NATIONAL UNIVERSITY OF SCIENCE AND TECHNOLOGY
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ELECTRICAL ENERGY SYSTEMS DEPARTMENT
DOCTORAL SCHOOL OF ENERGY ENGINEERING

CONTRIBUTIONS ON THE USE OF FACTS DEVICES OF SVC TYPE IN TRANSMISSION NETWORKS FOR IMPROVING POWER SYSTEM OPERATING PARAMETERS AND INCREASING THE INTEGRATION CAPACITY OF RENEWABLE ENERGY SOURCES

DOCTORAL THESIS – SUMMARY

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TABLE OF CONTENTS

1. CHAPTER 1 – INTRODUCTION 1

1.1. CURRENT CONTEXT 1
1.2. IDENTIFYING THE PROBLEM 1
1.3. OBJECTIVE OF THE PAPER 2
1.4. METHODOLOGY OF THE PAPER 2

2. CHAPTER 2 – BASIC CONCEPTS OF ELECTRICITY SYSTEMS 4

2.1. GENERAL 4
2.2. CLASSIFICATION AND NETWORK-SPECIFIC CONFIGURATIONS IN THE ELECTRICITY SYSTEM 6
2.2.1. Architecture of the power system 6
2.2.2. Classification of electricity networks 7
2.2.2.1. Electricity transmission networks 7
2.2.2.2. Electricity distribution networks 7
2.3. SYMMETRICAL STATIONARY REGIME OF ELECTRICITY SYSTEMS 8
2.4. DYNAMIC REGIMES AND STABILITY OF ELECTRICITY SYSTEMS 9
2.4.1. General aspects of dynamic regimes 9
2.4.2. General notions on the stability of electricity systems 10
2.4.3. Classification of stability of power systems 11

3. CHAPTER 3 – FACTS DEVICES, THE STATIC REACTIVE POWER COMPRESSOR 6

3.1. FACTS TECHNOLOGIES USED IN POWER SYSTEMS 16
3.2. STATIC REACTIVE POWER COMPENSATOR 21
3.2.1. Components of the SVC installation 21
3.2.2. Configurations of the SVC 25
3.2.2.1. SVC configuration with fixed capacitor in parallel with thyristor-controlled coil 25
3.2.2.2. SVC configuration with thyristor-controlled capacitor in parallel with thyristor-controlled coil 26
3.2.3. Deployment models of SVC devices in substations 26
3.2.4. SVC control strategies 29

4. CHAPTER 4 – USE OF THE NEPLAN ELECTRICITY SOFTWARE SOLUTION FOR THE SIMULATION OF NETWORK OPERATING REGIMES 31

4.1 GENERAL DESCRIPTION 31
4.2 MODULES AND FUNCTIONALITIES 31
4.2.1. Calculation of the steady regime and contingency analysis: 31
4.2.2. Short-circuit analysis 32
4.2.3. Voltage stability analysis 34
4.2.4. Dynamic analysis mode 34

5. CHAPTER 5 - CASE STUDY 1: THE NEED AND BENEFITS OF USING SVCS TO IMPROVE STATIONARY OPERATING REGIMES 35

5.1. OBJECTIVE OF THE CASE STUDY 35
5.2. NETWORK NORDIC32 35
5.3. METHODOLOGIES 37
5.3.1. Use of methodologies for the integration of FACTS devices into the electricity transmission network 37
5.3.2. Methodology for choosing a device type FACTS 38
5.3.3. Methodology for choosing the SVC device location node 40
5.4. MODELLING OF THE SVC DEVICE IN NEPLAN10 FOR STEADY-STATE CALCULATION 43
5.5. IMPLEMENTATION OF THE PROPOSED METHODOLOGIES IN THE NORIDC32 NETWORK 46
5.5.1. Choosing the FACTS device in the NORDIC32 network 46
5.5.2. Determination of the optimal location for the SVC device in the NORDIC32 network 52
5.6. CONCLUSIONS OF THE CASE STUDY 64

6. CHAPTER 6 – CASE STUDY 2: ANALYSIS OF THE IMPACT OF RENEWABLES ON THE DYNAMIC STABILITY OF GRIDS AND THE APPROPRIATENESS OF USING SVC DEVICES 65

6.1. OBJECTIVE OF THE CASE STUDY 65
6.2. SIMULATION OF DYNAMIC OPERATING REGIMES OF TRANSMISSION NETWORKS 65
6.2.1. Regulator interconnection structures 65
6.2.2. Regulators used to control the operation of hydropower plants 67
6.2.2.1. Voltage regulator – ST6B 68

6.2.2.2. PSS2B Regulator ... 69
6.2.2.3. Turbine regulator GOVHYDRO1 ... 71
6.2.3. Regulators used to control the operation of thermal power plants ... 72
6.2.3.1. Excitation regulator AC1A ... 72
6.2.3.2. Regulator PSS1A ... 73
6.2.3.3. GGOV1 turbine regulator ... 74
6.2.4. Regulators used to control the operation of the SVC ... 76
6.2.4.1. Regulator for SVC type CSVGN1 ... 76
6.2.4.2. Regulator for SVC type CSVGN3 ... 77
6.2.4.3. Regulator for SVC type CSVGN4 ... 78
6.2.4.4. Regulator for SVC type CSVGN5 ... 79
6.2.4.5. Regulator for SVC type CSVGN6 ... 80
6.2.5. Wind turbines ... 81
6.2.5.1. Type 1 wind turbines ... 81
6.2.5.2. Type 2 wind turbines ... 82
6.2.5.3. Type 3 wind turbines ... 83
6.2.5.4. Type 4 wind turbines ... 85
6.2.5.5. Choosing the wind turbine model for the case study ... 87
6.2.6. Scenarios analysed ... 88
6.2.6.1. Initial scenario – S0 ... 88
6.2.6.2. Renewable energy scenario – H1 ... 89
6.2.7. Analysis of the dynamic behavior of the network in the studied scenarios ... 91
6.2.7.1. Dynamic event 1 – triggering of the 400 kV line L432-444 ... 92
6.2.7.2. Dynamic event 2 – disconnection and reconnection of the C3 consumer ... 96
6.2.7.3. Dynamic event 3 – triggering of the 400/130 kV power transformer T144-444 ... 101
6.2.7.4. Dynamic event 4 – the start-up of the G16 thermal power plant ... 104
6.2.7.5. Dynamic event 5 – short circuit in 130kV node 141 ... 108
6.2.7.6. Dynamic event 6 – three-phase short circuit on the 400 kV line L446-447 ... 112
6.2.8. Conclusions ... 116

7. CHAPTER 7 - CASE STUDY 3: ANALYSIS OF THE OPPORTUNITY OF INSTALLING SVC DEVICES IN SEN ... 118

7.1. DESCRIPTION OF THE CURRENT SITUATION AT THE LEVEL OF THE NES ... 118
7.2. PROSPECTS FOR THE DEVELOPMENT AND INTEGRATION OF RENEWABLES ... 119
7.3. Analysis of stationary operating regimes ... 120
7.3.1. Analysis of the initial operating regime ... 120
7.3.2. VDV operating level ... 122
7.3.3. CNG operating stage ... 124
7.3.4. VDI operating level ... 125
7.3.5. VSI operating level ... 127
7.4. CONCLUSIONS ... 128

8. CHAPTER 8 – CONCLUSIONS AND PERSONAL CONTRIBUTIONS ... 130

8.1.CONCLUSIONS ... 130
8.2. PERSONAL CONTRIBUTIONS ... 131
8.3. DIRECTIONS TO FOLLOW IN RESEARCH ... 135

BIBLIOGRAPHY ... 136

ANNEXES

1. CHAPTER 1 – INTRODUCTION

1.1. Current context

Currently, electric power systems are undergoing a profound transformation in the sense of the transition from classic centralized generation carried out in high and very high power plants to distributed generation involving small electricity production units, and at the same time a large-scale development of renewable sources for electricity production (wind, photovoltaic, biomass, micro-hydropower plants, etc.). At the same time, consumers who in the past had an exclusively passive role are becoming more and more actively involved in the operation of energy systems by assuming the role of prosumer,. This transition, while bringing new challenges, is necessary to ensure climate sustainability and minimise environmental impact.

The main challenge encountered in the transition process at the level of electricity systems is represented by increasing safety and ensuring continuity of supply for all users in a technically and economically efficient way. It is necessary to assess the impact of all these transition processes both in terms of static operating regimes and in terms of dynamic regimes.

A recent example is the events, which took place on April 28 in Spain, where the disconnection of several photovoltaic power plants resulted in a sudden decrease in the energy generated, prompting the frequency in the system to decrease to 48 Hz [1]. This rapid decline in the amount of energy produced led to a sharp increase in energy imports from France to the point where the separation of the two systems was inevitable. Following these events, the blackout affected only the Iberian Peninsula and a small part of France [1]. This example perfectly illustrates the challenges posed by the transition to renewable energy sources on the stability of electricity systems. The problems related to the decrease of mechanical inertia and implicitly of operational safety following the energy transition are studied at the level of European policies in order to identify the optimal solutions.

All these challenges need tailor-made technical solutions to help the proper functioning of energy systems in an ever-changing environment.

A set of solutions to these problems is represented by FACTS (Flexible AC Transmission System) devices that allow the increase of operational flexibility and operational safety of energy systems by using technologies based on power electronics [2]. FACTS equipment offers a wide range of benefits and can be used in electricity transmission and distribution systems to increase system stability, voltage level regulation, reduction of energy losses and control of power circulation [3].

In order to be able to determine the optimal solutions to respond to all these challenges, it is necessary to use standardized test networks and simulation environments. Standardized test networks help assess impact and model response cases for multiple operating scenarios. Through the use of test networks, the operating regimes in several transitional situations can be compared, starting from the basic regime in which the energy sources are conventional ones (hydropower plants, thermal power plants, nuclear power plants) and up to regimes in which the main energy source in a certain area of the network is renewable.

1.2. Identifying the problem

Electric power systems are constantly changing by trying to adapt to both user needs and environmental policies to ensure an efficient transition to environmentally low-impact energy sources. All these changes generate problems in terms of ensuring the operational safety of electricity systems.

The main problems identified in this transition process are:

- Increasing operational safety;

- Control of power circulation in interconnected systems to ensure efficient operation with as little energy loss as possible;
- Control of the voltage level in the grid due to variations in the processes of electricity production and consumption;
- Ensuring the dynamic stability of systems in the event of high-impact incident.

1.3. Objective of the paper

The objective of this paper is to carry out a complex analysis in order to identify the main operational problems of the electric power systems that can be solved by using SVC FACTS devices and how could the integration capacity of renewable energy sources be increased at the level of the electricity transmission network .

To achieve this goal, it is necessary to:

- Carry out a research process of the current state in terms of the operation of the electric power systems, of the FACTS devices and of the mode of operation and parameterization of the SVC type equipment.
- Use standardized test networks to carry out a detailed analysis on the impact of renewable energy sources on the operation of electricity systems.
- Study the behavior and modeling of the main components of the network in the dynamic operating regimes.
- Conduct studies on the behavior of electrical energy transmission networks in various operating scenarios and for a series of dynamic events.
- Analyze the opportunity to implement SVC devices in the national energy system in Romania, by conducting simulations for several scenarios, analyze the optimal connection node and sizing the FACTS device.

1.4. Methodology of the paper

In the research process, a series of steps were taken in order to determine the opportunity to use SVC type FACTS devices in electricity transmission networks in the context of energetic transition to renewable energy sources. In this regard, as a first stage, a documentation process was carried out on topics such as the dynamic operating regimes of electricity systems and FACTS equipment.

In the first stage of the case study, two methodologies applicable in electricity transmission networks were proposed, analyzed and implemented. The first methodology aims to choose the optimal FACTS device to respond to the problems identified at the system level, and the second methodology aims to correctly size and place the SVC equipment in the network. Both methodologies have been implemented, tested and validated using the NORDIC32 test network. After a series of simulations, the first conclusions were drawn on the opportunity of utilizing the SVC devices to improve voltage control in grid nodes, in order to reduce operating losses and increase the integration capacity of renewable energy sources.

The second stage of the case study aimed to analyze the dynamic regimes of network operation and the benefits of implementing SVC solutions. This process began with the analysis and parameterization of the regulators used in the control of generators in dynamic operating regimes. Another important step was the choice of the wind turbine model to be used in simulations according to the design characteristics and control functions available. For the assessment of the dynamic impact, several scenarios were studied, including a case dedicated to the transition to renewable energy sources. The study compared the response of the SVC with that of the classical synchronous compensator. This comparison was made for a series of dynamic events that aimed to assess the dynamic stability of the system. The simulations showed that the SVC device significantly improves

the dynamic stability of the grid, especially the voltage stability, making it ideal for use in grids with a high degree of integration of renewable energy sources.

In the third stage of the case study, the previously presented hypotheses were tested for a complex, large-scale network, namely the Romanian energy system. The simulations concluded that SVC devices represent a solution to a number of challenges produced by renewable energy sources in the system, such as voltage control, increased stability and reduced power losses.

