ANALYSIS OF THE INTEGRATION OF NEW ENERGY SOURCES AND AN ENERGY STORAGE SYSTEM INTO AN ELECTRIC NETWORK AREA OF THE POWER SYSTEM

ANALIZA INTEGRĂRII UNOR NOI SURSE DE ENERGIE ȘI A UNEI INSTALAȚII DE STOCARE ÎNTR-O ZONĂ DE REȚEA ELECTRICĂ DIN SISTEMUL ELECTROENERGETIC

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Abstract: *This paper presents an analysis of the integration of a wind power plant, a battery storage system, and a natural gas power plant in an electrical grid area within the power system. The results of the simulations performed highlight the impact of the integration of these energy sources and the energy storage system on voltage stability, the loading of the electric grid elements, and power losses, both under normal and contingency operating conditions. The proposed methodology can be applied to evaluate and optimise other similar grid areas.*

Keywords: power system, wind power plant, energy storage system, natural gas power plant.

Rezumat: *Lucrarea prezintă analiza integrării unei centrale electrice eoliene, a unei instalații de stocare cu baterii de acumulatoare și a unei centrale electrice pe gaze naturale într-o zonă de rețea electrică din cadrul sistemului electroenergetic. Simulările efectuate evidențiază impactul integrării acestor surse de energie și a instalații de stocare asupra stabilității tensiunii, a gradului de încărcare a elementelor rețelei electrice și a pierderilor de putere, atât în condiții normale de funcționare, cât și în condiții de contingență. Metodologia propusă poate fi aplicată în evaluarea și optimizarea altor zone de rețea electrică similare.*

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Cuvinte cheie: sistem electroenergetic, centrală electrică eoliană, instalație de stocare a energiei, centrală electrică pe gaze naturale.

1. Introduction

The integration of renewable energy sources (RES) into an electrical network area, part of the power system (PS), introduces issues regarding voltage stability, maintaining the balance between electricity generation and demand, as well as the analysis of steady-state operating conditions of the PS. Studies conducted in network areas characterized by a high density of RES, such as Dobrogea region in Romania, highlight the significant impact of these new energy sources on the operating parameters of the PS [1].

This article presents an electrical grid area operating at a nominal voltage of 110 kV located in Dobrogea region, in which the integration of a wind power plant (WPP), a battery energy storage system (BESS), and a natural gas power plant (NGPP) as a backup power source is analysed. The simulations were performed using the NEPLAN software (version 5.5.5), starting from a reference steady-state regime of the analysed electrical network.

This analysis requires defining and evaluating a grid area where new electricity sources will be connected, assessing the operating conditions after the integration of the new energy sources, and developing new specific operating scenarios, by modifying the power generation of the new energy sources to evaluate the grid's behaviour under load conditions [2].

BESS contributes to the integration of RES, the maintenance of PS stability, reducing losses, and can provide ancillary services such as Frequency Containment Reserve (FCR) or Frequency Restoration Reserve (aFRR or mFRR). Although the costs for BESS are still considerable, decreasing prices, increasing performance, and implementing national strategies to encourage their integration into the electricity systems may make them more attractive in the near future [3, 4].

In the energy mix, the integration of reserve sources is essential for maintaining flexibility in the operation of PS. NGPPs are used due to their high operational flexibility to compensate for the variability of RES electricity generation, contribute to reducing the demand on classic power plants, and increase the operational security of the PS with a high share of RES [5, 6].

The results obtained allow a detailed assessment of the impact of integrating new energy sources and energy storage systems (ESS) on power system operations and support the technical validation of the proposed solutions.

2. Principles of verification and implementation of steady-state regimes for the integration of new energy sources into the analysed electrical network area

To verify the integration of new energy sources and ESS in a grid area, network models are built to correspond to representative operating conditions of the PS [7]:

- *Reference steady-state regime (RSR)*: a stable operation regime of the PS, including both existing power plants and new generation capacities that have approved grid condition studies;
- *Stressed steady-state regime (SSR)*: corresponds to the occurrence of demand situations in PS operation and is developed based on the reference steady-state regime with the aim of simulating the impact of commissioning new energy sources on the existing grid.

In the operational management of the PS, load curves play a particularly important role, especially daily and annual load curves. The daily load curve provides essential information regarding the evolution of electricity demand during the day and is the basis for planning the operation of electricity production sources [8].

In order to size the capacity of a network area within the PS, several characteristic levels of the load curves are analysed. These include [7]:

- *Winter evening peak load (WEP)*: a working day with low temperatures;
- *Summer morning peak load (SMP)*: a summer morning on a working day;
- *Winter morning peak load (WMP)*: a winter morning on a working day;
- *Summer night minimum load (SNM)*: a holiday night during the summer period.

The study evaluates the reference steady-state and stressed steady-state regimes of the electrical network, corresponding to the characteristic levels on the load curve. The results are analysed for the configuration with all the elements of the grid in operation (N elements) and for the configuration with one grid element disconnected (N-1 elements), using steady-state calculations according to the specialized methodology [10, 11].

The modelling of the energy sources and the ESS is carried out depending on its type and the characteristic level analysed according to Table 1.

