type	Active Power MW	Reactive Power Mvar	Power Factor -	Current, Magnitude kA	Loading %
	Bare S. Polje	2-Winding Transformer	0,1	0,1	0,794	0,007	76,5
Terminal	Nominal Line-Line Voltage kV	Voltage, Magnitude p.u.		Line-Line Voltage, Magnitude kV		Voltage, Angle deg	
10 (25)	10,0	0,931		9,3		-1,4	
	Name	Element type	Active Power MW	Reactive Power Mvar	Power Factor -	Current, Magnitude kA	Loading %
	Vodovod S. Polje	2-Winding Transformer	0,0	0,0	0,623	0,001	38,2
Terminal	Nominal Line-Line Voltage kV	Voltage, Magnitude p.u.		Line-Line Voltage, Magnitude kV		Voltage, Angle deg	
10 (26)	10,0	0,928		9,3		-1,4	
	Name	Element type	Active Power MW	Reactive Power Mvar	Power Factor -	Current, Magnitude kA	Loading %

Figure 24. Busbar/Terminals Report

Terminal	Nominal Line-Line Voltage kV	Voltage, Magnitude p.u.	Line-Line Voltage, Magnitude kV	Voltage, Angle deg
10 (27)	10,0	0,928	9,3	-1,4

Name	Element type	Active Power MW	Reactive Power Mvar	Power Factor -	Current, Magnitude kA	Loading %
Polje 2 M. Brijesnica	2-Winding Transformer	0,1	0,1	0,735	0,005	50,3

Terminal	Nominal Line-Line Voltage kV	Voltage, Magnitude p.u.	Line-Line Voltage, Magnitude kV	Voltage, Angle deg
10 (28)	10,0	0,926	9,3	-1,5

Name	Element type	Active Power MW	Reactive Power Mvar	Power Factor -	Current, Magnitude kA	Loading %
Manicom Load	General Load	0,1	0,1	0,820	0,007	

Terminal	Nominal Line-Line Voltage kV	Voltage, Magnitude p.u.	Line-Line Voltage, Magnitude kV	Voltage, Angle deg
10 (29)	10,0	0,926	9,3	-1,5

Name	Element type	Active Power MW	Reactive Power Mvar	Power Factor -	Current, Magnitude kA	Loading %

Terminal	Nominal Line-Line Voltage kV	Voltage, Magnitude p.u.	Line-Line Voltage, Magnitude kV	Voltage, Angle deg
10 (31)	10,0	0,925	9,3	-1,5

Name	Element type	Active Power MW	Reactive Power Mvar	Power Factor -	Current, Magnitude kA	Loading %
Trenica	2-Winding Transformer	0,3	0,1	0,947	0,017	114,5

Terminal	Nominal Line-Line Voltage kV	Voltage, Magnitude p.u.	Line-Line Voltage, Magnitude kV	Voltage, Angle deg
ČTS 110/10(20)/10 kV DOBOJ ISTOK - KRAJ	10,0	0,925	9,2	-1,5

Name	Element type	Active Power MW	Reactive Power Mvar	Power Factor -	Current, Magnitude kA	Loading %

Figure 25. Busbar/Terminals Report

5. Conclusion

Successful run of Load Flow Analysis ensures that our network functions properly. As mentioned, Newton – Raphson method converged in 3 iterations. Following this, the reports can be printed. The following reports are printed:

- Load Flow Report gives us information about calculation method for Power Flow, special conditions if they are set, and the Maximum Acceptable Load Flow Error.

- Grid Summary Report focuses on losses and external network active/reactive/apparent power. Power factors of the loads are also given to us. Per unit maximum and minimum voltages are given. They are in acceptable range close to 1 which ensures that our network functions properly.

Additionally, an overview of the network yields the following information:

* Number of Voltage Levels (3) – 35 kV, 10 kV and 0.4 kV

* Number of Busbars - 35

* Number of Terminals - 20

* Number of Lines/Cables – 37

* Number of 2-Winding Transformers – 17

* Number of Other Elements (1) – Kruta Mreža

Finally, in the Power Summary we obtain additional info about active/reactive/apparent powers for generators and motors (if they are present) and loads. Nominal powers are calculated as well to get the difference between the nominal and actual active power. Losses are also calculated.

- Busbar/Terminals Report contains data about every busbar/node in the network and any component connected to it. Firstly, for the busbar/node we have the nominal line-to-line voltage (kV), voltage magnitude in per unit, line-to-line voltage magnitude (kV) and voltage angle in deg.

When it comes to the elements that connect to the busbar/terminal we get info about their name, the element type (line, transformer and load), active power (MW), reactive power (MVAR), power factor, current magnitude (kA) and loading (%).

LAB 3 – POWER FLOW ANALYSIS (MATLAB)

1. Introduction

In Lab 3, the task was to model the part of the 'Gracanica' network we previously modelled in DIGSILENT. It is done in MATLAB, more precisely by downloading and using the MATPOWER toolbox. I used matpower7.1 version. A case which contains the data from our network is created. Case files are based on the existing cases in the 'data' folder of the toolbox.

MATPOWER is a package of tools for power system simulation and optimization. It is used in the field of power systems and electrical engineering. The main purpose of MATPOWER is to provide a set of functions and tools for solving power system optimization problems, particularly in the areas of power flow, optimal power flow, and other related analyses.

Power flow analysis is performed using Newton-Raphson and Gauss-Seidel Methods. The task is described. The modelled network is shown. Finally, the results of power flow analysis are to be obtained and discussed commenting aspects like power generation, consumption and losses.

2. THEORY

This segment of the lab will dive into the theoretical aspects of power flow analysis. Two main methods used are Newton-Raphson and Gauss-Seidel. They are iterative methods which reach convergence after a certain number of iterations. Their applications will be mentioned as well.

2.1. Power Flow Analysis

Power flow (or load flow) is the solution for the balanced three-phase steady-state operating conditions of a power system. The data from power flow studies is used for the studies of normal operating mode, loss analysis, security assessment, and optimal dispatching and stability. The basic assumption is that the given power system is a balanced three-phase system operating in steady state with a constant 50/60-Hz frequency.

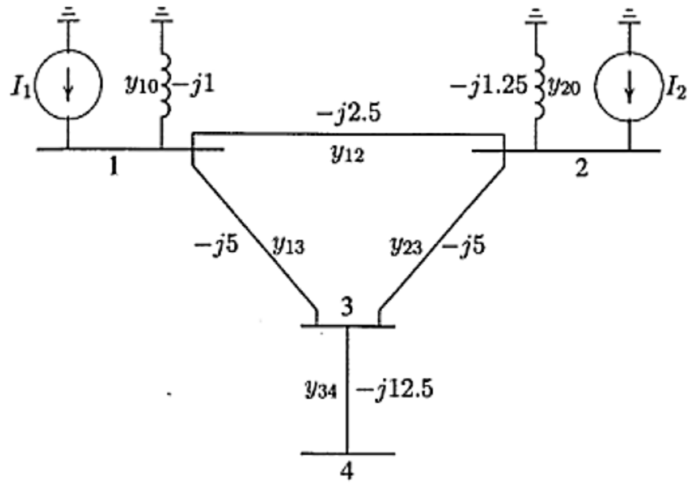


Figure 1. The Network for The Bus Admittance Matrix

The network in Figure is represented using the bus admittance matrix (Y_{bus}) or the bus impedance matrix (Z_{bus}). Node-voltage equations are used, and the admittance is obtained from this formula:

$$y_{ij} = \frac{1}{z_{ij}} = \frac{1}{r_{ij} + jx_{ij}}$$

According to Figure, the Kirchhoff Current Law (KCL) is used at each of the four nodes:

$$I_1 = y_{10}V_1 + y_{12}(V_1 - V_2) + y_{13}(V_1 - V_3)$$

$$I_2 = y_{20}V_2 + y_{12}(V_2 - V_1) + y_{23}(V_2 - V_3)$$

$$0 = y_{23(}V_3 - V_2) + y_{13}(V_3 - V_1) + y_{34}(V_3 - V_4)$$

$$0 = y_{34(}V_4 - V_3)$$

The admittances are expressed as:

$$Y_{11} = y_{10} + y_{12} + y_{13} \qquad Y_{22} = y_{20} + y_{12} + y_{23} \qquad Y_{33} = y_{13} + y_{23} + y_{34}$$

$$Y_{44} = y_{34} \qquad Y_{12} = Y_{21} = -\,y_{12} \qquad Y_{13} = Y_{31} = -\,y_{13}$$

$$Y_{23} = Y_{32} = -\,y_{23} \qquad Y_{34} = Y_{43} = -\,y_{34}$$

By obtaining this, the current equations will now look like:

$$I_1 = Y_{11}V_1 + Y_{12}V_2 + Y_{13}V_3 + Y_{14}V_4 \qquad I_2 = Y_{21}V_1 + Y_{22}V_2 + Y_{23}V_3 + Y_{24}V_4$$

$$I_3 = Y_{31}V_1 + Y_{32}V_2 + Y_{33}V_3 + Y_{34}V_4 \qquad I_4 = Y_{41}V_1 + Y_{42}V_2 + Y_{43}V_3 + Y_{44}V_4$$

It is possible to define the bus power in terms of generated power, load power, and transmitted power at a given bus. The bus power of the ith bus of an n bus power system is expressed as:

$$S_i = P_i + jQ_i = (P_{Gi} - P_{Li} - P_{Ti}) + j(Q_{Gi} - Q_{Li} - Q_{Ti})$$

where:

S_i = three-phase complex bus power at ith bus

P_i = three-phase real bus power at ith bus

Q_i = three-phase reactive bus power at ith bus

P_{Gi} = three-phase real generated power flowing into ith bus

P_{Li} = three-phase real load power flowing out of ith bus

P_{Ti} = three-phase real transmitted power flowing out of ith bus

Q_{Gi} = three-phase reactive generated power flowing into ith bus

Q_{Li} = three-phase reactive load power flowing out of ith bus

Q_{Ti} = three-phase reactive transmitted power flowing out of ith bus

The system busses are categorized into three different types:

Slack Busses – one bus, taken as reference, where the magnitude and phase angle of the voltage are specified. This bus makes up for the difference between loads and generated power, caused by the losses in the network.

Load Busses – the busses where the active and reactive powers are specified. These P-Q busses have their voltage phase angle and magnitude unknown.

Regulated Busses (Generator Busses) – at these P-V busses, the real power and voltage magnitude are always specified. The voltages phase angles and reactive power have to be determined.

Due to the physical characteristics of generation and load, each bus has its conditions defined in terms of active and reactive power, rather than by bus current. Thus, the complex power, flowing into the ith bus is:

$$V_i I_i^* = P_i + jQ_i \qquad \text{, with the bus current being: } I_i = \frac{P_i - Q_i}{V_i^*}$$

When performing power flow analysis, it is crucial to know that the lagging reactive power is a positive reactive power due to the inductive current and the leading reactive power is a negative power due to the capacitive current. Additionally, the positive bus current is in the direction that flows toward the bus.

Since the generator current flows towards the bus and the load current flows away from the bus, the generator bus power sign is positive and for the load bus it is negative.

In summary, the power flow equations are summarized for a mathematical model:

$$I_i = \sum_{j=1}^{n} Y_{ij} V_j \qquad I_i = \sum_{j=1}^{n} |Y_{ij}||V_j| \angle \theta_{ij} + \delta_j$$

$$P_i - jQ_i = V_i^* I_i \qquad P_i - jQ_i = |V_i| \angle - \delta_i \sum_{j=1}^{n} |Y_{ij}||V_j| \angle \theta_{ij} + \delta_j$$

$$P_i = \sum_{j=1}^{n} |V_i||V_j||Y_{ij}| \cos(\theta_{ij} - \delta_i + \delta_j) \qquad Q_i = -\sum_{j=1}^{n} |V_i||V_j||Y_{ij}| \sin(\theta_{ij} - \delta_i + \delta_j)$$

2.2. Newton-Raphson Method

Initially, all power flow calculations were made by hand. However, eventually the iterative methods were developed. They were based on the Gauss–Seidel method. As the size of the networks grew, the Newton–Raphson method was developed. Newton-Raphson method is based on solving quadric equations of the network. It needs a larger time per iteration, but only a few iterations. It is also largely independent of the network size. The approximation of the initial state and use of Taylor series expansion are the basis of this method.

This method first finds the tangent line of the function at the initial guess point. Then, it is observed where the tangent line intersects the x-axis. This point is taken as the value for the new guess, known as iteration. It is performed until the difference from previous iteration becomes negligible.

Firstly, it is assumed that a single-variable equation is given as:

$$f(x) = 0$$

The given function can be expanded by Taylor series about a point x_0 as:

$$f(x) = f(x_0) + \frac{1}{1!}\frac{df(x_0)}{dx}(x - x_0) + \frac{1}{2!}\frac{df^2(x_0)}{dx^2}(x - x_0)^2 + \cdots + \frac{1}{n!}\frac{df^n(x_0)}{dx^n}(x - x_0)^n = 0$$

If it is assumed that convergence happened after the first two terms, everything after first derivative is dropped:

$$f(x) = f(x_0) + \frac{df(x_0)}{dx}(x - x_0) = 0 \qquad\qquad x_1 = x_0 - \frac{f(x_0)}{\frac{df(x_0)}{dx}}$$

For a better understanding, this expression is formulated as:

$x^{(1)} = x^{(0)} - \frac{f(x^{(0)})}{\frac{df(x^{(0)})}{dx}}$, from which a recursion formula is: $x^{(k+1)} = x^{(k)} - \frac{f(x^{(k)})}{\frac{df(x^{(k)})}{dx}}$

$x^{(0)}$ = initial approximation ; $x^{(1)}$ = first approximation

In matrix notation, if the given function is expanded by Taylor series, and terms beyond the first derivative are dropped:

$$F(x) = F\left(x^{(x)}\right) + \left[J\left(x^{(0)}\right)\right]\left[x - x^{(0)}\right] = 0$$

The coefficient matrix is called the Jacobian matrix and is expressed in the following way:

$$[J(x)] \triangleq \begin{bmatrix} \frac{\partial f_1}{\partial x_1} & \frac{\partial f_1}{\partial x_2} & \cdots & \frac{\partial f_1}{\partial x_n} \\ \frac{\partial f_2}{\partial x_1} & \frac{\partial f_2}{\partial x_2} & \cdots & \frac{\partial f_2}{\partial x_n} \\ \cdots & \cdots & & \cdots \\ \frac{\partial f_n}{\partial x_1} & \frac{\partial f_n}{\partial x_2} & \cdots & \frac{\partial f_n}{\partial x_n} \end{bmatrix}$$

This fast-converging method is not sensitive to any factors that could disturb the convergence. Rectangular or polar coordinates can be used for the bus voltages. Bus admittance matrix is used. Since the magnitude and phase angle of the slack bus are known, it is not in the iteration process.

The power at bus i in a system with n-busses is formulated as:

$$S_i = P_i - jQ_i = V_i^* I_i = V_i^* \sum_{j=1}^{n} Y_{ij} V_j$$

The following equations are formulated, where I_i is the current flowing into bus i:

$$V_i \triangleq e_i + jf_i \qquad V_{ij} \triangleq G_{ij} - jB_{ij} \qquad I_i = \sum_{j=1}^{n} Y_{ij} V_{ij} \triangleq c_i + jd_i$$

Thus, Newton-Raphson method is expressed in rectangular coordinates:

$$P_i - jQ_i = (e_i - jf_i) \sum_{j=1}^{n} (G_{ij} - jB_{ij})(e_j + jf_j)$$

$$P_i = \sum_{j=1}^{n} [\left(e_i G_{ij} e_j + jB_{ij} f_j\right) + f_i\left(G_{ij} f_j - B_{ij} e_j\right)]$$

$$Q_i = \sum_{j=1}^{n} [(f_i G_{ij} e_j + jB_{ij} f_j) - e_i(G_{ij} f_j - B_{ij} e_j)]$$

For each PV generator bus, the bus voltage magnitude is obtained from estimated e and f values:

$$|V|_i^2 = e_i^2 + f_i^2 \qquad \Delta P_i^{(k)} = P_{i,spec} - P_{i,calc}^{(k)} \qquad \Delta Q_i^{(k)} = Q_{i,spec} - Q_{i,calc}^{(k)}$$

If Newton-Raphson method is applied to load flow equations in polar coordinates:

$$V_i \triangleq |V_i| \angle \delta_i \qquad V_i \triangleq |V_i| \angle - \theta_{ij}$$

$$\frac{\partial P_i}{\partial \delta_j} = \sum_{j=1}^{n} |V_i| \left| |V_j| |Y_{ij}| \right| \sin(\theta_{ij} + \delta_i - \delta_j), \; i \neq j \qquad \frac{\partial P_i}{\partial \delta_j} = |V|_i^2 |Y_{ii}| \sin \theta_{ii} - Q_i, \; i = j$$

$$\frac{\partial P_i}{\partial |V_i|} = \sum_{j=1}^{n} |V_j| |Y_{ij}| \cos(\theta_{ij} + \delta_i - \delta_j) + |V_i||Y_{ii}| cos\theta_{ii}, \quad i \neq j$$

$$\frac{\partial P_i}{\partial |V_i|} = \frac{P_i}{|V_i|} + |V_i||Y_{ii}| cos\theta_{ii}, \quad i = j$$

The reactive power is formulated as:

$$\frac{\partial Q_i}{\partial \delta_i} = \sum_{j=1}^{n} |V_j||Y_{ij}| \cos(\theta_{ij} + \delta_i - \delta_j) + |V_i||Y_{ii}| cos\theta_{ii}, \qquad i \neq j$$

$$\frac{\partial Q_i}{\partial \delta_i} = -|V|_i^2 |Y_{ii}| \sin \theta_{ii} + P_i, \qquad i = j$$

$$\frac{\partial Q_i}{\partial |V_i|} = |V_i||Y_{ii}| cos\theta_{ii} + \sum_{j=1}^{n} |V_j| |Y_{ij}| \cos(\theta_{ij} + \delta_i - \delta_j), \qquad i \neq j$$

$$\frac{\partial P_i}{\partial |V_i|} = |V_i||Y_{ii}| sin\theta_{ii} + \frac{Q_i}{|V_i|}, \qquad i = j$$

2.3. Gauss–Seidel Method

The Gauss–Seidel iterative method is based on the Gauss iterative method. The only difference is that in the Gauss–Seidel iterative method, a more efficient substitution technique is used. In the iterations, therefore, the newly computed values of x are immediately used in the right sides of the following equations:

$$x_1^{(k+1)} = \frac{1}{a_{11}}(b_1 - a_{12}x_2^{(k)} - a_{13}x_3^{(k)} - \cdots - a_{1n}x_n^{(k)}) \qquad x_2^{(k+1)} = \frac{1}{a_{22}}(b_2 - a_{21}x_1^{(k+1)} - a_{23}x_3^{(k)} - \cdots - a_{2n}x_n^{(k)})$$

$$x_3^{(k+1)} = \frac{1}{a_{22}}(b_3 - a_{31}x_1^{(k+1)} - a_{32}x_2^{(k+1)} - \cdots - a_{3n}x_n^{(k)}) \qquad x_n^{(k+1)} = \frac{1}{a_{nn}}(b_n - a_{n1}x_1^{(k+1)} - a_{n3}x_3^{(k+1)} - \cdots - a_{nn}x_{n-1}^{(k+1)})$$

The iterative process goes on until: $\left|x^{(k+1)} - x^{(k)}\right| \leq \varepsilon$

Assume an n-bus network, then the n current equations can be expressed in terms of the n unknown voltages:

$$[\mathbf{I}_{\text{bus}}] = [\mathbf{Y}_{\text{bus}}][\mathbf{V}_{\text{bus}}] \qquad \mathbf{I}_n = \mathbf{Y}_{n1}\mathbf{V}_1 + \mathbf{Y}_{n2}\mathbf{V}_2 + \mathbf{Y}_{n3}\mathbf{V}_3 + \cdots + \mathbf{Y}_{nn}\mathbf{V}_n$$

This can be expressed in a matrix form:

$$\begin{bmatrix} \mathbf{I}_1 \\ \mathbf{I}_2 \\ \mathbf{I}_2 \\ \cdot \\ \cdot \\ \cdot \\ \mathbf{I}_n \end{bmatrix} = \begin{bmatrix} \mathbf{Y}_{11} & \mathbf{Y}_{12} & \mathbf{Y}_{13} & \cdots & \mathbf{Y}_{1n} \\ \mathbf{Y}_{21} & \mathbf{Y}_{22} & \mathbf{Y}_{23} & \cdots & \mathbf{Y}_{2n} \\ \mathbf{Y}_{31} & \mathbf{Y}_{32} & \mathbf{Y}_{33} & \cdots & \mathbf{Y}_{3n} \\ \cdot & \cdot & \cdot & \cdots & \cdot \\ \cdot & \cdot & \cdot & \cdots & \cdot \\ \cdot & \cdot & \cdot & \cdots & \cdot \\ \mathbf{Y}_{n1} & \mathbf{Y}_{n2} & \mathbf{Y}_{n3} & \cdots & \mathbf{Y}_{nn} \end{bmatrix} \begin{bmatrix} \mathbf{V}_1 \\ \mathbf{V}_2 \\ \mathbf{V}_3 \\ \cdot \\ \cdot \\ \cdot \\ \mathbf{V}_n \end{bmatrix}$$

The bus voltages for the (k + 1) iteration can be determined when $V_{(i)}^{(k)}$ and $I_{(i)}^{(k)}$ are found after the k iteration. This can be formulated in a following way:

$$\mathbf{V}_n^{(k+1)} = \frac{1}{\mathbf{Y}_{nn}}\left(\mathbf{I}_n^{(k)} - \mathbf{Y}_{n1}\mathbf{V}_1^{(k+1)} - \mathbf{Y}_{n2}\mathbf{V}_2^{(k+1)} - \cdots - \mathbf{Y}_{n,n-1}\mathbf{V}_{n-1}^{(k+1)}\right) \qquad \mathbf{I}_i = \frac{P_i - jQ_i}{\mathbf{V}_i^*}$$

A general formula to determine the bus voltage at the ith (PQ) bus can be developed:

$$\mathbf{V}_i^{(k+1)} = \frac{1}{\mathbf{Y}_{ii}}\left(\frac{P_i - jQ_i}{\mathbf{V}_i^{(k)*}} - \sum_{\substack{j=1 \\ j \neq i}}^{n} \mathbf{Y}_{ij}\mathbf{V}_j^{(k)}\right) \quad \text{for } i = 2, \ldots, n$$

In here, bus 1 is the slack bus with known voltage magnitude and phase angle. This means that the bus voltage calculations start with bus 2.

If the ith bus is a PV bus where real power and voltage magnitude are given, then the unknown reactive power has to be determined first before each iteration. Thus, for the generator bus i:

$$\mathbf{I}_{\text{gen}} = \frac{P_i - jQ_i}{\mathbf{V}_i^*} = \mathbf{Y}_{i1}\mathbf{V}_1 + \mathbf{Y}_{i2}\mathbf{V}_2 + \mathbf{Y}_{i3}\mathbf{V}_3 + \cdots + \mathbf{Y}_{in}\mathbf{V}_n \qquad P_i - jQ_i = \mathbf{V}_i^{(k)}\left[\sum_{j=1}^{n} \mathbf{Y}_{ij}\mathbf{V}_j^{(k)}\right]$$

This means that the reactive power is formulated in a following way:

$$Q_i = -\mathrm{Im}\left[\mathbf{V}_i^{(k)*}\left(\sum_{j=1}^{n} \mathbf{Y}_{ij}\mathbf{V}_i^{(k)}\right)\right]$$

In summary, the iteration process starts by assuming initial phasor values for the unknown bus voltages (except for the slack bus) and computing their new values (corrected values).

As the corrected voltage value is determined at each bus, it is used to find the corrected voltage at the next. The process is repeated at each bus for the rest of the buses to finish the first iteration. This iteration process for the network system is repeated until the voltage correction required for each bus is less than a specified precision index, that is, tolerance.

After the bus voltages V_2, V_3, V_4, …, V_n are found, the power at the slack bus is determined:

$$\frac{P_1 - jQ_1}{\mathbf{V}_i^*} = \mathbf{Y}_{11}\mathbf{V}_1 + \mathbf{Y}_{12}\mathbf{V}_2 + \mathbf{Y}_{13}\mathbf{V}_3 + \cdots + \mathbf{Y}_{1n}\mathbf{V}_n$$

3. The Network

The case file in MATPOWER was written based on the 'Gračanica' network, going from 'Klokotnica', modelled in DIGSILENT.

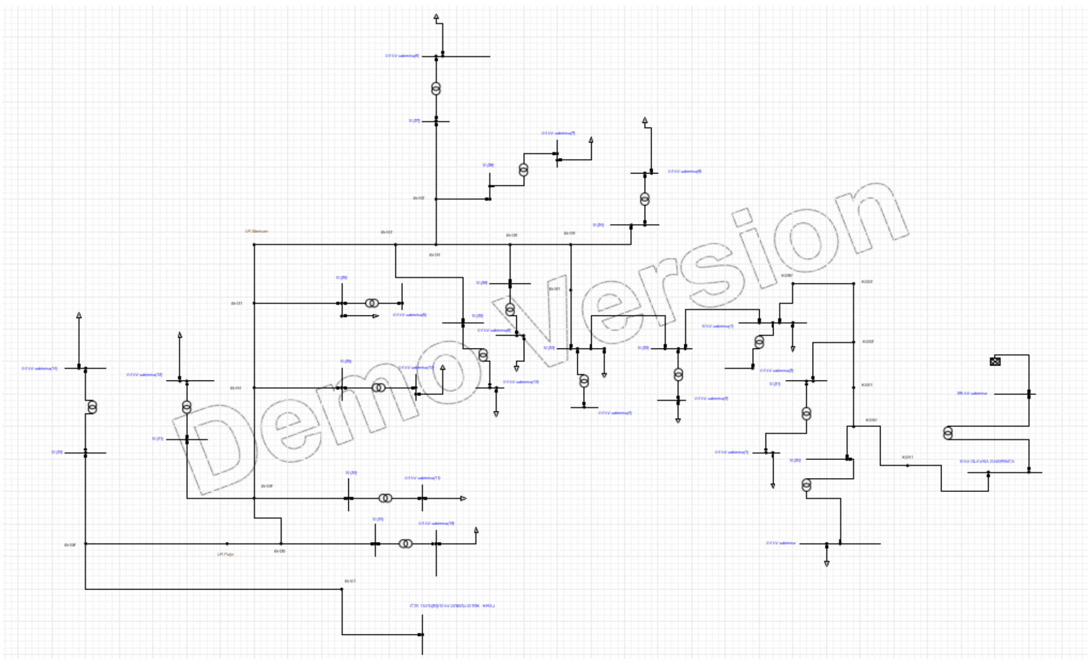


Figure 2. The Network in DIGSILENT

The network consists of around 55 busses, which include both junction nodes and busbars. Transformers, ranging from 50 to 1600 kVA are present to step the voltage down from 10 kV to 0.4 kV, where the loads will be located.

External grid is set as a reference point (later slack bus), connected to the 35 kV busbar. After that, 35 kV / 10 kV transformers steps the voltage down and that is where the original network starts. Cables and transmission lines of different lengths are used.

4. Caseformat

A MATPOWER case file is an M-file or MAT-file that defines or returns a struct named mpc, referred to as a "MATPOWER case struct". The fields of this struct are baseMVA, bus, gen, branch, and (optional) gencost. With the exception of baseMVA, a scalar, each data variable is a matrix, where a row corresponds to a single bus, branch, gen, etc.

Certain values are entered in scalar values, as said, but certain are entered in per unit system. We run a case file by typing in ‘runpf’ in the command window. It has arguments of bus data, generator data, branch data and generator cost data (optionally).

5. Formulas

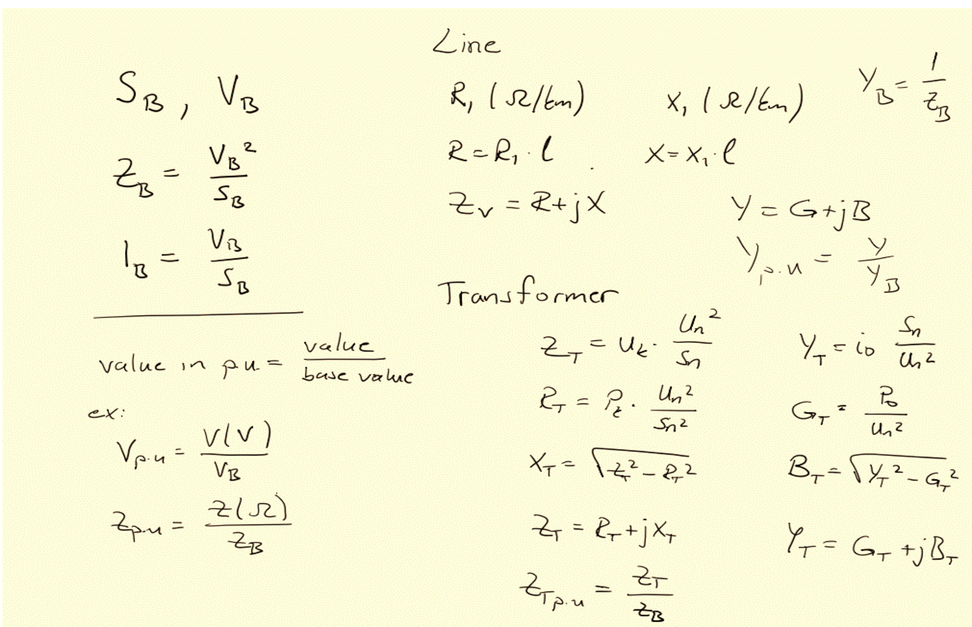


Figure 3. The Formulas used

In order for us to be able to enter the data, we have to convert values to their correct form. Impedance in pu – consisting of resistance and reactance is obtained by dividing the value by the base value. Before converting the value to pu, we multiply it by length of the cable/line, in order to obtain the value.

The base impedance is obtained by diving the base voltage of 10 kV squared and the base complex power of 100 MVA. In general, pu is obtained by diving the real value with the base value.

The admittance is the inverse of the impedance. It consists of conductance and admittance.

Finally, for the transformer, special formulas are used to obtain the impedance and admittance. Nominal voltages and nominal complex power are used alongside the copper losses, short circuit voltage and no load current. After finding impedance and resistance, we find the reactance. Similarly, after finding the admittance and conductance, we find the admittance.

6. Network Parameters in MATLAB's Matpower

The following data is entered for the DIGSILENT network. Firstly, the bus data has:

1 – bus number

2 – bus type: slack (3), PV (2), PQ (1)

3 – rated active power (in MW)

4 – rated reactive power (in MVAR)

5, 6 – conductance, admittance

7 – area – always 1 (positive integer)

8, 9 – voltage magnitude (in pu), voltage angle

10 – base kV voltage (10 kV)

11 – zone, loss zone: always 1

12, 13 – minimum and maximum voltage values (+5 % or -5% from 1 pu)

Active and reactive power values entered only at 0.4 kV (where the loads are located).

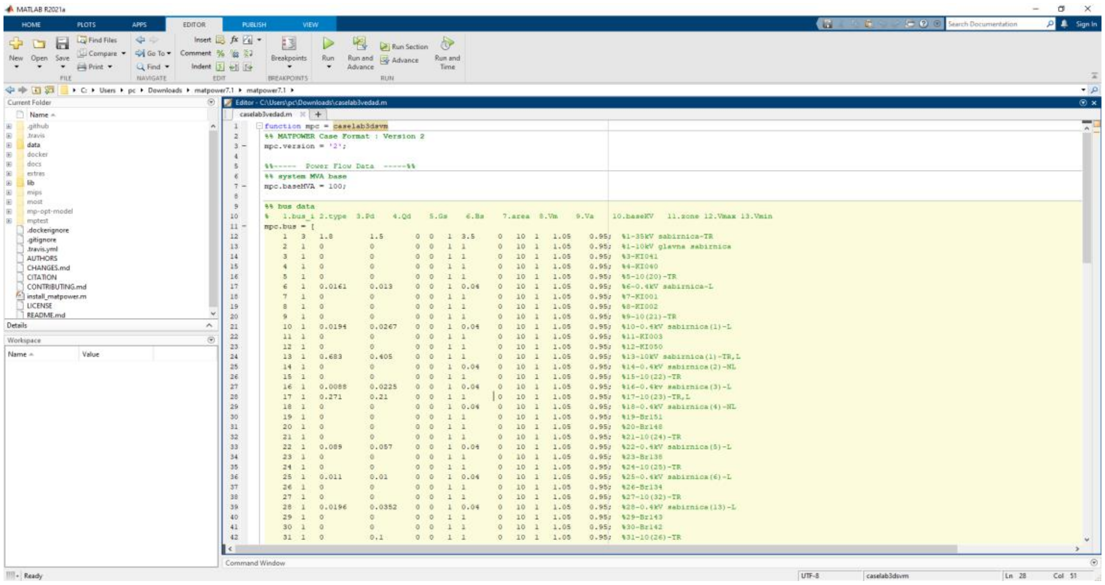


Figure 4. Bus Data

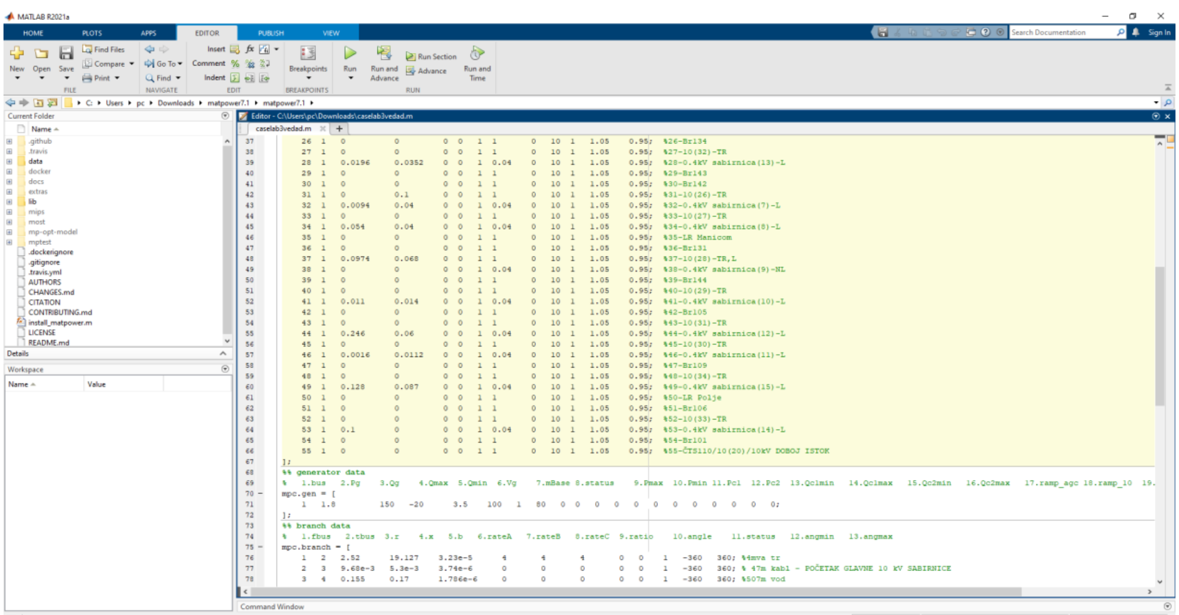


Figure 5. Bus Data and Generator Data

Although we do not have any real generators, we had to enter at least the slack bus to fill runpf argument. Its active power in MW is entered.

The branch data has:

1 – from bus

2 - to bus

3, 4, 5 – resistance, reactance, admittance (in pu)

6, 7, 8 – rated complex power in A, B, C – 0 for lines and cables, has the value for transformers

9 – ratio – turn ratio

10 – angle

11 – status – always 1

12, 13 – minimum and maximum angle

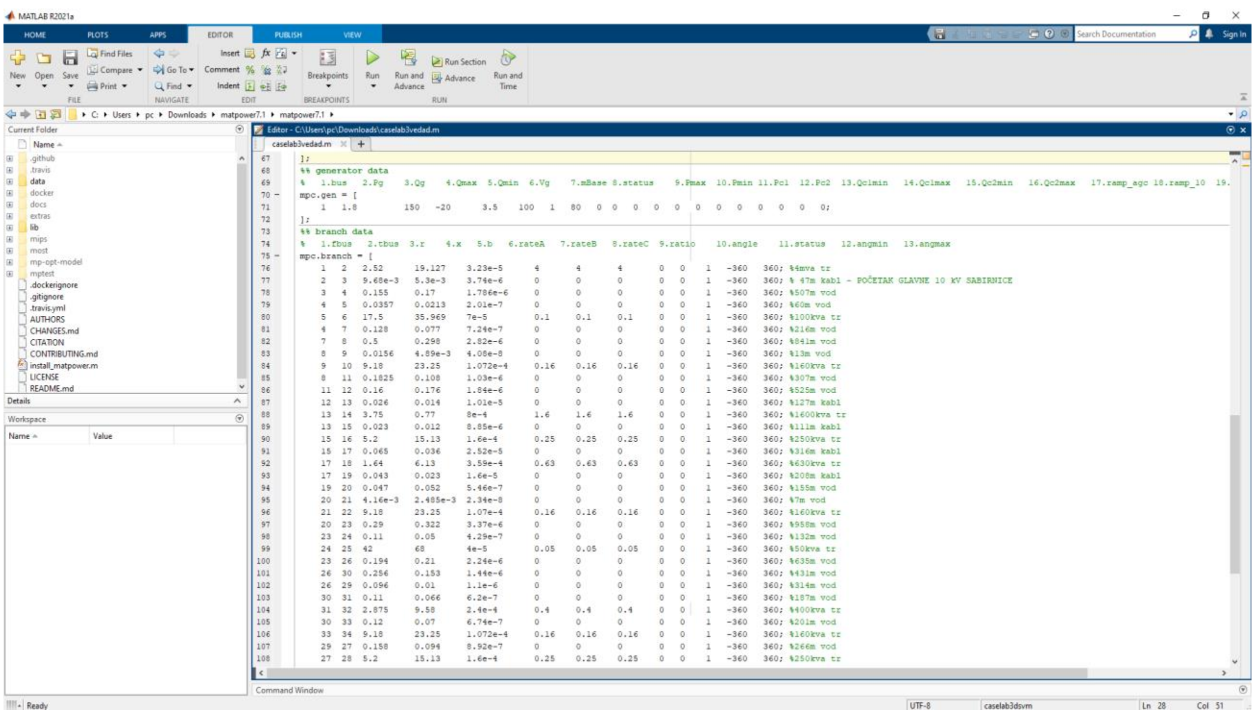


Figure 6. Branch Data

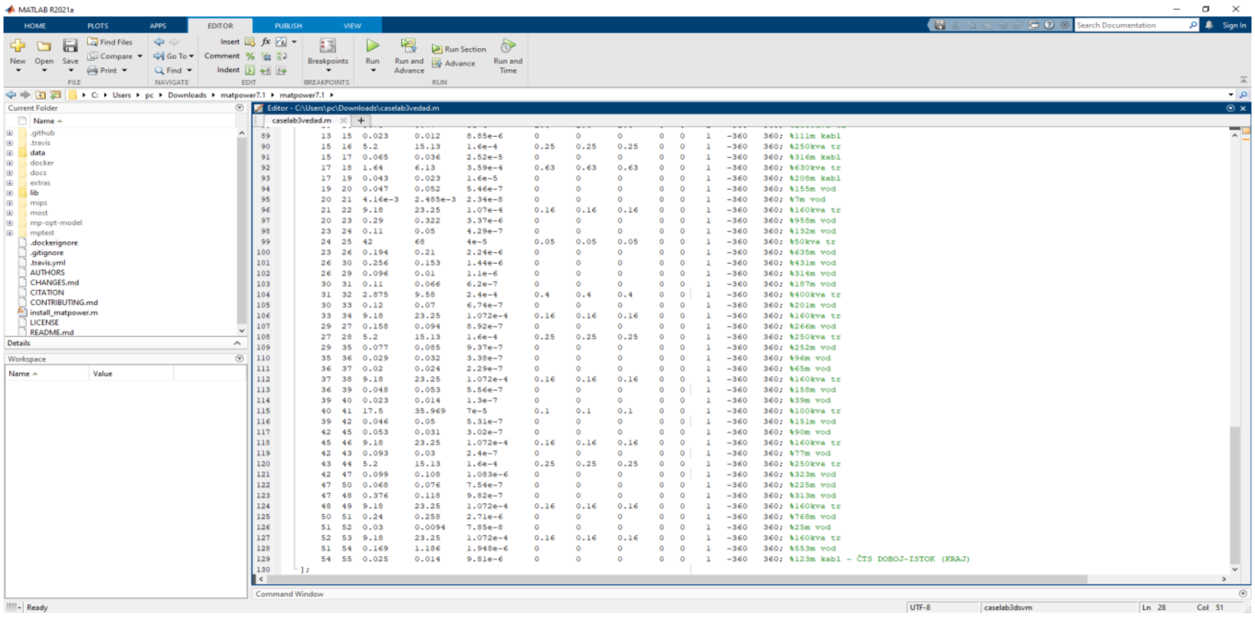


Figure 7. Branch Data

7. Newton-Raphson in Matpower

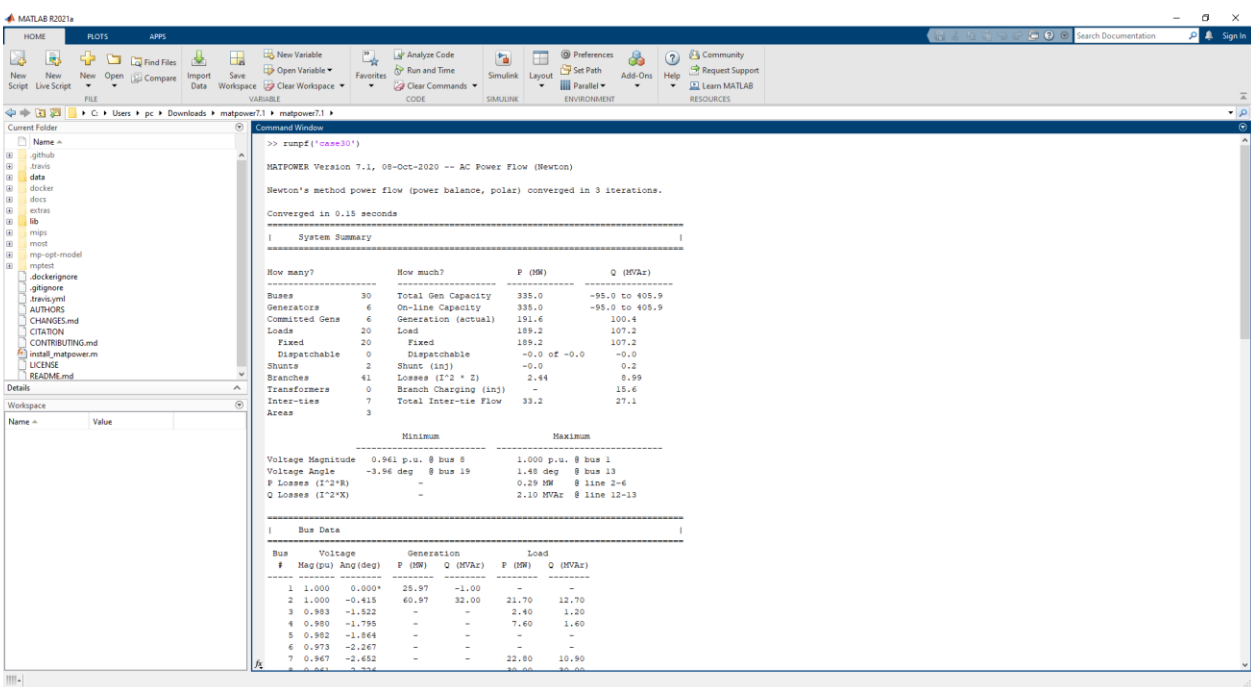


Figure 8. Newton-Raphson Method Results

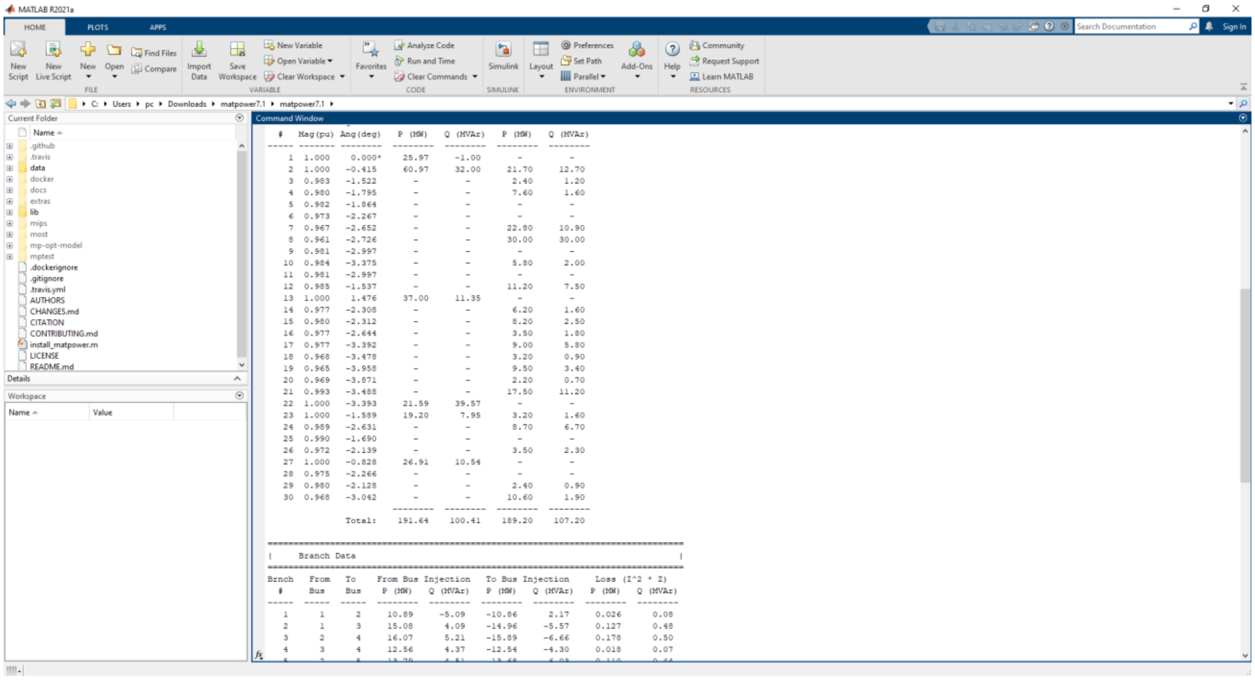


Figure 9. Bus Data NR Results

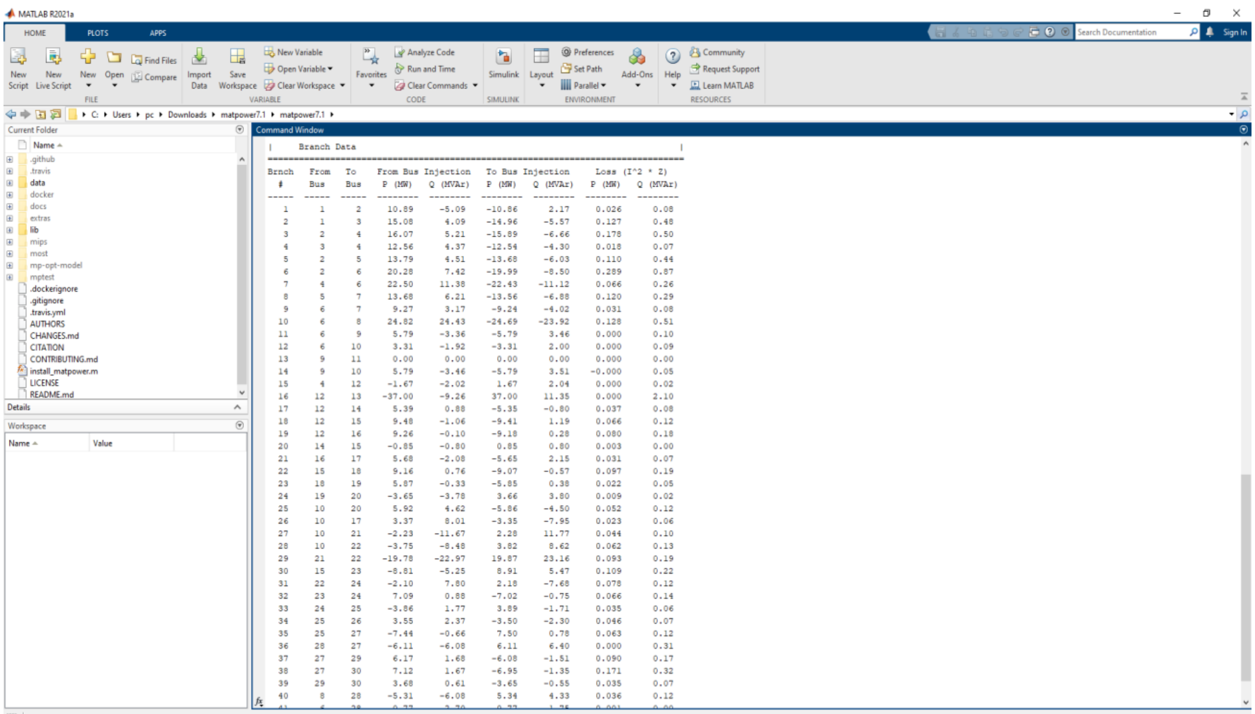
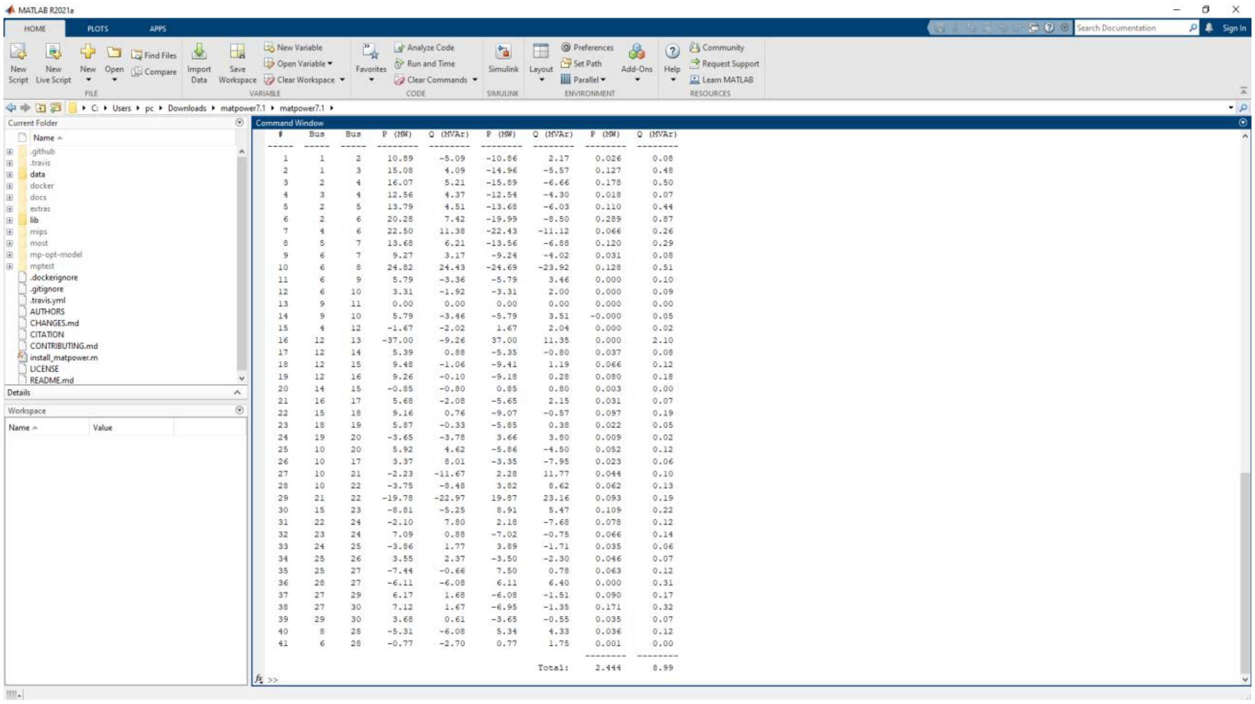


Figure 10. Branch Data NR Results



#	Bus	Bus	P (MW)	Q (MVAr)	P (MW)	Q (MVAr)	P (MW)	Q (MVAr)
1	1	2	10.89	-5.09	-10.86	2.17	0.026	0.08
2	1	3	15.08	4.09	-14.96	-5.57	0.127	0.48
3	2	4	16.07	5.21	-15.89	-6.66	0.178	0.50
4	3	4	12.56	4.37	-12.54	-4.30	0.018	0.07
5	2	5	13.79	4.51	-13.68	-6.03	0.110	0.44
6	2	6	20.28	7.42	-19.99	-8.50	0.289	0.87
7	4	6	22.50	11.38	-22.43	-11.12	0.066	0.26
8	5	7	13.68	6.21	-13.56	-6.88	0.120	0.29
9	6	7	9.27	3.17	-9.24	-4.02	0.031	0.08
10	6	8	24.82	24.43	-24.69	-23.92	0.128	0.51
11	6	9	5.79	-3.36	-5.79	3.46	0.000	0.10
12	6	10	3.31	-1.92	-3.31	2.00	0.000	0.09
13	9	11	0.00	0.00	0.00	0.00	0.000	0.00
14	9	10	5.79	-3.46	-5.79	3.51	-0.000	0.05
15	4	12	-1.67	-2.02	1.67	2.04	0.000	0.02
16	12	13	-37.00	-9.26	37.00	11.35	0.000	2.10
17	12	14	5.39	0.88	-5.35	-0.80	0.037	0.08
18	12	15	9.48	-1.06	-9.41	1.19	0.066	0.12
19	12	16	9.26	-0.10	-9.18	0.28	0.080	0.18
20	14	15	-0.85	-0.80	0.85	0.80	0.003	0.00
21	16	17	5.68	-2.08	-5.65	2.15	0.031	0.07
22	15	18	9.16	0.76	-9.07	-0.57	0.097	0.19
23	18	19	5.87	-0.33	-5.85	0.38	0.022	0.05
24	19	20	-3.65	-3.78	3.66	3.80	0.009	0.02
25	10	20	5.92	4.62	-5.86	-4.50	0.052	0.12
26	10	17	3.37	8.01	-3.35	-7.95	0.023	0.06
27	10	21	-2.23	-11.67	2.28	11.77	0.044	0.10
28	10	22	-3.75	-8.48	3.82	8.62	0.062	0.13
29	21	22	-19.78	-22.97	19.87	23.16	0.093	0.19
30	15	23	-8.81	-5.25	8.91	5.47	0.109	0.22
31	22	24	-2.10	7.80	2.18	-7.68	0.078	0.12
32	23	24	7.09	0.88	-7.02	-0.75	0.066	0.14
33	24	25	-3.86	1.77	3.89	-1.71	0.035	0.06
34	25	26	3.55	2.37	-3.50	-2.30	0.046	0.07
35	25	27	-7.44	-0.66	7.50	0.78	0.063	0.12
36	28	27	-6.11	-6.08	6.11	6.40	0.000	0.31
37	27	29	6.17	1.68	-6.08	-1.51	0.090	0.17
38	27	30	7.12	1.67	-6.95	-1.35	0.171	0.32
39	29	30	3.68	0.61	-3.65	-0.55	0.035	0.07
40	8	28	-5.31	-6.08	5.34	4.33	0.036	0.12
41	6	28	-0.77	-2.70	0.77	1.75	0.001	0.00
						Total:	2.444	8.99

Figure 11. Branch Data NR Results

The command: results = runpf('case30') executes power flow analysis using the Newton-Raphson method. The Newton-Raphson method converges in 3 iterations. The convergence time is mentioned as 0.15 seconds.

The summary provides information about the system, including the number of buses, generators, loads, branches, transformers, and areas. It also provides details about generation, load, losses, as well as voltage magnitudes and angles at each bus.

Bus Data provides magnitude for all voltages (in pu), alongside angles (in degrees). All of the magnitudes are in the optimal range (close to 1). The allowed range is between 0.95 and 1.05 and all of the voltages fall inside of it. Load busses have their Active and Reactive power specified in Bus Data segment. Generation busses also have the Active and Reactive power generation shown.

The total, or the sum, of all the values is shown after every Data list. As well, minimum and maximum values of voltage magnitude, angle, P losses and Q losses are shown. Branch Data shows Active and Reactive power, as well as Active and Reactive power, in terms of the losses.

8. Gauss-Seidel Method in Matpower

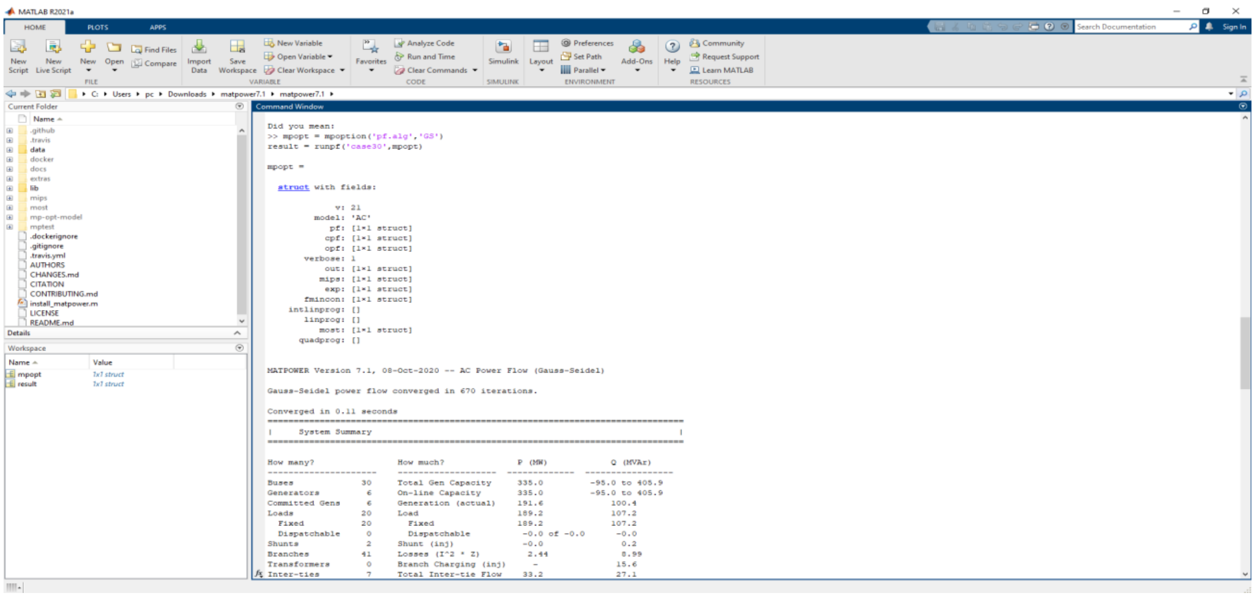


Figure 12. Gauss-Seidel Method Results

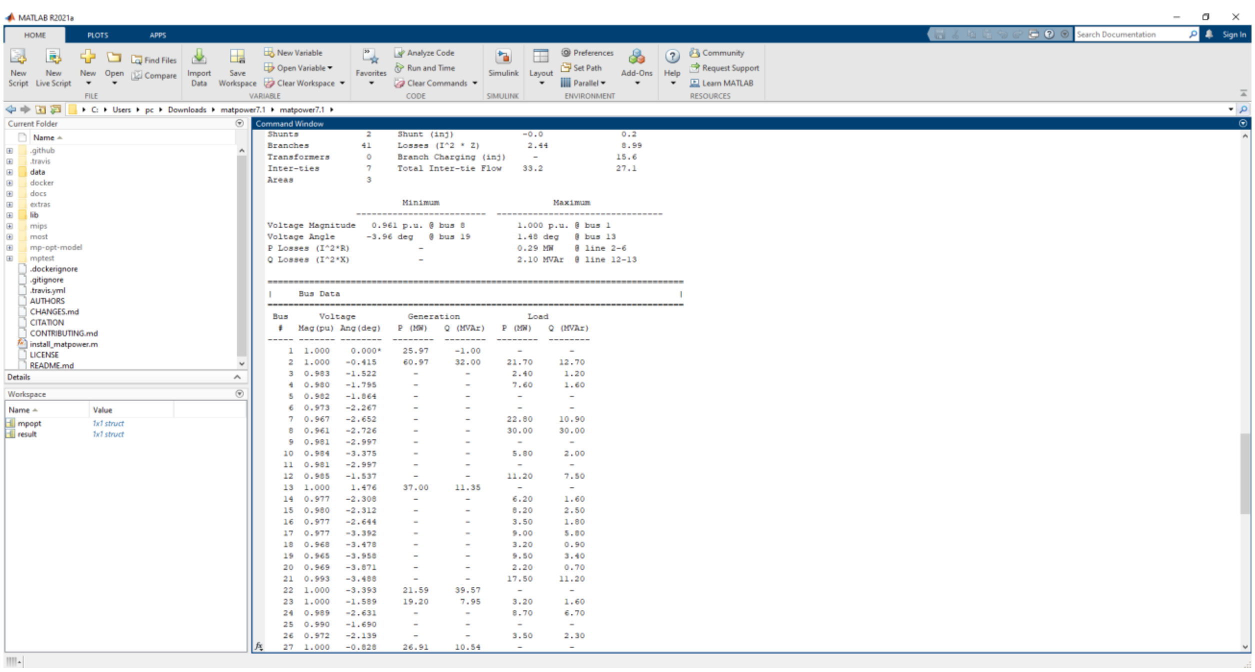


Figure 13. Bus Data GS Results

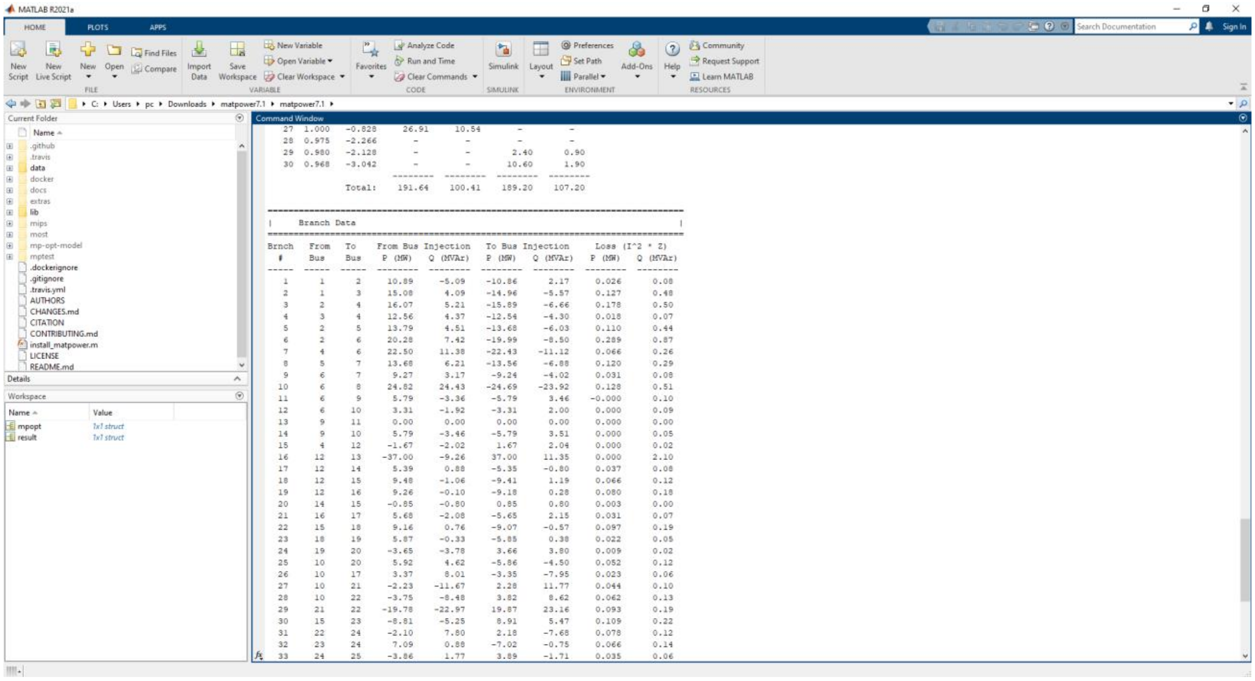


Figure 14. Branch Data GS Results

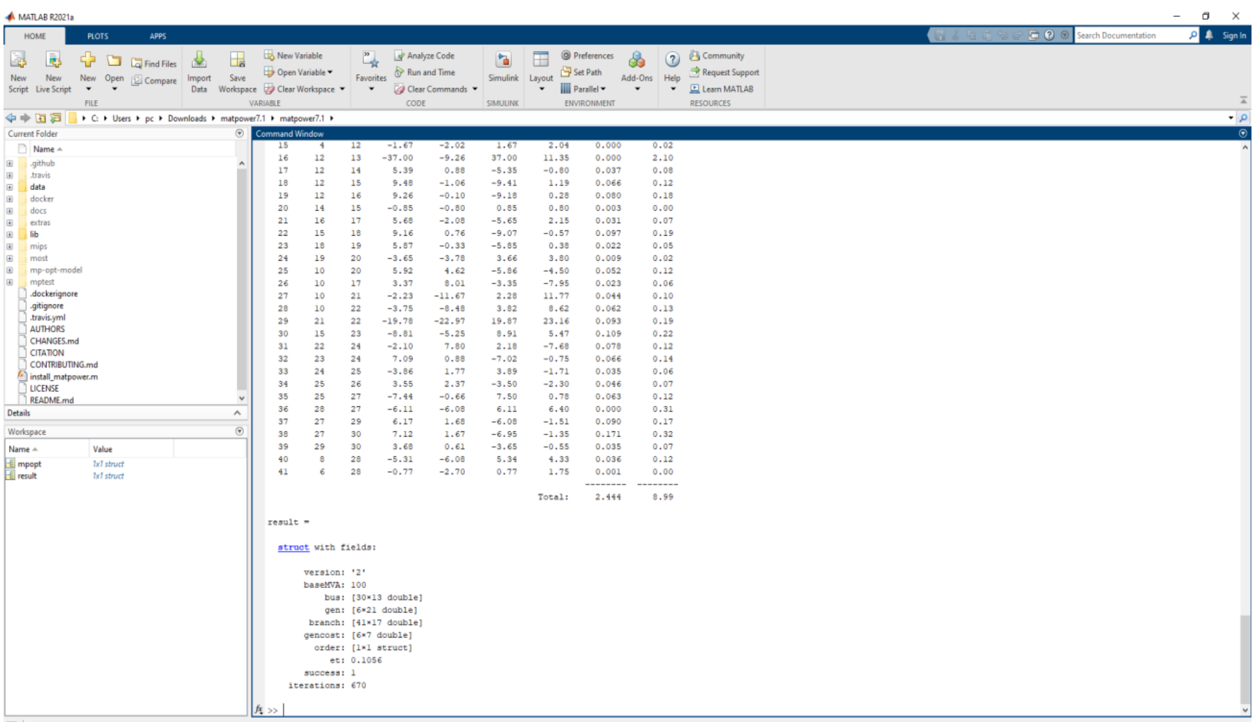


Figure 15. Branch Data GS Results

The Gauss-Seidel method is selected with the command: mpopt = mpoption('pf.alg', 'GS').

The command results = runpf('case30', mpopt) then executes the power flow analysis using the Gauss-Seidel method.

The Gauss-Seidel method converges in 670 iterations and the convergence time is 0.11 seconds.

Similar to the Newton-Raphson method, the summary provides information about the system, including the number of buses, generators, loads, branches, transformers, and areas. It also provides details about generation, load, losses, and voltage magnitudes and angles at each bus.

Bus Data provides magnitude for of the all voltages (in pu), alongside angles (in degrees). All of the magnitudes are in the optimal range (close to 1). The allowed range is between 0.95 and 1.05 and all of the voltages fall inside of it. For Generator busses, the Active and Reactive power are specified. Load busses have their Active and Reactive power specified in Bus Data segment.

The total, or the sum, of all the values is shown after every Data list. As well, minimum and maximum values of voltage magnitude, voltage angle, P losses and Q losses are shown. Branch Data has Active and Reactive power specified, as well as Active and Reactive power, in terms of the losses experienced.

In terms of results, the ones obtained with Newton-Raphson method are exactly the same as the ones obtained with Gauss-Seidel method, in here. The methods difference between themselves, not in the results they provide, because they should be exactly the same. Methods have different converging speeds and number of iterations.

9. Conclusion

This lab was about modelling a power network using MATLAB and MATPOWER toolbox. We learned about power flow analysis. We used methods like Newton-Raphson and Gauss-Seidel to figure this out. By creating a case file, we organized the network data. Data was in expressed in different unit systems, which meant that different conversions and formulas had to be utilized.

The network had many parts like buses, transformers, loads, cables and lines, making it complex. We had to carefully handle the data to make sure our analysis was accurate. This lab taught us how to use math and computers to understand and manage power networks better.

Newton-Raphson Algorithm solves the simultaneous quadratic equations of the power network. Unlike Gauss-Seidel Algorithm, it needs a larger time per iteration, but only a few iterations, and is significantly independent of the network size.

Newton-Raphson method uses the derivative of the power flow equations to update the solution. It requires solving a system of nonlinear equations. Gauss-Seidel is an iterative method that updates the solution sequentially, with each variable updated using the most recent values of the other variables. It is requires less time per iteration, but convergence is reached in a much larger number of iterations.

LAB 4 – SHORT CIRCUIT ANALYSIS (POWERFACTORY)

1. Problem Statement

Tasks:

1. For your modelled part of the network Gracanica perform Short circuit analysis.

2. Take 3 different types of faults for the 3 different buses.

3. Simulate faults separately and all together.

4. Make plots for each case.

5. Write the report:

• Describe the task;

• Describe the faults you performed;

• Show your network;

• Show the Short circuit analysis;

• Show the plots obtained;

• Discuss obtained results for each case.

2. THEORY

In the theoretical part, the symmetrical components will be explained, followed by the faults.

2.1. Symmetrical Components

When dealing with a single-phase three-wire electrical setup, it's considered unbalanced if the neutral current is not zero. This typically occurs when the loads connected between the line and neutral are not the same. This imbalance leads to uneven currents and voltages, resulting in a nonzero current in the neutral line. The necessary calculations can be done by using the method of symmetrical components. Any unbalanced three-phase system of phasors can be shown as three balanced systems of phasors: (1) positive-sequence system, (2) negative-sequence system, and (3) zero-sequence system, as shown in the figure below.

