National University of Science and Technology POLITEHNICA Bucharest
Faculty of Power Engineering
Doctoral School of Energy Engineering





DOCTORAL THESIS SUMMARY

ANALYSIS OF THE INTEGRATION OF RENEWABLE ENERGY SOURCES INTO POWER SYSTEMS

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PhD Supervisor
Prof. Dr. Eng. Ștefan GHEORGHE

Bucharest
2025

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Abstract

The integration of renewable energy sources into power systems generates significant changes in their operation and exploitation. The variable and intermittent nature of renewable energy sources requires the continuous adaptation of power systems in order to maintain the balance between electricity demand and generation, as well as to ensure the quality of electricity delivered to end users. The concentration of photovoltaic and wind power plants in areas with favorable natural conditions creates critical situations in which the operational security and stability of the power system are strongly affected. In this context, the development of modern coordination methods become necessary, capable of managing production fluctuations and supporting the integration of increasingly large renewable energy capacities.

A relevant direction is represented by the implementation of an integrated management algorithm, designed to correlate the operation of energy storage systems, reserve generation sources, and advanced control equipment. The application of such an algorithm in a power network area characterized by a high penetration of renewable power plants demonstrated the possibility of controlling power flows and maintaining electricity quality, even under critical operating conditions.

The results highlight the importance of a coordinated approach and the use of modern management solutions for enhancing the operational security of power grids, in line with the requirements of the energy transition.

Introduction

The integration of renewable energy sources (RES) into power systems (PS) represents one of the major development directions of the energy sector, both nationally and globally. The theme of this thesis focuses on investigating the technical and regulatory aspects associated with the connection of photovoltaic power plants (PVPP) and wind power plants (WPP) to the electrical grids and proposes technical solutions for maintaining the security and stability of power networks under conditions of high-RES penetration.

The importance and timeliness of this research are supported by national and European energy policies and strategies, which aim to diversify electricity generation sources and increase the share of RES in the energy mix, in the context of the gradual depletion of conventional resources.

The main aspects addressed in this thesis start from the premise that the large-scale integration of RES can be achieved safely and efficiently through complementary solutions such as battery energy storage systems (BESS), reserve generation sources (e.g., natural gas-fired power plants), and FACTS devices (Flexible Alternating Current Transmission Systems), such as STATCOM (Static Synchronous Compensator). The analysis investigated how these technical solutions can be sized and coordinated in order to mitigate the negative effects of RES variability and their impact on the stability of power networks.

The overall objective of this thesis is to develop an analysis methodology and propose technical solutions that allow the integration of RES into power systems, while ensuring operational security, system stability, and continuity of electricity supply to end users. To achieve this objective, the research is structured along several specific directions: analysis of active and reactive power generation curves for WPPs and PVPPs, evaluation of the influence of meteorological parameters on production and forecasting methods, determination of electricity generation and capacity factor, sizing of technical solutions such as energy storage systems, reserve generation sources, and FACTS devices, as well as the development of an integrated management algorithm to coordinate the operation of these solutions.

The adopted methodology combines the analysis of real production data from WPPs and PVPPs with simulations performed in the NEPLAN software, for which critical operating scenarios that may occur in power system operation have been defined, later being applied in a case study for a specific power network area, thus providing a basis for the evaluation and implementation of the proposed technical solutions.

1. Renewable energy sources in modern power

1.1. Electricity generation systems from solar energy sources

PVPPs are usually located in areas with high solar potential, where the level of irradiance favours the maximization of electricity production.

Electricity generation from solar energy sources is influenced by several factors that affect the performance and efficiency of photovoltaic systems, which can be classified into three categories [4]:

a) Climatic factors: the environmental parameters at the location of the photovoltaic system, namely solar irradiance, temperature, humidity level, precipitation, and dust deposition;

b) Technical factors: the design characteristics and operating conditions of the photovoltaic system, such as the type and nature of the materials used for solar cells, shading of the solar panels, their tilt angle and orientation, as well as the type of inverter used;

c) Economic factors: the elements that influence the development and implementation of photovoltaic systems, among which are initial investment costs, operating costs, governmental incentives, regulatory frameworks, and technological advancements.

1.2. Electricity generation systems for wind energy sources

The kinetic energy of the wind represents the energy resulting from the movement of air masses and constitutes the main element of electricity conversion using wind power plants (WPPs).

In the case of WPPs, electricity generation is influenced by the same categories of factors as for PVPPs, but with specific particularities, as follows [4]:

a) Climatic factors: the wind resource is characterized by the intensity and variability of wind speed, its direction, and statistical distribution, which determine the energy potential available for converting the kinetic energy of the wind into electricity;

b) Technical factors: the type of wind turbines, the efficiency of the components, and the losses associated with electrical equipment;

c) Economic factors: similar to those analyzed in the case of PVPPs, namely investment and operating costs, the lifetime of the installations, and the capacity factor, an indicator that reflects the degree of utilization of the installed power.

1.3. Technical and regulatory aspects regarding the connection of renewable energy sources to power grids

The connection of RES to public power networks is regulated by technical standards that establish minimum requirements for performance, safety, and compatibility. In Romania, these requirements are defined in specific regulations that are periodically updated in accordance with European standards and directives [27, 28].

2. Power characteristics of renewable energy sources

2.1. Meteorological parameters and forecasting methods for renewable energy sources

2.1.1. Meteorological parameters and forecasting methods for solar energy sources

Meteorological parameters such as solar irradiance, temperature, humidity, wind speed, and cloud cover are among the key factors that directly influence the efficiency of electricity generation in photovoltaic power plants (PVPPs). Forecasting methods are generally classified into five main categories [32]: persistence methods, physical methods, statistical methods, artificial intelligence (AI) methods, and hybrid methods.

The accuracy of forecasts is essential for the efficient integration of renewable energy sources (RES) into power systems (PS), while technological advances contribute to reducing uncertainty and improving the management of variability in electricity generation from RES.

2.1.2. Meteorological parameters and forecasting methods for wind energy sources

In a period marked by the transition of RES into PS, wind energy plays an increasingly important role in the energy mix. However, the intermittent nature of the wind resource requires the use of highly accurate forecasting methods. These methods rely primarily on meteorological parameters (wind speed and direction, air temperature, atmospheric pressure, and air density) and are enhanced by advanced technologies, including artificial intelligence and optimization algorithms [35].

2.2. Analysis of generation curves P, Q = F (t) for renewable energy sources

2.2.1. Analysis of generation curves P, Q = F (t) for a photovoltaic power plant

The analysis of active (P) and reactive (Q) power curves for a PVPP enables the evaluation of its operation over a day or longer periods of time.

The active power generated by a PVPP can be expressed by the relation [47]:

$$P_{(t)} = n \cdot A \cdot G_{(t)} \cdot \eta_T \ [W] \tag{2.5}$$

where:

$P_{(t)}$ – active power generated at time *t* [W];

n – number of photovoltaic panels;

A – surface area of a photovoltaic panel [m^2]

$G_{(t)}$ – solar irradiance level at time *t* [W/m^2];

η_T – efficiency of converting solar irradiance into electrical energy of the photovoltaic panel [%].

The reactive power generated by a PVPP depends on the inverter settings and can be expressed as a function of active power and the power factor through the relation [48]:

$$Q_{(t)} = \frac{P_{(t)}}{PF} \cdot \sqrt{1 - PF^2} \ [VAr] \tag{2.6}$$

where:

$P_{(t)}$ – active power generated at time t [W];
PF – power factor (the ratio between active and apparent power).

For the analysis of active and reactive power generation curves over time, hourly values of electricity production from a 45 MW PVPP in Romania were used. The analyzed interval covers two distinct days: a working day and a weekend day, in order to assess how the PVPP contributes to the stability of the power system under different operating conditions.

Figure 2.4 and 2.5 present the active and reactive power generation curves as a function of time for the two analyzed days, highlighting the differences in PVPP operation throughout the 0-24 hour interval.

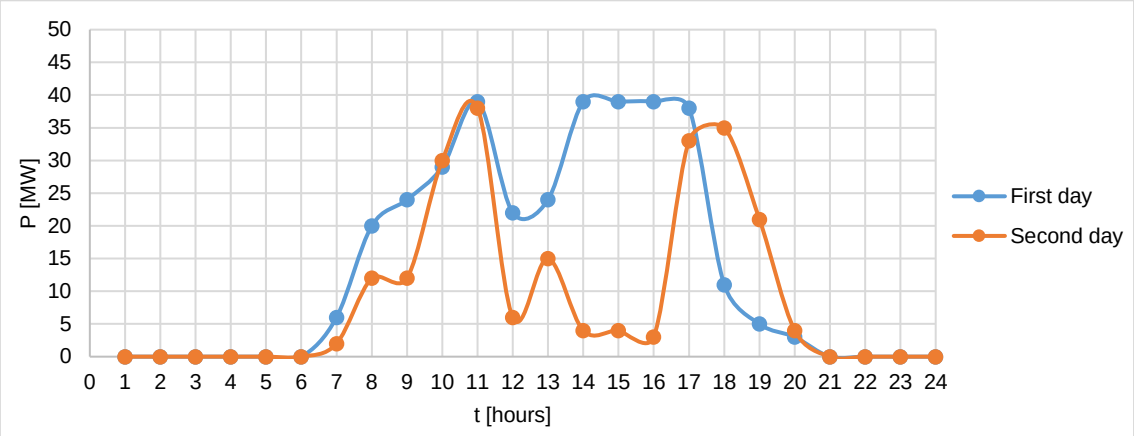


Fig. 2.4. Active power generation curves P = F(t) of a PVPP for two distinct days

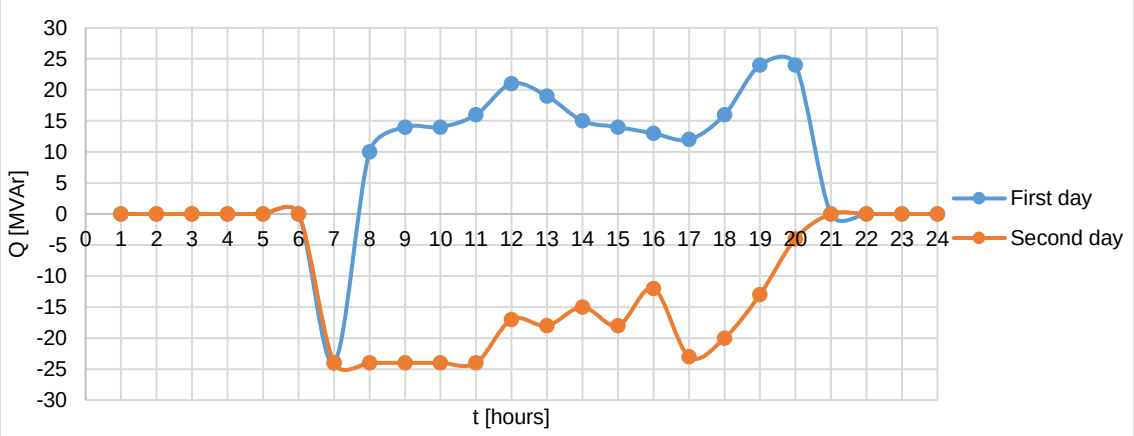


Fig. 2.5. Reactive power generation curves Q = F(t) for a PVPP for two distinct days

The comparative analysis of the P and Q curves as a function of time for the two analyzed days highlights how meteorological conditions and electricity demand simultaneously affect both the generation of active power and the contribution of the PVPP to the injection or absorption of reactive power, underlining its role in maintaining voltage stability within the electrical network.

2.2.2. Analysis of generation curves P, Q = F (t) for a wind power plant

For the analysis of active and reactive power generation curves as a function of time for a WPP, hourly production values from a 90 MW WPP in Romania were used.

The electricity production of a WPP is characterized by two main components: active power P [MW] and reactive power Q [MVAr].

The active power generated at time t can be expressed by the relation [26]:

$$P = \frac{1}{2} \cdot \rho \cdot A \cdot v^3 \cdot \eta \text{ [W]} \quad (2.7)$$

where:

ρ – air density [kg/m^3];

A – area measured by the wind turbine blades [m^2];

v – wind speed [m/s];

η - efficiency of the wind turbine [%].

The analysis of the generation curves $P, Q = F(t)$ for the WPP was carried out over three consecutive days in a summer month, an interval chosen due to representative operating conditions determined by the variability of the wind energy resource.

Figures 2.6 and 2.7 present the active and reactive power generation curves as a function of time for the three analyzed days, with the objective of highlighting the differences in WPP operation during the 0-24 hour interval.