Table 1. **Loading of existing power plants, as a percentage o f installed capacity, to achieve the reference steady-state regimes at different characteristic levels of the load curve [7]**

Energy source	**Characteristic levels of the load curve**			
	WEP	**WMP**	**SMP**	**SNM**
WPP	30%	30%	20%	20%
PVPP	0%	65%	65%	0%
NGPP	According to merit order	According to merit order	According to merit order	According to merit order
ESS	100% discharging	100% discharging	100% discharging	100% charging

Assumptions established for stressed steady-state regimes [7]:

- For a conventional power plant or a RES, their operation will be considered at 100% of the installed capacity, both in the operating regimes with N and N-1 elements in operation, in order to evaluate the maximum loading conditions in critical scenarios;
- In the case of ESS integration, it will be considered at 100% of installed capacity, both in the operating regimes with N and N-1 elements in operation, in accordance with the specific requirements of the user.

The stressed steady-state regimes are achieved by applying loading assumptions to the existing power plants, depending on the type of new electricity source analysed and the characteristic level of the load curve. Table 2 presents the loading criteria used in the simulations.

Table 2. **Loading assumptions for existing power plants, as a percentage of installed capacity, depending on the new integrated facility at different characteristic levels of the load curve [7]**

New facility	**Loading of the new facility**	**Type of existing power plants**			
		WPP	**PVPP**	**NGPP**	**BESS**
RES	100%	85% (WEP/WMP, SMP, and SNM)	80% (SMP), 30% (WMP)	According to RSR	Discharging 100% (WEP/WMP, SMP), 100% Charging (SNM)

New facility	Loading of the new facility	Type of existing power plants			
		WPP	PVPP	NGPP	BESS
NGPP	100%	According to RSR	According to RSR	According to RSR	According to RSR
BESS	Discharging 100% (WEP/WMP, SMP), 100% Charging (SNM)	According to RSR	According to RSR	According to RSR	Discharging 100% (WEP/WMP, SMP), 100% Charging (SNM)

3. Overview of the analysed electrical network

The analysed electrical network is part of the 110 kV electrical distribution network in Dobrogea, Romania, being a strategic area due to the favourable conditions for RES energy generation, especially from WPP [1].

The electrical network consists of overhead power lines (OHL) and electrical transformer substations, which ensure both the evacuation of electricity generated by RES and the supply of local users. The electrical network was modeled in NEPLAN software, by implementing 23 110/20 kV power stations (numbered from N1 to N23), 37 OHLs with AL-OL type active conductors, and two connection power stations with the PS, operating at 400/110/20 kV. In total, the analysed network comprises 29 nodes: N1 to N23, A1, A2, B1, B2-110 kV, A-400 kV and B-400 kV.

The electricity generation sources are represented by 12 WPPs and one PVPP, which evacuated the electricity generated in the analysed 110 kV network. The connection nodes with the PS are represented by the A-400 kV and B-400 kV nodes, as well as their associated busbar systems A1, A2, B1 and, B2-110 kV. The analysed network includes three power transformers (400/110 kV) with a nominal apparent power of 250 MVA each, which contribute to voltage regulation, maintaining the continuity of electricity supply to local users, as well as the evacuation of additional electricity generated by RES. Figure A.1 in the appendix presents the single-line diagram of the analysed grid area, modelled using the NEPLAN software.

Figure 1 presents the measured values of the active electrical power demand of users in the analysed electrical network area, depending on the time of year, as well as the total installed capacity of RES connected to this grid.

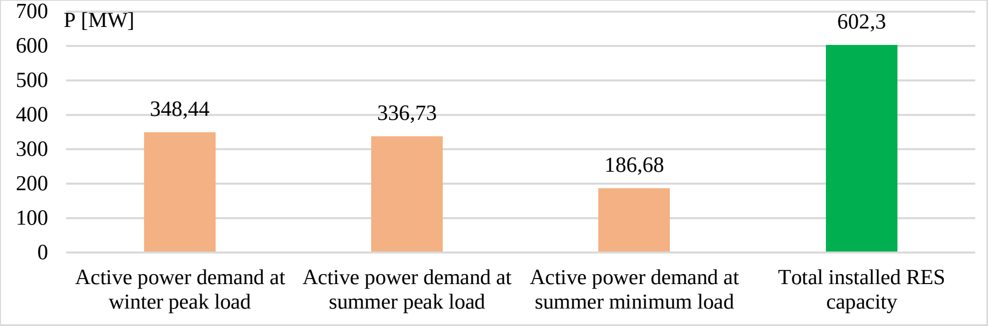

Figure 1. Active power demand of users depending on the analysed characteristic level and the total installed capacity of existing RES [9]

4. Scenarios and steady-state regimes calculated for the integration of a renewable energy source, an energy storage system, and a reserve power source into the analysed network area

To perform the steady-state regimes calculation, four operating scenarios of the analysed network area were defined in the NEPLAN software:

- *Scenario 1*: it is the reference scenario, called the reference regime, which reflects the basic configuration of the analysed network without the integration of additional energy sources;
- *Scenario 2*: involves the connection of a WPP, with an installed capacity of 50 MW, as a new integrated RES into the existing network area in node N8;
- *Scenario 3*: consists of connecting a BESS, with an installed power capacity of 30 MW and a storage capacity of 60 MWh in node N3, in addition to Scenario 2;
- *Scenario 4*: involves connecting an NGPP as a reserve power source, with an installed capacity of 80 MW in node N16, in addition to Scenario 3.