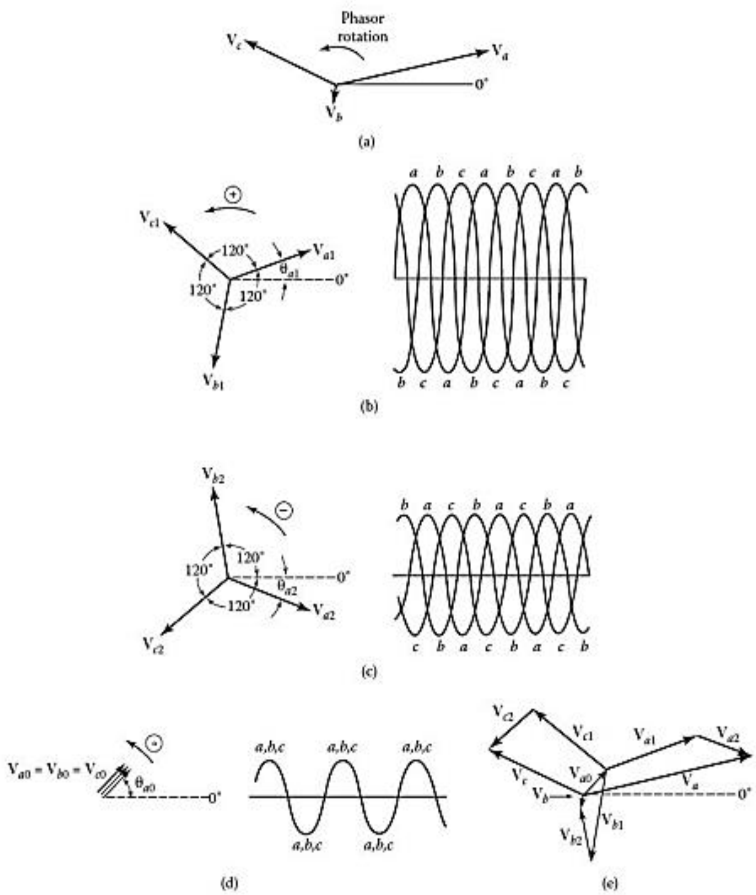


Figure 1. Analysis and combination of set of three unbalanced voltage phasors: (a) original system of unbalanced phasors; (b) positive-sequence components; (c) negative-sequence components; (d) zero-sequence components; (e) representation of phasors for obtaining original unbalanced phasors.

The positive-sequence system (Figure 1-b) is represented by a balanced system of phasors having the same phase sequence as the original unbalanced system. The phasors of the positive-sequence system are equal in magnitude but are moved from each other by 120°.

The negative-sequence system (Figure 1-c) is represented by a balanced system of phasors having the opposite phase sequence from the original system. The phasors of the negative-sequence system are equal in magnitude and moved from each other by 120°.

The zero-sequence system (Figure 1-d) is represented by three single phasors equal in magnitude and angle. Because of the use symmetrical components theory, there is a need for a unit phasor (or operator) that will rotate another phasor by 120° in the counterclockwise direction but leave its magnitude unchanged. Such operator is a complex number of magnitude 1 with an angle of 120° and is defined by:

$$a = 1\angle 120°$$

The three voltage phasors V_a, V_b, V_c are expressed in terms of their symmetrical components as:

$$V_a = V_{a1} + V_{a2} + V_{a0} \qquad V_b = V_{b1} + V_{b2} + V_{b0} \qquad V_c = V_{c1} + V_{c2} + V_{c0}$$

2.2. Double Line-To-Ground Fault

A double line-to-ground fault (DLG) is a serious event in a three-phase symmetrical system that can lead to significant asymmetry. It is an unbalanced (unsymmetrical) fault type, alongside single line-to ground (SLG) and line-to-line (L-L) faults. If not addressed quickly, DLG might grow into a three-phase fault.

In Figure (2-a), there is the general representation of a double line-to-ground fault, denoted as F, with associated impedances Z_f and the impedance from line to ground, Z_g. Figure (2-b) illustrates the sequences network diagram. For the simplicity in fault analysis calculations, it is assumed that phase b and phase c are the faulted phases.

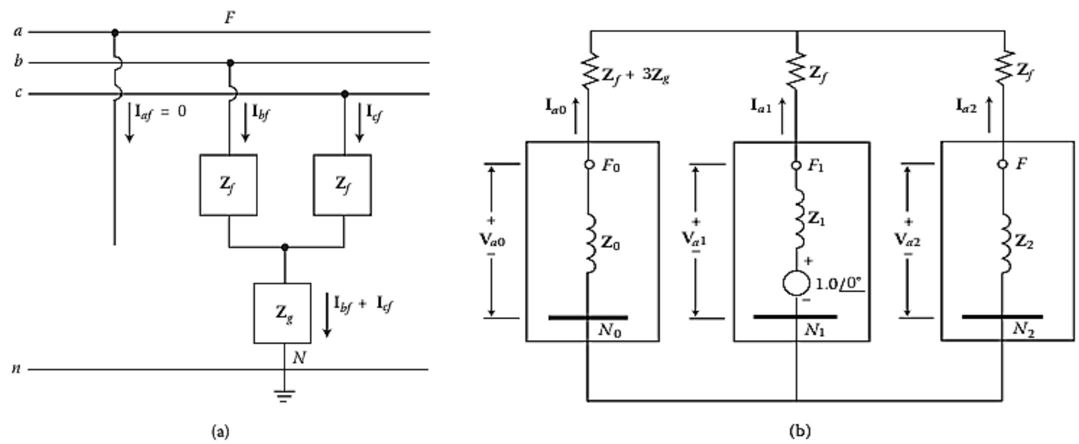


Figure 2. General representation of a Double Line-to-Ground Fault (a), Sequence Network Diagram of a Double Line-to-Ground Fault (b)

From observing the Figure above, it can be concluded that:

$$I_{af} = 0$$

$$V_{bf} = (Z_f + Z_g)I_{bf} + Z_g I_{cf}$$

$$V_{cf} = (Z_f + Z_g)I_{cf} + Z_g I_{bf}$$

When it comes to the positive sequence currents, they are obtained as:

$$I_{a1} = \frac{1.0\angle 0^\circ}{(Z_1 + Z_f) + \frac{(Z_2 + Z_f)(Z_0 + Z_f + 3Z_g)}{(Z_2 + Z_f) + (Z_0 + Z_f + 3Z_g)}}$$

$$I_{a2} = -[\frac{(Z_0 + Z_f + 3Z_g)}{(Z_2 + Z_f) + (Z_0 + Z_f + 3Z_g)}]I_{a1}$$

$$I_{a0} = -[\frac{(Z_2 + Z_f)}{(Z_2 + Z_f) + (Z_0 + Z_f + 3Z_g)}]I_{a1}$$

Another way to obtain this is:

$$I_{af} = 0 = I_{a0} + I_{a1} + I_{a2} \qquad I_{a0} = -(I_{a1} + I_{a2})$$

If the two impedances, Z_f and Z_g, are both zero, then the positive-, negative-, and zero-sequences are expressed from:

$$I_{a1} = \frac{1.0\angle 0°}{(Z_1) + \frac{(Z_2)(Z_0)}{(Z_2+Z_0)}} \qquad I_{a2} = -[\frac{(Z_0)}{(Z_2+Z_0)}]I_{a1} \qquad I_{a0} = -[\frac{(Z_2)}{(Z_2+Z_0)}]I_{a1}$$

The fault currents for each phase are:

$$I_{af} = 0 \qquad I_{bf} = I_{a0} + a^2 I_{a1} + aI_{a2} \qquad I_{cf} = I_{a0} + aI_{a1} + a^2 I_{a2}$$

The total fault current, flowing into the neutral, can be expressed as:

$$I_n = 3I_{a0} = I_{bf} + I_{cf}$$

Using the obtained information, phase voltages are obtained in the following form:

$$V_{af} = V_{a0} + V_{a1} + V_{a2} = 3V_{a1} \qquad V_{bf} + V_{cf} = 0$$

In the end, the line-to-line voltages have this formulation:

$$V_{abf} = V_{af} - V_{bf} = V_{af} \qquad V_{bcf} = V_{bf} - V_{cf} = 0 \qquad V_{caf} = V_{cf} - V_{af} = -V_{af}$$

2.3. Three-Phase Faults

Typically, a three-phase (3φ) fault is considered a balanced or symmetrical fault, meaning it can be analyzed using symmetrical components. Although rare, it is the most severe fault. Due to the balanced nature of the network, it is addressed on a per-phase basis. The other two phases are carrying identical currents, although with a phase shift. These faults can usually be categorized as either Three-phase direct (L–L–L) faults or Three-phase faults through a fault impedance to ground (L–L–L–G). The two impedances, Z_f and Z_g are present.

The reactance of the synchronous generator under short-circuit conditions is a time-varying quantity. For the network analysis, three reactances are defined. The subtransient reactance X_d'' is during the first cycle after the fault occurs (0.05-0.1s). Transient reactance X_d' determines the fault current after a few cycles. In about 0.2-2s, it increases to the synchronous reactance X_d. This reactance determines the fault current after steady state conditions are reached. Three different reactances are used, since the flux across the air gap of the machine is much greater at the instant the fault occurs than it is a few cycles later.

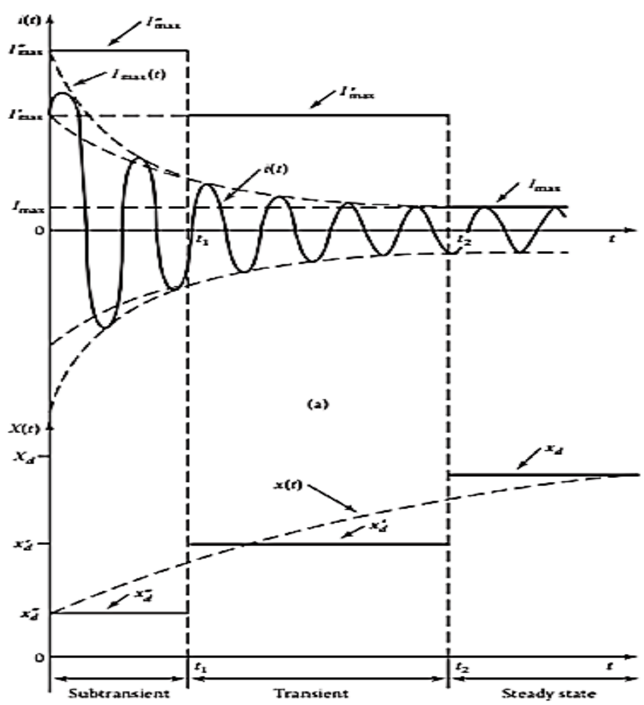


Figure 3. The Graphical Representation of Three Reactances

The subtransient (initial) reactance X_d'' is the leakage reactance of the stator and rotor windings of the generator, as well as the damper windings effects. The larger, transient reactance X_d' is the leakage reactance of the stator and excitation generator windings. Finally, the synchronous reactance X_d is the total reactance of the armature winding. That involves the leakage reactance of the stator and the armature reaction reactance of the generator. This reactance is much larger than the transient reactance X_d'.

Additionally, in the quadrature axis, the generator has reactances. These are the reactances due to the flux path between the field poles and are designated as X_q'', X_q', and X_q. In a machine with cylindrical rotor, values of X_d and X_q are practically equal. Because of this, the synchronous reactance X_s is only called, while X_d and X_q do not have to be differentiated.

Using the maximum voltage of the generator, the three reactances are expressed as:

$$X_d'' = \frac{E_{max}}{I_{max}''} \qquad X_d' = \frac{E_{max}}{I_{max}'} \qquad X_d = \frac{E_{max}}{I_{max}}$$

In Figure, there is a balanced three-phase fault between the points F and N:

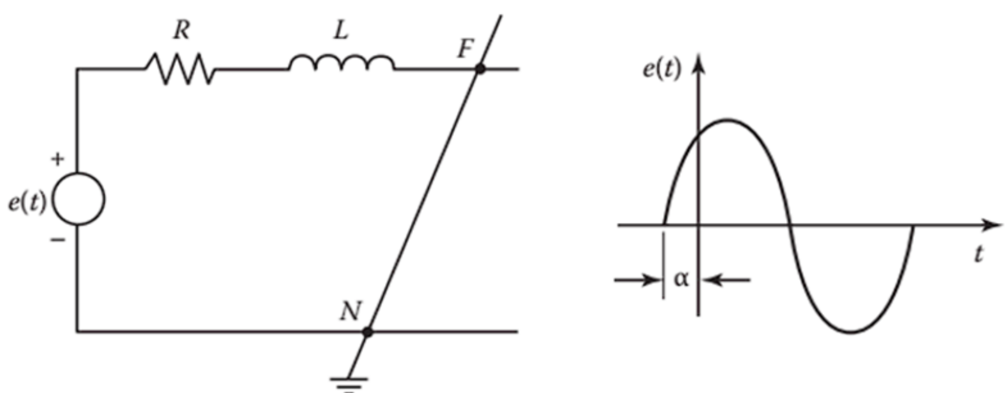


Figure 4. Balanced Three Phase Fault at No Load (Left), Generator Voltage (Right)

If the generator voltage is e(t) = V_m sin(ωt + α) and the fault occurs at t=0, transient current i(t) is:

$$i(t) = \frac{V_m}{Z}[\sin(\omega t + \alpha - \theta) - \sin(\alpha - \theta)\, e^{\frac{-Rt}{L}}]$$

$$Z = (R^2 + \omega^2 L^2)^{\frac{1}{2}} \qquad \theta = tan^{-1}(\frac{\omega L}{R})$$

If the fault occurs at t = 0 when the angle α – θ = – 90°, the value of the transient current becomes twice the steady-state maximum value and can be expressed as:

$$i(t) = \frac{V_m}{2}\left[-\cos(\omega t) + e^{\frac{-Rt}{L}} \right] \qquad \tan(\alpha) = -\frac{R}{\omega L}$$

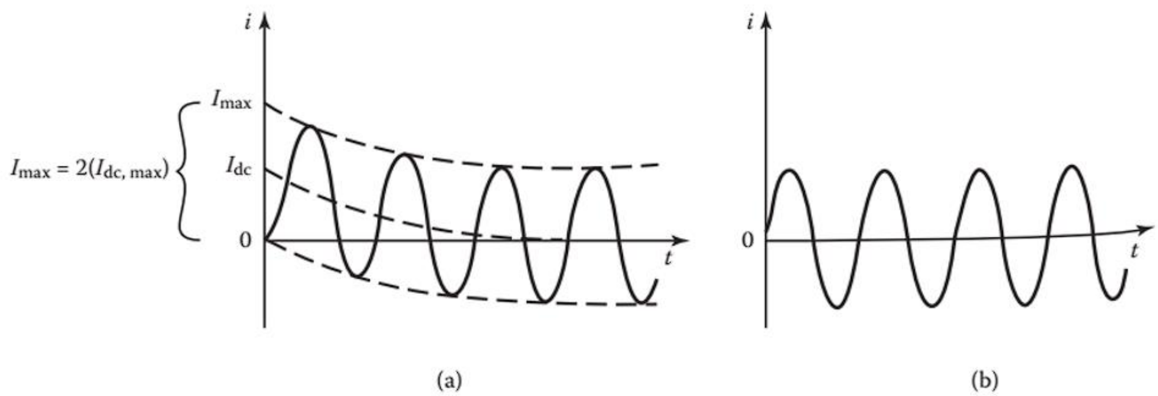


Figure 5. Transient Current Waveform (a), Transient Current if α=0, at t=0 (b)

As shown in Figure (b), if α=0, at t=0, the DC offset does not exist, and the transient current is expressed as:

$$i(t) = \frac{V_m}{Z}\sin(\omega t)$$

A fault is a change in the structure of the network. It is caused by an addition of an impedance at the place of fault. If fault impedance (Z_f) is zero, the fault is categorized as a bolted or solid fault. However, this network can be solved using the Thevenin equivalent.

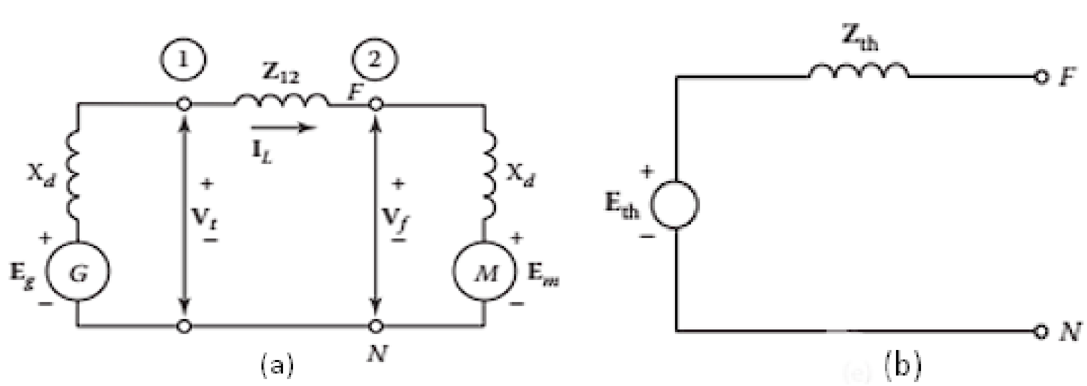


Figure 6. Balanced Three-Phase Fault at Full Load (a), Thevenin Equivalent of this Circuit (b)

In Figure (a), the load current (I_L) flows before the fault. The voltage at the fault point F is V_F. The line impedance between the generator and the motor is Z_{12}. In Figure (b), the Thevenin voltage, E_{th}, is the equivalent of V_f voltage before the fault, in Figure (a).

The Thevenin impedance and the subtransient fault current, at fault point F, are:

$$Z_{th} = \frac{(X_d'' + X_{12})X_d''}{(X_d'' + X_{12}) + X_d''} \qquad\qquad I_f'' = \frac{E_{th}}{Z_{th}} = \frac{V_f}{Z_{th}}$$

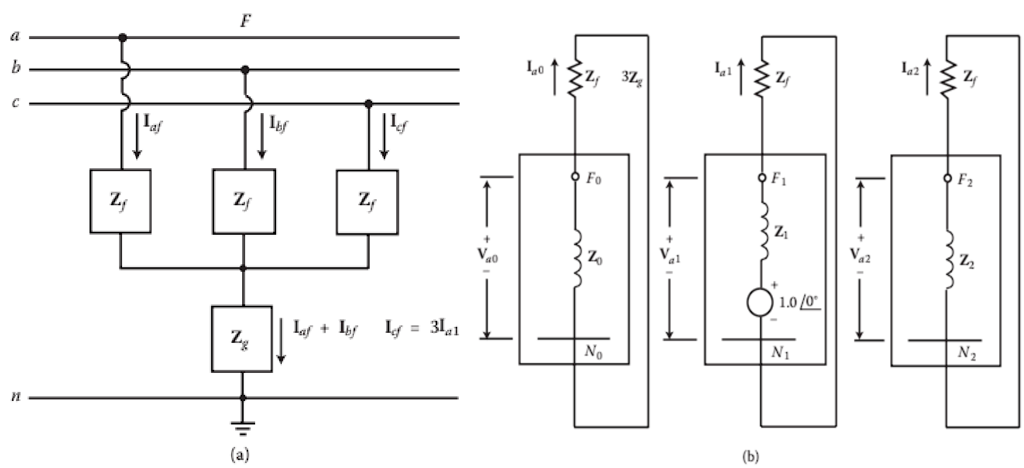


Figure 7. Three-phase fault: (a) general representation; (b) interconnection of sequence networks.

2.4. Single Line-To Ground Fault

In power systems, unbalanced faults, particularly single line-to-ground faults (SLG), are more common than balanced three-phase faults. Although three-phase faults are more severe, SLG faults can surpass them in severity under specific conditions. This is true when the generators involved in the fault have solidly grounded neutrals or low-impedance neutral impedances, and when the fault occurs on the wye-grounded side of delta–wye-grounded transformer banks.

The single line-to-ground fault is usually referred to as “short circuit”. As mentioned, the SLG fault occurs when one conductor falls to ground or contacts the neutral wire. Figure (7-a) shows the general representation of a SLG fault at a fault point F with a fault impedance Zf. Usually, the fault impedance Zf is ignored in fault studies. Figure (7-b) shows the interconnection of the resulting sequence networks. For the simplicity in fault analysis calculations, the faulted phase is assumed to be phase a, as shown in Figure (7-b).

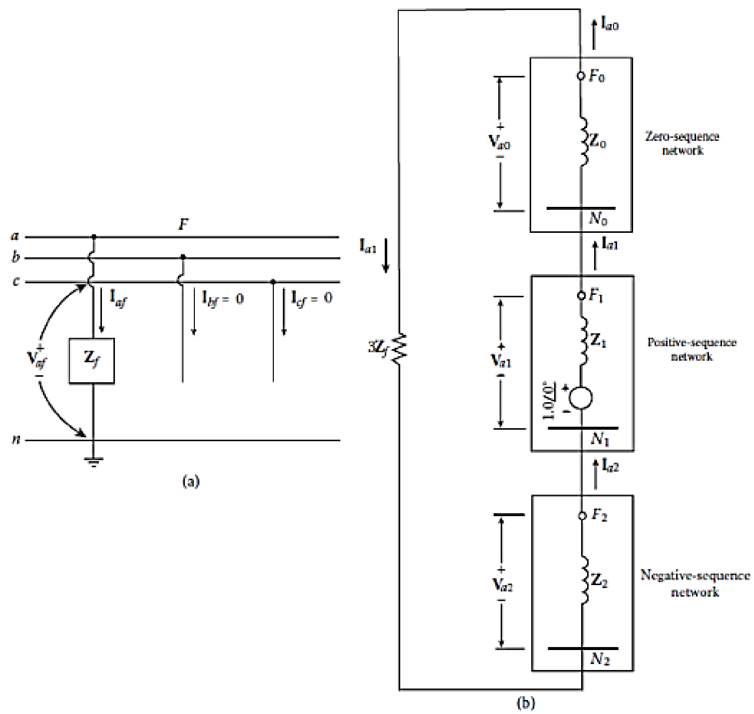


Figure 8. SLG fault: (a) general representation; (b) interconnection of sequence networks

The zero-, positive-, and negative-sequence currents are all equal as can be observed in Figure 1.4. From this, the following formulation is obtained:

$$I_{a0} = I_{a1} = I_{a2} = \frac{1.0\angle 0°}{Z_0 + Z_1 + Z_2 + 3Z_f}$$

The results are obtained for sequence currents. This means that sequence voltages are obtained from:

$$\begin{bmatrix} V_{a0} \\ V_{b1} \\ V_{c2} \end{bmatrix} = \begin{bmatrix} 0 \\ 1.0\angle 0^\circ \\ 0 \end{bmatrix} - \begin{bmatrix} 1 & 1 & 1 \\ 1 & a^2 & a \\ 1 & a & a^2 \end{bmatrix} \begin{bmatrix} I_{a0} \\ I_{a1} \\ I_{a2} \end{bmatrix}$$

By solving the equations, it is obtained that:

$$V_{a0} = -Z_0 I_{a0} \quad V_{a1} = 1.0 - Z_1 I_{a1} \quad V_{a2} = -Z_2 I_{a2}$$

The matrix representation for fault currents can be written in the following way:

$$\begin{bmatrix} I_{af} \\ I_{bf} \\ I_{cf} \end{bmatrix} = \begin{bmatrix} 1 & 1 & 1 \\ 1 & a^2 & a \\ 1 & a & a^2 \end{bmatrix} \begin{bmatrix} I_{a0} \\ I_{a1} \\ I_{a2} \end{bmatrix}$$

As an example, the fault current of phase a can be found as:

$$I_{af} = I_{a0} + I_{a1} + I_{a2} \quad \text{or} \quad I_{af} = 3I_{a0} = 3I_{a1} = 3I_{a2}$$

From Figure (a), it can be seen that:

$$V_{af} = Z_f I_{af} = 3Z_f I_{a1}$$

In case of SLG fault occurring on phase b or phase c, the voltages are obtained by the relation that exists from the known phase voltage components:

$$\begin{bmatrix} V_{af} \\ V_{bf} \\ V_{cf} \end{bmatrix} = \begin{bmatrix} 1 & 1 & 1 \\ 1 & a^2 & a \\ 1 & a & a^2 \end{bmatrix} \begin{bmatrix} V_{a0} \\ V_{a1} \\ V_{a2} \end{bmatrix}$$

3. SHORT CIRCUIT ANALYSIS IN DIGSILENT

For the three faults, I have selected three different faults, all at three different locations. Firstly, all of them are simulated individually with IEC 60909 method. After that, all three faults are simulated together with „Complete“ method.

Alongside this, before the short circuit analysis is performed, the calculation method is AC Load flow, unbalanced, 3-phase (ABC). Finally, following the implementation of short circuit analysis, we obtain information and short circuit calculation in the output window. Additionally, after right clicking on a certain bus, we selected „Plots“ option and chose numerous values we want to plot.

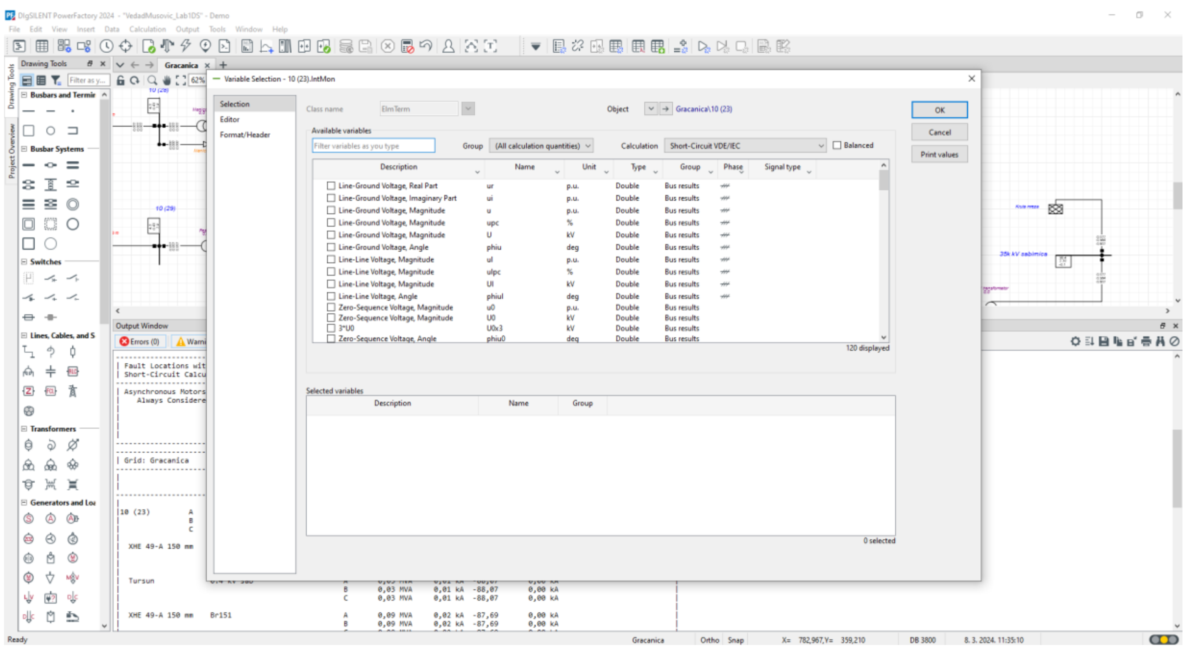


Figure 9. Variable Selection in the „Plots“ Section

3.1. Double-Phase To Ground Fault At Bus 10 (23)

A double-phase to ground fault is succesfully executed at bus 10(23). In the command window, the currents will rise to large values in kA (under short circuit) at the bus 10(23) and the adjacent cable. In DLG fault, the currents rise to noticeably higher values in two sequences, compared to the third one. This is for all sequences. Pre fault, the voltage will have its normal value, while it exibits significant drops in all sequences (Positive, Zero, Negative) when the fault occurs.

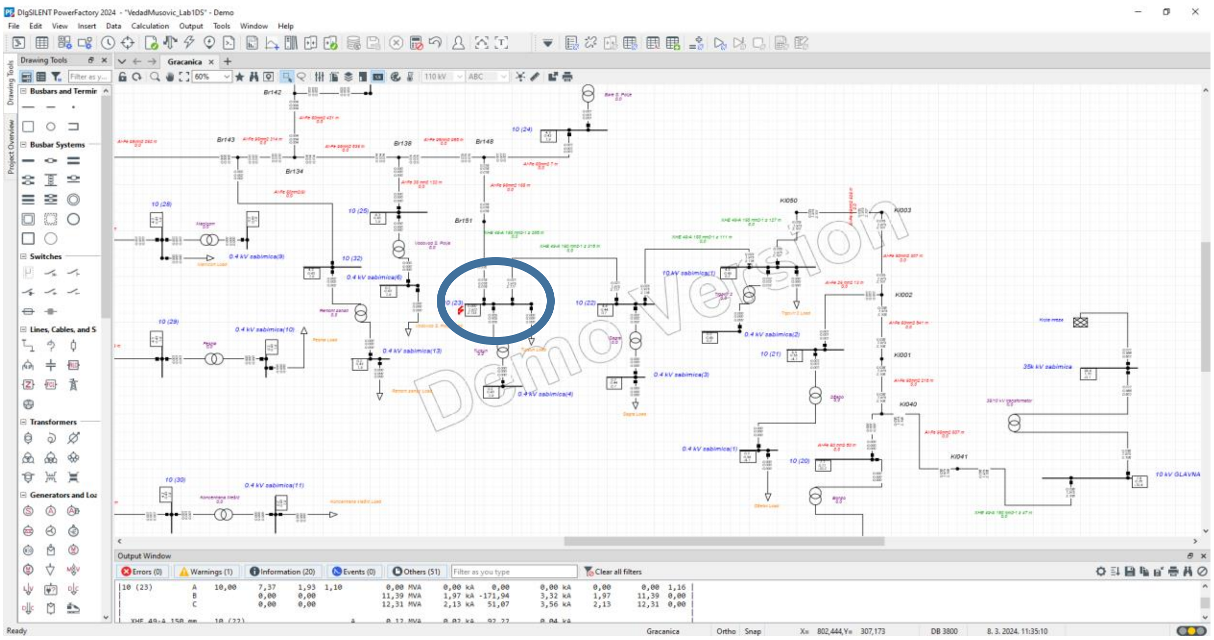


Figure 10. Fault Location at the Network

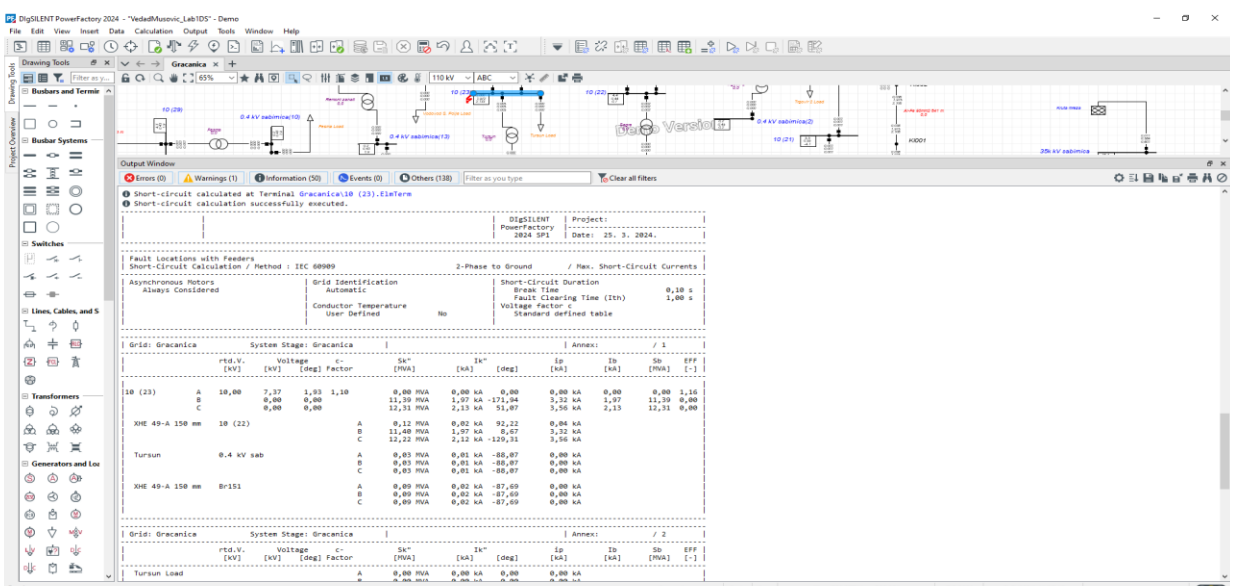


Figure 11. Output Window Results

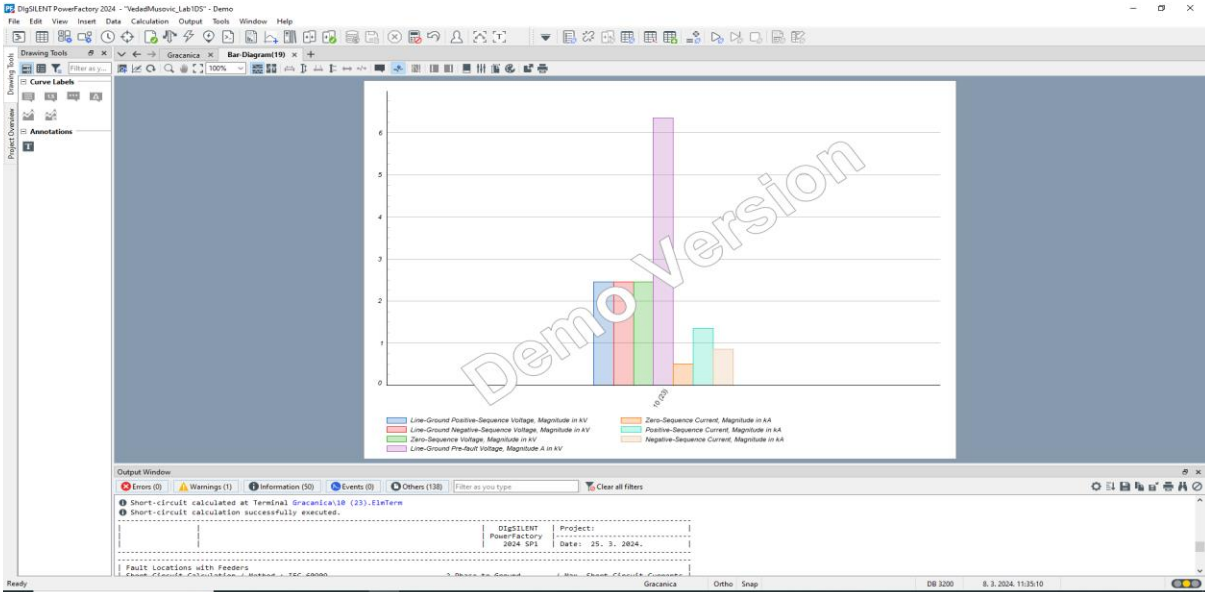


Figure 12. The Obtained Plots at the Fault Point

3.2. Single-Phase To Ground Fault At LR Manicom

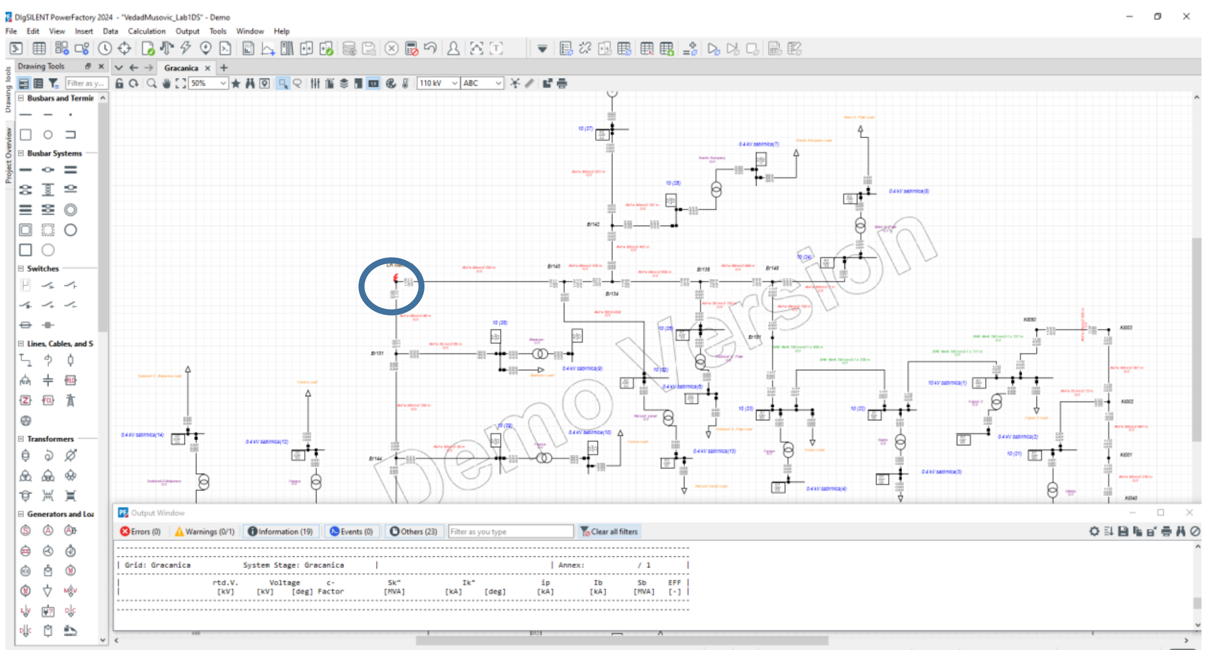


Figure 13. Short Circuit Location

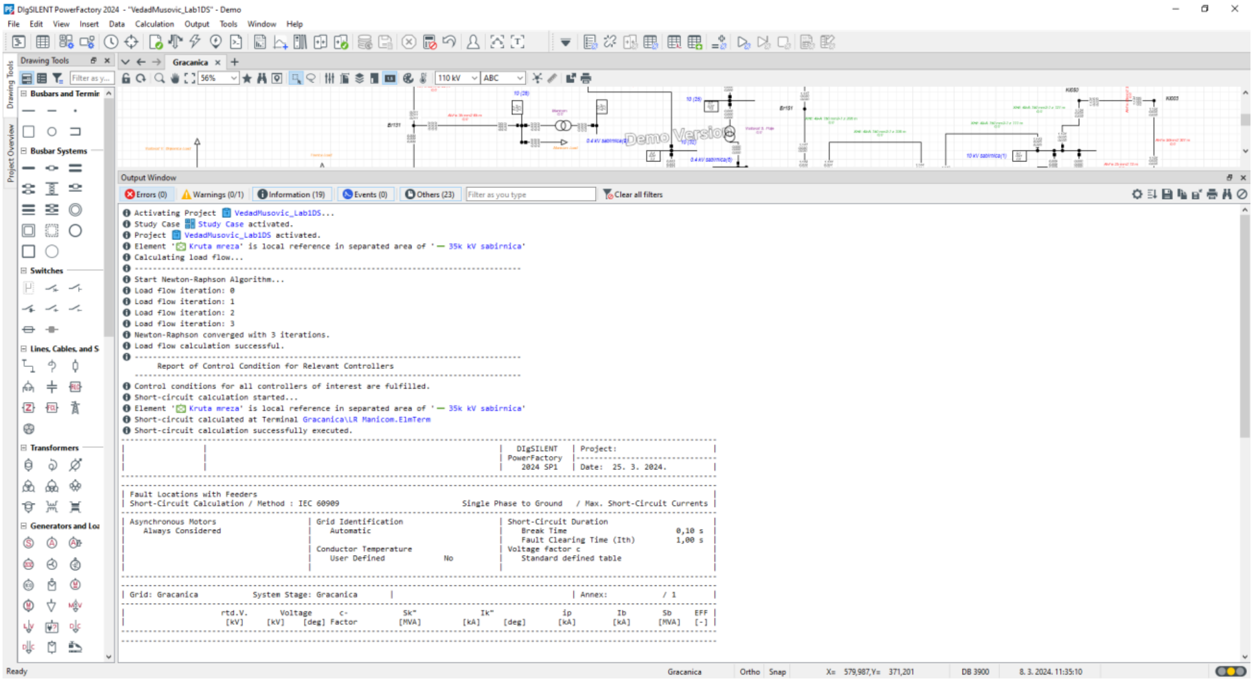


Figure 14. Output Window Results

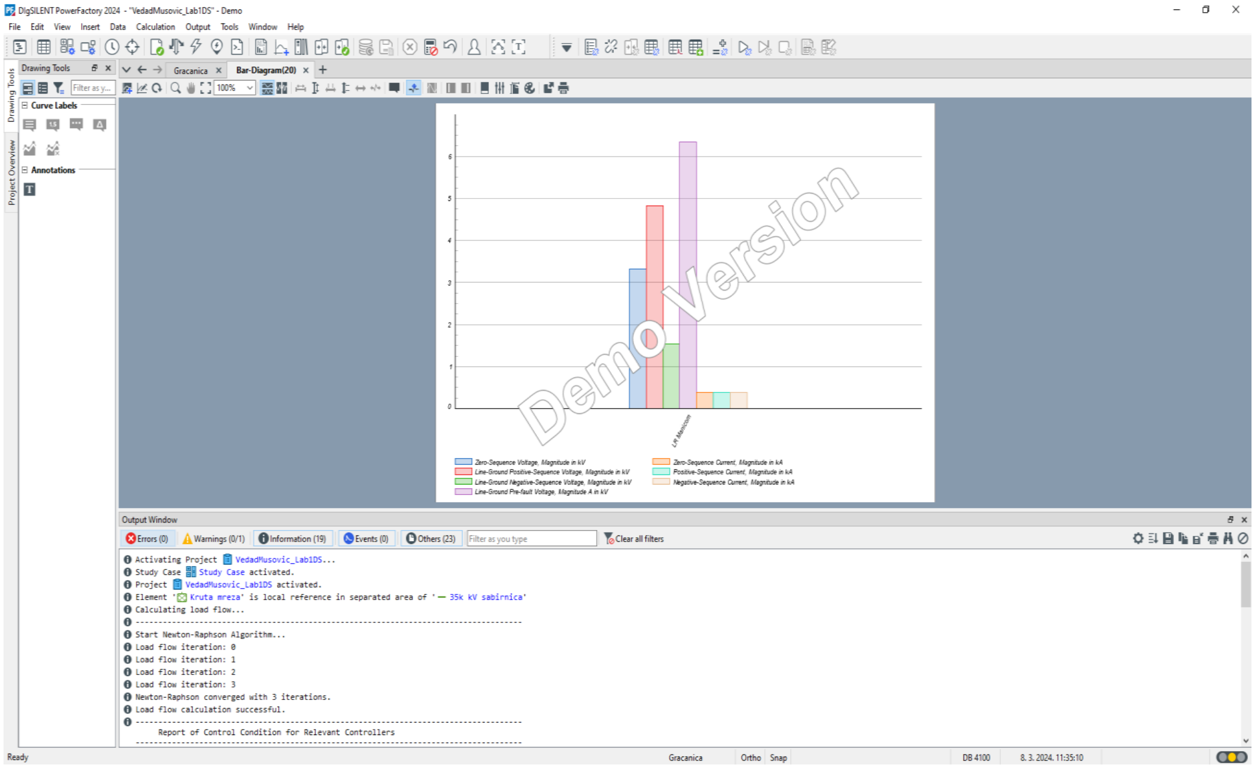


Figure 15. The Obtained Plots at the Fault Point

A single-phase to ground fault is successfully executed at **LR Manicom**.

In the command window we get this confirmation. Currents are measured in the three sequences (in kA), while the voltages are also measured in them. Line-Ground Voltage magnitudes are measured (in kV).

The pre-fault voltage maintains its high value, prior to the fault occuring. When the single-phase to ground faults occurs, the voltage in one of the three sequences will drop a lot more than in the other two. However, they will still be affected to some degree.

The short circuit current experience a rise approximately the same in all three sequences.

3.3. Three-Phase Short Circuit At 10 kV Main Bus

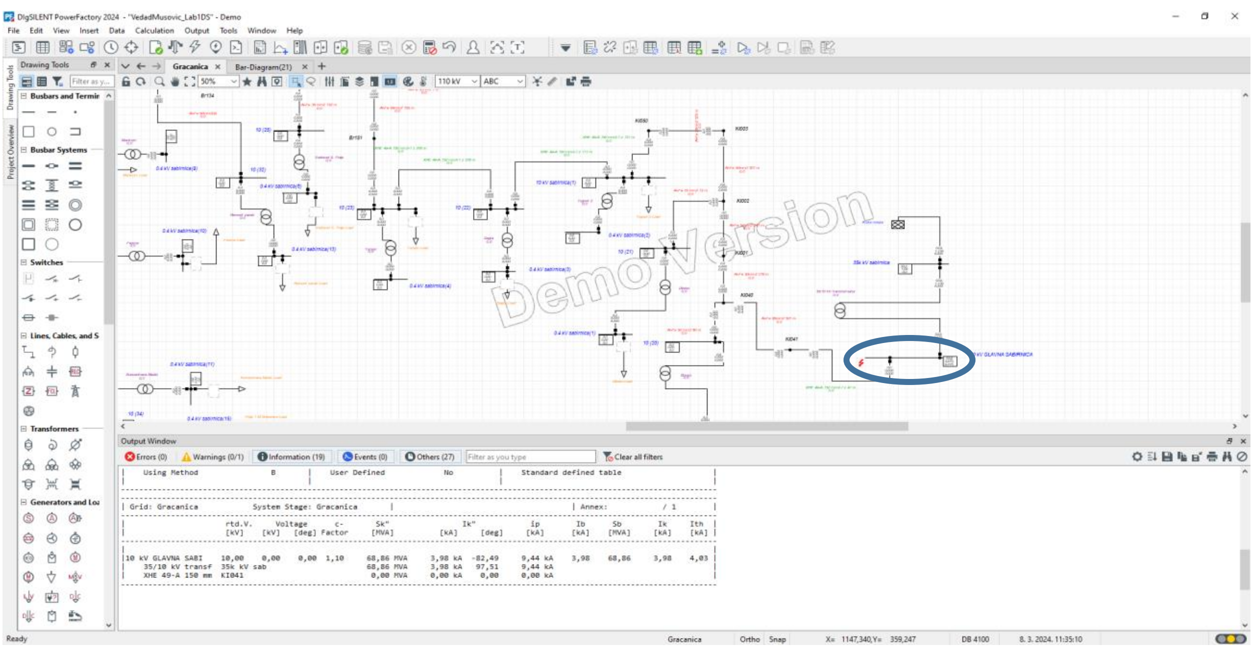


Figure 16. Fault Location

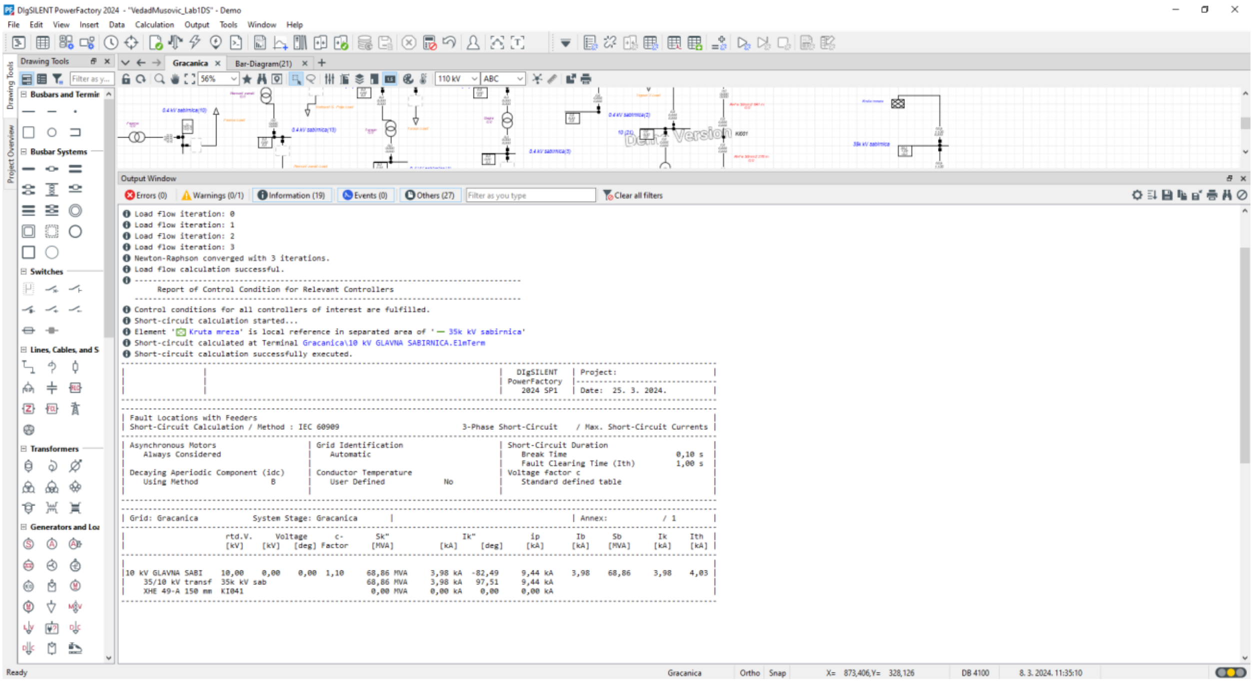


Figure 17. Output Window Results

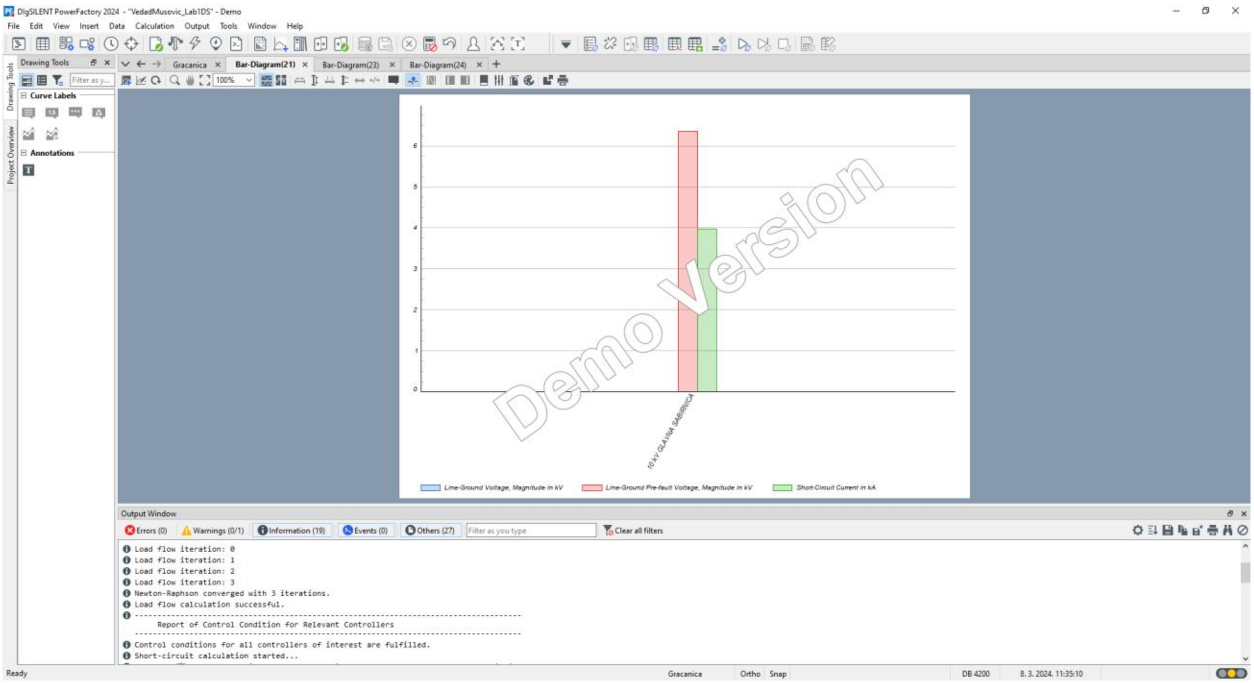


Figure 18. The Obtained Plots at the Fault Point

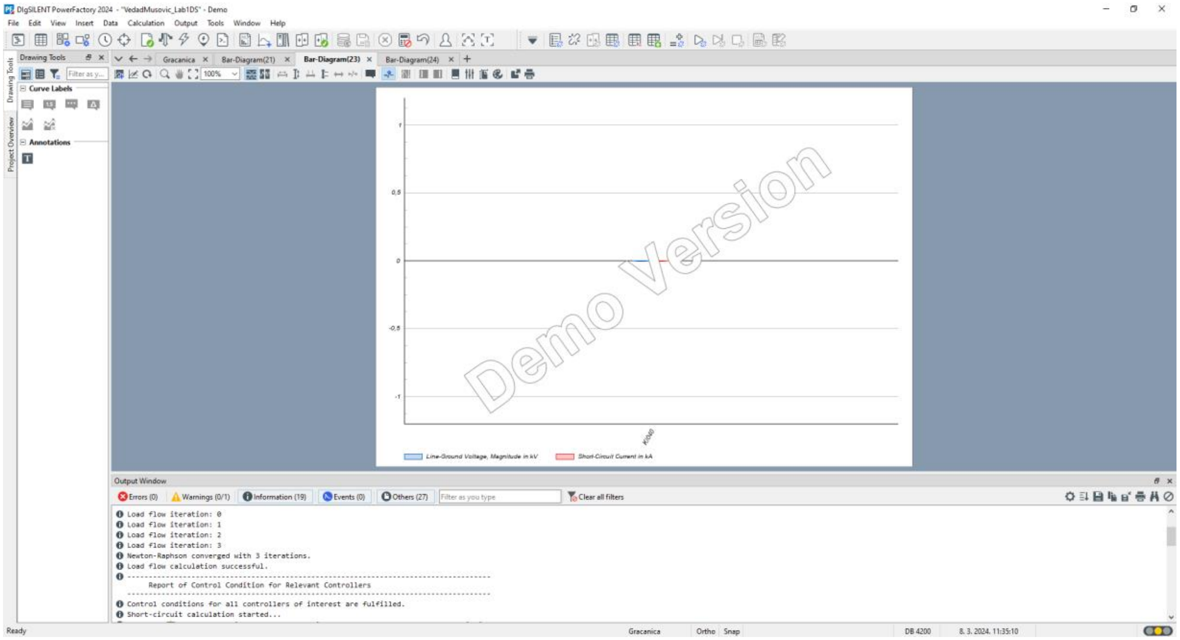


Figure 19. The Obtained Plots at the Location after the Fault Point

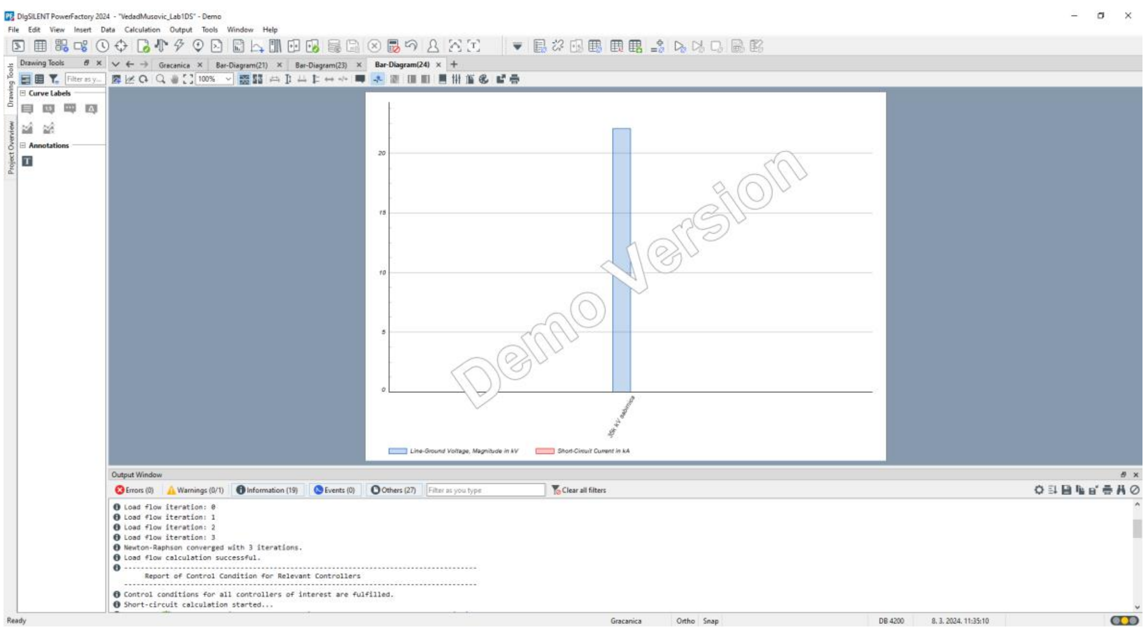


Figure 20. The Obtained Plots at the Location before the Fault Point

A three-phase short circuit is simulated at **10 kV „GLAVNA SABIRNICA“.** It continues from the 35/10 Kv transformer and is the original main bus in the „Gracanica“ network.

Short circuit analysis was executed succesfully. Since this is the main bus, the effects of this fault on the entire network will be significant. In the command window, we see that the current will rise to extreme kA values at both the bus and 35/10 kV transformer.

When it comes to the obtained plots at the fault point, the voltage sees a complete drop in value, after having a normal pre-fault line-ground voltage magnitude. The current, as talked about before, has an abnormal rise towards abnormal values. At the location at the network right after the fault, the voltage will drop significantly, but the currents will maintain the normal values. At the 35 kV bus, which is in the network location before the fault location, the currents have normal (small) values. On the other side, the voltages will have a normal (high) values.

3.4. Every Short-Circuit Occurs Together

For simulating every short-circuit event together, the following faults are taken: double-phase to ground fault at bus 10(23), single-phase to ground fault at lr manicom, three-phase short circuit at 0.4 kV sabirnica – Bonzo Load.

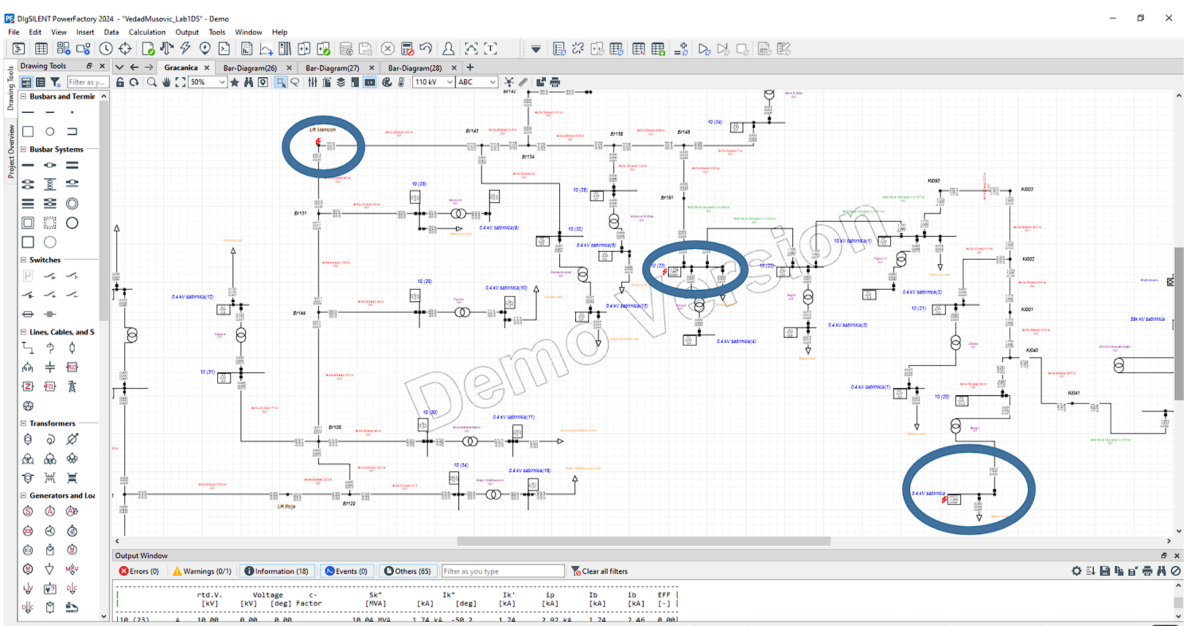


Figure 21. Fault Locations

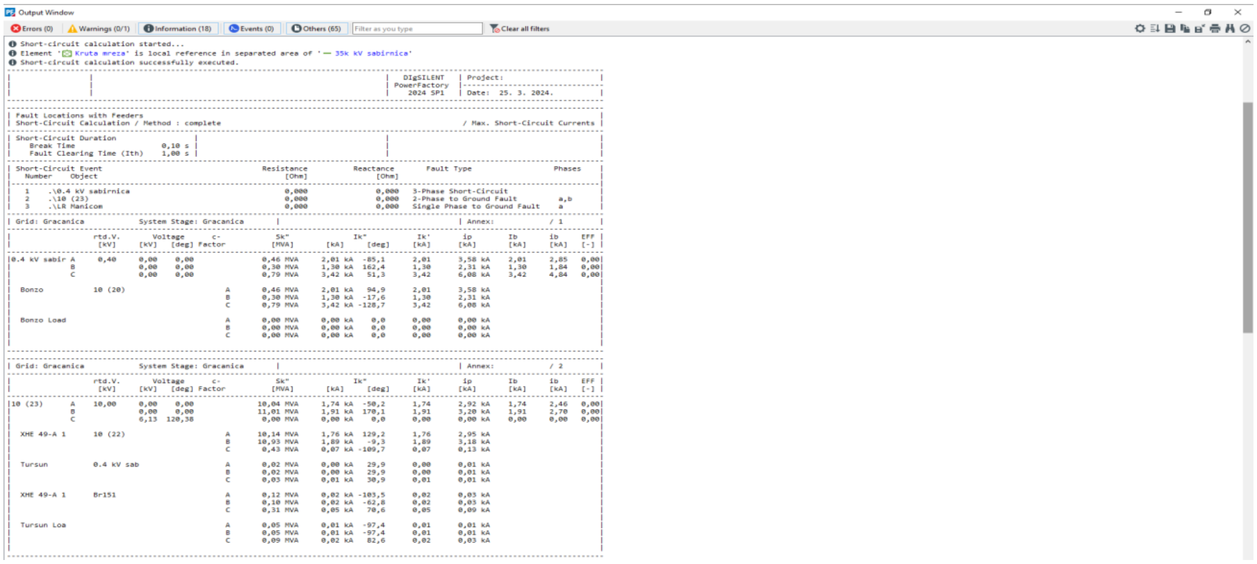


Figure 22. Output Window Results

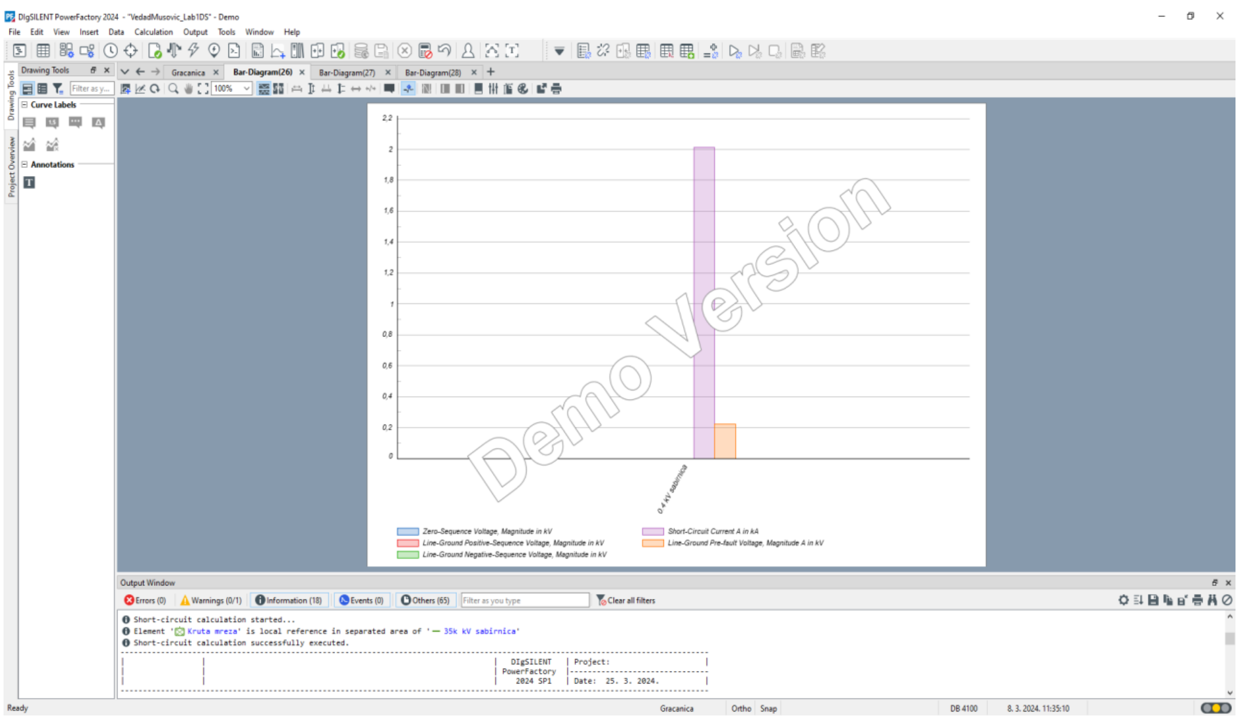


Figure 23. The Obtained Plots at 0.4 kV sabirnica

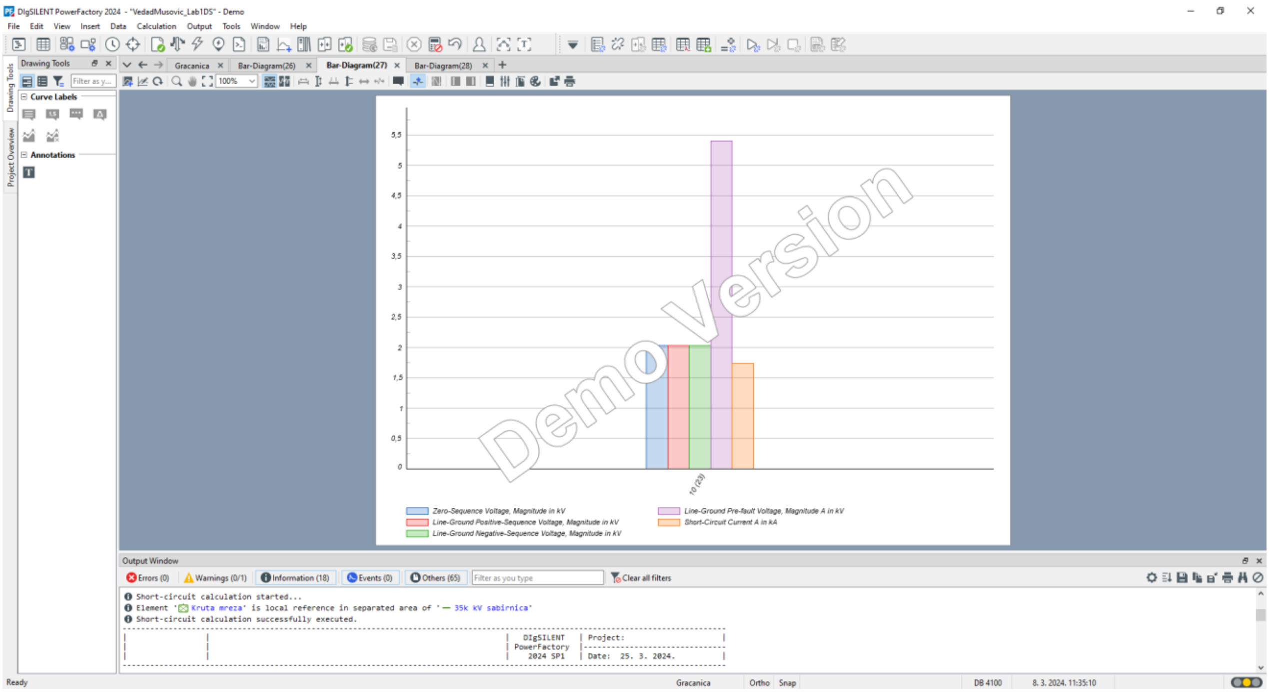


Figure 24. The Obtained Plots at Bus 10 (23)

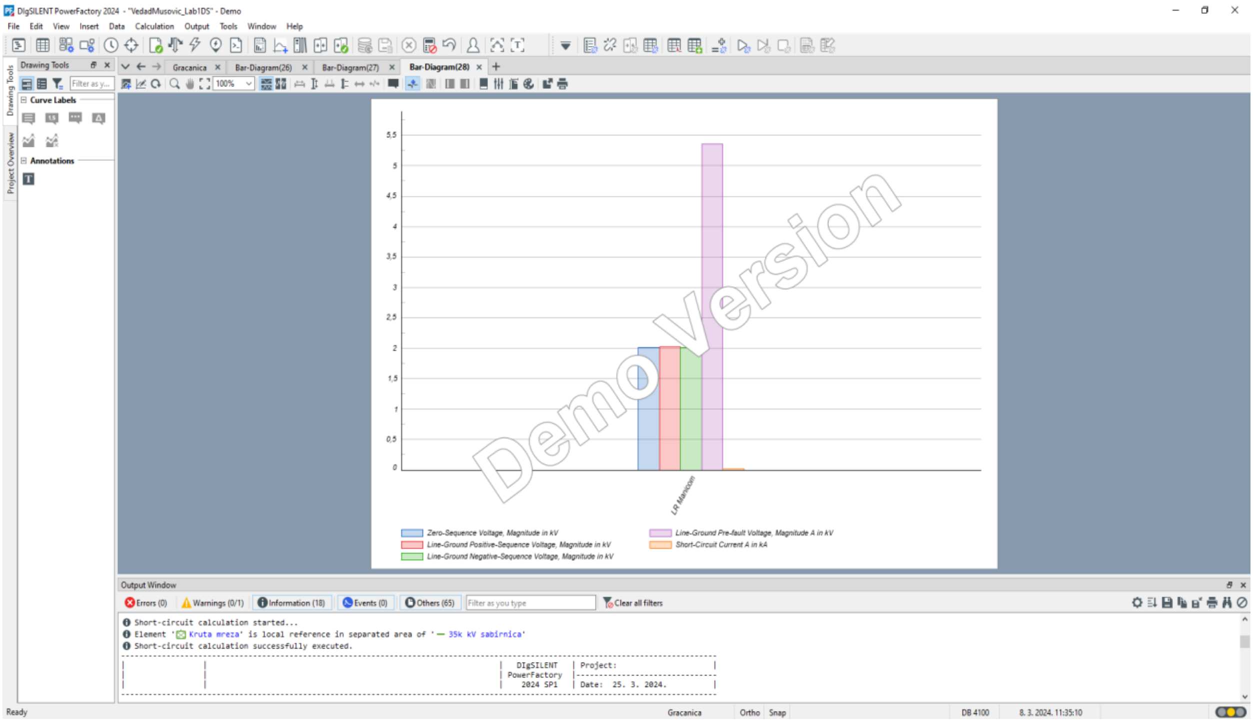


Figure 25. The Obtained Plots at LR Manicom

The fault is not simulated for 10 kV main bus, since its effects on the other busses were shown earlier, and also, the faults at the other busses would be negligible compared to this main fault.