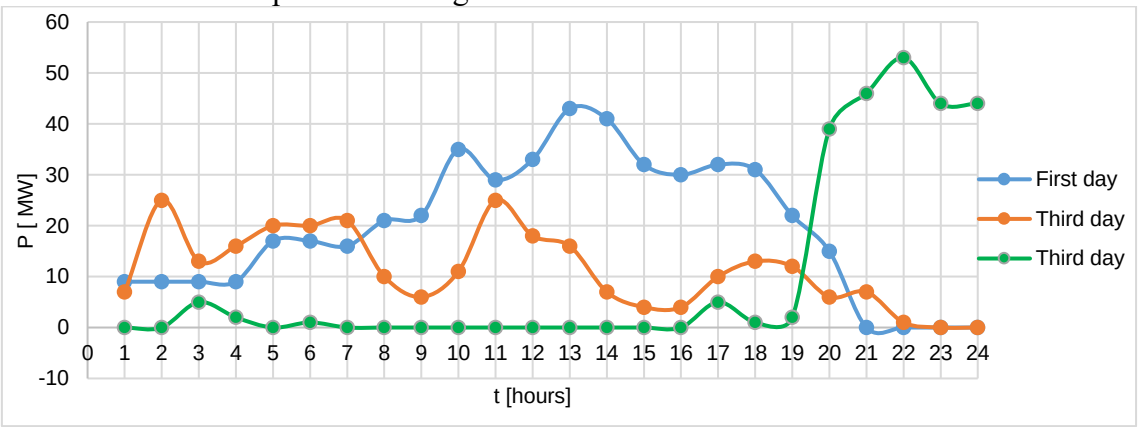


Fig. 2.6. Active power generation curves P = F(t) of a WPP for three distinct days [48]

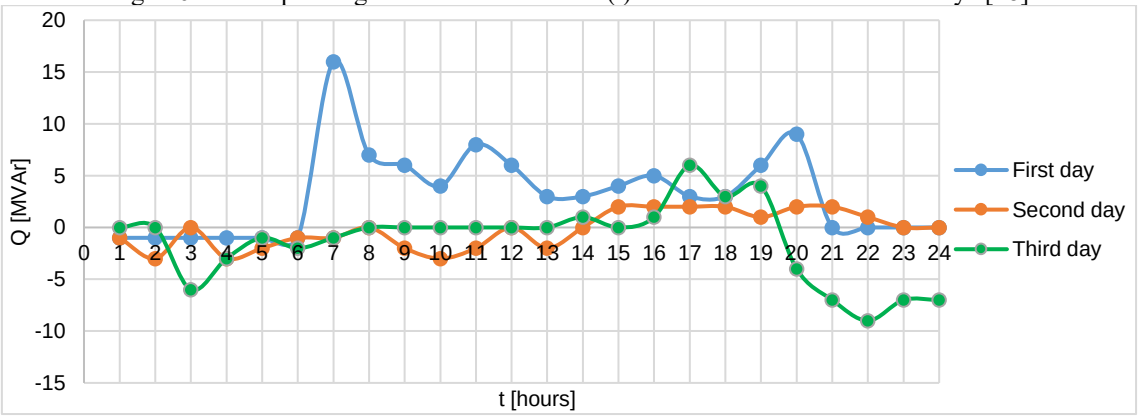


Fig. 2.7. Reactive power generation curves Q = F(t) of a WPP for three distinct days [48]

The comparative analysis of the P, Q = F(t) curves for the WPP highlights the impact of wind variability on electricity production and its contribution to voltage regulation in the power system. Active power directly reflects wind conditions, with high production during favorable situations, significant reductions at low wind speeds, and rapid fluctuations during sudden wind speed increases. A notable aspect is observed on the third day, when a sudden increase in electricity generation occurred, emphasizing

the importance of integrating flexible generation sources or storage systems capable of balancing these variations. Reactive power depends on the operating mode of the WPP, on the first day, being a working day, the WPP contributed through reactive power injection to increase voltage levels, while during the weekend period it operated with reactive power absorption to reduce voltage levels in the network.

2.3. Calculation of the annual electricity generation and the capacity factor for renewable energy sources

The capacity factor (CF) represents the ratio between the actual electricity generated by a power plant over a given period of time (usually one year) and the maximum possible electricity it could have produced during the same period, operating continuously at its rated power [4, 48].

$$CF = \frac{Actual\ energy\ produced}{Maximum\ possible\ energy} \cdot 100\ [\%] \tag{2.8}$$

The calculation of the electricity generated by a power plant requires taking into account several important parameters such as meteorological factors, the efficiency of electrical equipment, system losses, and local environmental conditions.

The general formula for calculating the generated electricity is [4, 48]:

$$E = P_{nom} \times t \times CF\ [Wh] \tag{2.9}$$

where,
P_{nom} – rated electrical power of the power plant [W];
t – operating time of the power plant [hours];
CF – capacity factor [%].

2.3.1. Calculation of the annual electricity generation and the capacity factor for a photovoltaic power plant

For the determination of the annual electricity generation and the capacity factor (CF), daily production data from a PVPP with an installed capacity of 45 MW were used. The continuous monitoring of electricity production enabled a detailed analysis of the variability of the solar energy resource depending on the meteorological conditions specific to the analyzed period.

Figure 2.8 presents the monthly electricity generation and the capacity factor of the analyzed PVPP during the monitored period of one year.

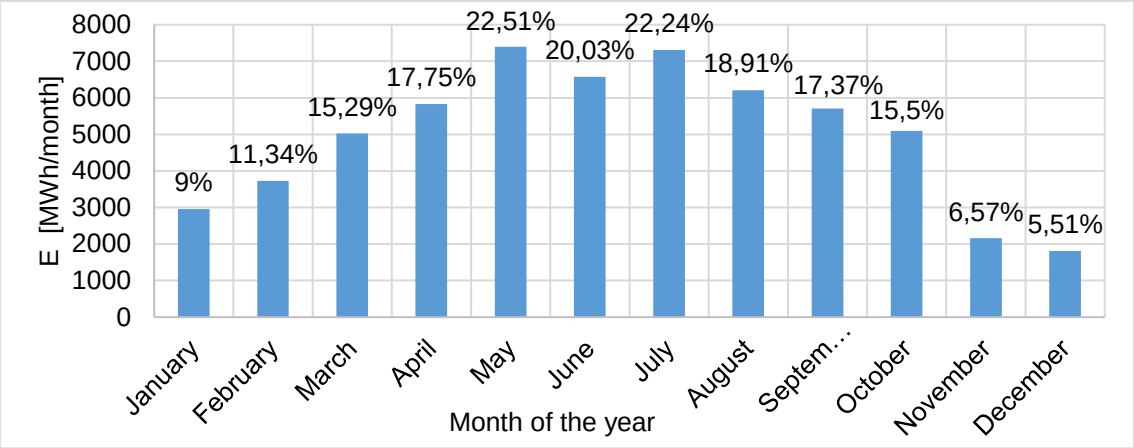


Fig. 2.8. Electricity generation and capacity factor of the analyzed PVPP during one monitored year [48]

Figures 2.9 and 2.10 present the electricity generation analysis for May and December, highlighting the contrast between a month with optimal electricity generation conditions and a month with reduced solar irradiance, providing insights into the seasonal variability of PVPP performance.

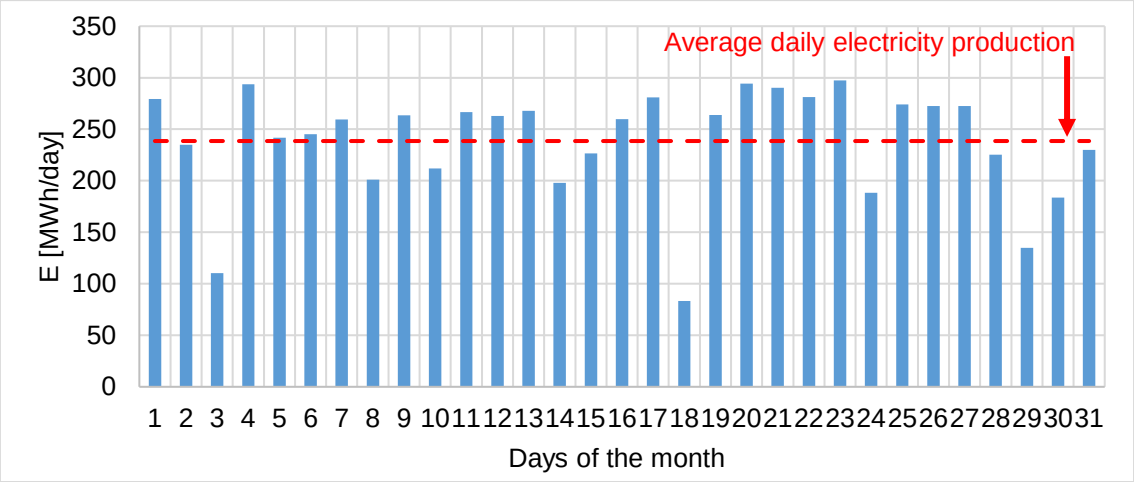


Fig. 2.9. Daily electricity generation of the PVPP in May [48]

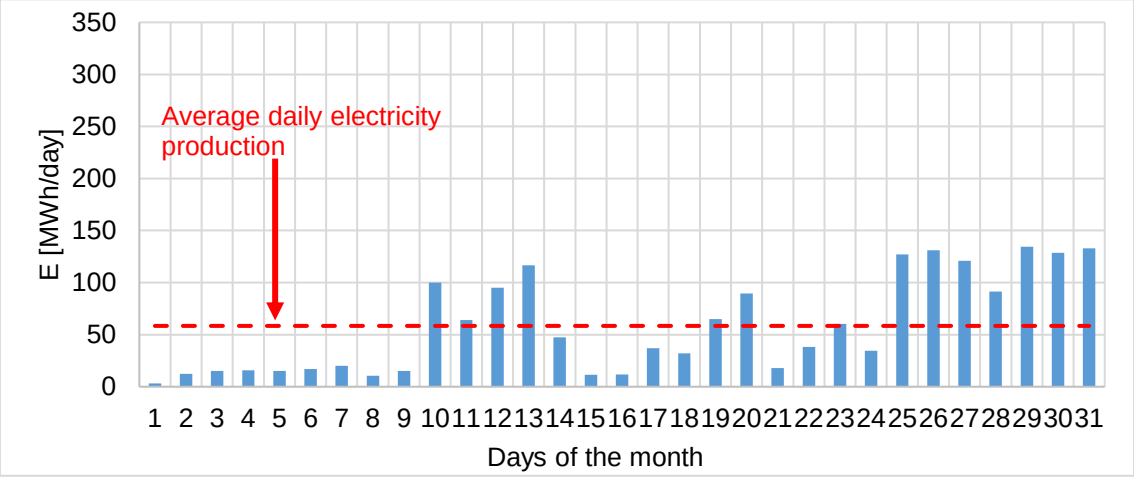


Fig. 2.10. Daily electricity generation of the PVPP in December [48]

The analysis of daily electricity generation for May and December highlights the seasonal differences in the operation of the PVPP. Over the monitored year, the PVPP generated a total of 59,797.4 MWh, corresponding to a capacity factor of 15.17% and a utilization time of the rated power of 1,328.86 hours/year, with an average daily production of 238 MWh/day in May and 58 MWh/day in December.

2.3.2. Calculation of the annual electricity generation and the capacity factor for a wind power plant

For the determination of the annual electricity generation and the capacity factor (CF), daily production data from a WPP with an installed capacity of 50 MW were used. The continuous monitoring of electricity production enabled a detailed analysis of the variability of the wind energy resource depending on the meteorological conditions specific to the analyzed period.

Figure 2.11 presents the monthly electricity generation and capacity factor of the analyzed WPP during the monitored period of one year.

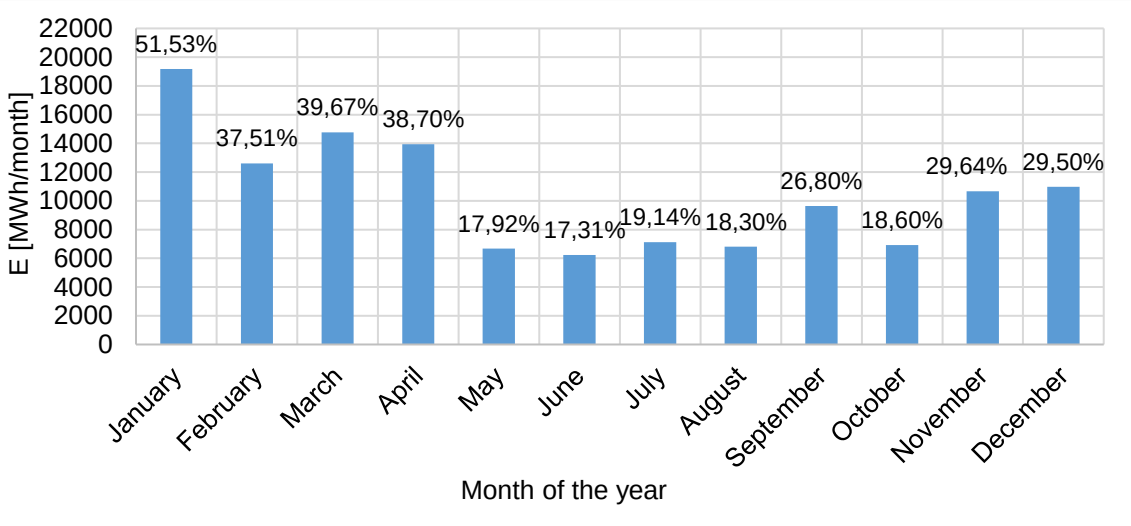


Fig. 2.11. Electricity generation and capacity factor of the analyzed WPP over a year [48]

A pronounced seasonality of electricity production can be observed, with a maximum value recorded in January of approximately 19,800 MWh, corresponding to a capacity factor of 51.53%, determined by the intensification of wind speeds characteristic of the cold season, and a minimum value obtained in June of around 6,900 MWh, associated with a capacity factor of 17.31%, influenced by lower average wind speeds during this period.

Figures 2.12 and 2.13 present the electricity generation analysis for January and June, highlighting the contrast between a month with optimal electricity generation conditions and a month with lower wind speeds. This comparison provides an overview of the seasonal variability of WPP performance.