2. CHAPTER 2 – BASIC CONCEPTS OF ELECTRICITY SYSTEMS

2.1. General

An energy system can be defined as the totality of electrical installations whose role is the consumption, production, distribution and transmission of electricity. In order to form an electrical energy system between all the composing elements, there must be some form of connection. In the operation of an electricity system, elements such as: electric generators, power transformers, transmission and distribution power lines as well as consumers are required. In the case of electricity systems, all these elements are present in a large number [4].

2.3. Symmetrical stationary regime of electricity systems

In the process of designing and operating electricity systems, it is considered that the normal operating and dimensioning regime is the symmetrical stationary regime. In order to determine the operating regime of an electrical system, it is necessary to solve a system of nonlinear equations, in this regard, over time, a series of methods for determining the circulation of power have been developed, the most often used being the nodal methods [12].

We can characterize the electrical state of a node by using four values: voltage value, active power, reactive power, and voltage phase with respect to a reference axis. The electrical values of the nodes in the system have an interdependent relationship with each other, so all four characteristic quantities cannot be imposed in a node simultaneously.

Two values can be imposed for a node, the other two resulting from the calculation of the steady state. This mode of assigning the quantities imposed in each node divides the nodes of a network into three categories: equilibrium nodes, generating nodes, and consuming nodes [13].

2.4. Dynamic regimes and stability of electricity systems

2.4.1. General aspects of dynamic regimes

The analysis of dynamic operating regimes due to faults in the network, such as short circuits or triggering of elements, is an activity with an increased level of complexity. Firstly, the location and type of defects that can occur present an increased variety, and secondly, the entire process of unfolding a dynamic event has multiple aspects that can influence the result. Another aspect considered in the analysis of dynamic phenomena is the presence of defects in the actuation mode of the protective equipment having a different operation during the defect than normal [15]. Currently, for interconnected energy systems, a particularly important problem, which is intensively analyzed, is represented by the study of the possibility of extending events that can generate instability over a large area of transmission networks. The correct choice and parameterization of protection and automation equipment in the transmission network is a particularly important aspect in the proper functioning of electricity systems, helping to avoid the extension of phenomena in unstable regimes [15] [16].

In the analysis of dynamic regimes, of particular importance are the events that are generated by large power variations in the system that can generate oscillations of the voltage level on the busbars of power plants with groups of more than 15% and that can produce changes in the relative rotational angles exceeding 50º. In general, dynamic events that can generate such a high impact on the system have one of the following causes[17]:

- Tripping of important lines in the high-voltage network, with a high load, especially in cases where as a result of this tripping a new operating regime of the network is generated, which is characterized by a low voltage level that may favor the oscillations of the generators due to the depletion of the static stability reserve.
- A three-phase short circuit or a two-phase short circuit with earth, in certain situations, for areas with high load, intense dynamic regimes can also be generated by single-phase short circuits.

- In the case of large generator sets, their tripping can generate an intense dynamic regime with risk to the operation of the system.
- In the case of high-power generators, a strong dynamic event can also be triggered by a fault in the automatic excitation adjustment circuits [12].

The dynamic events presented above have been analysed in Chapter 6.2.7. to determine the stability of the NORDIC32 grid in the presence of renewable energy sources.

2.4.2. General notions on the stability of electricity systems

As is known, the notion of stability of power systems can be defined in relation to the ability of a system to remain in a state of equilibrium after the occurrence of a small disturbance and to return to an acceptable state of equilibrium after the occurrence of a large disturbance. Disturbance is a phenomenon that produces a rapid change or series of rapid changes in one or more parameters of the system. [5]

Instability phenomena in electricity systems can have different manifestations depending on the mode of operation and the configuration of the system. In most cases, stability issues refer to maintaining synchronicity in operation [18].

2.4.3. Classification of stability of power systems

In relation to the dynamics of phenomena, the stability of electrical power systems can be grouped into three main concepts: rotor angle stability, frequency stability and voltage stability.

Depending on the physical interpretation of the stability phenomenon, they can be classified into:

a. **Stability of the rotor angle**, associated with rapid phenomena;

Rotor angle stability refers to the ability of each synchronous machine to maintain synchronization with the other machines in the system. Specifically, this implies that the relative angle between the rotors of two synchronous machines does not change significantly, so that no machine performs a complete rotation (sliding of 2π radians) with respect to another, regardless of whether the system operates in normal mode or after a disturbance [25].

b. **Frequency stability**, influenced by slow and/or fast dynamics;

Frequency stability refers to the ability of the system to maintain the frequency within permissible limits after a major disturbance, ensuring the balance between the power generated and consumed. One of the restoration measures is load discharge.

c. **Voltage stability**, characterized as a slow-evolving phenomenon.

Voltage stability refers to the ability of the system to maintain a level in the nodes of the network, preventing collapse. It is mainly determined by the balance of reactive powers [16].

A power system can enter a state of voltage instability when, following a disturbance (such as a sudden increase in load or a topological change in the grid), a progressive and uncontrollable decrease in the voltage level occurs, either in a node or in a larger area, or even in the entire system. The main cause of voltage instability is the loss of voltage in the network, caused by the circulation of power through the inductive components of the transmission network.

Voltage stability (load conditioned) [16].

The theoretical notions presented in this chapter are necessary in carrying out the case study in chapter 6 on the analysis of the impact of renewable sources on the dynamic stability of networks and the opportunity to use SVC devices. In the case study, all types of stability were analyzed, with a focus on voltage stability and its improvement through the use of SVC devices.

3. CHAPTER 3 – FACTS DEVICES, THE STATIC REACTIVE POWER COMPRESSOR

3.1. FACTS technologies used in power systems

A definition accepted in the international professional communities for FACTS (Flexible AC Transmission Systems) devices is: FACTS solutions are alternating voltage electricity transmission systems that are composed of static switches based on power electronics and that increase transfer capacity and controllability. [2]

A definition accepted by international energy professional organizations for Var compensators is: static VAr compensators are static reactive power generators in which a change in capacitive or inductive current results in a change in output quantities that allows the control or maintenance of certain parameters of the power system, generally the voltage in a node of the grid [31] [32]. The SVCs are connected in a branch consisting of coils and capacitors whose control is carried out using thyristors. They are used to increase the performance of the systems in which they are connected, being useful in both transmission networks and electricity distribution networks [33]. The main benefits obtained by using SVC devices are: controlling the voltage level and limiting its rapid variations, increasing the transmission capacity of power lines, decreasing power losses and improving the stability of the system. Figure 3.1 shows the schematic principle of an SVC equipment.

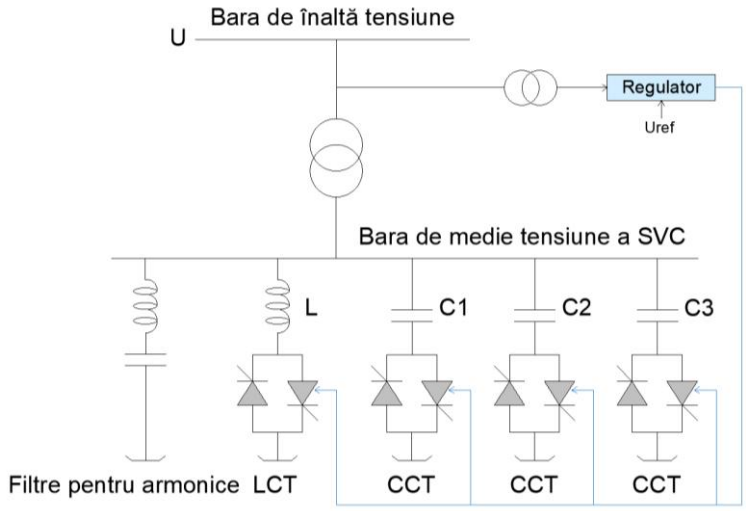


Figure 3.1. Principle diagram of an SVC [2]

3.2. Static reactive power compensator

3.2.1. Components of the SVC installation

SVC devices have a high degree of use in complex electrical networks where there are problems regarding voltage level oscillations and dynamic stability in operation. They are connected to important stations in the system through a connecting bay [57]. In terms of the components of the SVC installation, they are shown in Figure 3.8.

In Figure 3.8. a 3D view of an SVC installation is illustrated on which the main elements that make up the FACTS device are presented. Depending on the specific requirements of each site, the configuration can be adapted, but the main elements shown in Figure 3.8 are necessary.

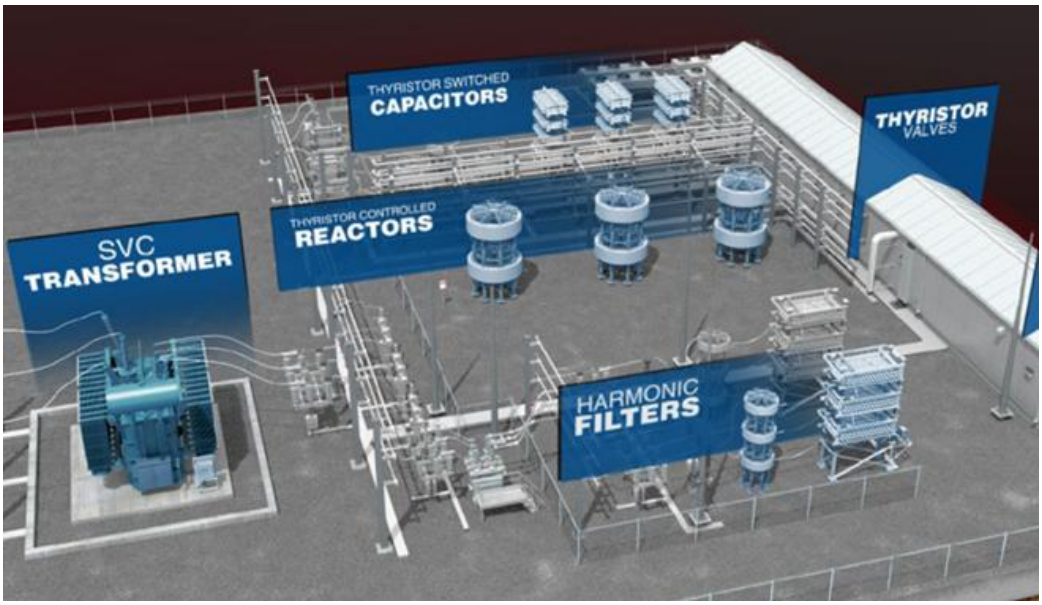


Figure 3.8 3D view of the main components of the SVC installation [58]

3.2.2.2. SVC configuration with thyristor-controlled capacitor in parallel with thyristor-controlled coil

A constructive version of the SVC device in which losses are lower and the control capacity is much higher is the one with a thyristor controlled capacitor in parallel with the thyristor controlled coil. The operating characteristic V-I for this design of the SVC is shown in Figure 3.17 [63].

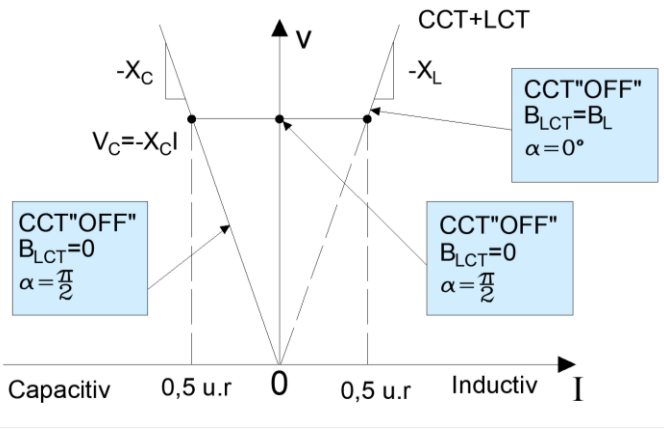


Figure 3.17. V-I feature for SVC in CCT configuration in parallel with LCT [2]

In this situation, the total current represents the algebraic sum of the current produced by the capacitor and the current taken over by the coil. If the capacitor controlled by thyristors is disconnected, the current will have the value of the inductive current in the coil. For this situation, the operating characteristic of the SVC is similar to the operating characteristic of the thyristor-controlled coil, and the current control is achieved in the zero – maximum inductive range by changing the angle α in the range 0 π/2. If the CCT is connected, the variation of the current from the inductive maximum to the capacitive maximum is achieved by changing the α angle between 0 and π/2 [2] [64].

5. CHAPTER 5 - CASE STUDY 1: THE NEED AND BENEFITS OF USING SVCS TO IMPROVE STATIONARY OPERATING REGIMES

5.1. Objective of the case study

In order to determine the opportunity, necessity and benefits obtained by using FACTS devices of the SVC type, it is necessary to carry out a detailed analysis of the operating regimes of the network in various scenarios of its evolution. Thus, the NORDIC32 test network was used to carry out the first case study. Given the structure of the test network, NORDIC32 in which electricity production is based on hydropower and high-power thermal power plants, it was considered suitable to be adapted to the current context on the integration of renewable energy sources.