The new energy sources and the BESS were connected to the respective nodes to enhance the operational reliability of the network area, WPP is connected to node N8 due to the high demand for electricity in this part of the network area. BESS was integrated into node N3, close to both RES and nodes with high electricity demand, but also due to the existence of a single TR-250 MVA in this part of the network area. NGPP was connected to node N16 due to the fact that is complexly looped with the adjacent nodes through several 110 kV OHLs, which provides high flexibility in the network area and enables a balanced distribution of active and reactive power flows, but also due to the existence of a small number of power plants in this area of the network.

Each operating scenario of the analysed network area was developed for three characteristic levels WEP, SMP, and SNM, resulting in 12 distinct steady-state regimes, used to analyse the behaviour of the electrical network under various operating conditions and these are presented in Table 3.

Table 3. **Steady-state regimes resulting from the combination of scenarios with characteristic load levels**

Analysed scenario	**WEP**	**SMP**	**SNM**
1	RSR (WEP)	RSR (SMP)	RSR (SNM)
2	Scenario 1 with the new WPP connected (WEP)	Scenario 1 with the new WPP connected (SMP)	Scenario 1 with the new WPP connected (SNM)
3	Scenario 2 with BESS connected (WEP)	Scenario 2 with BESS connected (SMP)	Scenario 2 with BESS connected (SNM)
4	Scenario 3 with NGPP connected (WEP)	Scenario 3 with NGPP connected (SMP)	Scenario 3 with NGPP connected (SNM)

The resulting steady-state regimes were used to evaluate the impact of integrating a RES, a BESS, and a NGPP on:

- Voltage levels in the grid nodes;
- Loading levels of grid elements (110 kV - OHLs și TR-250 MVA) relative to their rated apparent power;
- Losses of active and reactive electrical power in the analysed grid area;
- Behaviour of the network under contingency conditions, in order to determine the degree of operational safety.

Figure A.2 in the appendix presents the single-line diagram of the analysed network area, which includes the WPP connected in node N8, BESS in node N3, and NGPP in node N16.

5. Analysis of the steady-state regimes calculated before and after the integration of a renewable energy source, an energy storage system, and a reserve power source

Simulation results for the voltage levels, expressed as percentages of the nominal value (110 kV), at the nodes of the analysed network area are presented in Figures 2, 3, and 4 for the three characteristics load levels: WEP, SMP, and SNM.

An average voltage increase of approximately 2% was observed, compared to the voltage value in scenario 1, in the analysed network area for each characteristic load level as a result of the integration of the new energy sources (WPP and NGPP) and the BESS. The comparative analysis of the voltage levels in the network nodes highlights this general upward trend, in all nodes, especially in nodes N3, N8, and N16, where these sources are connected. All measured voltage levels in the network nodes remain within the admissible limits [11], indicating a stable operating regime.

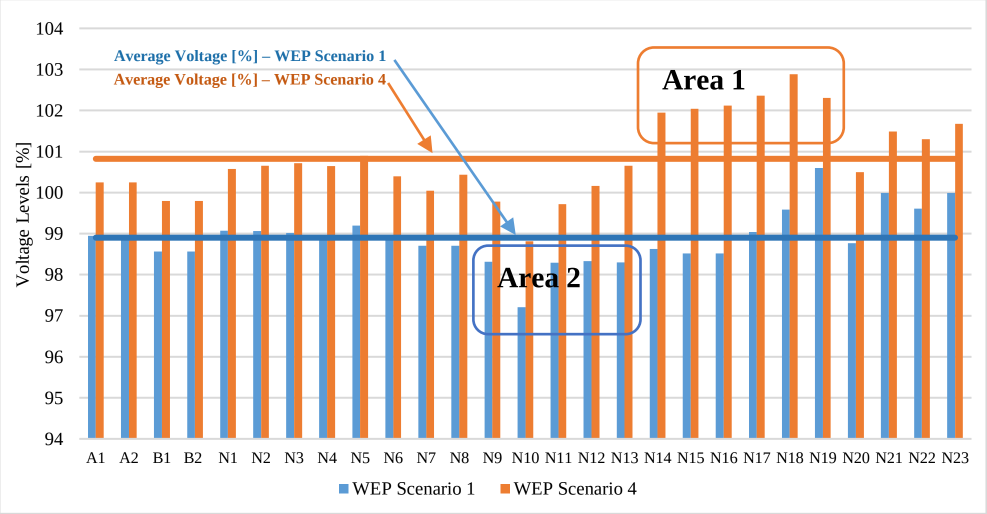

Figure 2. Comparison of the voltage level in the network nodes between Scenario 1 and Scenario 4 for the WEP characteristic load level

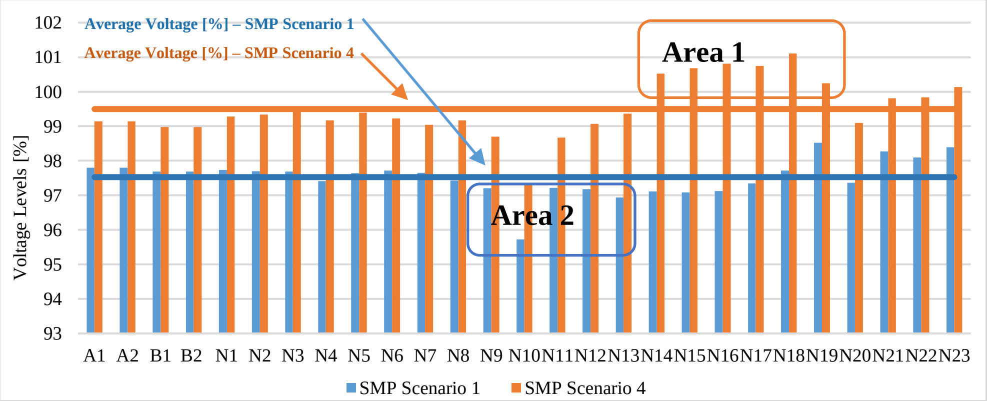

Figure 3. Comparison of the voltage level in the network nodes between Scenario 1 and Scenario 4 for the SMP characteristic load level