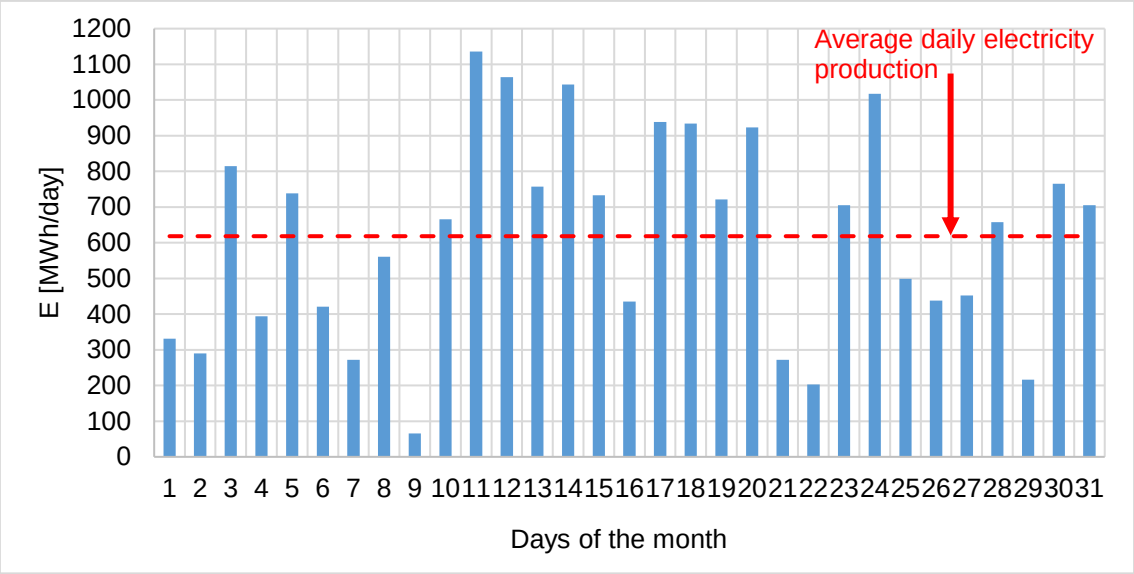


Fig. 2.12. Daily electricity generation of the WPP in January [48]

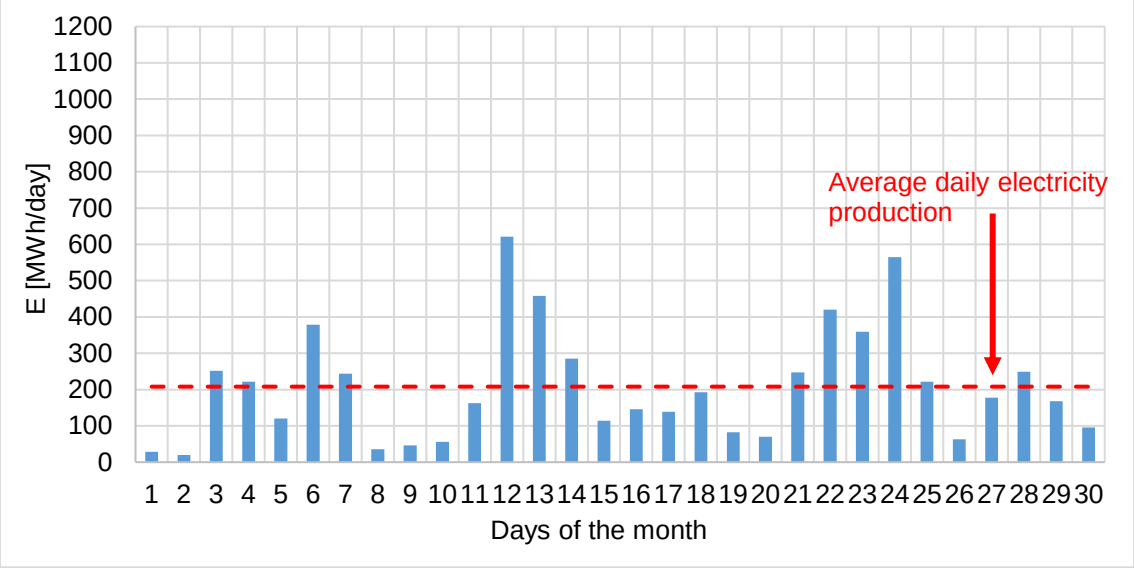


Fig. 2.13. Daily electricity generation of the WPP in June [48]

The daily electricity generation for January and June highlights the contrast between the month with the highest and the lowest electricity generation of the analyzed WPP.

By comparing the results obtained from the electricity generation analysis of the two RES, significant differences can be observed both in the annual electricity generation and in the efficiency of exploiting the specific energy resources used. At the same time, these resources prove to be complementary, contributing to the diversification of the energy mix.

The study of the *P, Q = F(t)* generation curves from solar and wind energy sources supports the need for integrating reserve generation sources and other technical solutions aimed at increasing the flexibility of the power network and ensuring the stability and operational security of the power system.

3. Technical solutions for enhancing the operational security of power systems: energy storage systems, reserve generation sources, and FACTS devices

3.1. Energy storage in power systems

3.1.1. Importance of electrical energy storage

The variability of electricity generation from renewable energy sources (RES), such as PVPPs and WPPs, together with the dynamic changes in electricity demand, generates significant challenges for the stable operation of power systems (PS) [4]. Energy storage systems mitigate these effects by storing electricity during periods of high generation and delivering it during periods of increased demand, thus contributing to maintaining the balance between electricity supply and demand in power systems.

3.2. Reserve generation sources in power systems

3.2.1. Role of reserve generation sources in power systems

The accelerated integration of RES, such as WPPs and PVPPs, into PS requires the use of reserve generation sources, which are indispensable for maintaining PS stability and security. Reserve generation sources ensure the continuity of electricity supply to final users, stabilize frequency and voltage, cover peak loads, manage congestion, and enhance the safety and operational flexibility of the power system [7].

3.3. FACTS devices used in power systems

FACTS (Flexible AC Transmission Systems) devices are power electronic based equipment that enable real-time control of voltage, electrical current, and power flows. Compared to the construction of new transmission lines, the integration of FACTS devices requires lower infrastructure investments, has minimal environmental impact, and involves a significantly shorter implementation time [66].

Their integration into the power grid provides benefits such as increased transmission capacity, enhanced controllability, reduced environmental impact, and improved economic efficiency. However, their implementation is also associated with challenges related to high costs, technological complexity, and conditional reliability (e.g., as complex systems, they may be exposed to failures or faults that require rapid and costly interventions) [66, 67, 68].

3.4. Algorithm for the integrated management of RES, energy storage, FACTS devices, and reserve generation sources

Figure 3.15 presents the main components of the management algorithm for RES, energy storage systems (ESS), FACTS devices, and reserve generation sources. The process includes input data acquisition, power generation forecasting, assessment of power imbalances against the maximum allowable operating limits, application of corrective measures through the activation of ESS, FACTS devices such as STATCOM (Static Synchronous Compensator), or the use of reserve generation sources, as well as continuous monitoring of the power grid.

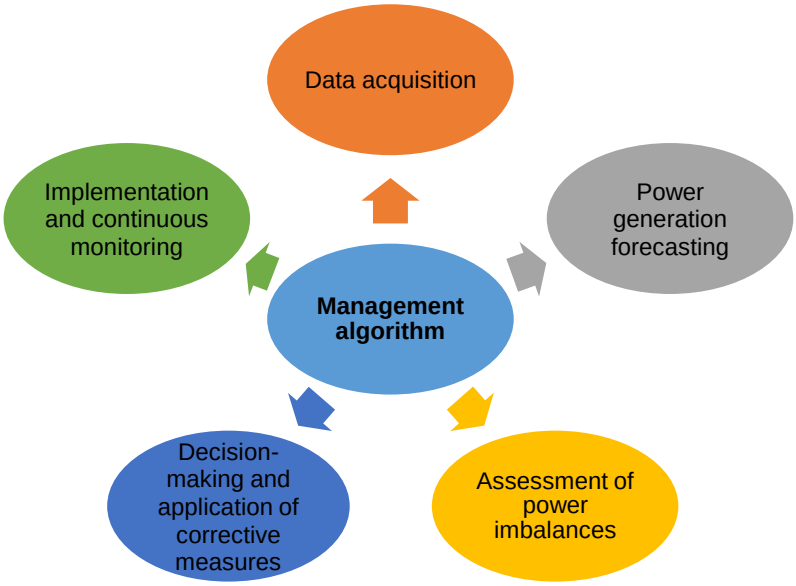


Fig. 3.15. Main elements of the proposed management algorithm

In Appendix A, Figure A.1 presents the proposed algorithm for maintaining the power balances in a power grid area, through the coordinated operation of ESS, reserve generation sources, and FACTS devices such as STATCOM, used for voltage regulation.

The role of the algorithm is to evaluate the availability and capacity of the grid, and in cases where technical restrictions are exceeded, such as voltage levels outside the admissible limits or the maximum transferable power of the grid elements being surpassed, corrective measures are automatically applied to ensure safe operation of the grid.

These measures are applied hierarchically as follows:

- adjustment of ESS operation mode (charging or discharging with electricity);
- increase or reduction of active power generated by the reserve generation sources;
- use of FACTS devices such as STATCOM to maintain voltage within admissible limits or to increase the transferable power of the grid elements;
- controlled reduction of RES production or disconnection of non-essential users.

The efficiency of the proposed algorithm for RES integration into PS is conditioned by several practical and technological limitations, such as:

- the accuracy of short-term RES generation forecasts;
- the high costs of ESS;
- the response times of different reserve generation sources;
- the technical constraints of the grid;
- the lack of a well-defined regulatory framework.

4. Analysis of a power network area under high renewable energy penetration: solution for improving power quality and enhancing operational security under critical operating conditions of power grids

4.1. Energy status of the analyzed power network area

The analyzed network area is a representative model developed based on real data and configuration of a power grid area in Romania and includes 37 overhead transmission lines (OHL) of the AL-OL type with different conductor cross-sectional areas, as well as 23 transformer substations of 110/20 kV, generically numbered from N1 to N23. In addition, two transformer substations of 400/110 kV are included, represented by nodes A-400 kV, A1 and A2-110 kV, and B-400 kV, B1 and B2-110 kV, respectively.

In Appendix B, Figure B.1 presents the single-line diagram of the analyzed network area, developed using the NEPLAN software.

4.3. Scenarios and steady-state regimes calculated for the analyzed power network area

The main objective of the analysis is to identify critical situations and apply corrective technical measures to increase the operational security of the analyzed network area.

The analyzed scenarios and the technical solutions applied are presented in Table 4.2, corresponding to characteristic load levels: summer night period (SNP), summer morning period (SMP), and winter evening period (WEP).

Table 4.2. Representative scenarios and corrective technical measures applied in the analyzed critical steady-state operating conditions

Analyzed scenario	Characteristic load level	RES generation	Technical description of the situation	Technical solution applied
Scenario 1	SNP	$P_{RES\ (WPP)} = P_{max}$	Low demand and maximum electricity generation	ESS
Scenario 2	SNP	$P_{RES} = 0$ MW	Low demand and absence of local electricity generation	ESS and FACTS devices
Scenario 3	SMP	$P_{RES\ (WPP,PVPP)} = P_{max}$	Moderate demand and maximum electricity generation	ESS and FACTS devices
Scenario 4	WPE	$P_{RES} = 0$ MW	Maximum deficit and no local electricity generation	Reserve generation source, ESS, and FACTS devices

The steady-state operating conditions resulting from the scenario analysis in Table 4.2 were evaluated in terms of [91, 92]:

- the voltage levels at the nodes of the power network area;
- the technical constraints and loading degree of the power grid elements (OHL and transformers) with respect to their rated apparent power;
- the active and reactive power losses in the analyzed power grid;
- the level of operational security of the power network area under contingency conditions.

4.3.1. Scenario 1 – *Electricity surplus during a summer night*

In the context of massive integration of renewable energy sources (RES) into the analyzed network area, during periods of maximum electricity generation overlapping with minimum local electricity demand, a local electricity surplus is generated, which can lead to reverse power flows from the analyzed grid to the transmission systems (TS) [75, 76].

The assumptions established for this scenario are:

- Sources of energy in operation:
  - WPPs are operating at their maximum installed capacity (P_{WPP} = 647.3 MW);
  - PVPPs do not generate electricity (P_{PVPP} = 0 MW).
- Electricity demand for the SNP characteristic load level: 217.41 MW.
- Electricity surplus:
  - The difference between RES generation and local electricity demand of users is 429.89 MW, which is exported from the 110 kV power grid to the TS.

To identify the optimal solution for reducing the electricity surplus and the loading degree of the grid elements, in this scenario two BESS installations with different installed power are considered, connected at node N3-110 kV:

- BESS with an installed power of 60 MW and a storage capacity of 120 MWh;
- BESS with an installed power of 120 MW and a storage capacity of 240 MWh.

Figures 4.4-4.7 present the simulation results regarding the evolution of voltages at the grid nodes, the loading degree of the 110 kV OHL and the 250 MVA transformers, as well as the active (ΔP) and reactive (ΔQ) power losses, before and after the integration of the BESS.