At 0.4 kV sabirnica, the current will have extreme values at the bus and at the Bonzo transformer. At the 10(23) Bus, as in the individual case, the current will rise to abnormal values at the bus and at the cable coming out from that bus. At 0.4 kV bus, the current will rise to extremely high values under three-phase short circuit, while the voltages will drop to near zero values. The load current maintains low value even during the fault occuring. The pre-fault voltage maintains the value approximately close to 0.4 kV.

At 10(23) sabirnica, the voltages will drop, compared to the pre-fault voltage. On the other hand, the current will naturally rise to extremely high values.

At LR Manicom, the voltages drop to low values. The pre-fault voltage maintains its high value. On the other hand, the current will rise, but not to the extremely high values, since we moved far away from the beginning (reference point – Kruza mreza) of my network.

4. Conclusion

In conclusion, the conducted short circuit analysis on the Gračanica network provided valuable insights into its behavior under various fault conditions. By simulating different types of faults at different locations in the network, we observed significant variations in current magnitude rises and voltage drops, showing the impact of each fault type. Initially, a successful load flow analysis was executed in order for us to perform the short circuit analysis.

The analysis revealed that double-phase to ground faults induced higher currents in two sequences compared to the third, while single-phase to ground faults caused significant voltage drops in one sequence. Additionally, the three-phase short circuit at the main bus exhibited extreme current values and voltage drops, highlighting its impact on the entire network. Simulating all faults together had the goal of showing the complexity of fault interactions, with each fault contributing differently to the overall system behavior.

LAB 5 – INTEGRATING RENEWABLE SOURCES (POWERFACTORY)

1. Problem Statement

Lab 5 is about integrating renewable modules inside of our network. In DIGSILENT, the comparative analysis on system performances of integrating PV modules is performed. Two different scenarios are taken: concentrated power at one location and dispersed power at more locations. Power flow analysis is performed with similarities and differences being compared.

2. Integrating PV Systems – Reasons and Advantages

PV systems use sunlight to generate electricity, providing a sustainable alternative to fossil fuels and cutting down on harmful emissions. By generating power closer to where it's needed (typically a load or a consumer), PV systems reduce the amount of electricity lost during transmission over long distances, which is particularly beneficial in networks with decentralized setups.

PV systems produce electricity during the periods of high demand, especially during daylight hours. This helps reduce the stress on the grid during peak usage hours. PV systems inject power at distribution voltages, helping to stabilize voltage levels and improve overall grid reliability. Distributed PV systems decentralize power generation, offering backup power during outages.

3. Case I – PV System at One Location

For the first case, one PV system is integrated at 0.4 kV sabirnica, next to Bonzo Load. Its power is 700 W. It value is just enough so the loading condition for the transformer, and the pu voltage for the bus are not violated. Rated Active Power = 700 W, i.e. 0.7 kW

For example, if we were to put 1 kW power, the maximum loading is violated. This means that the network and the PV system are not completely compatible.

If we were to try and up the PV system's active power to levels of few hundred KW, and later of MW, DIGISILENT will not be able to execute Load Flow Analysis and it will signal for error.

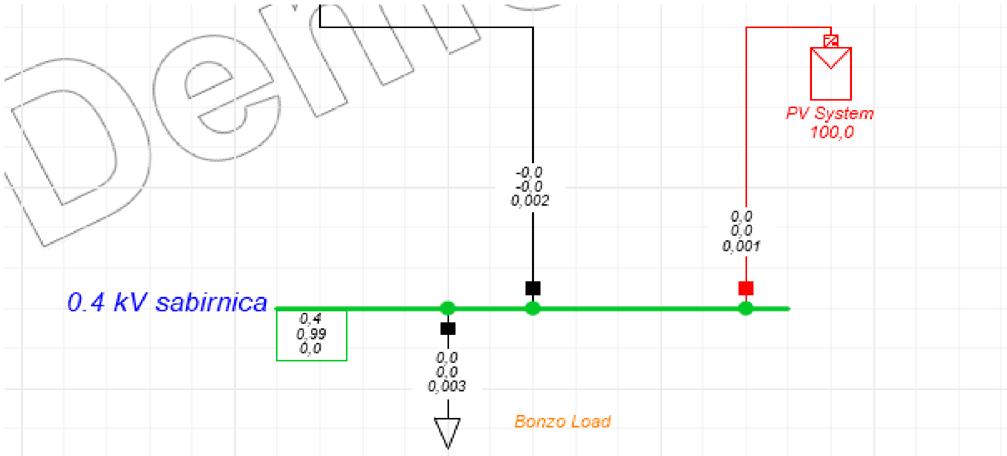


Figure 1. DIGSILENT will signal us if we enter too high PV System Active Power (kW)

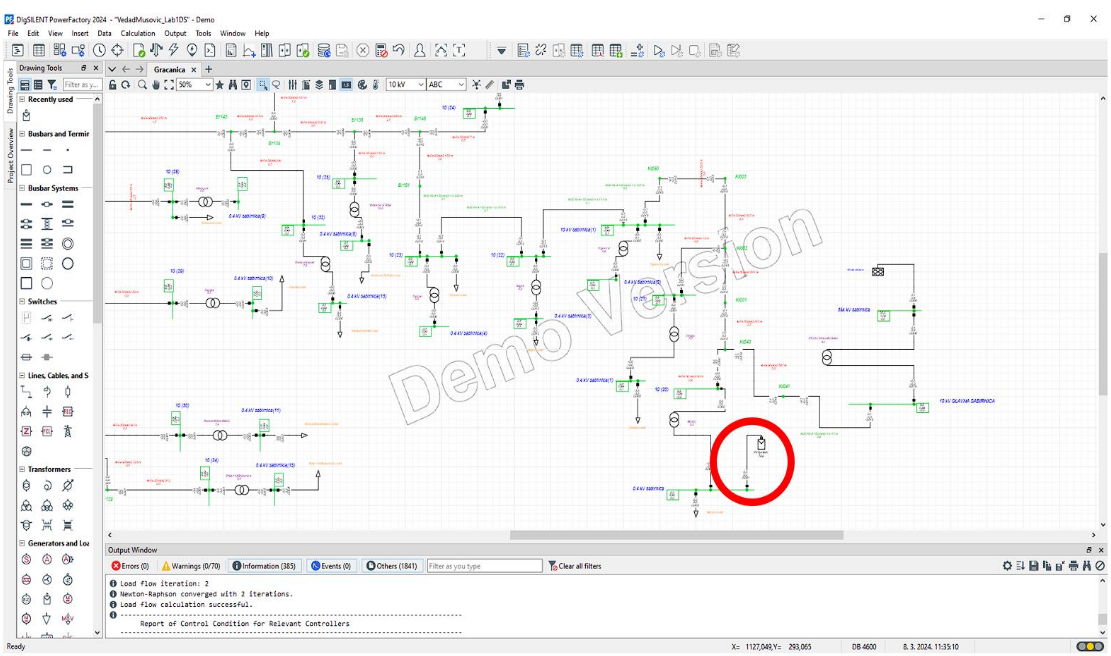


Figure 2. PV System Location

After inserting the PV system, Power Flow Analysis is successfully executed. The Newton-Raphson method successfully converged in 2 iterations. After this, the complete system report is generated. We were confirmed that no voltage or loading violations occurred.

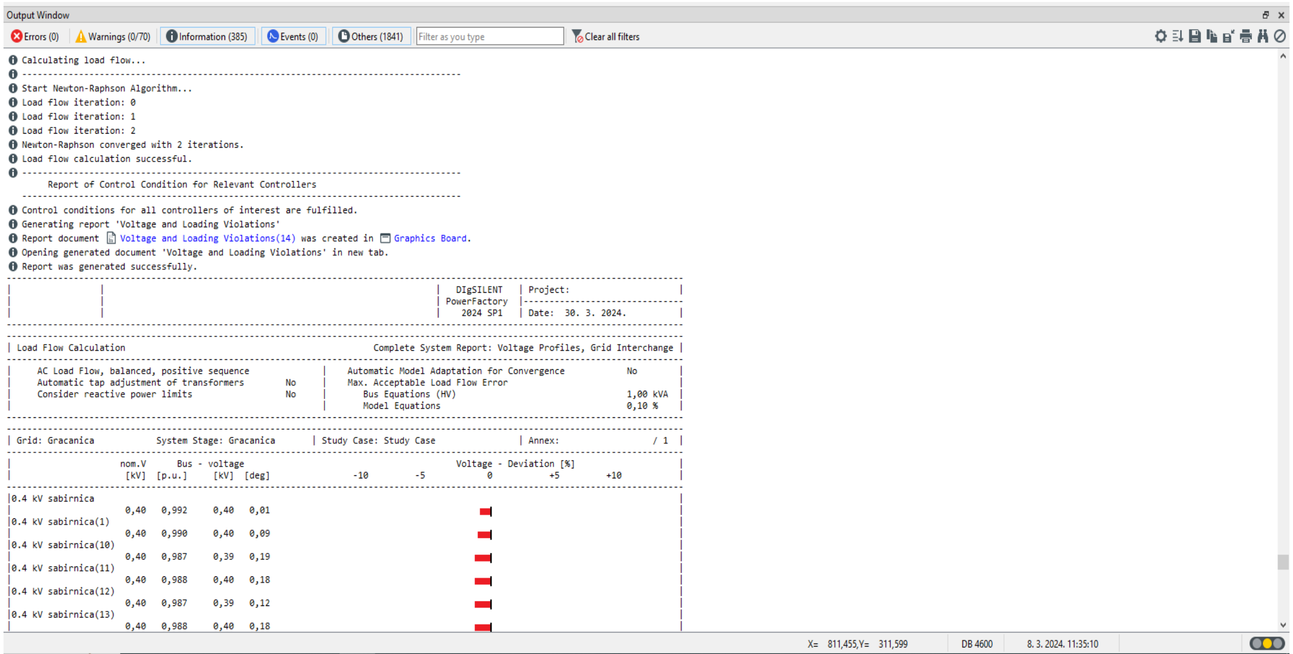


Figure 3. Output Window – PFA and Complete System Report

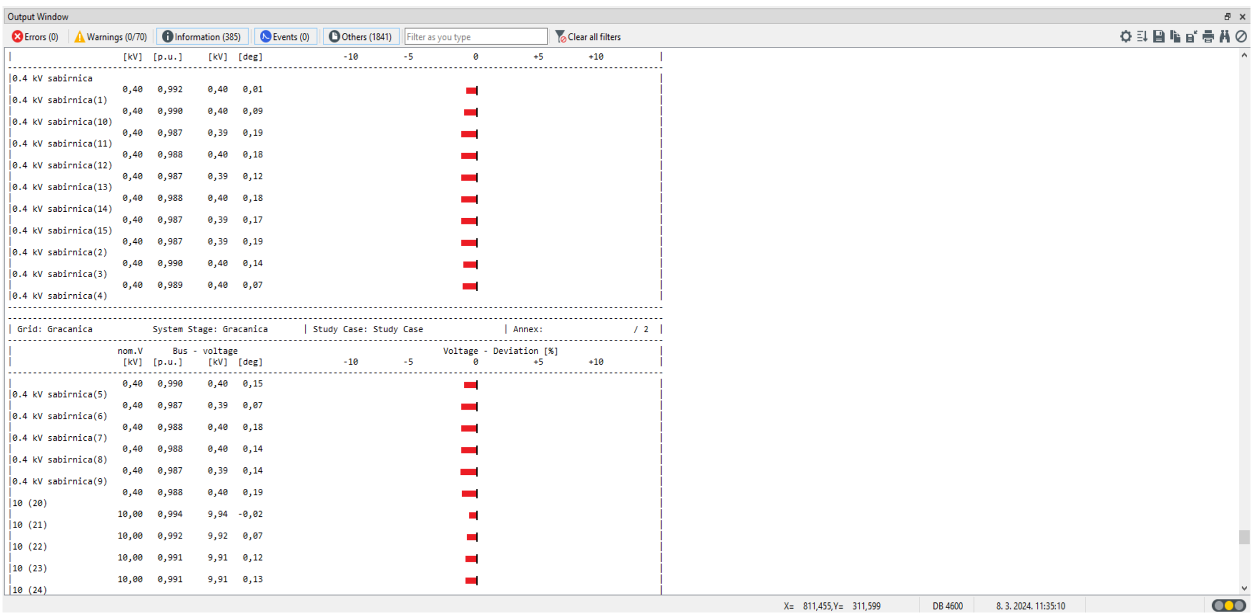


Figure 4. Complete System Report

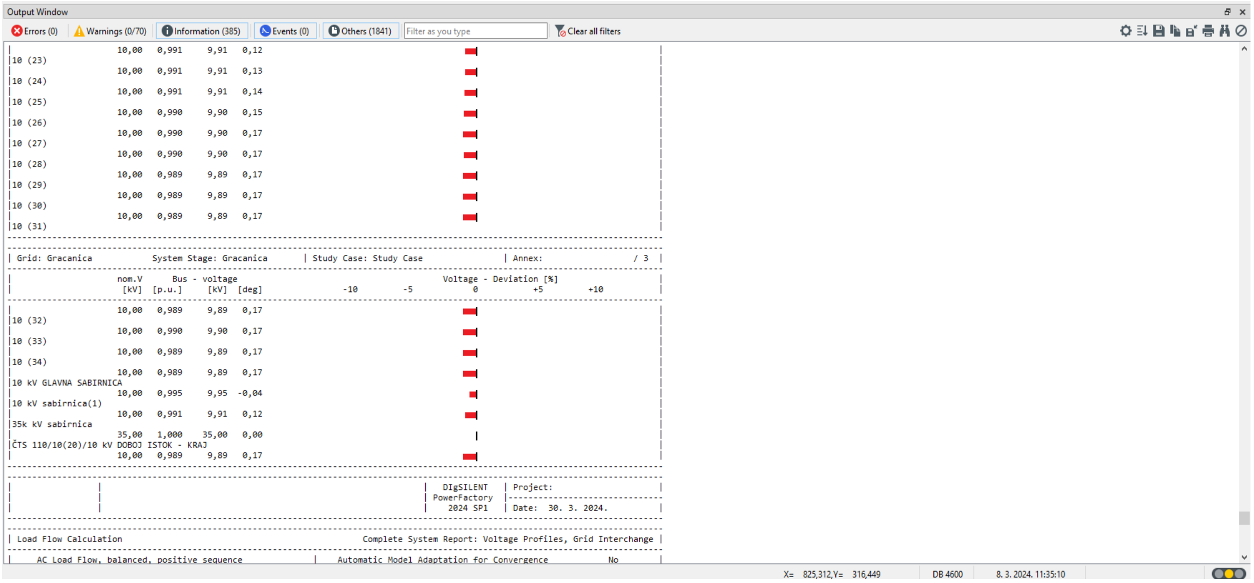


Figure 5. Complete System Report

For ‘Gračanica’ grid, we get the info about every bus voltage. As we see, all of them fall in the allowed range 0.95 pu - 1.05 pu. There are no deviations which are greater than -5% or +5%.

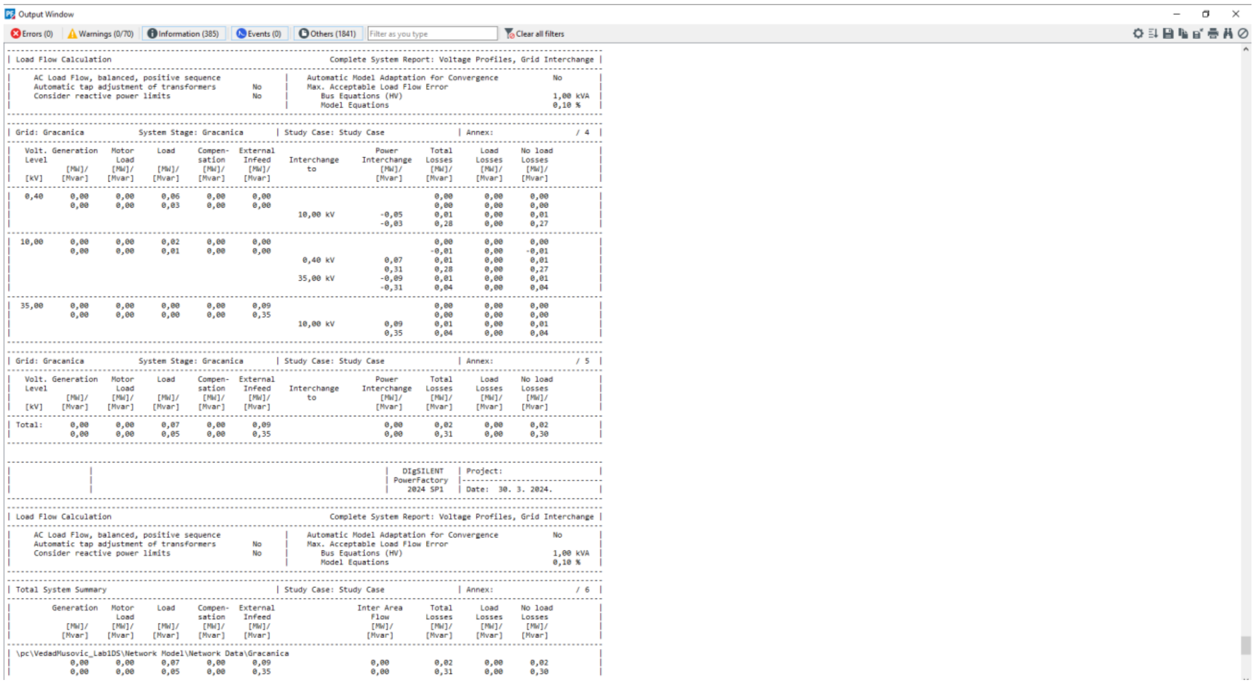


Figure 6. Complete System Report

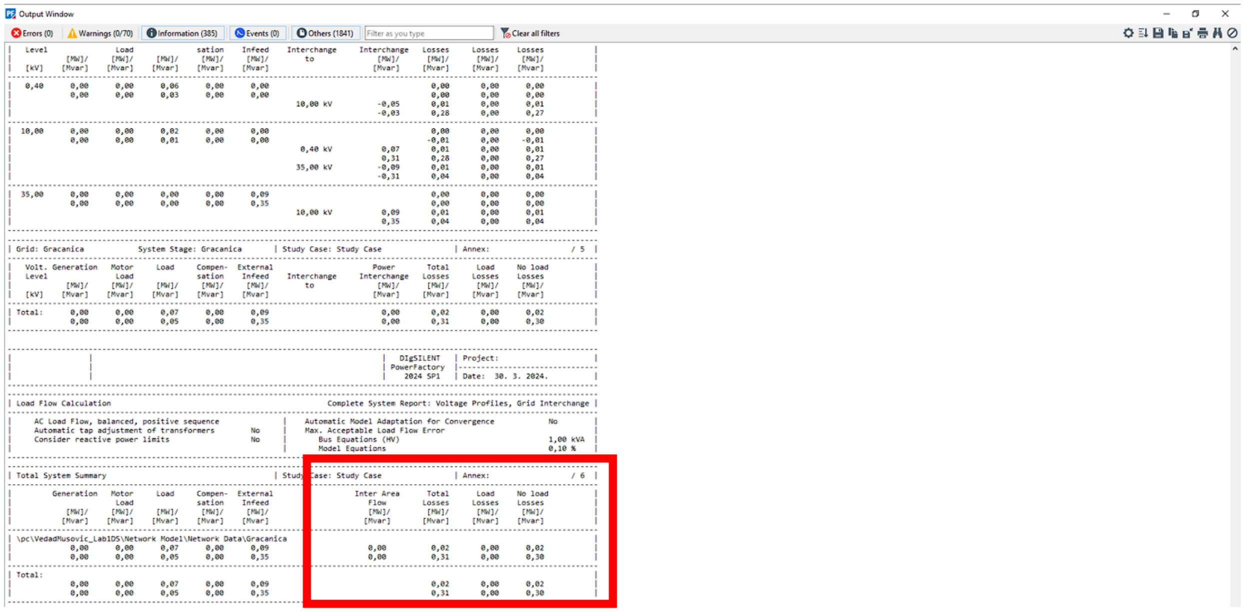


Figure 7. Complete System Report

The PV system improved the pu range of the voltages. As said, loading and voltage violations are fixed and they are not an issue. As shown in Figure 8, compared to our losses in Lab 2 (without PV systems), losses in Lab 5 are reduced.

In MVAR, the reactive power losses reduced closely to 25% - from 0.4 MVAR to 0.31 MVAR. On the other side, the losses in MW reduced by 80% – from 0.1 MW to 0.02 MW.

Voltages are regulated and transformers, lines and cables are less under stress.

Losses, Active Power MW	Losses, Reactive Power Mvar	
0,1	0,4	
Losses, Active Power (load) MW	Losses, Reactive Power (load) Mvar	
0,1	0,2	

Figure 8. The Losses in Lab 2

4. Case II – PV System Dispersed at Four Locations

For the second case, four PV systems are placed at four different locations.

- The first one is at 0.4 kV sabirnica, next to Bonzo again.
- The second one is at 0.4 kV sabirnica (4) – Sagra.
- The third one is at 0.4 kV sabirnica (8) – Polje 2 M. Brijesnica.
- The fourth one is at 0.4 kV sabirnica (15) – Polje 1 M. Brijesnica.

Each PV System has an active power operating point of 175 W, i.e. 0.175 kW

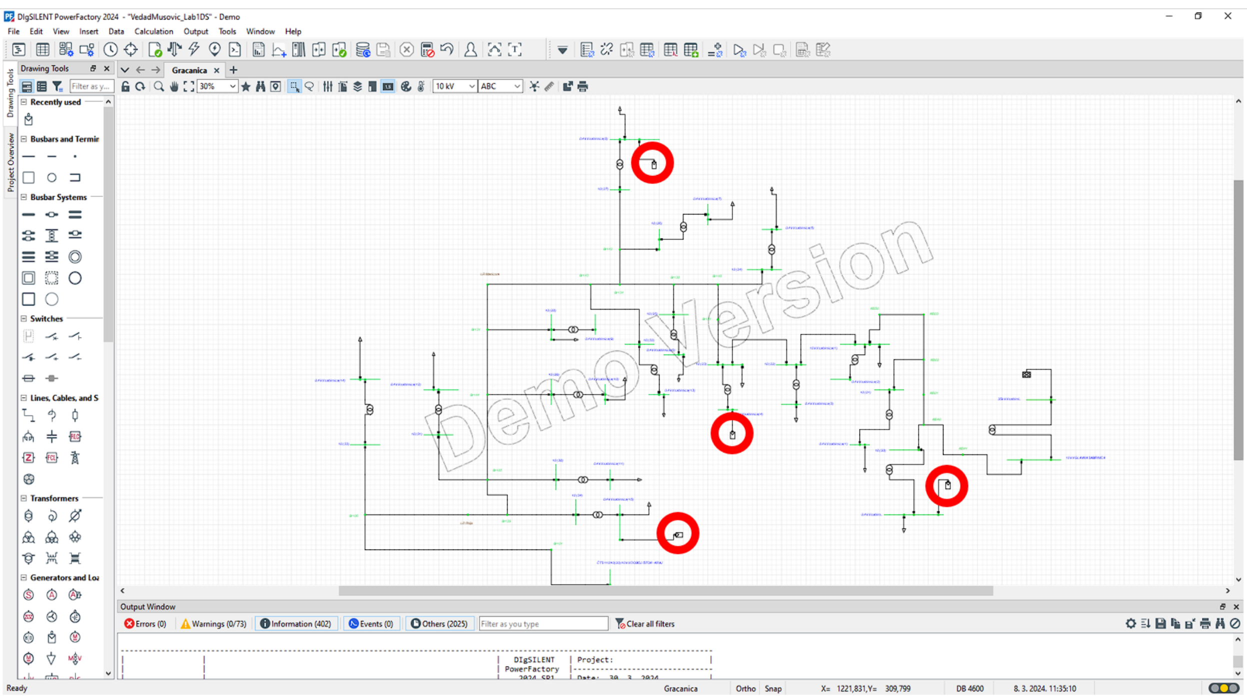


Figure 9. The Locations for four PV Systems

After this, Power Flow Analysis was successfully executed. The Newton-Raphson method successfully converged in 2 iterations. Following this, the complete system report is generated. It was confirmed that no loading and voltage violations occur.

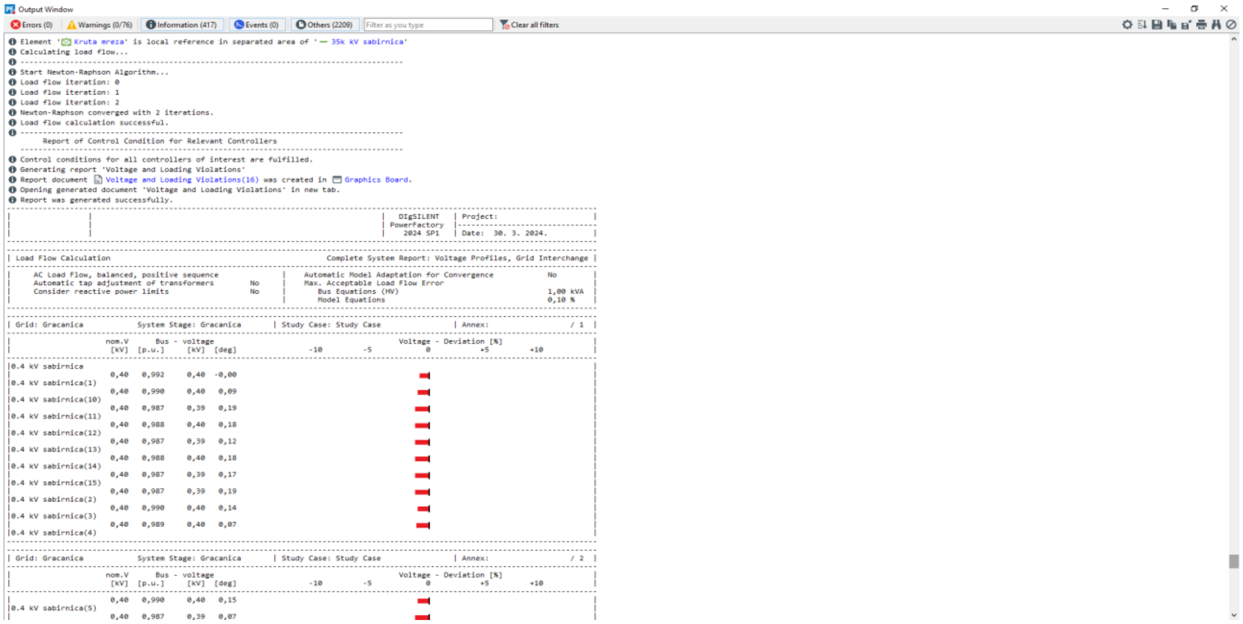


Figure 10. The Output Window – Power Flow Analysis and Complete System Report

For ‘Gračanica’ grid, we get the info about every bus voltage. As we see, all of them fall in the allowed range 0.95 pu - 1.05 pu. There are no deviations which are greater than -5% or +5%. These deviations are reduced by placing 4 PV’s instead of 1.

Figure 11. Complete System Report

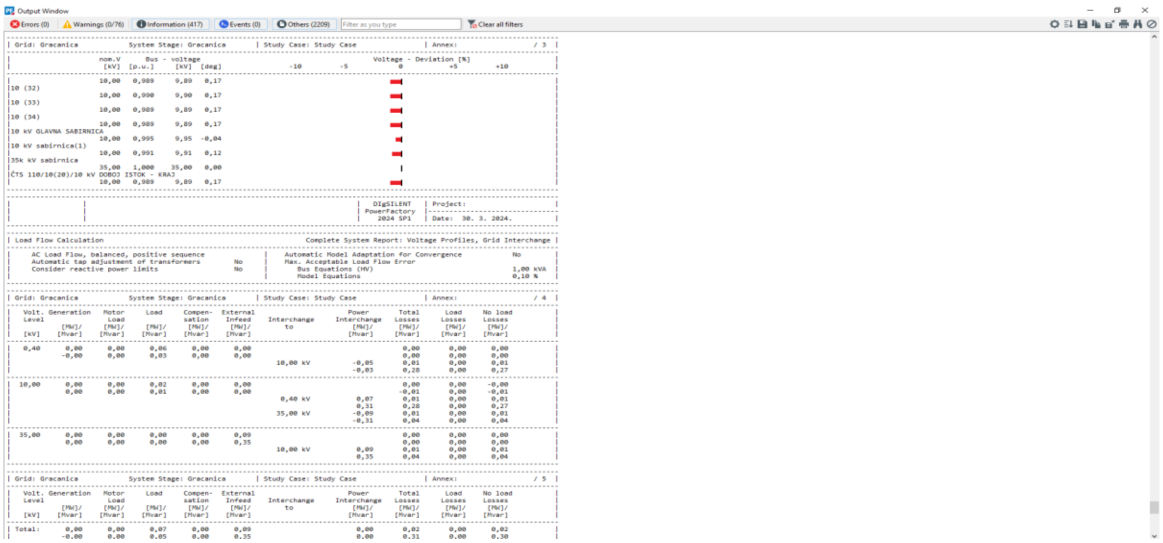


Figure 12. Complete System Report

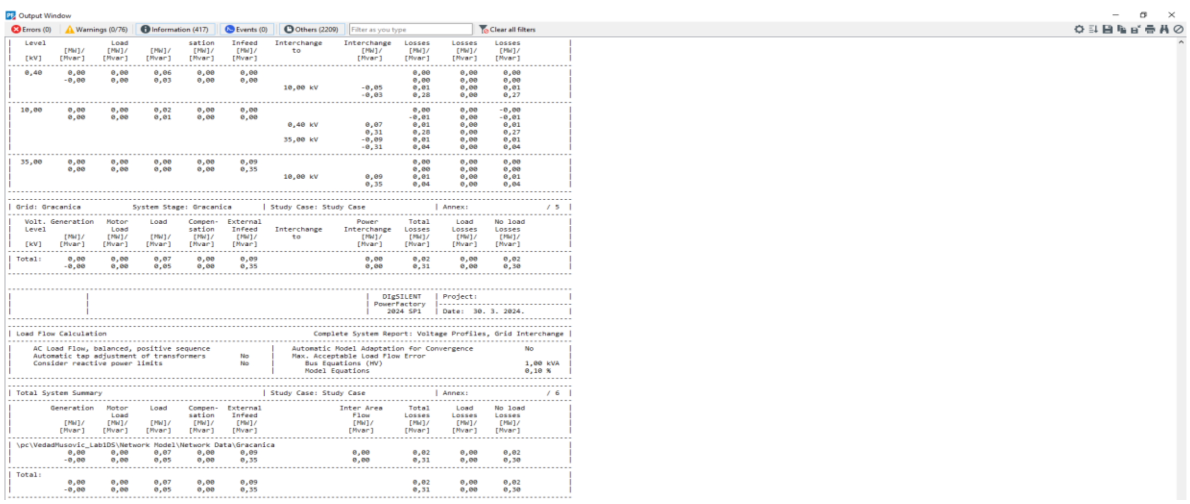


Figure 13. Complete System Report

The PV system improved the pu range of the voltages. As said, loading and voltage violations are fixed and they are not an issue. Compared to our losses in Lab 2 (without PV systems), losses in Lab 5 are reduced. In MVAR, the reactive power losses reduced closely to 25% - from 0.4 MVAR to 0.31 MVAR.

On the other side, the losses in MW reduced by 80% – from 0.1 MW to 0.02 MW. Voltages are regulated and transformers, lines and cables are less under stress. Overall, 4 PV’s will get our voltages close to the optimal pu value, that is 1.

5. Case III – PV Systems at 4 Different Locations, 4 Different Values

The locations stay the same as for the second, but the values are different.

• The first one is at 0.4 kV sabirnica, next to Bonzo again.

• The second one is at 0.4 kV sabirnica (4) – Sagra.

• The third one is at 0.4 kV sabirnica (8) – Polje 2 M. Brijesnica.

• The fourth one is at 0.4 kV sabirnica (15) – Polje 1 M. Brijesnica.

For the PV's, the four different active power values are: 600 W, 650 W, 700 W and 750 W.

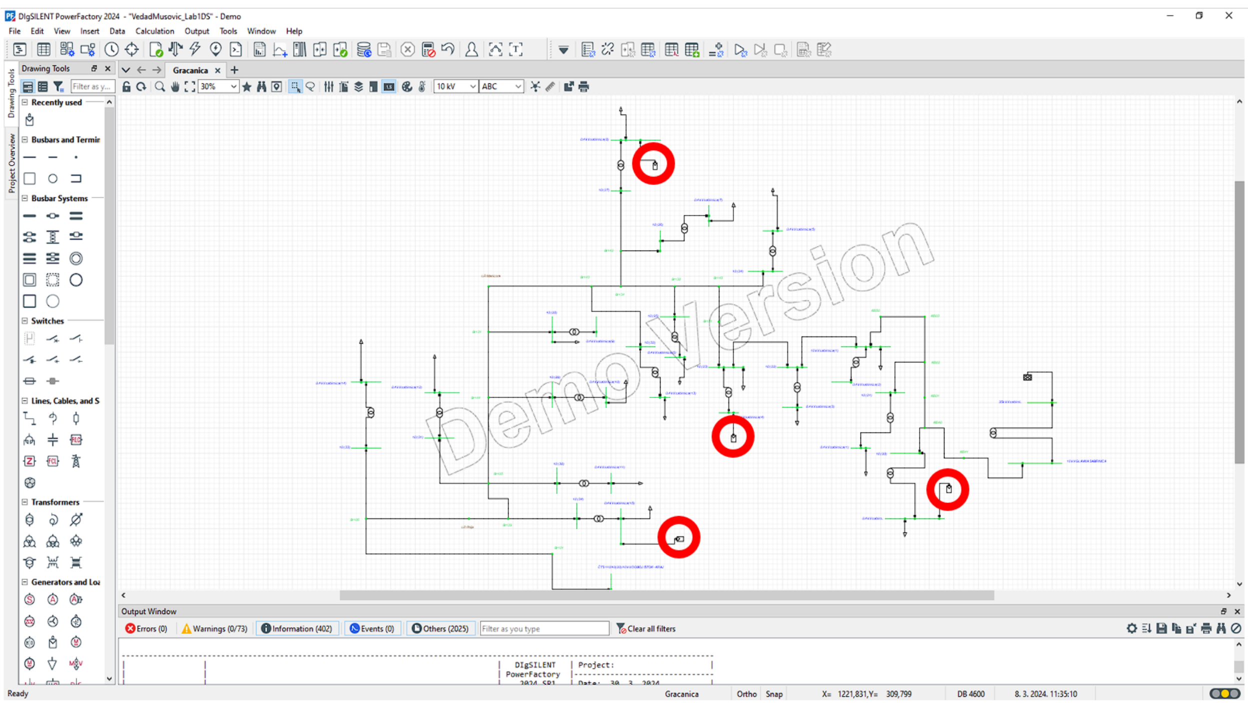


Figure 14. The Locations for four PV Systems

After this, Power Flow Analysis was successfully executed. The Newton-Raphson method successfully converged in 2 iterations. Following this, the complete system report is generated. It was confirmed that no loading and voltage violations occur.

Figure 15. The Output Window – Power Flow Analysis and Complete System Report

For ‘Gračanica’ grid, we get the info about every bus voltage. As we see, all of them fall in the allowed range 0.95 pu - 1.05 pu. There are no deviations which are greater than -5% or +5%. These deviations are reduced by placing 4 PV’s instead of 1. Even more when PV values are increased.

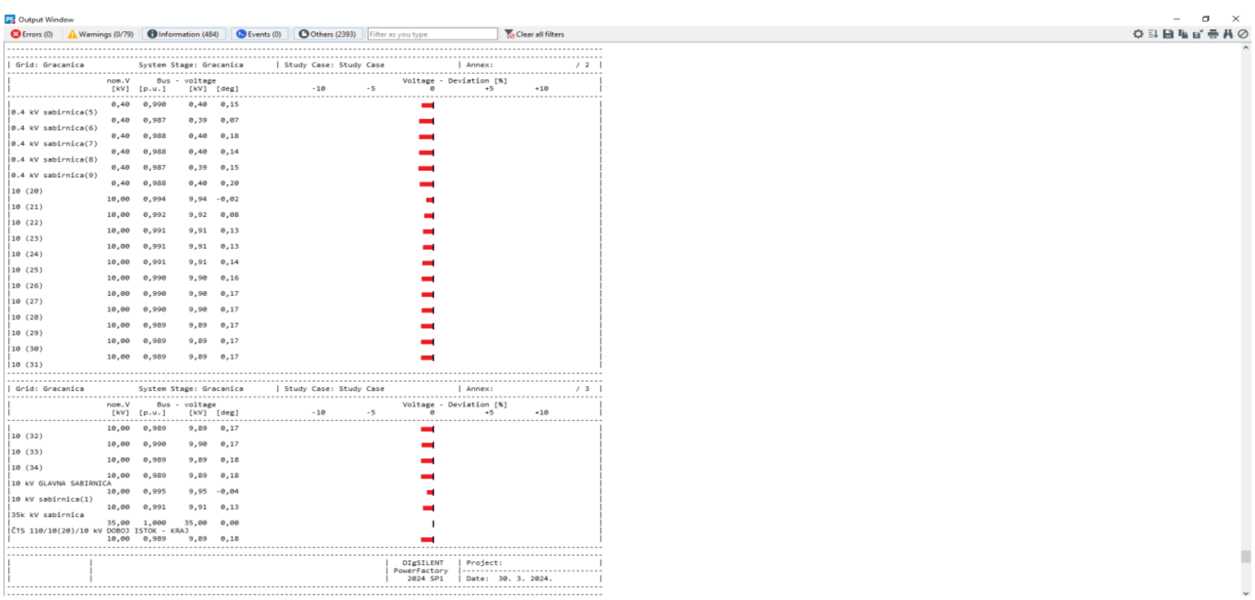
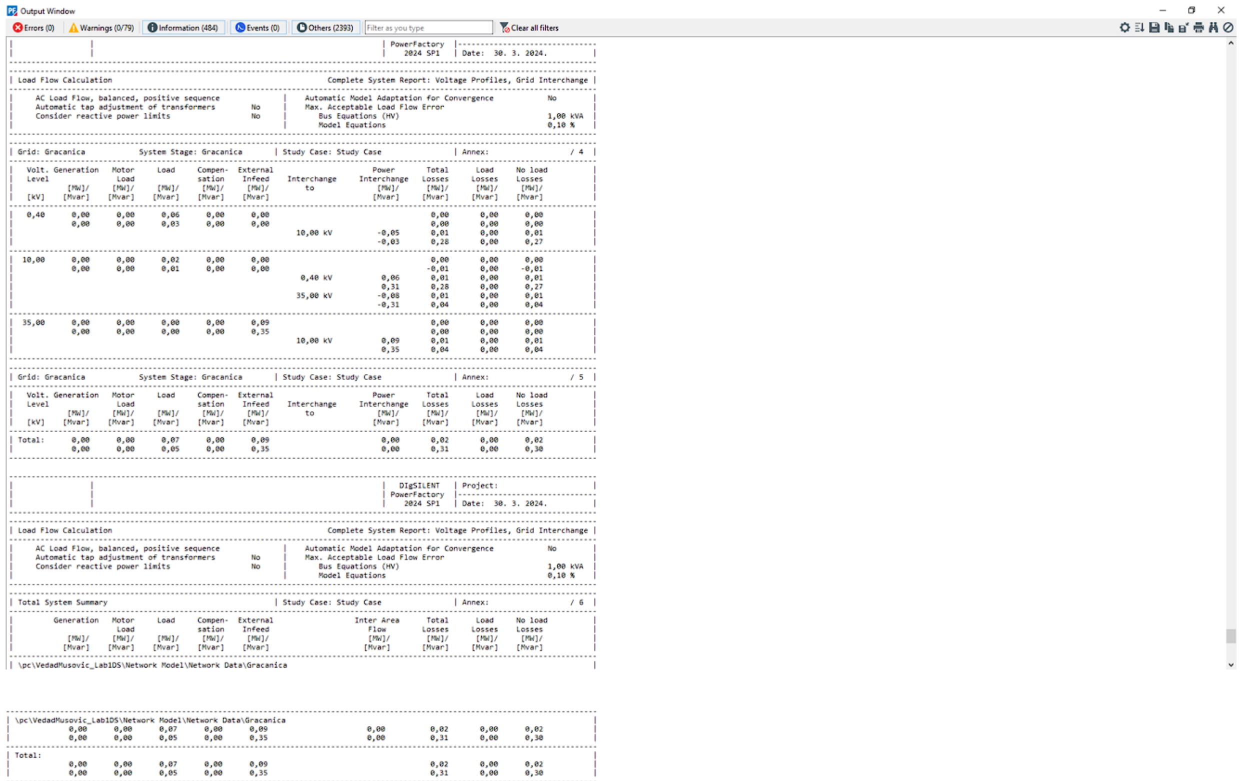


Figure 16. The Complete System Report



```
Output Window
Errors (0)  Warnings (0/79)  Information (484)  Events (0)  Others (2393)  Filter as you type  Clear all filters

|                |                                                        | PowerFactory |-----------------------------
|                |                                                        |   2024 SP1   | Date:  30. 3. 2024.          |
------------------------------------------------------------------------------------------------------------
| Load Flow Calculation                                   Complete System Report: Voltage Profiles, Grid Interchange |
------------------------------------------------------------------------------------------------------------
|    AC Load Flow, balanced, positive sequence            |   Automatic Model Adaptation for Convergence        No     |
|    Automatic tap adjustment of transformers        No   |   Max. Acceptable Load Flow Error                            |
|    Consider reactive power limits                  No   |      Bus Equations (HV)                           1,00 kVA |
|                                                         |      Model Equations                              0,10 %   |
------------------------------------------------------------------------------------------------------------
| Grid: Gracanica           System Stage: Gracanica      | Study Case: Study Case            | Annex:              / 4 |
------------------------------------------------------------------------------------------------------------
|  Volt. Generation  Motor     Load    Compen-  External                 Power     Total    Load    No load   |
|  Level               Load             sation   Infeed   Interchange  Interchange  Losses   Losses   Losses    |
|          [MW]/      [MW]/    [MW]/    [MW]/    [MW]/       to          [MW]/     [MW]/    [MW]/    [MW]/     |
|  [kV]   [Mvar]     [Mvar]   [Mvar]   [Mvar]   [Mvar]                   [Mvar]    [Mvar]   [Mvar]   [Mvar]    |
------------------------------------------------------------------------------------------------------------
|  0,40     0,00      0,00     0,06     0,00     0,00                               0,00     0,00     0,00     |
|           0,00      0,00     0,03     0,00     0,00                               0,00     0,00     0,00     |
|                                                         10,00 kV       -0,05      0,01     0,00     0,01     |
|                                                                        -0,03      0,28     0,00     0,27     |
------------------------------------------------------------------------------------------------------------
| 10,00     0,00      0,00     0,02     0,00     0,00                               0,00     0,00     0,00     |
|           0,00      0,00     0,01     0,00     0,00                              -0,01     0,00    -0,01     |
|                                                          0,40 kV        0,06      0,01     0,00     0,01     |
|                                                                         0,31      0,28     0,00     0,27     |
|                                                         35,00 kV       -0,08      0,01     0,00     0,01     |
|                                                                        -0,31      0,04     0,00     0,04     |
------------------------------------------------------------------------------------------------------------
| 35,00     0,00      0,00     0,00     0,00     0,09                               0,00     0,00     0,00     |
|           0,00      0,00     0,00     0,00     0,35                               0,00     0,00     0,00     |
|                                                         10,00 kV        0,09      0,01     0,00     0,01     |
|                                                                         0,35      0,04     0,00     0,04     |
------------------------------------------------------------------------------------------------------------

------------------------------------------------------------------------------------------------------------
| Grid: Gracanica           System Stage: Gracanica      | Study Case: Study Case            | Annex:              / 5 |
------------------------------------------------------------------------------------------------------------
|  Volt. Generation  Motor     Load    Compen-  External                 Power     Total    Load    No load   |
|  Level               Load             sation   Infeed   Interchange  Interchange  Losses   Losses   Losses    |
|          [MW]/      [MW]/    [MW]/    [MW]/    [MW]/       to          [MW]/     [MW]/    [MW]/    [MW]/     |
|  [kV]   [Mvar]     [Mvar]   [Mvar]   [Mvar]   [Mvar]                   [Mvar]    [Mvar]   [Mvar]   [Mvar]    |
------------------------------------------------------------------------------------------------------------
| Total:    0,00      0,00     0,07     0,00     0,09                    0,00      0,02     0,00     0,02     |
|           0,00      0,00     0,05     0,00     0,35                    0,00      0,31     0,00     0,30     |
------------------------------------------------------------------------------------------------------------


------------------------------------------------------------------------------------------------------------
|                |                                                        |  DIgSILENT   | Project:                     |
|                |                                                        | PowerFactory |-----------------------------
|                |                                                        |   2024 SP1   | Date:  30. 3. 2024.          |
------------------------------------------------------------------------------------------------------------
| Load Flow Calculation                                   Complete System Report: Voltage Profiles, Grid Interchange |
------------------------------------------------------------------------------------------------------------
|    AC Load Flow, balanced, positive sequence            |   Automatic Model Adaptation for Convergence        No     |
|    Automatic tap adjustment of transformers        No   |   Max. Acceptable Load Flow Error                            |
|    Consider reactive power limits                  No   |      Bus Equations (HV)                           1,00 kVA |
|                                                         |      Model Equations                              0,10 %   |
------------------------------------------------------------------------------------------------------------
| Total System Summary                                   | Study Case: Study Case            | Annex:              / 6 |
------------------------------------------------------------------------------------------------------------
|        Generation  Motor     Load    Compen-  External              Inter Area   Total    Load    No load   |
|                      Load             sation   Infeed                  Flow      Losses   Losses   Losses    |
|          [MW]/      [MW]/    [MW]/    [MW]/    [MW]/                  [MW]/     [MW]/    [MW]/    [MW]/     |
|         [Mvar]     [Mvar]   [Mvar]   [Mvar]   [Mvar]                 [Mvar]    [Mvar]   [Mvar]   [Mvar]    |
------------------------------------------------------------------------------------------------------------
| \pc\VedadMusovic_Lab1DS\Network Model\Network Data\Gracanica                                                |


------------------------------------------------------------------------------------------------------------
| \pc\VedadMusovic_Lab1DS\Network Model\Network Data\Gracanica                                                |
|           0,00      0,00     0,07     0,00     0,09                    0,00      0,02     0,00     0,02     |
|           0,00      0,00     0,05     0,00     0,35                    0,00      0,31     0,00     0,30     |
------------------------------------------------------------------------------------------------------------
| Total:                                                                                                      |
|           0,00      0,00     0,07     0,00     0,09                              0,02     0,00     0,02     |
|           0,00      0,00     0,05     0,00     0,35                              0,31     0,00     0,30     |
------------------------------------------------------------------------------------------------------------
```

Figure 17. Complete System Report

The PV system improved the pu range of the voltages. As said, loading and voltage violations are fixed and they are not an issue. Compared to our losses in Lab 2 (without PV systems), losses in Lab 5 are reduced. In MVAR, the reactive power losses reduced closely to 25% - from 0.4 MVAR to 0.31 MVAR.

On the other side, the losses in MW reduced by 80% – from 0.1 MW to 0.02 MW. Voltages are regulated and transformers, lines and cables are less under stress. Once again, we are using 4 PV system to create a test case, but this time, the values are significantly enhanced from 175 W.

As we see, the loss reduction will stay approximately the same as for the first two cases. Secondly, the voltages violations will not occur and overall, their values will be approaching 1 pu more and more. Once again, when choosing the active power values, we need to be sure that we are not entering values that are too high. Otherwise, we will get loading error and if we increase the values even more, DIGSILENT will signal for error and will not run power flow.

6. Conclusion

In conclusion, Lab 5 focused on integrating PV systems into the network to assess their impact on system performance. The integration of PV systems offers numerous advantages, including sustainable electricity generation, improved voltage values, reduced transmission losses and many more. In the first case, where one PV system was concentrated at a single location, significant improvements were observed in voltage stability and reduced losses. However, attempting to increase the power beyond a certain limit led to system incompatibility issues.

In the second case, dispersing four PV systems across different locations further enhanced voltage regulation and reduced losses. Similarly, in the third case, varying the power values of the four PV systems continued to improve system performance without causing violations.

It is observed that implementing more PV systems (rather than one) resulted in better voltage values. This is analogous to real life, when locating distributed generation close to the consumer is much better than using just one solar power plant to produce power for our entire network.

Overall, the integration of PV systems proved effective in stabilizing voltages, reducing losses, and enhancing grid reliability in comparison to not using PV modules. However, careful consideration of power limits is crucial to avoid compatibility issues and ensure successful integration of PV systems into our network both in DIGSILENT and in real life.

LAB 7 – HOSTING CAPACITY ANALYSIS (POWERFACTORY)

1. Introduction - Theory

The task for Lab 7 was to perform hosting capacity analysis in DIgSILENT on our modelled network. Hosting capacity will tell us the amount of solar energy that can be added to the local power grid before adjustments or upgrades are needed to handle it safely and reliably.

It is important to note that hosting capacity is not a strict limit but rather changes as the system is upgraded. We focus on analyzing these changes before and after adding PV systems as distributed generation inside of our network.

Determining hosting capacity involves considering various factors. These include the specifics of the solar energy system, like its size and location on the grid, as well as whether it uses advanced inverter settings.

Also crucial are the behavior and locations of all distributed energy resources on the grid, such as storage units. The existing equipment on the grid matters too, as it evolves with utility and owner investments. Additionally, how utilities plan distribution, especially in terms of upgrades and mitigations, plays a role.

The main goal of this lab is to evaluate how much solar energy our network can handle, both without a PV system and with five of them integrated.

The concept of hosting capacity revolves around how well the electrical infrastructure can cope with the fluctuations of renewable energy generation. While traditional grids were built for one-way power flow, the rise of PV systems and other DERs means power can now flow in both directions, complicating the grid.

Hosting capacity, specifically for PV systems, focuses on determining the maximum solar generation the grid can handle. This calculation considers factors like grid stability, voltage control, and thermal limitations, preventing situations where too much solar power comes to the grid.

2. Original Network

In this section, original network is shown, with Power Flow Analysis successfully performed. Additionally, Complete System report shows Losses and Voltage Deviations from 1 pu.

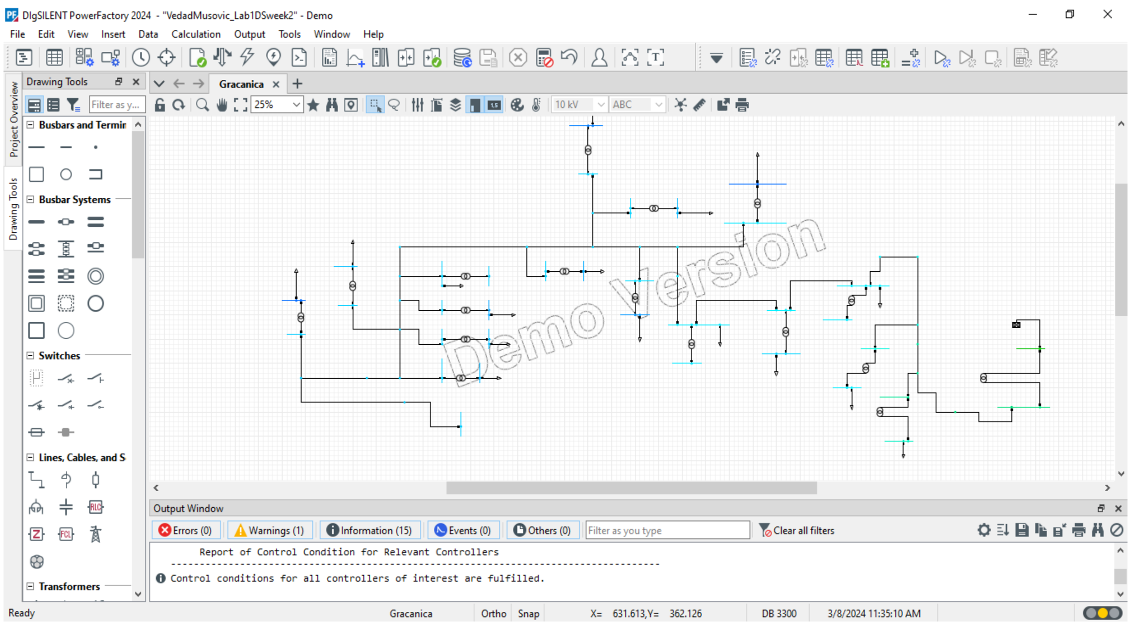


FIGURE 1. The Original Network

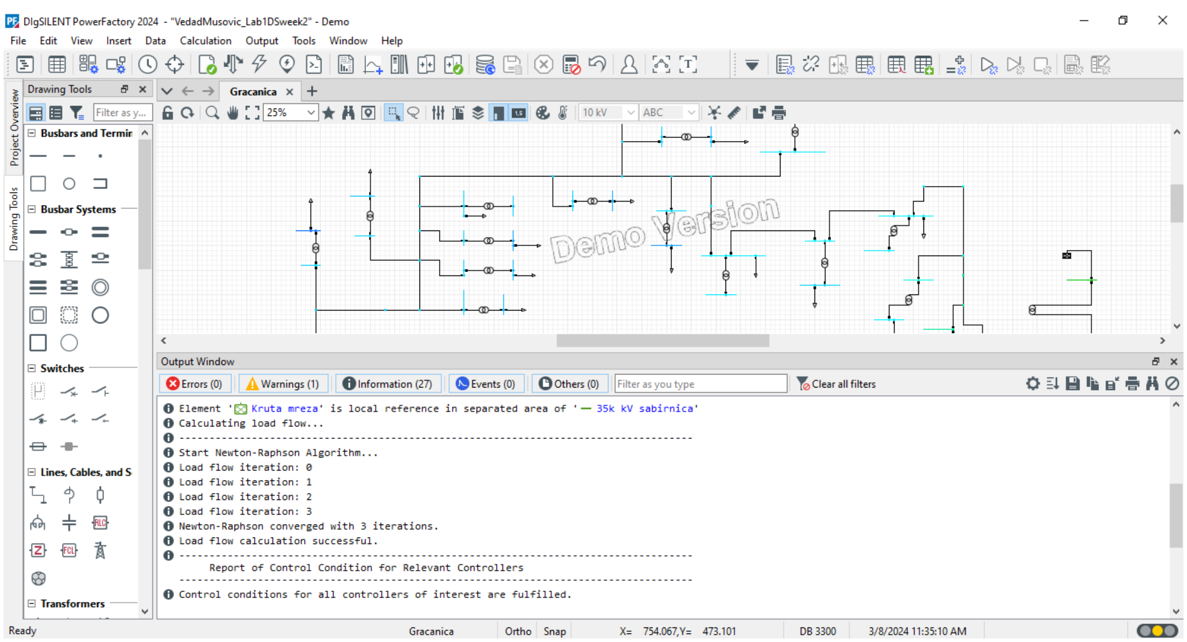


FIGURE 2. Power Flow Analysis (converging in 3 Iterations)

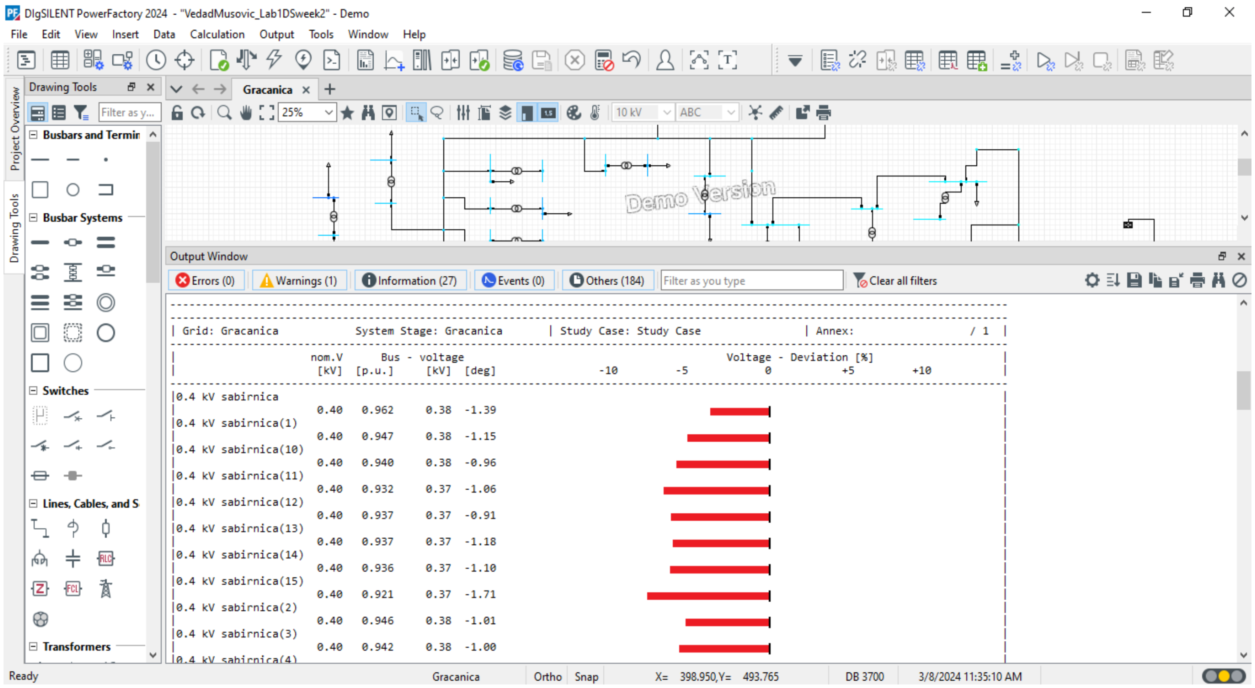


FIGURE 3. Complete System Report (Part 1)

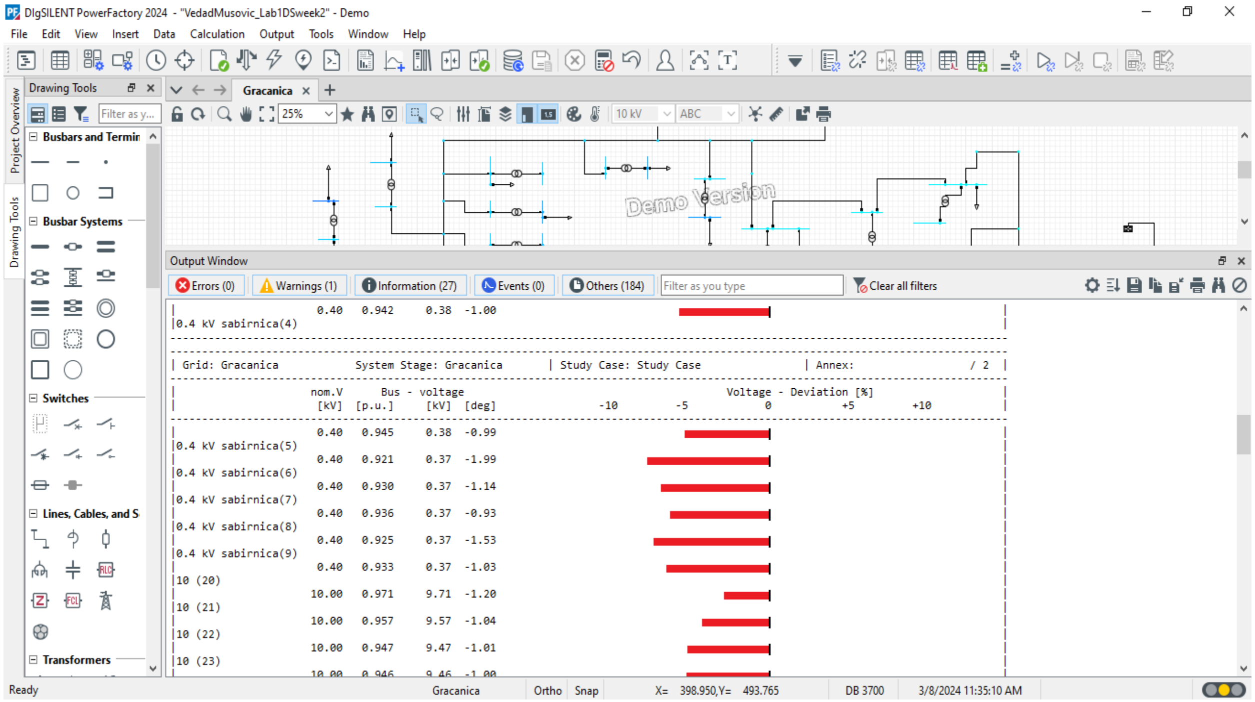


FIGURE 4. Complete System Report (Part 2)

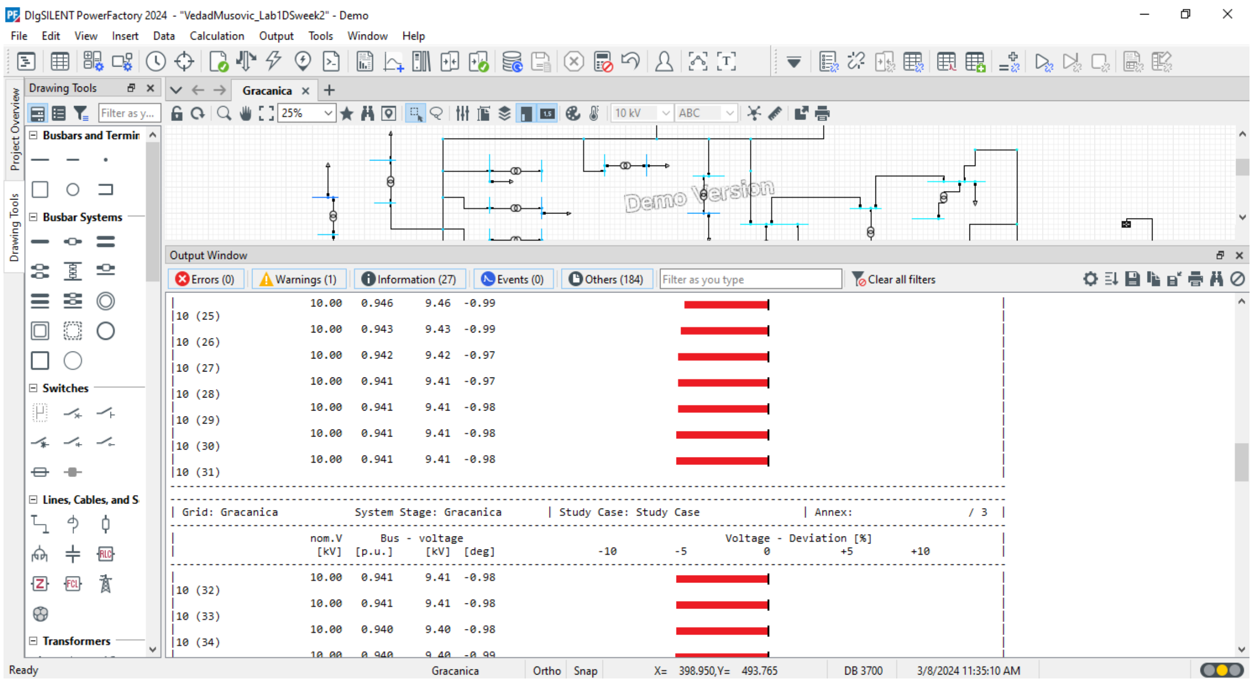


FIGURE 5. Complete System Report (Part 3)

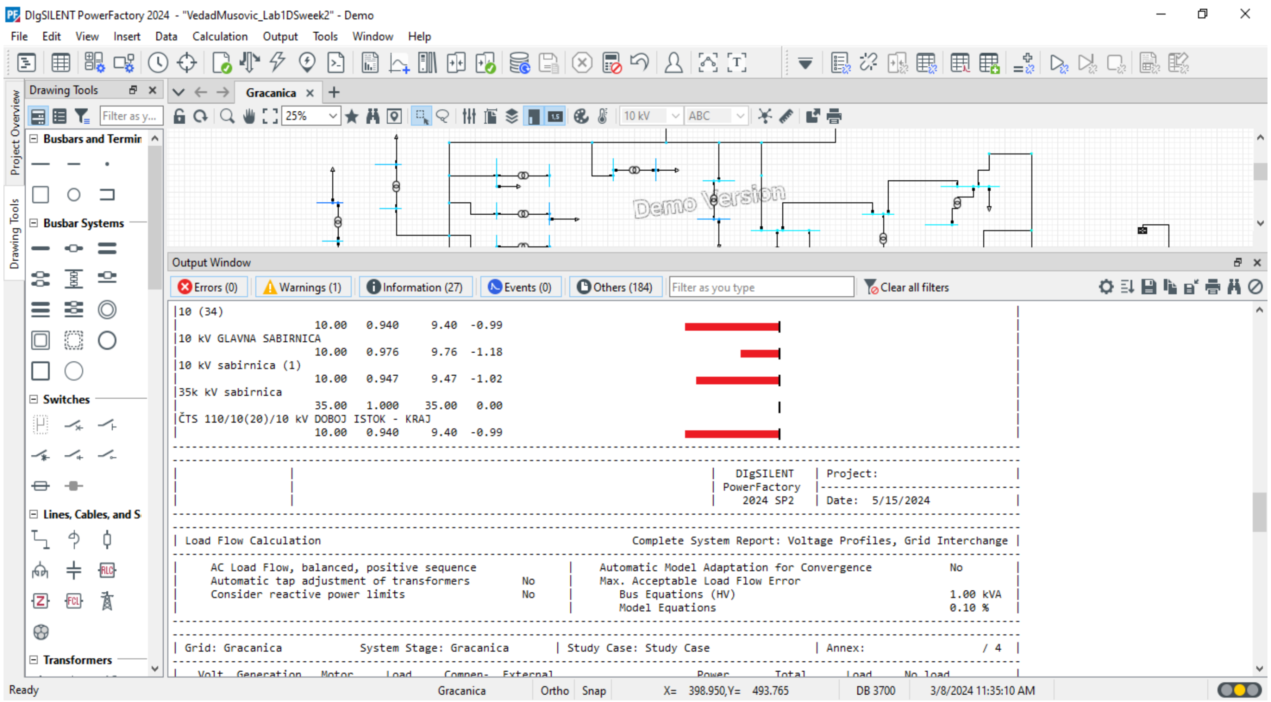


FIGURE 6. Complete System Report (Part 4)

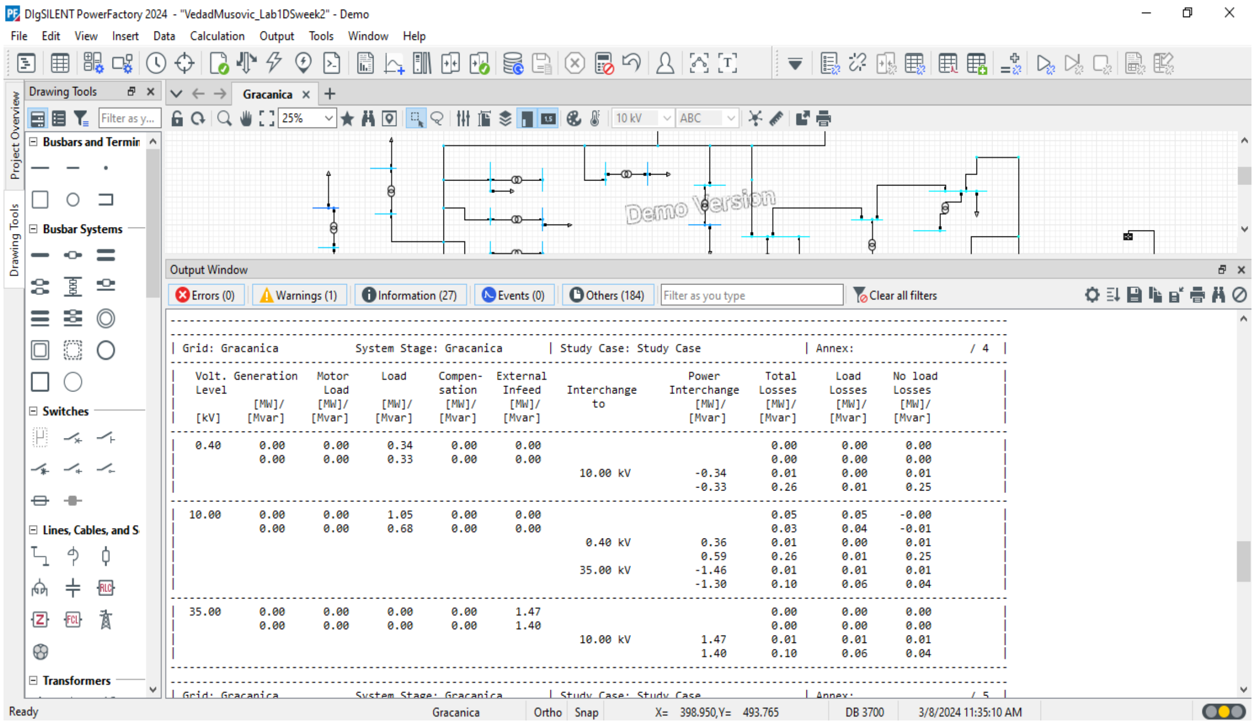


FIGURE 7. Complete System Report (Part 5)

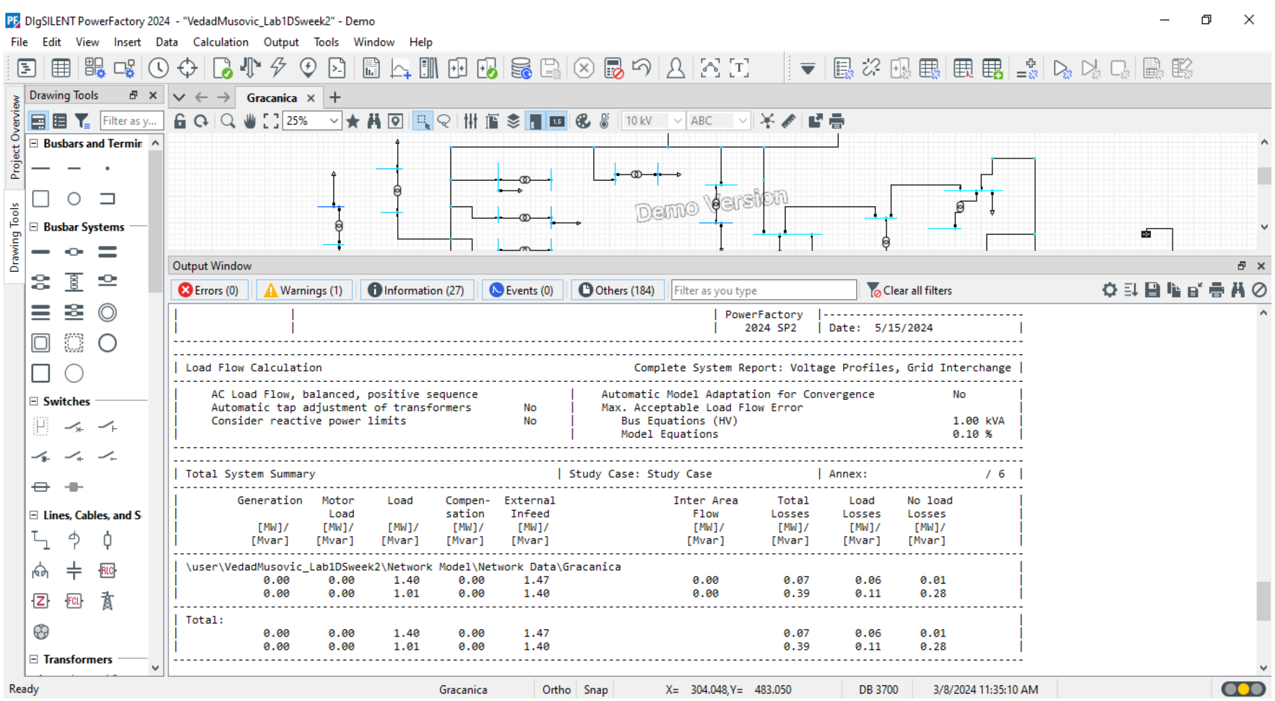


FIGURE 8. Complete System Report (Part 6)

3. HOSTING CAPACITY ANALYSIS WITHOUT PV'S ADDED

This heading represents hosting capacity analysis in thermal and tubular constraints before adding any PV systems inside of the network.