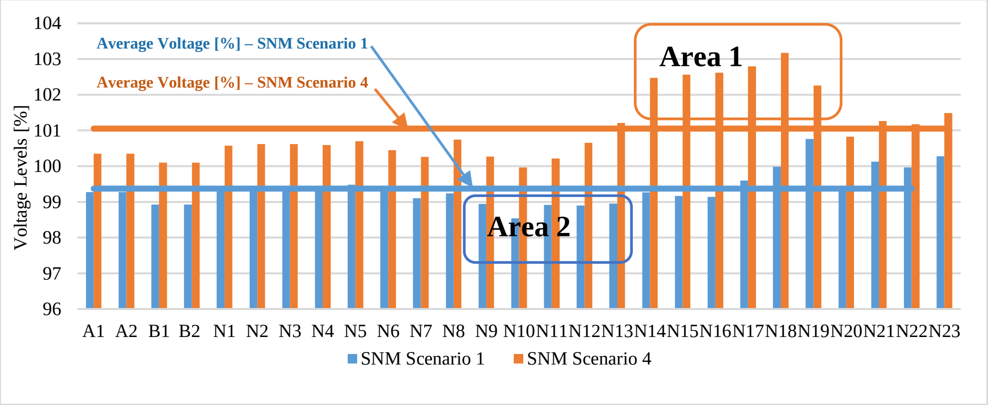

Figure 4. Comparison of the voltage level in the network nodes between Scenario 1 and Scenario 4 for the SNM characteristic load level

In detail, the following voltage increases were recorded after commissioning the new sources:

- In Node 3, where the BESS was installed: 1,74% in the WEP regime, 1,93% in the SMP and 1,34% in the SNM regime;
- In Node N8, where the WPP was connected, the values increased by 1,73% (WEP), 1,91 % (SMP), and 1,66% (SNM);
- In Node 16, where the NGPP was connected, the values increased by 3,6% (WEP), 4,05% (SMP), and 3,82% (SNM).

According to the results, the NGPP had the greatest influence on the improvement of the voltage profile in the analysed network.

The graphs also highlighted the areas where the highest and lowest voltage values were recorded, specific to each operating regime:

- *Area 1* includes the nodes where was recorded the highest voltage values, exceeding the nominal voltage by up to 3%, typically near the NGPP connection point (N16);
- *Area 2* includes the nodes where was recorded the lowest voltage values, up to 1% below the nominal voltage, especially in the vicinity of Node N10, where the local electricity demand is high.

Within the WEP and SMP characteristic load levels, where the electricity demand is high, the contribution of new energy sources and the BESS to improving the voltage profile is observed. The highest levels of voltage values in network nodes are recorded for the SNM characteristic load level, due to the reduced demand for electricity from local users, while the new sources and the BESS do not negatively affect the impact of network operation.

The results of the simulations for the loading levels of the power lines in the analysed network area, expressed as percentages of the maximum apparent power (S_{max}), are presented in Figures 5, 6, and 7 for the three characteristic load levels: WEP, SMP, and SNM.

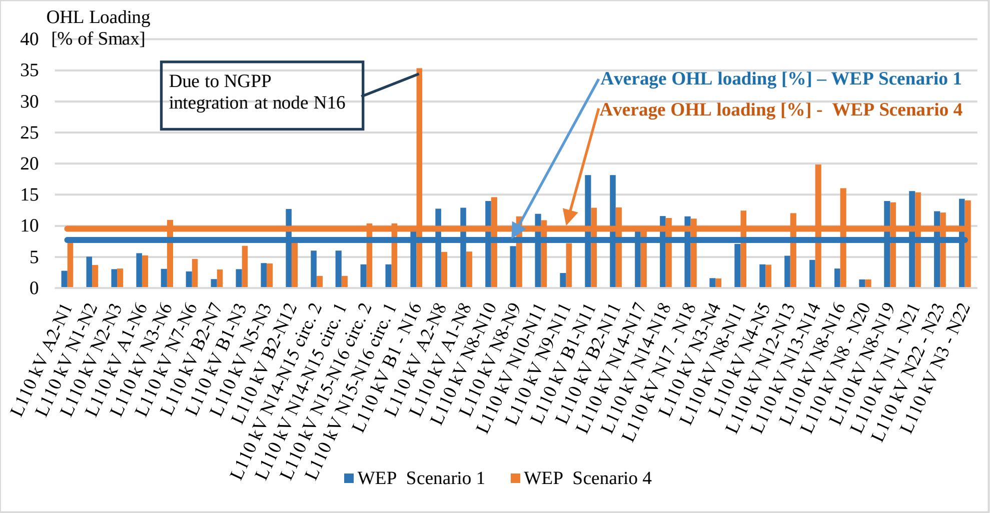

Figure 5. Comparison of the loading levels of the OHLs in the network area between Scenario 1 and Scenario 2 for the WEP characteristic load level