The initial operating regime of the NORDIC32 network was analysed to determine the optimal points for the use of FACTS devices and their type. Starting from the initial model of the NORDIC32 system, several operating scenarios were developed to analyze the problems that may arise when the consumption in the grid increases or in the situation when part of the classic sources of electricity production are replaced by renewable energy sources. For the deficiencies in the functioning of the system in the scenarios presented, FACTS technologies and SVC devices were used. They have been used both to keep the voltage level in the nodes within the maximum permissible limits and to reduce power losses in the grid.

In order to calculate the load flow of the network both in the initial situation and in subsequent scenarios, it was necessary to use a dedicated software solution for the calculation of the operating regimes of the electricity systems. All operating regimes of the NORDIC32 network in the presence of renewable energy sources and FACTS devices have been calculated using NEPLAN10 software. The main operating modules of NEPLAN10 software have been presented in chapter 4 of this paper.

The analysed operating regimes resulted in the main conclusions and recommendations on the use of modern means of reactive energy compensation in electricity transmission networks to increase the integration capacity of renewable energy sources.

5.3. Methodologies

5.3.1. Use of methodologies for the integration of FACTS devices into the electricity transmission network

Electrical transmission networks are characterized by complexity, increased number of interconnected elements and spread over a large geographical area. Given these defining characteristics, in the analyses carried out to determine the type of FACTS device and the optimal location for its implementation, clear methodologies are needed, with a correct staging and with an objectively well-defined function. In this regard, two distinct methodologies have been developed and presented in this chapter. The first of these aims to determine the optimal FACTS device for use in a transmission power grid. It starts from the identification of malfunctions at the system level and through successive steps determines from a series of FACTS devices which is the most suitable to be used. The second covers a field with a narrower spectrum, namely the choice of the optimal node for connecting an SVC type of equipment. This methodology identifies areas where SVC can benefit the operation of the system, and then chooses the connection node to maximize the results of the objective function.

5.3.2. Methodology for choosing a device type FACTS

Choosing the FACTS device tailored to the needs of the system is a complex process that requires a multidimensional approach that respects both technical requirements and economic constraints. The process starts from the determination of the initial operating regime of the network. From this stage, the main information on the status of the system and the main deficiencies that can

affect operational safety are obtained. Starting from the technical requirements defined during the analysis phase of the initial operating regime of the network, the objective function is established. In accordance with the chosen objective, the main types of FACTS equipment are analyzed, taking into account the benefits brought by each one, but also the specific conditions for installation. After a detailed comparison, the optimal option is chosen that meets the technical criteria, maximizing the results of the objective function while also respecting economic constraints. Finally, the chosen solution is validated through a series of simulations that analyze several possible scenarios for the evolution of the network so that the solution is correctly sized for a long-term time horizon in terms of network development. For this reason, five main steps to be followed have been defined in the methodology for choosing the FACTS device.

Step 1 – Analysis of the initial energy situation

At this stage, the data on the components of the studied electrical network are collected, the steady state of the network is calculated, the main contingencies that may affect the safety of the network operation are determined, the dynamic events with a major impact are identified and the short-circuit current value in the main nodes of the network is calculated. These initial steps are essential to be able to have a clear overview of the energy situation at the grid level.

As a result of this analysis, the following information on the situation of the network will be obtained:

- Network-wide power circulation;
- The voltage level in the network nodes;
- Active and reactive power losses at network level and zoning;
- Dynamic events that may affect the operational safety of the network;
- Elements whose level of load exceeds the maximum permissible limit;
- Areas of the network where operating parameters can be improved;
- Contingencies that generate exceedances of the maximum degree of load;
- The main deficiencies in the normal operating regime.

Step 2 – Establishing the objective function in relation to the problems identified in the operation of the network

In this stage, starting from the results obtained in phase 1, the main deficiencies identified are analyzed and a hierarchy is made according to the danger they generate for the operational safety of the system and according to the economic impact they have. Thus, after this clear classification of the deficiencies in the functioning of the network and the impact they generate, an objective function can be established to be followed in the selection process of the FACTS device. Each case analyzed has its own peculiarities, but in general the main objectives pursued when installing a FACTS device are:

- Voltage regulation, if fluctuations or exceedances of acceptable limits have been identified at the network level. By installing a FACTS device, the voltage level can be brought within the permissible limits or variations in the case of dynamic events can be limited;
- Improving the stability of the system, in the case of systems that have low inertia and in which strong dynamic events can cause instability phenomena;
- Solving congestion problems, if the limited capacity of the transmission lines has been found for the analyzed scenarios;
- Active and reactive power flow control at the grid level to optimize power circulation.
- Reducing situations where certain contingencies cause overloads on other elements in the network in the N-1 element operating scenario.
- Reduction of active and reactive power losses at the grid level.

Step 3 - Analysis of FACTS device categories

In step 3, the selection of the FACTS device whose technical characteristics best match the problem identified at network level is carried out. It is chosen according to the benefits it can bring,

but also according to the area and element where it is to be connected (electrical substation or power line). Depending on the problems identified in the operation of the network and the objectives pursued, the following division of FACTS devices is made:

1. Static Compensation Devices (SVC, STATCOM)
   a. SVC (Static VAr Compensator)
      - It is recommended in situations where reactive energy compensation is required;
      - It is effective for voltage stabilization, but less flexible in the case of rapid variations.
   b. STATCOM (Static Synchronous Compensator)
      - It is recommended in situations where a rapid response to voltage variations;
      - It is recommended in situations where reactive energy compensation is required.
2. Power flow control devices (SSSC, UPFC, IPFC)
   a. SSSC (Static Synchronus Series Compensator)
      - It is used for serial compensation and control of power flow through the line.
      - Effective in case of congestion on certain lines.
   b. UPFC (Unified Power Flow Controller)
      - It is used for active and reactive power flow control;
      - Allows adjustment of voltage, impedance and power flow.
   c. IPFC (Interline Power Flow Controller)
      - It is recommended for coordinating the flow of power between several lines;
      - It is used in complex networks with interdependent flows.

A more detailed description of the benefits and how to use each type of FACTS device can be found in Chapter 3.1.

Step 4 – Choosing the technically and economically optimal option

In this phase, the optimal option is chosen to be implemented. In order to choose the optimal device for each situation studied, both the technical needs of the network and the economic implications must be analyzed. Thus, the main criteria considered are:

- From a technical point of view:
  - The required response speed;
  - The necessary control capacity;
  - Stability and safety in operation of the system;
  - Location and level of integration.
- From an economic point of view:
  - Investment costs (purchase and assembly);
  - Maintenance and operating costs;
  - The benefits obtained from the investment;
  - Long-term profitability.

Step 5 – Validation of the chosen solution

The type of FACTS device chosen in step 4 is validated by integration and simulation into the power grid. The simulation of the operation of the FACTS device is carried out using specialized computing environments and analyzing multiple scenarios of network operation. Within this stage, multiple scenarios are studied, which also include the future stages of development of the system. Given the high costs and long deployment periods for a FACTS device, it is chosen and sized to match the use for a more distant time horizon.

5.3.3. Methodology for choosing the SVC device location node

SVC devices are complex equipment with high implementation costs, so it is very important to carry out a complete analysis before choosing the location where they will be connected and their sizing. In order to achieve the desired results, it is important to follow a well-defined methodology regarding the location of SVC devices in transmission electricity grid. Thus, this chapter presents a methodology that can be applied both for determining the connecting node of the SVC and for

optimizing its power. The first stage is represented by the analysis of the initial situation of the network in order to identify areas where there are deficiencies in operation and to have an overview of the operating conditions. The next step in this process is to establish the objective function, this has the role of establishing exactly the benefits that are intended by installing the SVC device and ranking them according to the deficiencies identified in the previous step. After this process, in the next step, several nodes are chosen that are considered suitable for the placement of the SVC device. From these, the node in which the connection of the FACTS equipment maximizes the results of the objective function is chosen. Once the node is chosen, the device is sized in terms of injection capacity and reactive power absorption. The next step is to check the sizing of the SVC device for the future stages of network development so that it can ensure optimal operation for as long as possible. After completing these processes, it is necessary to restore the network operating regimes with the SVC device connected to determine all the benefits obtained. The benefits will be quantified and analyzed if the investment is feasible in terms of implementation and operating costs. Finally, it will be concluded whether there is an opportunity to connect an SVC device to the network and which is the optimal node to be connected to the system.

Step 1 – Analysis of the initial energy situation:

At this stage, data on the components of the studied electricity grid are collected and the operating regimes of the network are calculated. The analysis includes steady-state scenarios, contingency analysis and study of the dynamic behavior of the network.

Following this analysis, the following information will be obtained on the initial situation of the network:

- Identification of nodes where the voltage level does not fall within the permissible limits or is close to the minimum/maximum limit;
- Variation of the voltage level in the network in case of certain events (breakdowns, trips, withdrawals from operation, reconfigurations of the normal operating scheme);
- Determine the losses of active and reactive power in the network and how it is distributed across the main areas of the network;
- Determination of the elements with a load close to the maximum nominal value in normal operation;
- Determination of overloaded elements in the event of a network contingency (N-1 element in operation scenario).
- The level of stability of the system in case of the occurrence of major dynamic events.

Step 2 – Define the objective function

In this step, starting from the results determined in the previous step, the main benefits that will be obtained after the installation of the SVC device are defined. Thus, the main optimization criteria pursued by using the SVC device in the studied network from the list below are established:

- Stabilization of the voltage level in the network nodes;
- Reduction of power losses on the lines;
- Increasing the transmission capacity of power lines;
- Damping of voltage oscillations in network nodes;
- Improved system stability.

Step 3 – Identifying the nodes

Starting from the network situation determined in step 1, the areas of the network where operational problems have been identified shall be identified. Taking into account the objective function set out in step 2, select the nodes where the need and opportunity to install an SVC device has been found. These nodes will be analyzed in the following steps to choose the optimal position for connecting the SVC.

Step 4 – Choosing the node

The nodes identified in step 3 are analyzed and a series of estimates are made regarding the benefits that can be obtained for each node. In each situation, it is analyzed how much the operational safety of the system is affected by the identified problem, but also what are the benefits to be obtained after the installation of the SVC. At the end of this step, the node that leads to maximizing the results of the objective function is selected.

Step 5 – SVC Device Sizing

Starting from the results of the steady state of operation, the need for generated/absorbed reactive power is established. The steady state of the network shall be recalculated after the connection of the SVC device and shall be analysed whether the objectives proposed in step 2 are achieved. If the objectives are not achieved, the parameters of the SVC device and its location shall be reconsidered.

Step 6 – Sizing check

In order to verify that the sizing of the SVC device also corresponds to future situations that may arise at the network level, operating scenarios are made by modifying its current parameters (power generated, power consumed, type of system sources). If the proposed objectives can no longer be met for the studied scenarios, the parameters of the SVC device and its location shall be reconsidered. These steps are repeated until the optimal location for connecting the SVC and its compensating capacity is identified.

Step 7 – Benefit Analysis

After the technical analysis on the connection area and capacity of the modern reactive energy compensation device has been completed, it is necessary to carry out a cost-benefit analysis to determine whether the investment is economically feasible. The analysis and quantification of the benefits obtained from the use of the SVC device in the studied network in relation to the construction costs will take into account the following elements:

Main benefits:

- Reduction of active and reactive energy losses in the grid;
- Increasing the transmission capacity on the power lines in the connection area of the SVC;
- Increasing the capacity to integrate renewable energy sources at the system level;
- Increasing the degree of safety in operation of the network;
- Decrease in the number of congestion in case of a contingency;
- Increase the dynamic stability of the system.

Main costs:

- The cost of acquiring the SVC device and the equipment associated with its operation;
- Cost of assembly, parameterization, testing and commissioning works;
- The cost generated by the necessary provisional steps (interruptions in operation, modification of the normal operating scheme);
- Maintenance and operating costs over the entire life of the SVC installation.

Step 8 – Conclusions of the analysis

At this stage, based on the technical analysis and economic evaluation regarding the location, dimensioning, necessity and opportunity of using an SVC device in the studied network, the final directions for the realization and implementation of the investment are drawn.

5.5. Implementation of the proposed methodologies in the NORIDC32 network

Table 5.10 highlights all the scenarios studied and the elements identified in the operation of the network from the perspective of voltage level, power losses and load level of the elements.

Table 5.10. The centralizer of the analyzed scenarios

Scenario	Description	Voltage level	Loss of power	Item Load Level
S0	The initial operation scenario of the network in which no changes have been made to the operating scheme or parameters of the network elements.	Falls within the permissible limits	Increased reactive power losses	No exceedances of the rated capacity
S1	In the H1 scenario, the proportional consumption across the network increased by 5 % compared to the consumption in the baseline scenario S0.	Voltage in node 141 drops below minimum limit 90% A	Higher than in the S0 scenario	No exceedances of the rated capacity
S2	In scenario S2, in order to improve the energy parameters of the network (power losses and voltage level), starting from scenario S1, SVC devices were added in turn in nodes 461, 422, 232 and 141.	Falls within the permissible limits	Lower than in the S0 scenario	No exceedances of the rated capacity
S3	In scenario S3, we started from baseline scenario S0 and halved the production capacity of the existing source in node 143, GEN-G7, and added a new wind energy source GEN-G21 with a total installed capacity of 180 MW.	Falls within the permissible limits	Higher than in the S6 scenario	No exceedances of the rated capacity
S4	In the S4 scenario, the S3 scenario was started and the GEN-G21 renewable energy source was disconnected.	Voltage in node 141 drops below minimum limit 90% A	Higher than in the S5 scenario	Double-circuit line 143-144 achieves a load level of 102.4%
S5	In scenario S5 we started from scenario S4 and added a connected SVC device in node 141.	Falls within the permissible limits	Lower than in the S4 scenario	No exceedances of the rated capacity
S6	In scenario S6, starting from scenario S3, an SVC device connected to node 141 was added.	Falls within the permissible limits	Lower than in the S3 scenario	No exceedances of the rated capacity

5.6. Conclusions of the case study

The case study looked at how electricity transmission networks operate and how they work. The main challenges analysed were the connection of new consumers and the integration capacity of renewable electricity producers.