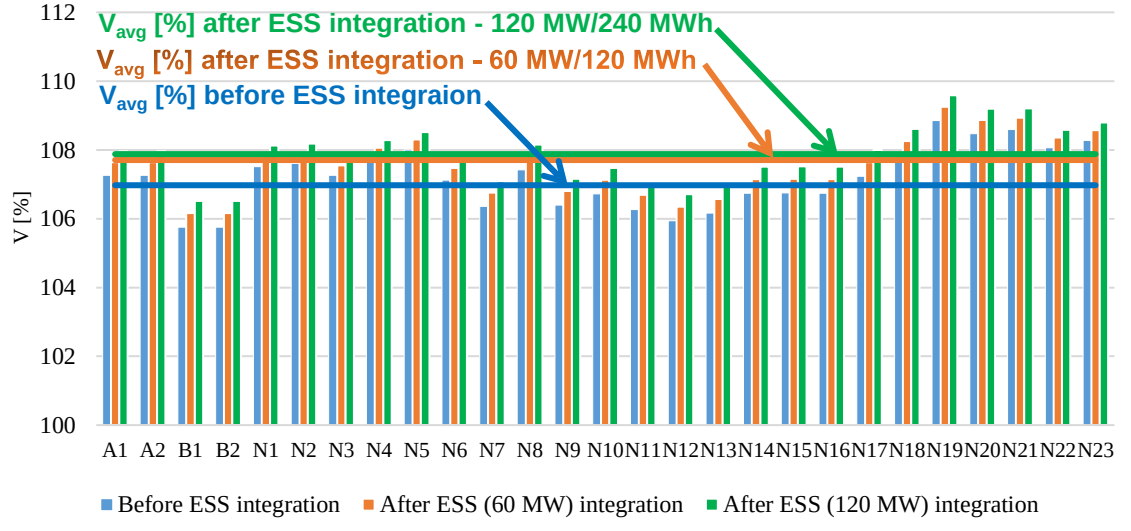


Fig. 4.4. Voltage values at the nodes of the analyzed network area, before and after ESS integration, expressed as percentages of V_n

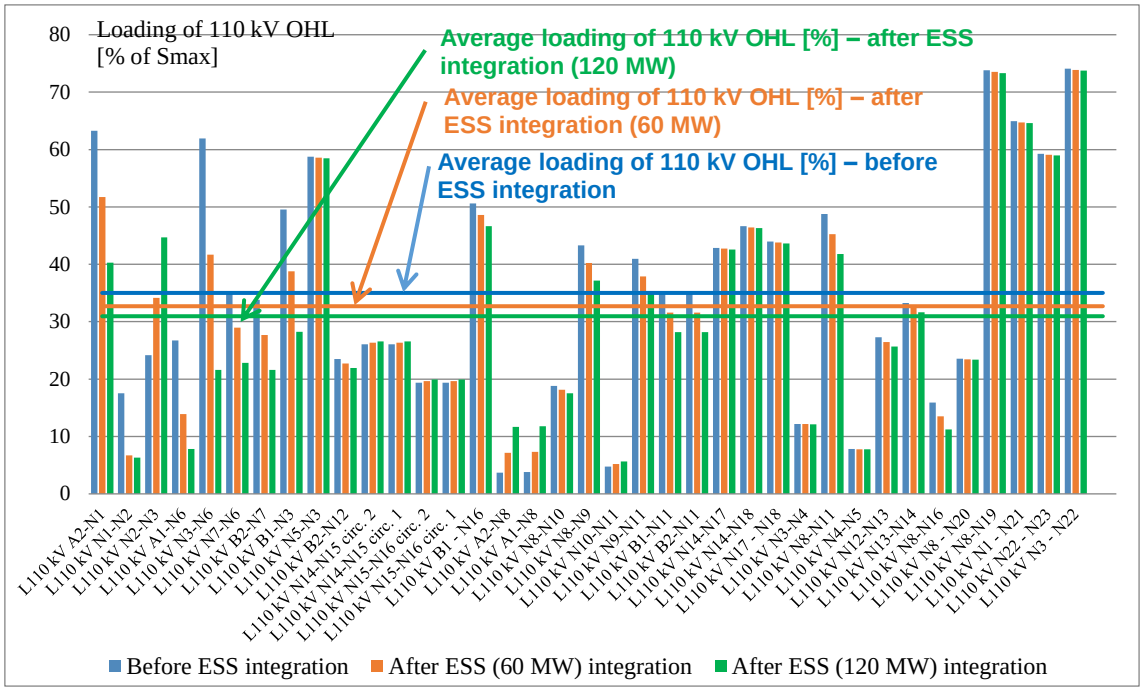


Fig. 4.5. Loading degree of 110 kV OHL, before and after ESS integration

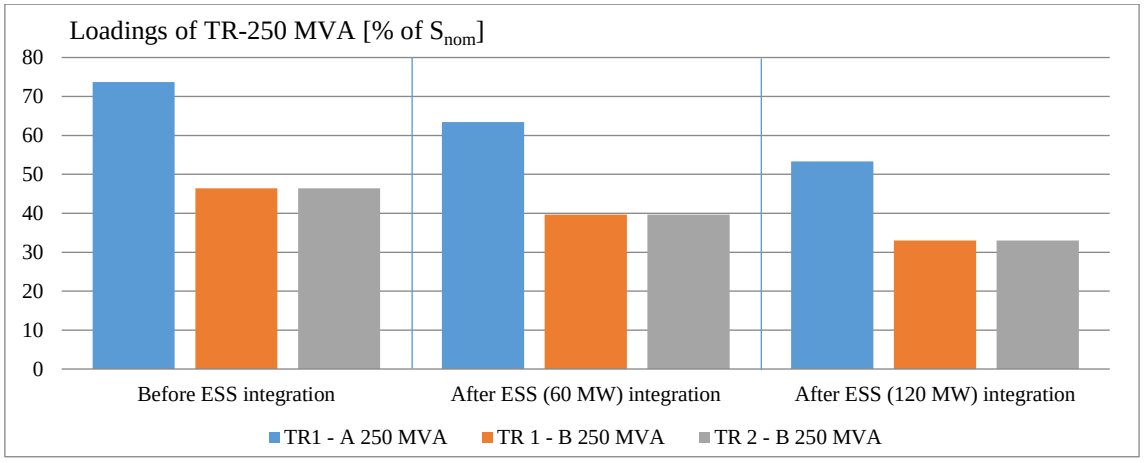


Fig. 4.6. Loading degree of the 250 MVA transformers, before and after ESS integration, expressed as percentages of S_{nom}

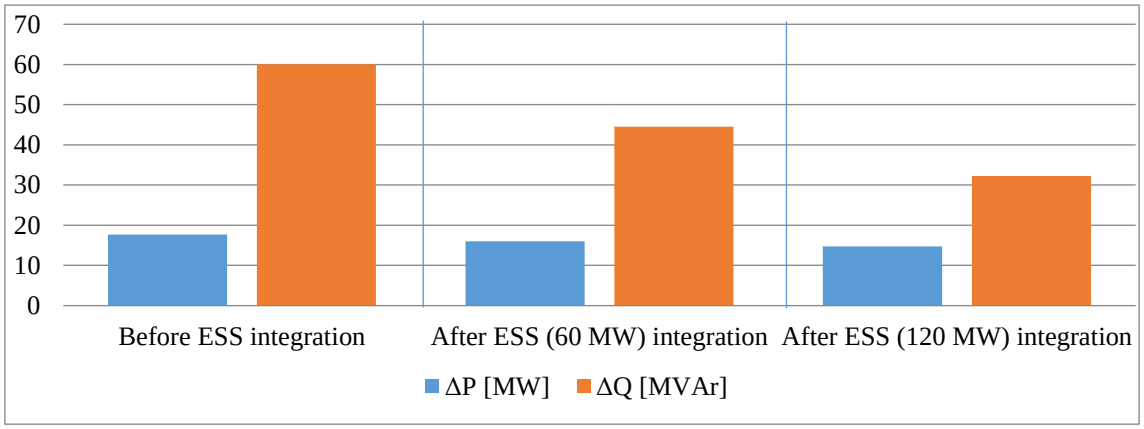


Fig. 4.7. Active (ΔP) and reactive (ΔQ) power losses before and after ESS integration

Based on the steady-state calculation, for the configuration with all power grid elements in operation, both without and with ESS connected at node N3-110 kV, the following aspects are highlighted:

a) The voltage values at the 110 kV grid nodes (Figure 4.4) fall within the admissible limits (±10% of V_n), with the voltage profile being improved after ESS integration;

b) The loading degree of the 110 kV OHL (Figure 4.5) reflects the redistribution of active and reactive power flows once the ESS is integrated, by reducing the loadings on certain OHL and achieving a more uniform load distribution across the grid;

c) The loading degree of the transformers (Figure 4.6) is reduced by ESS integration, which limits power transfers to the transmission system;

d) Active and reactive power losses (Figure 4.7) are diminished, highlighting the improvement of the energy efficiency of the power grid.

Subsequently, the operation of the power grid was analyzed under N-1 and N-2 contingency conditions, both for the initial case (without ESS integration), with the integration of a 60 MW/120 MWh ESS, and with a 120 MW/240 MWh ESS.

Table 4.3. N-1 contingencies analyzed with and without ESS integration

No.	**Contingency**	**Affected elements**	**Without ESS integration**	**With ESS 60 MW/ 120 MWh**	**With ESS 120 MW/ 240 MWh**
			Loading [% of S_{max}]	**Loading [% of S_{max}]**	**Loading [% of S_{max}]**
1.	**L110 kV A2-N1**	L110 kV N3-N6	112.78%	83.14%	53.86%
2.	**L110 kV N3-N6**	L110 kV A2-N1	105.18%	79.9%	54.88%
3.	**L110 kV N8-N20**	N20	Radial supply		
4.	**L110 kV N8-N19**	N19	Radial supply		
5.	**L110 kV N1-N21**	N21	Radial supply		
6.	**L110 kV N3-N22**	N22, N23	Common radial supply		
7.	**L110kV N22-N23**	N23	Radial supply		

Table 4.4. N-2 contingencies analyzed with and without ESS integration

No.	**Contingency**	**Affected elements**	**Without ESS integration**	**With ESS 60 MW/ 120 MWh**	**With ESS 120 MW/ 240 MWh**
			Loading [% of S_{max}]	**Loading [% of S_{max}]**	**Loading [% of S_{max}]**
1.	**L110 kV A2-N1 & L110 kV N3-N6**	L110 kV B1-N3	178.59%	133.13%	89.85%
2.	**L110 kV N3-N6 & L110 kV B1-N3**	L110 kV A2-N1	173.81%	131.07%	89.01%
		L110 kV N1-N2	127.8%	85.5%	43.94%
3.	**L110 kV A2-N1 & L110 kV B1-N3**	L110 kV N3-N6	174.01%	137.56%	99.32%
		L110 kV A1-N6	114.89%	89.24%	62.8%
4.	**TR 1-B 250 MVA & L110 kV A2-N1**	L110 kV N3-N6	120.66%	92.99%	67.52%
5.	**TR 1-A 250 MVA & L110 kV N8-N11**	L110 kV N8-N9	108.49%	98.38%	88.33%
		L110 kV N9-N11	106.11%	96.03%	85.88%
6.	**TR 1-A 250 MVA & TR 1-B 250 MVA**	TR2-B 250 MVA	169.89%	142.31%	117.34%

The results presented in Tables 4.3 and 4.4 highlight the positive impact of ESS integration. especially for 120 MW/240 MWh configuration. which significantly reduces overloads and increases the operational security of the power grid under contingency conditions. However, in the event of the simultaneous outage of two 250 MVA transformers, a temporary overload occurs on the remaining 250 MVA transformer in operation, a situation that can be managed through operative measures, such as the redistribution of power flows to other areas.

4.3.2. Scenario 2 – *Electricity deficit during a summer night*

In this scenario, no RES are in operation, and the power grid is supplied entirely from the transmission system, resulting in a deficit of 217.41 MW. This situation generates overvoltages at the grid nodes, which requires analyzing the integration of FACTS devices such as STATCOM.

Thus, four operating cases of the grid were analyzed to identify the most effective technical solution for reducing voltage levels at the grid nodes, as follows:

a) Case 1: without ESS integration and without FACTS devices (STATCOM);
b) Case 2: with ESS 120 MW/240 MWh integration and without FACTS devices;
c) Case 3: with ESS 120 MW/240 MWh integration and one STATCOM (± 60 MVAr) device connected at node B1-110 kV;
d) Case 4: integration of a second STATCOM (± 60 MVAr) device at node A1-110 kV, in addition to Case 3.

Figures 4.8-4.11 present the simulation results regarding the evolution of voltages at the grid nodes, the loading degree of 110 kV OHL and 250 MVA transformers, as well as active (ΔP) and reactive (ΔQ) power losses, before and after the integration of the 120 MW/ 240 MWh ESS and FACTS devices.