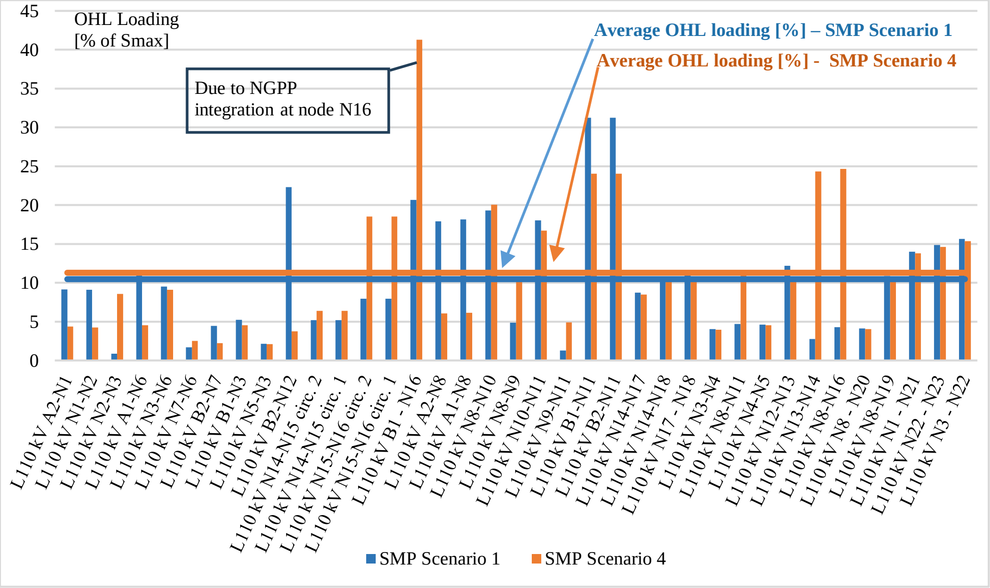

Figure 6. Comparison of the loading levels of the OHLs in the network area between Scenario 1 and Scenario 2 for the SMP characteristic load level

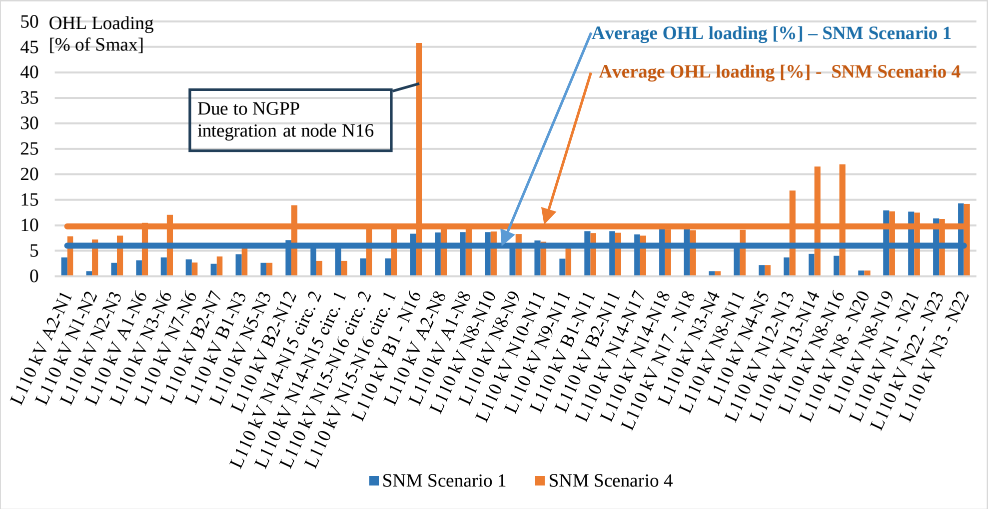

Figure 7. Comparison of the loading levels of the OHLs in the network area between Scenario 1 and Scenario 2 for the SNM characteristic load level

The simulation results highlight the fact that the integration of the new energy sources and the BESS does not generate overloads on the power lines, the loading level remaining within the admissible limits [12]. High local loads of the overhead lines near the connection nodes of the new energy sources and BESS are observed.

For the WEP and SMP characteristic load levels, where electricity demand is high and the contribution of RES is significant, certain OHLs register lower loading values in scenario 4 (with the new sources integrated), as compared to scenario 1. Conversely, within the SNM characteristic load level, where electricity demand is lower, the integration of the NGPP contributes to local increases in the loading of specific lines.

On average, the integration of the new energy sources led to the following increases in OHL loading, compared to scenario 1: 1,8% for the WEP regime, 0,8% for the SMP regime, and 3,78% for the SNM regime.

The highest loading values were recorded on the L110 kV B1-N16, directly connected to node N16, where the NGPP is connected. The loading levels on this line reached: 35,35% in WEP regime, 41,29% in SMP regime, and 45,74% in SNM regime, with the power flow direction being from N16 toward node B1, due to the lower electricity demand in node N16 and its surrounding area.

However, after the integration of the new energy sources and the BESS, no additional grid reinforcement measures are required and the loading levels remain within safe operational limits.

The loading levels of the 250 MVA – TR, expressed as percentages of the nominal apparent power, were analysed for all three characteristic load levels: WEP, SMP, and SNM. The simulation results are represented in Figure 8.

