

IMPROVING THE OPERATION OF POWER SYSTEMS THROUGH THE USE OF FACTS DEVICES

PhD Thesis – Summary

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A modern power system is a complex structure composed of power plants, electricity transmission and distribution networks, transformer substations, and consumers. In theory, its role is straightforward: the safe generation, transmission, and distribution of electrical energy. In practice, however, numerous challenges arise related to load variations, physical limitations of transmission lines, power losses, and external disturbances. System operators must continuously maintain the balance between generation and consumption, as well as ensure frequency and voltage stability across the entire power system.

The transition towards renewable energy sources (wind, photovoltaic, biomass, biogas) has introduced new challenges related to stability and flexibility. These transformations have highlighted the need for modern solutions for controlling and optimizing power flows, capable of maintaining operational security and the quality of electricity supply to consumers.

In the classical approach, massive investments are required for the construction of new transmission lines and the expansion of transformer substations, involving very high costs, long implementation periods, and difficulties in obtaining environmental approvals. In this context, Flexible AC Transmission Systems (FACTS) devices have emerged as an innovative alternative, based on the use of power electronics for rapid and efficient control of power flows and voltage levels.

At the international level, the implementation of FACTS devices has experienced accelerated development over the past decade. Countries such as India, China, and the United States have made substantial investments in these technologies. In Europe, their use is closely linked to the large-scale integration of renewable energy, particularly in Germany and the Nordic countries, where extensive wind farms are installed.

Romania also has significant potential for the application of these technologies, especially in the Dobrogea region, where most wind farms in the country are concentrated, as well as in other areas where there is a need to increase the level of transferred active power and to maintain the voltage profile closer to its upper limits.

In this context, the topic of the doctoral thesis aligns with current research concerns regarding the implementation of FACTS devices in power systems. The main objective of the thesis is the development and application of efficient practical methods, rigorously grounded from a scientific perspective, for the optimal placement and sizing of FACTS devices.

The research started from a relatively small-scale test system developed within the Department of Power Engineering at Politehnica University of Timișoara – TEST25 [Kilyeni 1988] – and was subsequently extended to a real large-scale power system – the power system of the Republic of Moldova.

The results and the conclusions formulated are highly useful both for transmission and distribution system operators in general and, in particular, for Moldelectrica (the transmission system operator of the Republic of Moldova).

The doctoral thesis, comprising 234 pages, is structured into seven chapters, a preface, four electronic annexes, and a bibliography, and includes 313 figures and diagrams and 159 tables. The bibliography contains 161 representative references, both classical and relatively recent, published nationally and in prestigious international journals.

Chapter 1 has an introductory character. The first part presents the context and the justification of the doctoral thesis topic, within the framework of the current stage of development of power engineering and the existing research concerns at the international level. The second part provides a concise overview of the content of each chapter. The final section highlights both the dissemination of the research (papers published in specialized journals or in the proceedings of conferences, scientific research or technical assistance contracts) and the usefulness of the results for electricity transmission and distribution system operators. Finally, the chapter outlines the perspectives regarding possible directions for the continuation and extension of the research.

Chapter 2 provides a concise synthesis of the main information regarding FACTS devices, highlighting their classification, operating principles, and the mathematical models used in power flow calculations.

FACTS devices are classified according to their location in the network into shunt devices (SVC – Static VAR Compensator, STATCOM – Static Synchronous Compensator), series devices (TCSC – Thyristor Controlled Series Capacitor, SSSC – Static Synchronous Series Compensator), and combined devices (UPFC – Unified Power Flow Controller, IPFC – Interline Power Flow Controller). From the perspective of switching technology, they can be categorized into devices based on mechanical switching, thyristor-controlled, and self-commutated semiconductor devices of the VSC (Voltage Source Converter) type.

SVC is a shunt device used for voltage regulation through reactive power compensation. From a mathematical perspective, the SVC is modeled as a variable susceptance connected in parallel to the network, implemented through combinations of TSC (Thyristor-Switched Capacitor) and TCR (Thyristor-Controlled Reactor) [Zhu2009].

STATCOM is a device based on voltage-source converters that provides fast and accurate reactive power control. Its modeling is performed in the dq0 coordinate system and includes PI control loops for DC voltage and current. Both the steady-state model and the linearized model for small disturbances are presented [Singh2015].

TCSC is a series device used to control line impedance and active power flow. The mathematical model of the TCSC highlights the possibility of increasing or decreasing the transmitted power by modifying the series reactance, as well as the use of POD (Power Oscillation Damping) channels for damping power oscillations [Maruf2015].

SSSC uses a VSC (Voltage Source Converter) to inject a controllable series voltage, allowing the direct modification of power flow. Its operation in capacitive or inductive mode is described through steady-state and dynamic mathematical models [Morsali2018].

UPFC is the most complex FACTS device, combining the functionalities of STATCOM and SSSC. Through coordinated control of the series and shunt converters, the UPFC enables simultaneous regulation of voltage, impedance, and phase angle [Mailah2015]. The extension of this concept to multiple lines is achieved through the IPFC, which is used for load balancing and for optimizing the use of transmission corridors [Talebi2015].

Chapter 3 presents, in a systematic manner, the main current methods used to solve the problem of optimal placement and sizing of FACTS devices in modern power systems.

The methods used to solve the problems discussed can be divided into two main categories:

- methods based on classical mathematical modeling – linear programming, integer or mixed-integer linear programming, nonlinear programming, dynamic programming, etc.;

- heuristic and metaheuristic techniques: Genetic Algorithms (GA), Evolutionary Programming (EP), Particle Swarm Optimization (PSO), Harmony Search (HS), Tabu Search (TS), Simulated Annealing (SA), Ant Colony Optimization (ACO), Artificial Bee Colony (ABC), Artificial Immune System (AIS), Charged System Search (CSS), Biogeography-Based Optimization (BBO), Cuckoo Search Algorithm (CSA), Firefly Algorithm (FA), Artificial Fish Swarm Algorithm (AFSA), Shuffled Frog Leaping Algorithm (SFLA), Bacterial Swarming Algorithm (BSA), Squirrel Search Algorithm (SSA), Imperialist Competitive Algorithm (ICA), Dragonfly Algorithm (DFA), Brainstorm Optimization Algorithm (BSOA), Cat Swarm Optimization (CSO), etc.

Several examples of studies that employ the methods mentioned above are as follows: Mixed Integer Linear Programming (MILP – mixed-integer linear programming) [Sharma 2005]; Heuristic Methods (HM – heuristic approaches) [Belkacem2006]; Artificial Bee Colony (ABC – algorithm inspired by the behavior of bee swarms) [Rafee 2016]; Genetic Algorithm (GA – genetic algorithm) [Barnigbade2020], [Ahmad 2020]; Particle Swarm Optimization (PSO – swarm-based optimization algorithm) [Raj2018]; Bacterial Swarming Algorithm (BSA – algorithm inspired by bacterial evolution) [Ayman 2018]; Biogeography Based Optimization (BBO – algorithm inspired by biological factors) [Kavitha2018]; Tabu Search (TS – tabu search algorithm) [Koster2020]; Squirrel Search Algorithm (SSA – algorithm inspired by squirrel movement) [Yun2020]; Cuckoo Search Algorithm (CSA – algorithm inspired by cuckoo behavior) [Shehab2017]; Evolutionary Programming (EP) [Zarkani2021]; Dragonfly Algorithm (DA – algorithm inspired by dragonfly behavior) [Abouazma2019]; Bat Search Algorithm (BSA – algorithm inspired by bat behavior) [Akbari 2014]; Brainstorm Optimization Algorithm (BSOA – “brainstorm”-type optimization algorithm) [Jordehi2015].