To exemplify the situations presented above, it was necessary to use a test network, so the NORDIC32 network was chosen. NORDIC32 is a test network developed by K. Walve and represents a simplified adaptation of an electricity system similar to that of Sweden. The network is divided into four main zones: the northern zone, the southern zone, the central zone, and the equivalent zone.

A set of solutions that promises to solve these problems is represented by FACTS (Flexible AC Transmission System) which allow increasing the operational flexibility and operational safety of energy systems through the use of technologies based on power electronics.

In order to reproduce the elements presented above in a simulation environment, the NEPLAN10 software was used in which the NORDIC32 network was modeled. For SVC FACTS devices, the configuration and simulation mode was presented in NEPLAN10. Thus, several scenarios were carried out that included increasing consumption in the grid and replacing a classic energy source with a renewable source. Applying the methodologies presented, the type of FACTS

equipment to be used was analyzed according to the deficiencies of the network and the objectives set.

As a result of the analysis, it was decided to use SVC devices to increase the operational safety of the system and its ability to switch from classic sources of electricity production to sources based on renewable energy. From the point of view of theoretical notions, aspects were presented regarding: the structure and operation of the SVC, configurations of the static reactive power compensator, the control of the operation of an SVC, its location in the network and the simplified model for the calculation of the steady state.

In order to carry out the system analysis, the establishment of the connection point and the sizing of the FACTS device, it was started from the presentation of the initial energy situation of the NORDIC32 network, thus calculating the active and reactive power losses, the loads of the network elements, the voltage level in the network nodes and the overloads that may occur in the event of a contingency. In the initial regime, no overloads or exceedances of the permissible voltage level in the nodes were identified.

In order to carry out the network analysis in the context of the main challenges regarding the integration of new renewable energy sources into the system and the system's ability to safely supply new consumers, 6 distinct scenarios were prepared.

After going through the scenarios regarding the changes that may occur in the normal operating regime of the NORDIC32 network and by applying the proposed methodologies, it resulted that the SVC type FACTS device will be connected in the 130 kV node 141, being sized to be able to inject 200 Mvar into the network and absorb 100 Mvar.

Following the analysis of the scenarios presented above, it was possible to conclude that SVC devices help both to regulate the voltage level in the network and to reduce energy losses and reduce loads on power lines in the area.

6. CHAPTER 6 – CASE STUDY 2: ANALYSIS OF THE IMPACT OF RENEWABLES ON THE DYNAMIC STABILITY OF GRIDS AND THE APPROPRIATENESS OF USING SVC DEVICES

6.1. Objective of the case study

Currently, global decarbonization policies require major changes in the functioning of electricity systems. The main objective of the case study is to analyze the impact on the dynamic stability of the electric power system driven by the transition from classical energy sources that have a high environmental impact to renewable energy sources. This process generates a number of challenges regarding the dynamic stability of power systems. The objective of the case study is to assess the impact generated by the massive integration of renewable energy sources at the level of the electricity transmission network and to analyze the opportunity to use SVC devices in this context. For this analysis, the NORDIC32 test network was used, its configuration and parameters were presented in Chapter 5.2. In order to carry out the simulations, it is necessary to configure the specific parameters of the generators, but also to choose the correct types of regulators. The case study analyzed how modern SVC devices improve the dynamic response of the network in the event of events. To highlight the contribution of the FACTS device to the same dynamic event, four distinct scenarios were studied: the initial grid operation scenario, the scenario with massive integration of wind power plants, the scenario with wind power plants and synchronous compensator, and the scenario with wind power plants and SVCs. From the point of view of the dynamic events that can occur in the operation of the transmission network, the following situations have been studied: the triggering of a power line, rapid load changes in the system, the triggering of a transformer unit, the triggering of a generator and the production of a short circuit in the network. In the process of dynamic analysis and simulation, the selection and parameterization of regulators used for hydroelectric power plants, thermal power plants and wind power plants was carried out. The logic diagram for connecting the regulators to the generator was presented and the operation of each type of regulator was analyzed. In order to define the scenarios in which thermal power plants have been replaced by wind power plants, an analysis of the types of wind turbines, their main characteristics and dynamic models was carried out. The system response for each event in all four scenarios studied was graphed to make a comparison in terms of node voltage, system frequency, and generator behavior.

6.2. Simulation of dynamic operating regimes of transmission networks

6.2.6. Scenarios analysed

6.2.6.1. Initial scenario – S0

In order to have an overview of the impact generated by the transition process from classic sources of electricity generation to renewable energy sources, two operating scenarios for the NORDIC32 test network were analyzed. In the S0 operating scenario, the classic structure of the NORDIC32 network was preserved, in which the sources of electricity are hydropower plants and thermal power plants.

In scenario S0 it is observed that there are no exceedances of the voltage level or the nominal capacity of the system elements. Figure 6.28 shows the distribution of energy sources at the grid level and in the Centre area in scenario S0. Given the fact that the production in the Central area of the grid is exclusively from thermal power plants, it was considered appropriate to analyze a transition in this area from thermal power plants to wind power plants.

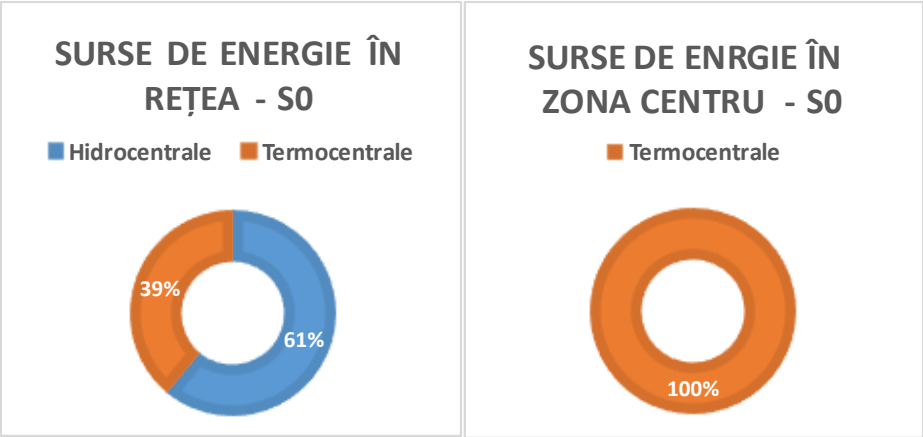


Figure 6.28. Distribution of energy sources in the grid in scenario S0

6.2.6.2. Renewable energy scenario – S1

The S1 scenario was proposed to study the impact generated by the transition from classical sources of electricity production to renewable energy sources. Considering the distribution of energy sources at the NORIDC32 grid level, the Center area for the integration of renewable sources was chosen. The Centre area is a grid area equivalent to the southern area of Sweden, so it is considered appropriate to install wind power plants.

The S1 scenario represents an analysis model for studying the impact of the energy transition from classic sources of electricity generation to renewable sources. In this scenario, several classic high-power plants were disconnected from the central area of the grid, and in their place, wind power plants distributed in several nodes of the grid were connected.

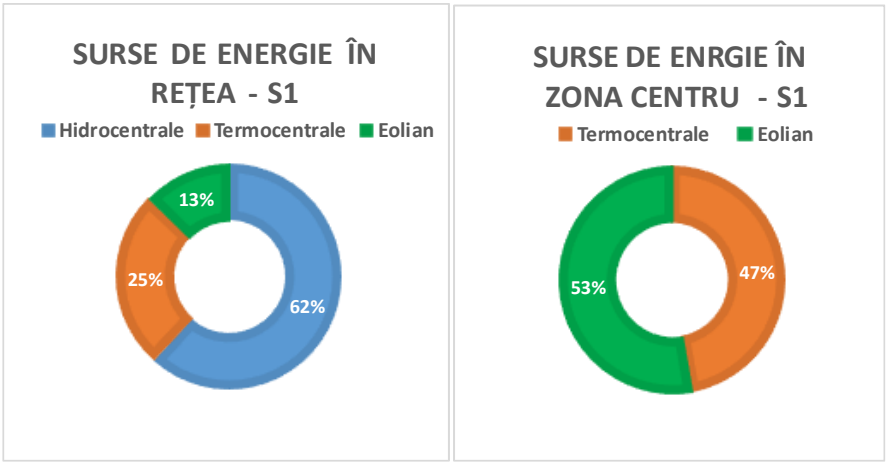


Figure 6.29. Distribution of energy sources in the grid in the H1 scenario

The distribution of energy sources in the grid is shown in figure 6.29, it is observed that in this scenario in the central area more than half of the energy is produced by wind power plants. This situation was driven by a number of changes compared to the initial S0 scenario:

- The parameters of the following thermal power plants have been modified:

Table 6.10. Thermal power plant parameters scenario S0

Central	Power in S0 [MW]	Power in S1 [MW]	Connection knot	Power plant
G15	1080	0	447	Thermal power plant
G16	600	300	451	Thermal power plant
G7	180	0	143	Thermal power plant

As can be seen in Table 6.10, the G15 and G7 thermal power plants were completely disconnected from the grid in scenario S1, while for the G16 thermal power plant the power injected into the grid was halved.

- The following wind power plants have been added:

Table 6.11. Wind farms in the S1 scenario

Central	Power in S0 [MW]	Power in S1 [MW]	Connection knot	Bloke
Wind1	0	360	447	Wind
Wind2	0	360	446	Wind
Wind3	0	100	444	Wind
Wind4	0	150	143	Wind
Wind5	0	170	144	Wind
Wind6	0	300	451	Wind

Table 6.11 shows the on-grid wind farms in scenario S1, for each of them the power and connection node have been specified. All the changes in the operation of the network were made in the Center area, the case study analyzing the dynamic operation of this area after the integration of wind energy sources. Figure 6.30 shows the diagram of the Centre area on which the thermal power plants that have been disconnected from the system or whose power has been reduced have been marked in red. The green color was used to highlight the connection point of the new wind farms in the grid. It can be seen that unlike thermal power plants that were smaller in number and with a much higher unit power, wind power plants are distributed at the grid level of 400 kV and 130 kV with a lower unit power.

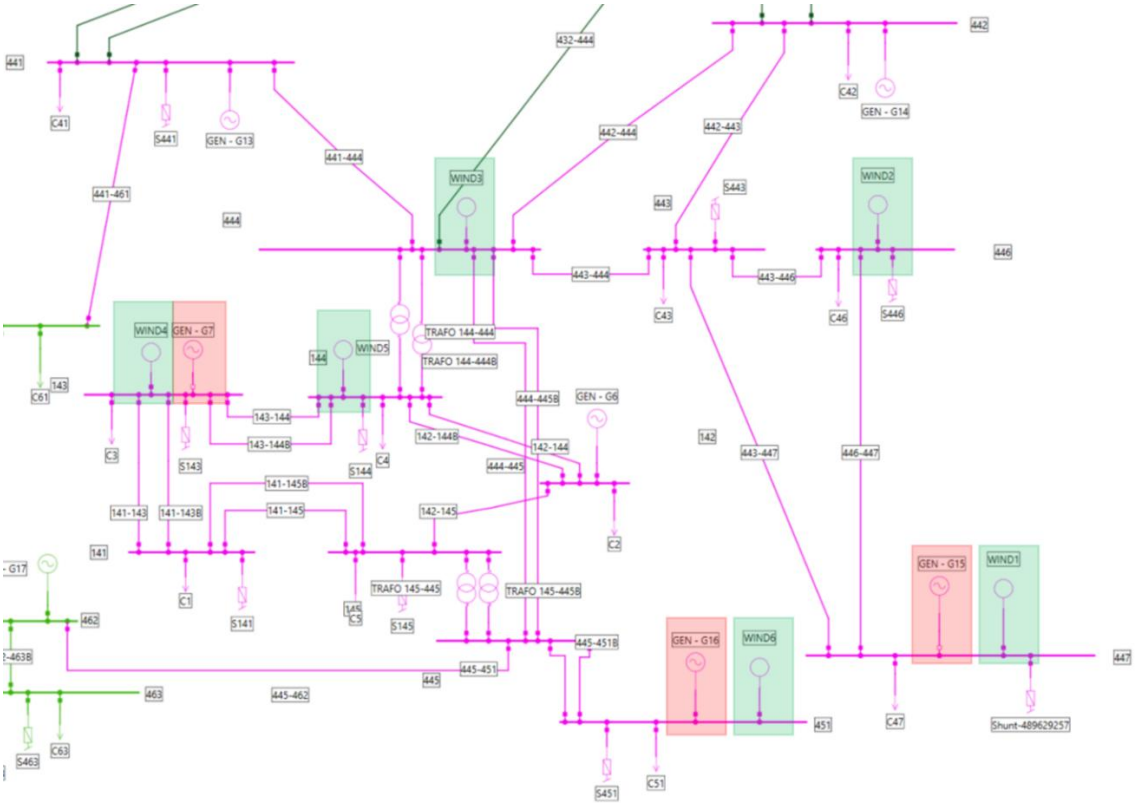


Figure 6.30. Network scheme for scenario S1 – steady state in the Centre area

6.2.7. Analysis of the dynamic behavior of the network in the studied scenarios

The aim is to determine the dynamic behavior of the grid in several operating scenarios in which renewable energy sources, namely wind power plants, have been massively introduced into

the grid. In order to achieve the proposed objectives, a series of operating scenarios were studied, and within each scenario six distinct dynamic events were analyzed to determine the reaction of the system. The dynamic events studied in the dynamic stability analyses are:

- Dynamic event 1 consists of the tripping of a 400 kV power line, with increased importance in the system, which connects the Center area and the North area. For this study, line L432-444 was chosen.
- Dynamic event 2 is represented by the sudden variation in grid consumption. The situation in which a consumer is disconnected and after a short period of time is reconnected to the network, the C3 consumer was chosen.
- Dynamic event 3 presents the situation of a fault that leads to the disconnection of a transformer unit that connects the transmission area to the electricity distribution area. The T144-444 transformer was used in this event.
- Dynamic event 4 is a sudden variation in the energy production in the system, i.e. a defect results in the complete triggering of the groups in a thermal power plant. In the system calculations performed, the situation presented for the G16 generator was analyzed.
- Dynamic event 5 is represented by the production of a short circuit on the busbars of a 130 kV station, for this case node N143 was chosen.
- Dynamic event 6 consists of a three-phase short circuit on a 400 kV line that triggers the line. The L446-447 line was considered as the place of occurrence of the defect.

For all six dynamic events presented, the following system parameters were analyzed in the area near the studied area: voltage variation, frequency measured in the nodes in the fault area, angular rotation speed of the rotor for the generators in the Center area and frequency variation rate. Comparative graphs were made for the four scenarios studied:

- Scenario S0 which represents the initial variant of the grid before the connection of wind power plants;
- Scenario S1 shows the situation in which some of the thermal power plants in the Centre area are replaced by wind power plants;
- Scenario S2 presents the same situation as scenario S1 with the difference that in scenario S2 a synchronous compensator is connected in the node in the immediate vicinity of the place of occurrence of the dynamic event studied (S1 + synchronous compensator);
- The S3 scenario has as its starting point the S1 scenario in which an SVC device is added that connects to the node closest to the area of occurrence of the analyzed dynamic event (S1 + SVC).

6.2.7.1. Dynamic event 1 – triggering of the 400 kV line L432-444

The event consists of the activation of the 400 kV L432-444 line, which is one of the most important lines in the Center area, ensuring the connection with the North area. This connection is very important because it ensures the import of power from the North area to cover the high consumption in the Center area. The triggering of the line occurs at time t=3 s from the moment of the start of the dynamic simulation. Dynamic simulation stops after 20 s. For this event, in scenario S2, a synchronous compensator with a compensation capacity of 300 MVAr is connected to node 444, and for scenario S3, an SVC with a reactive power of ± 300 MVAr is added to the network.

In the case of this event, the evolution over time of the following network parameters for both scenarios studied will be analyzed:

- The voltage in node 444, these being the end node of the line in the Center area;
- The evolution of the frequency measured in node 444;
- Frequency variation rate – ROCOF in node 444;
- Angular rotor speed for generators in the central area of the Nordic32 grid.

The results obtained from the simulations for event 1 in all four scenarios analysed are shown in Figure 6.31.

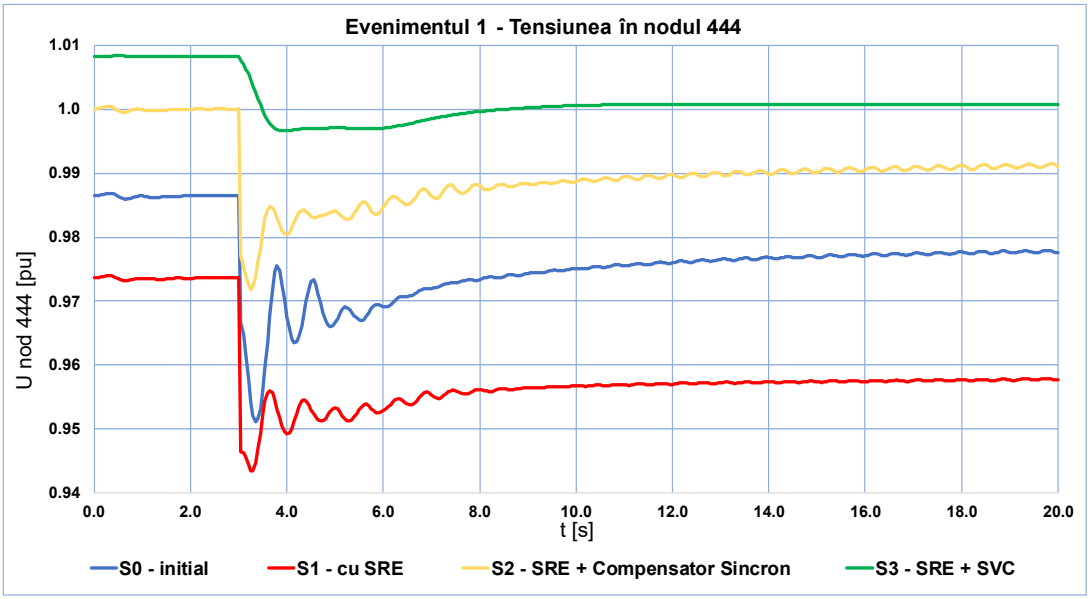


Figure 6.31. Event 1 – voltage in node 444

In scenario S0, before connecting renewable energy sources, the voltage in node 444 has a value of 0.98 pu. After the 432-444 line is tripped at time t=3 s, there is a sudden decrease in voltage to the value of 0.95 pu followed by a period of oscillations. Oscillations dampen after about 4 s after the line is disconnected. The system's response in this scenario is stable. In the S1 scenario, due to the disconnection of the thermal power plants, the inertia of the system and the voltage control capacity decreases, thus the response in case of triggering of the 400 kV line is stronger, the voltage drops below the minimum permissible limit and the oscillations attenuate over a longer period of time. By connecting the synchronous compensator, an improvement in the voltage level is observed, but in terms of oscillations and amortization time, this solution does not completely solve the problems generated by the massive connection of wind power plants. In the S3 scenario, connecting the SVC device to node 444 achieves a very good dynamic response in terms of voltage stability and oscillations. The voltage variation following the defect is reduced, ranging from 0.997 pu to 1.001 pu. The response time is very short, the FACTS device acts precisely on the voltage level, which is stabilized after about a second from the occurrence of the event. The oscillations are very small, being imperceptible compared to the other scenarios analyzed. From the point of view of voltage control, it can be concluded that the SVC device is the optimal solution for a fast and stable response even in the case of systems with a high degree of integration of renewable energy sources.

Table 6.12. Event 1 – voltage analysis in node 444

Criterion	**S0 (initial)**	**S1 with SRE**	**S2 with SRE + Synchronous Compensator**	**S3 with SRE +SVC**
Initial value [pu]	0.986	0.974	1	1.008
Minimum value [pu]	0.951	0.943	0.972	0.997
Maximum value [pu]	0.987	0.974	1.0	1.008
Stabilized value [pu]	0.978	0.958	0.991	1.001
Stabilization time [s]	4	5.5	4.5	1
Oscillations	Present, Medium	Pronounced, persistent	Pronounced, persistent	Imperceptible
Overall stability	Hi	Acceptable	Hi	Very good

Table 6.12 presents a summary of the results obtained for the simulation of dynamic event 1. The voltage values in each scenario, the stabilization time, the type of oscillations and a conclusion on the overall stability of the system in the analyzed situation are presented.

Figure 6.32 shows the evolution of the frequency measured in node 444 after the 400 kV power line 432-444 was triggered.

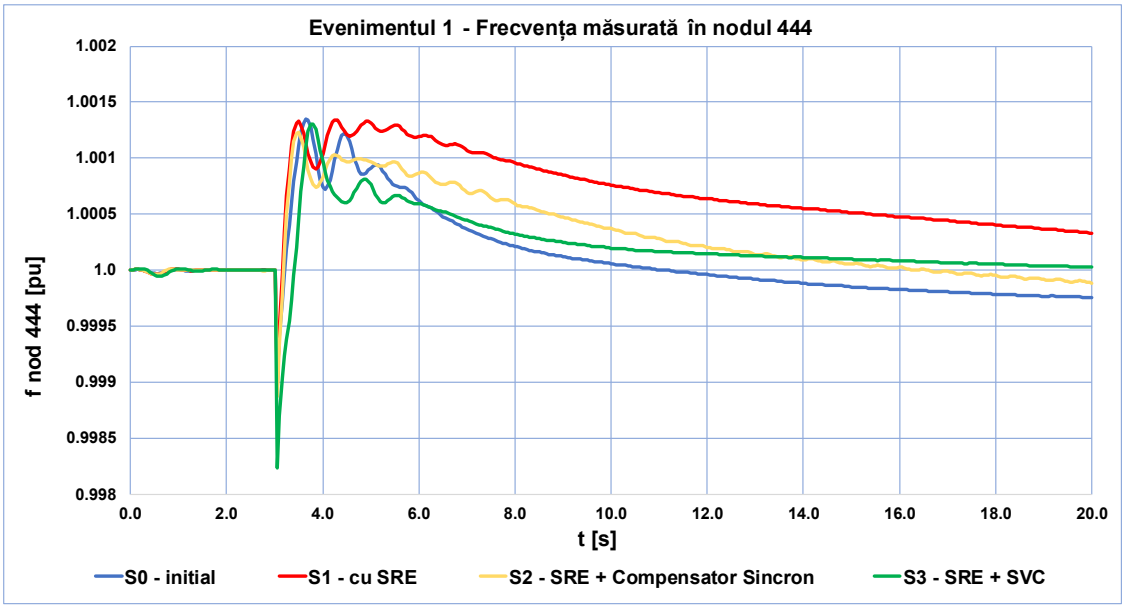


Figure 6.32. Event 1 - the frequency variation measured in node 444

In scenario S0, a rapid variation of the measured frequency in node 444 is observed up to the value of 1,001 pu, after which the oscillations are damped and the system remains stable. Following the connection of the wind power plants, in the S1 scenario the frequency has a more oscillating evolution in node 444 but without generating stability problems. In the S2 scenario, after the compensator is connected, the oscillations are lower in amplitude, but the damping time is similar to that in the S1 scenario. By connecting the SVC in the S3 scenario the response is more stable, with lower oscillations in amplitude and with a shorter stabilization time. In terms of frequency, the response of the system in case of triggering of the 400 kV 432-444 power line is improved by using the SVC type FACTS device, being superior to the response in the S0 scenario. Thus, it is concluded that the SVC device is necessary in the energy transition process towards renewable energy sources.

Table 6.13. Event 1 – analysis of the frequency measured in node 444

Criterion	S0 (initial)	S1 with SRE	S2 with SRE + Synchronous Compensator	S3 with SRE +SVC
Initial value [pu]	1	1	1	1
Minimum value [pu]	0.999	0.999	0.999	0.998
Maximum value [pu]	1.001	1.001	1.001	1.001
Stabilized value [pu]	0.99976	1.00033	0.99988	1.00003
Stabilization time [s]	10	12	13	9
Oscillations	Small, well amortized	Present, Medium	Present, Medium	Small, well amortized
Overall stability	Very good	Hi	Hi	Very good

Table 6.13 summarises the information obtained from the calculations for the dynamic operating regime of the network in the case of event 1 for all four scenarios studied. Conclusions on the stability of the system response and how to reduce oscillations after failure are presented. For each scenario, the interval in which the frequency measured in node 444 and the stabilization time vary are highlighted.

Figure 6.33 shows the rate of change of frequency – RoCoF in node 444 in case of dynamic event 1.