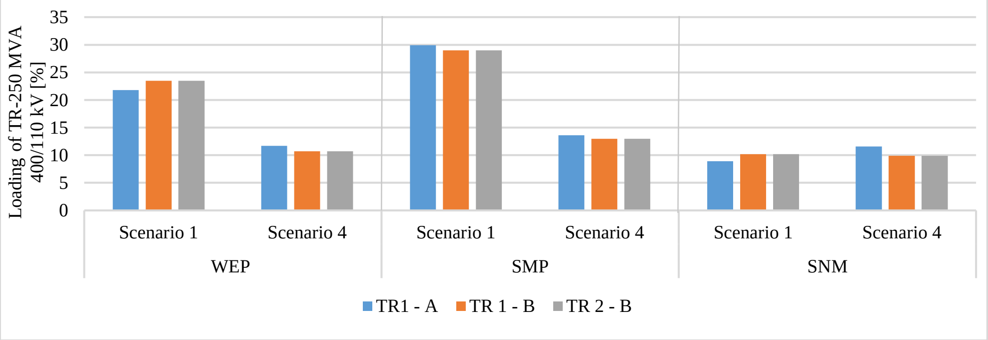

Figure 8. Comparison of the loading levels of TR-250 MVA between Scenario 1 and Scenario 4 for the characteristic load levels: WEP, SMP, and SNM

The simulation results indicate a tendency for the loading levels of 250 MVA transformers to decrease (TR1-A, TR1-B, and TR2-B), as a result of the increase in local generation of the new WPP, BESS, and NGPP. This decrease is particularly observed for the SMP characteristic load level, where the significant contribution of RES and NGPP reduces the power flow through the transformers. For example, the loading on TR1-A drops from 29,91% in scenario 1 to 13,64% in scenario 4.

Similarly, in the WEP characteristic load level, a reduction of the transformers loading is also observed from 23,45% (TR1-B and TR2-B) in scenario 1 to 10,74% in scenario 4, due to the increased local supply from RES and NGPP, which partially covers the local demand and reduce the power flow through this transformers.

The highest values of the transformer loading were recorded in scenario 1 for the SMP characteristic load level, as a result of the reduced electricity generation from RES. This is the characteristic of the SMP characteristic load level, where WPP operates at only 20% of their installed capacity, compared to 30% in the WEP characteristic load level. This reduction in local generation determines an increased demand for energy from the transmission network and an increasing transformer loading.

An exception occurs for the SNM characteristic load level at the TR1-A 250 MVA, where, the loading increases from 8,94% (scenario 1) to 11,6% (scenario 4). This increase is explained by the operation of BESS in the charging mode, which determines an increase in the loading of this transformer. However, after the integration of the new energy sources, no overloading of the three TR-250 MVA occurs.

To highlight the energy efficiency of the analysed network area, the active and reactive power losses were compared between Scenario 1 and Scenario 4, for all three characteristic levels: WEP, SMP, and SNM. The simulation results are represented in Figure 9.

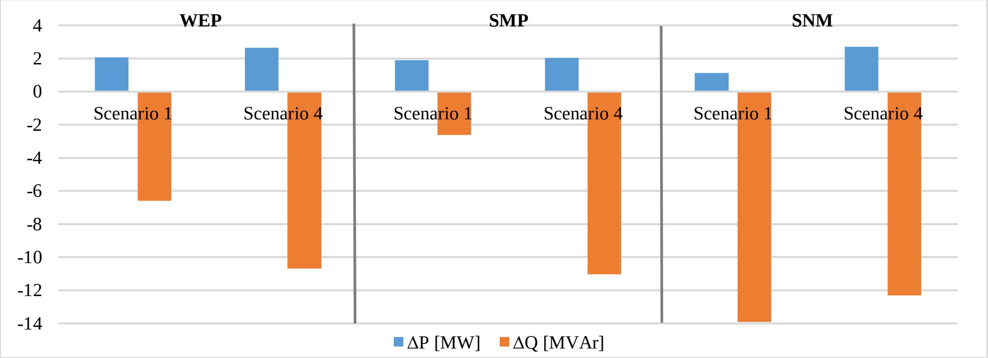

Figure 9. Comparison of active and reactive power losses between Scenario 1 and Scenario 4 for the characteristic load levels: WEP, SMP, and SNM

Active power losses indicate a moderate increase for all the characteristic load levels, due to the higher power flows resulting from the commissioning of the new energy sources and BESS. The highest active power losses were recorded at the SNM load level, where is observed an increase from 1,13 MW to 2,7 MW, indicating a significant rise in active power transfer across the network under conditions of reduced local demand. This increase is justified by the fact that in the absence of high local demand, the energy produced is evacuated over longer distances to other nodes of the network.

Reactive power losses recorded more pronounced variations. In the WEP and SMP load levels, they increased after the integration of the new sources from -6,6 MVAr to -10.7 MVAr in WEP, and from -2.6 MVAr to -11 MVAr in SMP load levels. These increases are attributed to the additional injection of reactive power from RES, but also from NGPP, which operates with an inductive power factor.

In contrast, for the SNM load level, reactive power losses decreased slightly from -13.9 MVAr to -12.3 MVAr. This relative decrease reflects the reduction in reactive power injection into the grid in low-demand conditions when the contribution of the new sources and BESS to voltage imbalances becomes less significant.