There are also so-called mixed (hybrid) methods, which result from the combination of two or more of the techniques mentioned above [Kang2017]. In some cases, fuzzy techniques are also incorporated within heuristic or metaheuristic methods [Rabian2020].

Chapter 4 aims at the development of the mathematical model for the optimal placement and sizing of FACTS devices.

Subchapter 4.1 presents the mathematical model and the procedure based on Q–U sensitivity analysis used to determine the optimal placement of FACTS devices. The first part of the subchapter addresses the steady-state analysis of complex power systems, while the second part focuses on the details related to sensitivity analysis.

Steady-state analysis involves determining the state vector (bus voltages in terms of magnitude and phase angle), the power flows through network elements (overhead and underground transmission lines, transformers, autotransformers, and compensation reactors), and power losses (both for the entire power system and for individual network elements) [Kilyeni2015b], [Das2018]. The mathematical model of the steady-state operating condition consists of a system of nonlinear equations of very large dimensions (hundreds or thousands of equations), with coefficient matrices characterized by a highly sparse structure. Its solution can be efficiently achieved exclusively by Newton-type numerical methods for large-scale nonlinear equation systems [Kilyeni2019], using specialized techniques for the storage and processing of sparse matrices [Kilyeni2015b].

Q–U sensitivity analysis examines the relationship between reactive power and voltage in order to assess the operational security of the network from this perspective [Munikoti2020]. The voltage at a bus in a power system depends on the local balance between absorbed and generated reactive power. If the injection of inductive reactive power at a given bus increases, the voltage value rises. Conversely, if the consumption of inductive reactive power at a given bus increases, the voltage decreases.

Q–U sensitivity expresses the variation of the voltage at a network bus as a function of a change in the reactive power at that bus:

$$S_{UQ} = \frac{\partial U}{\partial Q} \quad \text{or} \quad S_{QU} = \frac{\partial Q}{\partial U}$$

The two forms are equivalent through the reciprocity relationship. In practice, the most commonly used form is $\partial U / \partial Q$, because it shows how much the voltage changes (decreases or increases) when the reactive power changes (decreases or increases) by ΔQ . If S_{UQ} has a small value, the voltage is “stiff,” meaning that it changes only slightly in response to variations in reactive power. The power system is stable and well supported by reactive power sources. If S_{UQ} has a high value, the voltage varies significantly even for small changes in reactive power, which may represent a source of vulnerability.

In the present work, the sensitivity analysis was carried out by modifying the reactive power consumption by a given value (for example, 1 MVar) for each load bus (PQ type). In addition, a sensitivity analysis was also performed for variations in the reactive power generated by the FACTS device installed at the respective bus.

The analysis focused on voltage values at all system buses for relatively small-scale power systems (the TEST25 system in this work, which has 25 buses). For larger systems (hundreds of buses – the power system of the Republic of Moldova in this study, with 205 buses), an additional analysis was carried out based on the definition of several zones within the power system, considering voltage values only for the buses located in the respective zone.

In addition to voltage sensitivity, the influence on active power losses in the system was also monitored.

The optimal placement of FACTS devices is determined in descending order of the S_{UQ} sensitivity index values. In addition, the criterion of active power losses was also considered, aiming to achieve values as low as possible.

Subchapter 4.2 is dedicated to the optimal sizing of FACTS devices, based on the analysis of power system stability under large disturbances. Stability is examined from the perspective of the behavior of synchronous generators (SG) and automatic control systems, using dynamic models of various orders SG and standardized models for excitation systems [Kilyeni 2004], [Eremia2014], [Anderson2003], [Luștrea2012], [IEEE2016]. The studies are carried out through step-by-step simulations in the time domain, a method that allows a detailed evaluation of transient processes and oscillation damping.

Nowadays, there is no unified approach to defining the quality of transient processes associated with the operation of complex power systems under disturbed conditions (in other words, power system stability). In stability studies, most transient processes are oscillatory in nature, while the number of aperiodic processes is very small. In methods specific to automatic control theory, the quality of transient processes is generally assessed using integral criteria that provide a global perspective, taking into account all indicators: response speed, overshoot, transient duration, damping, etc.

For oscillatory transient processes, in most cases the integral of the squared deviation, defined by the relation below, is used as a performance index.

$$I = \int_0^{\infty} (x - x_r)^2 \cdot dt$$

The optimization of the transient process involves minimizing the value of the performance index. Considering the nature of the problem under study, stability analyses require the consideration of a large number of variables in defining the objective function (OF). Consequently, it may take the following form, where x_1, x_2, \dots, x_n are the variables considered, the index r denotes the reference value, and A_i are the weighting coefficients:

$$V = \sum_{i=1}^n A_i (x_i - x_{ir})^2$$

For the definition of the OF expression, the following additional clarifications are made:

- only the relative values of the objective function (OF) are of interest, not the absolute ones;
- in practical applications, the upper integration limit is taken as a finite value T , which, for reasonable disturbance scenarios, lies within the range (5–15) s;
- the reference value x_r is considered to be the one determined in the steady-state regime, either post-disturbance or pre-disturbance, the final system state being determined using a conventional power flow program;
- the selection of weighting coefficients represents a difficult task that can significantly influence the results.

In order to determine the form of the OF, the following issues must be addressed: selecting the form of the performance index; determining the expression of the penalty function related to the amplitude of the first oscillation and the damping of oscillations; selecting the variables to be considered in defining the objective function; synthesizing the expression of the objective function; the actual method of calculating the performance indices and the OF.

In this work, the performance indices adopt the quadratic form defined above, possibly corrected by a penalty function $FP(t)$:

$$I = \int_0^T FP(t) (x - x_r)^2 \cdot dt$$

Details regarding the penalty functions can be found in [Kilyeni2004].

The performance indices are calculated by considering the following variables: the voltage U at all buses of the power system; the angular speed ω for all synchronous generators in the system.

Indices of type I_U provide a measure of the electrical intensity of the disturbance, while those of type I_ω illustrate the dynamic effect of the electromechanical imbalance on the rotor motion of the synchronous generators.

In the practical calculation of the performance index values, the following additional aspects are taken into account:

- for I_ω , the synchronous angular speed is considered as the reference value;
- if the power system configuration in the post-disturbance steady state is similar to that in the pre-disturbance steady state, the reference value for I_U is taken as the terminal voltage value in the pre-disturbance regime;
- if the power system configuration in the post-disturbance steady state differs from that in the pre-disturbance regime, the reference value for I_U is taken as the terminal voltage value in the post-disturbance regime;
- the transient regime is analyzed over a duration of 15 s.

The synthesis of a global resulting objective function for complex power systems, based on the mentioned performance indices, is very difficult, as no analytical method exists that ensures the optimal solution. Even when this is achieved empirically, the individual analysis of the performance indices cannot be omitted when establishing the optimal solution, nor can the detailed analysis of the time variation of a large number of variables. Consequently, the performance index I_U , calculated at the level of the entire power system or for certain areas of the system, constitutes the first component of the objective function. The performance index I_ω , calculated for all synchronous generators within the power system, constitutes the second component of the objective function. The two components of the OF are analyzed separately, as their values are generally of different orders of magnitude.

In practice, the same objective can be achieved, without introducing significant errors, by simply summing the squared deviations.