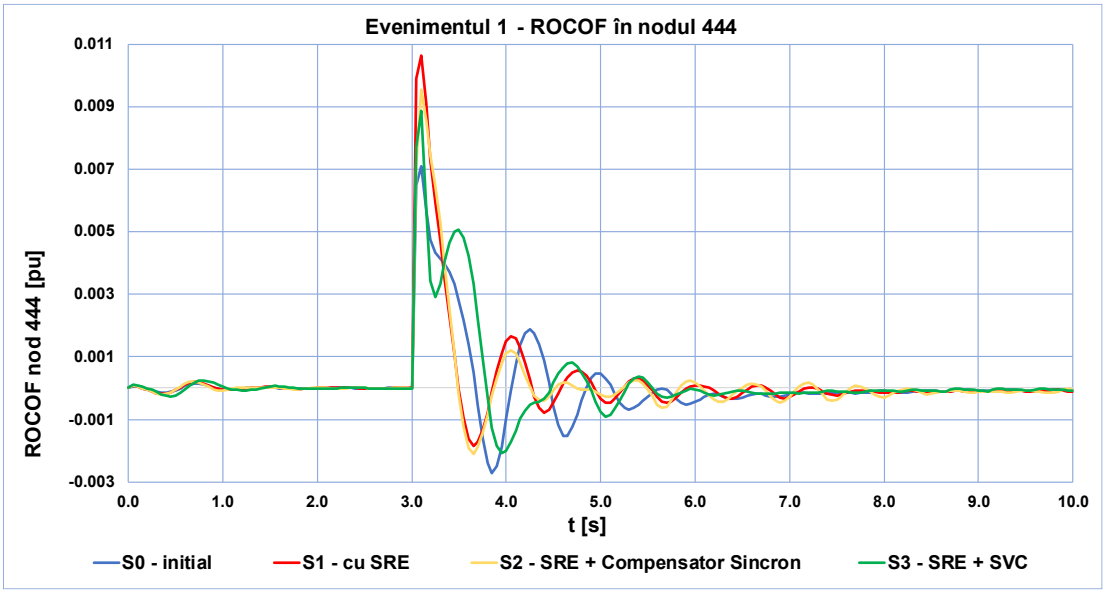


Figure 6.33. Event 1 - ROCOF in node 444

From the point of view of the rate of frequency variation in node 444 in the case of event 1, it is observed that the four scenarios studied have a similar response. In the S4 scenario, after connecting the device, the amplitude of the oscillations has a slight decrease, and the damping time of the oscillations is shorter.

Table 6.14. Event 1 – ROCOF analysis in node 444

Criterion	**S0 (initial)**	**S1 with SRE**	**S2 with SRE + Synchronous Compensator**	**S3 with SRE +SVC**
Initial value [pu]	0	0	0	0
Minimum value [pu]	-0.0027	-0.0019	-0.0021	-0.0021
Maximum value [pu]	0.0071	0.0106	0.0095	0.0089
Stabilized value [pu]	0	0	0	0
Stabilization time [s]	4.5	6	6	4
Oscillations	Strong initially but well damped	Strong initially with gradual damping	Strong initially with gradual damping	Strong initially but well damped
Overall stability	Very good	Hi	Hi	Very good

Table 6.14 centralizes the results obtained for ROCOF in node 444 after dynamic event 1. In all the scenarios studied, the system has a stable response, the best results being obtained in the case of the S0 scenario and in the case of the S1 scenario.

Figure 6.34 shows the evolution over time for the angular velocity of the generator rotor in the Center area in the four scenarios studied.

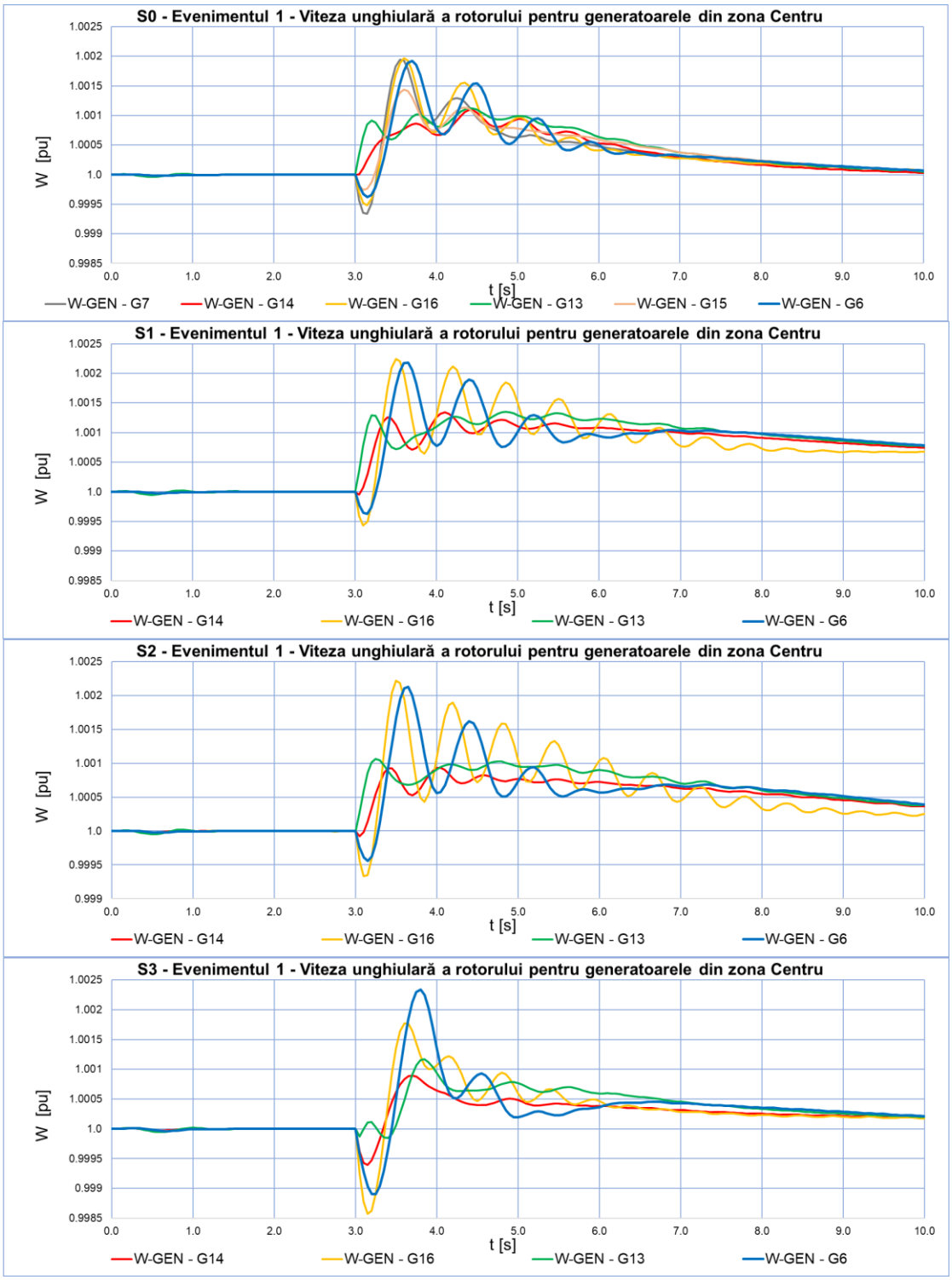


Figure 6.34. Event 1 – Rotor angular speed for generators in the Center area

Figure 6.34 shows the rotor angular speed for each generator in the Center area after event 1 in all four scenarios analyzed. The best behavior of the generators after the disconnection of line 432-444 is observed in scenario S0 and scenario S3. In scenarios S1 and S2 the generator response has a higher amplitude oscillation and a higher stabilization time, especially in the case of the G6 generator.

6.2.8. Conclusions

Case study 2 aimed to carry out a complex dynamic analysis on the operation of the grid in the conditions of the energy transition from classic energy sources, in the case NORDIC32 thermal power plants, to renewable energy sources, respectively wind power plants. In the first stage of the

study, a description of the dynamic parameters of the network was made and the regulators for the thermal power plants and hydropower plants in the network were parameterized. A correct definition of the parameters in the excitation regulator, PSS and turbine regulators is essential to ensure a stable response to disturbances. The next step was to choose the type of wind turbine to be used in the grid according to the constructive characteristics and dynamic response. Thus, following an analysis of the constructive characteristics but also of the dynamic control models of the wind turbines, it was decided to implement the 4A turbine model in the network.

In order to study the impact of renewable energy sources on the grid, several operating scenarios for the NORDIC32 grid were simulated:

- Scenario S0 – the initial operating regime of the network.
- Scenario S1 – the operation regime of the grid in the presence of RES. Some of the thermal power plants in the Center area have been replaced with wind power plants distributed at the grid level.
- Scenario S2 – in which a classical solution for reactive power compensation, namely the synchronous compensator, was studied.
- Scenario S3 – in which the benefits of using the SVC device to improve dynamic voltage stability and increase the integration capacity of renewable sources were analyzed.

Dynamic simulations showed that in the classic generator scenario the system response is more stable. This is due to the natural inertia of synchronous machines, their ability to dampen sudden variations in frequency and provide immediate inertial response. In order to increase the operational safety of the network, SVC devices were used. The benefits generated by the integration of FACTS devices at the level of the electricity transmission network were highlighted by the analysis of several network scenarios, operating variants and dynamic events.

Dynamic simulations were performed in all four scenarios for 6 dynamic events that can generate stability problems:

- Event 1 consists of the activation of the 400 kV L432-444 line, which is one of the most important lines in the Center area, ensuring the connection with the North area.
- Dynamic event 2 analyzes the dynamic behavior of the network in the situation where rapid variations in the power consumed in the system occur.
- Event 3 consists of the disconnection of the 400/130 kV T144-444 transformer, which plays an important role in ensuring the connection between the 400 kV network in the central area and the 130 kV network.
- Event 4 is represented by the triggering of the G16 – 360 MVA generator, which represents the largest thermal power plant inside the central area.
- Event 5 analyzes the system's response in the event of a short circuit in the 130kV 141 node.
- Event 6 consists of a short circuit on the L446-447 line halfway between the end nodes.

The analyses carried out on the six events clearly highlight the role and efficiency of the SVC device in maintaining the dynamic stability of the transmission power grid. In terms of voltage stability in all four events, the use of an SVC led to:

- Limiting the amplitude of voltage variations in the network nodes immediately after the dynamic event occurs.
- Fast damping of transient oscillations and increased stability in operation.
- Return of voltage to values close to nominal in a much shorter time compared to scenarios without SVC.
- Avoid excessive overvoltages in case of rapid recovery.
- By quickly compensating for imbalances, the SVC stabilizes power flows and supports the voltage profile in critical nodes.

In the case of frequency and rotor angle and frequency stability, an improvement is observed in most cases by connecting the SVC device, but the clearest effects have been identified for the increase in voltage stability.

Following the study, the conclusion is that SVC devices represent a feasible solution for increasing the dynamic stability of electricity transmission networks in the presence of renewable energy sources, having an increased impact on the stability of the voltage level in the event of a dynamic event.

7. CHAPTER 7 - CASE STUDY 3: ANALYSIS OF THE OPPORTUNITY OF INSTALLING SVC DEVICES IN SEN

7.1. Description of the current situation at the level of the NES

Currently, the electricity transmission network in Romania is going through a development process determined by the major changes generated by the objectives assumed at the European Union level regarding decarbonization and maximum reduction of environmental impact. Thus, at the grid level, there is a transition from classic sources of energy production such as thermal power plants to renewable energy sources. Although this process has a positive impact on the environment, at the level of the electricity transmission network it generates a series of challenges regarding operational safety and control of the voltage level in the network. Starting from this set of input data, a careful analysis of the functioning of the national energy system was carried out to determine the need and opportunity of using SVC devices in the TSO grid.

Given the complexity of the network and the large number of component elements, in system studies the network is divided into several areas depending on the geographical location and the electrical links that exist between the network nodes. The case study examined the appropriateness of using SVC devices in section 1 of the network.

In the simulations carried out, four levels of operation of the network were analyzed: the morning peak load for winter and summer, the peak load for evening winter and the load gap during the night in summer.

In figure 7.1. The division of the electrical transmission network into study areas is presented, the area of interest being marked.