To determine the behaviour of the network area under contingency conditions, simulations were performed by disconnecting each 110 kV- OHL one by one and 250 MVA-TR for every analysed scenario, and the results are presented in Table 4.

Table 4. **Elements affected under contingency conditions in the analysed grid area**

Contingency	Affected element	Scenario	Observations
L110 kV N8-N20	N20	Before and after integration of WPP, BESS, and NGPP	Radially node supplied
L110 kV N9-N19	N19	Before and after integration of WPP, BESS, and NGPP	Radially node supplied
L110 kV N1-N21	N21	Before and after integration of WPP, BESS, and NGPP	Radially node supplied
L110 kV N22-N23	N23	Before and after integration of WPP, BESS, and NGPP	Radially node supplied
L110 kV N3-N22	N22, N23	Before and after integration of WPP, BESS, and NGPP	Radially node supplied
TR1-A 250 MVA	N19	Before and after integration of WPP	With new WPP in operation: 110,22 kV With WPP disconnected: 110,9 kV

The analysis of the results shows that, both before and after the integration of the WPP, BESS, and NGPP, only the radially supplied nodes are affected following the disconnection of the associated 110 kV-OHLs. This is determined by the grid configuration and is not influenced by the commissioning of the new energy sources and BESS. An exception is represented by the disconnection of TR1-A 250 MVA, where the permissible voltage limits are exceeded in node N19, only before and after the WPP commissioning, due to the high generation of RES for this scenario. Otherwise, no overload appears on the analysed grid elements, regardless of the scenario.

6. Conclusions

The results obtained in this study consist of an impact analysis, through detailed steady-state regimes simulations, of the integration of a WPP, a BESS, and an NGPP as a reserve power source into a network area with a nominal voltage of 110 kV, as part of the PS. The methodology applied can be used for the design and sizing of similar solutions for the integration of RES, ESS, and reserve sources within other electrical network areas.

The integration of the WPP in node N8 leads to local increases in the voltage values in the grid nodes and redistributions of power flows, with significant effects on the SNM characteristic load level, without affecting grid stability or causing overloads, even in contingency situations.

The commissioning of the BES connected in node N3 does not affect the operational security of the network area, regardless of its operating mode charging or discharging. In fact, it can even contribute in the event of overloads on TR1-A 250 MVA to increasing the operational security.

The NGPP connected at node N16 contributes to voltage regulation and increased inertia in the PS, without causing any exceedance of admissible limits for the grid elements.

The integration of the WPP, BESS, and NGPP does not negatively affect the voltage levels at the network nodes, the loading of the 110 kV OHLs and 250 MVA-TR from the connection nodes with the PS, as well as the active and reactive power losses, all remaining within admissible limits.

This analysis confirms the technical feasibility of integrating a new energy source into a 110 kV electrical network area, without the need for additional reinforcement measures.