Chapter 5, together with Chapter 6, represents the applied part of the doctoral thesis. In this chapter, the optimal placement of SVC-type FACTS devices is carried out for two power systems: a 25-bus test network – TEST25 [Kilyeni1988] – and the real power system of the Republic of Moldova. For each power system, a characteristic steady-state operating condition was considered, for which a Q–U (voltage–reactive power) sensitivity analysis was performed in order to determine the optimal placement of SVC-type FACTS devices.

The main characteristics of the TEST25 power system (Fig. 5.1.1) are as follows: 25 buses – 6 PV type, one of which is the slack bus (A24), and 19 PQ type; 29 network elements – 18 overhead transmission lines rated at 110, 220, and 400 kV, 5 medium-to-high voltage transformers (10, 15, 24 kV on the medium-voltage side, 110, 220, 400 kV on the high-voltage side), and 6 autotransformers (t2 – 400 MVA, 400/220 kV, 4 – 200 MVA, 220/110kV).

The objective of the sensitivity analysis is to identify the buses for which the installation of FACTS devices has the maximum positive effect, both in terms of voltage levels and active power losses.

Initially, a sensitivity analysis was performed for the operating condition without FACTS devices (SVC), following the approach presented in Chapter 4. All power system buses were analyzed sequentially. The reactive power was successively modified by 1 MVAR, after which the new operating condition was calculated and the bus voltage values were extracted.

A synthesis of the results is presented in Fig. 5.1.2. The horizontal axis represents the buses (excluding PV buses), while the vertical axis corresponds to the voltage values (expressed as a percentage of the nominal value, i.e., per-unit values multiplied by 100). Fig. 5.1.3 presents the average voltage value across all power system buses, excluding generator buses, obtained as the mean of the cases illustrated in Fig. 5.1.2. Fig. 5.1.4 shows the average voltage values at the system buses as a function of the bus for which the sensitivity analysis was performed.

The analysis of the results highlights the following conclusions:

- from the perspective of the effect on the values across the entire power system, a ranking of the analyzed 110 kV buses is as follows: MM110, II110, HH110; LL110, NN110, DD110, JJ110 (in other words, the voltage is most strongly affected by changes in reactive power at bus MM110 and least affected at bus JJ110).

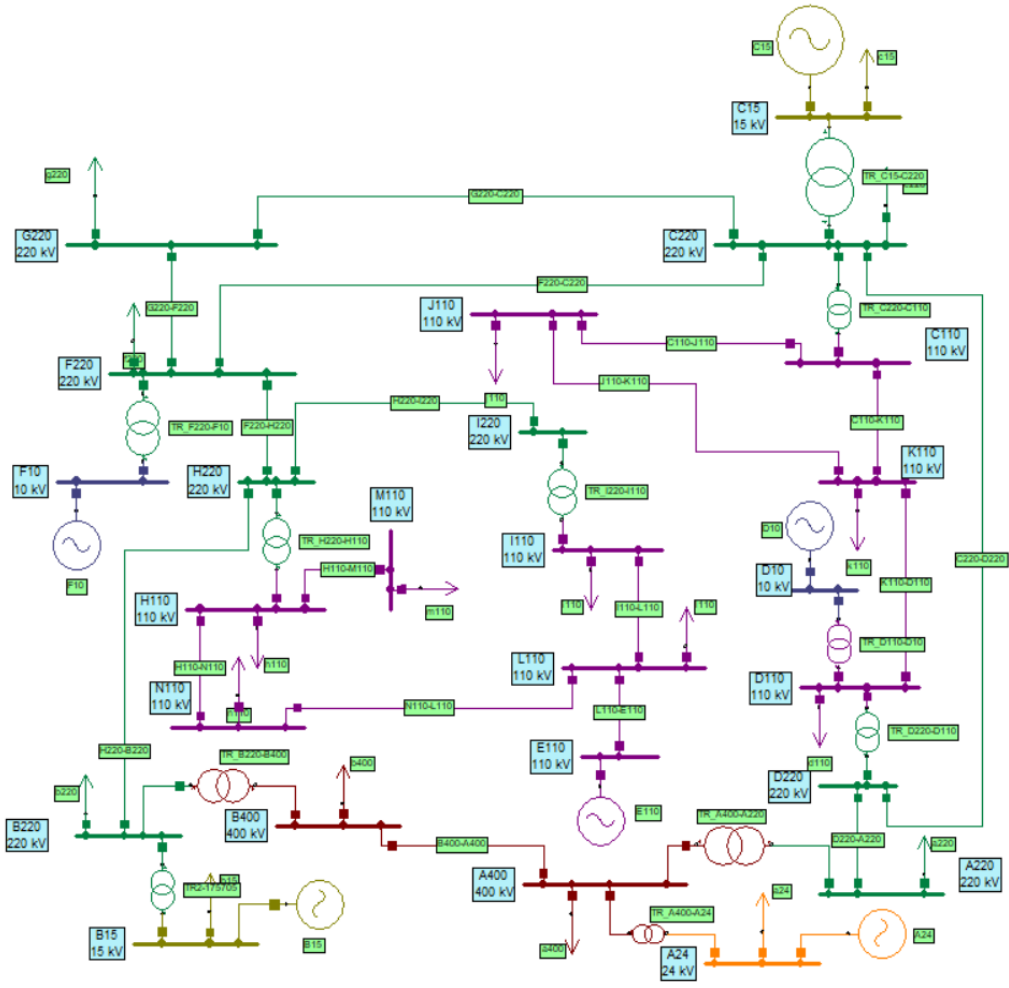


Fig. 5.1.1. TEST25 power system

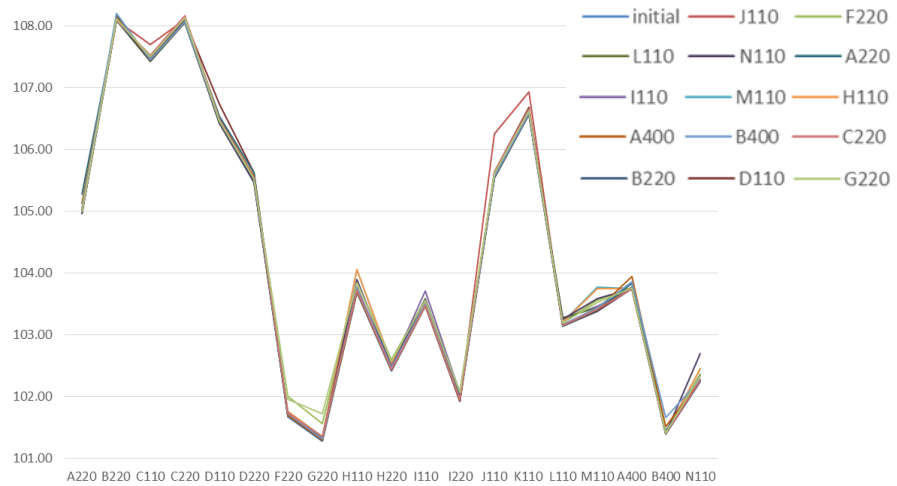


Fig. 5.1.2. Synthesis of voltage variation as a function of changes in the consumed reactive power



Fig. 5.1.3. Average voltage value at the power system buses for all analyses performed



Fig. 5.1.3. Average voltage value at the power system buses for all analyses performed

- b) from the perspective of the effect on the values across the entire power system, a ranking of the analyzed 220 kV buses is as follows: GG220, FF220, BB220; CC220, AA220.
- c) for the 400 kV buses, the ranking is BB400, AA400.
- d) from the perspective of voltage values, an ascending ranking of the analyzed 110 kV buses is as follows: NN110, LL110, MM110, II110, HH110, FF110, JJ110 (in other words, the voltage is lowest at bus NN110 and highest at bus JJ110).
- e) from the perspective of voltage values, an ascending ranking of the analyzed 220 kV buses is as follows: GG220, FF220, AA220; CC220, BB220.
- f) for the 400 kV buses, the ranking is BB400, AA400.