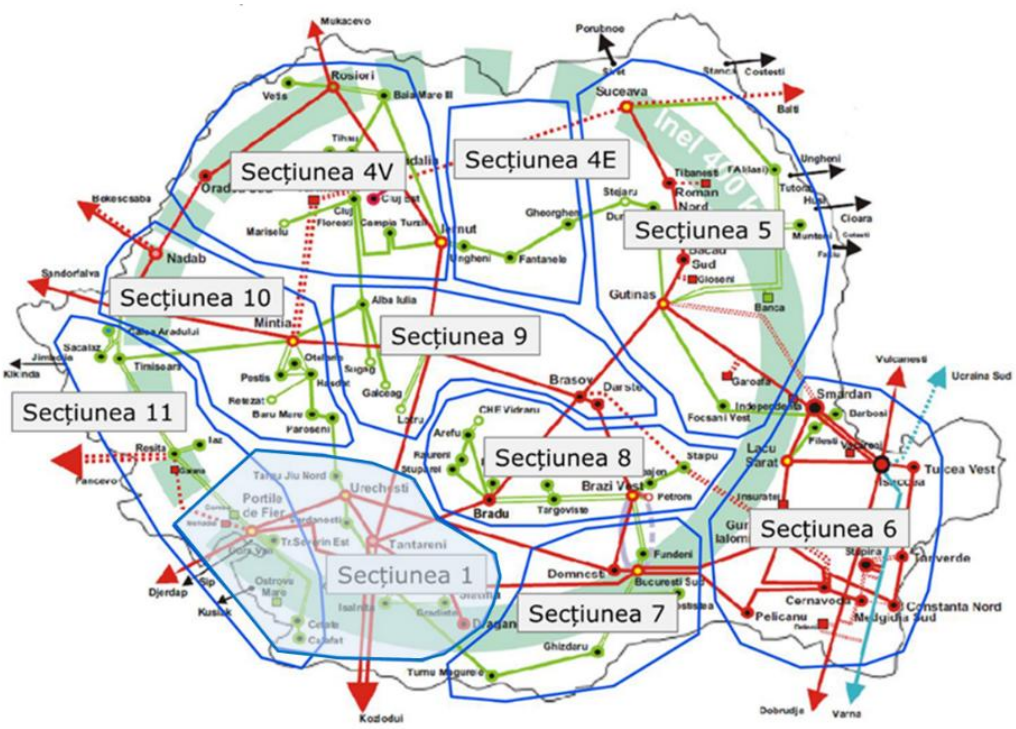


Figure 7.1. SEN map with operating sections [126]

7.2. Prospects for the development and integration of renewables

From the point of view of the network development perspective for this area, the complete closure of the thermal power plants in the area, respectively Rovinari and Turceni, is planned. The case study analyzes the scenario in which a 300 MW group of the Rovinari thermal power plant is

withdrawn from operation and production in the area is replaced by renewable energy sources. Given the climatic characteristics of the study area, as can be seen in Figure 7.2, the area allows the integration of photovoltaic plants ensuring a high energy potential.

Coal-fired power plants are expected to be shut down by 2030. Thus, in the simulations carried out, this period correlated with the implementation period necessary for both photovoltaic power plants and for the installation of the SVC device at the grid level was taken into account. In order to achieve the most correct sizing of the FACTS device, it was considered necessary to update the consumption or production of electricity according to the level, so as to ensure the conditions of good operation even in the most unfavorable perspectives. In this regard, the following changes have been made to the basic average regime of the network in order to obtain the S0 scenario of network operation:

- For the VDV level, the electricity consumption at the level of the study area was increased by 15%, the energy production remained unchanged.
- In the case of the CNG level, electricity consumption was maintained and production was increased by 15%.
- For the VSI operating regime, the electricity consumption at the level of the studied area was increased by 15%, without making changes in the energy production.
- For the VSI level, the energy consumption in the grid has been increased by 15%, keeping production constant.

In the S1 scenario of system analysis, group 6 of the Rovinari plant with a power of 300 MW was disconnected and the photovoltaic power plants presented in table 7.1 were connected in different nodes of the grid.

Table 7.1. Photovoltaic power plants used in the case study

Name	Connection knot	Connection tension	Rated power [MW]	CNG Power [MW]	Power VDI [MW]	Power VDV [MW]	Power VSI [MW]
CEF 1	Iașalnița	220 kV	120	0	36	96	0
CEF 2	Mosquitoes	400 kV	250	0	75	200	0
CEF 3	Târgu Jiu	220 kV	100	0	30	80	0

In the S2 system analysis scenario, an SVC device is used to improve the operating parameters of the system and verify its operating efficiency in scenarios with an increased renewable energy component.

7.3. Analysis of stationary operating regimes

7.3.1. Analysis of the initial operating regime

In the case study, 12 network operating scenarios, presented in Table 7.2, were analyzed in order to achieve a correct sizing of the SVC device and choose the optimal connection position. The main objective pursued by using the SVC device was to control the voltage level in the network.

Table 7.2. Operating regimes studied

Scenario	Features	Landing
Operation scenario S0	Initial diet with a 15% increase in consumption	VDV
	Initial regime with a 15% increase in production	CNG
	Initial diet with a 15% increase in consumption	VDI
	Initial diet with a 15% increase in consumption	VSI
Operation Scenario S1	VDV S0 + G6 Rovinari disconnect + 3 CEF connection	VDV
	CNG S0 + G6 Rovinari disconnection + 3 CEF connection	CNG
	VDI S0 + Disconnect G6 Rovinari + Connect 3 CEF	VDI

Scenario	Features	Landing
	VSI S0 + Disconnect G6 Rovinari + Connect 3 CEF	VSI
Operation Scenario S2	VDV S1 + SVC device connection to the 400 kV network	VDV
	NGV S1 + SVC device connection to the 400 kV network	CNG
	VDI S1 + SVC device connection to the 400 kV network	VDI
	VSI S1 + SVC device connection to the 400 kV grid	VSI

The first stage of the case study consisted of the analysis of the S0 and S1 regime to determine the nodes in which it is necessary to install the modern reactive power compensation device.

As a result of the steady-state calculations, the following voltage values in the 400 kV nodes of the network resulted in operating scenarios S0 and S1 for the four stages studied.

The results achieved for scenarios S0 and S1 are presented in Table 7.3.

Table 7.3. Voltage in 400 kV nodes in scenarios S0 and S1

Scenario	S0 – U [%]				S1 – U [%]			
Station name	CNG	VDI	VDV	VSI	CNG	VDI	VDV	VSI
Arefu	96.79	99.59	100.03	100.16	97.59	100.14	100.41	99.43
Drăgănești	96.7	96.45	97.69	96.63	96.86	96.92	98.02	96.07
PDF	98.83	98.68	100.3	99.56	99.3	99.38	100.73	98.85
Slatina	96.73	96.72	98.04	96.86	96.89	97.2	98.39	96.31
Mosquitoes	97.4	99.33	100.63	99.33	97.58	99.74	100.95	98.78
Ears	97.32	99.03	99.65	98.6	97.49	99.21	99.82	97.62

Considering the results obtained from the steady-state simulations for the two scenarios studied, it turns out that from the point of view of the voltage level in the 400 kV network we have two nodes that can benefit from the installation of an SVC device, namely the 400 kV Slatina substation and the 400 kV Drăgănești substation. In both nodes, in 6 of the 12 regimes analyzed resulted in voltages below 97.5% of Un. They carry the risk of falling below the minimum permissible limit of 95% in the event of adverse operating scenarios. Considering that the two nodes have a direct connection through the 400 kV Slatina – Drăgănești line and the fact that the Slatina substation is better connected with the rest of the system, it was considered appropriate for the SVC device to be connected on the 400 kV busbars of the Slatina substation.

After choosing the connection node of the SVC, the need for reactive power in each operating level was determined and thus it resulted that in order to have a good response in all the cases studied, the SVC device must be sized with the capacity to inject 250 MVAr and absorb 100 MVAr.

As a follow-up to the case study, simulations were carried out for all operating regimes in order to verify the achievement of the main objective of the SVC of voltage level control. Another benefit analysed was the reduction of power losses in the analysed area as a result of the use of SVC.

Thus, in scenario S2, the network configuration will be as shown in Figure 7.3.

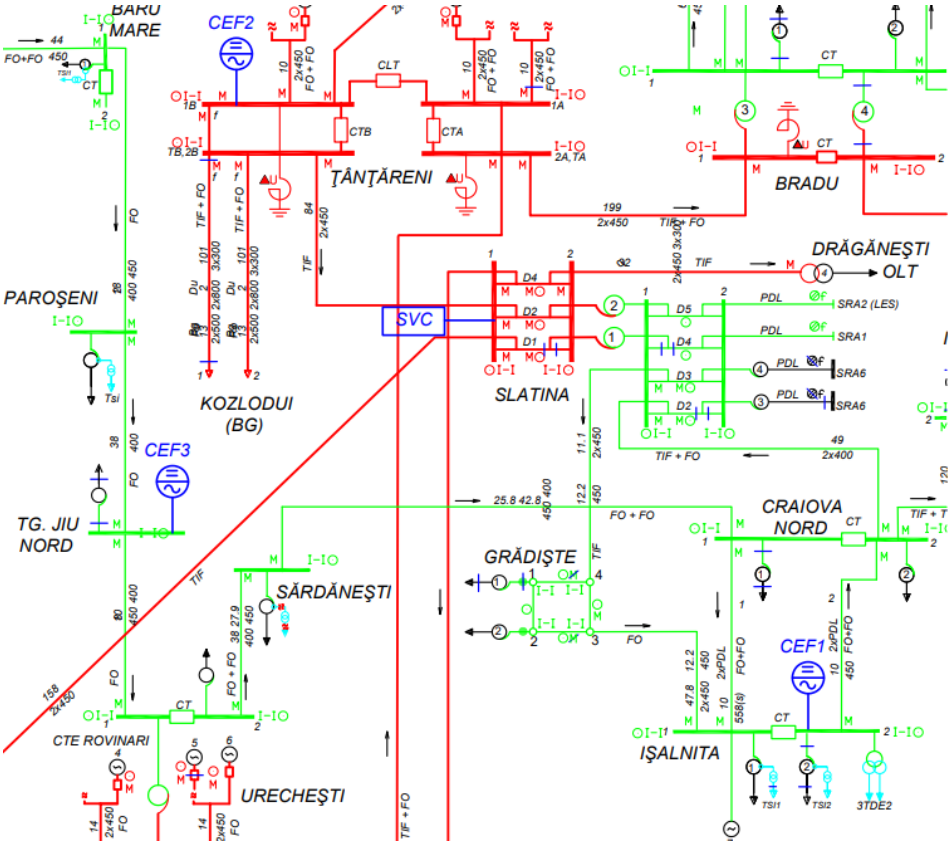


Figure 7.3. Location of the CEF and SVC in the normal operating scheme

7.3.2. VDV operating level

For the VDV operating level, a comparative analysis was carried out in terms of the level of voltage in the network and power losses. The voltage level analysis was divided into two components, namely the 400 kV nodes and the nodes with a nominal voltage of 220 kV in the analyzed area.

Figure 7.4 shows a comparative analysis of the voltage value in the 3 scenarios studied, for the VDV operating level, in the 400 kV nodes.

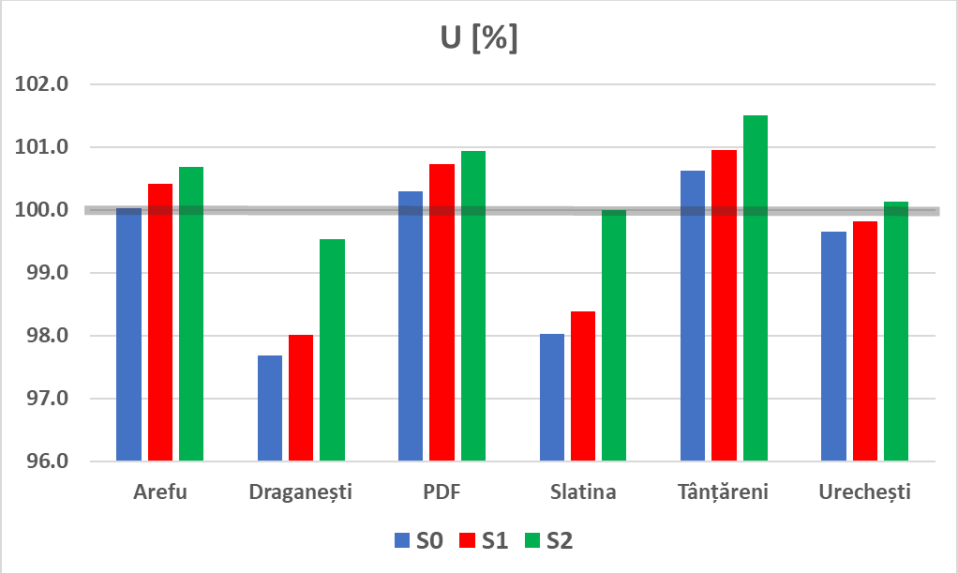


Figure 7.4. Voltage level in the 400 kV nodes in the area – VDV level

Figure 7.4 shows a significant improvement in the voltage level in the 400 kV nodes, especially in the two nodes identified in the previous stage, namely Slatina and Urechești. In all 400 kV nodes in the area, the voltage level is within the allowed limits, ensuring the proper functioning of the system.

Figure 7.5 shows the situation for the 220 kV network in a similar way. It is found that all the limits imposed for the voltage are also observed for the nodes in the 220 kV network, and after the connection of the SVC device in the Slatina substation, an improvement is also observed in the 220 kV nodes in the vicinity, respectively Craiova, Grădiște and Slatina. This confirms the efficiency of the SVC voltage control device in networks with an important renewable energy component.