3.1. Thermal Constraints with Tubular Reports

Thermal Constraints shows us Hosting Capacity, with evaluation of the maximum distributed energy resources (DER) and/or spare load capacity of a network. Setup is shown in Figure 9. Calculation method is for Standard Load Flow, with AC Load Flow, balanced, positive sequence.

Thermal conditions for maximum loading of each node are taken into account.

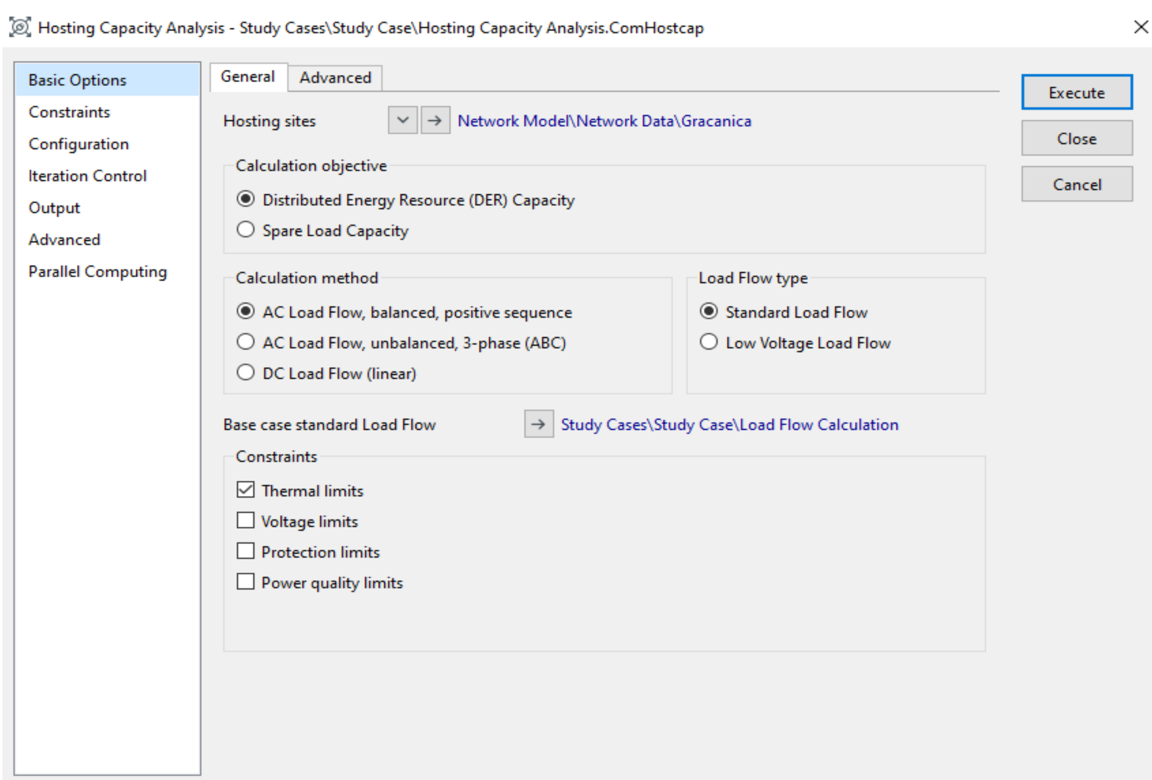


FIGURE 9. Hosting Capacity Analysis Setup for Thermal Constraints

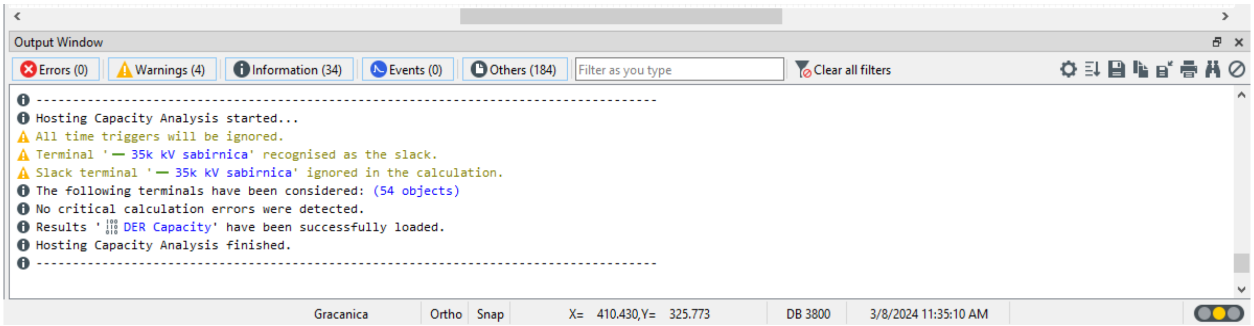


FIGURE 10. Hosting Capacity Analysis successfully performed

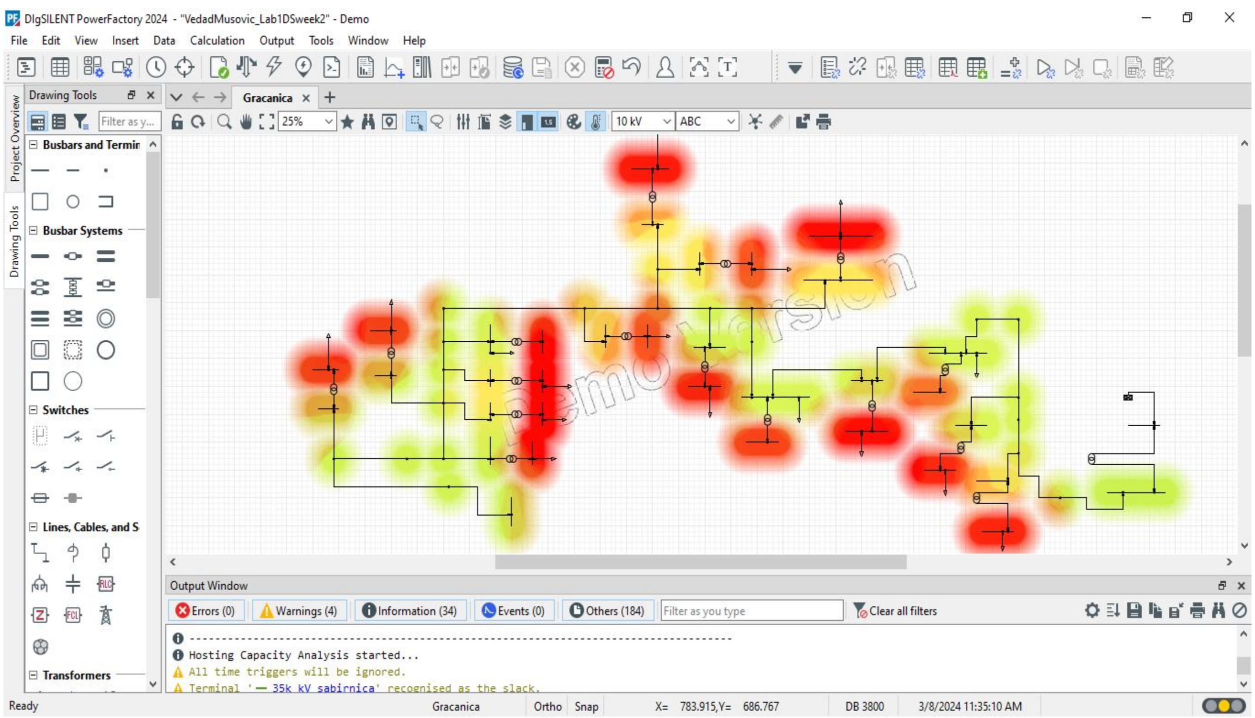
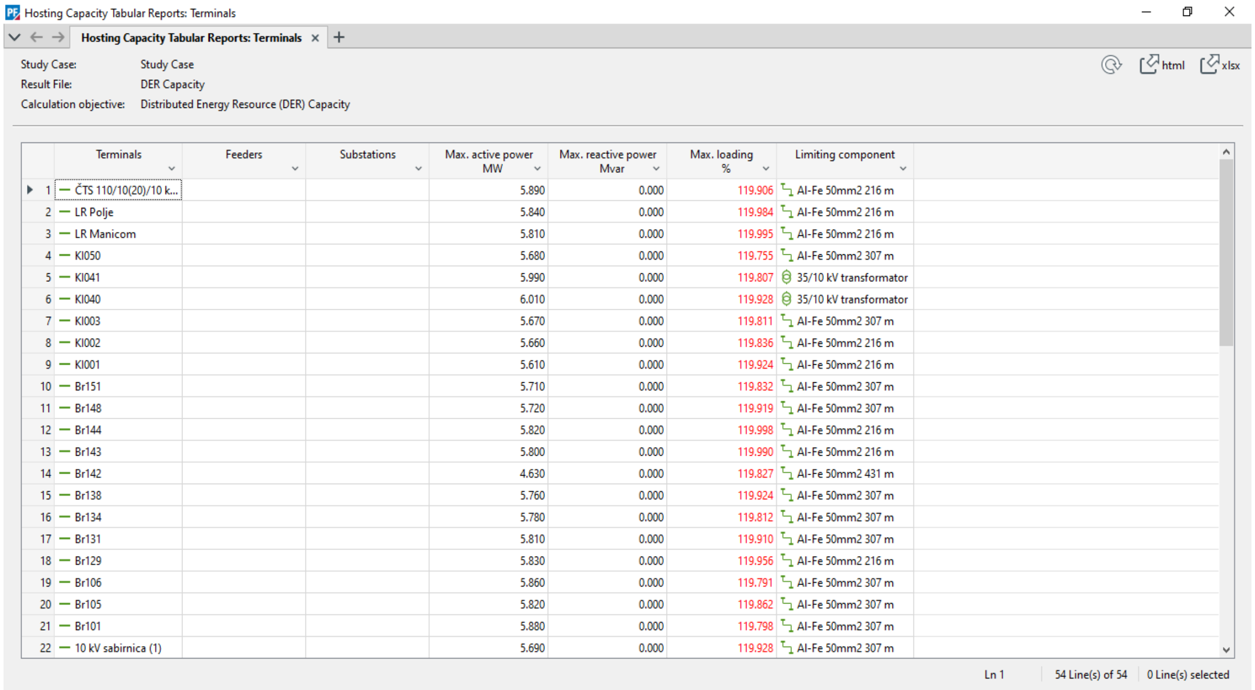


FIGURE 11. Network Heatmap for Thermal Constraint Hosting Capacity

Network Heatmap in Figure 11, shows us the individual hosted power at a designated node. The greener it is, this values is greater. The redder it is, this values is lower. It is typically in MW.

Tabular reports of the maximum capacities and limiting components for feeders and terminals. They are shown in Figures 12 and 13. Every terminal is represented with its limiting component.



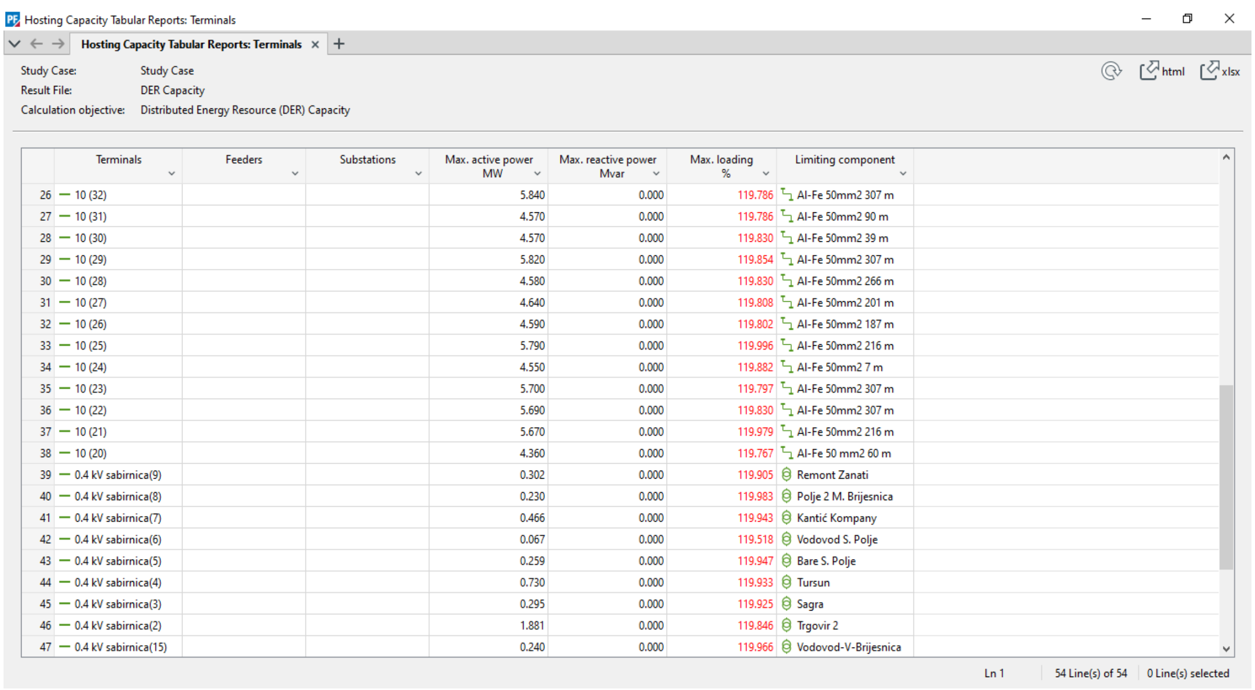
Hosting Capacity Tabular Reports: Terminals

Study Case: Study Case
Result File: DER Capacity
Calculation objective: Distributed Energy Resource (DER) Capacity

	Terminals	Feeders	Substations	Max. active power MW	Max. reactive power Mvar	Max. loading %	Limiting component
1	ČTS 110/10(20)/10 k...			5.890	0.000	119.906	Al-Fe 50mm2 216 m
2	LR Polje			5.840	0.000	119.984	Al-Fe 50mm2 216 m
3	LR Manicom			5.810	0.000	119.995	Al-Fe 50mm2 216 m
4	KI050			5.680	0.000	119.755	Al-Fe 50mm2 307 m
5	KI041			5.990	0.000	119.807	35/10 kV transformator
6	KI040			6.010	0.000	119.928	35/10 kV transformator
7	KI003			5.670	0.000	119.811	Al-Fe 50mm2 307 m
8	KI002			5.660	0.000	119.836	Al-Fe 50mm2 216 m
9	KI001			5.610	0.000	119.924	Al-Fe 50mm2 216 m
10	Br151			5.710	0.000	119.832	Al-Fe 50mm2 307 m
11	Br148			5.720	0.000	119.919	Al-Fe 50mm2 307 m
12	Br144			5.820	0.000	119.998	Al-Fe 50mm2 216 m
13	Br143			5.800	0.000	119.990	Al-Fe 50mm2 216 m
14	Br142			4.630	0.000	119.827	Al-Fe 50mm2 431 m
15	Br138			5.760	0.000	119.924	Al-Fe 50mm2 307 m
16	Br134			5.780	0.000	119.812	Al-Fe 50mm2 307 m
17	Br131			5.810	0.000	119.910	Al-Fe 50mm2 307 m
18	Br129			5.830	0.000	119.956	Al-Fe 50mm2 216 m
19	Br106			5.860	0.000	119.791	Al-Fe 50mm2 307 m
20	Br105			5.820	0.000	119.862	Al-Fe 50mm2 307 m
21	Br101			5.880	0.000	119.798	Al-Fe 50mm2 307 m
22	10 kV sabirnica (1)			5.690	0.000	119.928	Al-Fe 50mm2 307 m

Ln 1 | 54 Line(s) of 54 | 0 Line(s) selected

FIGURE 12. Tubular Reports for Thermal Constraints (Part 1)



Hosting Capacity Tabular Reports: Terminals

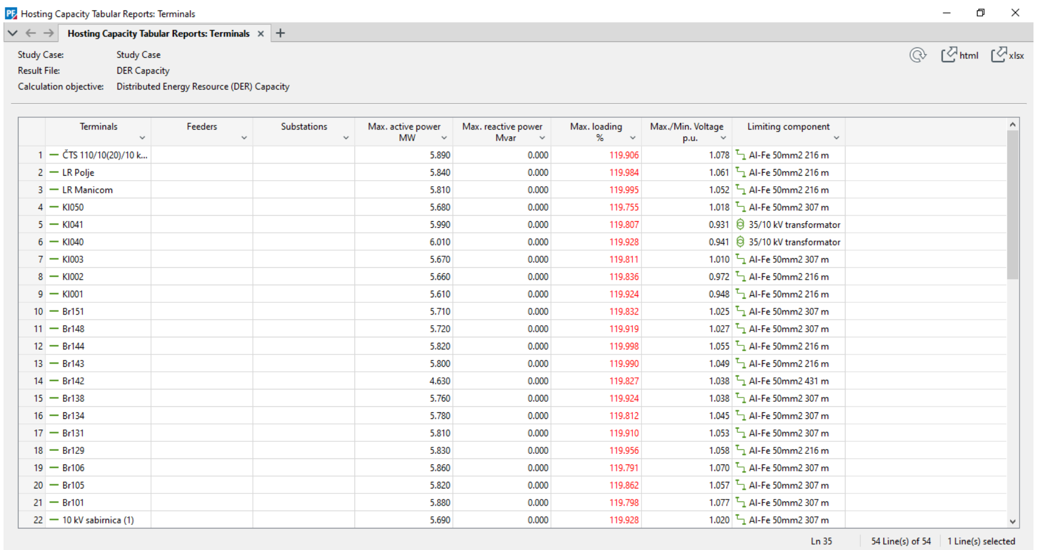
Study Case: Study Case
Result File: DER Capacity
Calculation objective: Distributed Energy Resource (DER) Capacity

	Terminals	Feeders	Substations	Max. active power MW	Max. reactive power Mvar	Max. loading %	Limiting component
26	10 (32)			5.840	0.000	119.786	Al-Fe 50mm2 307 m
27	10 (31)			4.570	0.000	119.786	Al-Fe 50mm2 90 m
28	10 (30)			4.570	0.000	119.830	Al-Fe 50mm2 39 m
29	10 (29)			5.820	0.000	119.854	Al-Fe 50mm2 307 m
30	10 (28)			4.580	0.000	119.830	Al-Fe 50mm2 266 m
31	10 (27)			4.640	0.000	119.808	Al-Fe 50mm2 201 m
32	10 (26)			4.590	0.000	119.802	Al-Fe 50mm2 187 m
33	10 (25)			5.790	0.000	119.996	Al-Fe 50mm2 216 m
34	10 (24)			4.550	0.000	119.882	Al-Fe 50mm2 7 m
35	10 (23)			5.700	0.000	119.797	Al-Fe 50mm2 307 m
36	10 (22)			5.690	0.000	119.830	Al-Fe 50mm2 307 m
37	10 (21)			5.670	0.000	119.979	Al-Fe 50mm2 216 m
38	10 (20)			4.360	0.000	119.767	Al-Fe 50 mm2 60 m
39	0.4 kV sabirnica(9)			0.302	0.000	119.905	Remont Zanati
40	0.4 kV sabirnica(8)			0.230	0.000	119.983	Polje 2 M. Brijesnica
41	0.4 kV sabirnica(7)			0.466	0.000	119.943	Kantić Kompany
42	0.4 kV sabirnica(6)			0.067	0.000	119.518	Vodovod S. Polje
43	0.4 kV sabirnica(5)			0.259	0.000	119.947	Bare S. Polje
44	0.4 kV sabirnica(4)			0.730	0.000	119.933	Tursun
45	0.4 kV sabirnica(3)			0.295	0.000	119.925	Sagra
46	0.4 kV sabirnica(2)			1.881	0.000	119.846	Trgovir 2
47	0.4 kV sabirnica(15)			0.240	0.000	119.966	Vodovod-V-Brijesnica

Ln 1 | 54 Line(s) of 54 | 0 Line(s) selected

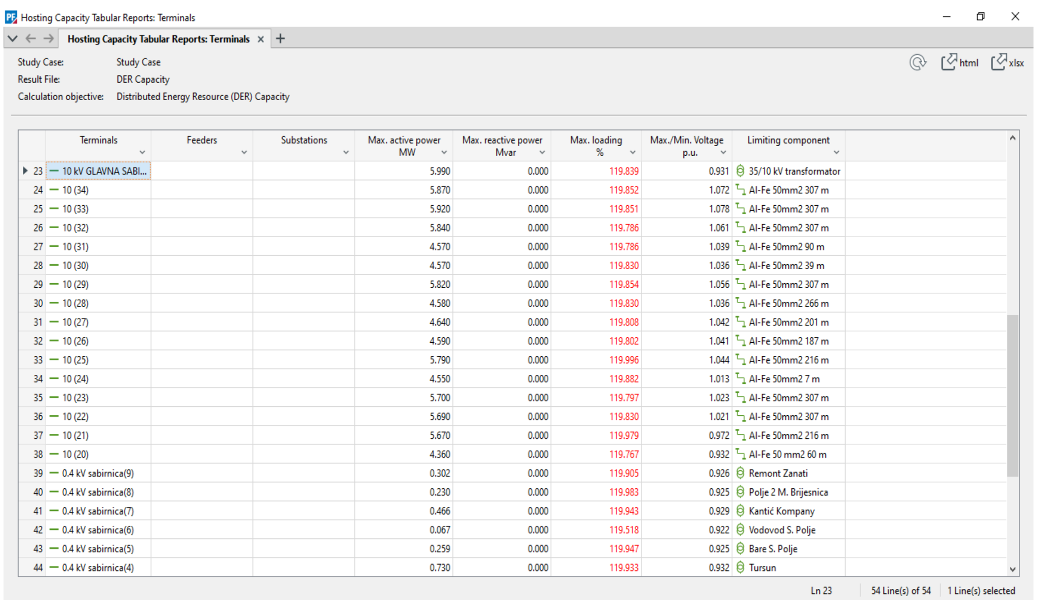
FIGURE 13. Tubular Reports for Thermal Constraints (Part 2)

3.2. Thermal and Voltage Constraints with Tubular Reports



	Terminals	Feeders	Substations	Max. active power MW	Max. reactive power Mvar	Max. loading %	Max./Min. Voltage p.u.	Limiting component
1	ČTS 110/10(20)/10 k...			5.890	0.000	119.906	1.078	Al-Fe 50mm2 216 m
2	LR Polje			5.840	0.000	119.984	1.061	Al-Fe 50mm2 216 m
3	LR Manicom			5.810	0.000	119.995	1.052	Al-Fe 50mm2 216 m
4	KI050			5.680	0.000	119.755	1.018	Al-Fe 50mm2 307 m
5	KI041			5.990	0.000	119.807	0.931	35/10 kV transformator
6	KI040			6.010	0.000	119.928	0.941	35/10 kV transformator
7	KI003			5.670	0.000	119.811	1.010	Al-Fe 50mm2 307 m
8	KI002			5.660	0.000	119.836	0.972	Al-Fe 50mm2 216 m
9	KI001			5.610	0.000	119.924	0.948	Al-Fe 50mm2 216 m
10	Br151			5.710	0.000	119.832	1.025	Al-Fe 50mm2 307 m
11	Br148			5.720	0.000	119.919	1.027	Al-Fe 50mm2 307 m
12	Br144			5.820	0.000	119.998	1.055	Al-Fe 50mm2 216 m
13	Br143			5.800	0.000	119.990	1.049	Al-Fe 50mm2 216 m
14	Br142			4.630	0.000	119.827	1.038	Al-Fe 50mm2 431 m
15	Br138			5.760	0.000	119.924	1.038	Al-Fe 50mm2 307 m
16	Br134			5.780	0.000	119.812	1.045	Al-Fe 50mm2 307 m
17	Br131			5.810	0.000	119.910	1.053	Al-Fe 50mm2 307 m
18	Br129			5.830	0.000	119.956	1.058	Al-Fe 50mm2 216 m
19	Br106			5.860	0.000	119.791	1.070	Al-Fe 50mm2 307 m
20	Br105			5.820	0.000	119.862	1.057	Al-Fe 50mm2 307 m
21	Br101			5.880	0.000	119.798	1.077	Al-Fe 50mm2 307 m
22	10 kV sabirnica (1)			5.690	0.000	119.928	1.020	Al-Fe 50mm2 307 m

FIGURE 14. Tubular Reports for Voltage and Thermal Constraints (Part 1)



	Terminals	Feeders	Substations	Max. active power MW	Max. reactive power Mvar	Max. loading %	Max./Min. Voltage p.u.	Limiting component
23	10 kV GLAVNA SABI...			5.990	0.000	119.839	0.931	35/10 kV transformator
24	10 (34)			5.870	0.000	119.852	1.072	Al-Fe 50mm2 307 m
25	10 (33)			5.920	0.000	119.851	1.078	Al-Fe 50mm2 307 m
26	10 (32)			5.840	0.000	119.786	1.061	Al-Fe 50mm2 307 m
27	10 (31)			4.570	0.000	119.786	1.039	Al-Fe 50mm2 90 m
28	10 (30)			4.570	0.000	119.830	1.036	Al-Fe 50mm2 39 m
29	10 (29)			5.820	0.000	119.854	1.056	Al-Fe 50mm2 307 m
30	10 (28)			4.580	0.000	119.830	1.036	Al-Fe 50mm2 266 m
31	10 (27)			4.640	0.000	119.808	1.042	Al-Fe 50mm2 201 m
32	10 (26)			4.590	0.000	119.802	1.041	Al-Fe 50mm2 187 m
33	10 (25)			5.790	0.000	119.996	1.044	Al-Fe 50mm2 216 m
34	10 (24)			4.550	0.000	119.882	1.013	Al-Fe 50mm2 7 m
35	10 (23)			5.700	0.000	119.797	1.023	Al-Fe 50mm2 307 m
36	10 (22)			5.690	0.000	119.830	1.021	Al-Fe 50mm2 307 m
37	10 (21)			5.670	0.000	119.979	0.972	Al-Fe 50mm2 216 m
38	10 (20)			4.360	0.000	119.767	0.932	Al-Fe 50 mm2 60 m
39	0.4 kV sabirnica(9)			0.302	0.000	119.905	0.926	Remont Zanati
40	0.4 kV sabirnica(8)			0.230	0.000	119.983	0.925	Polje 2 M. Brijesnica
41	0.4 kV sabirnica(7)			0.466	0.000	119.943	0.929	Kantić Kompany
42	0.4 kV sabirnica(6)			0.067	0.000	119.518	0.922	Vodovod S. Polje
43	0.4 kV sabirnica(5)			0.259	0.000	119.947	0.925	Bare S. Polje
44	0.4 kV sabirnica(4)			0.730	0.000	119.933	0.932	Tursun

FIGURE 15. Tubular Reports for Voltage and Thermal Constraints (Part 2)

In this case, both thermal and voltage constraints are taken into account. Voltage profile constraints for bi-directional power flow in systems with a high level of DER's are analyzed. Voltage limits are taken into account. The voltage values need to be as close to 1 pu as possible.

4. HOSTING CAPACITY WITH 5 PV'S ADDED

In this heading, we analyze the hosting capacity with 5 PV systems added to the network. They are all of 100 kW active power. When we add PV's to a 0.4 kV busbar, we expect fewer changes. That is why, in this case, 3 PV's are installed at 0.4 kV busbars and 2 are installed at 10 kV busbars.

With these we observe the effects of placing PV systems busbars with different voltage levels, but still close to the consumer as a DER. These locations are depicted in Figure 17.

4.1. Thermal Constraints with Tubular Reports

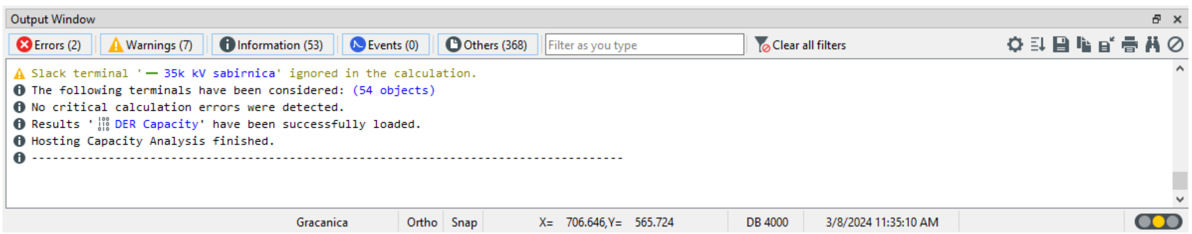


FIGURE 16. Hosting Capacity Analysis performed successfully

Hosting Capacity Analysis is performed successfully. Network Heatmap in Figure 20, shows us the individual hosted power at a designated node. The greener it is, this values is greater. The redder it is, this values is lower. It is typically in MW. Tabular reports of the maximum capacities and limiting components for feeders and terminals. They are shown in Figures 18 and 19. Every terminal is represented with its limiting component.

Thermal Constraints shows us Hosting Capacity, with evaluation of the maximum distributed energy resources (DER) and/or spare load capacity of a network.

PV's improve our voltage profile mainly. Integrating PV systems stabilizes voltages, reducing losses, and enhancing grid reliability in comparison to not using PV modules. However, careful consideration of power limits is crucial to avoid compatibility issues

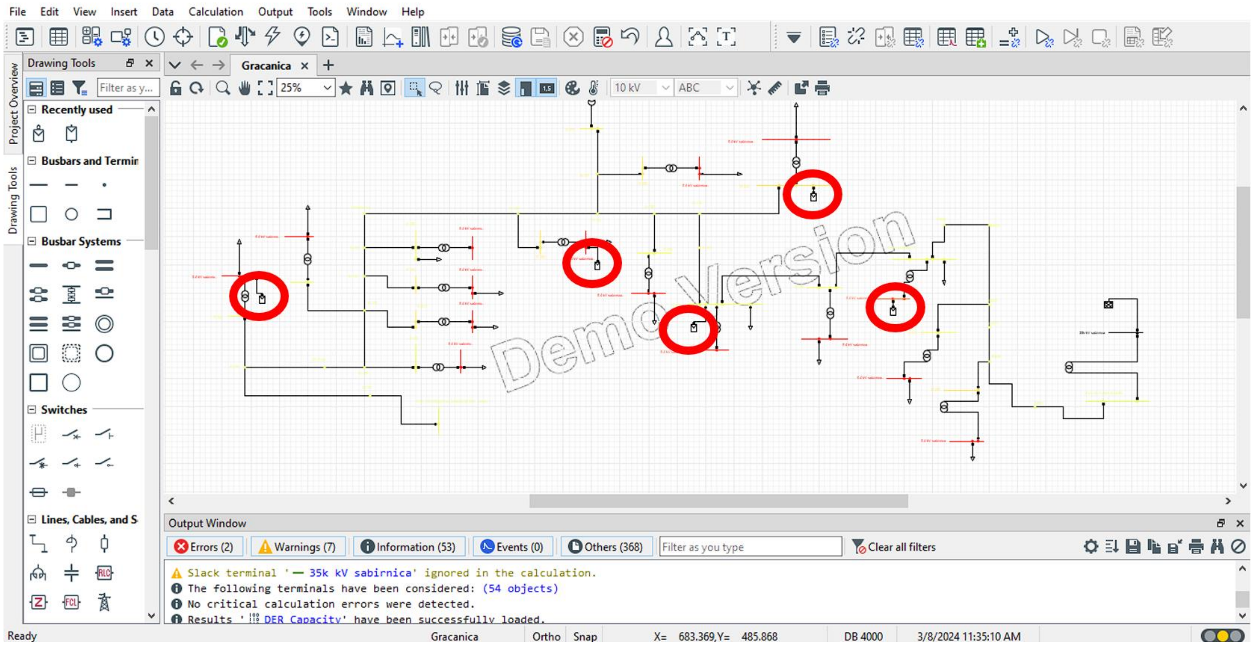
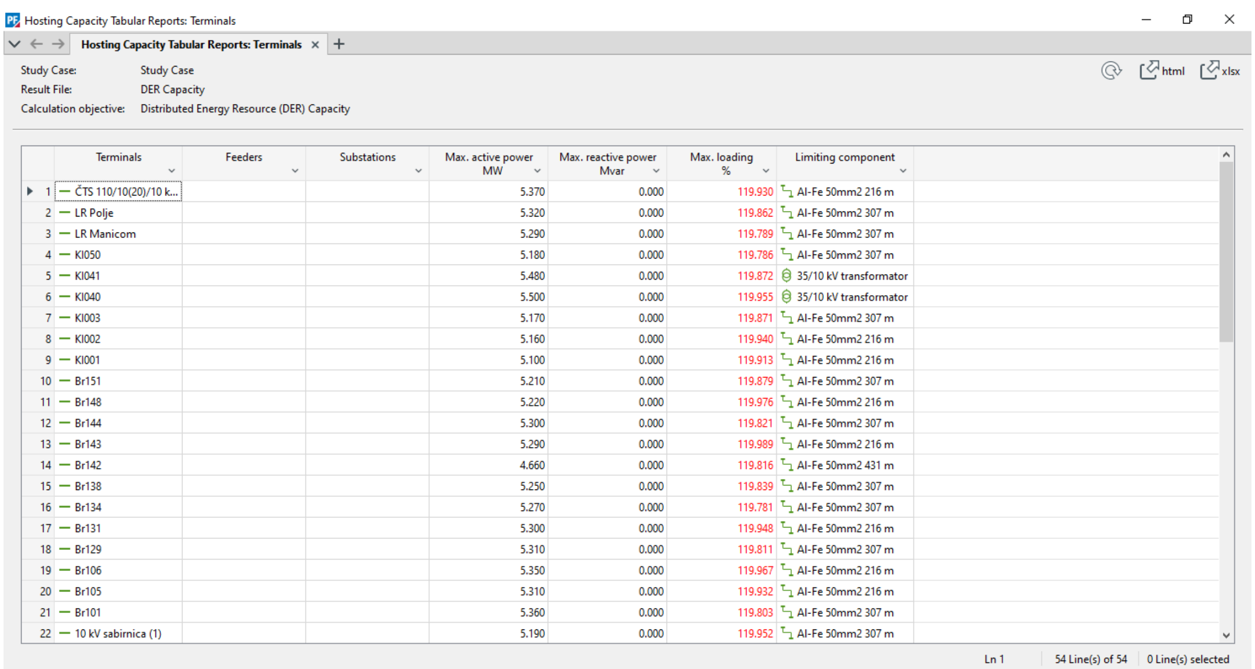


FIGURE 17. The Location where PV's are added



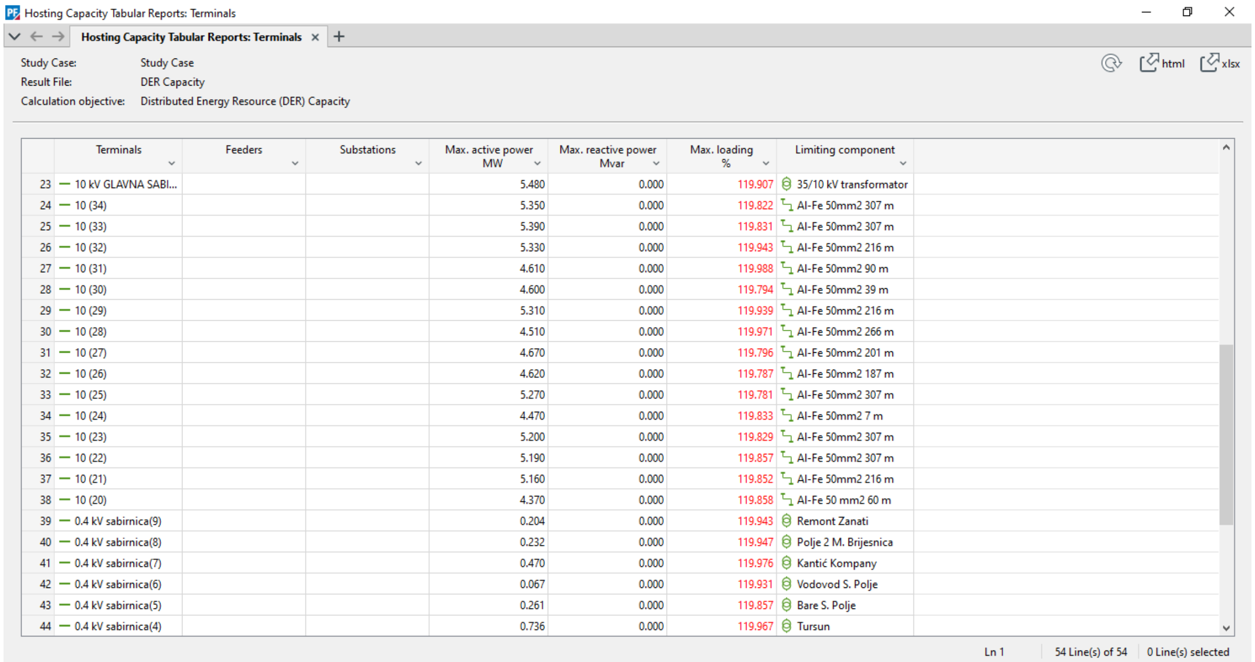
Hosting Capacity Tabular Reports: Terminals

Study Case: Study Case
Result File: DER Capacity
Calculation objective: Distributed Energy Resource (DER) Capacity

	Terminals	Feeders	Substations	Max. active power MW	Max. reactive power Mvar	Max. loading %	Limiting component
1	ČTS 110/10(20)/10 k...			5.370	0.000	119.930	Al-Fe 50mm2 216 m
2	LR Polje			5.320	0.000	119.862	Al-Fe 50mm2 307 m
3	LR Manicom			5.290	0.000	119.789	Al-Fe 50mm2 307 m
4	KI050			5.180	0.000	119.786	Al-Fe 50mm2 307 m
5	KI041			5.480	0.000	119.872	35/10 kV transformator
6	KI040			5.500	0.000	119.955	35/10 kV transformator
7	KI003			5.170	0.000	119.871	Al-Fe 50mm2 307 m
8	KI002			5.160	0.000	119.940	Al-Fe 50mm2 216 m
9	KI001			5.100	0.000	119.913	Al-Fe 50mm2 216 m
10	Br151			5.210	0.000	119.879	Al-Fe 50mm2 307 m
11	Br148			5.220	0.000	119.976	Al-Fe 50mm2 216 m
12	Br144			5.300	0.000	119.821	Al-Fe 50mm2 307 m
13	Br143			5.290	0.000	119.989	Al-Fe 50mm2 216 m
14	Br142			4.660	0.000	119.816	Al-Fe 50mm2 431 m
15	Br138			5.250	0.000	119.839	Al-Fe 50mm2 307 m
16	Br134			5.270	0.000	119.781	Al-Fe 50mm2 307 m
17	Br131			5.300	0.000	119.948	Al-Fe 50mm2 216 m
18	Br129			5.310	0.000	119.811	Al-Fe 50mm2 307 m
19	Br106			5.350	0.000	119.967	Al-Fe 50mm2 216 m
20	Br105			5.310	0.000	119.932	Al-Fe 50mm2 216 m
21	Br101			5.360	0.000	119.803	Al-Fe 50mm2 307 m
22	10 kV sabirnica (1)			5.190	0.000	119.952	Al-Fe 50mm2 307 m

Ln 1 54 Line(s) of 54 0 Line(s) selected

FIGURE 18. Tubular Reports for Thermal Constraints (Part 1)



Hosting Capacity Tabular Reports: Terminals

Study Case: Study Case
Result File: DER Capacity
Calculation objective: Distributed Energy Resource (DER) Capacity

	Terminals	Feeders	Substations	Max. active power MW	Max. reactive power Mvar	Max. loading %	Limiting component
23	10 kV GLAVNA SABI...			5.480	0.000	119.907	35/10 kV transformator
24	10 (34)			5.350	0.000	119.822	Al-Fe 50mm2 307 m
25	10 (33)			5.390	0.000	119.831	Al-Fe 50mm2 307 m
26	10 (32)			5.330	0.000	119.943	Al-Fe 50mm2 216 m
27	10 (31)			4.610	0.000	119.988	Al-Fe 50mm2 90 m
28	10 (30)			4.600	0.000	119.794	Al-Fe 50mm2 39 m
29	10 (29)			5.310	0.000	119.939	Al-Fe 50mm2 216 m
30	10 (28)			4.510	0.000	119.971	Al-Fe 50mm2 266 m
31	10 (27)			4.670	0.000	119.796	Al-Fe 50mm2 201 m
32	10 (26)			4.620	0.000	119.787	Al-Fe 50mm2 187 m
33	10 (25)			5.270	0.000	119.781	Al-Fe 50mm2 307 m
34	10 (24)			4.470	0.000	119.833	Al-Fe 50mm2 7 m
35	10 (23)			5.200	0.000	119.829	Al-Fe 50mm2 307 m
36	10 (22)			5.190	0.000	119.857	Al-Fe 50mm2 307 m
37	10 (21)			5.160	0.000	119.852	Al-Fe 50mm2 216 m
38	10 (20)			4.370	0.000	119.858	Al-Fe 50 mm2 60 m
39	0.4 kV sabirnica(9)			0.204	0.000	119.943	Remont Zanati
40	0.4 kV sabirnica(8)			0.232	0.000	119.947	Polje 2 M. Brijesnica
41	0.4 kV sabirnica(7)			0.470	0.000	119.976	Kantić Kompany
42	0.4 kV sabirnica(6)			0.067	0.000	119.931	Vodovod S. Polje
43	0.4 kV sabirnica(5)			0.261	0.000	119.857	Bare S. Polje
44	0.4 kV sabirnica(4)			0.736	0.000	119.967	Tursun

Ln 1 | 54 Line(s) of 54 | 0 Line(s) selected

FIGURE 19. Tubular Reports for Thermal Constraints (Part 2)

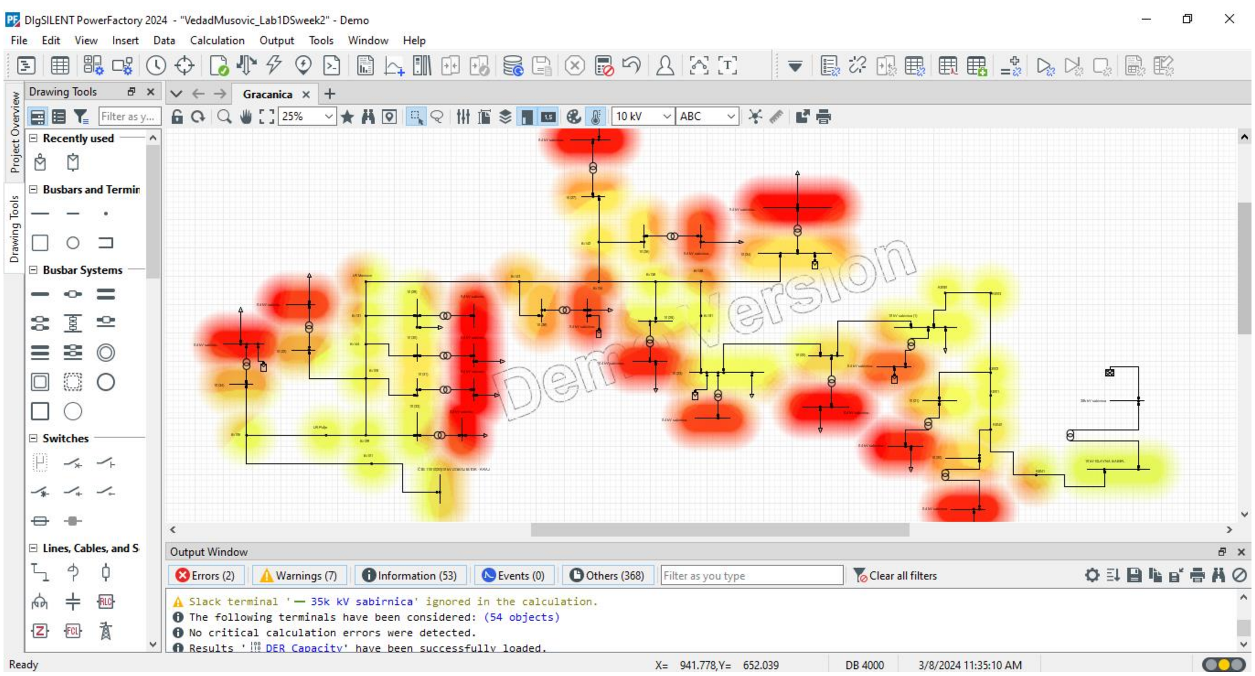


FIGURE 20. Network Heatmap for Thermal Constraint Hosting Capacity

4.2. Thermal and Voltage Constraints with Tubular Reports

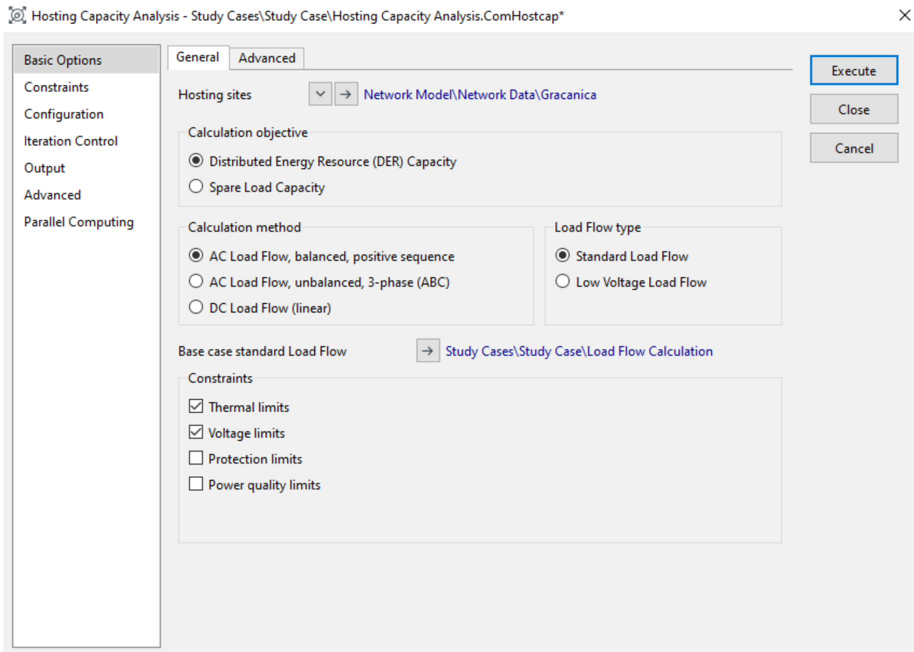


FIGURE 21. Hosting Capacity with Voltage and Thermal Constraints

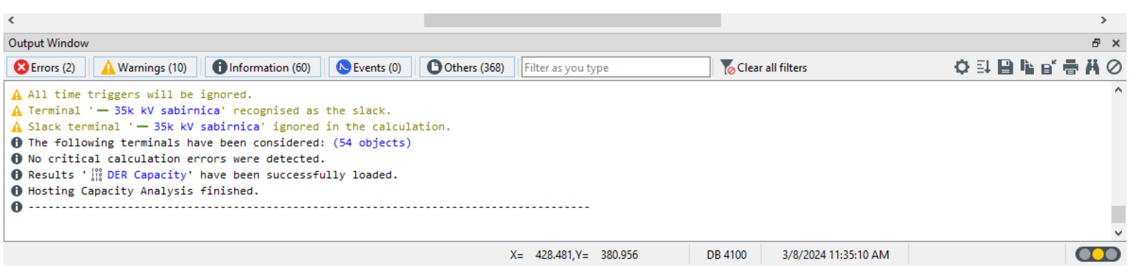


FIGURE 22. Hosting Capacity Analysis performed successfully

For this analysis type, both thermal and voltage constraints are taken into account. Voltage profile constraints for bidirectional power flow in systems with a high level of DER's are analyzed. Voltage limits are taken into account. The voltage values should be as close to 1 pu as possible.

Network Heatmap is depicted in Figure 23, while Hosting Capacity setup is shown in Figure 24.

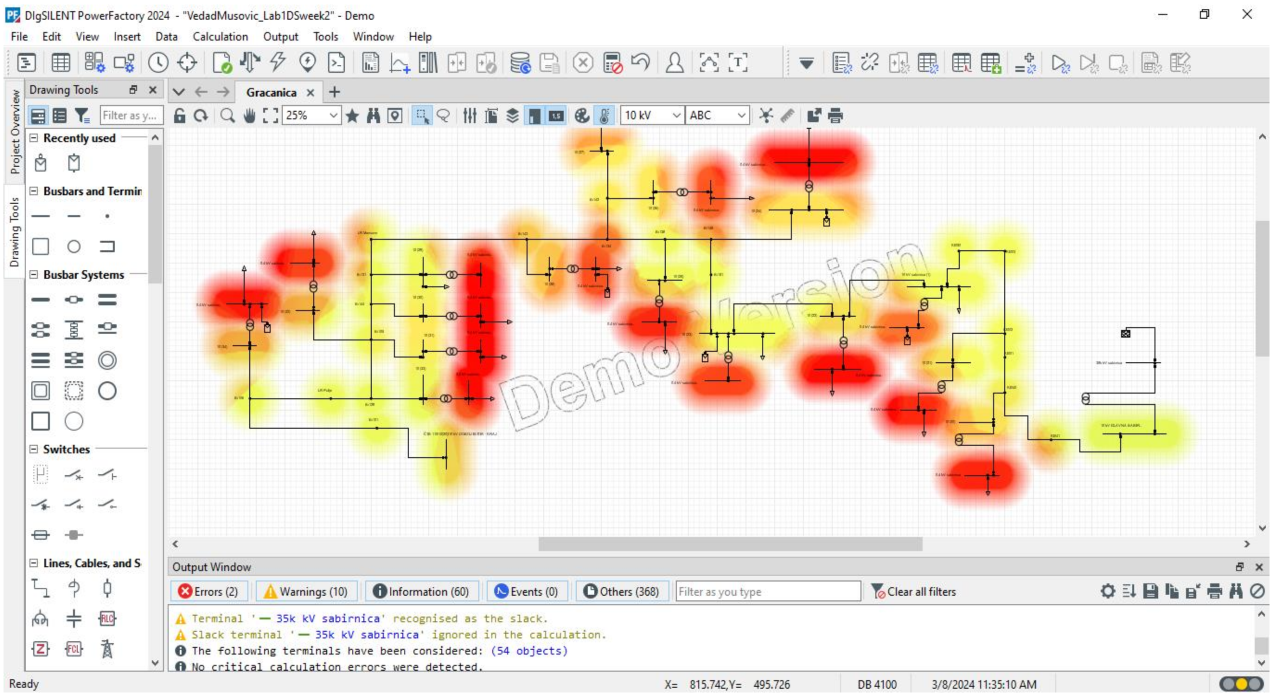


FIGURE 23. Network Heatmap for Voltage and Thermal Constraint Hosting Capacity

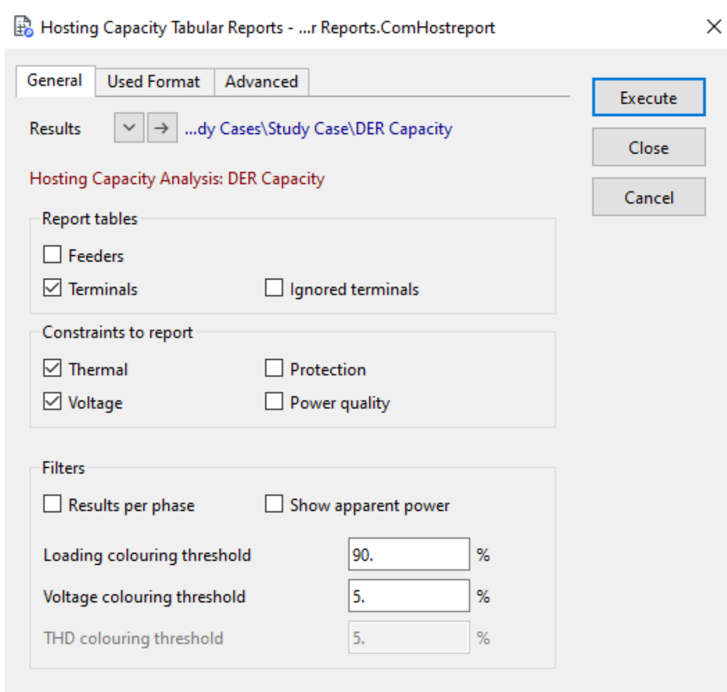
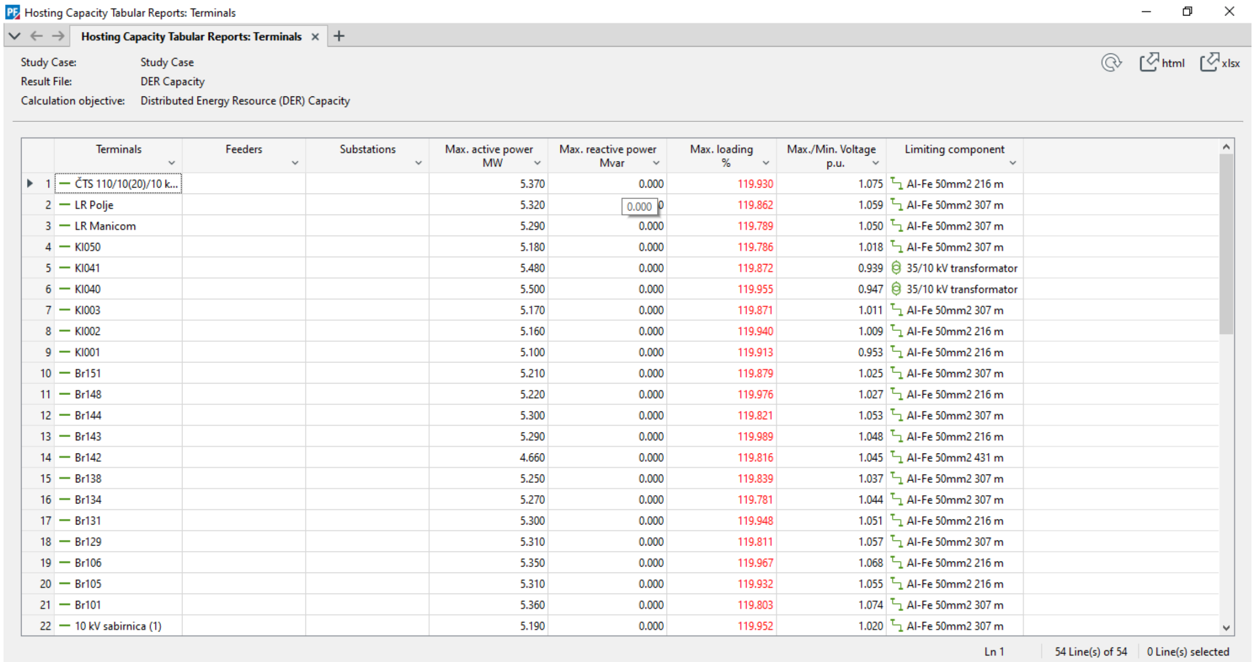
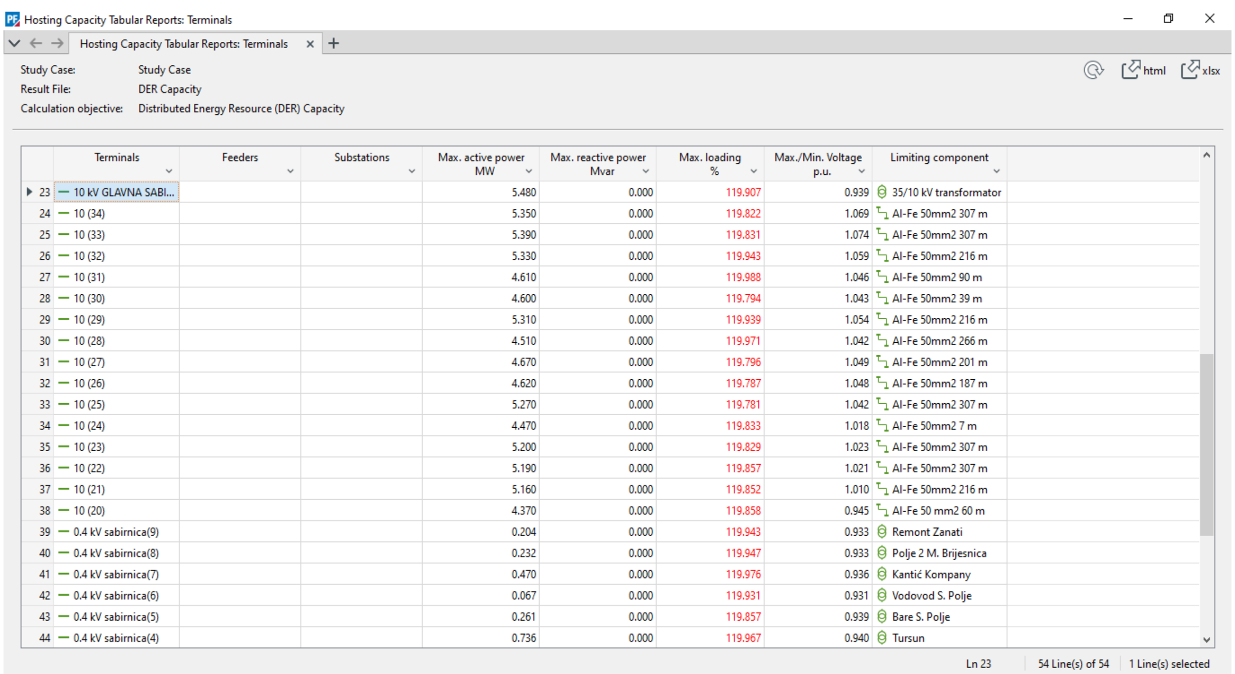


FIGURE 24. Hosting Capacity Tubular Report Setup



	Terminals	Feeders	Substations	Max. active power MW	Max. reactive power Mvar	Max. loading %	Max./Min. Voltage p.u.	Limiting component
1	ČTS 110/10(20)/10 k...			5.370	0.000	119.930	1.075	Al-Fe 50mm2 216 m
2	LR Polje			5.320	0.000	119.862	1.059	Al-Fe 50mm2 307 m
3	LR Manicom			5.290	0.000	119.789	1.050	Al-Fe 50mm2 307 m
4	KI050			5.180	0.000	119.786	1.018	Al-Fe 50mm2 307 m
5	KI041			5.480	0.000	119.872	0.939	35/10 kV transformator
6	KI040			5.500	0.000	119.955	0.947	35/10 kV transformator
7	KI003			5.170	0.000	119.871	1.011	Al-Fe 50mm2 307 m
8	KI002			5.160	0.000	119.940	1.009	Al-Fe 50mm2 216 m
9	KI001			5.100	0.000	119.913	0.953	Al-Fe 50mm2 216 m
10	Br151			5.210	0.000	119.879	1.025	Al-Fe 50mm2 307 m
11	Br148			5.220	0.000	119.976	1.027	Al-Fe 50mm2 216 m
12	Br144			5.300	0.000	119.821	1.053	Al-Fe 50mm2 307 m
13	Br143			5.290	0.000	119.989	1.048	Al-Fe 50mm2 216 m
14	Br142			4.660	0.000	119.816	1.045	Al-Fe 50mm2 431 m
15	Br138			5.250	0.000	119.839	1.037	Al-Fe 50mm2 307 m
16	Br134			5.270	0.000	119.781	1.044	Al-Fe 50mm2 307 m
17	Br131			5.300	0.000	119.948	1.051	Al-Fe 50mm2 216 m
18	Br129			5.310	0.000	119.811	1.057	Al-Fe 50mm2 307 m
19	Br106			5.350	0.000	119.967	1.068	Al-Fe 50mm2 216 m
20	Br105			5.310	0.000	119.932	1.055	Al-Fe 50mm2 216 m
21	Br101			5.360	0.000	119.803	1.074	Al-Fe 50mm2 307 m
22	10 kV sabirnica (1)			5.190	0.000	119.952	1.020	Al-Fe 50mm2 307 m

FIGURE 25. Tubular Reports for Voltage and Thermal Constraints (Part 1)



	Terminals	Feeders	Substations	Max. active power MW	Max. reactive power Mvar	Max. loading %	Max./Min. Voltage p.u.	Limiting component
23	10 kV GLAVNA SABI...			5.480	0.000	119.907	0.939	35/10 kV transformator
24	10 (34)			5.350	0.000	119.822	1.069	Al-Fe 50mm2 307 m
25	10 (33)			5.390	0.000	119.831	1.074	Al-Fe 50mm2 307 m
26	10 (32)			5.330	0.000	119.943	1.059	Al-Fe 50mm2 216 m
27	10 (31)			4.610	0.000	119.988	1.046	Al-Fe 50mm2 90 m
28	10 (30)			4.600	0.000	119.794	1.043	Al-Fe 50mm2 39 m
29	10 (29)			5.310	0.000	119.939	1.054	Al-Fe 50mm2 216 m
30	10 (28)			4.510	0.000	119.971	1.042	Al-Fe 50mm2 266 m
31	10 (27)			4.670	0.000	119.796	1.049	Al-Fe 50mm2 201 m
32	10 (26)			4.620	0.000	119.787	1.048	Al-Fe 50mm2 187 m
33	10 (25)			5.270	0.000	119.781	1.042	Al-Fe 50mm2 307 m
34	10 (24)			4.470	0.000	119.833	1.018	Al-Fe 50mm2 7 m
35	10 (23)			5.200	0.000	119.829	1.023	Al-Fe 50mm2 307 m
36	10 (22)			5.190	0.000	119.857	1.021	Al-Fe 50mm2 307 m
37	10 (21)			5.160	0.000	119.852	1.010	Al-Fe 50mm2 216 m
38	10 (20)			4.370	0.000	119.858	0.945	Al-Fe 50 mm2 60 m
39	0.4 kV sabirnica(9)			0.204	0.000	119.943	0.933	Remont Zanati
40	0.4 kV sabirnica(8)			0.232	0.000	119.947	0.933	Polje 2 M. Brijesnica
41	0.4 kV sabirnica(7)			0.470	0.000	119.976	0.936	Kantić Kompany
42	0.4 kV sabirnica(6)			0.067	0.000	119.931	0.931	Vodovod S. Polje
43	0.4 kV sabirnica(5)			0.261	0.000	119.857	0.939	Bare S. Polje
44	0.4 kV sabirnica(4)			0.736	0.000	119.967	0.940	Tursun

FIGURE 26. Tubular Reports for Voltage and Thermal Constraints (Part 2)

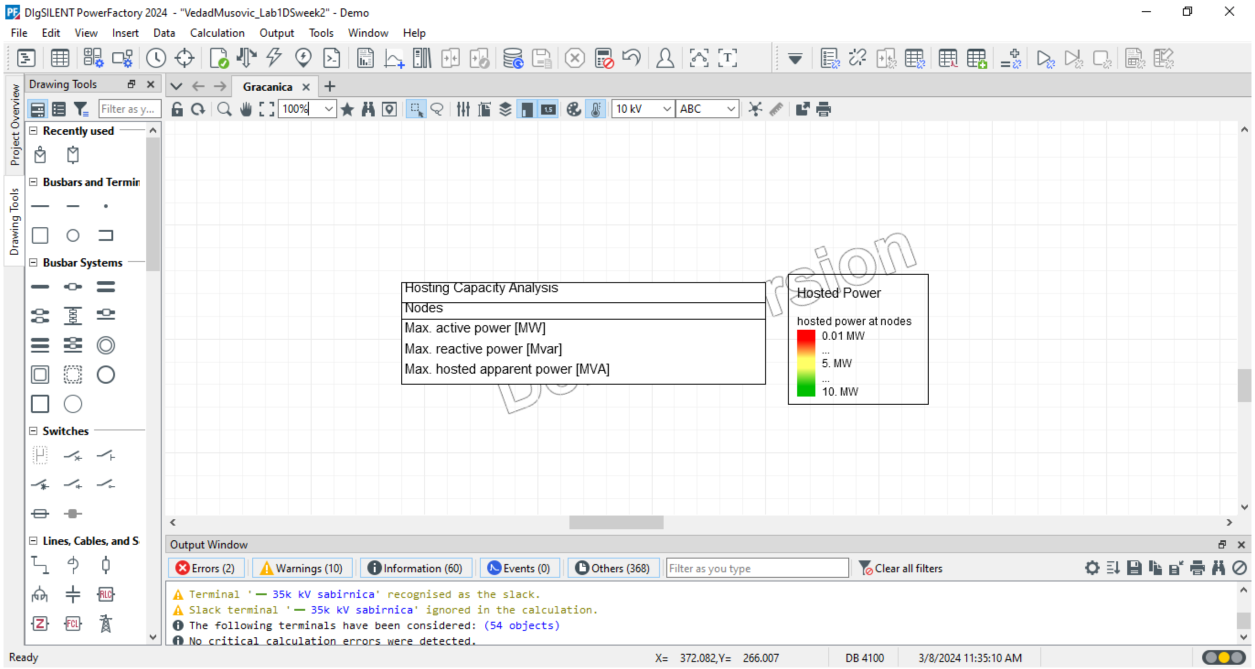


FIGURE 27. Legend Setup for Hosting Capacity Analysis

Legend Setup is shown in Figure 27 and it gives us the insight on Hosting Capacity Analysis. Maximum active and reactive powers are present. Besides them, there is as well the maximum hosted apparent power. The values are expressed in MW, MVAr and MVA. Finally, for the heatmap, the legend shows us the individual hosted power at a designated node. The greener it is, this values is greater. The redder it is, this values is lower. Yellow heatmap shows that it is in the middle between the minimum and maximum values.

Compared to the case before implementing PV systems, we have better voltage profile when adding them. This is especially present at the exact busbars where the PV's are implemented. If the voltage values in pu are below 1 then they are increased, while they are decreased if they are higher than 1. Voltage deviations are expected to be reduced, as well as the power losses. When choosing the value for our PV system, we need to be sure that we are not entering values that are too high, so we do not violate the loading violation of our network. Overall, PV systems offer multiple benefits to our distribution system.

5. Conclusion

In this lab, we explored how our network handles the addition of PV systems, focusing on incorporating solar panels into the grid without causing problems. We learned that hosting capacity is not a strict limit but rather a flexible concept that changes as the system gets upgraded.

By looking at factors like the size and location of solar systems and how they interact with other energy sources on the grid, we can figure out how much solar energy the grid can handle safely and effectively. It is observed that implementing more PV systems, dispersed over the distribution system, resulted in better voltage values. 100 kW PV systems improve the voltage profiles.

This is analogous to real life, when locating distributed generation close to the consumer, is much better than using just one solar power plant to produce power for our entire network. The lab showed us that adding solar panels improves voltage stability and reduces power losses, but we need to be careful not to overload the system.

Overall, it highlighted the importance of smart planning and using renewable energy sources wisely to build a stronger, more resilient power grid for the future. Hosting Capacity Analysis considers factors like grid stability, voltage control, and thermal limitations, preventing situations where too much solar power comes to the grid.

LAB 8 - OPTIMAL CAPACITOR PLACEMENT (POWERFACTORY)

1. Introduction - Theoretical

In Lab 8, the modelled network, with the name ‘Gračanica’ is modified for reactive power compensation. This time, in DIGSILENT, the optimal capacitor placement is performed with the aim to minimize the losses. We describe the task and the compensation. The original network and its parameters before compensation are shown. The reports and power flow analysis are shown.

The network and its parameters after compensation are shown then, after explaining the process. The places where capacitors should be placed and their power are shown and explained. The voltage profile – voltage on each bus before and after compensation are shown, alongside the deviations from acceptable pu values. The obtained results are explained in details.

Compensation means strategically situating capacitors at specific points within the network to enhance its voltage profile, aiming to reduce power losses and enhance efficiency and power factor. By strategically placing capacitors at selected busbars, reactive power demand is reduced, minimizing losses and improving the power factor. The process involves analyzing network characteristics, load profiles, and voltage levels to identify sites with high reactive power flow and significant losses. Capacitors are selected based on the reactive power demand of respective busbars to avoid overcompensation and potential overvoltage issues.

Two common types of equipment used for reactive power compensation are:

- synchronous condensers, and

- static capacitors or capacitor banks.

Synchronous condensers offer precise reactive power regulation but are costly and more suitable for high-voltage systems. Static capacitors, divided into shunt and series capacitors, offer cost-effective solutions with benefits like reduced line current, improved voltage levels, and lower system losses. Shunt capacitors are more commonly used across all voltage levels in the power system. They offer several advantages, like: reduction of line current, improvement of load voltage levels, reduction of system losses, improvement of power factor in the source, current reduction of alternator load, lower capital investment per MW of load.

Our lab aimed to implement optimal capacitor placement techniques to efficiently compensate for reactive energy and enhance the power system's overall performance. This involves identifying strategic positions to enhance power factor, minimize losses, and improve system performance.