By combining the conclusions from items (a) and (c), respectively (b) and (e), and then (c) and (f), the following ranking of the most “relevant” buses in terms of voltage sensitivity to changes in the consumed reactive power is obtained:

- a) 110 kV buses – MM110, followed (at the same rank) by II110, NN110, and LL110, then HH110, and finally (at the same rank) DD110 and JJ110;
- b) 220 kV buses – GG220, FF220, followed (at the same rank) by BB220, CC220, and AA220;
- c) 400 kV buses – BB400, AA400.

Subsequently, a sensitivity analysis was carried out for the operating condition with FACTS devices (SVC), following the approach presented in Chapter 4. All power system buses were analyzed sequentially. For each case, an SVC device was installed at the analyzed bus to inject a reactive power of 2 MVar, after which the new operating condition was calculated and the voltage values were extracted.

The analysis of the results highlights the following conclusions:

- a) from the perspective of the effect on the values across the entire power system, a ranking of the analyzed 110 kV buses is as follows: MM110, II110, HH110; LL110, NN110, DD110, JJ110;
- b) from the perspective of the effect on the values across the entire power system, a ranking of the analyzed 220 kV buses is as follows: GG220, FF220, BB220; CC220, AA220;
- c) for the 400 kV buses, the ranking is BB400, AA400;
- d) from the perspective of voltage values, an ascending ranking of the analyzed 110 kV buses is as follows: NN110, LL110, MM110, II110, HH110, FF110, JJ110;
- e) from the perspective of voltage values, an ascending ranking of the analyzed 220 kV buses is as follows: GG220, FF220, AA220; CC220, BB220;
- f) for the 400 kV buses, the ranking is BB400, AA400.

By combining the conclusions from items (a) and (c), respectively (b) and (e), and then (c) and (f), the following ranking of the most “relevant” buses in terms of voltage sensitivity is obtained:

- a) 110 kV buses – MM110, followed (at the same rank) by II110, NN110, and LL110, then HH110, and finally (at the same rank) DD110 and JJ110;
- b) 220 kV buses – GG220, FF220, followed by BB220, CC220, and AA220 (at the same rank);
- c) 400 kV buses – BB400, AA400.

By comparing the two categories of results, it can be observed that, from a qualitative perspective, they are practically similar.

Figure 5.1.8 presents the value of active power losses across the entire power system as a function of the bus for which the sensitivity analysis was performed with the modification of the consumed reactive power.

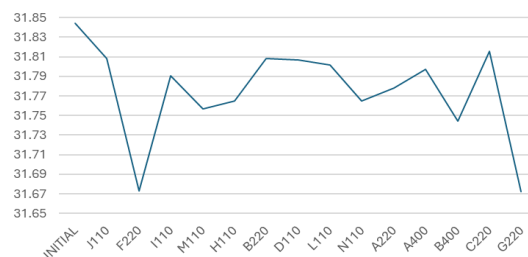


Fig. 5.1.8. Active power losses as a function of the bus for which the sensitivity analysis was performed with changes in the consumed reactive power

The analysis of the results highlights the following conclusions:

- a) in all cases, active power losses are lower than those in the initial operating condition;
- b) from the perspective of the effect on active power losses, a ranking of the analyzed 110 kV buses is as follows: MM110, HH110, NN110, II110, LL110, DD110, JJ110 (in other words, active power losses decrease the most when reactive power is modified at bus MM110 and the least at bus JJ110);
- c) from the same perspective, a ranking of the analyzed 220 kV buses is as follows: GG220, FF220, BB220; AA220, CC220;
- d) for the 400 kV buses, the ranking is BB400, AA400.

By comparing these results with those obtained from the Q–U sensitivity analysis (with modifications of the consumed reactive power), the only difference is that, in the ranking for the 110 kV buses, HH110 moves from fifth place to second place.

A similar analysis of power losses was then performed for the operating condition with FACTS devices (SVC).

By combining the conclusions from the sensitivity analyses and those related to active power losses, the final conclusions are as follows:

- a) there are two buses in which the installation of SVC is not recommended – CC220 and LL110;
- b) a ranking of the most “relevant” buses in terms of voltage sensitivity to changes in reactive power for the 110 kV level is as follows: MM110, followed (at the same rank) by II110 and NN110, then HH110, and finally (at the same rank) DD110 and JJ110;
- c) for the 220 kV buses – GG220, FF220, followed (at the same rank) by BB220 and AA220;
- d) for the 400 kV buses – BB400, AA400.

The main characteristics of the power system of the Republic of Moldova are as follows: 195 buses – 18 PV type) one of which is the slack bus NMoldova TEM330, 177 PQ type; 241 network elements – 235 overhead transmission lines (110, 330 kV, 6 autotransformers– 300 MVA, 330/110 kV (Fig. 5.2.1).

Considering the configuration and dimensions of the RM power system, for the subsequent analyses it was divided into five zones (Fig. 5.2.2): Zone 1 – north-western area; Zone 2 – north-eastern area; Zone 3 – central-eastern area; Zone 4 – central-western area; Zone 5 – central-southern area.