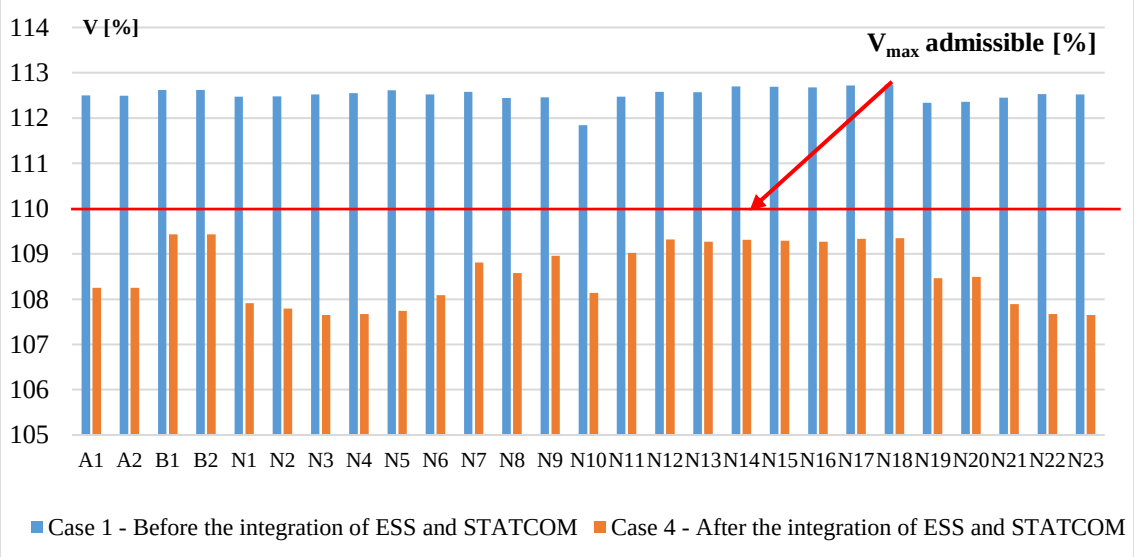


Fig. 4.8. Voltage values at the nodes of the analyzed network area, before and after ESS integration and two STATCOM devices, expressed as percentages of V_n (Scenario 2)

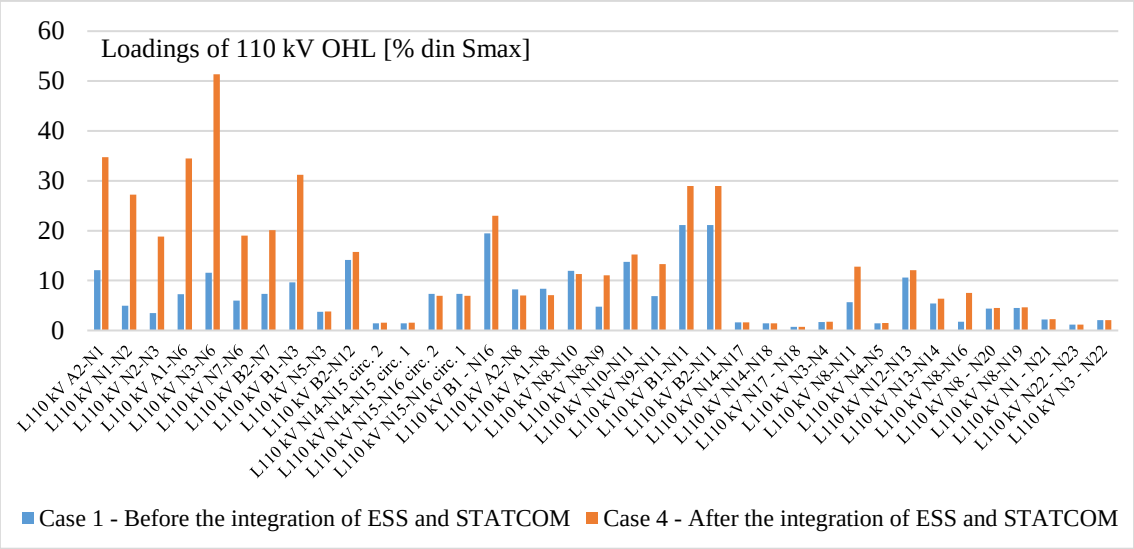


Fig. 4.9. Loading degree of 110 kV OHL before and after the integration of ESS and two STATCOM, expressed as percentages of S_{max} (Scenario 2)

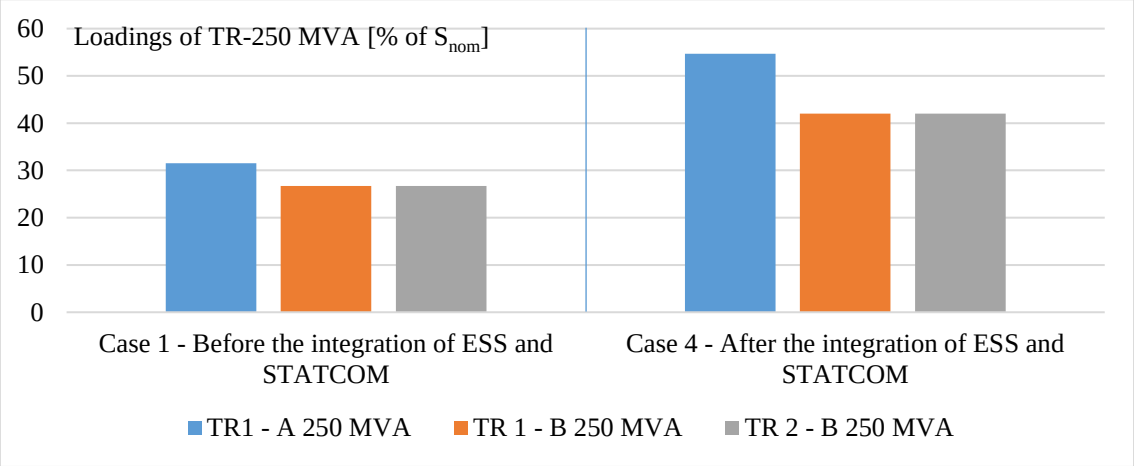


Fig. 4.10. Loading degree of the 250 MVA transformers before and after the integration of ESS and two STATCOM (Scenario 2)

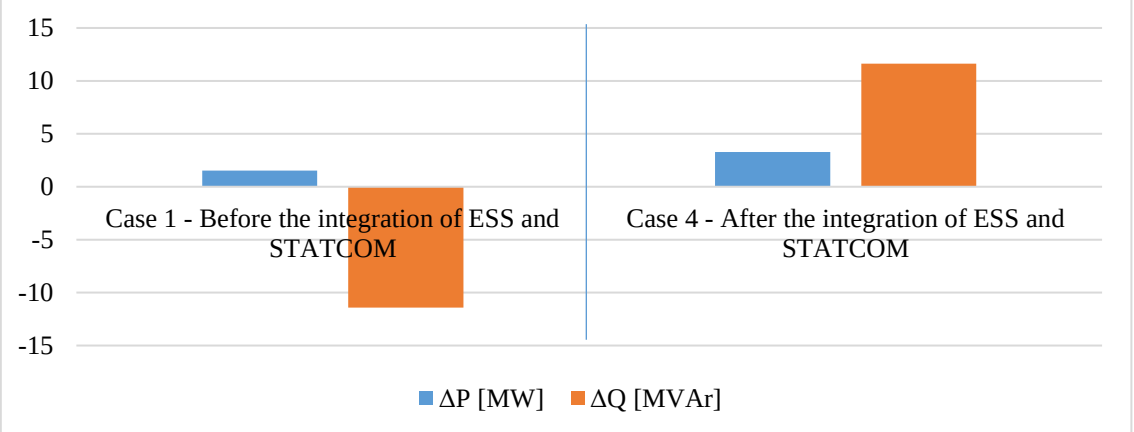


Fig. 4.11. Active (ΔP) and reactive (ΔQ) power losses before and after the integration of ESS and two STATCOM (Scenario 2)

Following the steady-state calculations, several relevant aspects are highlighted regarding the voltage levels at the nodes, the loading degree of the 110 kV OHL and the 250 MVA transformers, as well as the active and reactive power losses, as follows:

a) *The voltage values at the 110 kV grid nodes (Figure 4.8)* exceed the admissible limits of ±10% of V_n in Case 1, after the integration of the ESS and two STATCOM devices (Case 4), they are significantly reduced and fall within the admissible limits;
b) *The loading degree of the 110 kV OHL (Figure 4.9)* reflects the impact of ESS and FACTS device integration on the distribution of power flows, considering that the ESS operates in charging mode, with the values remaining within the admissible limits;
c) *The loading degree of the transformers (Figure 4.10)* highlights how the integration of ESS and FACTS devices influences the distribution of power flows in the analyzed grid, showing an increase due to the ESS operating in charging mode;
d) *The active and reactive power losses (Figure 4.11)* highlight the impact of the proposed technical solutions, showing a slight increase as a result of intensified power flows on the OHL, but remaining within the admissible limits.

Subsequently, the operation of the power grid was analyzed under N-1 and N-2 contingency conditions, both for Case 1 (without ESS and STATCOM integration) and for Case 4 (with ESS and the two STATCOM devices).

Table 4.5. N-1 contingencies analyzed before and after ESS and two STATCOM integration (Scenario 2)

No.	Contingency	Affected elements	For both analyzed cases (1 and 4)
1.	**L110 kV N8-N20**	N20	Radial supply
2.	**L110 kV N8-N19**	N19	Radial supply
3.	**L110 kV N1-N21**	N21	Radial supply
4.	**L110 kV N3-N22**	N22, N23	Common radial supply
5.	**L110kV N22-N23**	N23	Radial supply

Table 4.6. N-2 contingencies analyzed before and after ESS and two STATCOM integration (Scenario 2)

No.	Contingency	Affected elements	Case 1 (before ESS and STATCOM integration)	Case 4 (after ESS and STATCOM integration at nodes B1 and A1-110 kV)	Case 4 (after limiting ESS operation)
			Loading [% of S_{max}]	Loading [% of S_{max}]	Loading [% of S_{max}]
1.	**TR1-A250 MVA & TR2-B 250 MVA**	TR1-B 250 MVA	94.16% (Not applicable)	136.79%	97.83% *(After limiting ESS to 15% of P_i)*
2.	**L110 kV B1-N3& L110 kV N3-N6**	L110 kV N2-N3	18.21% (Not applicable)	104.95%	74.7% *(After limiting ESS to 67% of P_i)*
		L110 kV N1-N2	26.56% (Not applicable)	113.49%	83.17% *(After limiting ESS to 67% of P_i)*
		L110 kV A2-N1	34.01% (Not applicable)	121.05%	90.69% *(After limiting ESS to 67% of P_i)*

The results presented in Tables 4.5 and 4.6 indicate that, in the absence of ESS and FACTS devices, the loading degree of the grid elements remains within admissible limits. The integration of ESS may lead to overloads, however, by limiting its operation to a certain percentage of the installed power (P_i), these overloads are eliminated on the stressed elements of the grid, highlighting the importance of ESS controllability in critical operating scenarios.

4.3.3. Scenario 3 – *Electricity surplus during a summer morning*

The large-scale integration of RES into the analyzed power grid area has a significant impact on the local energy balance, especially during periods when RES generation approaches maximum values. Under these conditions, an electricity surplus occurs in the analyzed 110 kV grid, which must be evacuated to the transmission system (TS).

The assumptions established for this scenario are:

- Sources of energy in operation:
  - WPPs are operating at maximum installed capacity (P_{WPP} = 647.3 MW);
  - PVPPs are operating at maximum installed capacity (P_{PVPP} = 65 MW).
- The local electricity demand of users at SMP characteristic load level: 358.98 MW.
- Electricity surplus:
  - The difference between RES generation and the local electricity demand is 353.32 MW. which must be evacuated from the 110 kV distribution grid to the TS.

To manage this situation, the scenario considered the reduction of the electricity surplus and the loading degree of the grid elements by using a 120 MW/ 240 MWh ESS operating in charging mode at 100% of its installed power. In addition, the effects of integrating a ±60 MVAr STATCOM-type FACTS were analyzed, with the purpose of increasing the voltage level in the 110 kV grid and, implicitly, the transferable power on the 110 kV OHL under these conditions.

Figures 4.12-4.15 present the simulation results regarding the evolution of voltages at the grid nodes, the loading degree of 110 kV OHL and 250 MVA transformers, as well as active (ΔP) and reactive (ΔQ) power losses, before ESS and STATCOM integration, with the integration of the 120 MW/ 240 MWh ESS alone, and with the integration of the ESS, connected at node N3-110 kV, together with two STATCOM devices connected at nodes A1 and B1-110 kV.

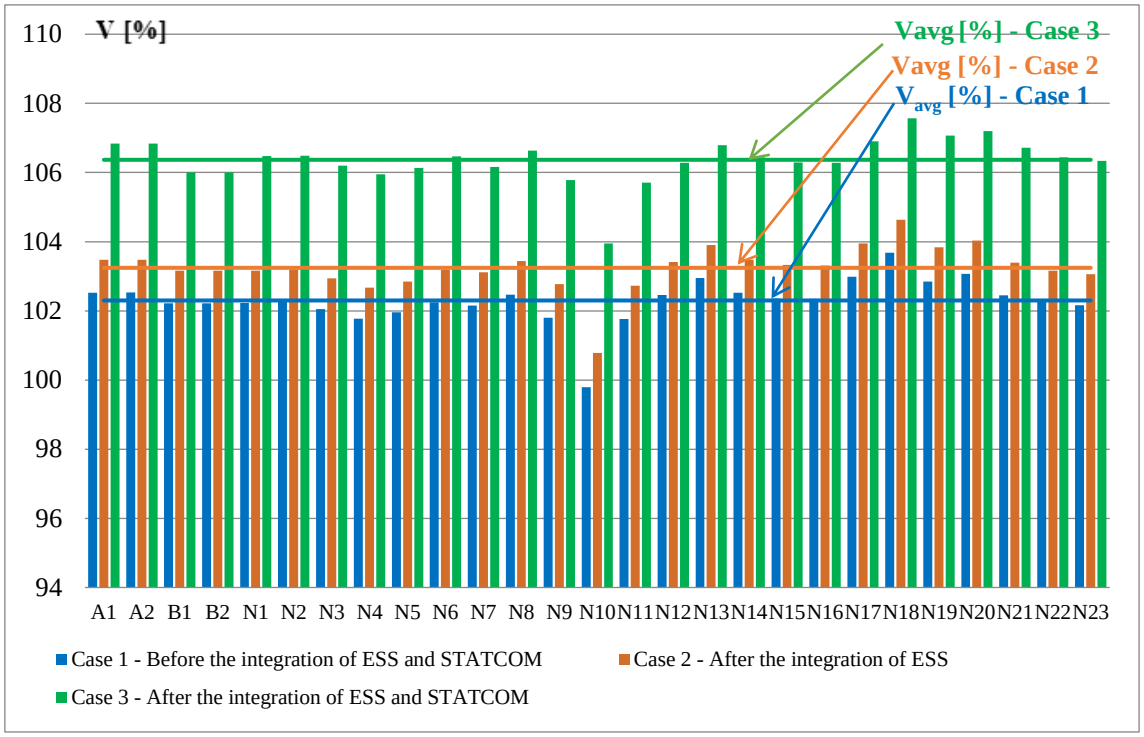


Fig. 4.12. Voltage values in the analyzed grid nodes, before and after the integration of ESS and two STATCOM, expressed as percentages of V_n (Scenario 3)