2. Case I – Before the Compensation

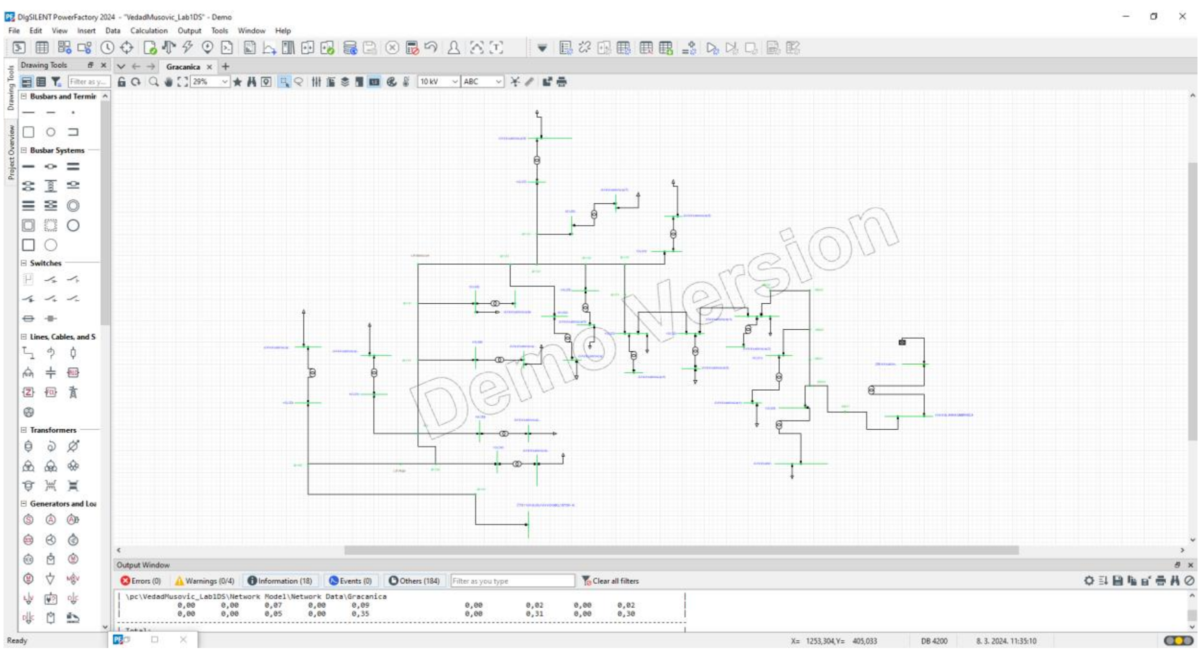


Figure 1. The Original Network

The first case can be called a reference case as well. This case shows our original ‘Gracanica’ network, before performing optimal capacitor placement, that is, the compensation.

We will perform load flow analysis. It is successful, as The Newton-Raphson Algorithm reaches convergence in 2 iterations. As see, voltage and loading violations show that there are no violations inside of the network. Control Conditions for all relevant controllers of interest are satisfied.

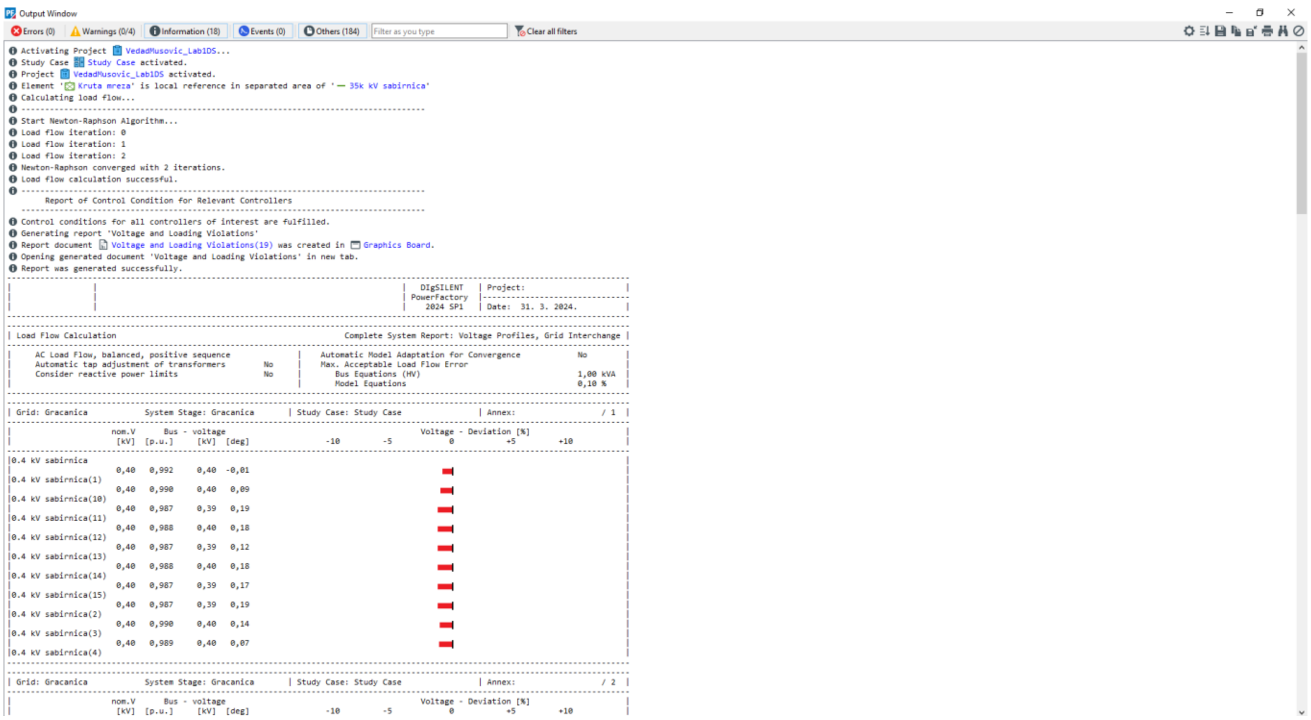


Figure 2. Output Window – PFA and Complete System Report

Following this, the complete system report is generated. As seen, the voltages satisfy the conditions by falling in the range between 0.95 and 1.05 pu and the losses in MW and MVAR are shown. The deviation is less than 5% for every bus in the network, but this will be further improved after performing the optimal capacitor placement.

The values for the losses are 0.1 MW and 0.4 MVAR (Figure 5). This will be improved as well. However, the main difference will be seen at bus' voltages, as they will approach 1 pu more, with less deviation. The compensation, i.e. optimal capacitor placement is shown in Case II.

Figure 3. Output Window – Complete System Report

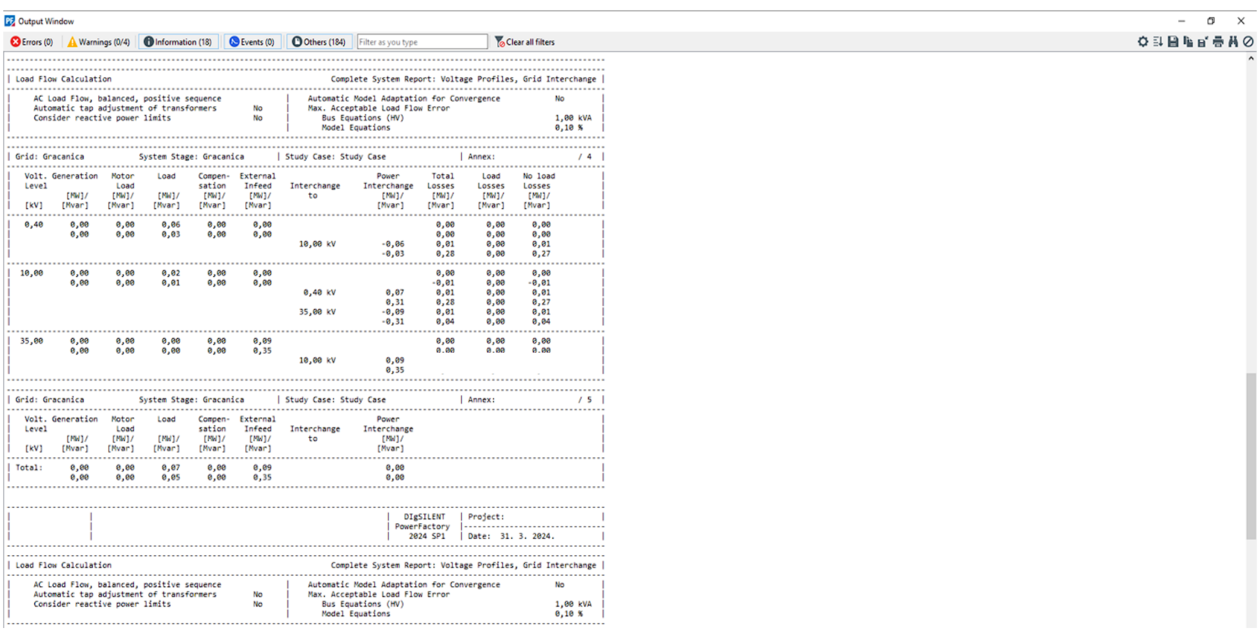


Figure 4. Output Window – Complete System Report

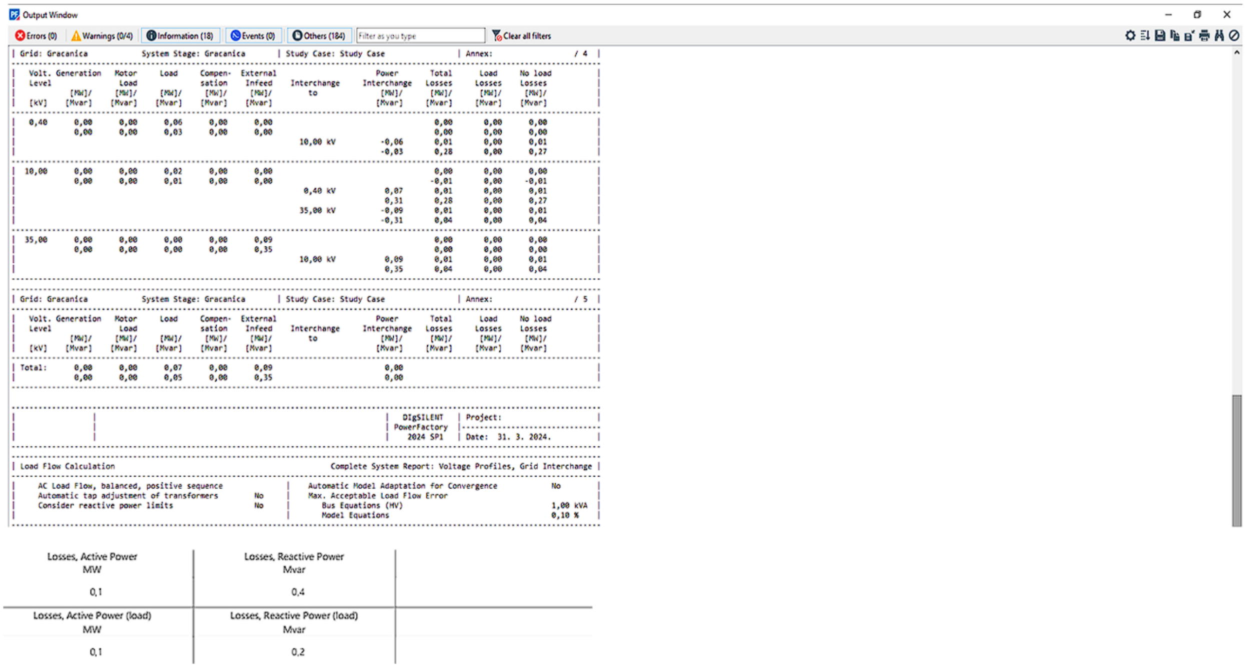


Figure 5. Complete System Report – Showing the Losses

3. Case II – After the Compensation

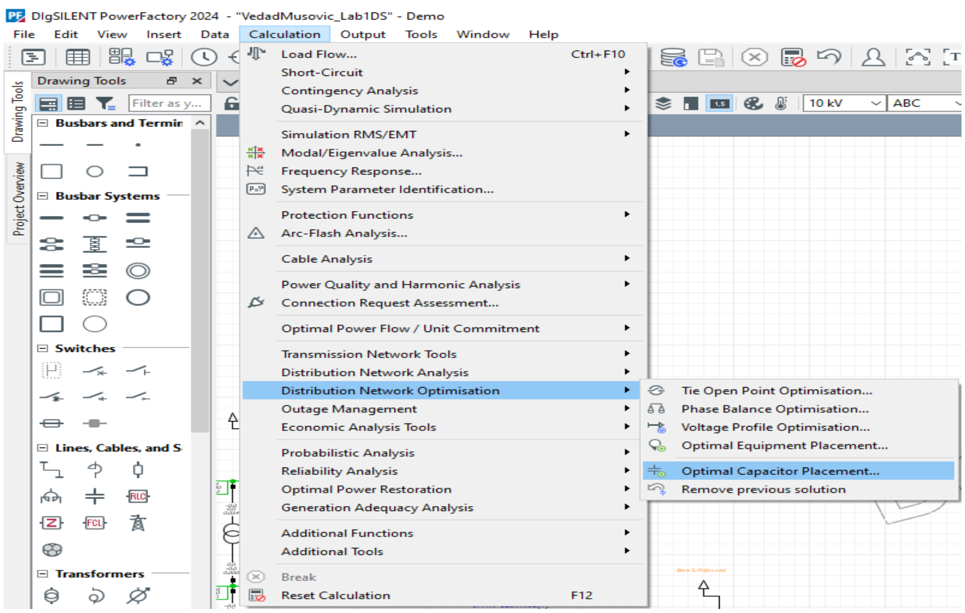


Figure 6. How to Select the Optimal Capacitor Placement

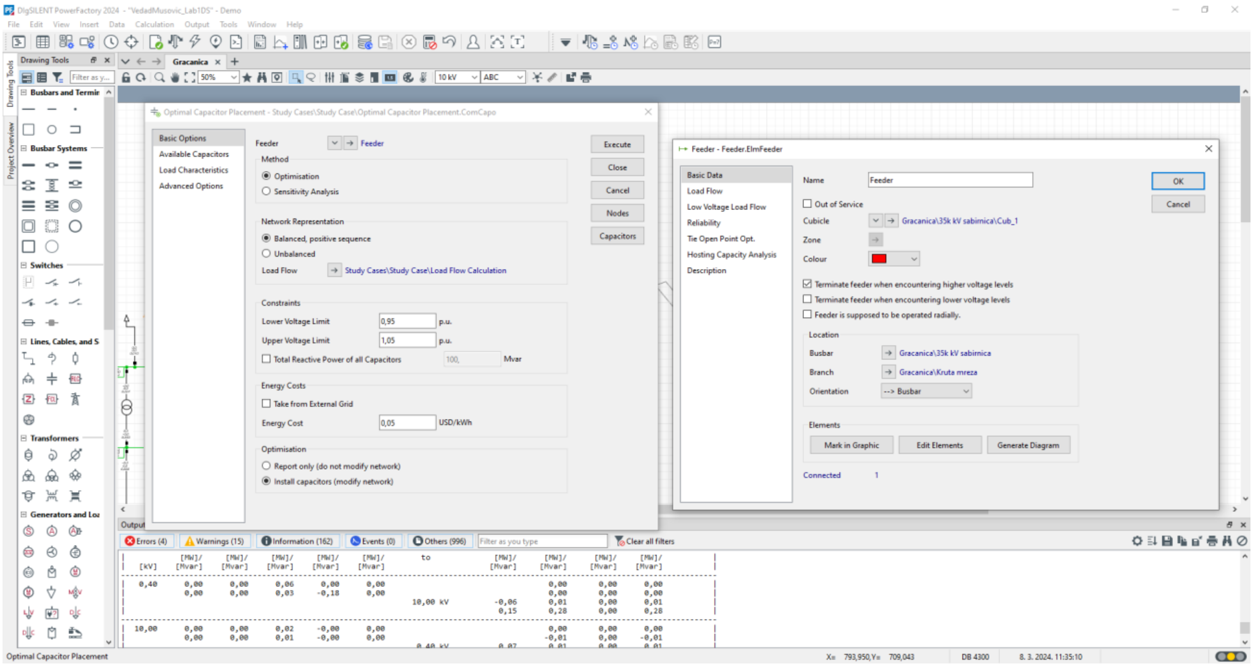


Figure 7. Selecting the Optimal Capacitor Placement and Main Reference Bus

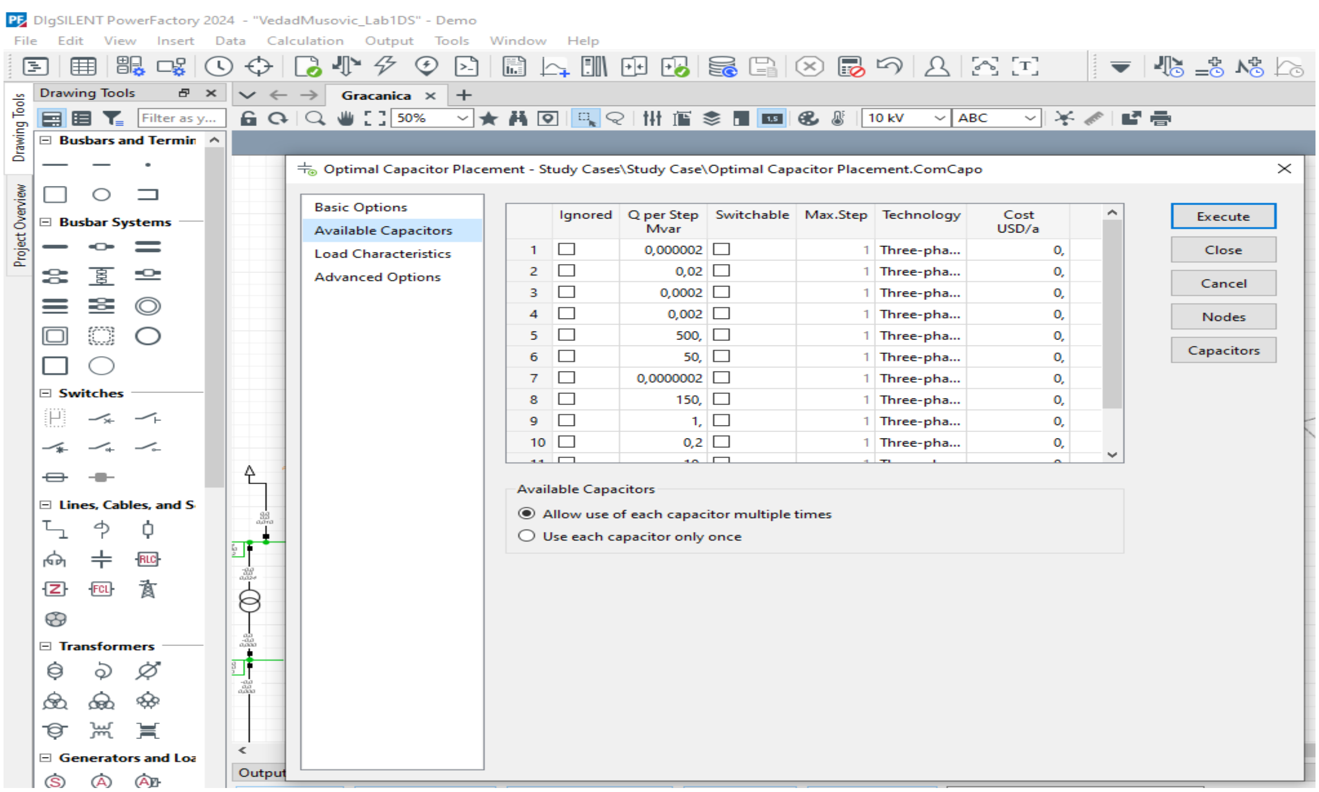


Figure 8. Inputting the Values for Available Capacitors

When we create a case for optimal capacitor placement, we start by selecting Calculation tab, then Distribution Network optimization, and then Optimal Capacitor Placement.

After this, we will configure and compute the optimal capacitor placement. As shown in Figure 7, we select 35 kV sabirnica as our main feeder. This allowes the method to determine the best position for capacitor installation, effectively minimizing losses. Optimization Method is selected, alongside the Install Capacitor (modify network). We are working in the Balanced, positive sequence. Lower voltage limit is set at 0.95 pu and the upper voltage limit to 1.05 pu.

Available capacitors are selected in the Available capacitor optimal capacitor placement window. Since we want to ensure every bus is optimized, various capacitors are used. The value to consider is Q per step MVAR. If we want to select all capacitors, we do it by right clicking and choosing Select all. The following values for capacitors MVAR are used:

- 0.0000002 MVAR and 0.000002 MVAR,

- 0.0002 MVAR and 0.002 MVAR,

- 0.02 MVAR and 0.2 MVAR,

- 1 MVAR, 10 MVAR, 50 MVAR, 150 MVAR and 500 MVAR.

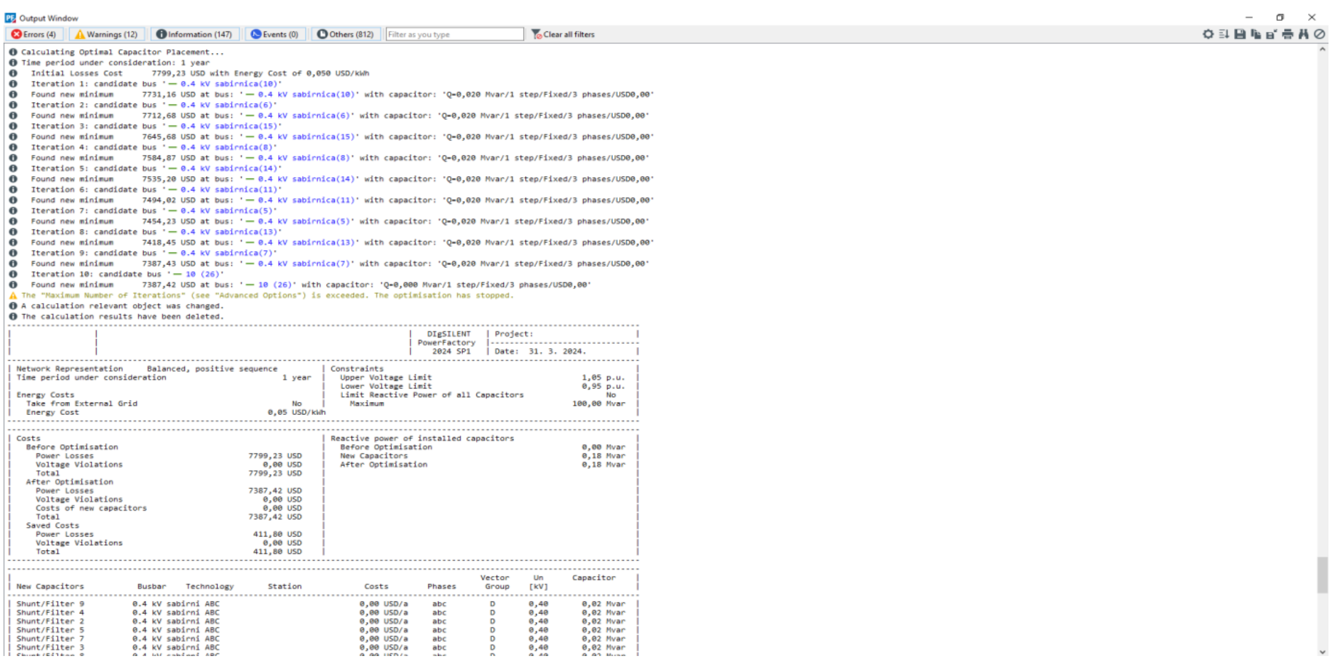


Figure 9. Calculating Optimal Capacitor Placement

After doing previous steps, we click ‘Execute’ in order to perform Optimal Capacitor Placement.

The period of analysis is 1 year. Initial losses cost and initial energy cost are calculated. The analysis will go through 10 iterations and will select a certain bus as its candidate. It select between our capacitors and selects the best value for installation, as well as the best location, i.e. bus, as already mentioned. In each iteration we get the price in USD (American Dollar) and reactive power Q in MVAR for the selected capacitor.

As seen in Figure 9, the power costs are 7800 USD before the compensation, and are reduced to 7387 USD, which means that 413 USD would be saved. Overall, the new capacitors would compensate for about 0.18 MVAR of power.

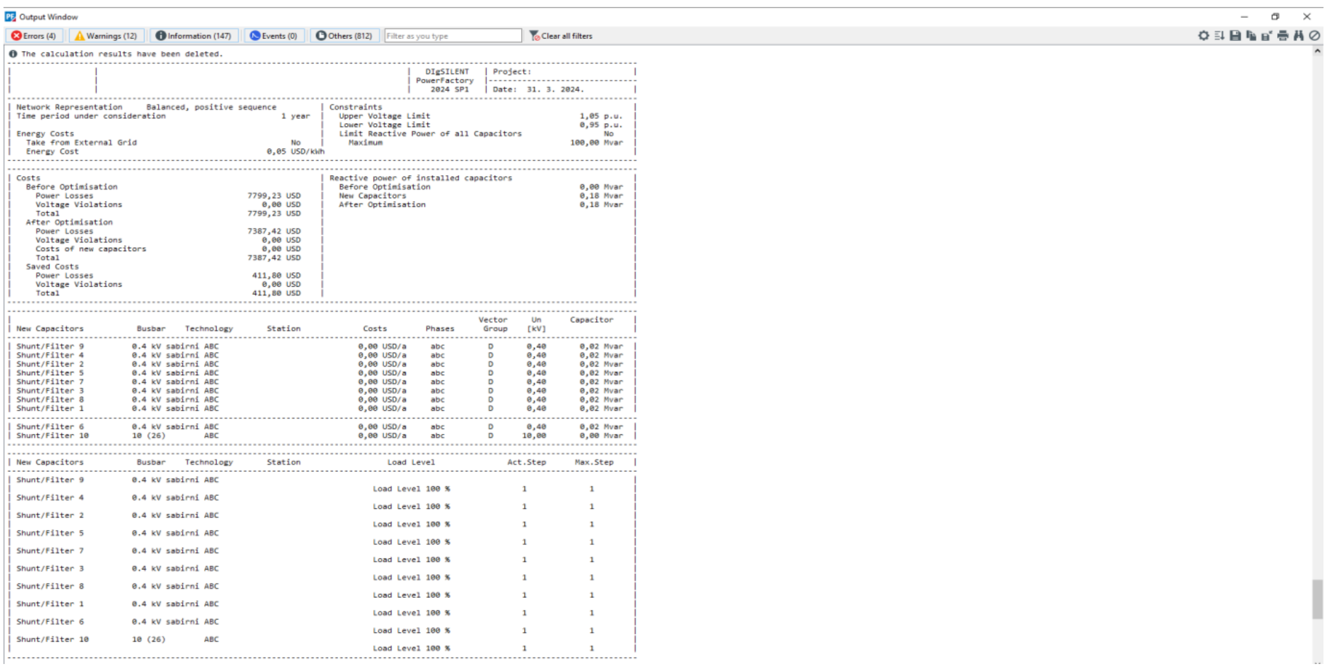
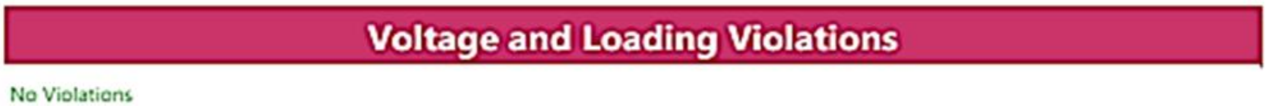

```
Output Window
Errors (4)  Warnings (12)  Information (147)  Events (0)  Others (812)  Filter as you type  Clear all filters
The calculation results have been deleted.
---------------------------------------------------------------------------------------------------
|              |                                          |  DIgSILENT   | Project:             |
|              |                                          | PowerFactory |----------------------|
|              |                                          |   2024 SP1   | Date:  31. 3. 2024.  |
---------------------------------------------------------------------------------------------------
| Network Representation    Balanced, positive sequence  | Constraints                           |
| Time period under consideration                1 year  |   Upper Voltage Limit        1,05 p.u.|
|                                                        |   Lower Voltage Limit        0,95 p.u.|
| Energy Costs                                           |   Limit Reactive Power of all Capacitors  No |
|   Take from External Grid                          No  |     Maximum                100,00 Mvar|
|   Energy Cost                            0,05 USD/kWh                                         |
---------------------------------------------------------------------------------------------------
| Costs                                                  | Reactive power of installed capacitors |
|   Before Optimisation                                  |   Before Optimisation       0,00 Mvar |
|     Power Losses                       7799,23 USD     |   New Capacitors            0,18 Mvar |
|     Voltage Violations                    0,00 USD     |   After Optimisation        0,18 Mvar |
|     Total                              7799,23 USD     |                                       |
|   After Optimisation                                   |                                       |
|     Power Losses                       7387,42 USD     |                                       |
|     Voltage Violations                    0,00 USD     |                                       |
|     Costs of new capacitors               0,00 USD     |                                       |
|     Total                              7387,42 USD     |                                       |
|   Saved Costs                                          |                                       |
|     Power Losses                        411,80 USD     |                                       |
|     Voltage Violations                    0,00 USD     |                                       |
|     Total                               411,80 USD     |                                       |
---------------------------------------------------------------------------------------------------
|                                                                    Vector    Un     Capacitor |
| New Capacitors     Busbar   Technology  Station   Costs     Phases  Group   [kV]               |
---------------------------------------------------------------------------------------------------
| Shunt/Filter 9     0.4 kV sabirni ABC            0,00 USD/a   abc     D      0,40   0,02 Mvar |
| Shunt/Filter 4     0.4 kV sabirni ABC            0,00 USD/a   abc     D      0,40   0,02 Mvar |
| Shunt/Filter 2     0.4 kV sabirni ABC            0,00 USD/a   abc     D      0,40   0,02 Mvar |
| Shunt/Filter 5     0.4 kV sabirni ABC            0,00 USD/a   abc     D      0,40   0,02 Mvar |
| Shunt/Filter 7     0.4 kV sabirni ABC            0,00 USD/a   abc     D      0,40   0,02 Mvar |
| Shunt/Filter 3     0.4 kV sabirni ABC            0,00 USD/a   abc     D      0,40   0,02 Mvar |
| Shunt/Filter 8     0.4 kV sabirni ABC            0,00 USD/a   abc     D      0,40   0,02 Mvar |
| Shunt/Filter 1     0.4 kV sabirni ABC            0,00 USD/a   abc     D      0,40   0,02 Mvar |
---------------------------------------------------------------------------------------------------
| Shunt/Filter 6     0.4 kV sabirni ABC            0,00 USD/a   abc     D      0,40   0,02 Mvar |
| Shunt/Filter 10    10 (26)        ABC            0,00 USD/a   abc     D     10,00   0,00 Mvar |
---------------------------------------------------------------------------------------------------
| New Capacitors     Busbar   Technology  Station      Load Level        Act.Step    Max.Step   |
---------------------------------------------------------------------------------------------------
| Shunt/Filter 9     0.4 kV sabirni ABC                                                         |
|                                                  Load Level 100 %        1           1        |
| Shunt/Filter 4     0.4 kV sabirni ABC                                                         |
|                                                  Load Level 100 %        1           1        |
| Shunt/Filter 2     0.4 kV sabirni ABC                                                         |
|                                                  Load Level 100 %        1           1        |
| Shunt/Filter 5     0.4 kV sabirni ABC                                                         |
|                                                  Load Level 100 %        1           1        |
| Shunt/Filter 7     0.4 kV sabirni ABC                                                         |
|                                                  Load Level 100 %        1           1        |
| Shunt/Filter 3     0.4 kV sabirni ABC                                                         |
|                                                  Load Level 100 %        1           1        |
| Shunt/Filter 8     0.4 kV sabirni ABC                                                         |
|                                                  Load Level 100 %        1           1        |
| Shunt/Filter 1     0.4 kV sabirni ABC                                                         |
|                                                  Load Level 100 %        1           1        |
| Shunt/Filter 6     0.4 kV sabirni ABC                                                         |
|                                                  Load Level 100 %        1           1        |
| Shunt/Filter 10    10 (26)        ABC                                                         |
|                                                  Load Level 100 %        1           1        |
---------------------------------------------------------------------------------------------------
```

Figure 10. Calculating Optimal Capacitor Placement

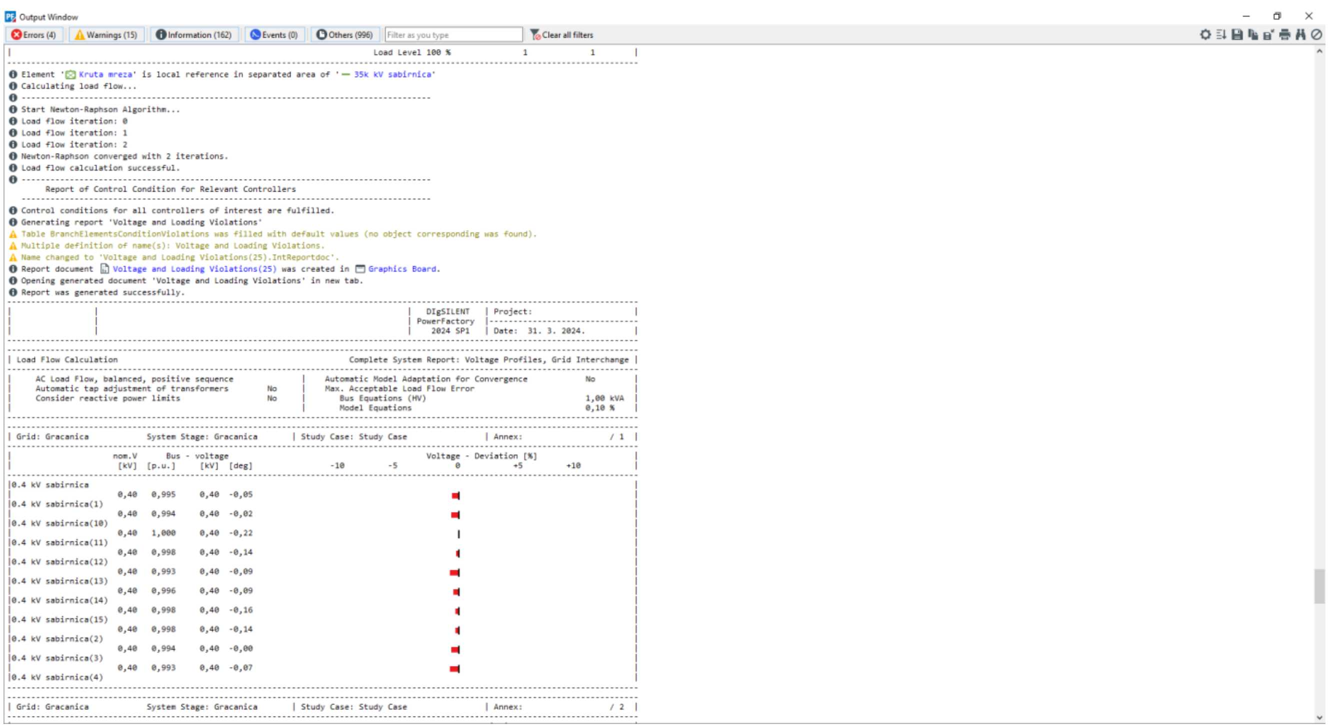
It is observed that 10 busses have capacitors placed at them (Figure 10). All but one are 0.4 kV busses. Those are the busses where the loads are connected. On the other hand, the one bus that is different has nominal voltage (U_n) of 10 kV. The calculations determined the 0.02 MVAR capacitor to best the best for compensation on the busses in the network that need to improve their voltage level and potentially reduce losses. Shunts / Filters are used and are loaded at 100%.

The power flow analysis is executed. The Newton-Raphson method successfully converges in 2 iterations. Report of control conditions for all relevant controllers are fulfilled. After this, we see than no voltage or loading violations occur. Finally, complete system report is generated.



As clearly seen, voltage values are more optimal. They are closer to 1 pu, with less deviation than in the case without performing optimal capacitor placement.

The voltages have very small phase angles (in degrees), but the key segment is that we got voltages closer to 1 pu with almost nonexistent value deviation.



```
Output Window
Errors (4)  Warnings (15)  Information (162)  Events (0)  Others (996)  Filter as you type  Clear all filters
|                                     Load Level 100 %          1           1        |
-------------------------------------------------------------------------------------
Element 'Kruta mreza' is local reference in separated area of '35k kV sabirnica'
Calculating load flow...
-----------------------------------------------------------------------
Start Newton-Raphson Algorithm...
Load flow iteration: 0
Load flow iteration: 1
Load flow iteration: 2
Newton-Raphson converged with 2 iterations.
Load flow calculation successful.
-----------------------------------------------------------------------
    Report of Control Condition for Relevant Controllers
-----------------------------------------------------------------------
Control conditions for all controllers of interest are fulfilled.
Generating report 'Voltage and Loading Violations'
Table BranchElementsConditionViolations was filled with default values (no object corresponding was found).
Multiple definition of name(s): Voltage and Loading Violations.
Name changed to 'Voltage and Loading Violations(25).IntReportdoc'.
Report document Voltage and Loading Violations(25) was created in Graphics Board.
Opening generated document 'Voltage and Loading Violations' in new tab.
Report was generated successfully.
-------------------------------------------------------------------------------------
|            |                                       |   DIgSILENT   | Project:            |
|            |                                       |  PowerFactory |---------------------|
|            |                                       |    2024 SP1   | Date:  31. 3. 2024. |
-------------------------------------------------------------------------------------
-------------------------------------------------------------------------------------
| Load Flow Calculation              Complete System Report: Voltage Profiles, Grid Interchange |
-------------------------------------------------------------------------------------
|   AC Load Flow, balanced, positive sequence      |  Automatic Model Adaptation for Convergence    No      |
|   Automatic tap adjustment of transformers   No  |  Max. Acceptable Load Flow Error                       |
|   Consider reactive power limits             No  |     Bus Equations (HV)                      1,00 kVA  |
|                                                  |     Model Equations                         0,10 %    |
-------------------------------------------------------------------------------------
-------------------------------------------------------------------------------------
| Grid: Gracanica        System Stage: Gracanica   | Study Case: Study Case        | Annex:         / 1 |
-------------------------------------------------------------------------------------
|                  nom.V     Bus - voltage                       Voltage - Deviation [%]              |
|                  [kV]  [p.u.]    [kV]  [deg]         -10       -5        0        +5       +10      |
-------------------------------------------------------------------------------------
|0.4 kV sabirnica                                                                                      |
|                  0,40  0,995     0,40  -0,05                                                         |
|0.4 kV sabirnica(1)                                                                                   |
|                  0,40  0,994     0,40  -0,02                                                         |
|0.4 kV sabirnica(10)                                                                                  |
|                  0,40  1,000     0,40  -0,22                                                         |
|0.4 kV sabirnica(11)                                                                                  |
|                  0,40  0,998     0,40  -0,14                                                         |
|0.4 kV sabirnica(12)                                                                                  |
|                  0,40  0,993     0,40  -0,09                                                         |
|0.4 kV sabirnica(13)                                                                                  |
|                  0,40  0,996     0,40  -0,09                                                         |
|0.4 kV sabirnica(14)                                                                                  |
|                  0,40  0,998     0,40  -0,16                                                         |
|0.4 kV sabirnica(15)                                                                                  |
|                  0,40  0,998     0,40  -0,14                                                         |
|0.4 kV sabirnica(2)                                                                                   |
|                  0,40  0,994     0,40  -0,00                                                         |
|0.4 kV sabirnica(3)                                                                                   |
|                  0,40  0,993     0,40  -0,07                                                         |
|0.4 kV sabirnica(4)                                                                                   |
-------------------------------------------------------------------------------------
-------------------------------------------------------------------------------------
| Grid: Gracanica        System Stage: Gracanica   | Study Case: Study Case        | Annex:         / 2 |
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```

Figure 11. Output Window – Power Flow Analysis and Complete System Report

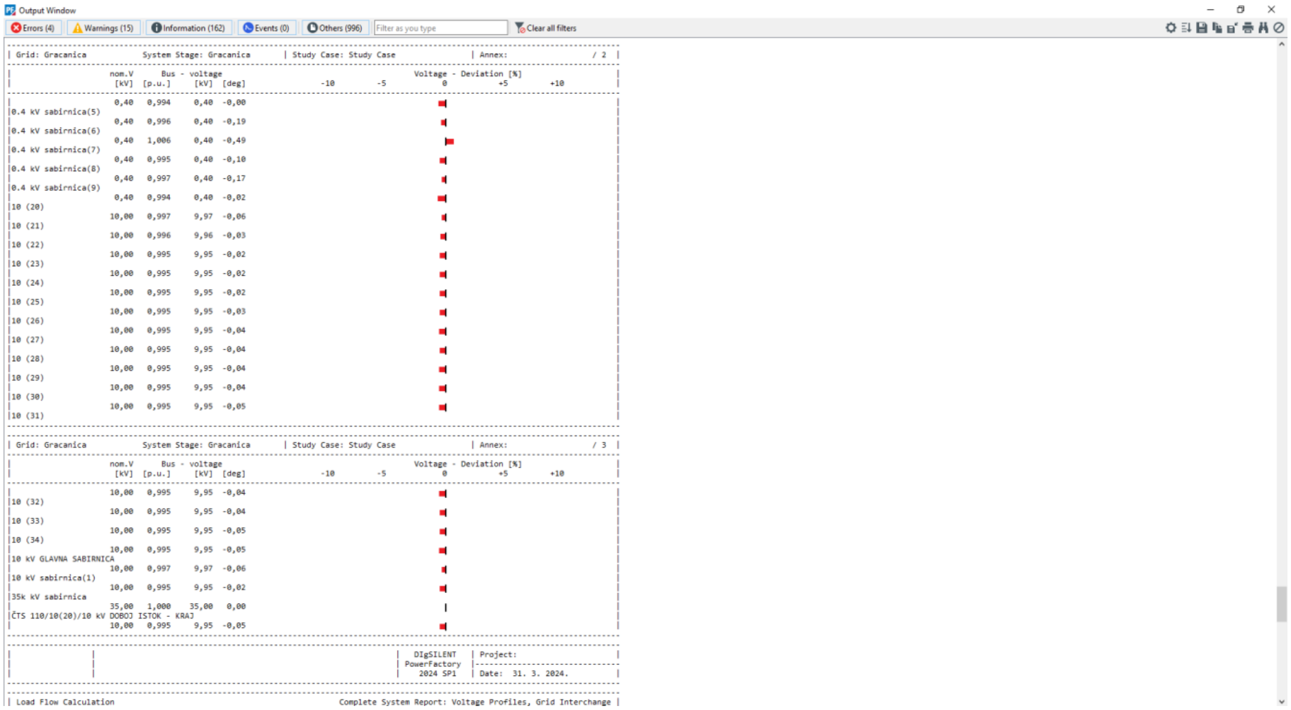


Figure 12. Complete System Report

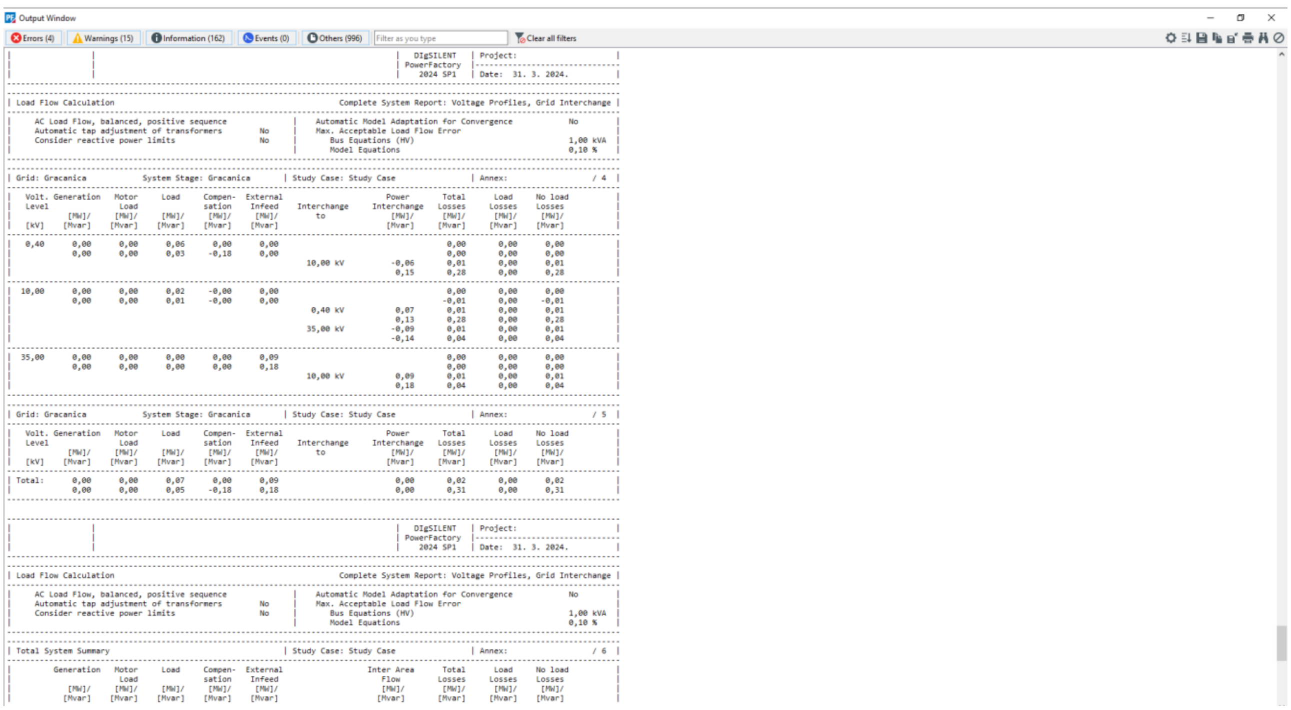
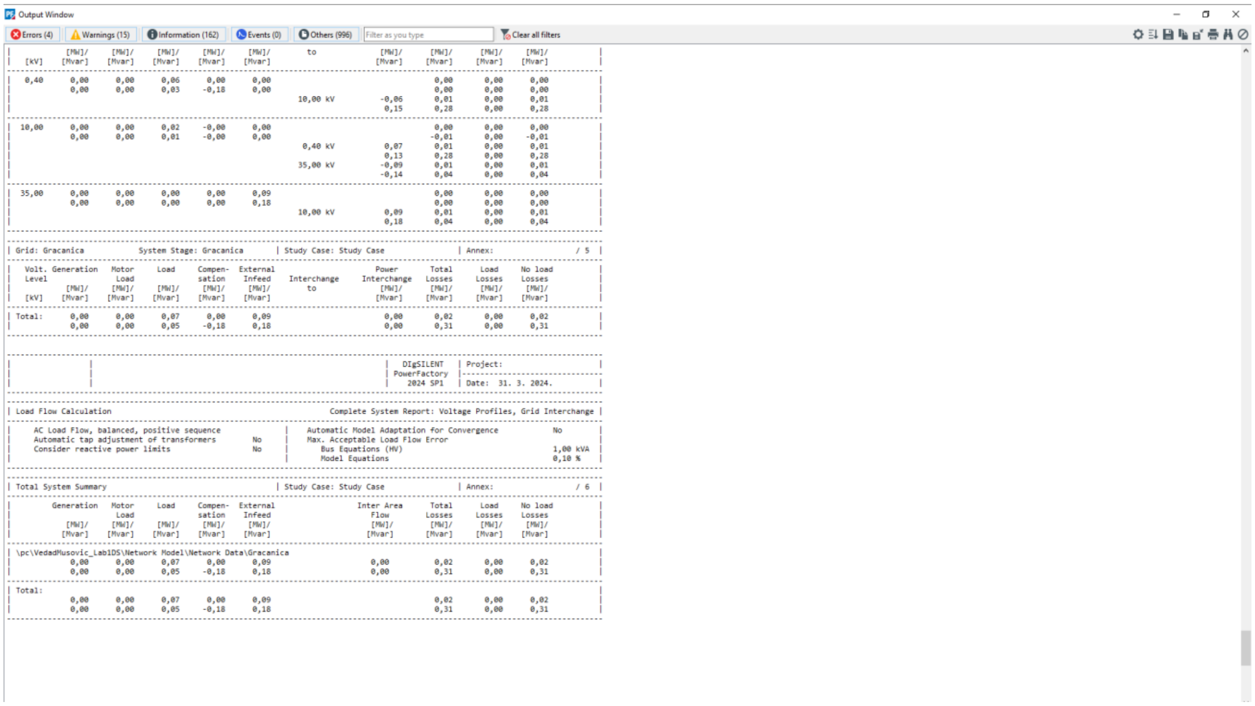


Figure 13. Complete System Report



```
Output Window
Errors (4)   Warnings (15)   Information (162)   Events (0)   Others (996)   Filter as you type   Clear all filters

|          [MW]/   [MW]/   [MW]/   [MW]/   [MW]/     to             [MW]/   [MW]/   [MW]/   [MW]/     |
|   [kV]  [Mvar]  [Mvar]  [Mvar]  [Mvar]  [Mvar]                   [Mvar]  [Mvar]  [Mvar]  [Mvar]     |
-----------------------------------------------------------------------------------------------------
|   0,40    0,00    0,00    0,06    0,00    0,00                            0,00    0,00    0,00     |
|           0,00    0,00    0,03   -0,18    0,00                            0,00    0,00    0,00     |
|                                                  10,00 kV        -0,06    0,01    0,00    0,01     |
|                                                                   0,15    0,28    0,00    0,28     |
-----------------------------------------------------------------------------------------------------
|  10,00    0,00    0,00    0,02   -0,00    0,00                            0,00    0,00    0,00     |
|           0,00    0,00    0,01   -0,00    0,00                           -0,01    0,00   -0,01     |
|                                                   0,40 kV         0,07    0,01    0,00    0,01     |
|                                                                   0,13    0,28    0,00    0,28     |
|                                                  35,00 kV        -0,09    0,01    0,00    0,01     |
|                                                                  -0,14    0,04    0,00    0,04     |
-----------------------------------------------------------------------------------------------------
|  35,00    0,00    0,00    0,00    0,00    0,09                            0,00    0,00    0,00     |
|           0,00    0,00    0,00    0,00    0,18                            0,00    0,00    0,00     |
|                                                  10,00 kV         0,09    0,01    0,00    0,01     |
|                                                                   0,18    0,04    0,00    0,04     |
-----------------------------------------------------------------------------------------------------

-----------------------------------------------------------------------------------------------------
| Grid: Gracanica          System Stage: Gracanica      | Study Case: Study Case        | Annex:      / 5 |
-----------------------------------------------------------------------------------------------------
|  Volt. Generation  Motor    Load   Compen-  External                Power     Total    Load   No load |
|  Level              Load           sation   Infeed   Interchange  Interchange Losses  Losses  Losses  |
|          [MW]/   [MW]/   [MW]/   [MW]/   [MW]/       to           [MW]/   [MW]/   [MW]/   [MW]/     |
|   [kV]  [Mvar]  [Mvar]  [Mvar]  [Mvar]  [Mvar]                   [Mvar]  [Mvar]  [Mvar]  [Mvar]     |
-----------------------------------------------------------------------------------------------------
| Total:    0,00    0,00    0,07    0,00    0,09                    0,00    0,02    0,00    0,02     |
|           0,00    0,00    0,05   -0,18    0,18                    0,00    0,31    0,00    0,31     |
-----------------------------------------------------------------------------------------------------