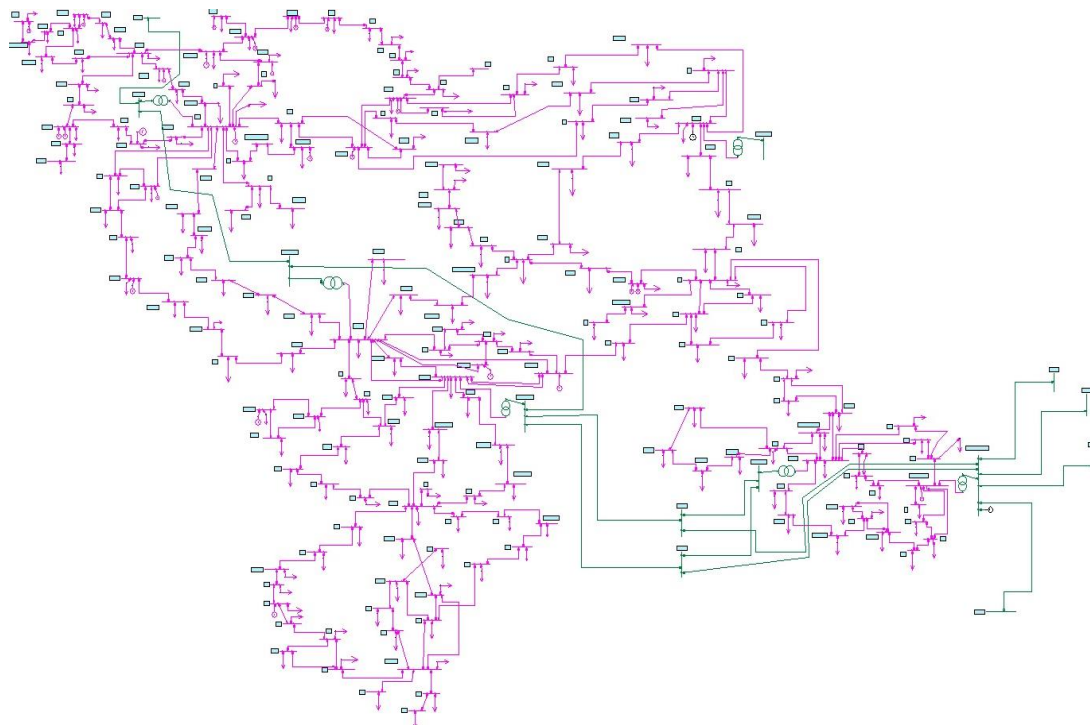


Fig. 5.2.1. Single-line diagram of the power system of the Republic of Moldova

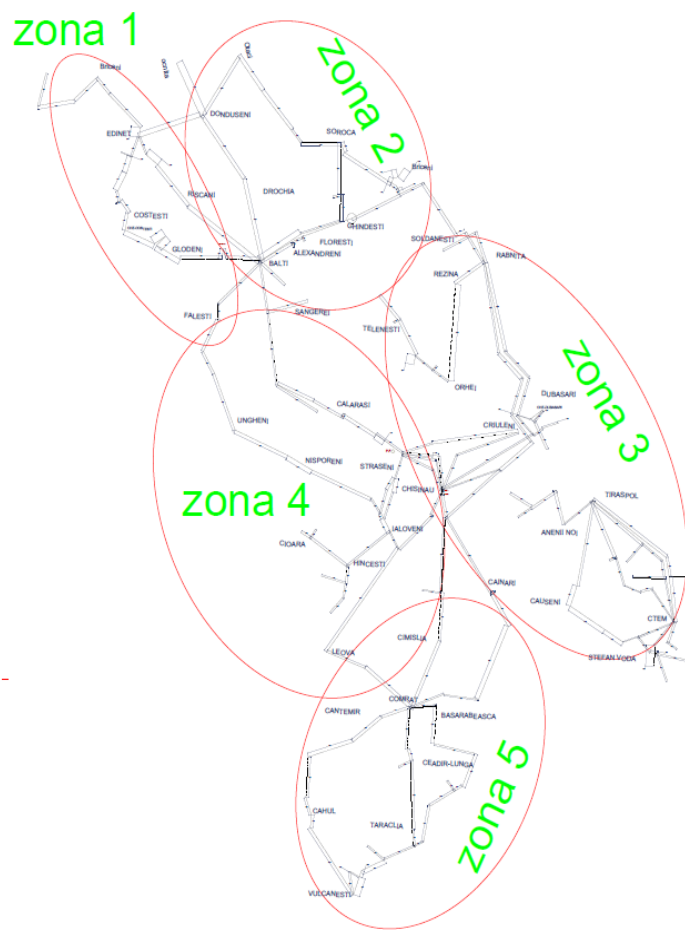


Fig. 5.2.2. Zones within the power system of the Republic of Moldova

By analyzing the voltage values at the buses of the power system of the Republic of Moldova and the configuration of the 110 kV network, an initial selection was made of the buses where FACTS (SVC) devices could be connected: Zone 1: Briceni, Edineț, Larga; Zone 2: Dondușeni, Ocnița, Otaci,

Soroca; Zone 3: Kamenka, Orhei, Ribnița, Telești; Zone 4: Anenii Noi, Ungheni; Zone 5: Cahul, Ceadar-Lunga, Komrat, Vulcănești. For the voltage–reactive power sensitivity analysis, a 2 MVar FACTS (SVC) device was successively installed at each of the selected buses.

Figure 5.2.3 presents the minimum voltage values in the presence of the SVC across all buses of the RM power system. The vertical axis shows the voltage values [kV], while the horizontal axis indicates the SVC installation location. Fig. 5.2.4 presents the maximum voltage values in presence of the SVC across all buses. Figure 5.2.5 presents the average voltage values in the presence of the SVC across all buses of the RM power system.

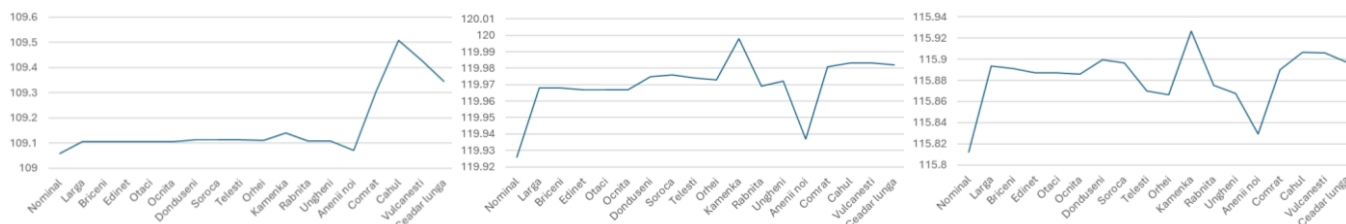


Fig. 5.2.3. Minimum voltage values Fig. 5.2.4. Maximum voltage values Fig. 5.2.5. Average voltage values

The buses where the SVC devices are installed were ranked in descending order of voltage values for the three analyzed cases (Table 5.2.5). The ranking positions were summed, and the resulting values were finally converted into scores from 10 to 1 (in ascending order).

Table 5.2.5. Analysis of the Influence of SVC

	Briceni	Larga	Edinet	Dundu	Ocnita	Otaci	Soroca	Rabni	Orhei	Kamen	Telesti	Unghe	Anenii	Komrat	Cahul	Vulcan	Ceadar
U _{min}	12	13	14	15	16	6	7	8	9	5	11	10	17	4	1	2	3
U _{max}	12	13	14	15	16	7	6	8	9	1	11	10	17	5	2	3	4
U _{med}	7	8	10	11	12	4	6	14	16	1	13	15	17	9	2	3	5
Sum	31	34	38	41	44	17	19	30	34	7	35	35	51	18	5	8	12
Note	4.92	4.33	3.55	2.96	2.37	7.65	7.26	5.11	4.33	9.61	4.13	4.13	1.00	7.46	10.0	9.42	8.63

The results presented in Table 5.2.5 highlight the following “ranking”: Cahul, Kamenka, Vulcănești, Ceadar-Lunga, Otaci, Komrat, Soroca, Ribnița, Briceni, Larga, and Orhei; Telești and Ungheni; Edineț, Donduseni, Ocnita, Anenii Noi.

Fig. 5.2.6 presents the minimum voltage values in presence of SVC at the Zone 1 buses. Fig. 5.2.7 presents the maximum voltage values in presence of SVC at the Zone 1 buses. Figure 5.2.8 presents the average voltage values in the presence of the SVC at the buses in Zone 1.

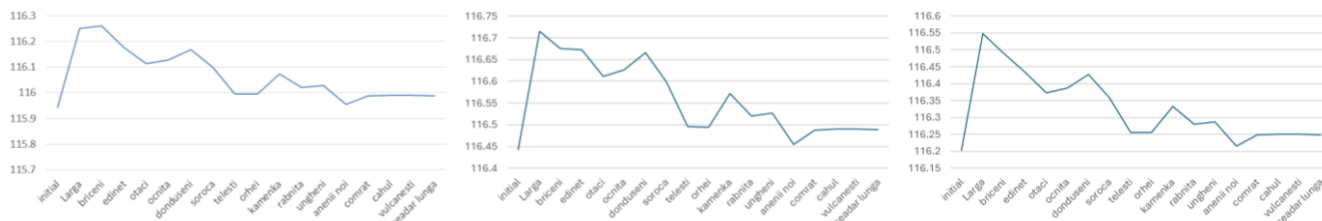


Fig. 5.2.6. Minimum voltage values for Zone 1

Fig. 5.2.7. Maximum voltage values for Zone 1

Fig. 5.2.8. Average voltage values for Zone 1

For the analysis of the results, the same procedure presented earlier was followed (Table 5.2.6).