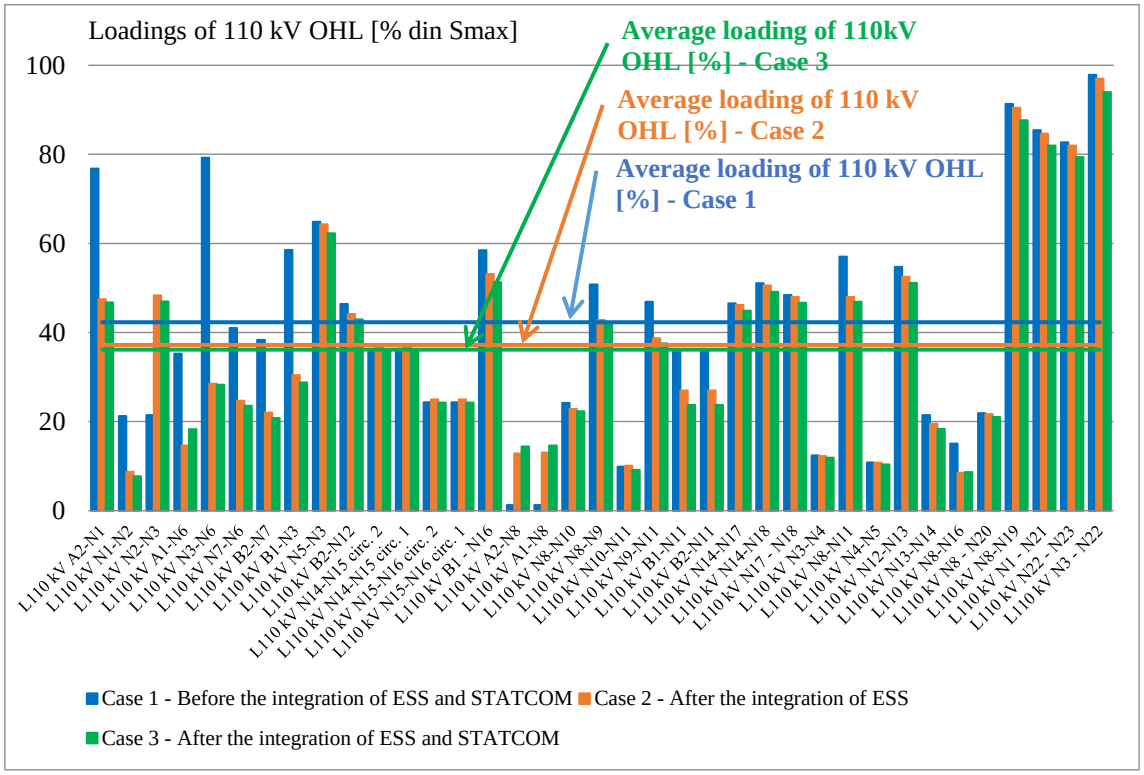


Fig. 4.13. Loading degree of 110 kV OHL before and after the integration of ESS and two STATCOM, expressed as percentages of S_{max} (Scenario 3)

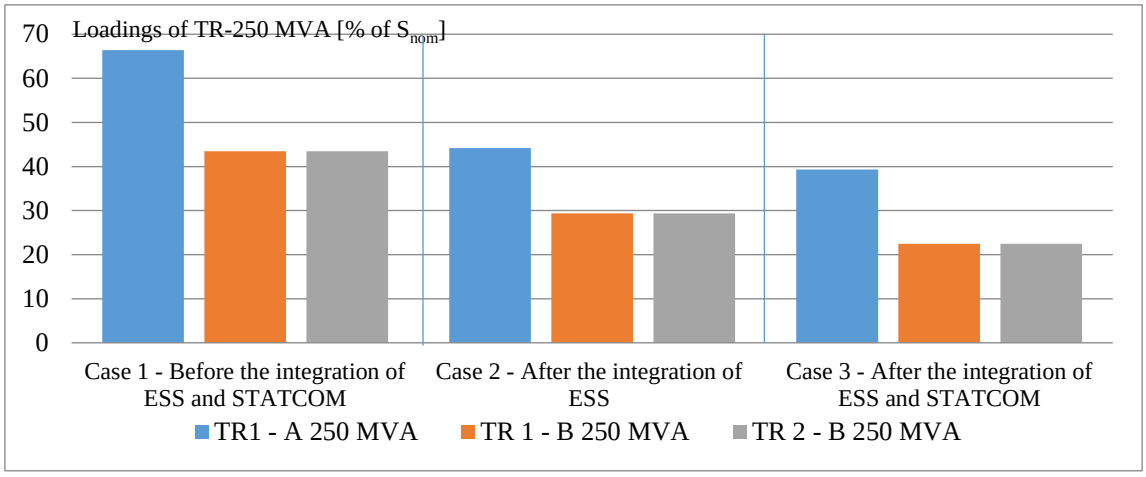


Fig. 4.14. Loading degree of TR-250 MVA before and after the integration of ESS and two STATCOM (Scenario 3)

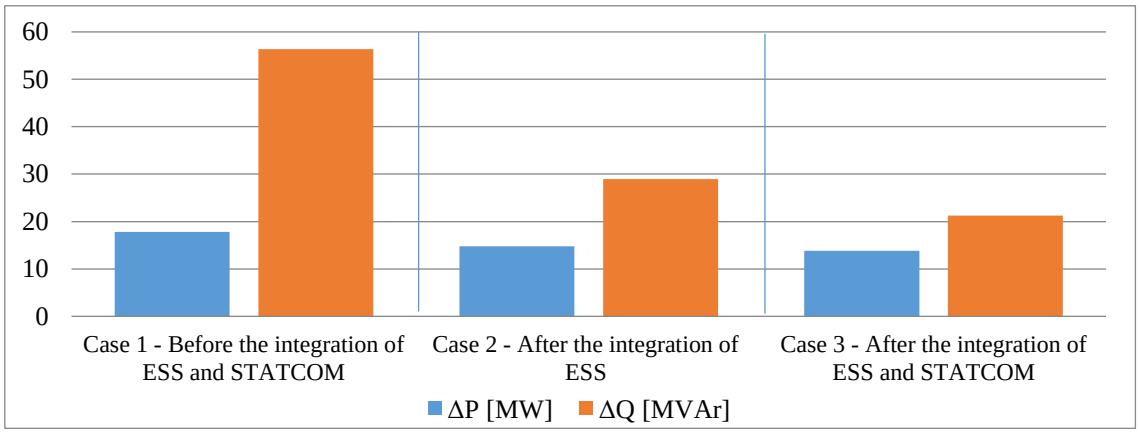


Fig. 4.15. Active (ΔP) and reactive (ΔQ) power losses before and after the integration of ESS and two STATCOM (Scenario 3)

Based on the steady-state calculations, for the configuration with all elements in operation, both in the absence and in the presence of the 120 MW/ 240 MWh ESS and the two ±60 MVAr STATCOM-type FACTS devices, the following aspects are highlighted:

a) *The voltage values at the 110 kV grid nodes (Figure 4.12)* show an increase in voltage levels without exceeding the admissible limits of ±10% of V_n for the three analyzed cases, while the STATCOM devices contribute to the improvement of the voltage profile;

b) *The loading degree of the 110 kV OHL (Figure 4.13)* reflects the impact of ESS and FACTS integration on the distribution of power flows in the analyzed grid;

c) *The loading degree of the 250 MVA transformers (Figure 4.14)* is high in the initial situation, decreases significantly after ESS integration, and is further reduced by the integration of STATCOM devices, remaining within the admissible limits;

d) *The active and reactive power losses (Figure 4.15)* highlight the impact of ESS and FACTS devices integration on the energy efficiency of the analyzed grid area.

Subsequently, the operation of the grid was analyzed under N-1 and N-2 contingency conditions, for Case 1 (without ESS and STATCOM integration), Case 2 (with ESS integration), and Case 3 (with ESS and the two STATCOM devices integration).

Table 4.7. N-1 contingencies analyzed before and after ESS and two STATCOM integration (Scenario 3)

No.	Contingency	Affected elements	Case 1	Case 2	Case 3
			Loading [% of S_{max}]	Loading [% of S_{max}]	Loading [% of S_{max}]
1.	**L110 kV A2-N1**	L110 kV N3-N6	142.04	66.86	66.15
2.	**L110 kV N3-N6**	L110 kV A2-N1	131.22	66.82	65.92
3.	**L110 kV B1-N3**	L110 kV N3-N6	118.36	48.26	46.22
4.	**TR1-A 250 MVA**	L110 kV N3-N22	101.45	99.05	93.01
5.	**TR1-B 250 MVA**	L110 kV N3-N22	100.27	98.62	94.22
6.	**TR2-B 250 MVA**	L110 kV N3-N22	100.27	98.62	94.22
7.	**L110 kV N8-N20**	N20	Radial supply		
8.	**L110 kV N8-N19**	N19	Radial supply		
9.	**L110 kV N1-N21**	N21	Radial supply		
10.	**L110 kV N3-N22**	N22, N23	Common radial supply		
11.	**L110kV N22-N23**	N23	Radial supply		

Table 4.8. N-2 contingencies analyzed before and after ESS and two STATCOM integration (Scenario 3)

No.	Contingency	Affected elements	Case 1	Case 2	Case 3
			Loading [% of S_{max}]	Loading [% of S_{max}]	Loading [% of S_{max}]
1.	**L110 kV A2-N1 & L110 kV N3-N6**	L110 kV B1-N3	234.26	105.41	99.49
2.	**L110 kV A2-N1 & L110 kV B1-N3**	L110 kV N3-N6	218.1	102.29	97.5%
3.	**TR 1-A 250 MVA & TR 2-B 250 MVA**	TR 1-B 250 MVA	190.8	110.52	83.04
4.	**TR 1-B 250 MVA & TR 2-B 250 MVA**	TR 1-A 250 MVA	176.34	112.41	84.18
5.	**TR 1-B 250 MVA & L110 kV A2-N1**	L110 kV N3-N6	154.08	74.03	65.19

The steady-state analysis of N-1 and N-2 operating conditions, presented in Tables 4.7 and 4.8, highlights the critical situations that may occur in the operation of the grid in the absence of technical solutions such as ESS and STATCOM-type FACTS devices integration. After the integration of STATCOM devices (Case 3) they contribute to increasing the voltage levels at the grid nodes and, implicitly, to reducing the loading degree of the grid elements under both N-1 and N-2 contingency conditions. Thus, according to Table 4.8, it can be observed that even under N-2 contingencies, no overloads occur on the grid elements.

4.3.4. Scenario 4 – *Electricity deficit during a winter evening*

Scenario 4 corresponds to the characteristic load level of the winter peak (WEP), characterized by high electricity demand. In the absence of local electricity generation (P_{RES} = 0 MW), the supply of users in the grid area is ensured through the three 250 MVA transformers, which may lead to low voltage values at the grid nodes, overloads of the 250 MVA transformers under contingency conditions, or high active and reactive power losses.

To mitigate these operational risks, the following operating cases of the grid were evaluated within the analyzed scenario:

- *Case 1 – Initial situation*: representing the base steady-state regime, without the integration of additional elements into the analyzed grid;
- *Case 2 – Integration of a 120 MW/240 MWh* ESS, operating in discharging mode at maximum installed power, to partially cover electricity demand, connected at node N3-110 kV;
- *Case 3 – Integration of a 100 MW natural gas power plant (NGPP)*, in addition to the ESS from Case 2, serving as a reserve generation source to ensure supply continuity under peak load conditions, connected at node N16-110 kV;
- *Case 4 – Integration of STATCOM-type FACTS devices*, ±60 MVAr each, in addition to the NGPP from Case 3, at nodes A1 and B1-110 kV, aimed at increasing voltage levels and reducing active and reactive power losses.

Figures 4.16-4.19 present the simulation results regarding the evolution of voltages at the grid nodes, the loading degree of 110 kV OHL and 250 MVA transformers, as well as active (ΔP) and reactive (ΔQ) power losses, before and after the integration of the ESS, the NGPP, and STATCOM devices.