-----------------------------------------------------------------------------------------------------
|            |                                            |  DIgSILENT   | Project:                  |
|            |                                            | PowerFactory |---------------------------|
|            |                                            |   2024 SP1   | Date:  31. 3. 2024.       |
-----------------------------------------------------------------------------------------------------
-----------------------------------------------------------------------------------------------------
| Load Flow Calculation                     Complete System Report: Voltage Profiles, Grid Interchange |
-----------------------------------------------------------------------------------------------------
|    AC Load Flow, balanced, positive sequence          |   Automatic Model Adaptation for Convergence    No   |
|    Automatic tap adjustment of transformers     No    |   Max. Acceptable Load Flow Error                    |
|    Consider reactive power limits               No    |      Bus Equations (HV)                    1,00 kVA  |
|                                                       |      Model Equations                       0,10 %    |
-----------------------------------------------------------------------------------------------------
-----------------------------------------------------------------------------------------------------
| Total System Summary                                  | Study Case: Study Case        | Annex:      / 6 |
-----------------------------------------------------------------------------------------------------
|        Generation  Motor    Load   Compen-  External             Inter Area  Total    Load   No load |
|                     Load           sation   Infeed                 Flow     Losses  Losses  Losses  |
|          [MW]/   [MW]/   [MW]/   [MW]/   [MW]/                    [MW]/   [MW]/   [MW]/   [MW]/     |
|         [Mvar]  [Mvar]  [Mvar]  [Mvar]  [Mvar]                   [Mvar]  [Mvar]  [Mvar]  [Mvar]     |
-----------------------------------------------------------------------------------------------------
| \pc\VedadMusovic_Lab1DS\Network Model\Network Data\Gracanica                                        |
|           0,00    0,00    0,07    0,00    0,09                    0,00    0,02    0,00    0,02     |
|           0,00    0,00    0,05   -0,18    0,18                    0,00    0,31    0,00    0,31     |
-----------------------------------------------------------------------------------------------------
| Total:                                                                                              |
|           0,00    0,00    0,07    0,00    0,09                            0,02    0,00    0,02     |
|           0,00    0,00    0,05   -0,18    0,18                            0,31    0,00    0,31     |
-----------------------------------------------------------------------------------------------------
```

Figure 14. Complete System Report

The voltage range is now between 0.994 pu and 1.006 pu. This is more than enough to ensure that our network is operating in quality voltage range. Active power losses are reduced after the optimal capacitor placement. They have the value of 0.02 MW. In general, these types of losses are usually associated with the real power dissipation in the system, mostly in components like resistive elements, transformers and transmission lines.

Reactive Power losses are also reduced. They have the value of 0.31 MVAR. The losses are reduced due to choosing the correct value for the capacitor MVAR. These losses occur primarily due to impedance inductance in various parts of the network. Inductive reactance in transmission lines contributes significantly to reactive power losses, particularly over long distances. Transformers also introduce reactive losses due to their magnetizing currents and leakage reactance. Additionally, distribution equipment such as switches, cables, and capacitors can contribute to reactive power losses within the network.

In general, connecting the proper capacitors will affect the voltage range, and ensure that value of voltage at specific bus is much closer to 1 pu, rather than before optimal capacitor placement.

4. Conclusion

In this lab, it was aimed to enhance the performance of the power system by strategically placing capacitors within the network busses. By conducting load flow analysis before and after compensation, we observed significant improvements in voltage profiles and certain reductions in both active (MW) and reactive (MVAr) power losses.

Through proper selection of capacitor values and their placement using the Newton-Raphson method, we achieved optimal results in minimizing losses and improving voltage stability. Both synchronous condensers and static capacitors allowed us to perform optimal capacitor placement process while considering being cost-effective in the process.

The systematic approach involved analyzing network characteristics and load profiles to identify the most critical areas for compensation. By implementing optimal capacitor placement analysis, we successfully reduced both active and reactive power losses, leading to enhanced system efficiency and performance.

The voltage deviations are significantly reduced, ensuring that the network operated within the acceptable voltage range, but this time making the deviation from 1 pu even smaller. Overall, this DIGSILENT project demonstrated the strategic capacitor placement in improving power system operation and efficiency, obtaining more reliable and sustainable electrical networks.

LAB 9 - GENERATING POWER QUALITY DISTURBANCES (MATLAB)

1. Introduction

In Lab 9, we are required to work with different power quality disturbances. We used MATLAB's Simulink. The task was to we to generate:

- Voltage sag,

- Voltage swell,

- Harmonics, and

- Transient.

These are different power quality disturbances, which will be explained.

The theoretical part is initially written for us to understand the concepts in MATLAB Simulation model later on. Different blocks are used, with different block parameters.

The entire process in MATLAB is performed and explained. The conclusion is written in the end. This concludes lab 9, which was about different variations of power quality disturbances.

2. THEORY

The electric power quality disturbances can be classified in terms of:

- **the steady-state disturbance** (that is often periodic and lasts for a long period of time), and

- **the transient disturbance** (that generally lasts for a few milliseconds and then decays to zero).

The first one is less obvious, less harmful, and lasts for a long time, but the cost involved may be very high. The second one is more obvious and harmful, with the costs involved being extremely high. The electric power quality issues include a wide variety of electromagnetic phenomena in power systems. The definition of waveform distortions includes:

- harmonics,

- interharmonics,

- DC in AC networks, and

- notching phenomena.

- Long-duration voltage variations are either **overvoltages** or **undervoltages.** They are usually not the result of system faults, but are caused by load variations and switching operations.

- A **sag**, or **dip**, is a decrease to between 0.1 and 0.9 pu in RMS voltage or current at the power frequency for durations from 0.5 cycles to 1 min.

- A **swell** is an increase to between 1.1 and 1.8 pu in rms voltage or current at the power frequency for durations from 0.5 cycle to 1 min. They are also usually not a result of some fault.

- **Waveform distortion** is defined as a steady-state deviation from an ideal sine wave.

The main types of waveform distortions include:

DC offset, **harmonics**, **interharmonics**, **notching**, and **noise.**

- Notching is a periodic disturbance caused by normal operation of a power electronic device, when its current is commutated from one phase to another.

2.1. Disturbance Types

Switching of reactive loads, transformers or capacitors, transients in the kHz range are created. Phase – neutral transients result from addition of capacitive load. Neutral – ground transients result from addition of inductive load.

Electromechanical switching device interacts with the distributed inductance and capacitance in the AC distribution and loads to create electric fast transients (EFTs). Phase – neutral transients usually are resulting from arching and bouncing contactor.

Harmonics are blamed for many power quality disturbances. They are usually transients. Although transients disturbances may also have high - frequency components, transients and harmonics are different and are analyzed differently.

Transients are practically dissipated within few cycles. A reason for this can be switching a capacitor bank. Harmonics are as well taking place in steady state and are integer multiplies of the fundamental frequency. Also, waveform distortion that produces the harmonics is continuously present or at least for several seconds.

Transformer energization is a transient case results in significant waveform distortion for several seconds. Furthermore, this is known for causing system resonance, especially when an underground cabled system is being fed by the transformer.

- **Nonlinear devices** cause harmonic distortion in distribution system. A nonlinear device is a device in which the current is not proportional to the applied voltage. This means that, when the applied voltage is sinusoidal, the resulting current is distorted. Increasing the voltage by small amounts cause the current to double in value and take a different waveform shape.

Any periodic and distorted waveform can be expressed as a sum of sinusoids with different frequencies. If the waveform is identical from one cycle to the next, we tend to represent it by the sum of pure sine waves in which of each sinusoid is an integer multiple of the fundamental frequency of the distorted wave. This multiple is called a **harmonic** of the fundamental.

- The sum of sinusoids is referred to as a **Fouries Series.** In this approach made, we are able to determine the system resonance to an input that is sinusoidal. The system is analyzed separately at each harmonic using steady-state analysis techniques.

The outputs at each frequency are then combined to form a new Fourier series, from which the output waveform can be determined. Usually, only the magnitudes of the harmonics are needed. When both the positive and negative half cycles of a waveform have identical shapes, the Fourier series has only odd harmonics. Figure 1 represents different types of disturbances.

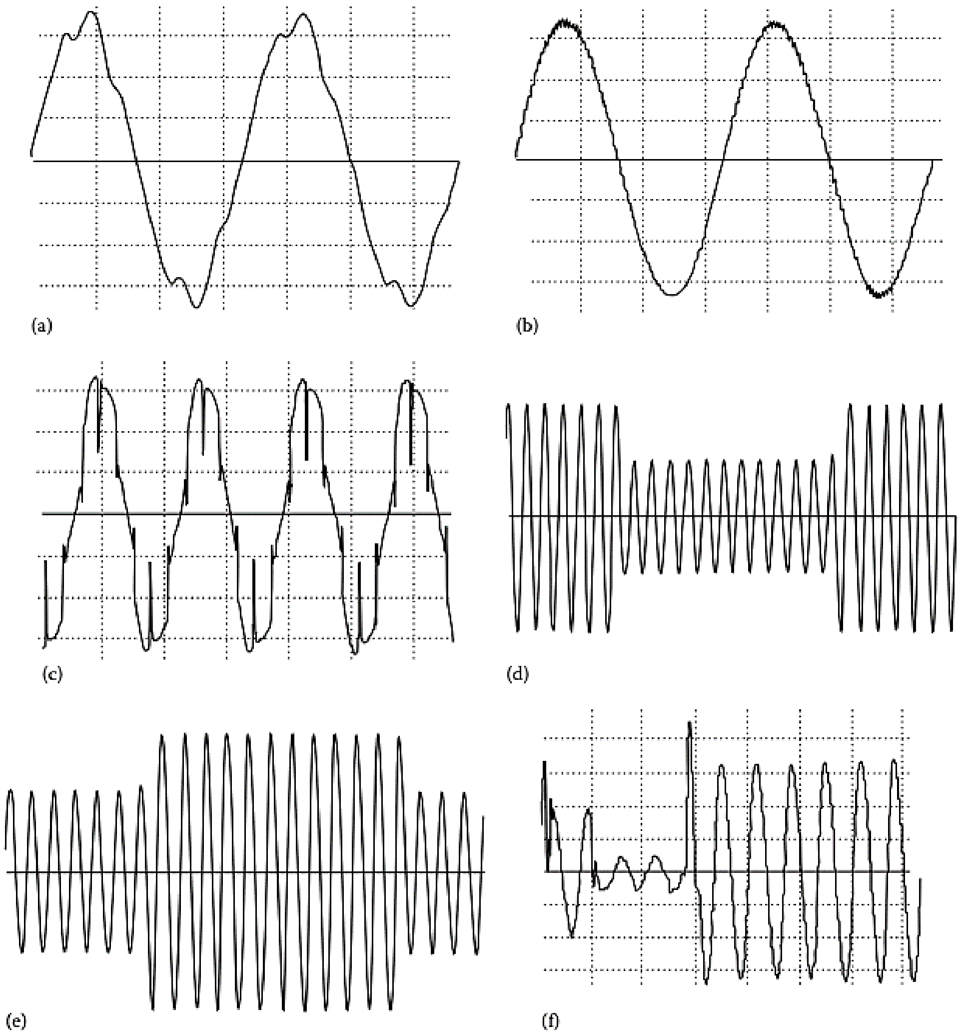


FIGURE 1. Different types of disturbances: (a) harmonic distortion, (b) noise, (c) notches, (d) sag, (e) swell, and (f) surge

Having even harmonics is often an indication that there is something wrong either with the load equipment or with the transducer used to make the measurement. Most nonlinearities can be found in shunt elements, that is, **loads**.

Nonlinear loads appear to be sources of harmonic current and injecting harmonic currents into the power system. For most of harmonics study, we treat harmonic - generating loads simply as harmonic current, that is, harmonic current generators.

Harmonics cause power losses in distribution systems. Harmonics also cause interference in communication circuits, resonance in power systems, and abnormal operations of protection and control equipment. Additionaly, various transients are shown in Figure 2.

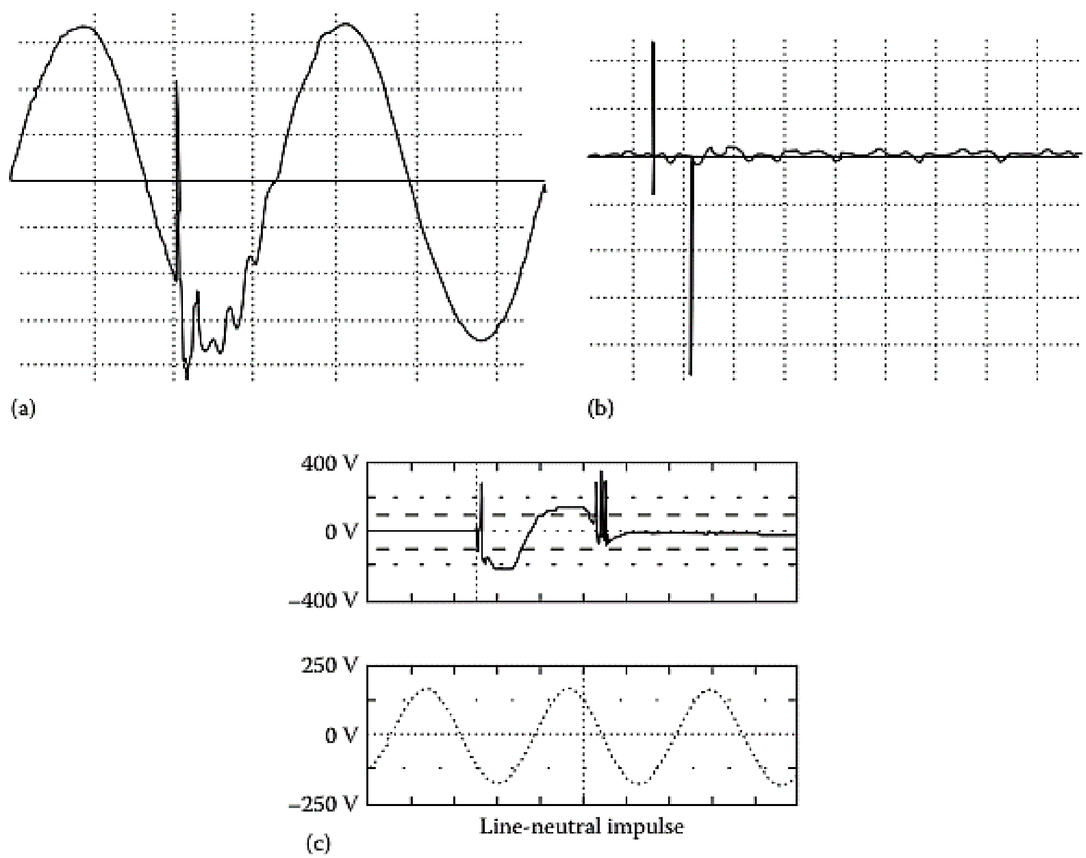


FIGURE 2. Different Transient Types in Distribution Systems

3. Voltage Sag

Voltage dips, or sags, are brief moments when the electricity flowing through a system takes a bit of a dive, dropping below its usual level.

They are like tiny blips, lasting just milliseconds to a few seconds, before things get back to normal. These dips can happen for various reasons—maybe there is a fault in the power grid, a big motor starts, or there is a fault in a nearby electrical network. Additionally, they can cause damage to the other equipment in the distribution system.

Voltage dips are caused by different factors such as thunderstorms, earth faults, short circuits, motor starting, pumps, an mills.

These disturbances temporary decrease voltage magnituds, leading to an energy deficit that affects a wide range of equipment. The consequences of voltage dips include disruptions, blinking of lightbulbs, disturbances in thermal processes, machine breakdowns, shutdowns, and more.

Figure 3 shows this circuit, modelled in Simulink.

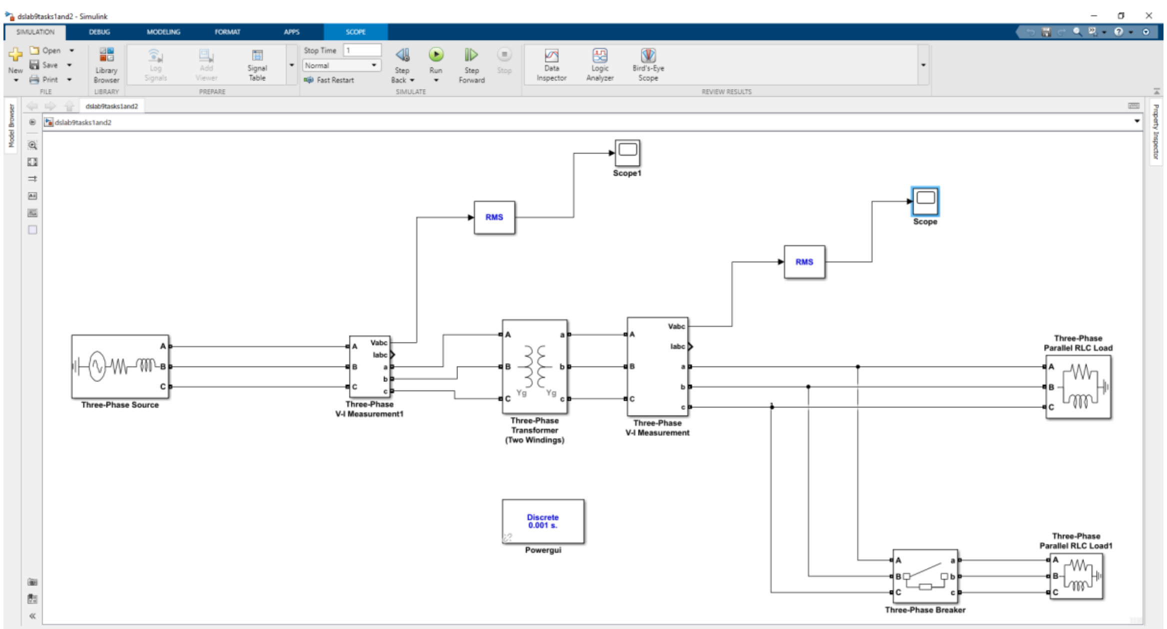


FIGURE 3. Voltage Sag and Voltage Swell Circuit in Simulink

Simulation Stop time is set to 1 second. Powergui is set to discrete: 0.001 seconds. The blocks used are: Three – Phase: Source, Load, V – I Measurement, Breaker, as well as different scopes and rms blocks. Figure 4, Figure 5, Figure 6 and Figure 7 show Block Parameters.

With RMS block from: Simscape / Electrical / Specialized Power Systems / Sensors and Measurements the following observations are made.

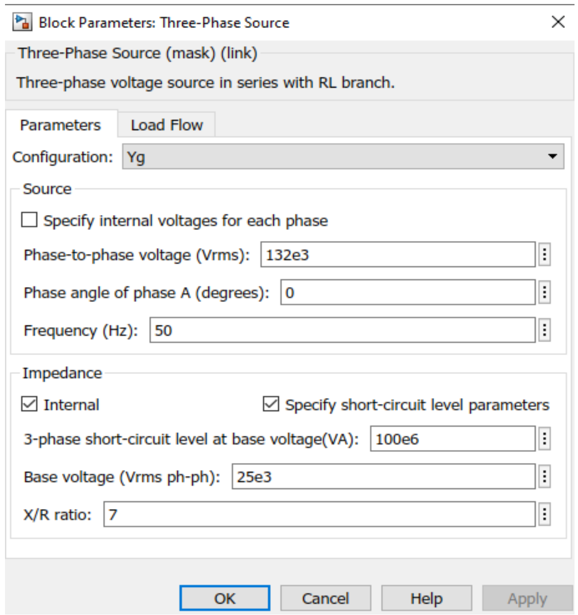


FIGURE 4. Three – Phase Source Block Parameters

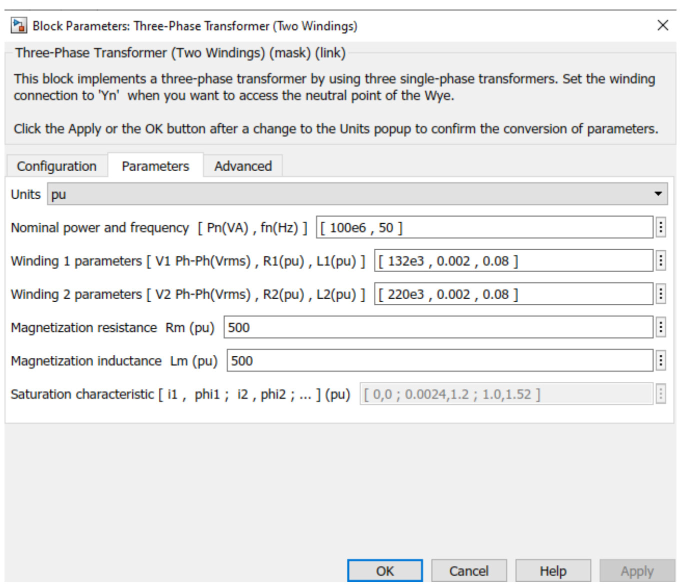


FIGURE 5. Three – Phase Transformer Block Parameters

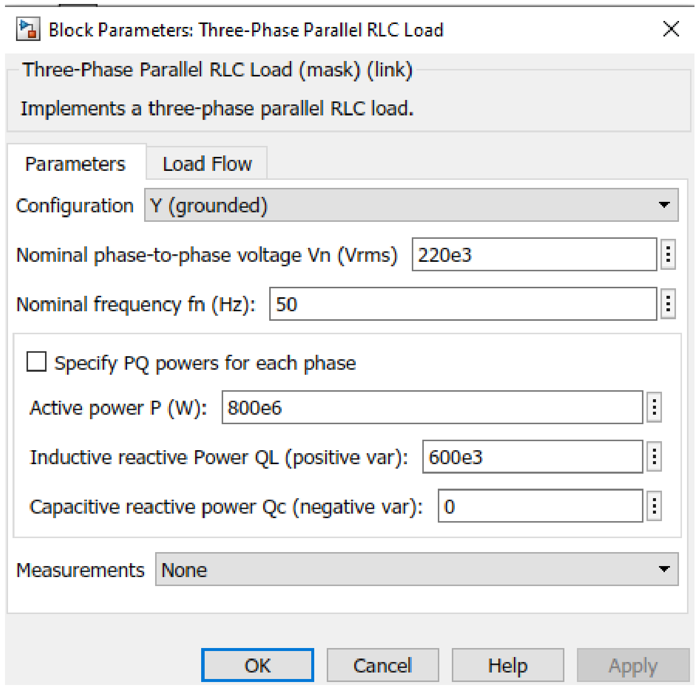


FIGURE 6. Three – Phase Parallel RLC Load Block Parameters

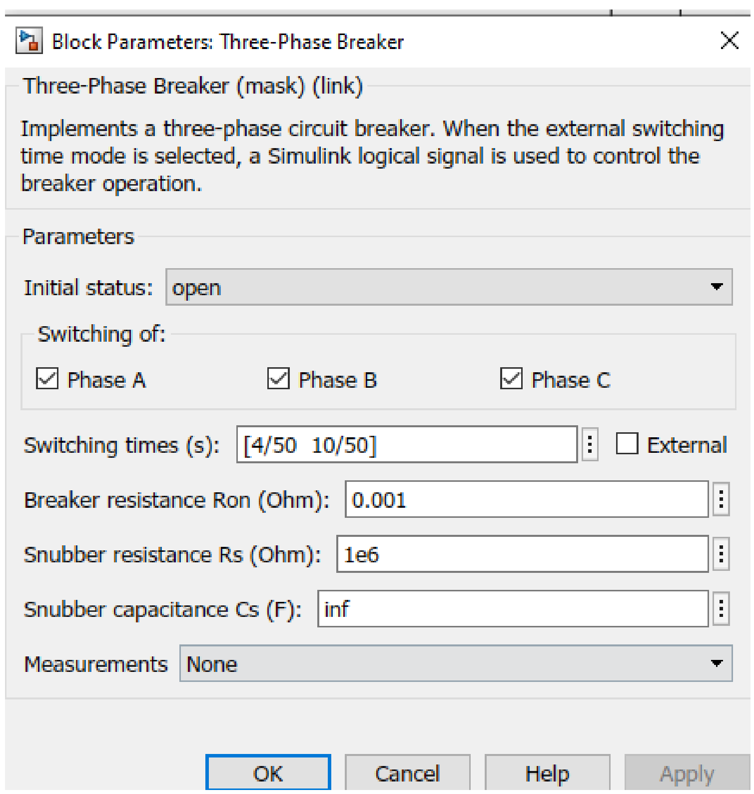


FIGURE 7. Three – Phase Breaker Block Parameters

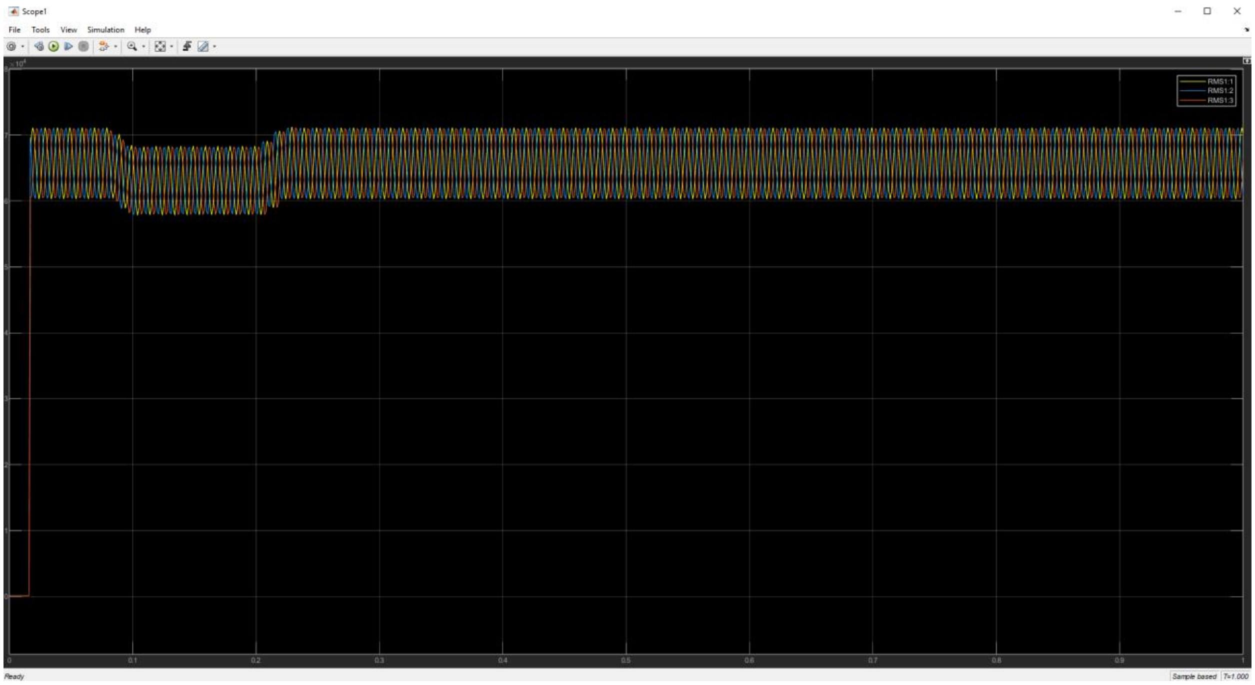


FIGURE 8. Scope1: Source

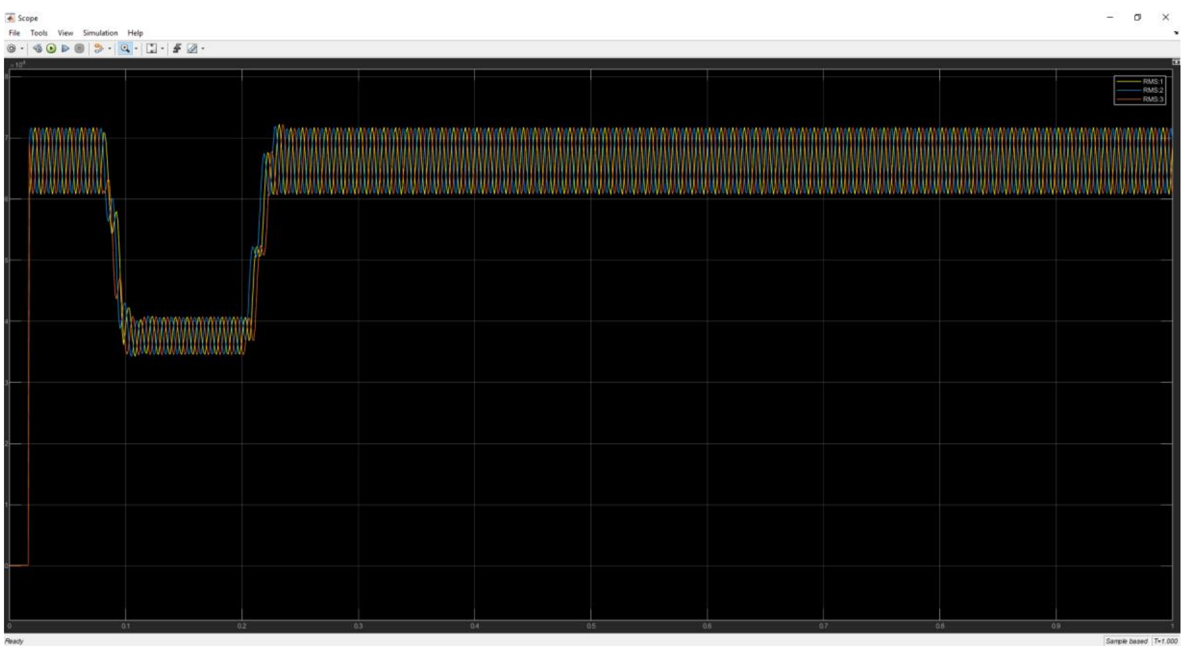


FIGURE 9. Scope: Output - Transformer

If we put RMS block from DSP System Toolbox we observe the shape without the three phases:

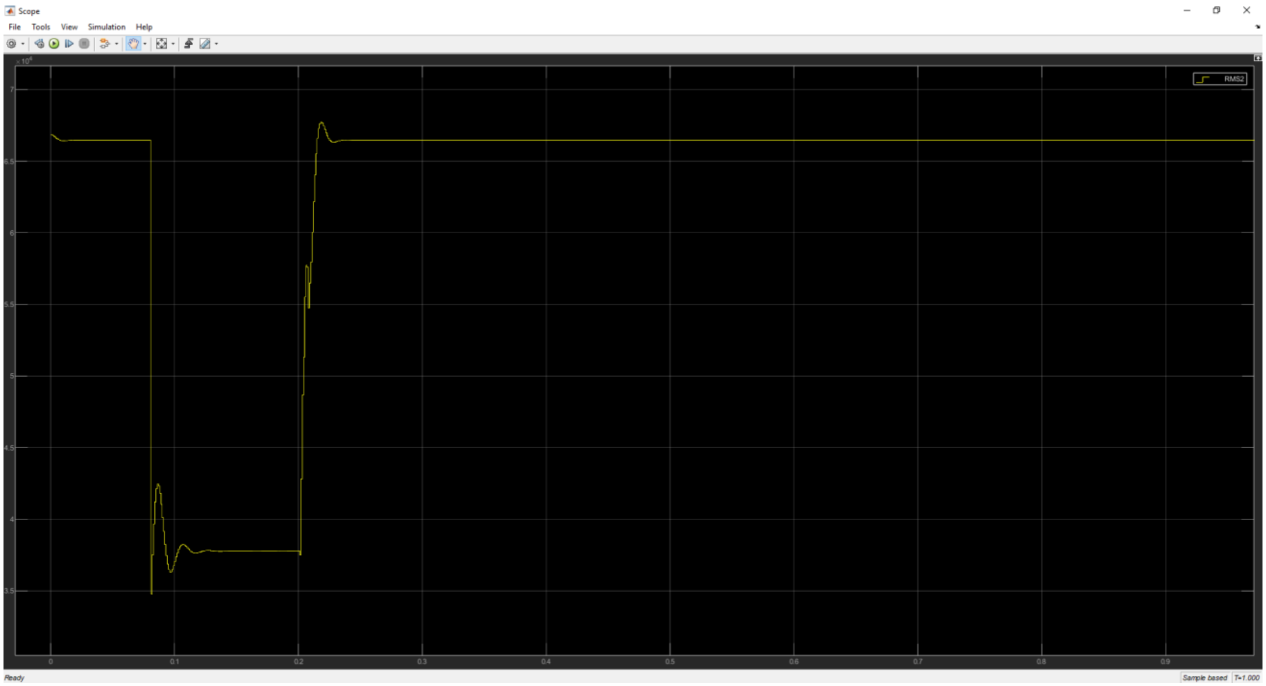


FIGURE 10. Scope: Output - Transformer for DSP Library RMS

As mainly observed in Figures 8 and Figure 9, we see that the voltage dips from about 0.1 to 0.2 seconds. For the source, the dip is existent, but significantly smaller that for the output, on the transformer part of the Simulink circuit.

The dip last for more than one cycle (approximately 0.1 s to 0.2 s).

Our period is the stop time of 1 second. Finally, on these graphs we observe all three phases behaving as a sinusoidal wave, experiencing distortions during the dip itself and at the beggining of our period, since the switch is initially open.

4. Voltage Swell

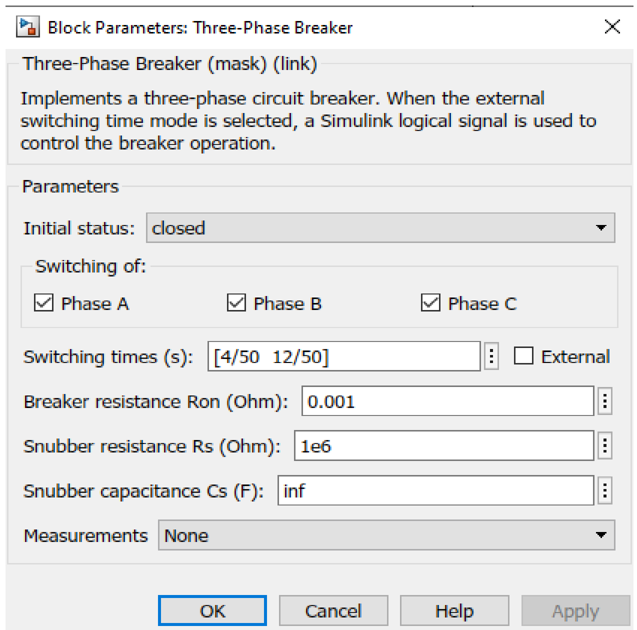


FIGURE 11. The only Block Parameters that has changed. The Switch is now initially closed.

For the voltage swell, the only parameter that has changed is the breaker itself, which is now initially open. Our break time is slightly increased additionally. Simulation Stop time is 1 second.

Powergui is set to discrete: 0.001 seconds. The blocks used are: Three – Phase: Source, Load, V – I Measurement, Breaker, as well as different scopes and rms blocks.

Voltage swell is the opposite of the voltage sag, where the voltage magnitude increases for a brief duration. It occurs when the voltage rises significantly above the normal level and then returns to the normal level. They can happen for various reasons, like when capacitor banks kick in, reactors are disconnected, or there are errors in compensation and balancing of the network. These surges can last only for a few seconds, but can cause big problems.

Sometimes, it is because a big load got disconnected suddenly or because there are devices in the system that change with the power flow. These surges can mess with insulation and cause sparks, leading to more faults. When a swell hits, the voltage level goes way above normal for a short time. Unlike dips, which are quick blips, swells have a wider impact because they last longer and affect more cycles of the electrical flow.

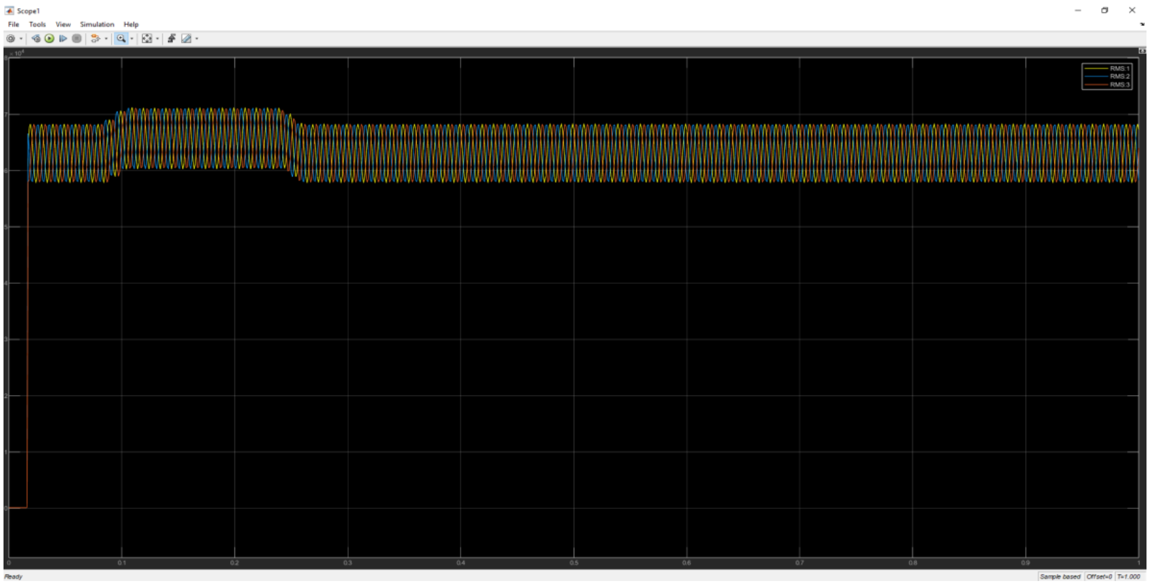


FIGURE 12. Scope1: Source

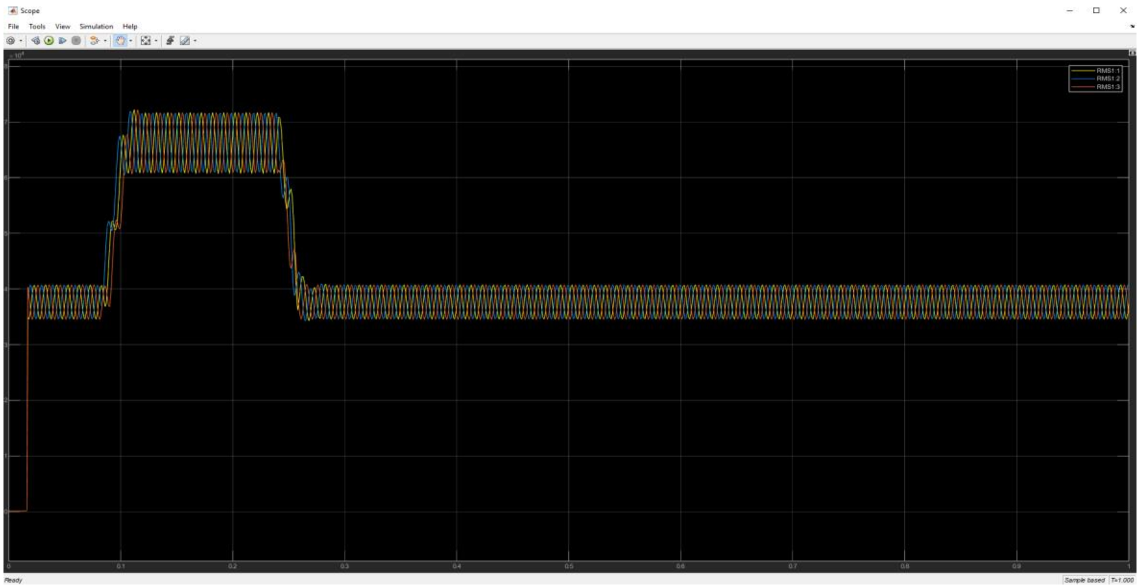


FIGURE 13. Scope: Output - Transformer

If we put RMS block from DSP System Toolbox we observe the shape without the three phases:

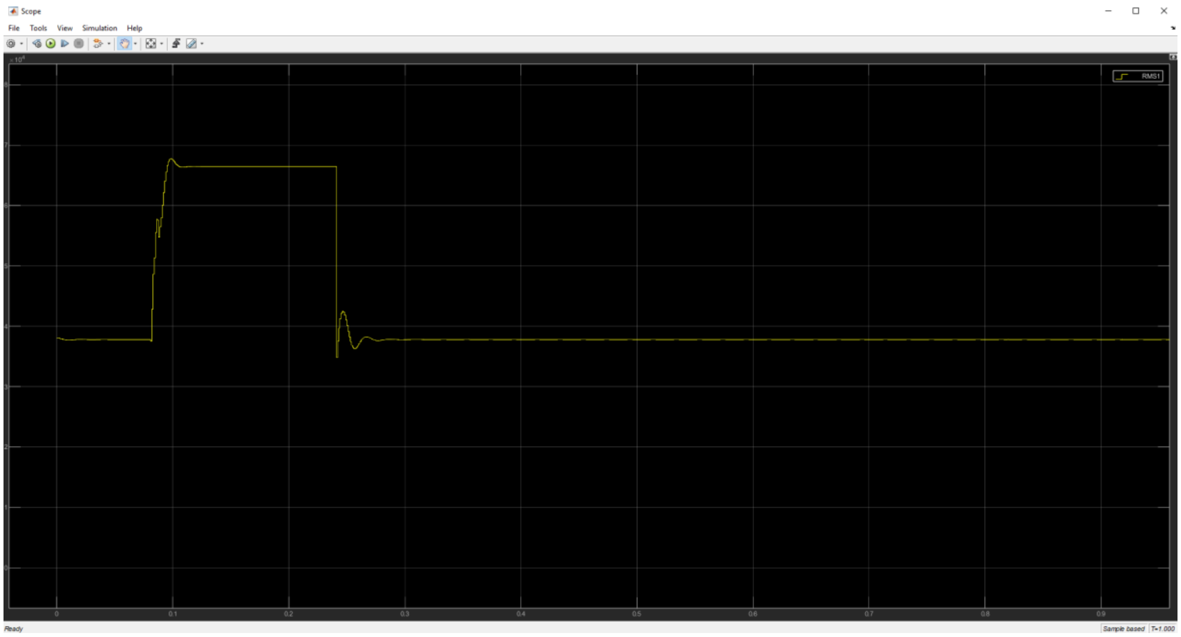


FIGURE 14. Scope: Output - Transformer for DSP RMS

As seen in Figures 12 and 13, voltage swells are indeed typically longer in duration, compared to voltage dips. Source voltage does not exhibit that major of a rise during the period when the output voltage exhibits a significant rise. Our period is the stop time of 1 second

This lasts from approximately 0.1 to 0.25 seconds, longer than the voltage dip was. We observed this by setting the breker block parameter to initially closed.

Finally, on these graphs we observe all three phases behaving as a sinusoidal wave, experiencing distortions during the swell itself and at the beggining of period, since the switch is initially closed.

5. Harmonics

in this system, three phase 440V supply is given to three phase diode bridge. Voltage and current measurement is given to both AC and DC side of the bridge. As non linear load is a source of harmonics, harmonics can be observed at the source current.

This circuit is modelled in MATLAB's Simulink, using the following components: Three – Phase: Source, V – I Measurement; Universal Bridge (Diode), Scopes, Voltage Measurements, Current Measurements, Scopes, topped by Series RLC Load. Powergui is set to Continuous.

Simulation stop time is put at 0.2 seconds.

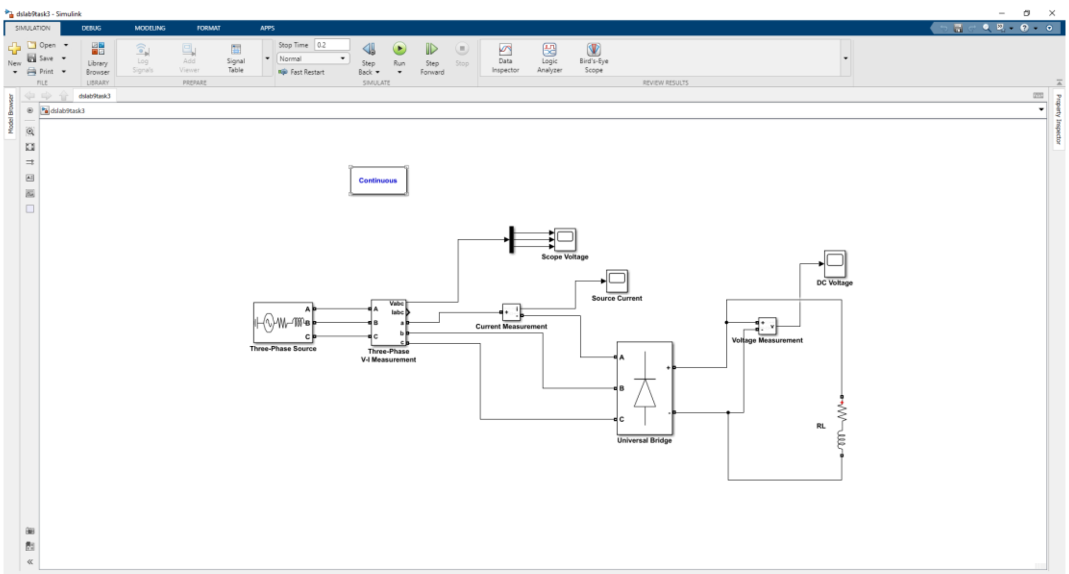


FIGURE 15. Harmonic Circuit in Simulink

Nonlinear load causes harmonic distortion in a distribution system. A nonlinear device is a device in which the current is not proportional to the applied voltage. This means that, when the applied voltage is sinusoidal, the resulting current is distorted. Increasing the voltage by small amounts cause the current to double in value and take a different waveform shape. In the case of harmonics, the key characteristic is the distortion of current. Nonlinear loads are responsible for this distortion because the current they draw does not have the same waveform as the voltage supplying them.

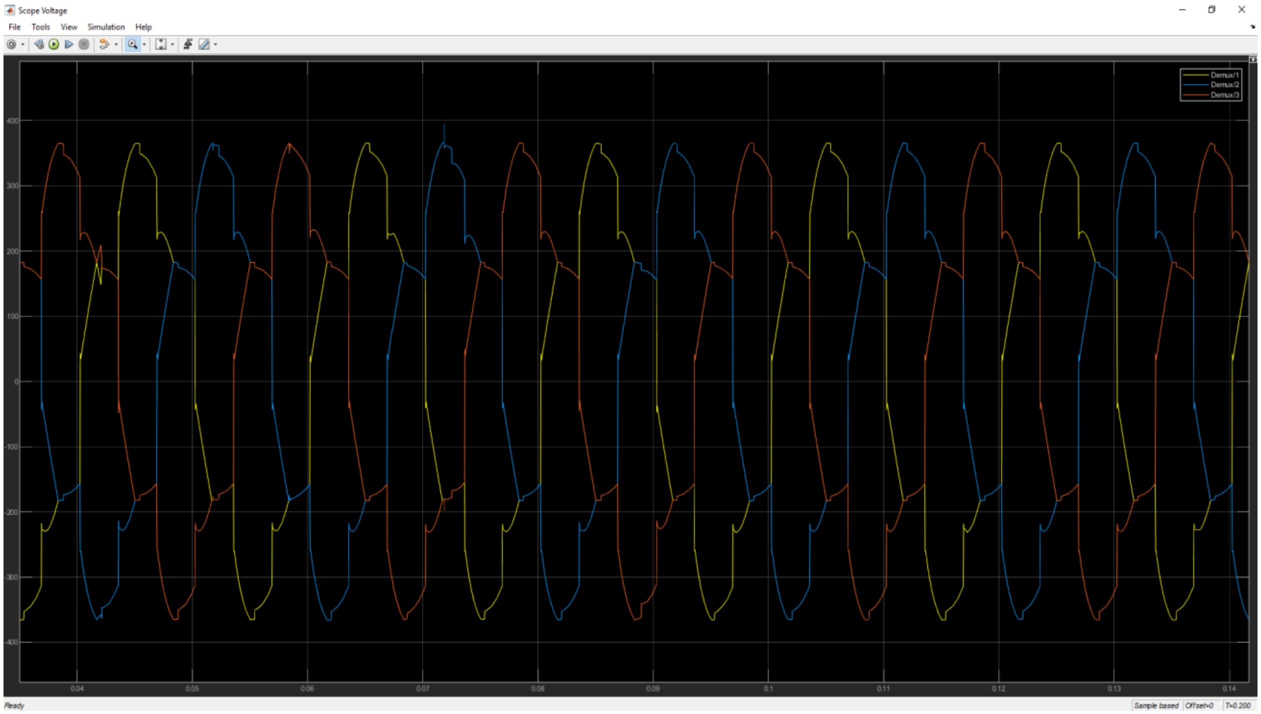


FIGURE 16. Three – Phase Voltage

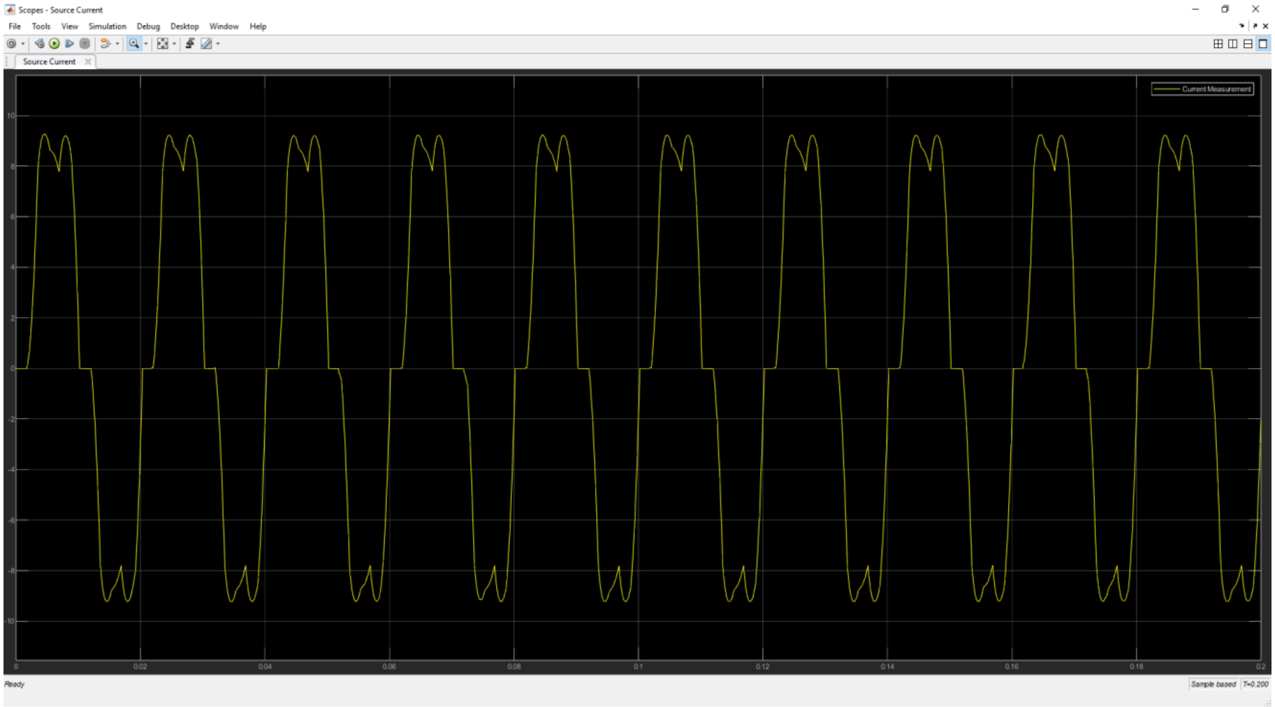


FIGURE 17. Source Current Measurement

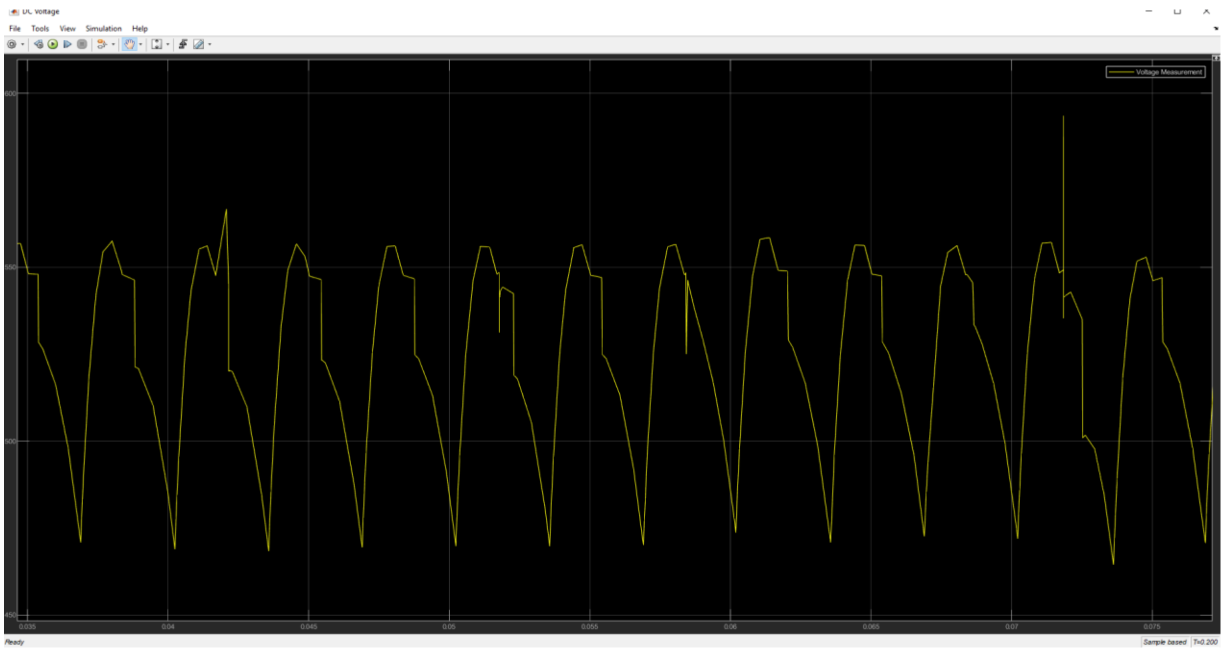


FIGURE 18. DC Voltage Measurement

As already discussed in theoretical parts, which included Figure 1, we observe clear harmonics in all of our scopes. This is due to the presence of nonlinear loads.

Figure 17 depicts our current. Harmonics caused by nonlinear loads are best represented by current because these loads disrupt the balance between voltage and current in electrical systems. Unlike linear loads, which draw current in proportion to the applied voltage (resulting in a sinusoidal waveform), nonlinear loads draw nonsinusoidal current waveforms. This means that even if the voltage remains sinusoidal, the current waveform becomes distorted due to the nonlinear relationship between voltage and current.

Nonlinear loads, such as those found in electronic devices, draw current in short, intense bursts, causing rapid changes in current magnitude and direction. These abrupt changes in current create harmonic distortion, introducing additional frequency components that are integer multiples of the fundamental frequency. Representing harmonics in terms of current allows for a more accurate assessment of their impact on electrical systems and equipment. Since current is the actual flow of electric charge through a system, it directly reflects the presence and magnitude of harmonics generated by nonlinear loads.

6. Transients

Transient Analysis Circuit is correctly modelled in Simulink. It is done by using the following components: Three – Phase: Source, Breaker, V – I Measurement and Parallel RLC load. Additionally, Continuous Powergui is used with scopes and Three Capacitor banks put in delta connection (Series RLC Load), with the stop time being 0.2 seconds.

Three phase load is connected to 33kV source and delta connected capacitor bank is energized by using a circuit breaker. Switching transients can be observed at current scope.

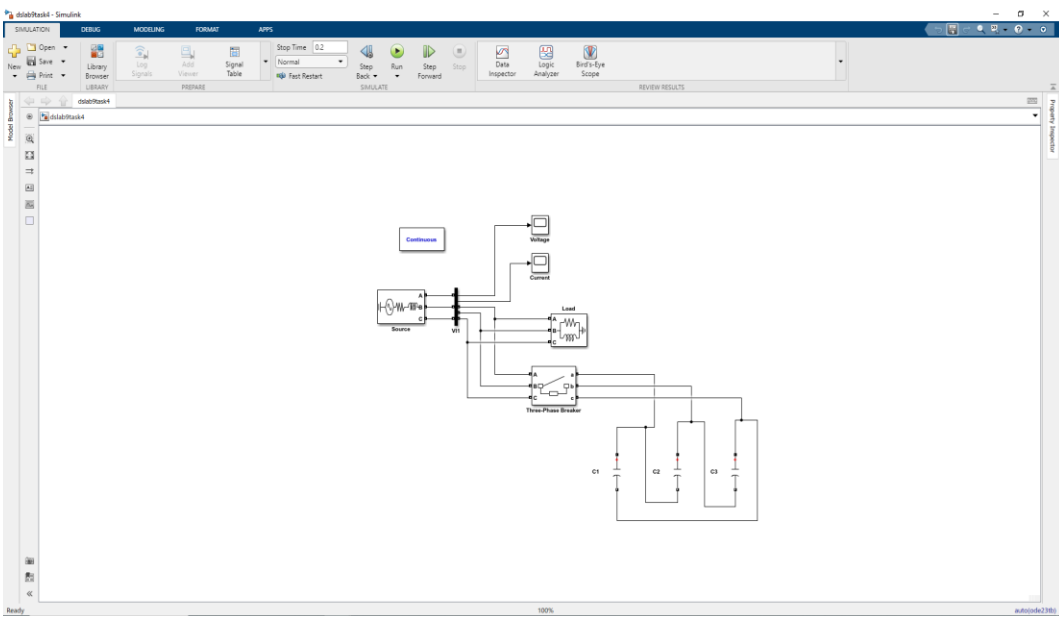


FIGURE 19. Transient Analysis Circuit in Simulink

Transients, also known as voltage spikes or surges, are short-duration, high-amplitude deviations from the normal voltage waveform. Transients are a faster voltage change than, for example, voltage dips.

During the high -amplitude periods, amplitude goes pretty wild and after mention period, it quickly returns to its general state before the period. The consequences of transients include equipment breakdowns, disruptions in electronics, control systems, computers, and drives. Transients that break through the zero-crossing point of the voltage waveform can also cause disturbances in synchronization devices that rely on the zero-crossing for triggering.

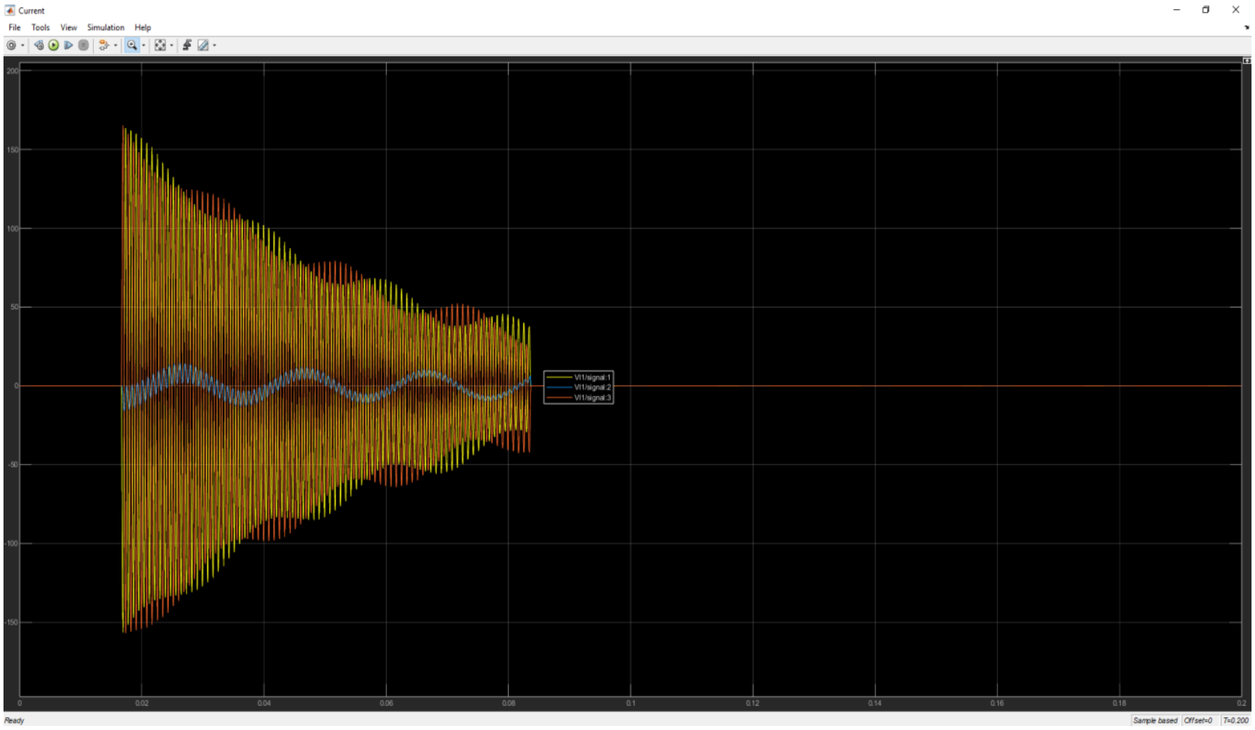


FIGURE 20. Transient Current Scope

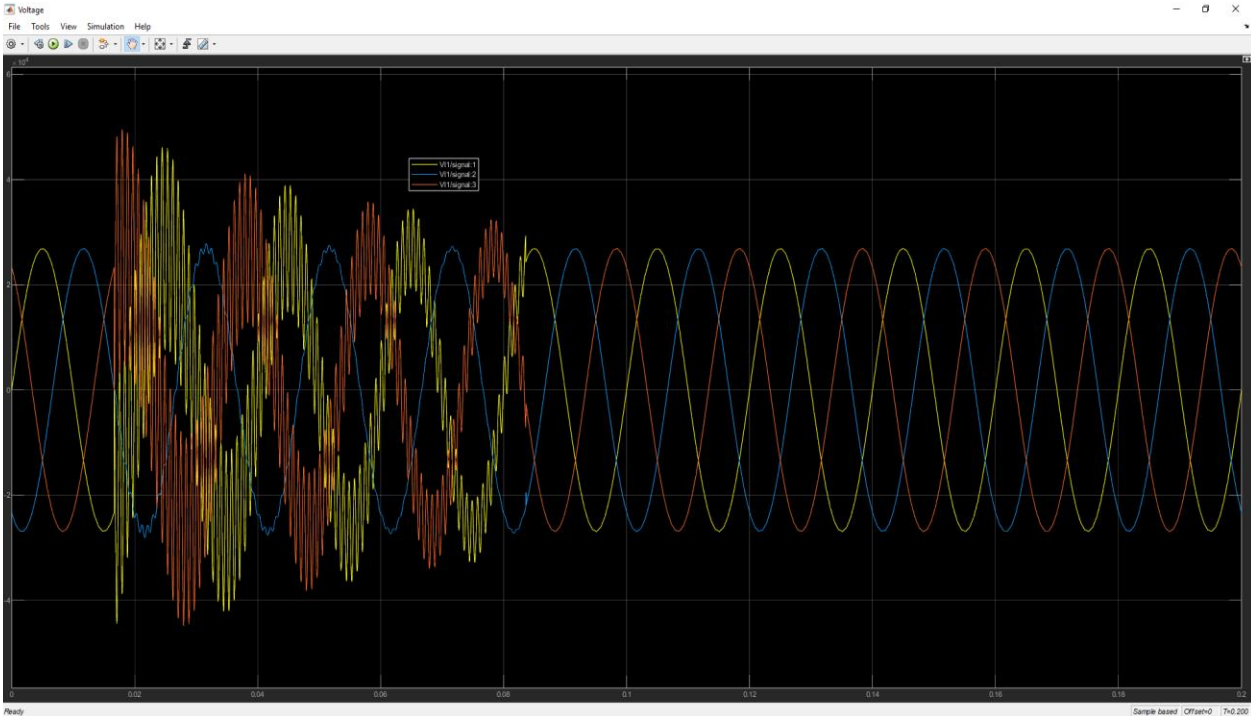


FIGURE 21. Voltage Scope

The abnormal patterns in mainly current, but in the voltage as well, although not that drastic, are depicted. Figure 20 and Figure 21 represent this on their individual scopes.

In our specific case, these spikes caused rapid fluctuations in voltage phases because they carried enough energy to really shake things up while the system was running. They caused both positive and negative voltage peaks and stuck around for about 0.05 seconds. Similarly, while the currents might be rising across all phases, the voltage experience some deviations during these periods.

Even though there is a three-phase breaker in place, which protects from overcurrent situations by interrupting the flow of electricity when necessary, it may not respond quickly enough to prevent the initial surge of current caused by the transient event.

The event may include an increase in the current drawn by the equipment due to the sudden voltage fluctuation. The characteristics of the transient event, such as its duration and magnitude, can influence the response of the electrical system and the behavior of the current.

7. Conclusion

In Lab 9, we experimented with the power quality disturbances using MATLAB's Simulink. Through our simulations, we explored various disturbances such as voltage sags, swells, harmonics, and transients, each with its unique characteristics and effects on electrical systems.

We learned that these disturbances can have significant impacts, from causing equipment malfunctions to disrupting sensitive electronics and control systems. By studying these phenomena, we gained insights into the complexities of power systems and the importance of maintaining high-quality electrical supply.

Through our theoretical understanding and practical simulations, we not only identified the different types of disturbances but also observed their behavior and effects in real-world scenarios.

The use of simulation tools like Simulink allowed us to visualize and analyze these disturbances in a controlled environment, helping with understanding their effect on power system operation.

LAB 10 - HARMONICS ANALYSIS (POWERFACTORY)

1. Introduction

In this lab, for our modelled network in the DIGSILENT, we should perform the harmonics analysis by inserting an additional nonlinear load to your network. We will write the report. The task and the harmonics are described. The network, its parameters, and graphs **before the nonlinear load is inserted** to the network are shown first. After this, we will show our network, its parameters, and graphs **after nonlinear load is inserted** to the network.