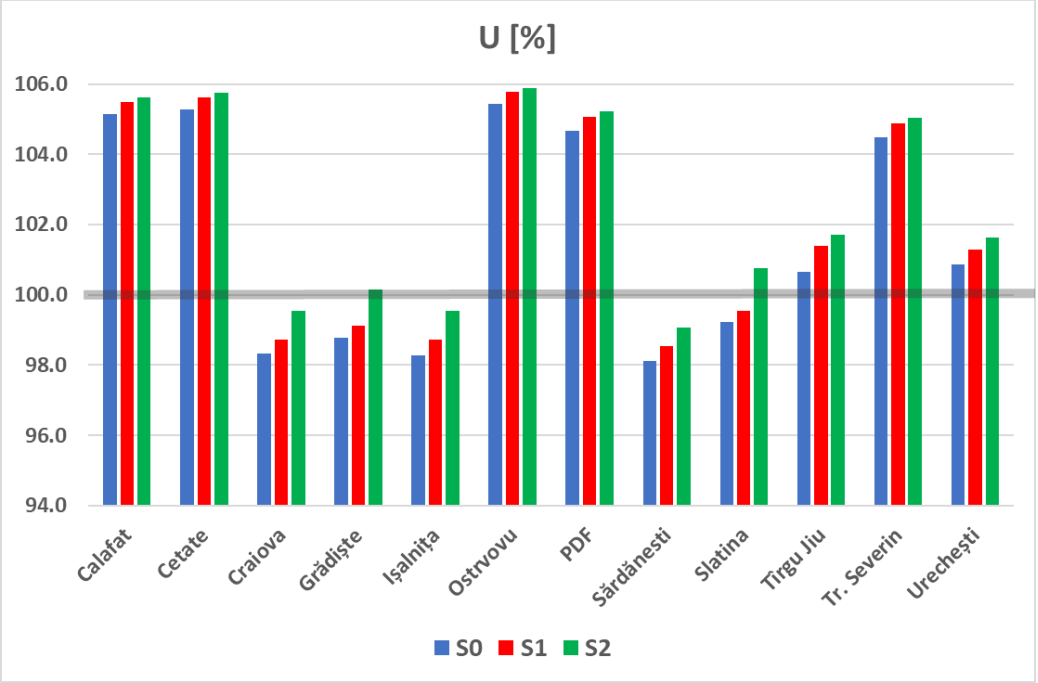


Figure 7.5. Voltage level in the 220 kV nodes in the area – VDV bearing

Another aspect pursued in the analysis is the influence of the SVC device and renewable energy sources on energy losses in the grid. Table 7.4 shows a comparison between the three scenarios in terms of active energy losses in each county.

Table 7.4. Power loss analysis – VDV level

Area	P losses [MW]	P losses [MW]	P losses [MW]	SVC contribution [MW]
	S0	S1	S2	S1-S2
DJ	2.424	2.444	2.208	0.237
GJ	12.558	10.304	8.845	1.459
MH	9.675	8.198	7.086	1.112
OT	4.647	4.668	4.331	0.337
Total	**29.304**	**25.614**	**22.469**	**3.144**

From the data presented in Table 7.4 it can be concluded that the SVC device has a positive effect on active power losses in the studied area. In all regions in the area, in the S2 scenario, there is a decrease in losses, in total they are reduced by 3.1 MW. Another aspect found is that by distributing renewable energy sources in several nodes, power losses at the grid level are reduced compared to the S0 scenario.

7.4. Conclusions

The case study aimed to analyze a complex network to determine the need and opportunity of using SVC FACTS devices to control the voltage level and improve the operating parameters of the system in the presence of renewable energy sources. Thus, in order to test the methodologies and principles studied in the case of a complex, robust and well-sized system, the national energy system in Romania was used. This transition has made the switch from standardized test networks to the deployment of SVC devices in an existing large network.

The main objective was the control of the voltage in the network nodes, and the secondary objective was to improve the operation of the system by reducing active power losses.

In the analysis process, section 1 of the SEN was chosen, for which the optimal location for the location of the SVC was determined so as to improve the voltage level in the area. Following the steady-state calculations, the optimal connection position to the 400 kV busbars of the Slatina substation was determined.

Starting from the system's operating levels, namely VDV, NGV, VDI and VSI, three scenarios were built. The scenarios include both the development of the system in terms of increasing energy consumption and production in the grid and the transition process from conventional power plants to renewable energy sources.

The system analyses have shown that the methodologies and principles set out in the previous chapters for the NORDIC32 test network can also be applied to a complex network such as SEN. The results of the system calculations confirm that the use of SVC devices is a solution for voltage level control in networks with a high degree of integration of renewable sources. An additional benefit is also achieving a decrease in power losses in the network.

8. CHAPTER 8 – CONCLUSIONS AND PERSONAL CONTRIBUTIONS

8.1.Conclusions

The objective of the documentation, research, and simulation activities was represented by the analysis of the impact on the operating regimes of the electricity systems determined by the transition from classic energy sources to renewable energy sources and the opportunity to use FACTS devices in the electricity transmission networks to improve the operating parameters, especially in the context of increasing the capacity to integrate renewable energy sources.

The thesis aimed to demonstrate the benefits that can be obtained by using CVS devices, the situations in which implementation is recommended and the limitations observed in operation. In order to achieve these aspects, in addition to the documentation and synthesis process that was the basis of the research, three case studies were carried out in order to demonstrate the extracted hypotheses.

Following the documentation process, a presentation was made of the theoretical notions regarding the operation of electricity systems, network operating configurations and aspects related to the stability of electricity systems.

In the analysis phase, the main types of FACTS solutions were studied in terms of operating principle and recommendations for use. Subsequently, the SVC device, its operating principle, components and control mode were presented in detail. For the SVC device, the design for integration into a high-voltage station was explained. The single-wire electrical diagram, the location of the equipment in plan view and an example of the partitioning of the building related to the SVC device were illustrated.

The first case study focused on the stationary operating regimes of electrical transmission networks. Within this study, two distinct methodologies were proposed, implemented and tested. The first methodology addresses the issue of choosing the appropriate FACTS device according to the needs identified at the network level, and the second aims to choose the optimal location for connecting the SVC device to the network and its sizing. Both methodologies have been implemented, tested and validated using the NORDIC32 test network.

Simulations have been carried out for several operating scenarios, including variants in which renewable energy sources are connected to the grid.

The results obtained for each of the scenarios studied confirmed the benefits of using SVC devices for grid voltage regulation in the presence of the integration of renewable energy sources.

As a result of the analyses, it turned out that the SVC device is recommended for use in electricity transmission networks to improve voltage level control, reduce power losses and increase operational safety. In renewable energy scenarios, SVC has proven adequate to address identified issues, including control, injection/absorption of reactive power.

The second case study had as its main objective the analysis of the dynamic operating regimes of the electricity transmission networks. From this perspective, both the operating regimes with renewable energy sources and the use of SVC and synchronous compensators were analyzed.

In order to carry out the case study, it was necessary to go through a stage of choosing, modeling and parameterizing the types of regulators used for the control of hydropower plants and thermal power plants in the dynamic operating regimes studied. In order to achieve the operating scenario with the massive integration of renewable energy sources, it was necessary to make a comparison between the wind turbine models both in terms of construction characteristics and in terms of available control devices. Thus, following the comparative analysis, the WT4A turbine model resulted as a recommended variant for the simulation of dynamic regimes. For this model, the configuration of the operating parameters in dynamic mode was carried out.

Several operating scenarios have been defined for the NORDIC32 test network for the purpose of assessing the impact of the massive integration of renewables in an area of the grid.

The analyses carried out on the six events in the 4 scenarios studied clearly highlight the role and efficiency of the SVC device in maintaining the dynamic stability of the transmission power grid.

In terms of voltage stability in all four events, the use of an SVC led to:

• Limiting the amplitude of voltage variations in the network nodes immediately after the dynamic event occurs.

• Rapid damping of transient oscillations and increased stability in operation.

• Return of voltage to values close to nominal in a much shorter time compared to scenarios without SVC;

• Avoid excessive overvoltages in case of quick recovery

• By quickly compensating for imbalances, the SVC stabilizes power flows and supports the voltage profile in critical nodes.

In the case of frequency and rotor angle stability, an improvement is observed in most cases by connecting the SVC device, but the clearest effects have been identified for increasing voltage stability.

Within the case study, a comparative analysis was carried out between the dynamic response of the classical means of reactive power compensation, namely the synchronous compensator and the modern FACTS equipment, more precisely the SVC device. As a result of the analysis and simulations carried out, it was determined that the SVC device has a better dynamic response than the synchronous compensator, being capable of a rapid reaction and a precise compensation of the variations resulting from the occurrence of a defect.

The third case study aimed to validate the conclusions reached on the use of SVC devices in a complex, large and highly interconnected energy system. Thus, the simulations were carried out using a real network, namely the national energy system in Romania.

A transition scenario towards renewable sources was studied, namely the integration of several photovoltaic plants into the grid and the disconnection of a coal-fired thermal power plant.

For the analyzed scenarios, the SVC was used in order to increase the voltage control in the network nodes and optimize the operation by reducing losses. The hypotheses from which the case study was started were demonstrated, SVC being capable of an exact control of the voltage in the system.

8.2. Personal contributions

The main personal contributions made within the process of research and completion of the doctoral thesis can be divided into the following categories:

A. Documentation and research on the following aspects:

- Documentation and analysis on the theoretical notions regarding the operation of electricity systems.
- Classification and presentation of the specific configurations of the networks in the electricity system.
- Documentation and analysis on the dynamic and stationary operating regimes of the electricity transmission networks.
- Presentation of the theoretical aspects regarding the stability of electricity systems, classification of types of stability and how these notions can be used in the case studies carried out.
- Analysis of the main FACTS devices in terms of operating principle and recommendations for use.
- Documentation on the operating principle of SVC FACTS devices and how to control them in multiple operating modes.

- Presentation of how to implement an SVC device in a high-voltage substation including elements such as the single-wire electrical diagram of the installation, the plan view with the location of the main components and the building module related to the FACTS system.
- Description of the software for simulating the operating regimes of NEPLAN10 electrical networks and explaining its operating modules.
- Analysis of operating regimes, components and boundary areas in the system for the NORDIC32 test network.

B. Simulations, calculations, analyses and methodologies developed:

- Elaboration and development of a methodology for choosing the type of FACTS device adapted to the conditions and needs of the studied electricity grid. This is a complex process that needs a multidimensional approach that respects both technical requirements and economic constraints.
- Elaboration and development of a methodology for choosing the optimal node for connecting the SVC device in an electrical transmission network.
- Implementation, testing and validation of the two proposed methodologies using the Nordic32 network as a test environment.
- Modeling of the operating parameters of the SVC device in order to perform steady-state calculations for all the scenarios studied.
- Definition, simulation and analysis of several scenarios for the operation of the Nordic32 test network, including in the presence of renewable energy sources.
- Optimal sizing of the SVC device to correspond to the criteria imposed by the objective function proposed for a series of hypotheses regarding the development of the analyzed system.
- Centralise and interpret the results obtained for all scenarios studied in order to draw the main conclusions on the benefits of using CVS devices in electricity transmission networks and how they can increase the capacity to integrate renewable energy sources into electricity systems.
- Choosing and parameterizing the regulators used to control the operating mode of the hydropower plants in order to ensure dynamics in the system analyses performed.
- Choosing and parameterizing the regulators that ensure the control of the thermal power plants in order to determine a stable dynamic response in the studied regimes.
- Carrying out a comparative analysis between the types of wind turbines according to the constructive characteristics and the available control equipment. The purpose of this analysis is to choose the optimal wind turbine model to be used in the transition process to renewable energy sources.
- Configuration and simulation of dynamic models for WT4A wind turbines in order to implement scenarios of massive integration of renewable energy sources into the transmission grid.
- Description and implementation of the Nordic32 test grid operating scenarios in order to assess the impact of renewables on system stability and determine the benefits of using SVC.
- Define and simulate multiple dynamic events in all analyzed scenarios to determine their impact on system stability.
- Carrying out a complex comparative analysis on the impact of the massive integration of renewable energy sources on the energy system.

- Comparative analysis, from the point of view of dynamic behavior, between classic reactive power compensation solutions, such as the synchronous compensator, with a modern FACTS solution, respectively the SVC device.
- Graphical representation of all the values obtained from the scenarios studied for each dynamic event analyzed to determine the main differences in terms of system stability.
- Assessment of the current energy situation in Romania's national energy system and analysis of development prospects in the context of the transition to renewable energy sources and compliance with European Union regulations on sustainability and energy efficiency.
- Definition, implementation and simulation of several scenarios regarding the evolution of the electricity transmission network in Romania, including scenarios regarding the reduction of the installed power in thermal power plants and the increase of the electricity production capacity in photovoltaic power plants.
- Modeling of a section of the national energy system for several levels of operation in order to perform steady-state calculations.
- Validation of the methodologies proposed in the previous study stages by testing their efficiency in a real energy system, with an increased complexity and a very large number of elements.
- Determining the influence of the transition process towards renewable energy sources on the national energy system for several levels of network operation.
- Evaluation of the voltage level and power losses in the SEN for the analyzed area in all scenarios and operating levels studied.
- Analysis of the benefits of using SVC devices in the national energy system in order to improve the operating parameters of the network.
- Identify the opportunity to install SVC devices in the national energy system in order to increase the capacity for the integration of renewable sources.

8.3. Directions to follow in research

In the future, the following topics can be further researched in this paper:

- Analysis of the opportunity to use other types of FACTS devices, e.g. STATCOM devices, to increase the integration capacity of renewable sources and to increase the static and dynamic performance of the grid.
- Analysis of the technical and economic feasibility of using SVC devices in the presence of renewables and energy storage facilities.

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