Table 5.2.6. Analysis of the Influence of SVC

	Briceni	Larga	Edinet	Dundu	Ocnita	Otaci	Soroca	Rabni	Orhei	Kamen	Telesti	Unghe	Anenii	Komrat	Cahul	Vulcan	Ceadar
U _{min}	2	1	3	6	5	4	7	11	12	8	10	9	17	15	13	14	16
U _{max}	1	2	3	6	5	4	7	11	12	8	10	9	17	15	13	14	16
U _{med}	1	2	3	6	5	4	7	11	12	8	10	9	17	15	13	14	16
Sum	4	5	9	18	15	12	21	33	36	24	30	27	51	45	39	42	48
Note	10.0	9.81	9.04	7.32	7.89	8.47	6.74	4.45	3.87	6.17	5.02	5.60	1.00	2.15	3.30	2.72	1.57

The results presented in Table 5.2.5 highlight the following “ranking”: Briceni, Larga, Edineț, Otaci, Ocnita, Donduseni, Soroca, Kamenka, Ungheni, Telești, Ribnița, Orhei, Cahul, Vulcănești, Komrat, Ceadar-Lunga, Anenii Noi.

A similar approach was applied for the other zones as well.

For the final conclusions, the obtained scores were combined and an overall average was then calculated (Table 5.2.11).

Table 5.2.11. Calculation of the Overall Average

	Briceni	Larga	Edinet	Dundu	Ocnita	Otaci	Soroca	Rabni	Orhei	Kamen	Telesti	Unghe	Anenii	Komrat	Cahul	Vulcan	Ceadar
Zone1	10.0	9.81	9.04	7.32	7.89	8.47	6.74	4.45	3.87	6.17	5.02	5.60	1.00	2.15	3.30	2.72	1.57
Zone2	8.20	7.60	7.00	9.60	9.60	10.0	8.80	4.60	4.00	7.20	5.60	5.40	1.00	1.60	3.40	2.80	2.20
Zone3	5.89	5.30	4.72	6.87	5.70	7.85	8.43	9.41	8.83	10.0	9.02	5.30	1.00	1.98	3.54	2.96	2.17
Zone4	6.94	6.36	5.02	5.40	4.03	7.89	7.70	5.60	5.02	9.43	5.60	10.0	3.68	1.0	3.30	2.70	2.15
Zone5	3.81	3.25	3.69	2.13	1.56	6.81	7.00	6.06	5.50	7.75	4.38	4.94	1.00	8.31	10.0	9.44	8.88
Avrg	6.96	6.46	5.89	6.26	5.75	8.20	7.75	6.02	5.44	8.11	5.92	6.24	1.53	3.01	4.70	4.12	3.39

The results are then analyzed separately for the five zones, using the data from Tables 5.2.5, 5.2.11, and the table corresponding to each zone. Based on the assigned scores, a ranking is established for each case. Finally, based on the position obtained in each table, the overall ranking is determined.

Table 5.2.12. Final Ranking for Zone 1

	Briceni		Larga		Edineț	
	Note	Ranking	Note	Ranking	Note	Ranking
Table 5.2.5	4.92	1	4.33	2	3.55	3
Table 5.2.11	6.96	1	6.46	2	5.89	3
Table 5.2.6	10.0	1	9.81	2	9.04	3
Average	7.29	1	6.86	2	6.16	3

Table 5.2.13. Final Ranking for Zone 2

	Dondușeni		Ocnița		Otaci		Soroca	
	Note	Ranking	Note	Ranking	Note	Ranking	Note	Ranking
Table 5.2.5	2.96	3	2.37	4	7.65	1	7.26	2
Table 5.2.11	6.26	3	5.75	4	8.20	1	7.75	2
Table 5.2.7	9.60	2	9.60	2	10.0	1	8.80	4
Average	6.27	3	5.90	4	8.61	1	7.93	2

Table 5.2.14. Final Ranking for Zone 3

	Rîbnița		Orhei		Kamenka		Telești	
	Note	Ranking	Note	Ranking	Note	Ranking	Note	Ranking
Table 5.2.5	5.71	2	4.33	3	9.61	1	4.13	4
Table 5.2.11	6.02	2	5.44	4	8.11	1	5.92	3
Table 5.2.8	9.41	2	8.83	4	10.0	1	9.02	3
Average	7.04	2	6.20	4	9.24	1	6.35	3

Table 5.2.15. Final Ranking for Zone 4

	Ungheni		Arienii Noi	
	Note	Ranking	Note	Ranking
Table 5.2.5	4.83	1	1.00	2
Table 5.2.11	6.24	1	1.53	2
Table 5.2.6	10.0	1	3.68	2
Average	7.02	1	2.07	2

Table 5.2.16. Final Ranking for Zone 5

	Komrat		Cahul		Vulcănești		Ceadarlunga	
	Note	Ranking	Note	Ranking	Note	Ranking	Note	Ranking
Table 5.2.5	7.46	4	10.0	1	9.42	2	8.63	3
Table 5.2.11	3.01	4	4.70	1	4.12	2	3.69	3
Table 5.2.8	8.31	4	10.0	1	9.44	2	8.88	3
Average	6.26	4	8.23	1	7.66	2	7.06	3

Based on the obtained results, the following final conclusions can be drawn: considering the RM power system the installation of SVC devices is most advantageous at the buses Cahul, Kamenka, Vulcănești, and Ceadar-Lunga; for Zone 1 – Briceni; for Zone 2 – Otaci; for Zone 3 – Kamenka; for Zone 4 – Ungheni; for Zone 5 – Cahul.

For the dynamic operating condition analyses (chapter 6), all buses with an overall rating higher than 7 are considered: Zone 1 – Briceni; Zone 2 – Otaci, Soroca; Zone 3 – Kamenka, Rîbnița; Zone 4 – Ungheni; Zone 5 – Cahul, Vulcănești, Ceadar-Lunga.

Chapter 6 focuses on the optimal sizing of SVC-type FACTS devices for the power systems presented in the previous chapter: TEST25 and the real power system of the Republic of Moldova. A series of large-disturbance stability studies were carried out in order to determine the optimal sizing of SVC-type FACTS devices from the perspective of the dynamic behavior of the power system. Due to space limitations, only part of the studied cases are presented, while the final conclusions take into account all results.

Following the analyses performed in accordance with the methods presented in Chapter 4, the optimal SVC rating was determined from the perspective of the dynamic behavior of the power system. Based on this, an optimal operating range was identified, considering that the variation of the objective function (OF) around its best value is relatively "flat."

The dynamic regimes analyses were performed comparatively, both in the absence and in the presence of SVC devices. For the TEST25 system, based on the conclusions from Chapter 5, disturbance scenarios were considered in the areas of buses NN110, MM110, II110, HH110 (110 kV), and GG220, FF220, BB220, AA220 (220 kV), where SVC devices were also installed.

For presentation purposes, stability analyses were selected for three-phase short circuits on lines located in the areas of the respective buses (and not only there), followed by line disconnection and subsequent reclosing by means of a fast automatic reclosing device (RAR). After reclosing, both the case of a non-persistent fault (successful RAR) and that of a persistent fault (unsuccessful RAR) were considered. In the second situation, the

protection system permanently disconnects the affected line. In the case of successful RAR, the post-disturbance steady-state regime is identical to the pre-disturbance regime. In the case of unsuccessful RAR, the post-disturbance steady-state regime differs from the pre-disturbance regime.