2. Theoretical

Harmonics are additional frequencies generated when a periodic waveform deviates from its ideal form, often occurring as multiples of the fundamental frequency. They arise due to nonlinear operations or distortion in a signal, enriching its tonal characteristics. Overall, harmonic analysis is crucial for assessing power quality and ensuring efficient operation of electrical systems.

The analysis of power quality involves examining the harmonic content of voltages and currents, which can be done in either the frequency domain or the time-domain using Fourier analysis. DIGSILENT offers various functions for harmonic analysis, including the Harmonic Load Flow and Frequency Sweep. The Harmonic Load Flow function calculates harmonic indices related to voltage or current distortion caused by non-linear loads.

It analyzes steady-state network conditions at each frequency defined by harmonic sources. This function can also assess flicker disturbance factors in wind turbine generators according to IEC standards. Frequency Sweep, on the other hand, performs continuous frequency domain analysis, useful for calculating network impedances and identifying resonance points. Both functions can consider contingencies to analyze network behavior under different fault cases.

3. Case I – Before the Nonlinear Load is inserted

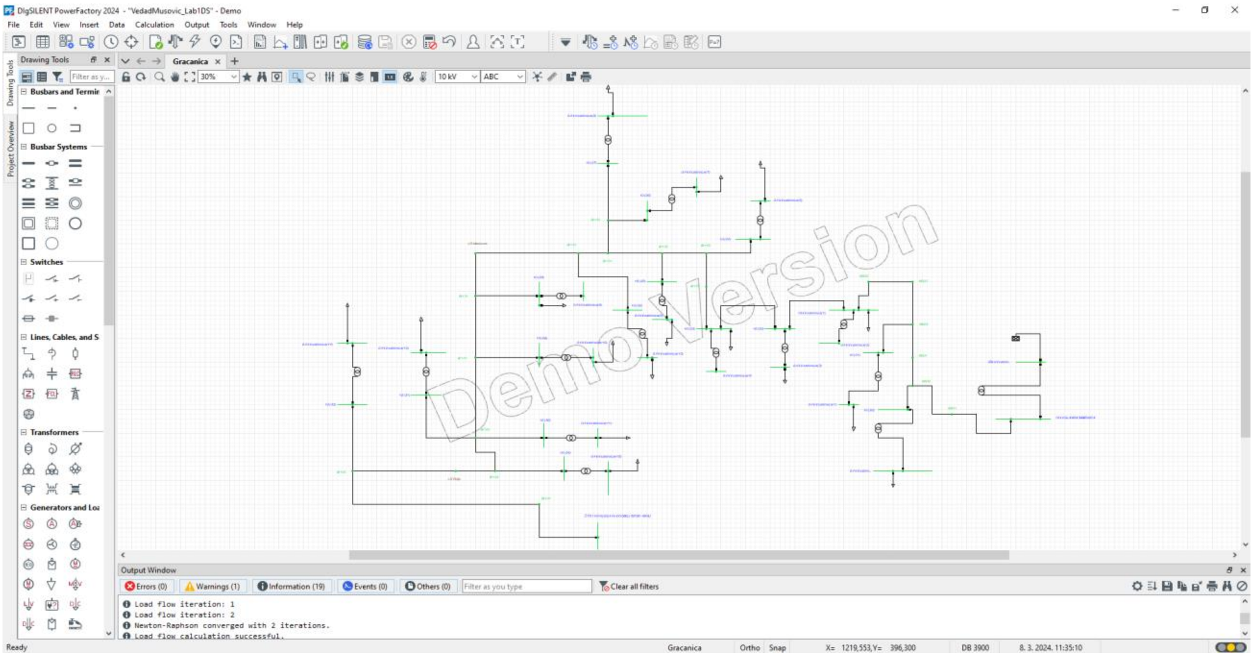


Figure 1. The Original Network

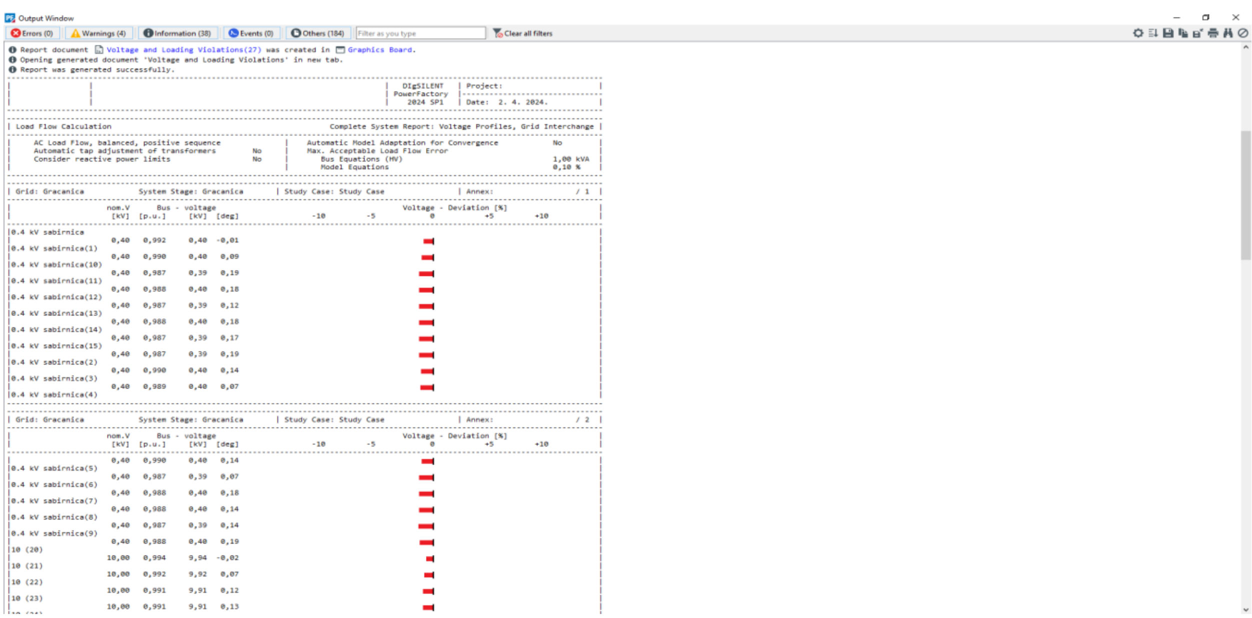


Figure 2. Complete System Report

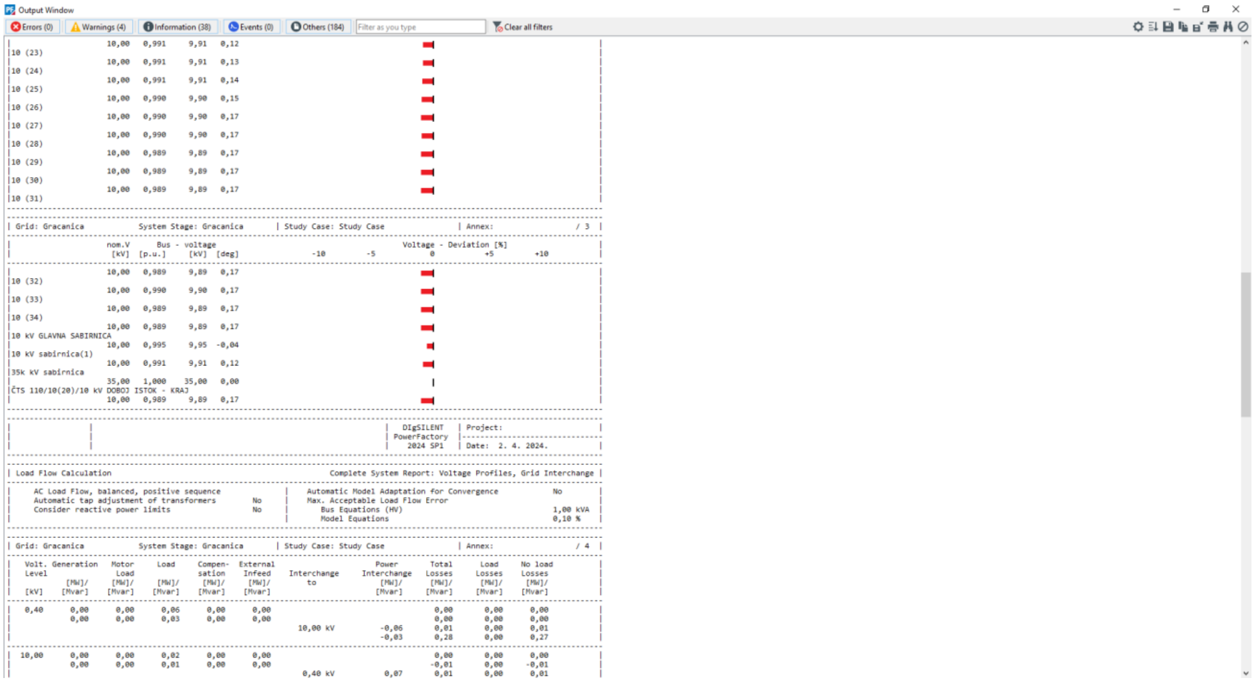


Figure 3. Complete System Report

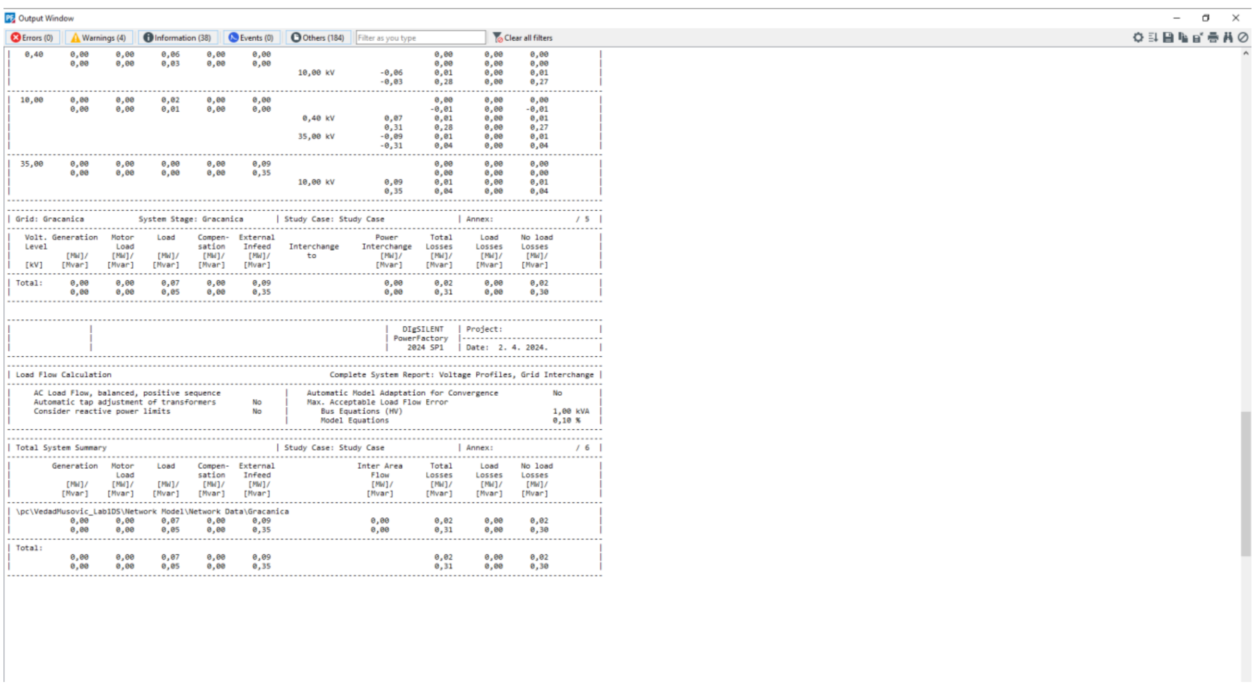


Figure 4. Complete System Report

The first case to look at is the case before the nonlinear load is connected to the network. In here, a regular power flow analysis will be performed. It will converge successfully in 2 iterations. Voltage and loading conditions for all relevant controllers are satisfied. This means that all voltages in the network are close to 1 pu. Complete system report shows this.

We also obtain the necessary information about losses in the network. “Kruta mreza” is our external grid used as reference. Voltage deviations are very small, as shown in complete system report. They are all less than 5%.

The Harmonic Load Flow Analysis is performed the following way:

1. Enter Calculation Tab on the upper menu

2. Select Power Quality and Harmonics Analysis

3. Choose Harmonic Load Flow

After that, the window, shown in Figure 5 will appear:

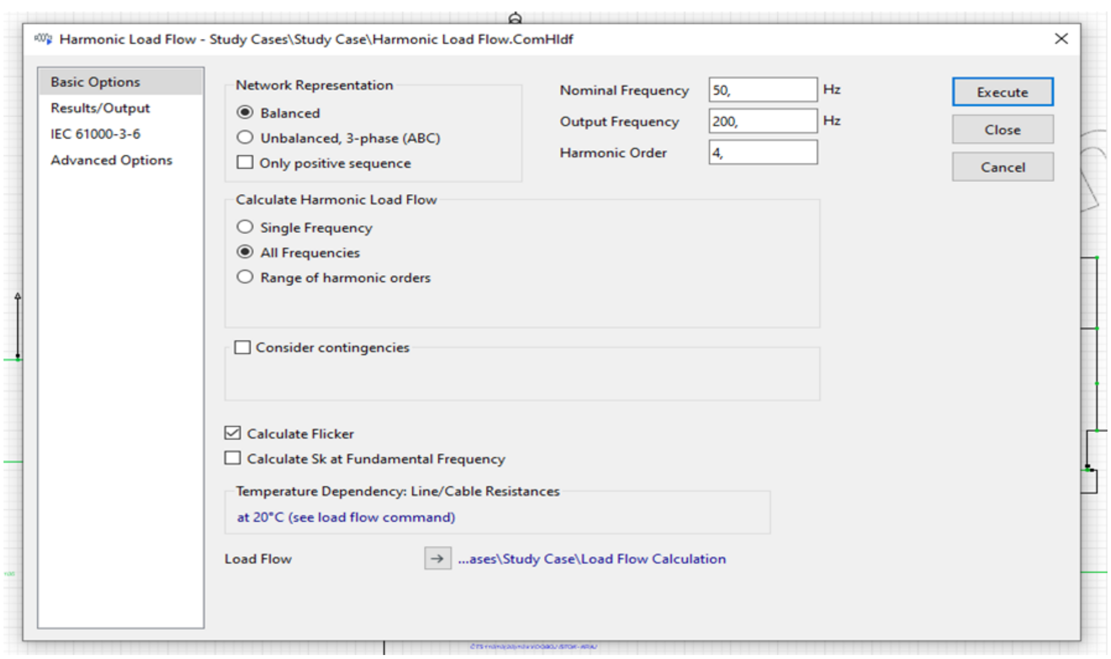


Figure 5. Setting up the Harmonic Load Flow

The network is shown using the balanced representation. Nominal frequency is 50 Hz. This is our operating frequency for the whole network. Output frequency is set to 200 Hz. Harmonic order is calculated to be 4 (Figure 5).

Harmonic Order is the harmonic order equivalent of the Output Frequency. The Harmonic Order multiplied by the Nominal Frequency always equals the Output Frequency. Both floating-point and integer values are valid as inputs. IEC 61000-3-6 protocol is used, with ensurance that our Load Flow Calculation in Study Case is selected for the load flow data.

After this, we will get a confirmation in the output window that our Harmonic Load Flow Analysis was executed successfully. Control conditions for all controllers of interest are fulfilled.

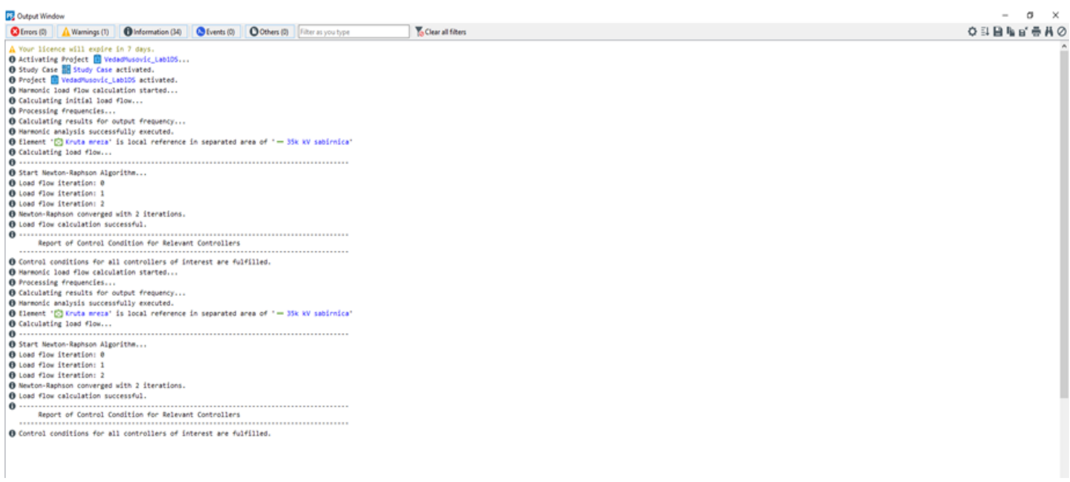


Figure 6. Output Window – Harmonic Load Flow

If were to generate Harmonic Load Flow Tubular Report for our tubular reports, we do these steps:

1. Enter Output Tab on the upper menu

2. Select Power Quality and Harmonics Analysis

3. Choose Harmonic Load Flow Tubular Reports

In order to generate reports, we need to set the harmonic distortion limits. In this case, a range between 0 and 100 kV. Once again, the standard used is IEC-61000-3-6 (2008). This protocol gets its category set to Voltage – MV (1 kV to 35 kV) for 0 kV and Voltage – HV-EHV (above 35 kV) for 100 kV limit. The Harmonic distortion (HD) violations report shows no violations, since we have not entered the nonlinear load in this case.

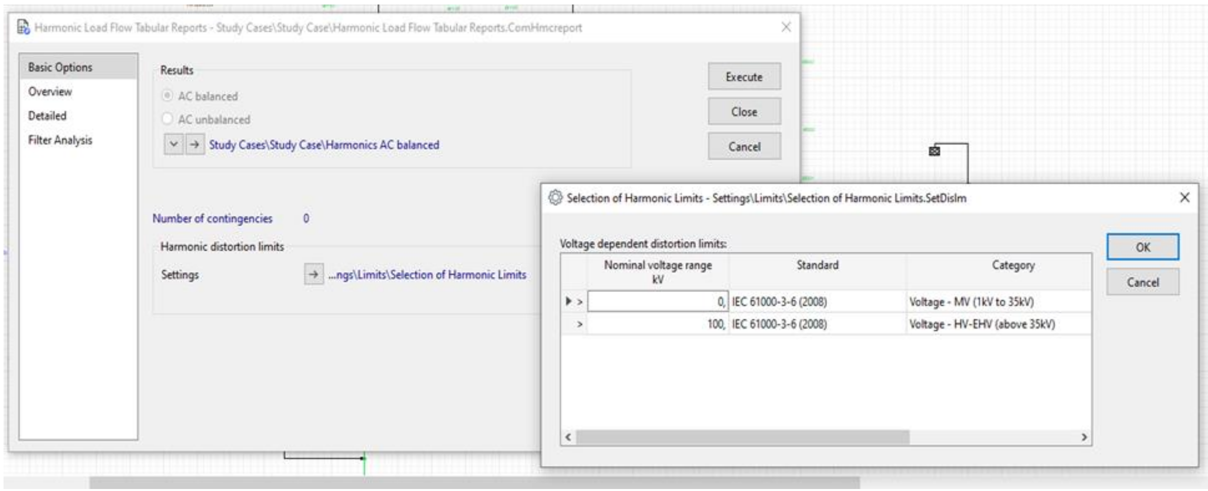


Figure 7. Generating Harmonic Distortions Violation Report & setting their Limits

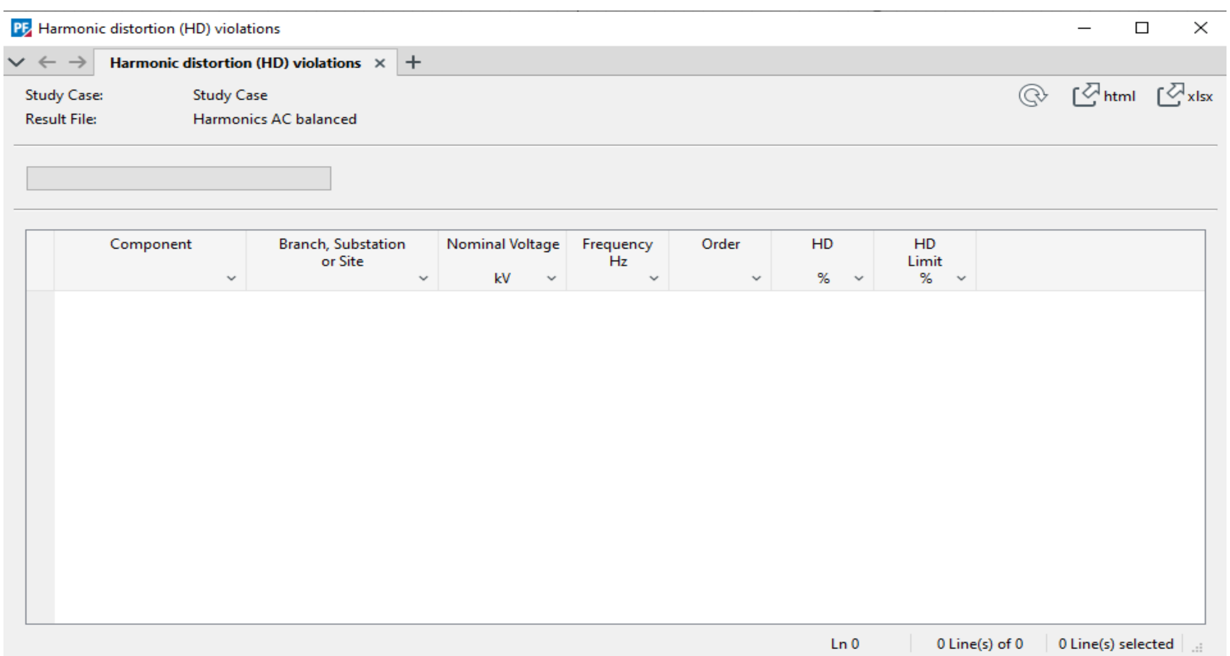


Figure 8. Harmonic Tubular Report – No Harmonic Distortion Violations

4. Case II – Inserting the Nonlinear Load

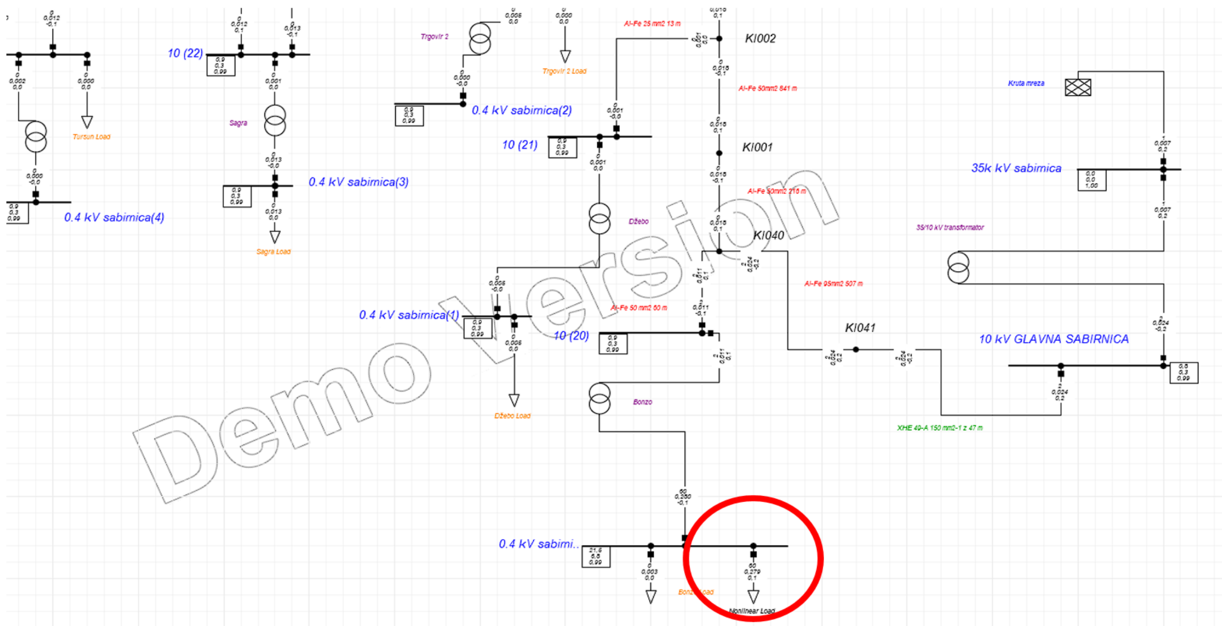


Figure 9. The Network after implementing a Nonlinear Load

The second case involves performing a Harmonic Load Flow Analysis, after implementing a nonlinear load inside the network.

A nonlinear load is placed at 0.4 kV sabirnica, at Bonzo transformer, 10(20) sabirnica, after Al-Fe 50mm2 60m overhead line. Its value is 0.08 MW for active and 0.025 MVAR for reactive power.

For the other data, the load is balanced and its voltage is 1 pu. The complex MVA power also had to be set in order to perform the analysis. We entered 0.0838 as the value for MVA complex power.

For IEC 61000 standard, we are going to Power Quality / Harmonics on the left side of the General Load window, and switching Harmonic Currents to Harmonic Sources. The harmonic source type will we set to IEC 61000 for the Harmonic Load Flow to be performed.

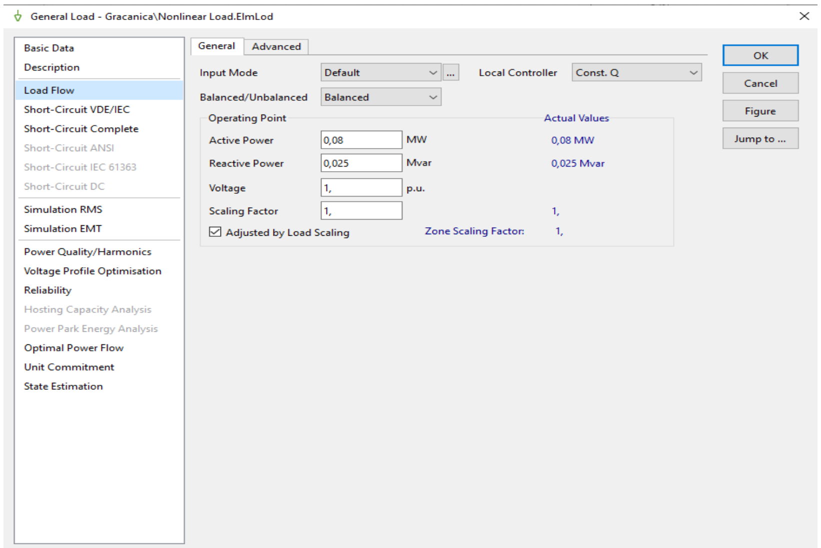


Figure 10. Nonlinear Load Parameters

In the coming step, we chose balanced harmonic sources and identified various different harmonics, each with its respective distortion percentage. I have gone for variety of values, so the wide range can be covered and for correct ones to be selected. It is crucial to note that in a three phase system, only odd harmonics will be generated, and multiples of three will not be present.

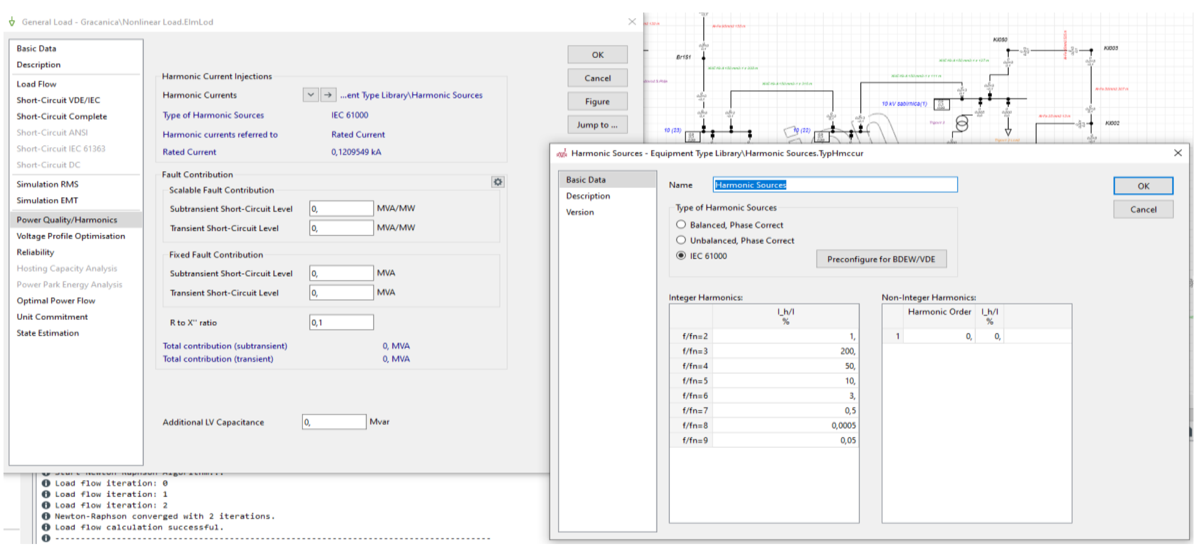


Figure 11. General Load / Harmonic Source Parameters

After setting up the parameters for the non-linear load, the next step is to perform a harmonic load flow analysis to calculate and obtain the results for the busses in our network. This analysis helps determine the harmonic voltage and current levels at each busbar, considering the presence of non-linear loads and their harmonic components.

Harmonic Order is the harmonic order equivalent of the Output Frequency. The Harmonic Order multiplied by the Nominal Frequency always equals the Output Frequency. Both floating-point and integer values are valid as inputs.

IEC 61000 protocol needs to be followed in order to obtain these results. Thus, when defining the load, we enter that as our protocol. For a given harmonic order, a current and voltage superposition arising in the network produced by all phase correct sources and each IEC source is computed.

For each location the magnitude of all phase correct contributions (m = 0) is taken into account, but additionally, for each location, the current (or voltage) arising at that location from each IEC source (m = 1,2...N) is summed using the second summation law (according to IEC 61000-3-6).

The Harmonic Sources type set to option IEC 61000 allows the definition of integer and non-integer harmonic current magnitude injections. It should be noted that in order to execute a harmonic load flow according to IEC 61000-3-6, at least one harmonic source in the network must be defined as IEC 61000.

Alpha Exponent Value	**Harmonic Order**
1	h < 5
1.4	5 <= h <= 10
2	h > 10

Table 1. IEC 61000-3-6 Summation Exponents According to Harmonic Order

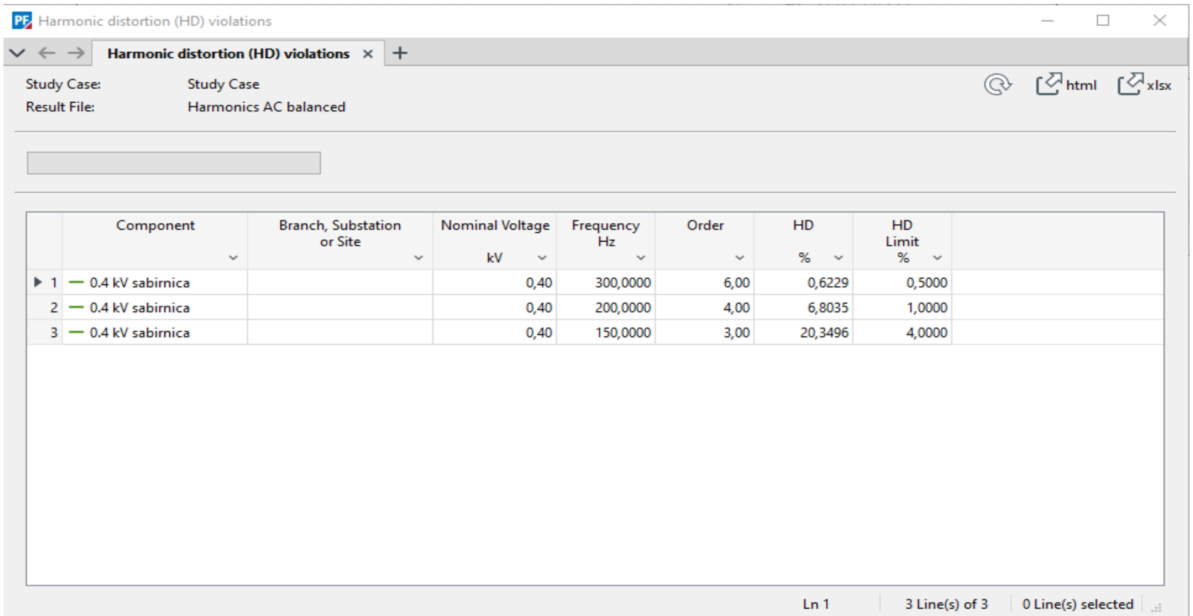


Figure 12. Harmonic Distortion (HD) Violations

After setting up all of the components we execute Load Flow Analysis, which converges in 2 iterations, and the Harmonic Load Flow Analysis, which is executed successfully as well.

At 0.4 kV sabirnica, where the Nonlinear Load is put, we will get the violations of harmonic distortions (Figure 12). In the tubular report, we get information about, nominal voltage, frequency, order, harmonic distortion and its limit.

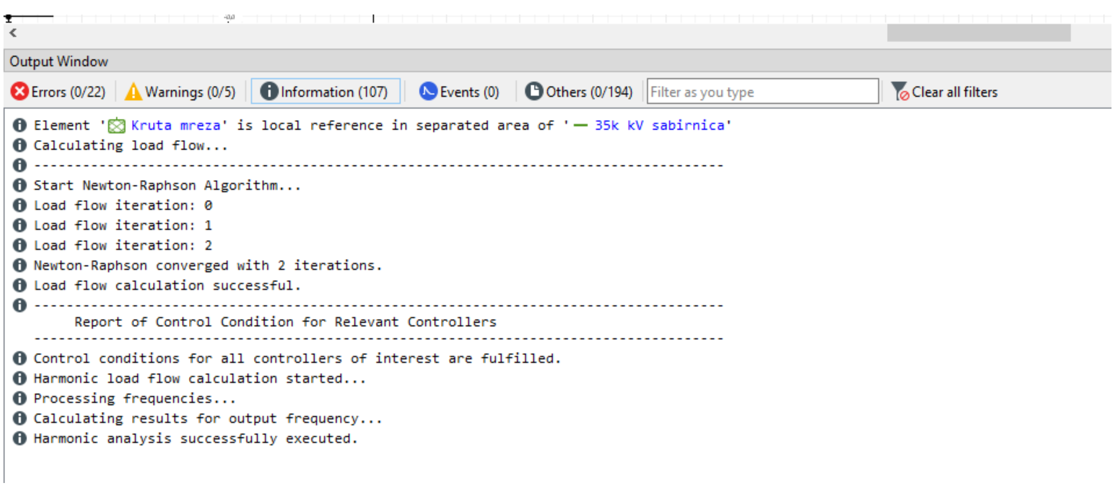
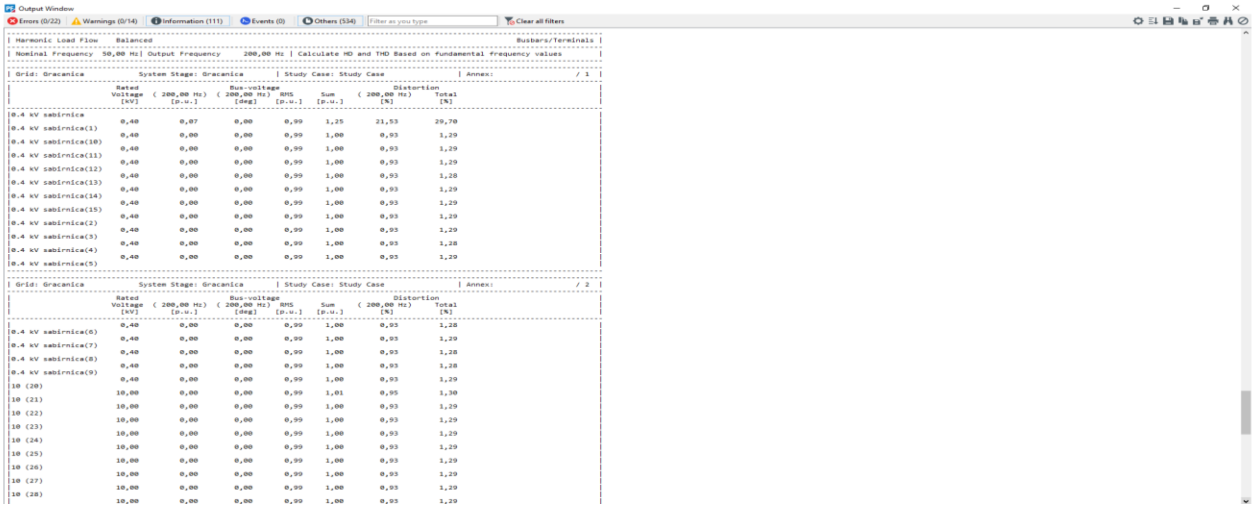


Figure 13. Output Window – Harmonic Load Flow executed successfully



Output Window

Errors (0/22) | Warnings (0/14) | Information (111) | Events (0) | Others (534) | Filter as you type | Clear all filters

| Harmonic Load Flow   Balanced   Busbars/Terminals |

| Nominal Frequency 50,00 Hz | Output Frequency 200,00 Hz | Calculate HD and THD Based on fundamental frequency values |

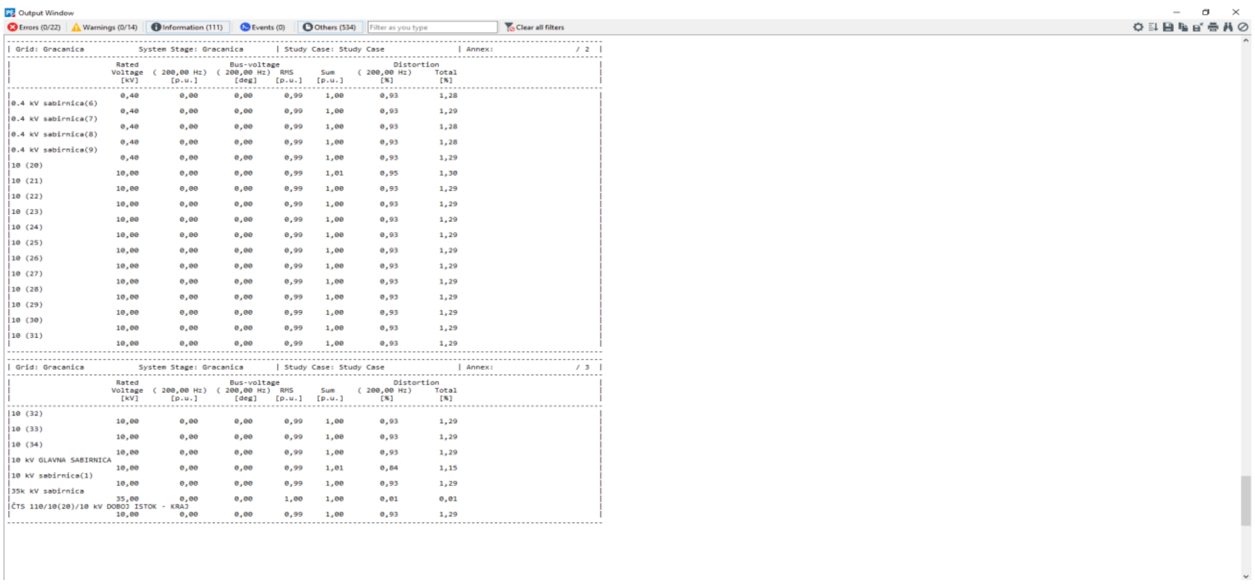
| Grid: Gracanica   System Stage: Gracanica | Study Case: Study Case | Annex: / 1 |

	Rated Voltage [kV]	Bus-voltage (200,00 Hz) [p.u.]	(200,00 Hz) [deg]	RMS [p.u.]	Sum [p.u.]	Distortion (200,00 Hz) [%]	Total [%]
0.4 kV sabirnica	0,40	0,07	0,00	0,99	1,25	21,53	29,70
0.4 kV sabirnica(1)	0,40	0,00	0,00	0,99	1,00	0,93	1,29
0.4 kV sabirnica(10)	0,40	0,00	0,00	0,99	1,00	0,93	1,29
0.4 kV sabirnica(11)	0,40	0,00	0,00	0,99	1,00	0,93	1,29
0.4 kV sabirnica(12)	0,40	0,00	0,00	0,99	1,00	0,93	1,28
0.4 kV sabirnica(13)	0,40	0,00	0,00	0,99	1,00	0,93	1,29
0.4 kV sabirnica(14)	0,40	0,00	0,00	0,99	1,00	0,93	1,29
0.4 kV sabirnica(15)	0,40	0,00	0,00	0,99	1,00	0,93	1,29
0.4 kV sabirnica(2)	0,40	0,00	0,00	0,99	1,00	0,93	1,29
0.4 kV sabirnica(3)	0,40	0,00	0,00	0,99	1,00	0,93	1,28
0.4 kV sabirnica(4)	0,40	0,00	0,00	0,99	1,00	0,93	1,29
0.4 kV sabirnica(5)							

| Grid: Gracanica   System Stage: Gracanica | Study Case: Study Case | Annex: / 2 |

	Rated Voltage [kV]	Bus-voltage (200,00 Hz) [p.u.]	(200,00 Hz) [deg]	RMS [p.u.]	Sum [p.u.]	Distortion (200,00 Hz) [%]	Total [%]
	0,40	0,00	0,00	0,99	1,00	0,93	1,28
0.4 kV sabirnica(6)	0,40	0,00	0,00	0,99	1,00	0,93	1,29
0.4 kV sabirnica(7)	0,40	0,00	0,00	0,99	1,00	0,93	1,28
0.4 kV sabirnica(8)	0,40	0,00	0,00	0,99	1,00	0,93	1,28
0.4 kV sabirnica(9)	0,40	0,00	0,00	0,99	1,00	0,93	1,29
10 (20)	10,00	0,00	0,00	0,99	1,01	0,95	1,30
10 (21)	10,00	0,00	0,00	0,99	1,00	0,93	1,29
10 (22)	10,00	0,00	0,00	0,99	1,00	0,93	1,29
10 (23)	10,00	0,00	0,00	0,99	1,00	0,93	1,29
10 (24)	10,00	0,00	0,00	0,99	1,00	0,93	1,29
10 (25)	10,00	0,00	0,00	0,99	1,00	0,93	1,29
10 (26)	10,00	0,00	0,00	0,99	1,00	0,93	1,29
10 (27)	10,00	0,00	0,00	0,99	1,00	0,93	1,29
10 (28)	10,00	0,00	0,00	0,99	1,00	0,93	1,29

Figure 14. Harmonic Load Flow Report



Output Window

Errors (0/22) | Warnings (0/14) | Information (111) | Events (0) | Others (534) | Filter as you type | Clear all filters

| Grid: Gracanica   System Stage: Gracanica | Study Case: Study Case | Annex: / 2 |

	Rated Voltage [kV]	Bus-voltage (200,00 Hz) [p.u.]	(200,00 Hz) [deg]	RMS [p.u.]	Sum [p.u.]	Distortion (200,00 Hz) [%]	Total [%]
	0,40	0,00	0,00	0,99	1,00	0,93	1,28
0.4 kV sabirnica(6)	0,40	0,00	0,00	0,99	1,00	0,93	1,29
0.4 kV sabirnica(7)	0,40	0,00	0,00	0,99	1,00	0,93	1,28
0.4 kV sabirnica(8)	0,40	0,00	0,00	0,99	1,00	0,93	1,28
0.4 kV sabirnica(9)	0,40	0,00	0,00	0,99	1,00	0,93	1,29
10 (20)	10,00	0,00	0,00	0,99	1,01	0,95	1,30
10 (21)	10,00	0,00	0,00	0,99	1,00	0,93	1,29
10 (22)	10,00	0,00	0,00	0,99	1,00	0,93	1,29
10 (23)	10,00	0,00	0,00	0,99	1,00	0,93	1,29
10 (24)	10,00	0,00	0,00	0,99	1,00	0,93	1,29
10 (25)	10,00	0,00	0,00	0,99	1,00	0,93	1,29
10 (26)	10,00	0,00	0,00	0,99	1,00	0,93	1,29
10 (27)	10,00	0,00	0,00	0,99	1,00	0,93	1,29
10 (28)	10,00	0,00	0,00	0,99	1,00	0,93	1,29
10 (29)	10,00	0,00	0,00	0,99	1,00	0,93	1,29
10 (30)	10,00	0,00	0,00	0,99	1,00	0,93	1,29
10 (31)	10,00	0,00	0,00	0,99	1,00	0,93	1,29

| Grid: Gracanica   System Stage: Gracanica | Study Case: Study Case | Annex: / 3 |

	Rated Voltage [kV]	Bus-voltage (200,00 Hz) [p.u.]	(200,00 Hz) [deg]	RMS [p.u.]	Sum [p.u.]	Distortion (200,00 Hz) [%]	Total [%]
10 (32)	10,00	0,00	0,00	0,99	1,00	0,93	1,29
10 (33)	10,00	0,00	0,00	0,99	1,00	0,93	1,29
10 (34)	10,00	0,00	0,00	0,99	1,00	0,93	1,29
10 kV GLAVNA SABIRNICA	10,00	0,00	0,00	0,99	1,01	0,84	1,15
10 kV sabirnica(1)	10,00	0,00	0,00	0,99	1,00	0,93	1,29
35k kV sabirnica	35,00	0,00	0,00	1,00	1,00	0,01	0,01
ČTS 110/10(20)/10 kV DOBOJ ISTOK - KRAJ	10,00	0,00	0,00	0,99	1,00	0,93	1,29

Figure 15. Harmonic Load Flow Report

The Harmonic Load Flow Report is executed at the nominal 50 Hz and the output frequency of 200 Hz. As seen, the angle of all of the voltages at 200 Hz is 0. The RMS voltage in pu is either 0.99 or 1.00, which is excellent precision for voltage value. The sum in pu is normal for every bus, except the 0.4 kV sabirnica, where the nonlinear load is placed (1.25 pu). The % distortion is 21.53 % for this bus, but is below 1 % for every other location in this network.

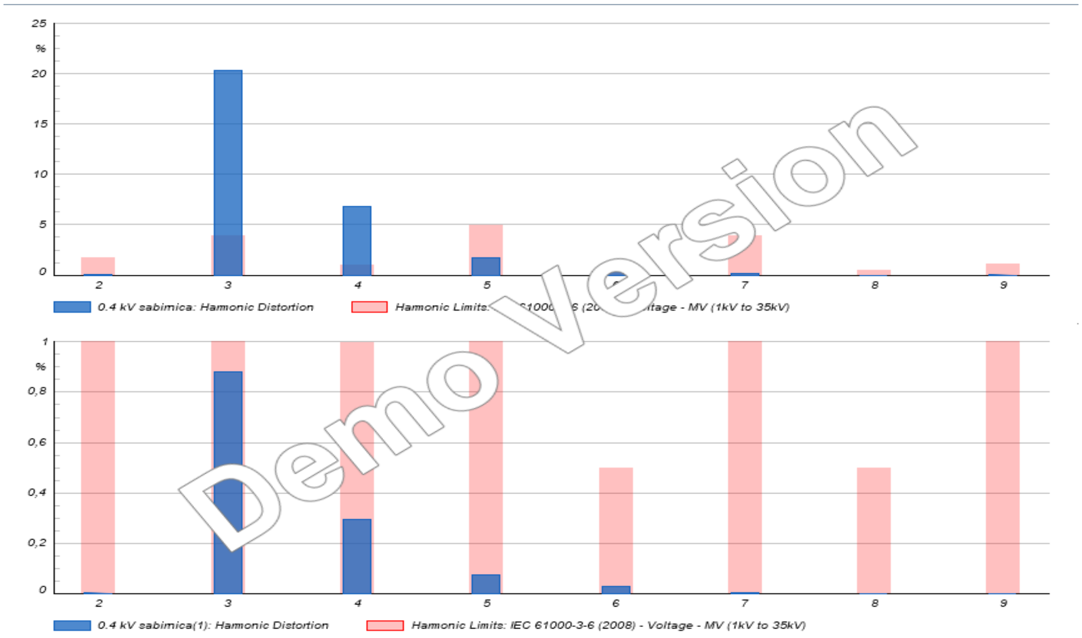


Figure 16. Harmonic Distortion exceeds its Limits at 0.4 kV sabirnica, where the nonlinear load is located; HD is within its Limits for 0.4 kV sabirnica (1) – the neighboring Bus

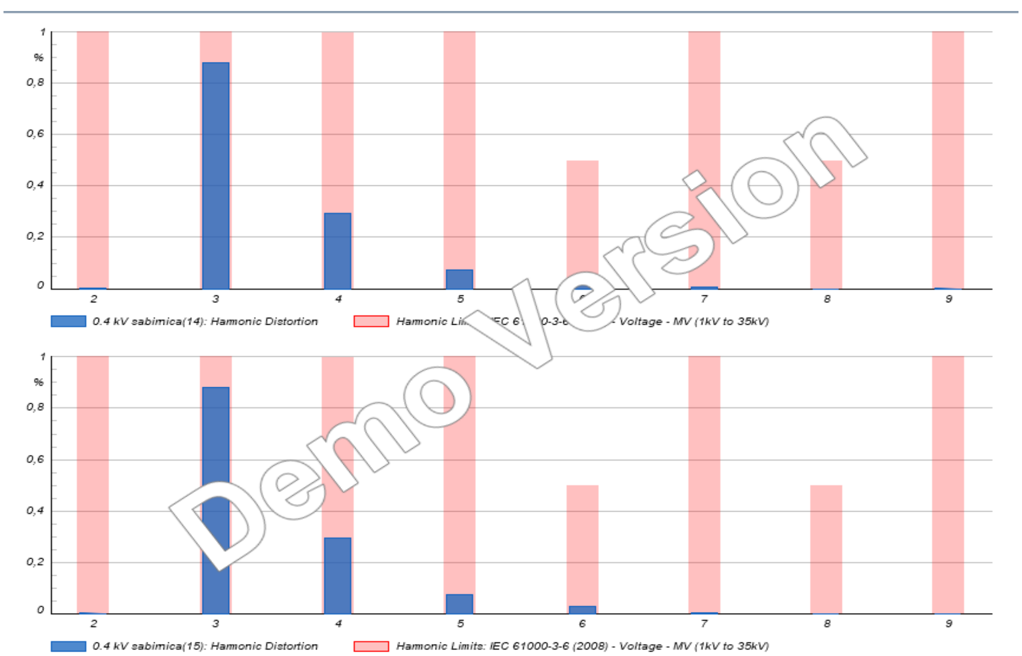


Figure 17. HD is within its Limits for 0.4 kV sabirnica (14) and 0.4 kV sabirnica (16) – the Busses far away in the Network

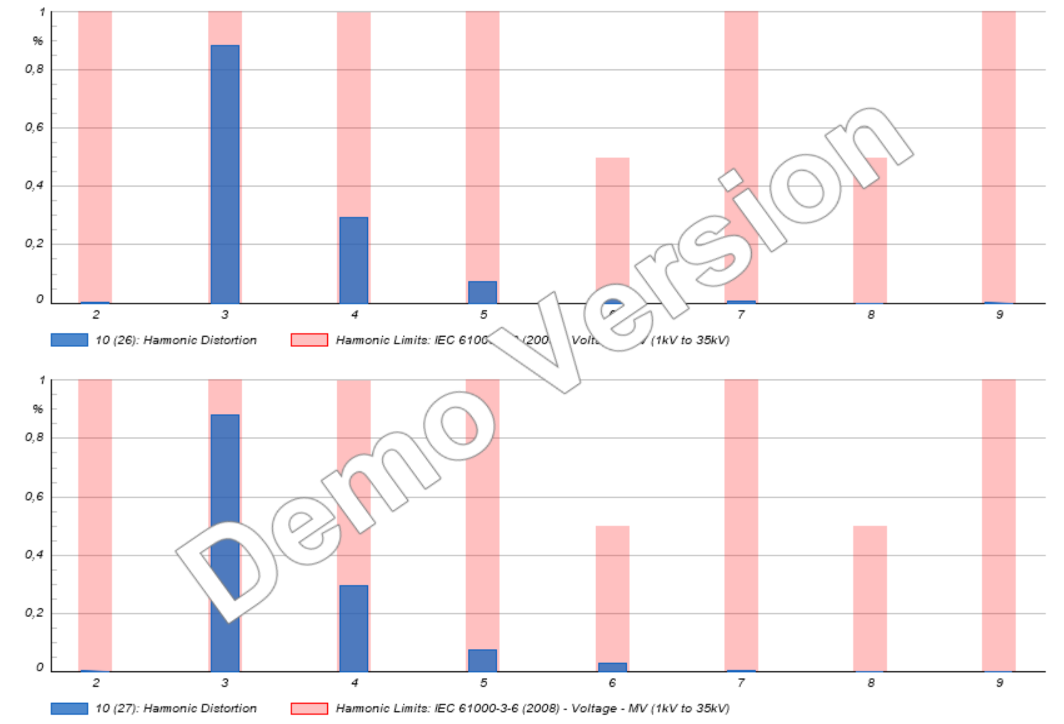


Figure 18. HD is within its Limits for 10 kV sabirnica (26) and 10 kV sabirnica (27) –Busses far away in the Network

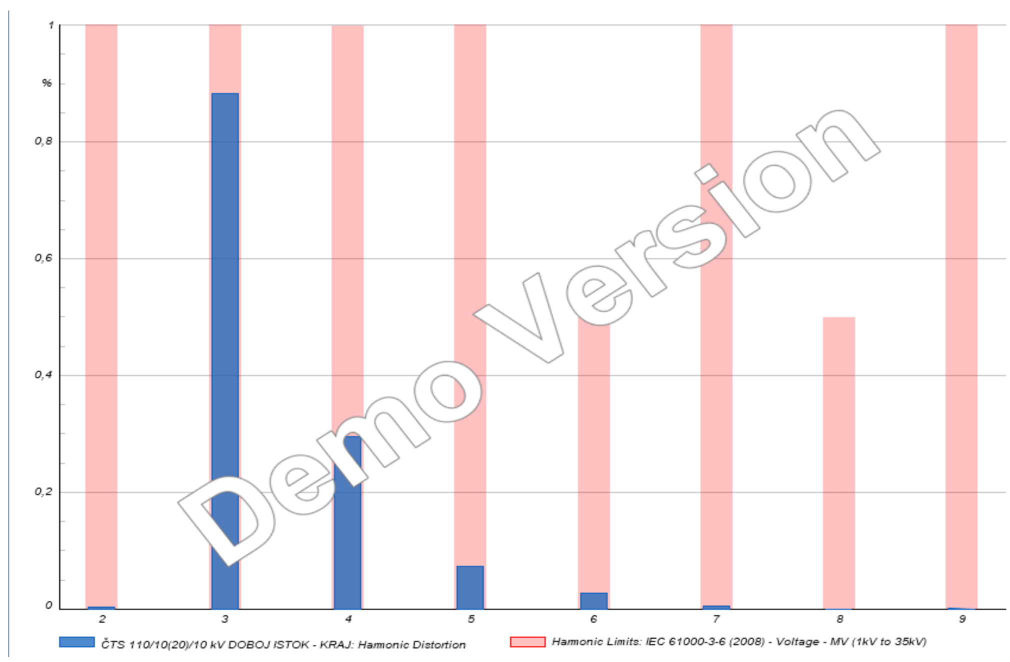


Figure 19. HD is within its defined Limits at the End of the Network (ČTS Doboj Istok)

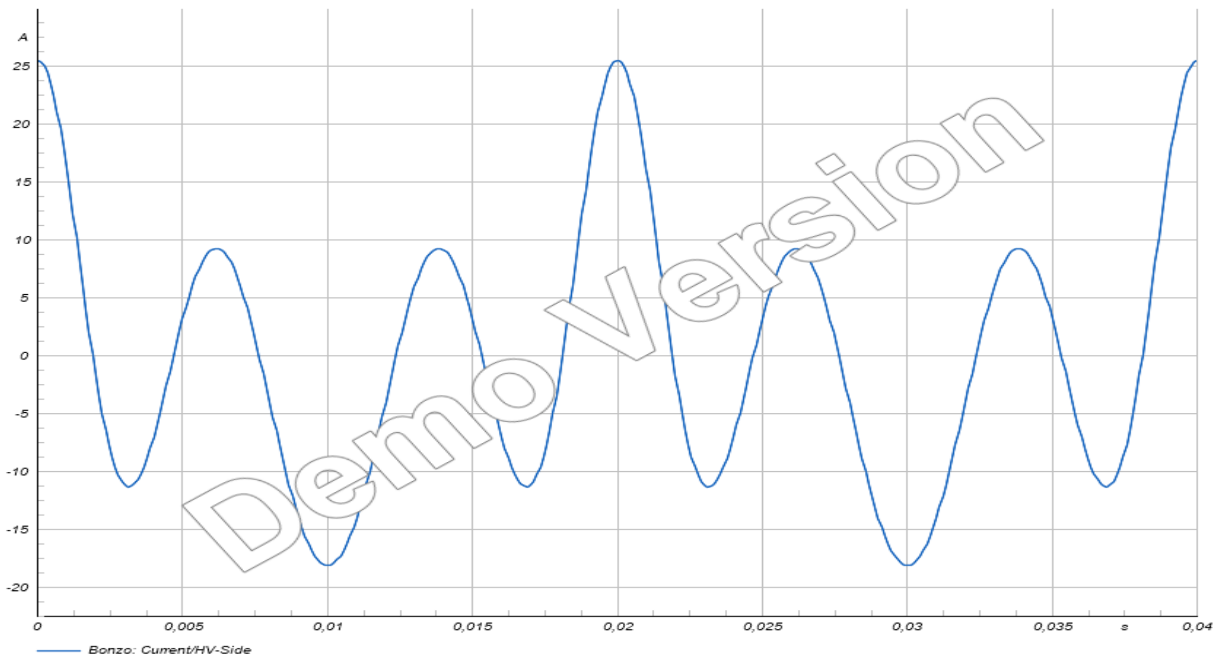


Figure 20. Harmonic Waveform of Current at Bonzo Transformer HV Side

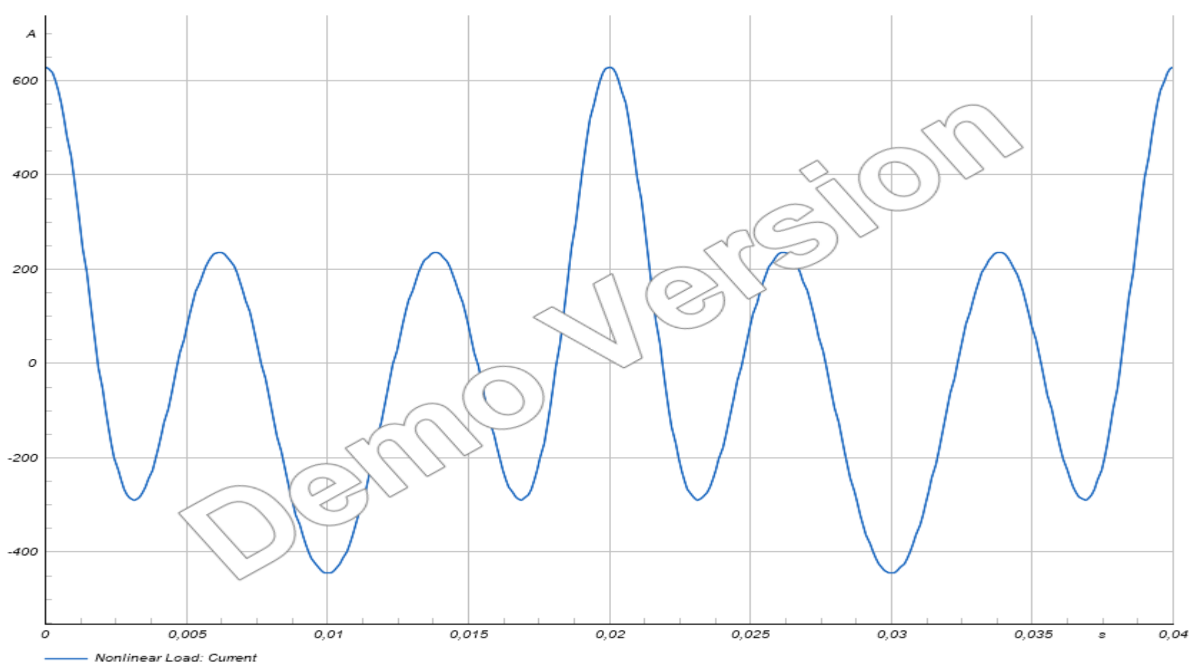


Figure 21. Harmonic Waveform of Current at 0.4 kV sabirnica Nonlinear Load

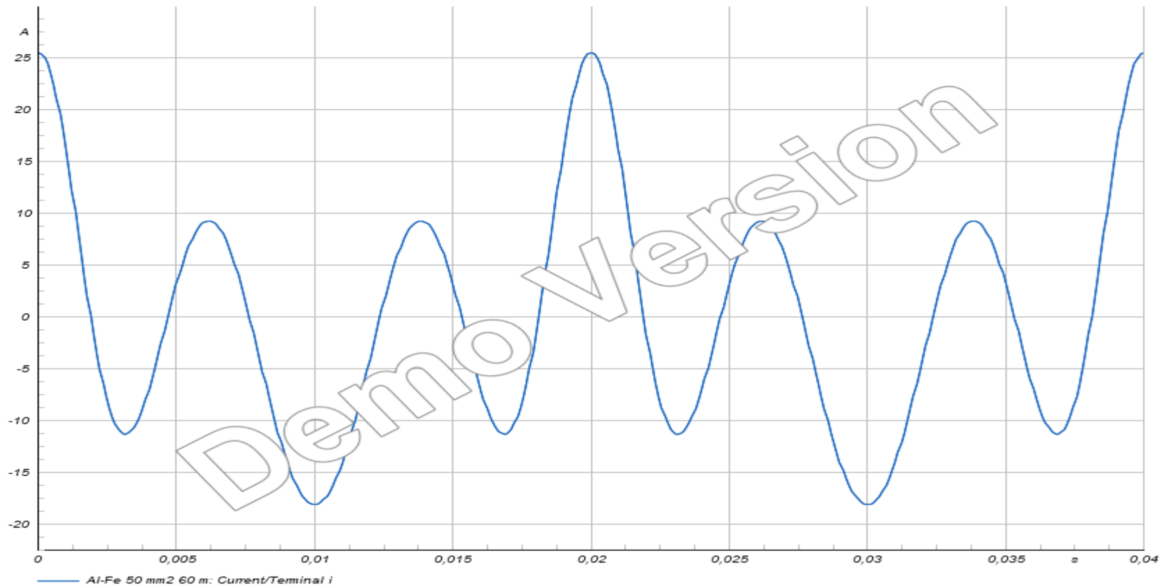


Figure 22. Harmonic Waveform of Current at Al-Fe 50 mm^2 Line

By defining Result Variables for Bonzo Transformer HV side, Nonlinear Load and Al-Fe 50 mm^2 Line, we are able to insert the waveform plots of this harmonic distortions. The frequency becomes inconsistent and deviations are observed. As mentioned, the greatest deviations are at 0.4 kV sabirnica, since our nonlinear load is there.

Nonlinear loads can cause harmonic distortions in a network due to the way they draw current from the power supply. Unlike linear loads, which draw current in proportion to the applied voltage, nonlinear loads exhibit non-sinusoidal current waveforms. This nonsinusoidal current waveform results from the nonlinear relationship between voltage and current of these loads.

When it comes to the waveforms, sine waveform is distorted and moves away from its ideal sinusoidal shape and flow. The current rises to extremely high values at the Nonlinear Load. Value approximation: It has a peak-to-peak value of approximately 1000 A, but since the waveform is distorted it has a maximum positive value of 600 A, and a minimum value of -400 A.

On the other two network locations, the sine waveform is distorted in the same way as for Nonlinear Load. Value approximation: Since we are not at the Nonlinear Load, the peak-to-peak value is 40 A. The maximum positive value is 25 A, and a minimum value of – 17.5 A.

5. Conclusion

In this lab, we explored harmonics analysis in our modeled network using DIGSILENT. Our goal was to understand how a nonlinear load influences network behavior and harmonic distortions. Before introducing the nonlinear load, we examined the network's parameters and conducted load flow analysis, observing nominal voltages and very small voltage deviations.

The Harmonic Load Flow Analysis was executed after that, according to the IEC 61000 standard of this analysis protocol. After introducing the nonlinear load into the network, we observed significant changes in Harmonic Distortions (HD) - in %, particularly at the 0.4 kV bus, where harmonic distortions go over the acceptable limits.

Our analysis proved the impact of nonlinear loads, by giving us distorted sine waves and increased current levels both at Nonlinear Load and at other elements within the network. Through waveform plots and harmonic analysis, we observed the influence of nonlinear loads on voltages and currents in the network. In real life, harmonic distortions present a great issue, which needs to be addressed.

Implementing harmonic filters can mitigate the impact of nonlinear loads by stopping unwanted harmonics from entering the system. Additionally, optimizing the distribution of nonlinear loads across phases and ensuring balanced operation can help minimize harmonic distortions as well. Regular monitoring and maintenance of equipment, along with scheduled harmonic analysis, are essential for identifying and addressing potential harmonic issues.

LAB 11 - PROTECTION RELAYS (POWERFACTORY)

1. Introduction

Lab 11 is about seeing what is the impact of protective relay in short-circuit event created on specific busbar. We track and assume what is relays role when short-circuit event occur.

The relays in two cases are positioned at the LV side of the transformer. Their parameters are carefully defined, with the Power Flow Analysis and Short Circuit event conducted before that. Time-overcurrent plots will be obtained, and machines will be implemented inside the network to show the effect it has on the individual plot.

2. Theory

Protective relays play a crucial role in protecting distribution networks by monitoring for abnormalities like overcurrent, overvoltage, or underfrequency. Positioned strategically at substations and along feeders, these relays detect irregular conditions and activate measures to isolate faulty sections, preventing further damage. Simply put, we will set up an overcurrent relay. The plots can be generated from the relay setups. This gives us a better insight what we can do with them, especially when we can modify the plot values and see the changes instantly, by using DIGSILENT Power factory.

In distribution networks, primary relays are the first line of defense, quickly detecting faults and initiating protective actions. Meanwhile, backup relays provide an additional layer of protection in case the primary relay fails. They are programmed to intervene when needed, improving system reliability without being redundant. Primary and backup relays collaborate to ensure fault detection and isolation. While the primary relay takes the lead in identifying issues, the backup relay serves as a safety net in case of primary relay is passed or is not working probably, ensuring constant protection and minimizing network downtime along the way.

3. Relay at 0.4 kV Sabirnica (1) – Džebo

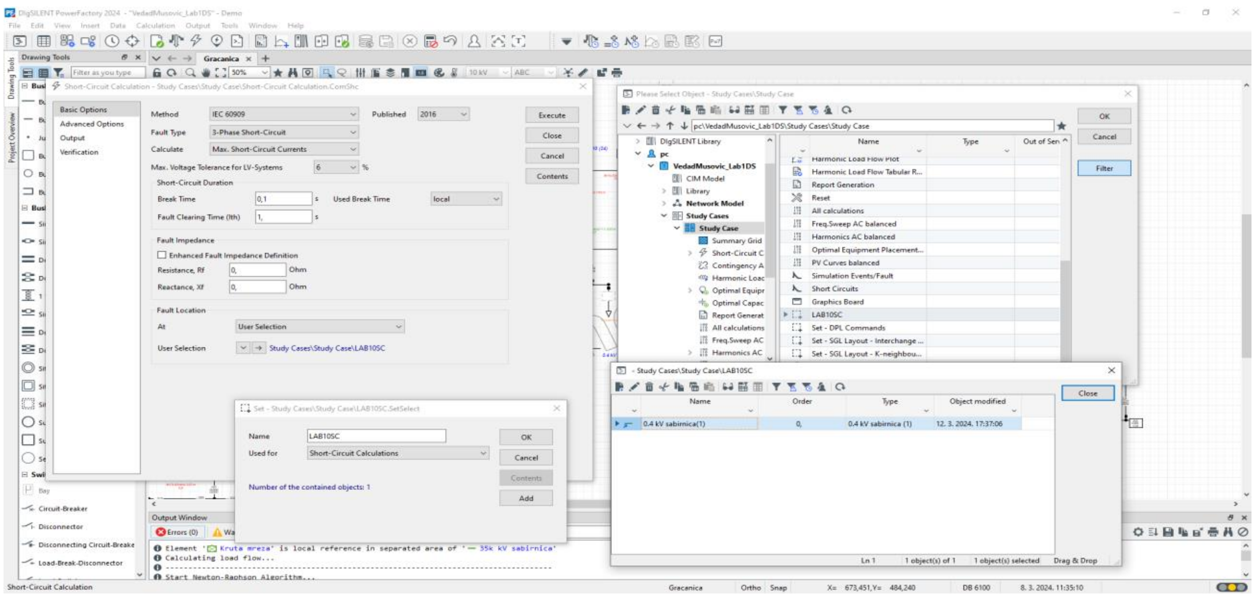


Figure 1. Defining the Three-Phase Short-Circuit and its Location

In the start, we have to define a 3-Phase Short-Circuit. 0.4 kV sabirnica (1) is selected as our fault location. Short circuit calculation is done to obtain both max and min short-circuit currents.

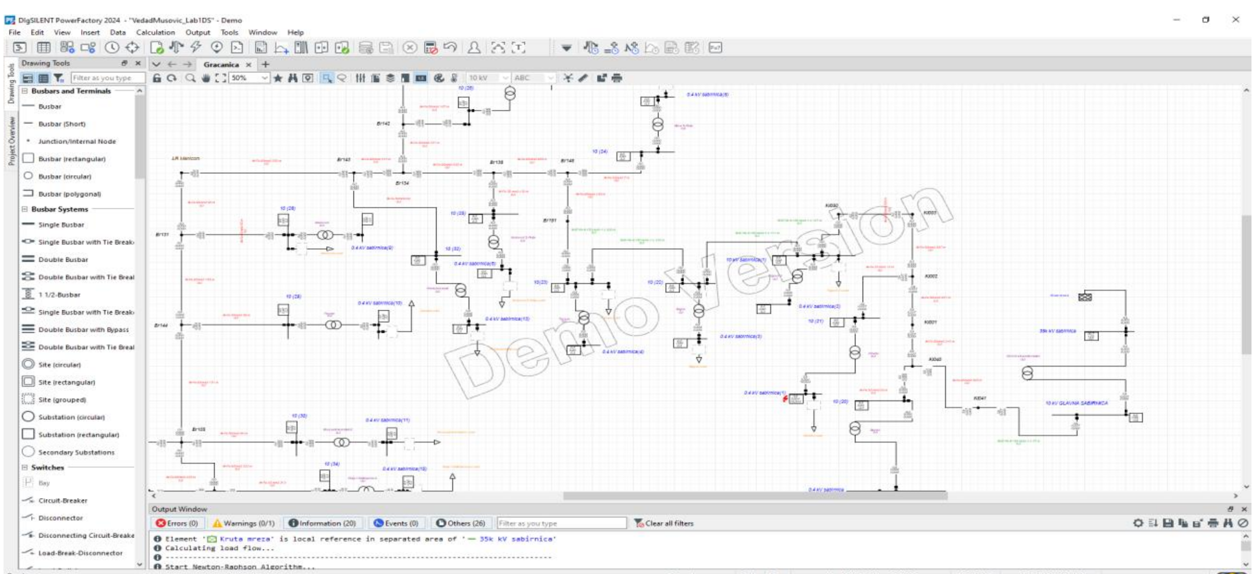


Figure 2. Fault Point at 0.4 kV sabirnica (1)

Newton-Raphson method converges in 2 iterations with no violations and short circuit analysis is successful. Maximum short-circuit current is 5.66 kA, while the minimum one is 5 kA.

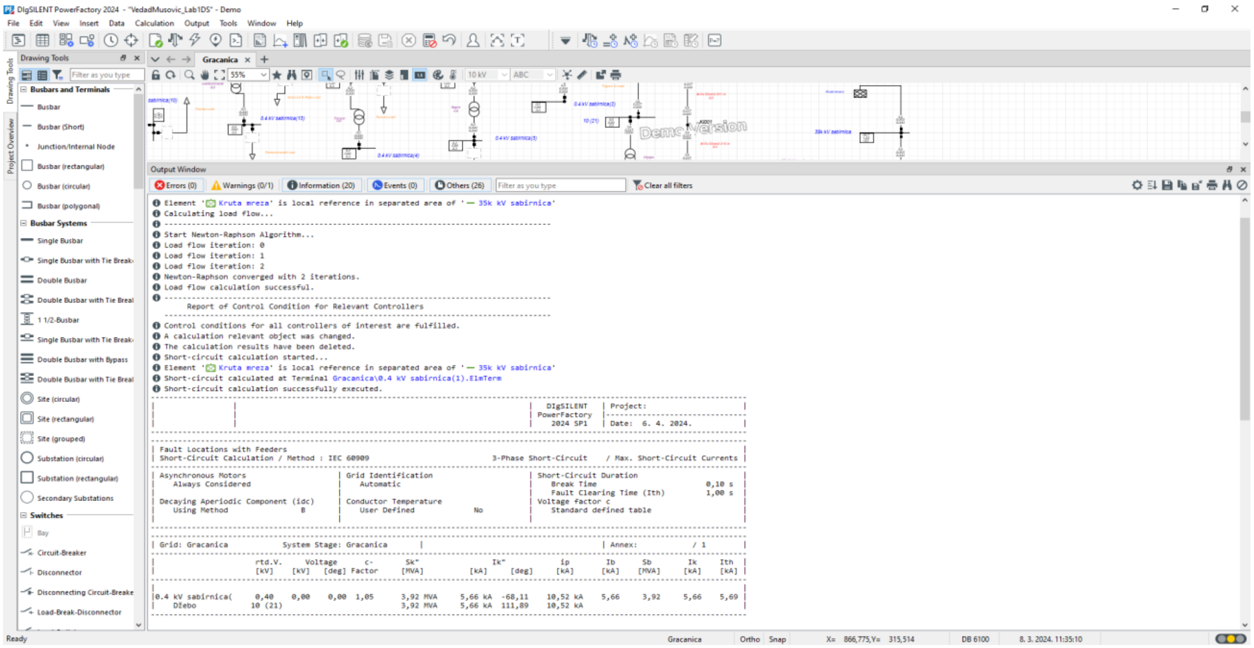


Figure 3. Maximum Short Circuit Currents

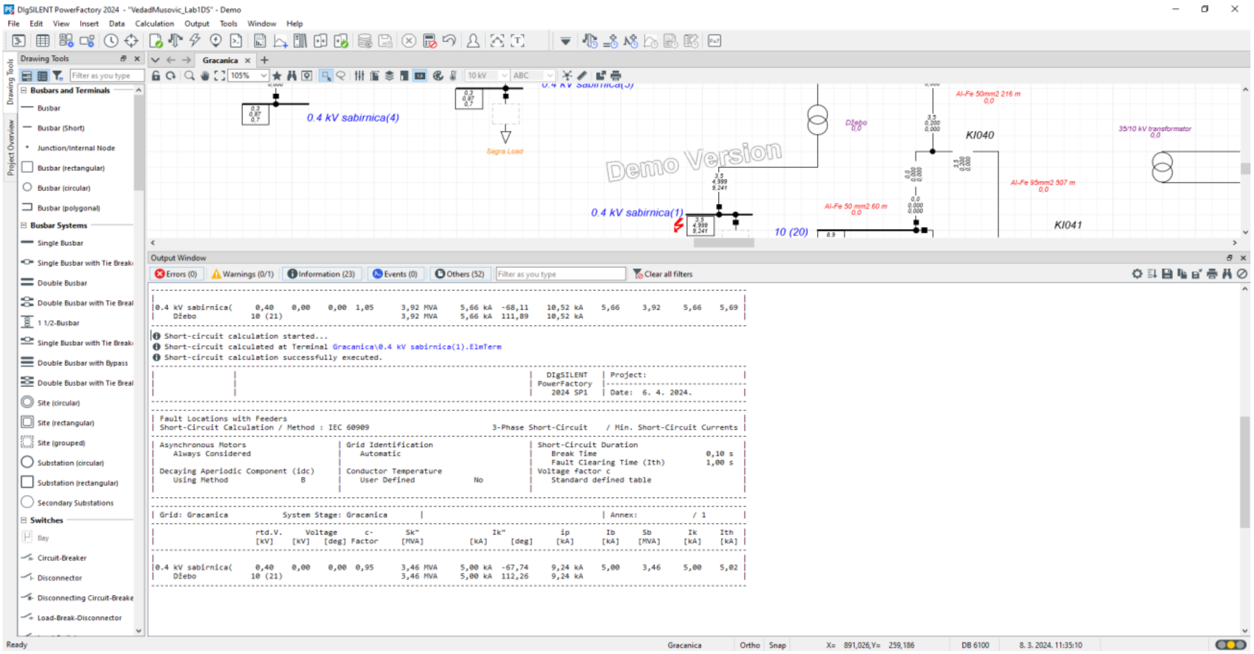


Figure 4. Minimum Short Circuit Currents

After that, we will create a relay on the LV side of the Džebo transformer.

This is the side where the voltage is lowered from 10 kV to 0.4 kV towards our Džebo load. This is 0.4 kV sabirnica (1).

We select the LV side, and Add New Devices and add a relay. In the DIgSILENT Library from the Protection Devices, we can choose a specific relay. Gec Alstom Relays are chosen, and from that MCGG-22 model.

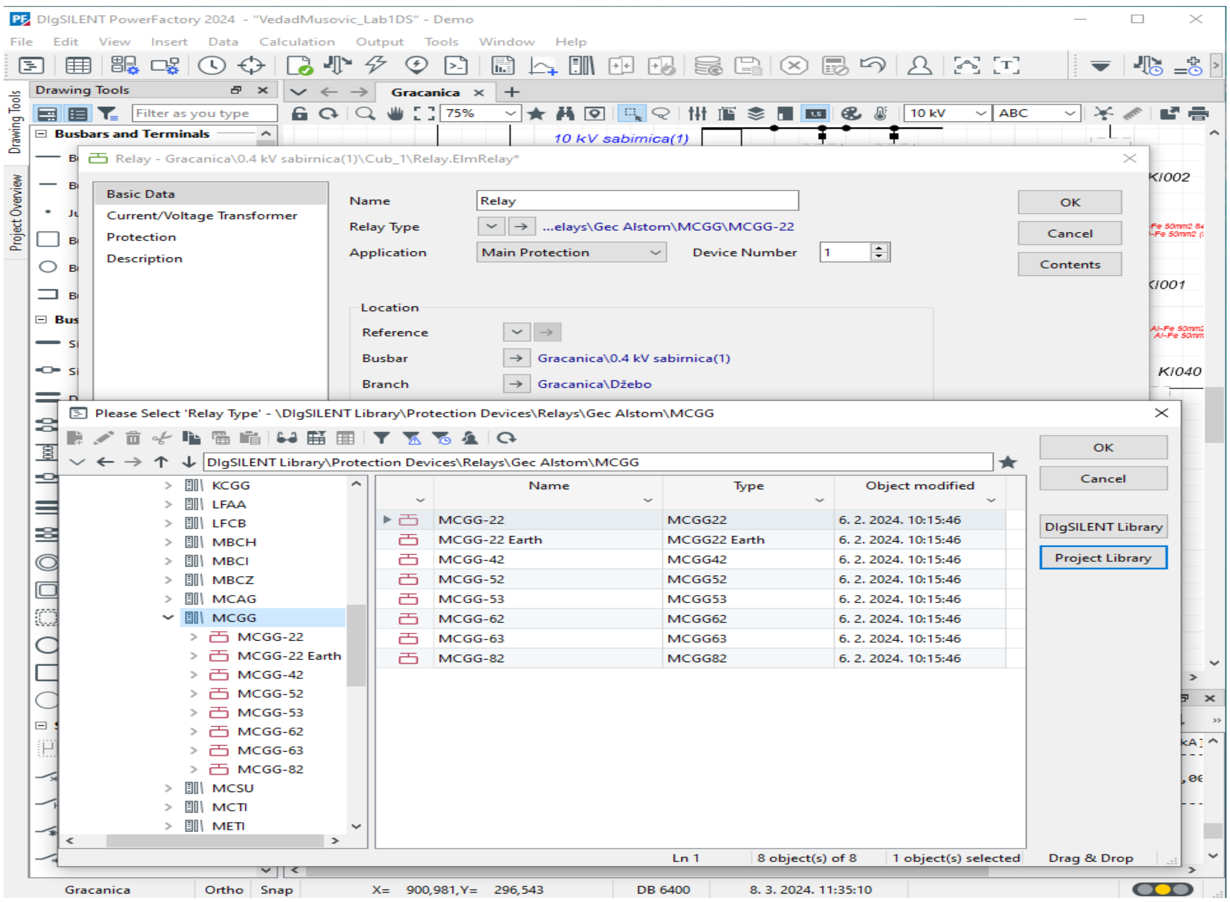


Figure 5. Selecting the Relay Type

Our relay is linked to 0.4 kV sabirnica (1) busbar, and to the Džebo branch. It serves as a main protection in the network.

Ct-1Ph is set to current transformer type, and the current range is set between 5 A and 800 A.

Figure 6 shows all of the inside components relay's, which make the relay work the correct way.

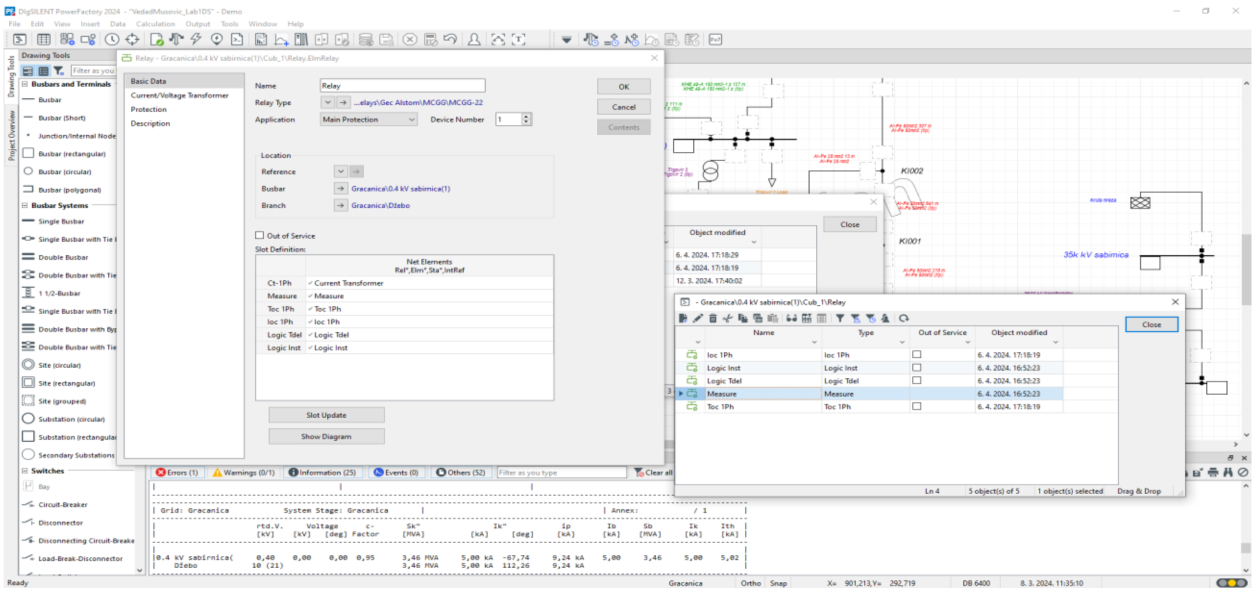


Figure 6. All of the Relay's Components

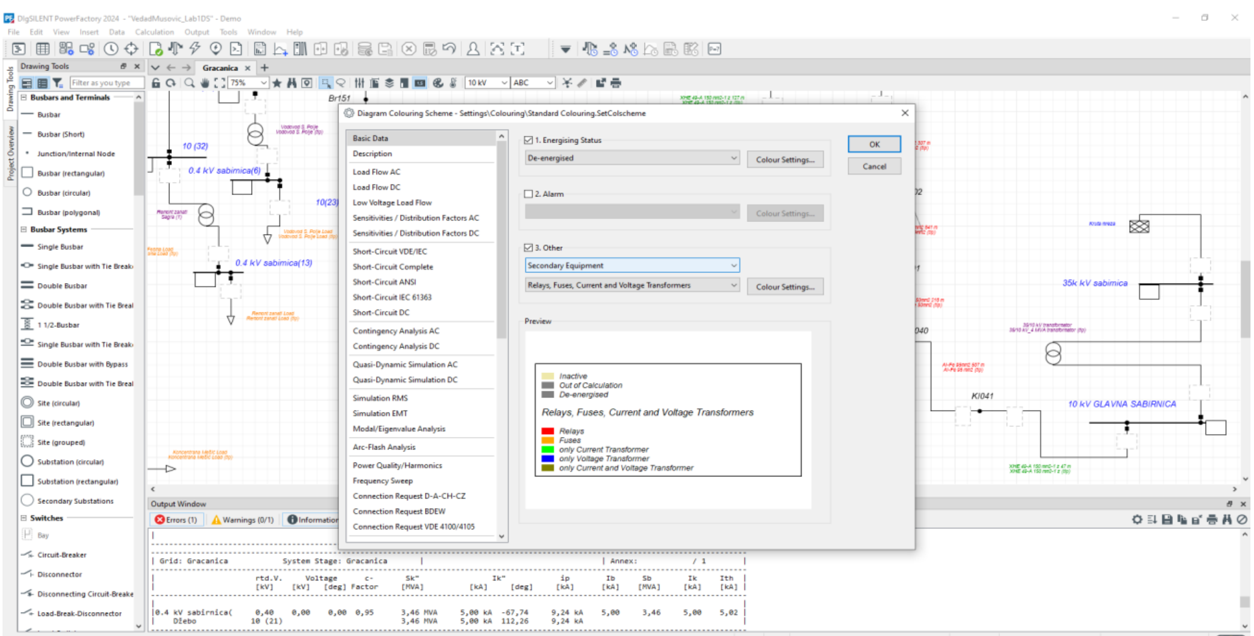


Figure 7. Setting up the Coloring

On the Dropdown Menu, we select Diagram Coloring Scheme, and select 3. Other to make relays and any other secondary equipment visible.

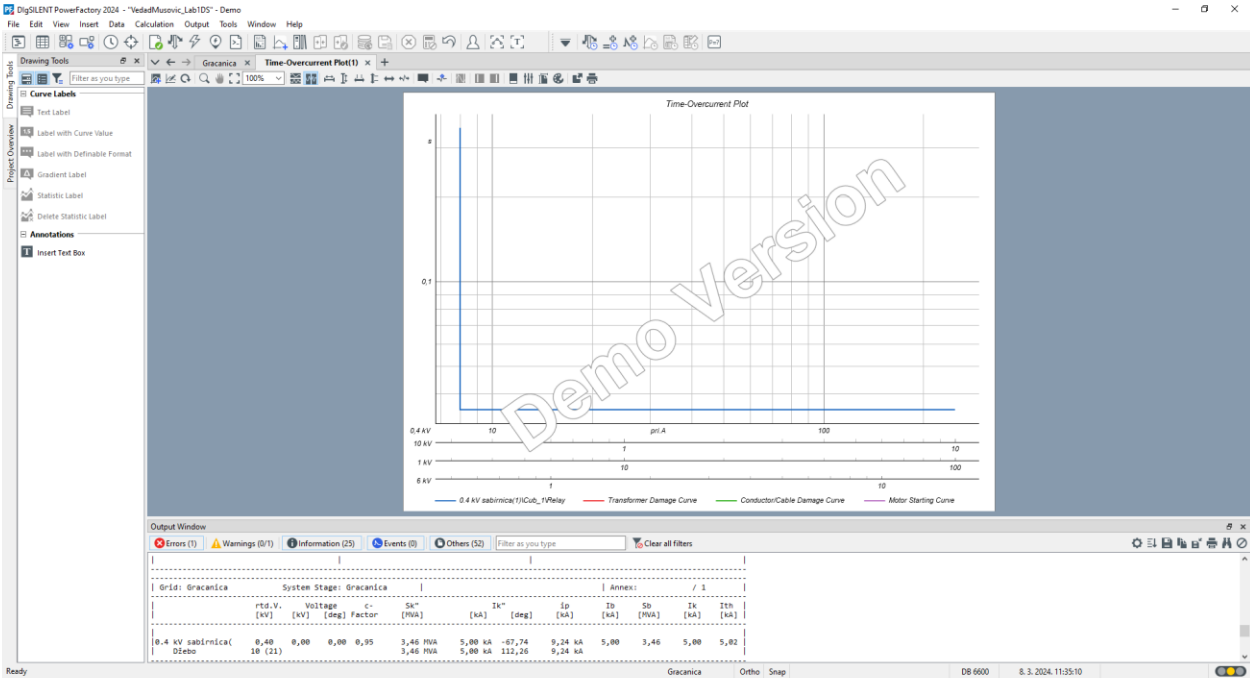


Figure 8. The Time-Overcurrent Plot

Single phase overcurrent with instantaneous element is now visible. We click on the side of the transformer where the relay is located, and select Insert Time-Overcurrent Plot.

The plot illustrates the relationship between relay reaction speeds, particularly focusing on overcurrent condition. When overcurrent occurs, the relay transitions from a slower response mode to a faster response mode. This intentional delay is beneficial as it allows the relay to wait and observe if the system returns to normal on its own.

If the abnormal condition remains and the system does not recover, the relay will eventually react and initiate the necessary protective actions. This response mechanism ensures that the relay avoids unnecessary operations in transient or minor deviations. On the other hand, it still provides reliable protection when the network is in demand for secondary equipment.

However, for slightly higher but less severe currents, the relay exhibits a significantly slower response time, which can last for several seconds. It also depends if there is a fault on any other positions, requiring slower response time. Moreover, if the fault is not particularly at the location where the fault is located. Then the graph would be slightly exponential. This intentional delay is beneficial as it allows the relay to wait and observe if the system returns to normal on its own. Thus, different scenarios can be observed. Responses change depending on faults and all currents.

By observing different relay types, Figure 9 shows the different relays and the way they can impact the network. For example, we used MCGG-22 model in this lab, since it was supposed to be used. However, in order to get a response from Figure 9, we need to try different relays and see which individual one suits our network the best and helps us obtain this type of response.

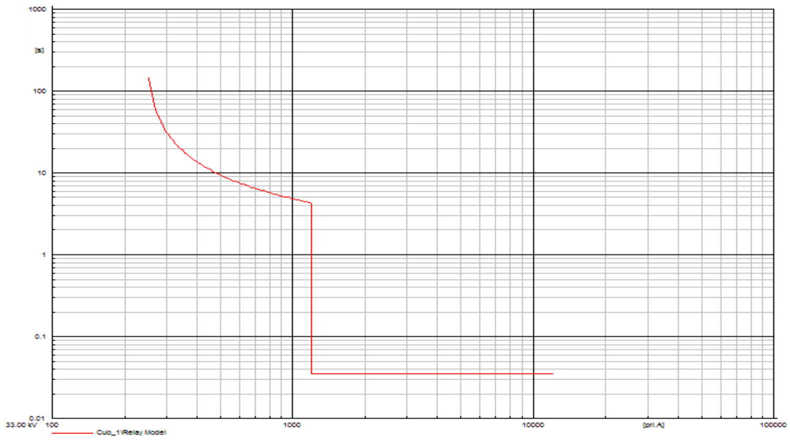


Figure 9. Possible Different Responses

Additionally, other element can be appended to the graph. In order to see them properly, we insert Asynchronous Machine of 1 kW. It acts as a motor and enables us to see graphs of other elements.

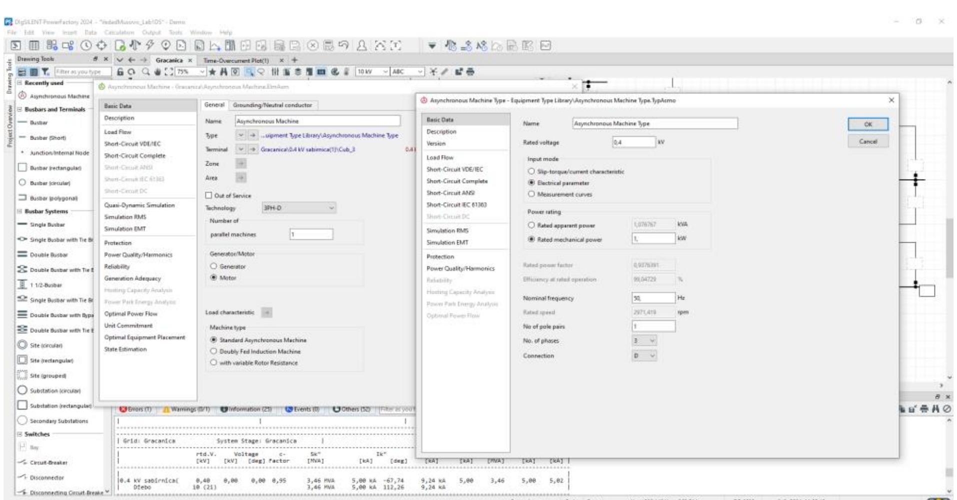


Figure 10. Adding the Asynchronous Machine

The asynchronous machine, the transformer damage curve, the motor starting curve, the cub relay and the conductor/cable damage curve are presented on the time-overcurrent plot.

As seen, the relay are there to trip when the current exceeds a certain value.

Inserting asynchronous machine leads to changes in the other curves. Firstly, the machine curve intersects the relay curve. Additionally, conductor / cable damage curves intersect each other.

The transformer damage curve intersects the conductor / cable damage curve as well.

Motor starting curve operates separately, as expected, but later on machine curve interferes with the relay curve. As seen, the relay curve operates at 10 kV at Time-Overcurrent plot.

That is the point when it experiences a sudden drop, not exponential. This is due to the fact that we have the large incoming current from the inserted asynchronous machine later on.

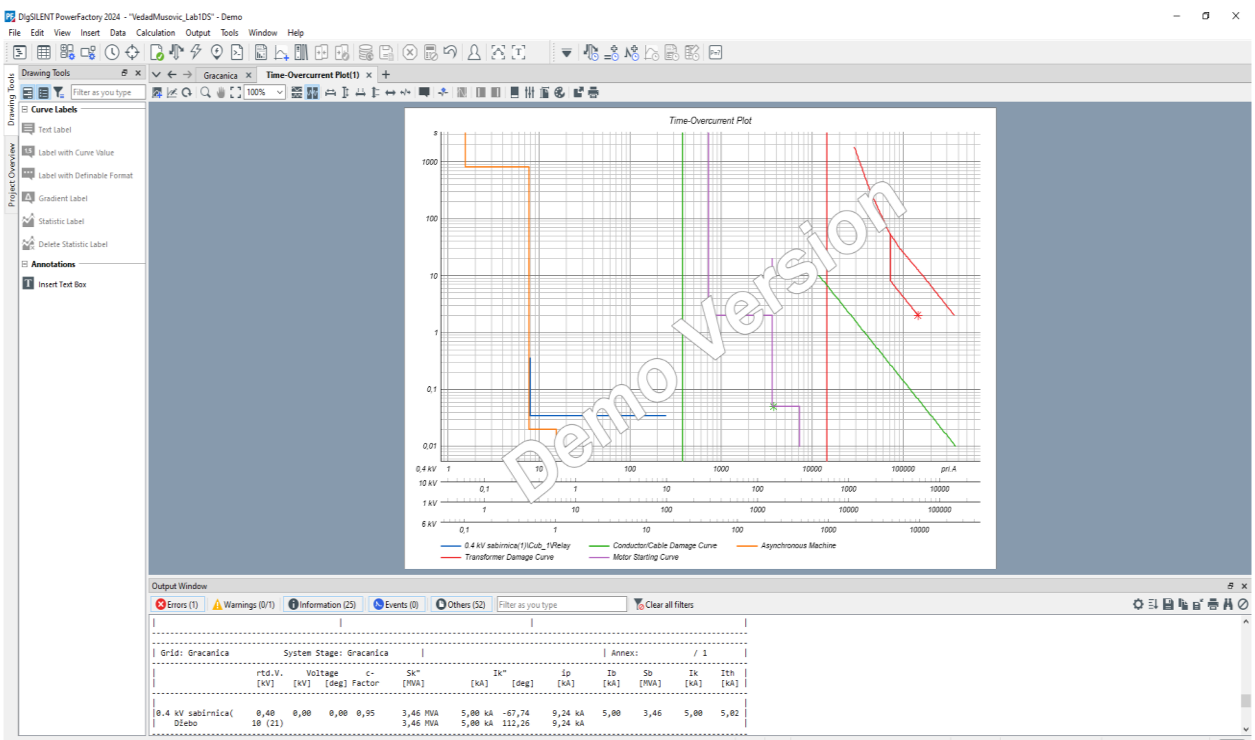