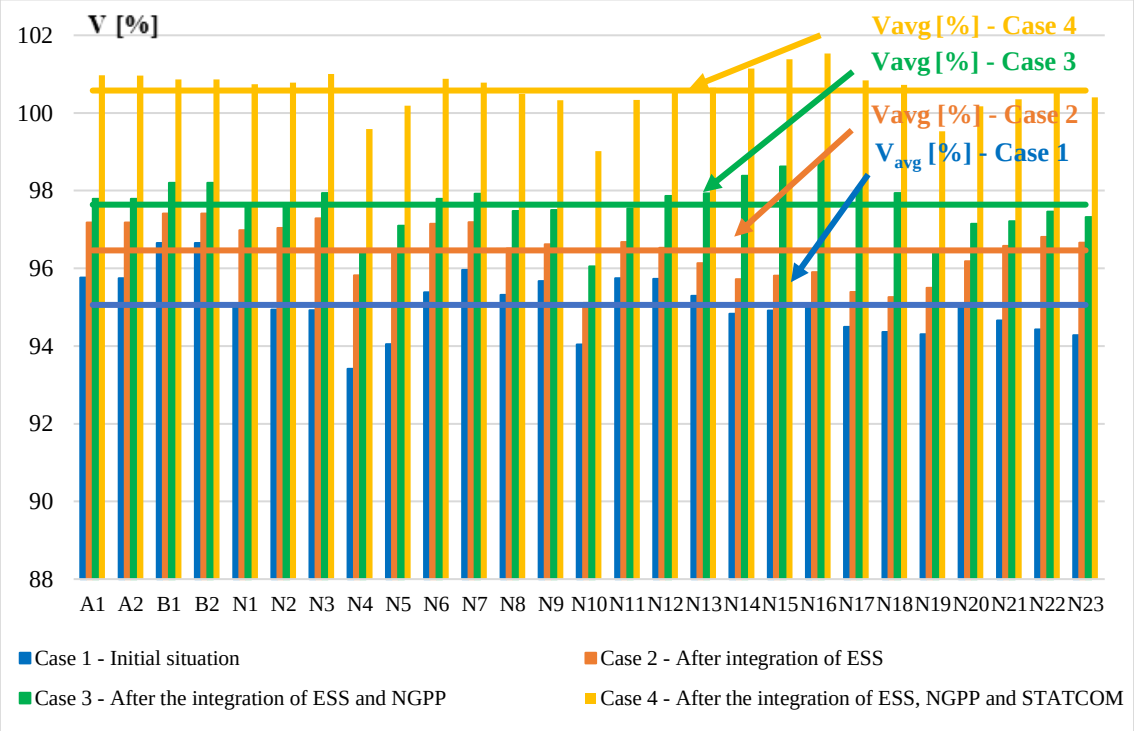


Fig. 4.16. Voltage values at the grid nodes before and after the integration of the ESS, the NGPP and two STATCOM devices

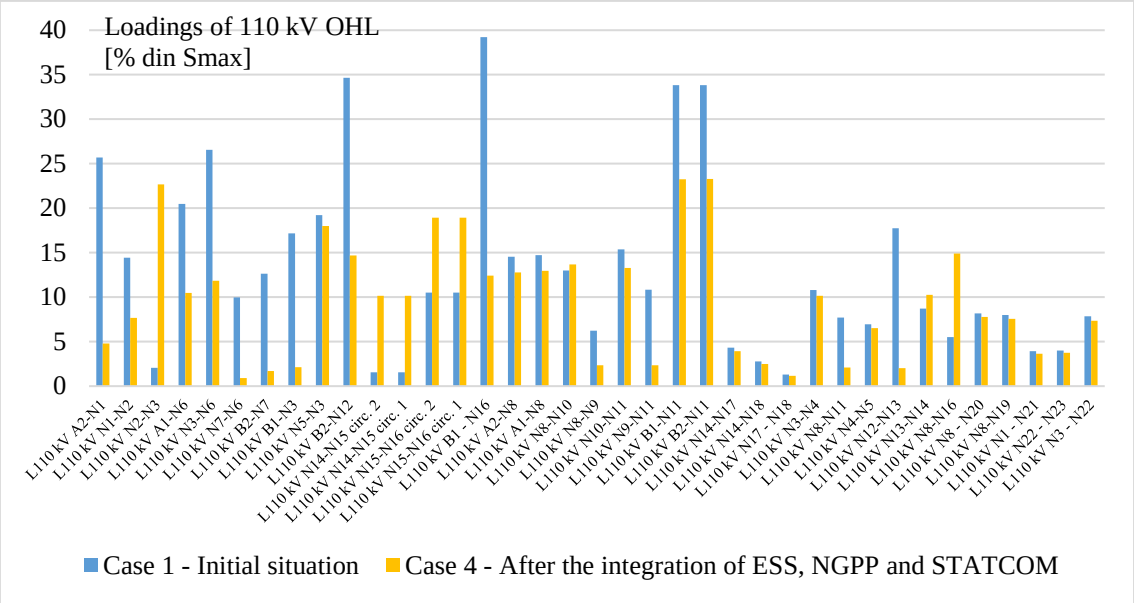


Fig. 4.17. Loading degree of 110 kV OHL before and after the integration of the ESS, the NGPP, and two STATCOM devices, expressed as percentages of S_{max}

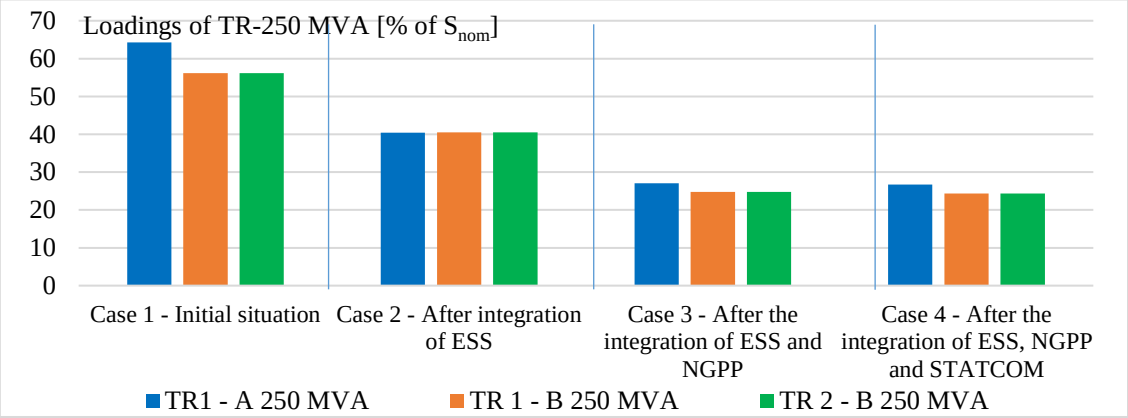


Fig. 4.18. Loading degree of 250 MVA transformers, before and after the integration of the ESS, the NGPP, and two STATCOM devices

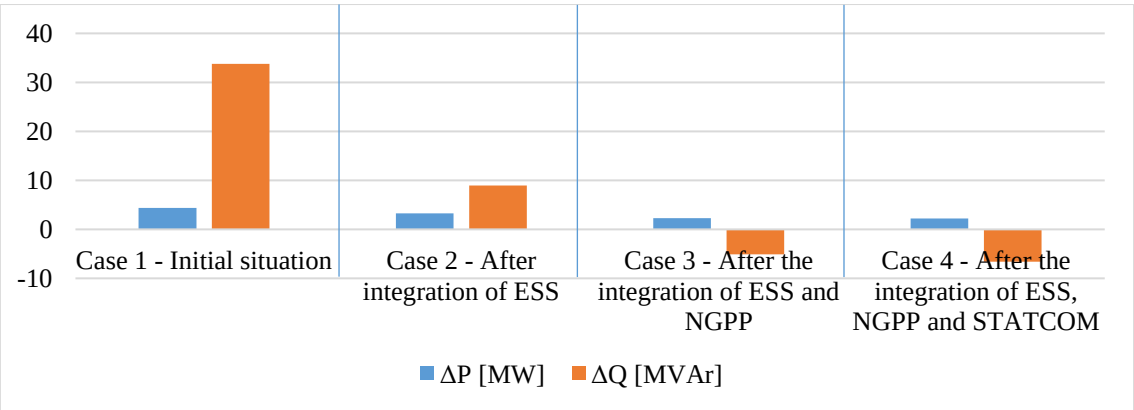


Fig. 4.19. Active (ΔP) and reactive (ΔQ) power losses, before and after the integration of the ESS, the NGPP, and two STATCOM devices

Following the steady-state calculations for the four analyzed cases, both in the absence and in the presence of the 120 MW/240 MWh ESS, the 100 MW NGPP, and the two ±60 MVAr STATCOM devices, the following aspects are highlighted:

a) *The voltage values at the 110 kV grid nodes (Figure 4.16)* show an overall increase across all nodes, without exceeding the admissible limits (±10% of V_n), with the integration of STATCOM devices contributing to the improvement of the voltage profile;

b) *The loading degree of 110 kV OHL (Figure 4.17)* reflects the impact of integrating the ESS, the NGPP, and the STATCOM devices on the distribution of power flows within the analyzed grid, under high electricity demand conditions;

c) *The loading degree of 250 MVA transformers (Figure 4.18)* highlights how the integration of the ESS, the NGPP, and the STATCOM devices influences the distribution of power flows in the analyzed grid. The loading values of the three 250 MVA transformers indicate a significant reduction in their stress levels;

d) *Active and reactive power losses (Figure 4.19)* underline the impact of the integration of the ESS, the NGPP, and the FACTS devices on the operating regime of the analyzed grid. The reduction in reactive power losses is more pronounced, as in the initial condition (Case 1) they had high values due to the lack of local compensation sources.

Subsequently, the operation of the power grid was analyzed under N-1 and N-2 contingency conditions, for Case 1 (without the integration of ESS and STATCOM), Case 2 (with ESS integration), Case 3 (with ESS and NGPP integration), and Case 4 (with ESS, NGPP, and two STATCOM devices integration).

Table 4.9. N-1 contingencies analyzed before and after the integration of the ESS, the NGPP, and two STATCOM devices

No.	Contingency	Affected elements	Case 1	Case 2	Case 3	Case 4
			Voltage deviations [% of V_n]	Voltage deviations [% of V_n]	Voltage deviations [% of V_n]	Voltage deviations [% of V_n]
1.	**TR1-A 250 MVA**	N19	89.07	92.71	94.6	100.37
		N1	89.09	93.74	95.41	101.61
		N2	89.11	93.91	95.56	101.61
		N3	89.31	94.92	95.06	101.84
2.	**L110 kV N5-N3**	N5	88.44	91.18	91.89	95.2
3.	**L110 kV N8-N20**	N20	Radial supply			
4.	**L110 kV N8-N19**	N19	Radial supply			
5.	**L110 kV N1-N21**	N21	Radial supply			
6.	**L110 kV N3-N22**	N22, N23	Common radial supply			
7.	**L110kV N22-N23**	N23	Radial supply			

Table 4.10. N-2 contingencies analyzed before and after the integration of the ESS, the NGPP, and two STATCOM devices

No.	Contingency	Affected elements	Case 1	Case 2	Case 3	Case 4
			Loading [% of S_{max}] / Voltage deviations [% of V_n]	**Loading [% of S_{max}] / Voltage deviations [% of V_n]**	**Loading [% of S_{max}] / Voltage deviations [% of V_n]**	**Loading [% of S_{max}] / Voltage deviations [% of V_n]**
1.	**L110 kV A2-N1 & L110 kV N3-N6**	N4	86.58	95.78	96.61	99.33
		N21	87.22	96.35	97.17	99.88
		N3	87.23	97.25	98.07	100.74
		N5	87.24	96.4	97.23	99.93
2.	**L110 kV A2-N1 & TR1-A 250 MVA**	N4	87.43	92.79	94.41	100.29
		N5	88.13	93.43	95.05	100.88
		N21	88.06	93.81	94.99	100.82
		N3	89.06	94.31	95.91	101.68
3.	**TR1-A 250 MVA & TR1-B 250 MVA**	N4	74.48	86.94	91.27	102.36
		N5	75.21	87.64	91.93	102.93
		N21	75.65	87.54	91.88	103.11
		N3	76.44	88.59	92.83	103.71
		TR2-B 250 MVA	215.11	132.14	80.16	74.69

The results presented in Tables 4.9 and 4.10 demonstrate that, in Case 1, major voltage deviations occur (down to 90% of V_n), and critical overloads appear on transformer TR2-B 250 MVA (up to 215%). The integration of the ESS and NGPP reduces these values, while the additional integration of the two STATCOM devices (Case 4) restores voltages within admissible limits and decreases the loading of the 250 MVA transformer, confirming the effectiveness of the proposed solutions.

5. General conclusions, personal contribution, and research perspectives

This chapter synthesizes the main conclusions of the research, highlighting the results obtained and how they contribute to the understanding and addressing of issues related to the integration of RES into power systems. At the same time, personal contributions are presented, along with directions for future development that may serve as starting points for further research.

5.1. General conclusions

The large-scale integration of RES into power systems represents both a challenge, due to their variable and intermittent nature, and an opportunity for reducing dependence on conventional energy resources. The analyses carried out confirm that, in addition to the evident advantages, the increasing share of photovoltaic and wind power plants raises stability and security issues in the operation of power networks, which requires the integration of advanced technical solutions and careful planning of their operation.

Based on the conducted research, the main conclusions are:

a) The variability of electricity generation from RES directly affects the operation of power systems, leading to imbalances between electricity generation and demand, changes in power flows, and deviations of voltage and frequency values beyond admissible limits. This characteristic, specific to photovoltaic and wind sources, highlights the need for continuous adaptation of power networks and demonstrates the large-scale integration of these energy sources cannot be achieved without additional technical solutions to increase grid operational flexibility;

b) The analysis of generation curves and the capacity factor goes beyond a purely descriptive role and becomes an essential tool for assessing system stability and supporting decision-making in power system operation. By quantifying and identifying the maximum amplitude of production deviations, the need for sizing reserve generation sources is justified, as they are indispensable for real-time balancing and for maintaining system security. This aspect is of major importance considering that the power system forms the backbone of energy infrastructure, and maintaining its stability and operational security is a fundamental condition for the entire economy and society as a whole;

c) Photovoltaic and wind power plants, through their operational characteristics, must comply with technical requirements for connection to public grids. Their efficient integration into the energy mix requires not only harnessing the available natural resources but also aligning them with the technical constraints of the grid infrastructure. At the same time, permanent coordination between producers, grid operators, and regulatory authorities is necessary to ensure operational security, power quality, and continuity of supply to end users;

d) Modern technical solutions such as energy storage systems, reserve generation sources, and FACTS devices are essential for enhancing flexibility and security in power system operation. They contribute to reducing imbalances, compensating for

RES production variability, and improving power quality, playing a decisive role in the integration of RES into power systems;

e) The use of an integrated management algorithm, which coordinates the operation of modern technical solutions, represents an effective direction for the operation of power network with high-RES penetration. The algorithm enables the simultaneous coordination of energy storage systems, reserve generation sources, and FACTS devices, contributing to stability maintenance and power flow redistribution in critical operating scenarios. The obtained results show that such an approach facilitates the secure and efficient operation of power networks, even under critical conditions;

f) The progressive reduction of natural inertia in power systems, caused by the decreasing share of synchronous generators in operation, highlights the necessity of developing and implementing synthetic inertia solutions. This must be ensured through inverter-based resources and energy storage systems, being essential to limit the rate of change of frequency (RoCoF) during the first few hundred milliseconds after a contingency. Synthetic inertia therefore becomes an indispensable alternative to the lack of mechanical inertia, providing the minimum conditions required for the stability of modern power systems;

g) The analysis carried out on a 110 kV network area characterized by high-RES penetration confirmed the relevance and applicability of the proposed technical solutions. The four elaborated critical scenarios demonstrated that, through integrated coordination of available resources, it is possible to reduce overloads, maintain voltages within admissible limits, decrease active and reactive power losses, and redistribute power flows. These aspects underline that modern management solutions can support the secure and efficient operation of power networks, in line with the objectives of the energy transition.