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APPENDIX

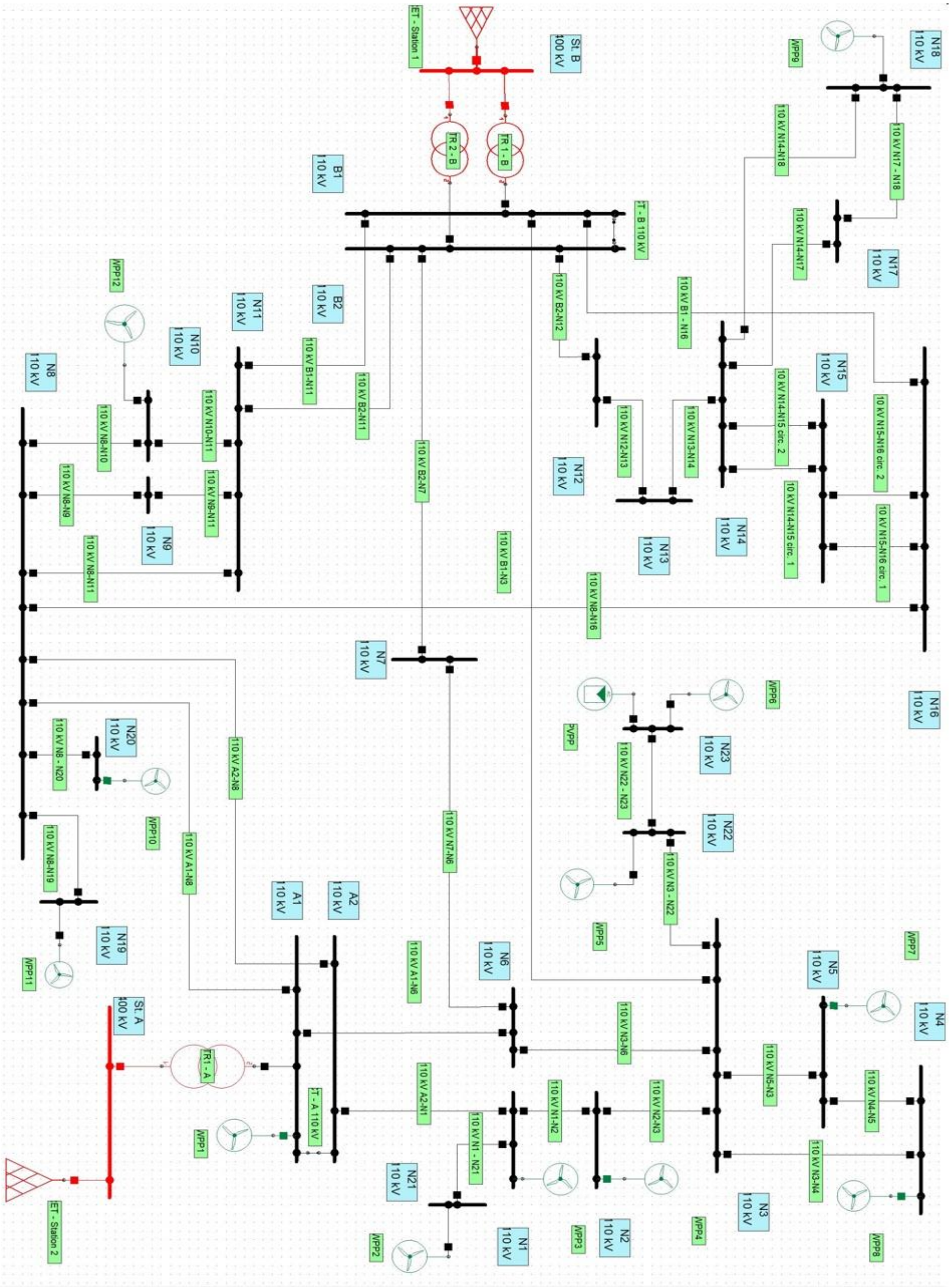

Figure. A.1. Single-line diagram of the analysed grid area

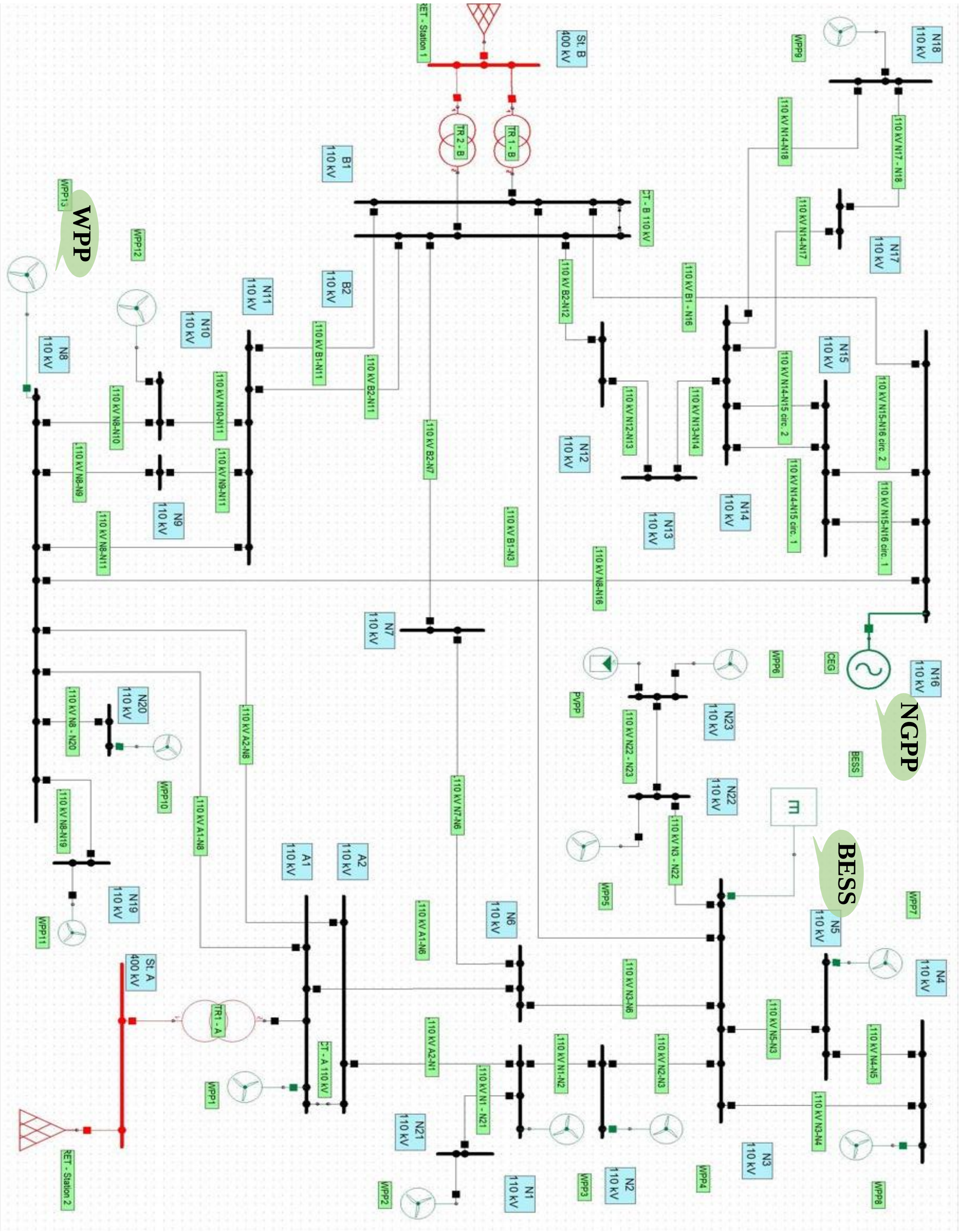

Figure. A.2. Single-line diagram of the analysed network area with the WPP, BESS, and NGPP connected in the corresponding nodes

Authors' biographies

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