Figure 11. The Time-Overcurrent Plot for the Relay

4. RELAY AT 10 KV GLAVNA SABIRNICA

Secondly, the protection relay is inserted at 10 kV main bus, i.e. the LV side of the 35/10 kV transformer. But firstly, we have to conduct short circuit analysis. Maximum and minimum short-circuit current are obtained. Max current is 3.98 kA and the min one is 3.64 kA.

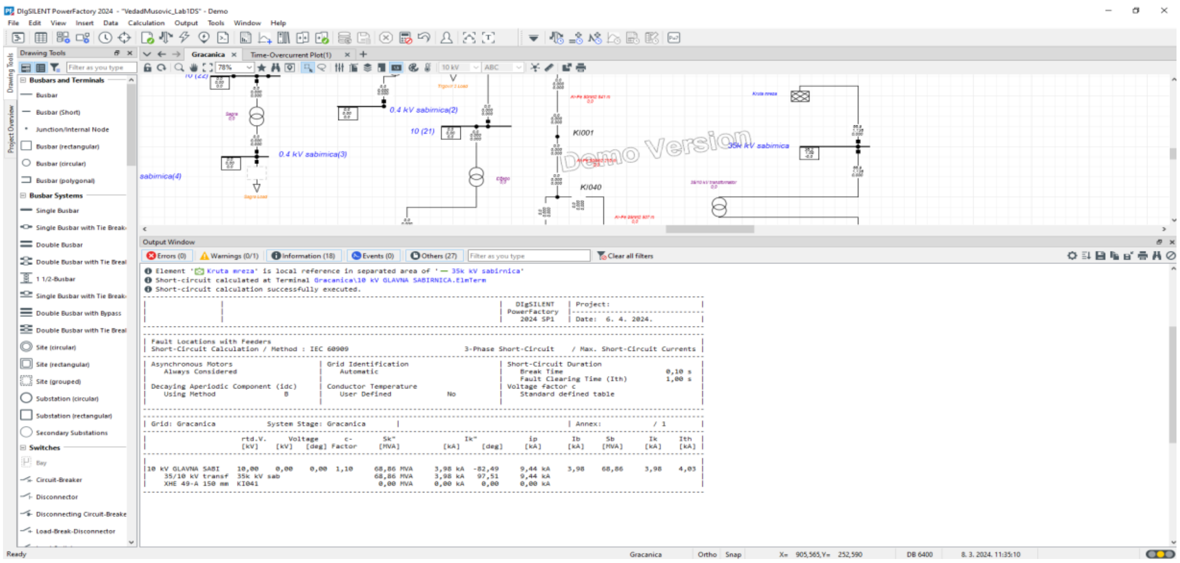


Figure 12. Maximum Short-Circuit Currents

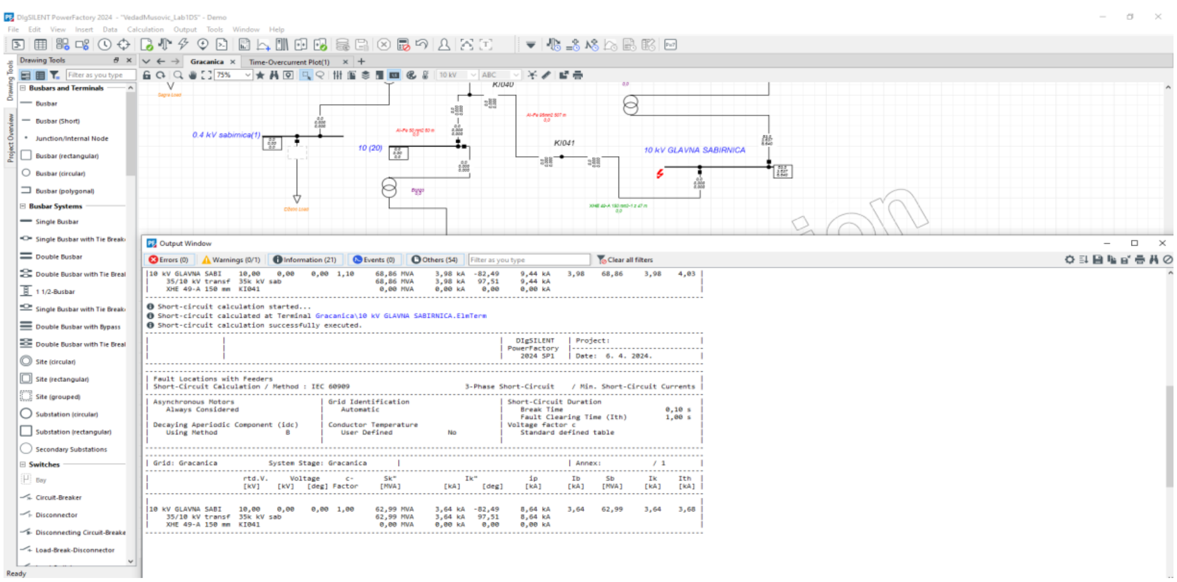


Figure 13. Minimum Short-Circuit Currents

In the same manner as in 0.4 kV sabirnica (1), the relay is inserted for main protection. Following this, the synchronous machine of 1 MVA power and 0.8 pf is inserted at the 10 kV glavna sabirnica.

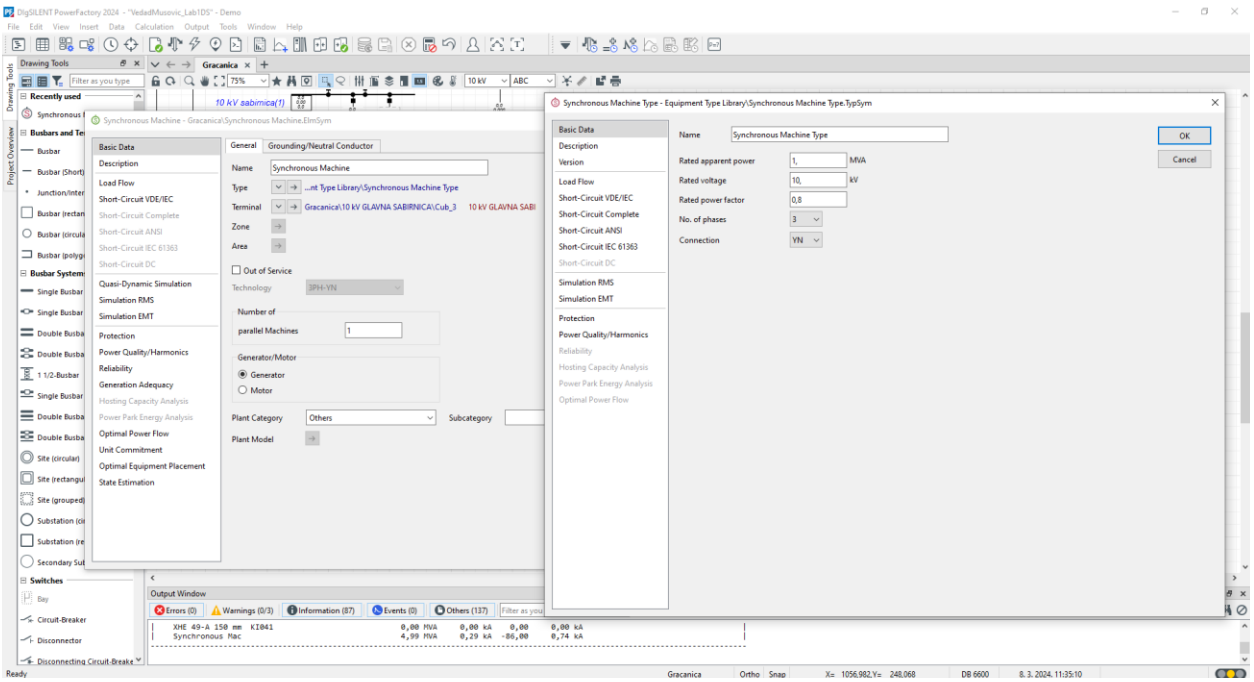


Figure 14. Adding the Synchronous Machine

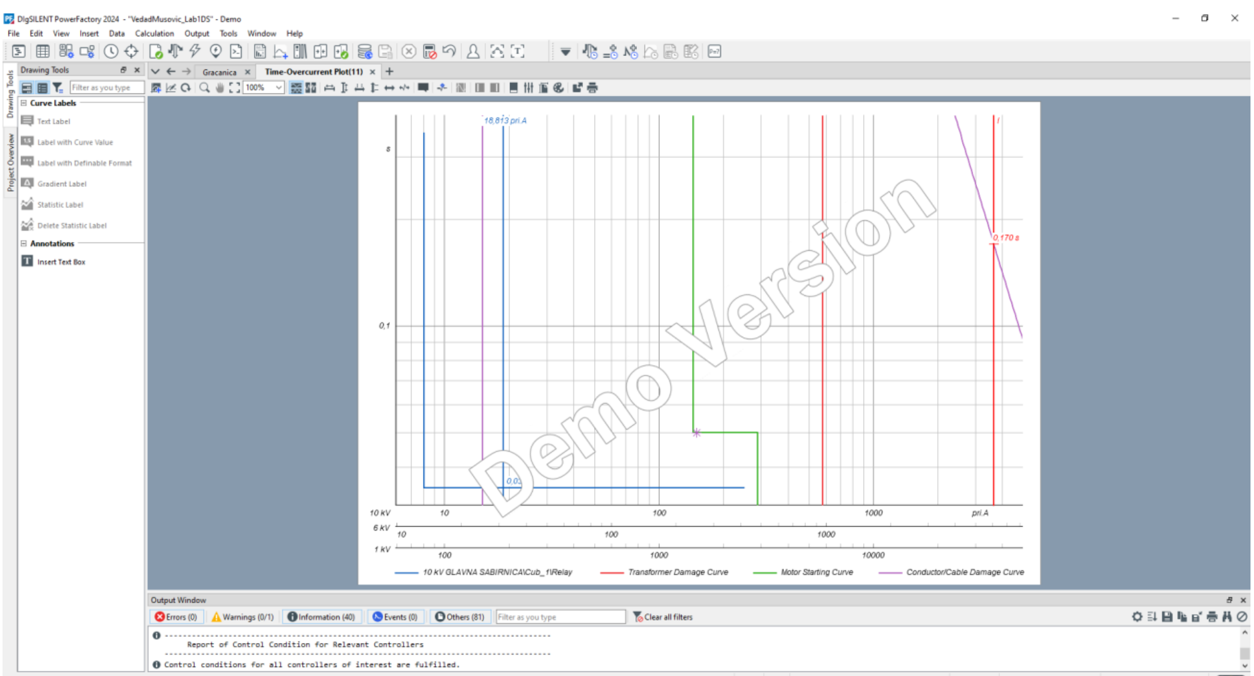


Figure 15. The Time-Overcurrent Plot for the Main Relay

The Time-Overcurrent Plot for the main relay is obtained. Initially, the cub relay curve is only shown, but we insert other plots as well, after the addition of the synchronous machine to the network.

Transformer damage curve, motor starting curve and the conductor / cable damage curves are shown. As shown, the conductor / cable damage curves intersect each other at 0.17 seconds. The motor starting curve will not intersect with the relay curve in this case.

At 0.03 s, our relay will trip and intersect the faulty current when it has the value of 18.813 A. This means that our relay will react early to the faulty current. Additionally, just before it trips the faulty current, the relay will trip the conductor / cable damage curve as well.

When overcurrent occurs, the relay transitions from a slower response mode to a faster response mode. This intentional delay is beneficial as it allows the relay to wait and observe if the system returns to normal on its own.

If the abnormal condition remains and the system does not recover, the relay will eventually react and initiate the necessary protective actions. This response mechanism ensures that the relay avoids unnecessary operations in transient or minor deviations. On the other hand, it still provides reliable protection when the network is in demand for secondary equipment.

However, for slightly higher but less severe currents, the relay exhibits a significantly slower response time, which can last for several seconds. It also depends if there is a fault on any other positions, requiring slower response time. Moreover, if the fault is not particularly at the location where the fault is located. Then the graph would be slightly exponential.

This intentional delay is beneficial as it allows the relay to wait and observe if the system returns to normal on its own. Thus, different scenarios can be observed. Responses change depending on faults and all currents. However, this type of response will not be present for this relay, when the fault is at this particular location. Moreover, since the fault is at the same busbar as the relay itself, it is expected that the relay’s response will be a type of a step response, when the relay curve drops suddenly. It will trip the faulty current early into the process, so it definitely tackles it early on.

4.1. Addition of Backup Relay At 10 kV Glavna Sabirnica

The protection relay in inserted at the nearby cable to serve as a secondary protection, i.e. the backup protection relay. Current transformer has its currents defined, and it is again MCGG-22.

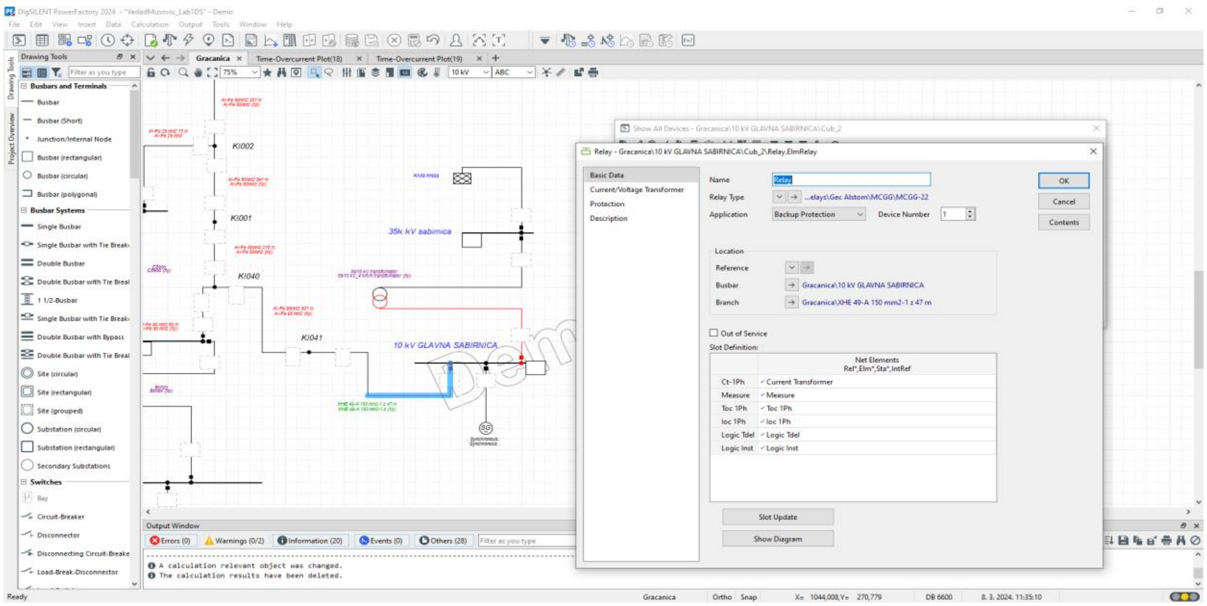


Figure 16. Inserting Backup Protection on the Cable

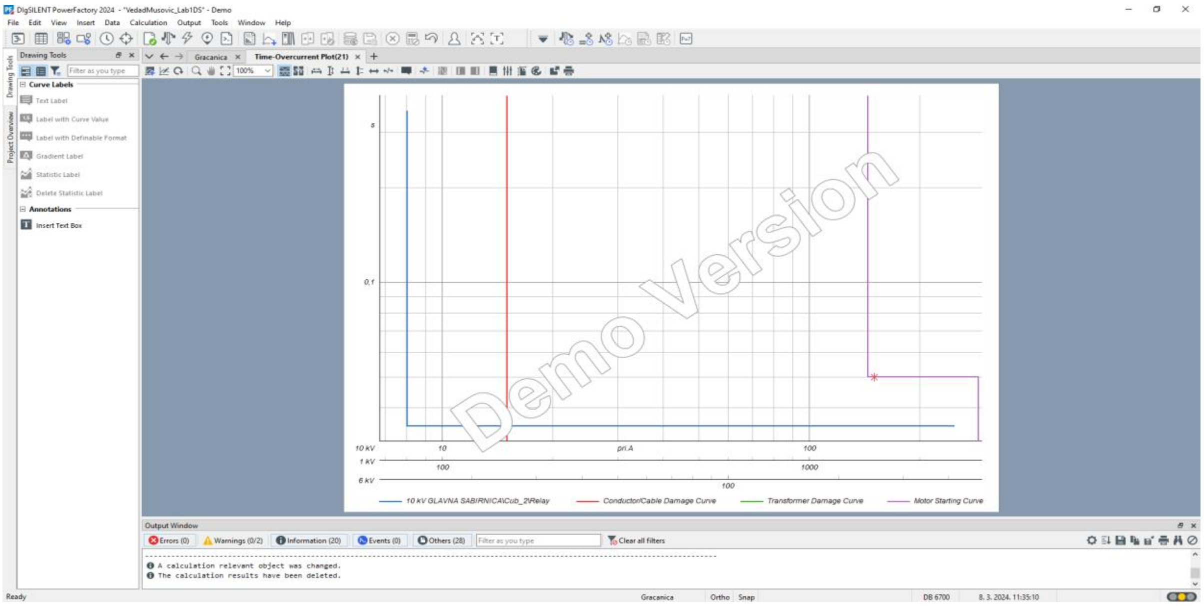


Figure 17. The Time-Overcurrent Plot for the Backup Relay

The Time-Overcurrent Plot for the backup relay is finally obtained. The transformer damage is not present after we are not at the sides where transformer is. However, the motor starting curve will still be present, since the synchronous machine is in the network.

Since we are working at a cable, the conductor / cable damage curve is our main concern. The cub relay will trip the current eventually. The cub relay curve will intersect conductor / cable damage curve. This occurs at a certain time. However, still, the relay will react to high currents, promptly.

When overcurrent occurs, the relay transitions from a slower response mode to a faster response mode. This intentional delay is beneficial as it allows the relay to wait and observe if the system returns to normal on its own.

Moreover, since the fault is at the same busbar as the relay itself, it is expected that the relay's response will be a type of a step response, when the relay curve drops suddenly. It will trip the faulty current early into the process, so it definitely tackles it early on.

Additionally, current setting and time dial are adjusted by clicking on the particular curve on the Time-Overcurrent Plot. By clicking on the particular cub relay curve, we have different points shown and we click on them in order to obtain the additional information about the fault currents.

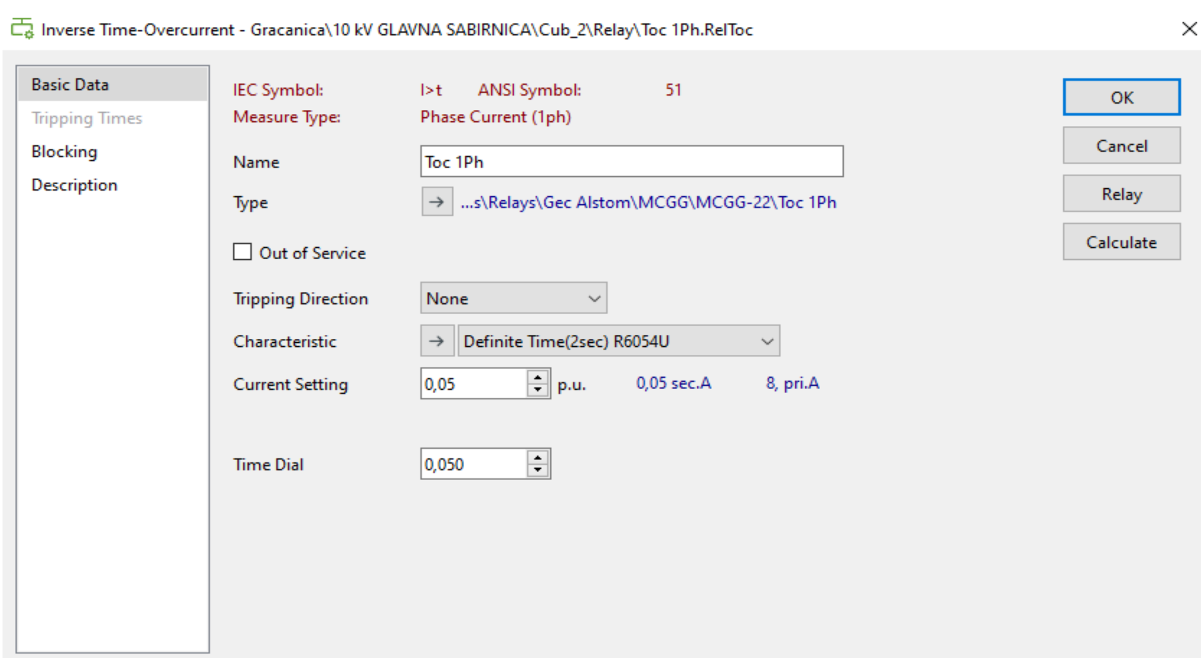


Figure 18. Adjusting the Plot Data to Change the Graph

As observed, the cub relay curve will change accordingly after making changes in parameters.

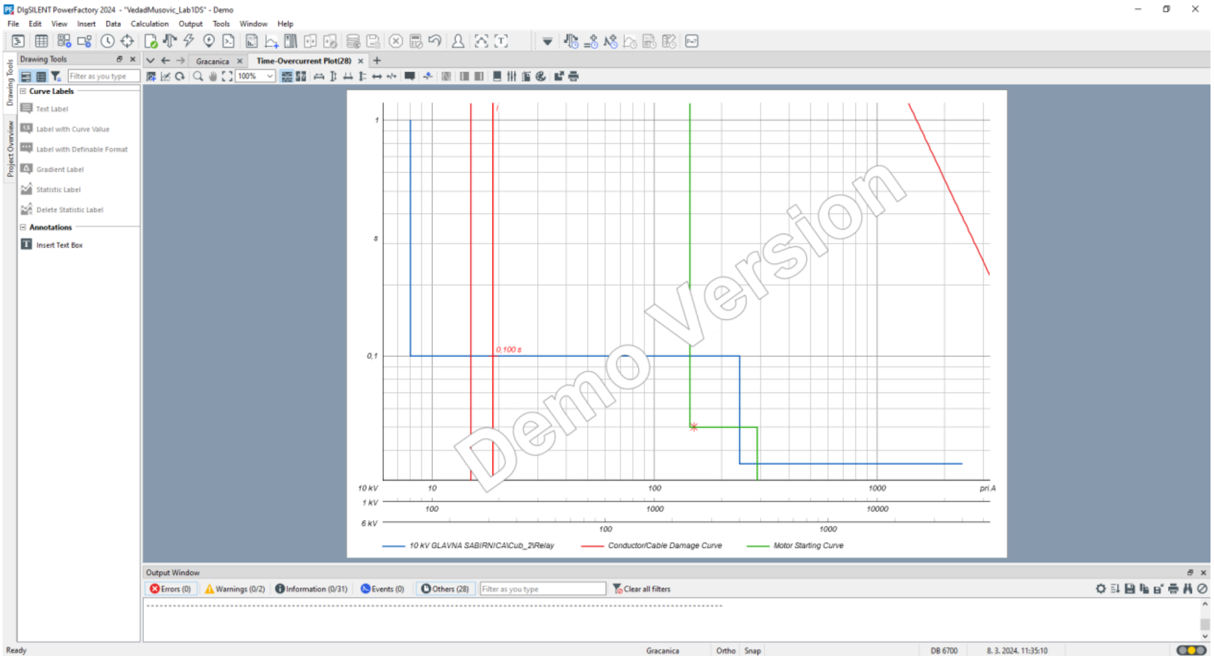


Figure 19. Changes on the Graph and the Information obtained by clicking on it

As mentioned in the previous sections, relay has its complex design which we can see by viewing his Properties. It consist of current transformers (the two current values chosen), the measure block, two current block, and finally two logic blocks which generate binary output – logic 0 or 1.

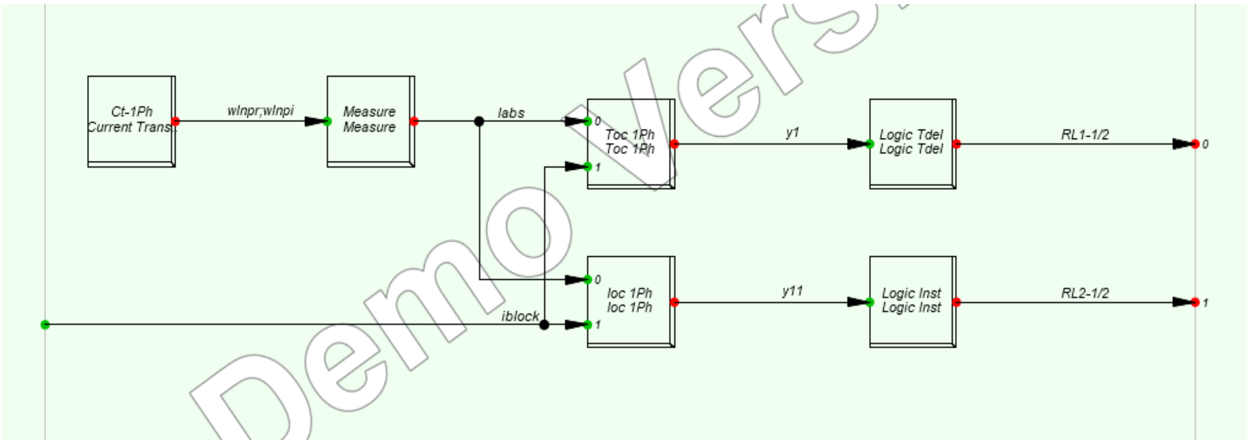


Figure 20. The Components of a Protection Relay

5. Conclusion

In this Lab, we studied how protective relays work in electrical networks when a short circuit occurs. These relays are like guards that watch for problems like excess electricity flowing.

We learned that they are set up in different places, like near transformers, to keep an eye on things. We saw that when there is a short circuit, these relays act fast to stop the problem from spreading and causing damage. This will almost represent the certain type of a step response plot.

By using DIgSILENT Power Factory, we could see how the relays react to different situations. We also found out that there are primary relays, which are like the main guards, and backup relays, which are like extra helpers in case the main ones are not able do the job alone. Through the experiments, we saw graphs on how the relays respond to different levels of short-circuits / faults.

Sometimes they act quickly, and sometimes they take a bit longer to make sure it is a real problem. We added both asynchronous and synchronous machines into the network to see how they affect the graphs and how the relays interact with them. It was important to see how changing settings on the relays affected their behavior in the graphs.

LAB 12 - INTEGRATION OF ELECTRIC VEHICLES (POWERFACTORY)

1. Introduction

In Lab 12, we will explore the integration of electric vehicles (EVs) into the power distribution network. Our primary goal is to simulate how EVs charge and discharge when connected to a charging station. We will achieve this by modeling EVs as generators, which will allow us to replicate their behavior as they interact with the electrical grid. By setting the EVs in the storage category and defining their nominal apparent power, we can accurately simulate their charging and discharging cycles.

One important aspect of this task is performing a harmonic analysis. Harmonics are additional frequencies introduced by the power electronics in EV chargers, which can deviate from the main frequency of the power supply. These harmonics can cause voltage distortions that may affect the performance and power quality of electrical equipment.

In this analysis, we will change the load type of every load component in the network to Current Source, as harmonics typically originate from consumers. By configuring the harmonic model as Thevenin's Equivalent, we can evaluate the presence and impact of harmonic currents and voltages in the system. We will compare two scenarios: one before connecting the synchronous machine to the system and the other after its connection. Additionally, the cases with both low and high harmonic source currents will be taken into account.

Through this laboratory task, we aim to understand the harmonic characteristics of the EV charging and discharging process and assess any potential issues related to harmonics. This knowledge is crucial for managing the growing integration of EVs into our power systems, ensuring that we maintain power quality and system stability.

2. Theory

Electric vehicles (EVs) have become a promising solution for tackling environmental issues and reducing our dependency on traditional fossil fuels. However, integrating EVs into the power distribution network introduces both opportunities and challenges for managing the power system. A critical factor to consider is the impact of EVs on harmonic voltages within the network. These harmonics, which are additional frequencies differing from the main power supply frequency, are generated by the power electronics in EV chargers.

As the use of EVs increases, so does their effect on harmonic voltages in the distribution network. These harmonics can lead to voltage distortions that negatively affect power quality and the performance of electrical equipment. Problems such as increased heating, lower power factor, and interference with sensitive electronics can arise due to these distortions. The growing number of EVs and their charging requirements can exacerbate these issues, placing additional stress on the distribution network. If not properly managed, the higher harmonic voltages introduced by EVs can compromise the grid's capacity and stability. Harmonics are additional frequencies generated when a periodic waveform deviates from its ideal form, often occurring as multiples of the fundamental frequency.

They arise due to nonlinear operations or distortion in a signal, enriching its tonal characteristics. Overall, harmonic analysis is crucial for assessing power quality and ensuring efficient operation of electrical systems. The analysis of power quality involves examining the harmonic content of voltages and currents, which can be done in either the frequency domain or the time-domain using Fourier analysis. DIGSILENT offers various functions for harmonic analysis, including the Harmonic Load Flow and Frequency Sweep. The Harmonic Load Flow function calculates harmonic indices related to voltage or current distortion caused by non-linear loads. It analyzes steady-state network conditions at each frequency defined by harmonic sources.

This function can also assess flicker disturbance factors in wind turbine generators according to IEC standards. Frequency Sweep, on the other hand, performs continuous frequency domain analysis, useful for calculating network impedances and identifying resonance points. Both functions can consider contingencies to analyze network behavior under different fault cases.

3. Procedure

Firstly, every load has its load type already set to General Load Type. Inside of window for defining it, we change the load type from Impedance to Current Source. By doing it, we create nonlinear loads at every single place where a load is located. Most of them are at 0.4 kV busbars.

The second step includes adding a Synchronous Machine to the Network. We add it at 0.4 kV sabirnica (4), which is at 10 (23) busbar. This location is shown in Figure 1.

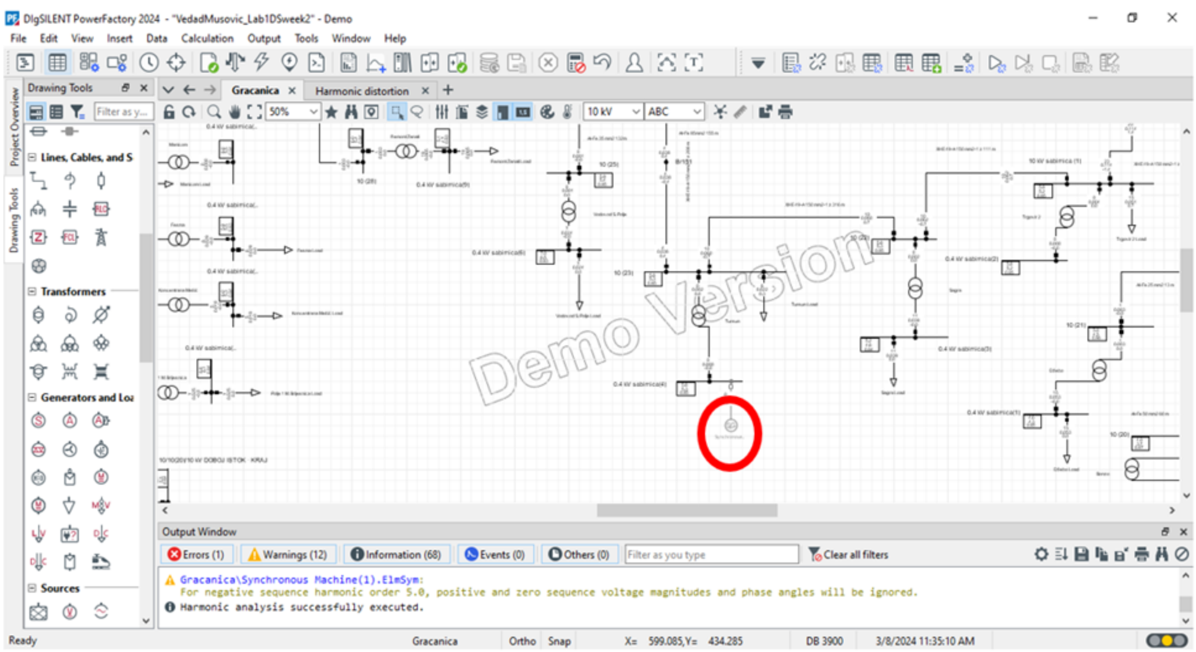


FIGURE 1. The Location of the Synchronous Machine

The output power is 2 MVA, with the voltage set to 6 kV at 0.8 power factor. Figure 2 shows this.

Inside of Power Quality / Harmonics window, we set harmonic voltages for the 5^{th} and 7^{th} harmonic. For the 5^{th} we chose 0.6 p.u, and for the 7^{th} 0.9 p.u. Figure 3 represents this.

Additionally, inside of the Synchronous Machine, inside Power Quality / Harmonics, we set the Harmonic Model as Thevenin's Equivalent. After this we are set for the Harmonic Load Flow Analysis, whose window is depicted in Figure 4.

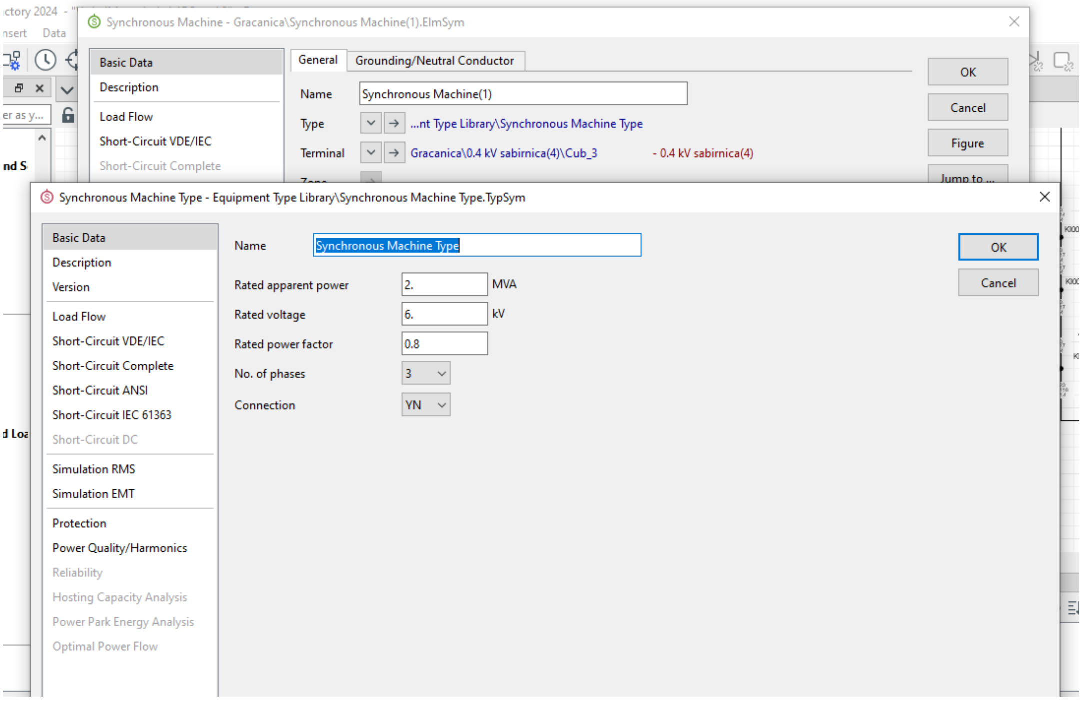


FIGURE 2. Synchronous Machine Type Window

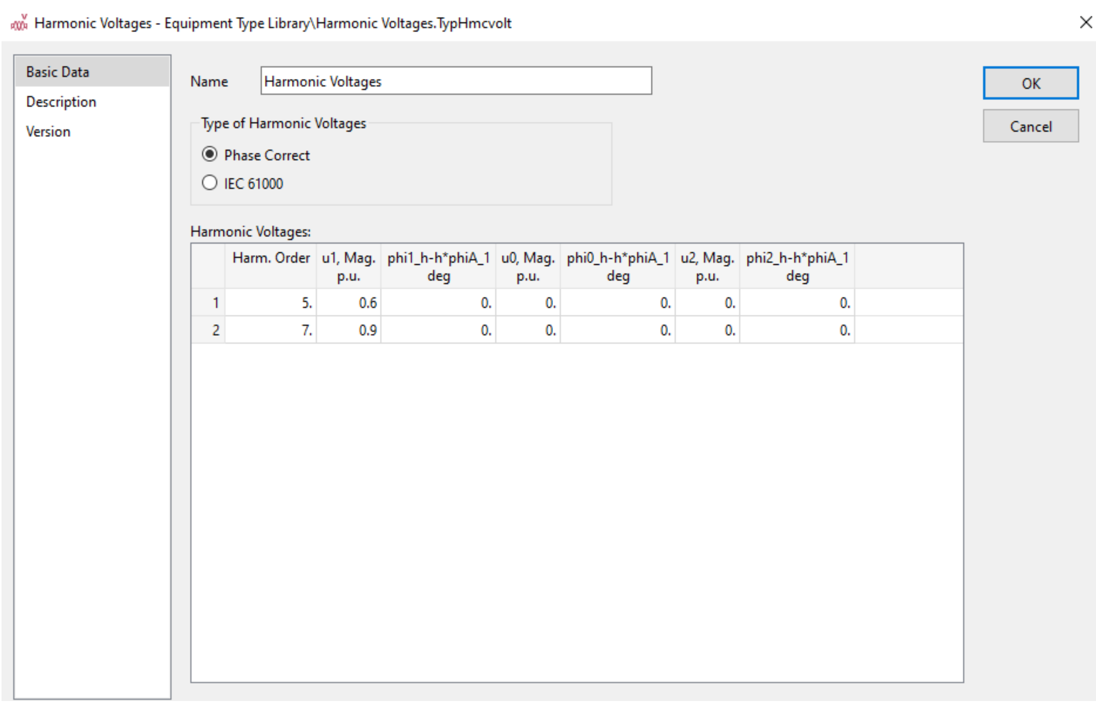


FIGURE 3. Harmonic Voltages Window

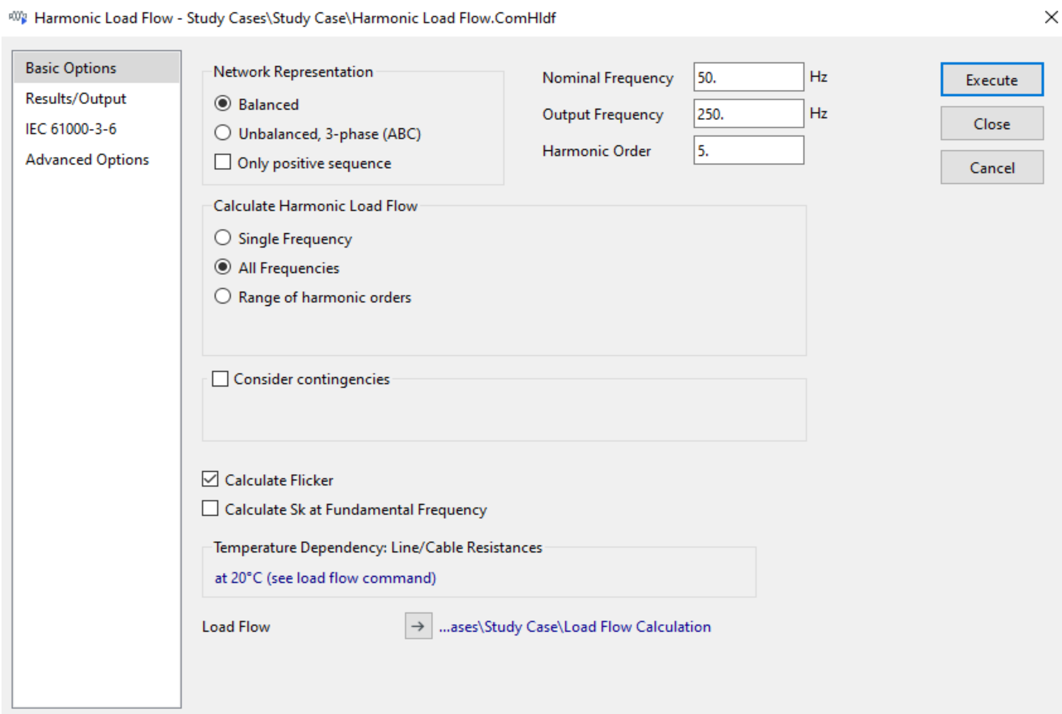


FIGURE 4. Harmonic Load Flow Window for Execution

After setting everything up, we will conduct the analysis for two different cases for two different network configurations.

The voltage values for the 5^{th} and 7^{th} harmonic allow us to specifically observe and evaluate the impact and behavior of these particular harmonics in our system.

Firstly, before connecting the synchronous machine (when it is switched off), we will conduct the analysis for lower and higher magnitudes of harmonic currents.

Secondly, after the synchronous machine is connected (switched on), we will conduct the analysis for lower and higher magnitudes of harmonic currents.

These means that both cases have two cases for themselves. This creates a total of four cases.

4. CASE I – BEFORE ADDING THE SYNCHRONOUS MACHINE

In this case, we are conducting harmonic analysis before implementing synchronous machine.

4.1. Lower Magnitudes of Harmonic Currents

As seen, for each load in the network, Harmonic Sources have 5th harmonic current set to 5% and 7th harmonic current to 1.5%. This is seen in Figure 5.

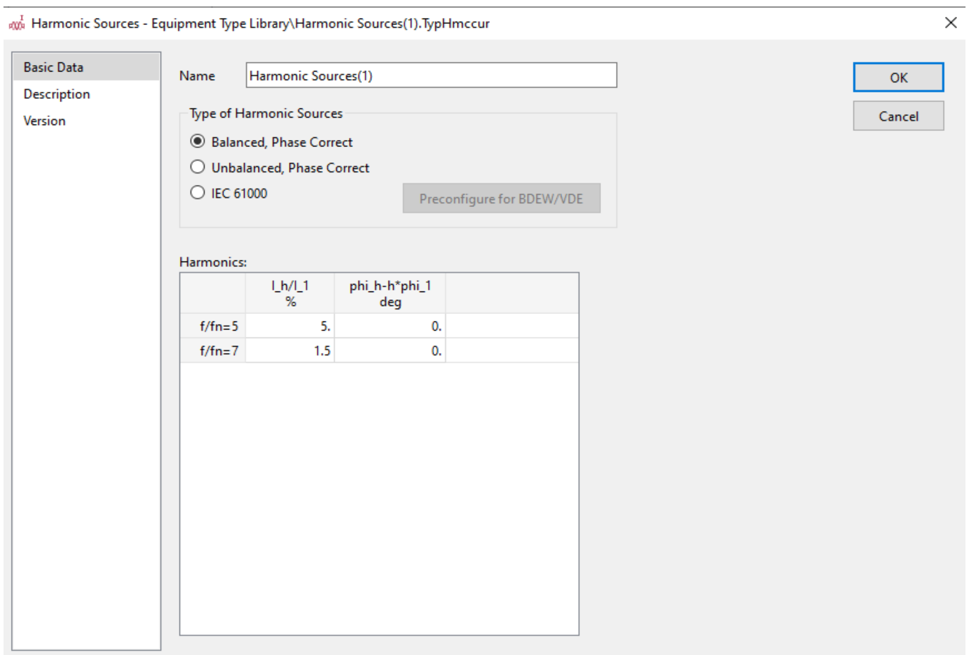
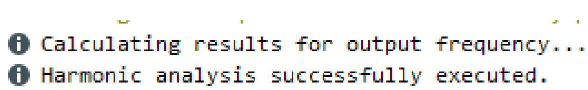


FIGURE 5. Harmonic Sources for Lower Harmonic Current Magnitudes

We recall Figure 4 and go to Calculation tab. We click Power Quality / Harmonics and click Harmonic Load Flow and execute it.



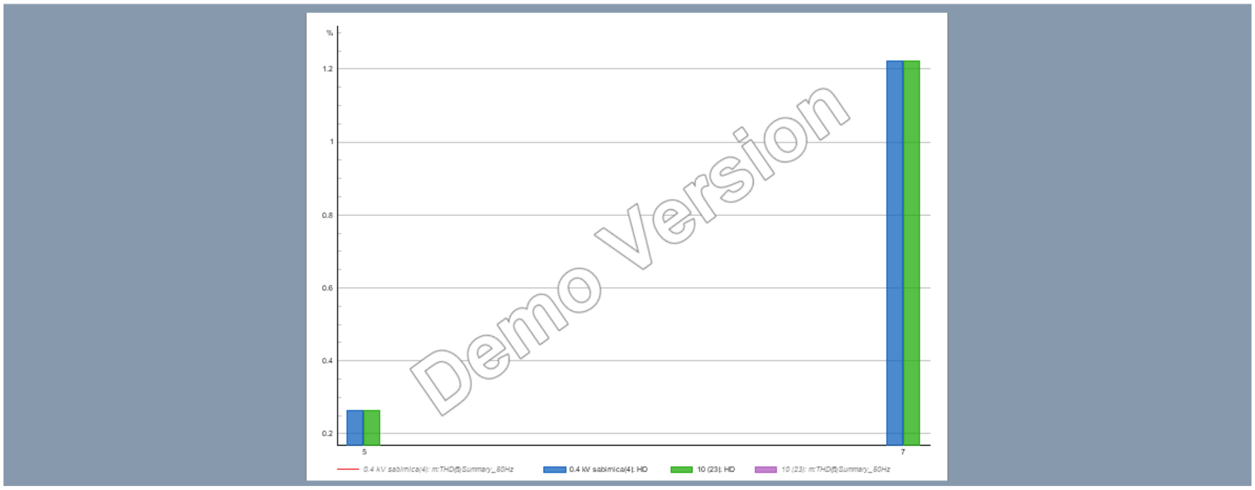


FIGURE 6. Harmonic Distortions (HDs) at 0.4 kV sabirnica (4) and 10 (23) Busbar

As seen in Figure 6, at the two busbars, the harmonic distortions are at 0.2 for the 5th and 1.2 for the 7th harmonic. This is expected, since 7th harmonic typically have larger % rise of harmonic distortions, due to a combination of nonlinear load characteristics and impedance profile.

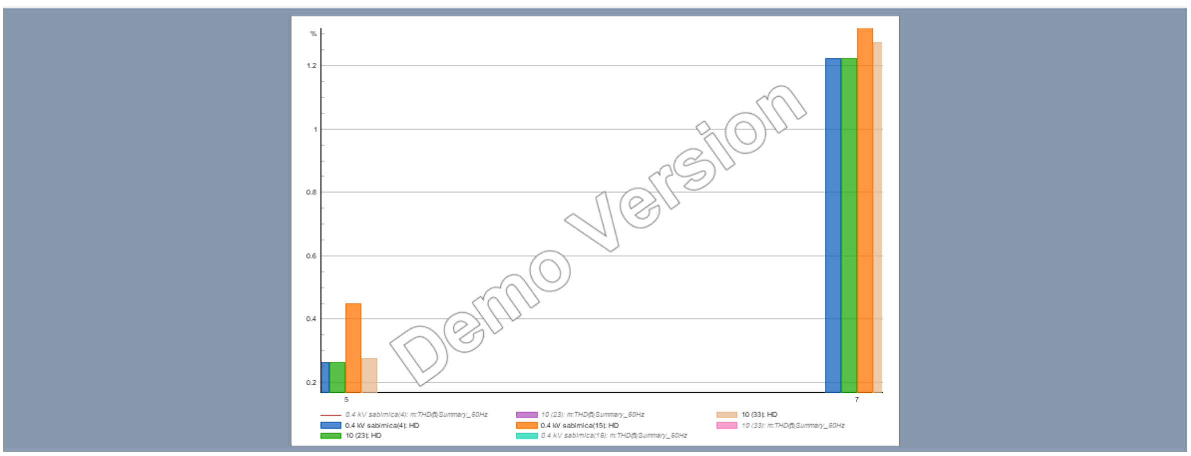


FIGURE 7. HDs at other Busbars

In Figure 7, we took the graphs of some additional 0.4 kV and 10 kV busbars in our network. They are all approximately the same, except for one 0.4 kV busbar which has slightly higher rises at the 5th harmonic, compared to other busbars. This is due to its nonlinear load having higher values.

4.2. Higher Magnitudes of Harmonic Currents

In Figures 8 and 9, As seen, for each load in the network, Harmonic Sources have 5^{th} harmonic current set to 30% and 7^{th} harmonic current to 10%. The rises in % harmonic distortions are going to extreme, and much higher than 1.2%, as we see that our graph cannot even truly represent these values. From this, we conclude that harmonic currents are not allowed to have these high values.

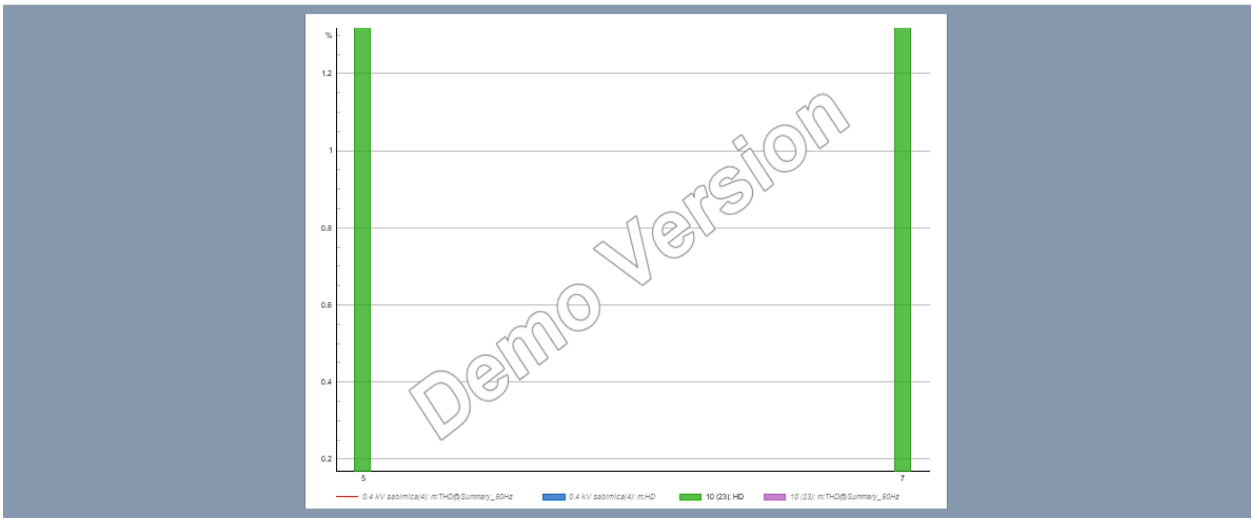


FIGURE 8. HDs at 0.4 kV sabirnica (4) and 10 (23)

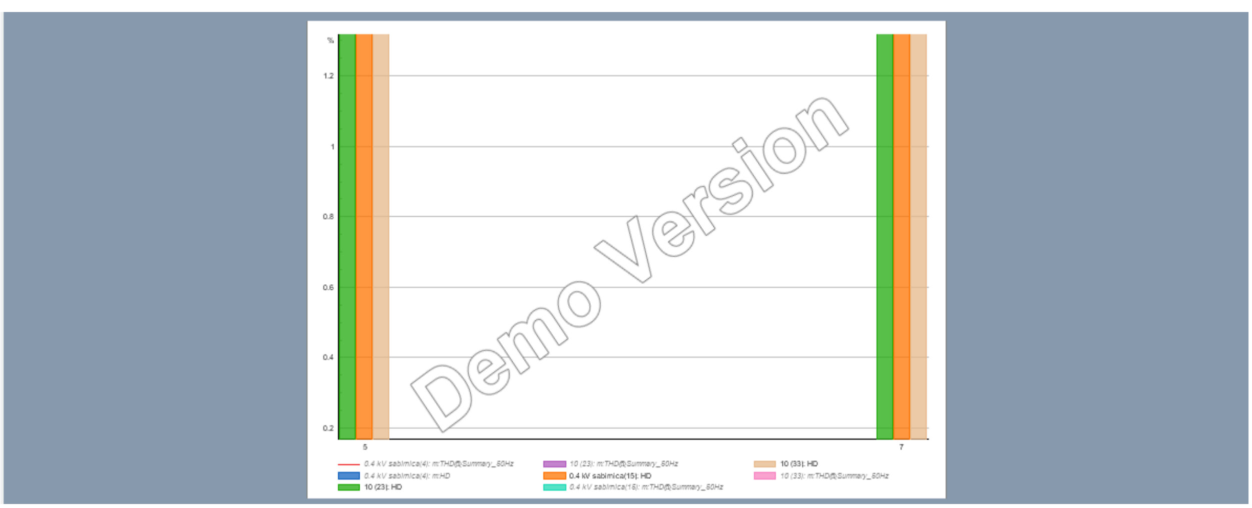


FIGURE 9. HDs at different Busbars

For the appropriate values, we have to lower harmonic current. This time, they are set to 10% for the 5th, and 5% for the 7th harmonic. This is seen in Figure 10.

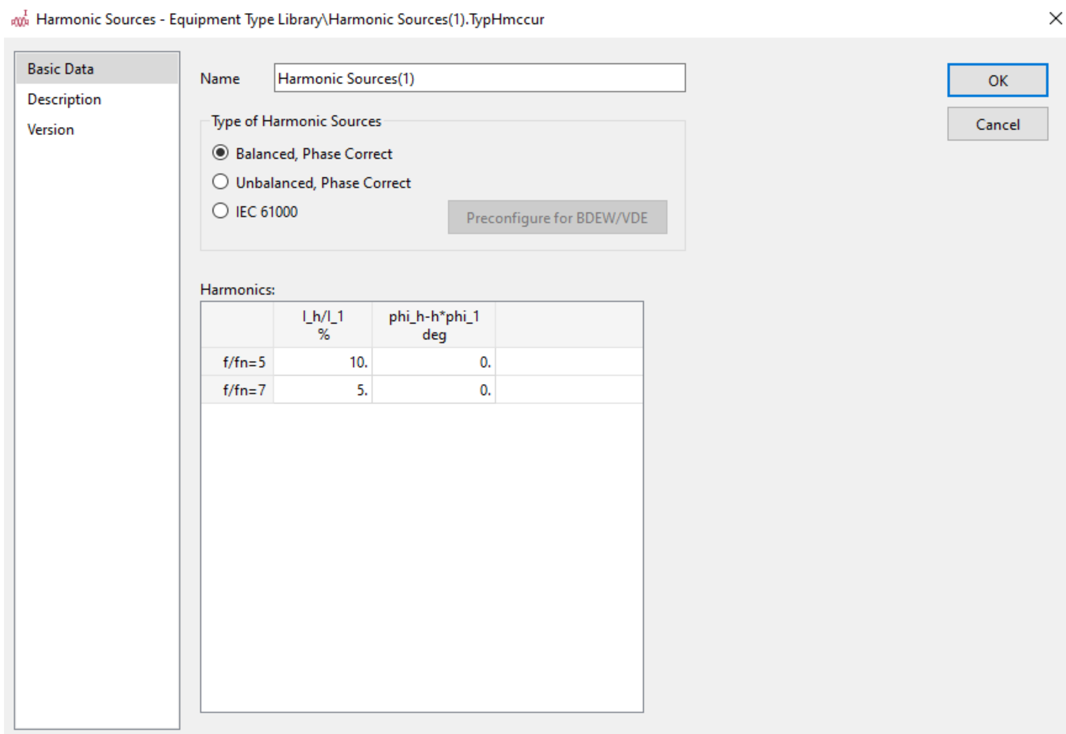


FIGURE 10. Harmonic Sources for Higher Harmonic Current Magnitudes

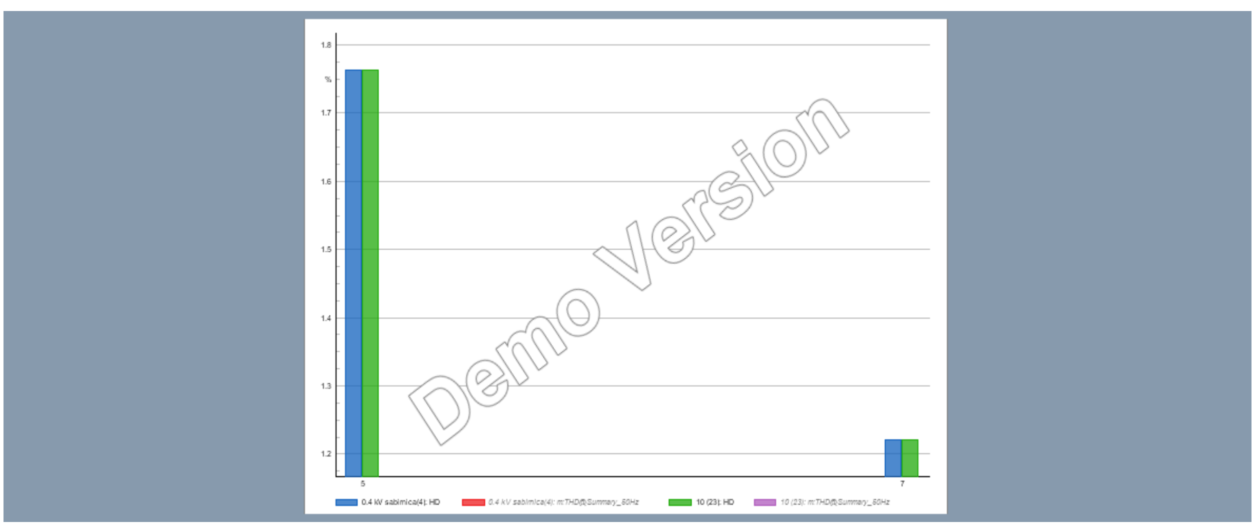


FIGURE 11. HDs at 0.4 kV sabirnica (4) and 10 (23) Busbar

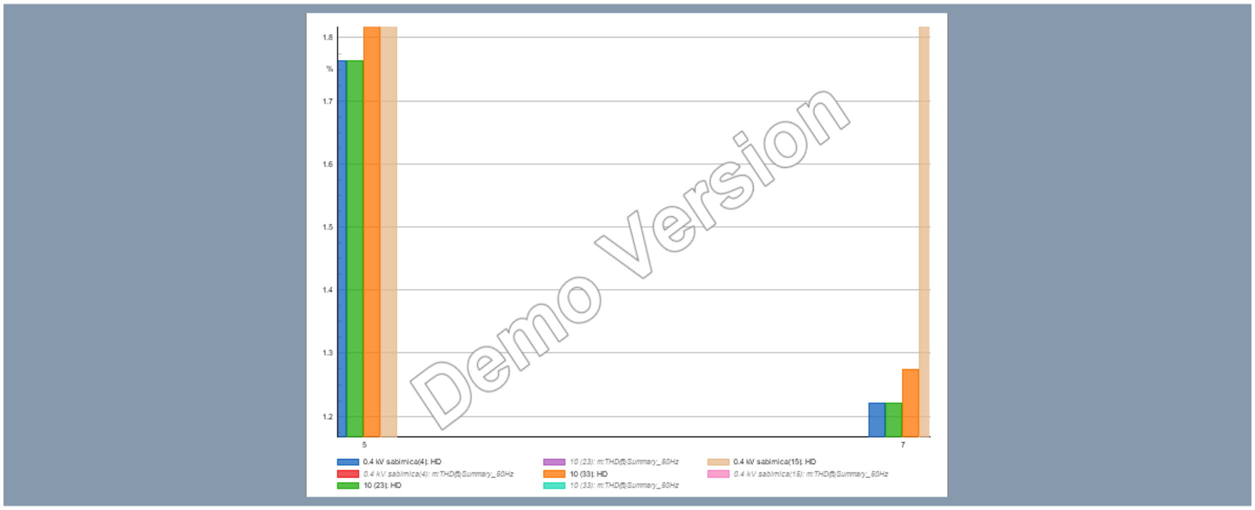


FIGURE 12. HDs at different Busbars

As seen in Figure 11, at the two busbars, the harmonic distortions are at 1.75 for the 5th and 1.2 for the 7th harmonic. With increased harmonic currents, the 5th harmonic has larger % rise of harmonic distortions, due to a combination of nonlinear load characteristics and impedance profile. Compared to the case with lower harmonic currents, we are having higher HD % rises.

Higher harmonic currents increased HDs at 5th harmonic significantly, while the change is very small at the 7th harmonic. As we observe the graphs in Figure 12, we conclude that the harmonic distortions overall have approximately the same values at the 5th harmonic (at different busbars).

At the 7th harmonic, they vary to a small extent, without major differences, unless at a certain busbar, one nonlinear load has significantly higher power ratings.

5. CASE II – AFTER ADDING THE SYNCHRONOUS MACHINE

This case includes adding a Synchronous Machine to the Network. We add it at 0.4 kV sabirnica (4), which is at 10 (23) busbar. This location is shown in Figure 1.

5.1. Lower Magnitudes of Harmonic Currents

As seen, for each load in the network, Harmonic Sources have 5th harmonic current set to 5% and 7th harmonic current to 1.5%. This is seen in Figure 5.

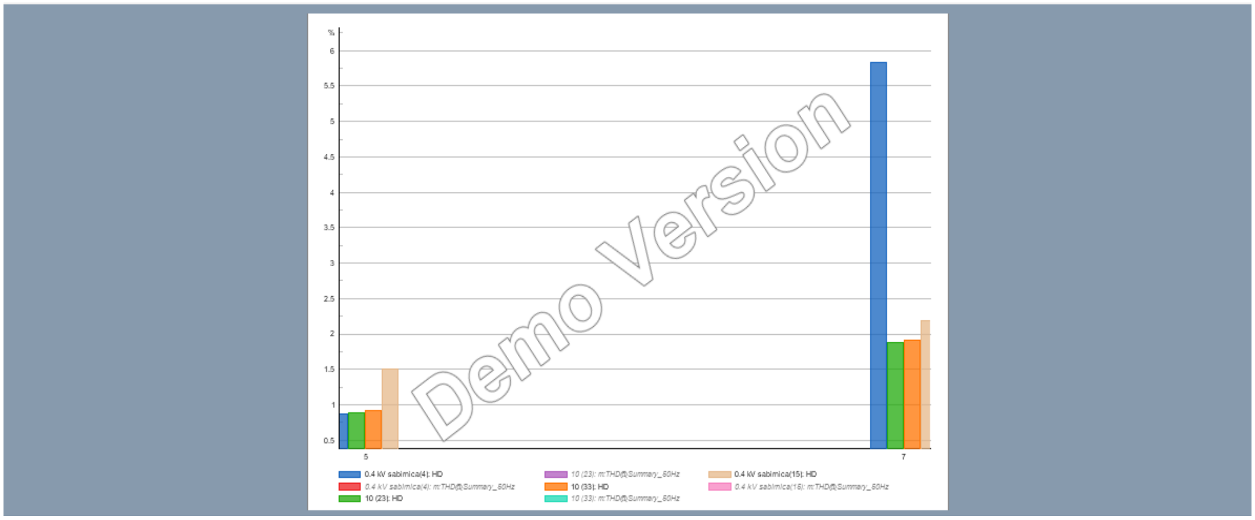


FIGURE 13. HDs at different Busbars

As seen in Figure 13, at 5th harmonic, the values of harmonic distortion are ranging from 1 to 1.5 %. At the 7th harmonic, the values at all busbars are around 2%, except at the 0.4 kV busbar. The value of its harmonic distortion is nearly 6%. This shows the effect of adding an electric vehicle to the network and we see its charging and discharging from these graphs.

5.2. Higher Magnitudes of Harmonic Currents

This time, the harmonic currents are set to 10% for the 5th, and 5% for the 7th harmonic. This is seen in Figure 10. The changes in the graphs are observed.

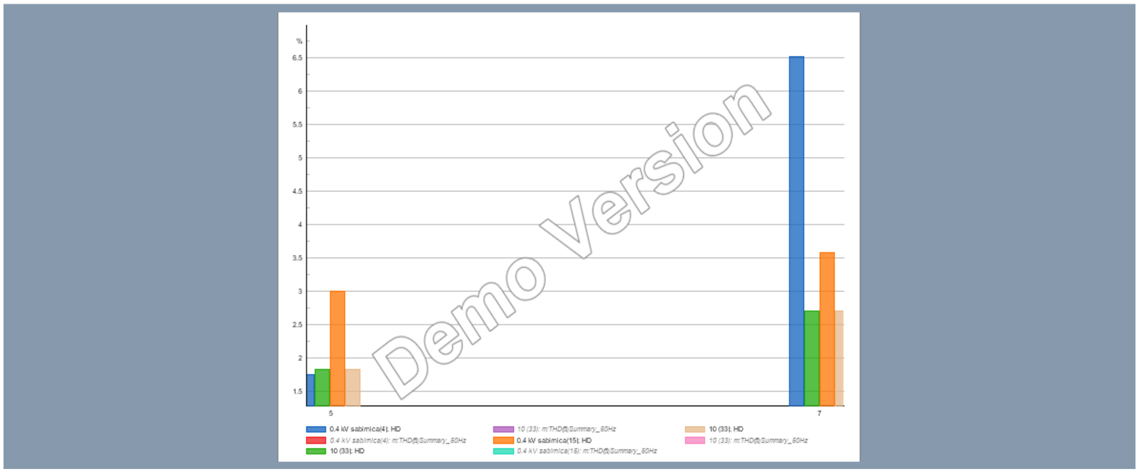


FIGURE 14. HDs at different Busbars

Figure 14 represents the observations seen when we increase the harmonic source currents for the nonlinear loads in our network. The harmonic distortions at the 5th harmonic rise to close to 2%. The only apparent rise is present at a 0.4 kV busbar, but not the one where is synchronous machine.

At the 7th harmonic, the values of harmonic distortions will rise to different values between 2.5 % and 3.5 %. The 0.4 kV busbar, where the electric vehicle is added, has harmonic rises from 6% for lower harmonic currents, to 6.5% for higher harmonic current levels.

Overall, when adding electric vehicle, we have changes occurring with both 5th and 7th harmonic, with low and high harmonic source current values set. Harmonic distortions will exhibit a significant location at a particular busbar where the electric vehicle is placed.

6. Conclusion

This lab demonstrates the significant impact of electric vehicles (EVs) on harmonic voltages in a distribution network. By modeling EVs as generators and simulating their charging and discharging cycles, we gained insights into the harmonic distortions they introduce. The harmonic analysis reveals that nonlinear loads affect power quality, particularly at the 5th and 7th harmonic.

Before connecting the synchronous machine, the network experienced harmonic distortions, especially at higher (%) magnitudes of harmonic currents. This shows the importance of managing harmonic currents to prevent voltage distortions. The addition of the synchronous machine showed how harmonic distortions can vary with different network configurations and loading conditions.

Our analysis showed that the harmonic distortions at the 0.4 kV busbars were more apparent, compared to the 10 kV busbars, showing the sensitivity of lower voltage levels to nonlinear loads. The synchronous machine also influenced the harmonic behavior.

Overall, the results confirmed that the increasing presence of EVs in power distribution networks is challenging for maintaining power quality. Effective harmonic management is crucial to ensure grid stability and the reliable operation of electrical equipment. Solutions include advanced control strategies, harmonic filters, or optimized network configurations. By implementing appropriate measures, we can support the transition to a more sustainable energy future.

CONCLUSION

This complete lab report offers a detailed analysis of various aspects of power system engineering, using DIgSILENT PowerFactory as a primary analytical tool for a total of 10 specific labs. The analysis begins with network modeling, where parameters are defined and integrated, either from scratch or based on existing representations. This foundational model enables simulations to evaluate network performance and propose potential strategies for expanding our network.

Power flow analysis, or load flow study is as a fundamental component, employing numerical methods to calculate electric power flow in the interconnected system. Simplified notations, such as single line diagrams and per-unit systems, enable the analysis of key AC power parameters. This study focuses on the steady-state operation under normal conditions, providing insights into voltage magnitudes, angles, real power, and reactive power distribution.

Short circuit analysis is crucial for understanding the network behavior during fault conditions. By simulating various faults, we can identify potential risks and ensure that protective devices are able to handle fault currents. This step is crucial for maintaining system reliability and safety as networks evolves and short circuit currents increase.

Integration of renewable energy sources is another significant method, emphasizing the use of distributed generation, energy storage, and demand response. This integration considers technical, economic, regulatory, and institutional problems. The development of business models for renewable technologies is also explored, ensuring their effective incorporation into the grid.

Optimal capacitor placement is examined to improve voltage profile and correct power factor while minimizing costs. Through advanced graphical interfaces and precise calculation methodologies, optimal capacitor bank locations and sizes are determined. This strategy improves voltage profile and reduces both active and reactive losses, contributing to network efficiency.

Harmonic analysis deals with decomposition of complex waveforms into basic components, extending the principles of Fourier series. The presence of harmonics in the system can cause voltage distortions and power quality issues, needing analysis to ensure the system performance.

The concept of hosting capacity is introduced to evaluate the maximum integration of renewable energy without negative effects. As the use of electric vehicles (EVs) increases by day, their charging activities add harmonics to the distribution system, affecting voltage quality. Different strategies are discussed to maintain performance and reliability.

Protection schemes are vital for protecting electrical circuits against faults and irregularities. This report analyses the role of protective devices, such as relays, in detecting abnormalities and isolating faulty sections. Proper setup and placement of these devices are crucial for reliable system operation, especially primary and secondary-level relays.

In conclusion, this complete lab report provides valuable insights into the design and optimization of modern electrical distribution systems in DIgSILENT PowerFactory. Through detailed analysis and simulations, it focuses on critical aspects of power system engineering, ensuring quality and efficient network performance. The findings determine the high importance of integrating advanced technologies and strategies to meet the evolving demands of the electrical grid.