5.2. Personal contributions

The personal contributions obtained within this thesis are structured into two main categories, as follows:

a) Theoretical and documentation contributions:

- *A critical review of the specialized literature on the integration of renewable energy sources into power systems was conducted in Chapter 1*, with emphasis on the variability and intermittency of their electricity generation, as well as on the solutions identified in international research. Furthermore, the main types of renewable power plants, their components, and connection solutions were identified and classified, highlighting the specific advantages and limitations of each technology, which enable a comparative understanding of their role in power system operation;

- *The regulations in force regarding the integration of renewable energy sources into public power grids were analyzed and synthesized*, focusing on the technical connection requirements. The analysis highlighted safety and compatibility criteria, as

well as the contribution of these sources to power system operation, aspects presented in Chapter 1;

- *The main meteorological parameters and forecasting methods used for solar and wind energy sources were presented and synthesized*. This analysis, carried out in Chapter 2, emphasized the essential role of meteorological data in estimating electricity generation and planning power system operation;

- *Active and reactive power generation curves as functions of time were developed and analyzed for both a photovoltaic power plant and a wind power plant*, *together with the calculation of the annual electricity generation and the determination of the capacity actor based on real data*. This analysis illustrated the variability of electricity generation from these sources and their contribution to maintaining power quality in power system. The results are presented in Chapter 2;

- *An analysis of energy storage systems was carried out, including the classification of existing storage systems and their methods of application, covering a wide range of use cases*. In this context, relevant technical indicators for evaluating their operational performance were compiled, and aspects related to their integration into public power grids were examined, with a proposed methodology outlined. The content is presented in Chapter 3;

- *Reserve generation sources and their role in power systems were analyzed in Chapter 3*, highlighting their contribution to maintaining power quality and ensuring supply continuity under conditions of RES production variability;

- *FACTS devices were classified, and their operating principles were presented in Chapter 3*, along with a synthesis of the advantages and disadvantages associated with different existing technologies. The analysis addressed both the benefits of using advanced devices in modern power system operation and the practical limitations of their implementation;

- *A management algorithm for coordinating the operation of renewable energy sources, energy storage systems, reserve generation sources, and FACTS devices was developed*. Detailed in Chapter 3, it aims to ensure the secure operation of power networks while respecting technical constrains and maintaining power quality;

b) Applied contributions:

- *A 110 kV power network area characterized by high-RES penetration was modeled and simulated in Chapter 4 using the NEPLAN software.* The analysis included steady-state calculations that evaluated the impact of RES generation variability on the stability and operational security of the analyzed grid area;

- *Technical solutions were integrated*, such as a Battery Energy Storage System (BESS), two STATCOM-type FACTS devices, and a natural gas power plant as a reserve generation source, aimed at increasing the operational flexibility of the analyzed power network area with high-RES penetration;

- *Critical operating scenarios that may occur in power network operation were developed*, based on which the proposed technical solutions and the designed management algorithm were validated, demonstrating overload reduction, voltage level maintenance within admissible limits, and improved grid efficiency through reduced power losses.

5.3. List of publications

The works published during the doctoral studies are:

I. **A. F. Vlada** and S. Gheorghe, "Comparative study of renewables energy sources: power characteristics and capacity factor," U.P.B. Sci. Bull., Ser. C, Vol. 87, Iss. 4/2025, ISSN: 2286-3540, 2025;

II. **A. F. Vlada** and S. Gheorghe, "Management of integrated renewable energy sources, storage systems, and reserve generation sources in power systems," *12th Int. Conf. on ENERGY and ENVIRONMENT (CIEM)*, Bucharest, Romania, 2025, pp. 1-5, DOI: 10.1109/CIEM67454.2025.11284655;

III. **A. F. Vlada** and S. Gheorghe, "Analysis of the integration of new energy sources and an energy storage system into an electric network area of the power system," EMERG, Vol. X, Iss. 3/2025, ISSN: 2668-7003, ISSN-L: 2457-5011, 2025, DOI:10.37410/EMERG.2025.3.08.

5.4. Future research developments:

The research carried out may serve as a starting point for a series of further developments and studies, among which the following can be mentioned:

- *Extension of the analysis to other power network areas within power systems*, with different topologies and operating conditions, in order to validate the proposed methodology in various contexts;
- *Integration of dynamic models*, to capture the behavior of the power network under transient regimes, for the evaluation of frequency stability in the event of contingencies;
- *Analysis of the impact on the electricity market and on the operation of power systems with high-RES penetration*, by correlating technical results with economic and regulatory aspects.

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Appendix A – Flowchart of the proposed algorithm

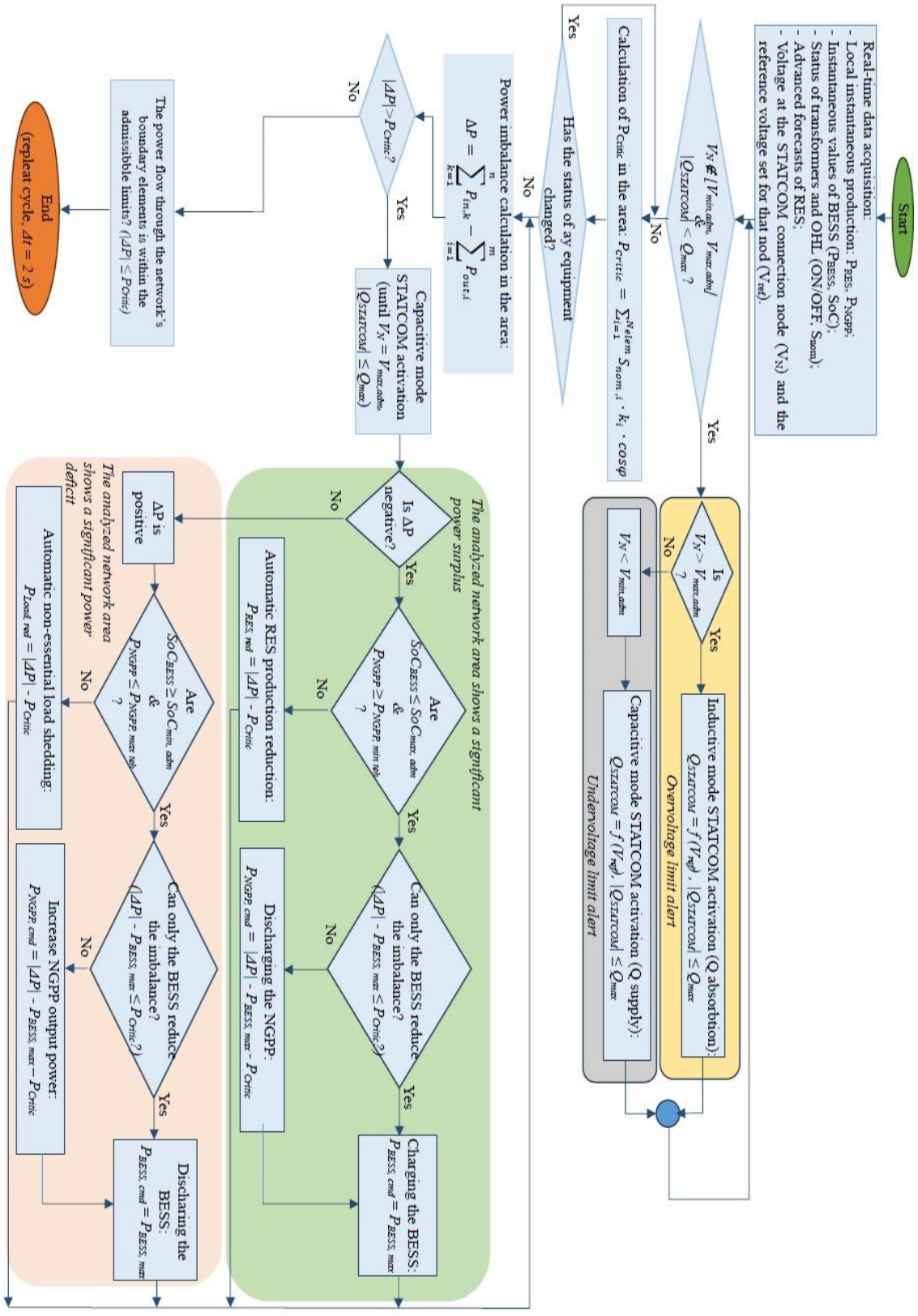


Fig. A.1. Flowchart of the proposed algorithm for coordinating the operation of energy storage systems, FACTS devices, and reserve generation sources in a power network area

Appendix B – Single-line diagram and technical data of the analyzed power network area

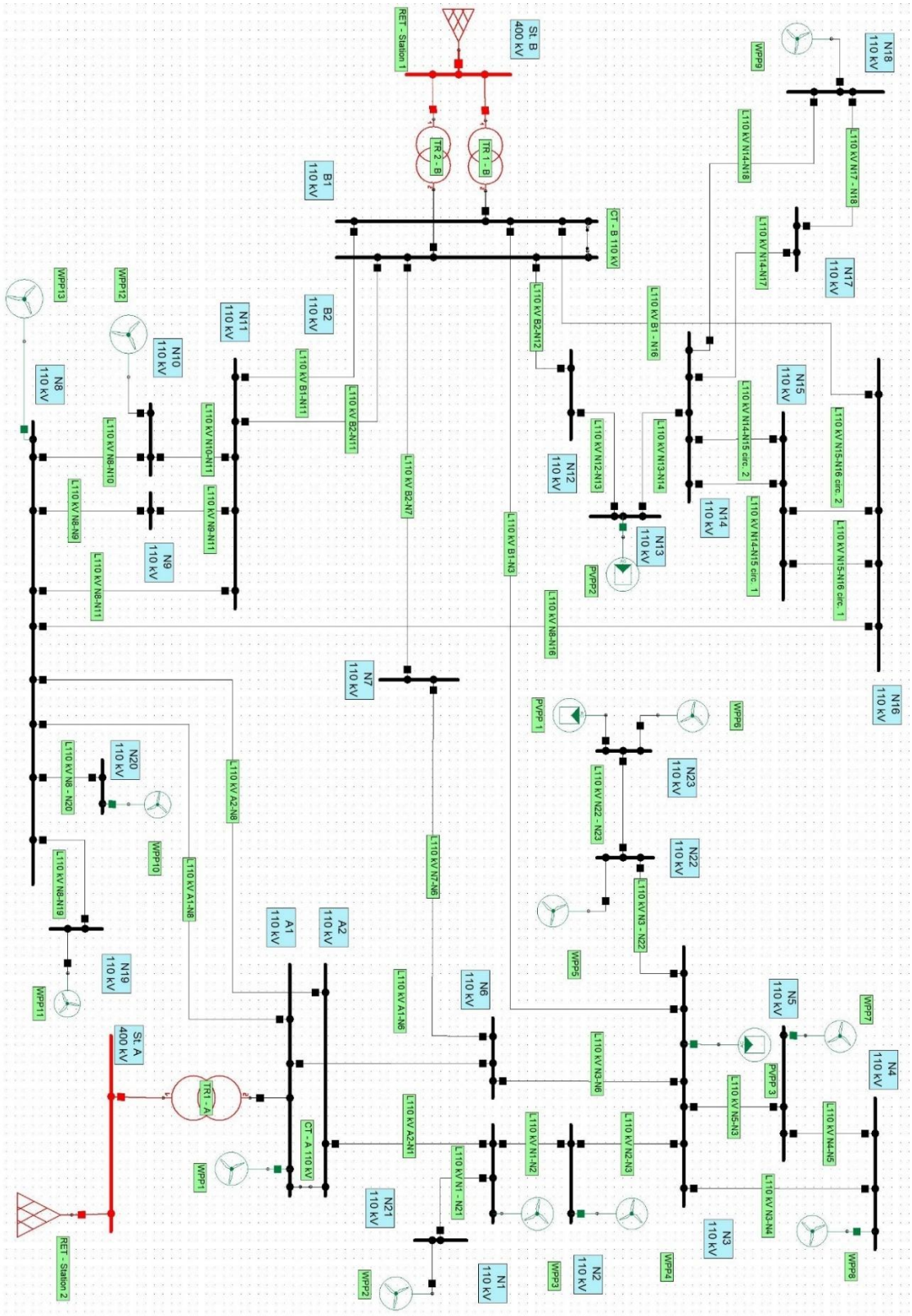


Fig. B.1. Basic single-line diagram of the analyzed power network