The disturbance scenario for a short circuit on a 110 kV (220 kV, 400 kV) line, with successful fast automatic reclosing (RAR), is as follows: three-phase short circuit at $t = 1$ s; the protection system disconnects the line at $t = 1.2$ s (1.1 s); successful reclosing of the line at $t = 2.2$ s (2.1 s).

The disturbance scenario for a short circuit on a 110 kV (220 kV, 400 kV) line, with unsuccessful RAR, is as follows: three-phase short circuit on the 110 kV line at $t = 1$ s; the protection system disconnects the line at $t = 1.2$ s (1.1 s); unsuccessful reclosing of the line at $t = 2.2$ s (2.1 s); the protection system permanently disconnects the line at $t = 2.4$ s (2.2 s).

For illustration, the case of a three-phase short circuit on the 110 kV line NN110–HH110 is presented, considering both successful and unsuccessful reclosing. The analysis was performed using the NEPLAN software tool [Neplan], with a time step of 0.01 s, and the results are presented over a 15 s interval. The SVC rating is 5 MVAR.

For the case with successful RAR, Figures 6.1.1 and 6.1.2 present the voltage variation at all buses of the power system, with and without SVC.

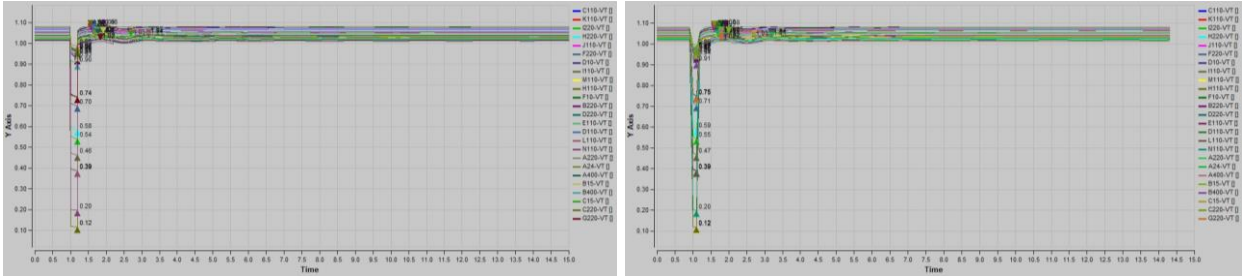


Table 6.1.1 presents a comparative analysis of the sum of squared voltage deviations (FOB_U), calculated for all buses. Considering that the case with successful reclosing is analyzed, the deviations are calculated with respect to the values in the pre-disturbance steady-state regime (the power system returns to its initial state). It can be observed that the effect of the SVC is positive – oscillations are damped more rapidly and the maximum values are reduced.

Table 6.1.1. Comparative Values of FOB_U

FOB_U	
Without SVC	With SVC
87.532	81.720

Figures 6.1.3 and 6.1.4 present the variation of the angular speed of the SG rotors at buses BB15 and CC15, with and without SVC.

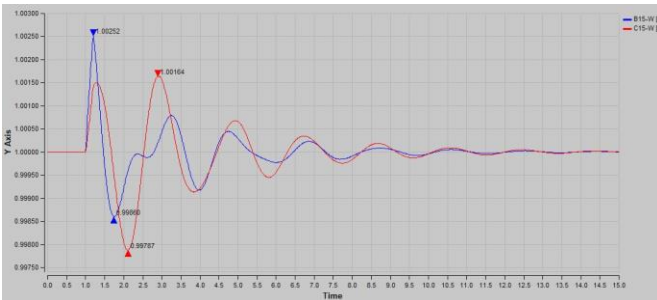


Fig. 6.1.3. Variation of angular speeds in the absence of the SVC

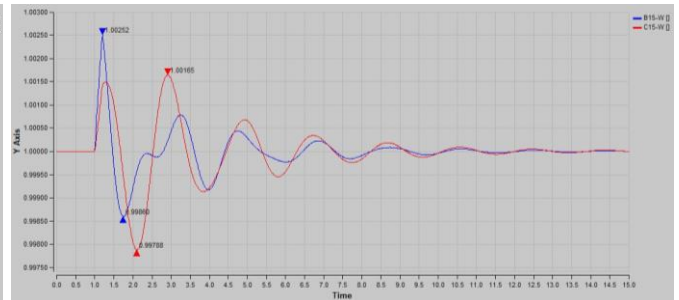


Fig. 6.1.4. Variation of angular speeds in the presence of the SVC

Table 6.1.2 presents a comparative analysis of the sum of squared angular speed deviations (FOB_ω), calculated for the SG at buses BB15 and CC15, with and without SVC. It can be observed that the effect of the SVC is positive – oscillations are damped more rapidly and the maximum values are reduced.

Table 6.1.2. Comparative Values of FOB_ω

FOB_ω	
Without SVC	With SVC
7.12×10^{-4}	6.48×10^{-4}

Figures 6.1.5 and 6.1.6 present the variation of the internal angle for the generators at buses B15 and C15, with and without SVC.

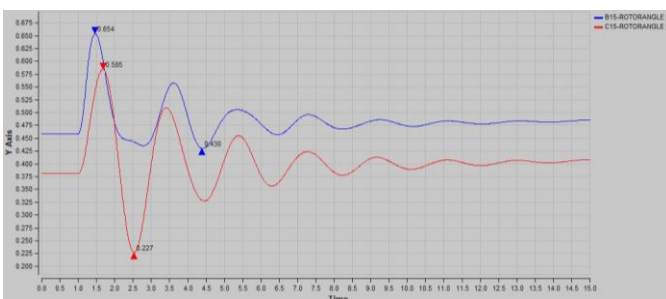


Fig. 6.1.5. Variation of the internal angle in the absence of the SVC

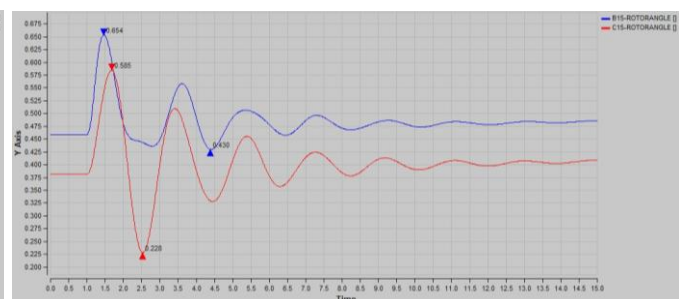


Fig. 6.1.6. Variation of the internal angle in the presence of the SVC

Subsequently, the analyses presented above were repeated for other SVC power ratings within the range of (1–20) MVar. A synthesis of the results regarding the sum of squared voltage deviations (FOB_U), calculated for all buses of the power system, is presented in Table 6.1.4.

Table 6.1.4. Comparative Values of FOB_U for Various SVC Power Ratings

Q_{SVC} [MVar]	FOB_U	
	Without SVC	With SVC
1	87.532	80.776
2	87.532	80.610
5	87.532	81.720
10	87.532	82.111
20	87.532	83.871

The results presented in Table 6.1.4 are graphically illustrated in Fig. 6.1.11 and 6.1.12.

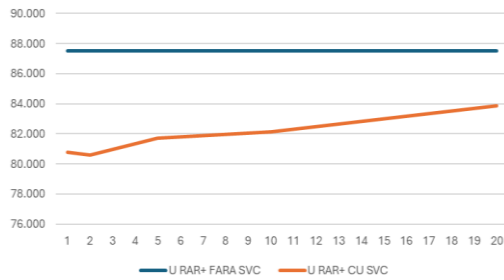


Fig. 6.1.11. Variation of FOB_U as a function of SVC power, compared with the case without SVC

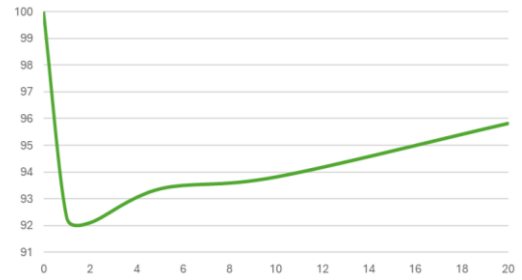


Fig. 6.1.12. Variation of FOB_U as a function of SVC power

The analysis of the results presented in Table 6.1.4 and Fig. 6.1.11 and 6.1.12 highlights the conclusion that the optimal SVC power rating lies within the range of (0.8–2.1) MVar.

For the case with unsuccessful RAR, Figures 6.1.29 and 6.1.30 present the voltage variation at all buses of the power system, with and without SVC.

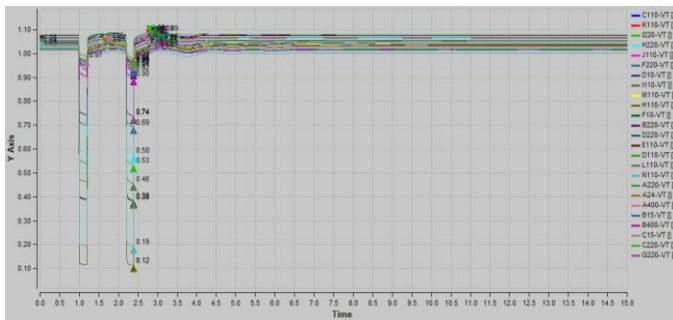


Fig. 6.1.29. Voltage variation in the absence of the SVC

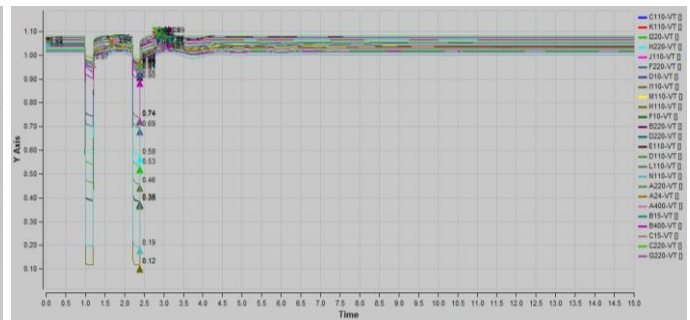


Fig. 6.1.30. Voltage variation in the presence of the SVC

Table 6.1.13 presents a comparative analysis of the sum of squared voltage deviations (FOB_U), calculated for all buses. Considering that the case with unsuccessful reclosing is analyzed, the deviations are calculated with respect to the values in the post-disturbance steady-state regime. It can be observed that the effect of the SVC is positive – oscillations are damped more rapidly and the maximum values are reduced.

Table 6.1.13. Comparative Values of FOB_U

FOB_U	
Without SVC	With SVC
175.414	170.828

Figures 6.1.31 and 6.1.32 present the variation of the angular speed of the generator rotors at buses BB15 and CC15, with and without SVC.

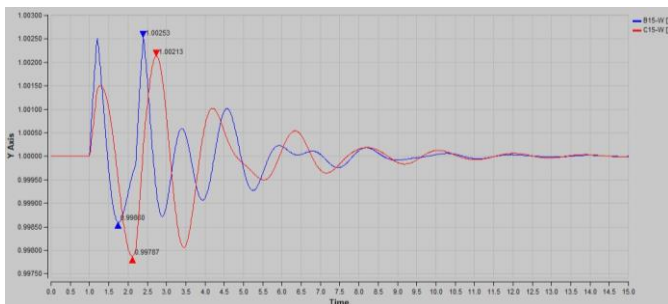


Fig. 6.1.31. Variation of angular speeds in the absence of the SVC

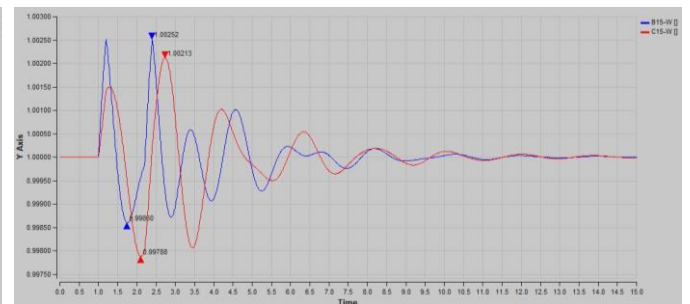


Fig. 6.1.32. Variation of angular speeds in the presence of the SVC

Table 6.1.14 presents a comparative analysis of the sum of squared angular speed deviations (FOB_{ω}), calculated for the SG at buses BB15 and CC15, with and without SVC. It can be observed that the effect of the SVC is positive – oscillations are damped more rapidly and the maximum values are reduced.

Table 6.1.2. Comparative Values of FOB_{ω}

FOB_{ω}	
Without SVC	With SVC
10.72×10^{-4}	10.07×10^{-4}

Figures 6.1.33 and 6.1.34 present the variation of the internal angle for the generators at buses B15 and C15, with and without SVC.

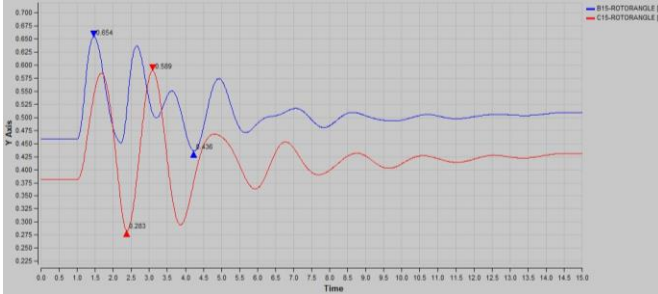


Fig. 6.1.33. Variation of the internal angle in the absence of the SV

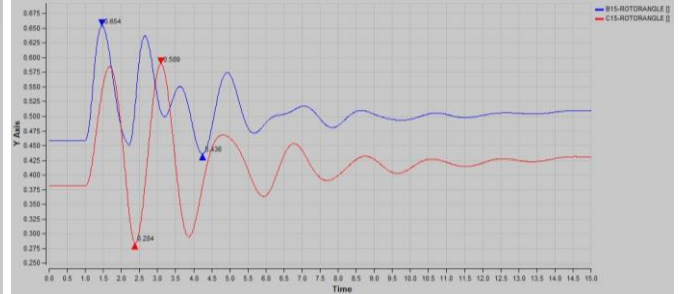


Fig. 6.1.34. Variation of generator terminal voltage in the absence of the SVC

Subsequently, the analyses presented above were repeated for other SVC power ratings within the range of (1–20) MVar. A synthesis of the results regarding the sum of squared voltage deviations (FOB_U), calculated for all buses of the power system, is presented in Table 6.1.16.

Table 6.1.16. Comparative Values of FOB_U for Various SVC Power Ratings

Q_{SVC} [MVar]	FOB_U	
	Without SVC	With SVC
1	175.414	169.935
2	175.414	169.629
5	175.414	170.828
10	175.414	171.339
20	175.414	172.563

The results presented in Table 6.1.4 are graphically illustrated in Fig. 6.1.11 and 6.1.12.

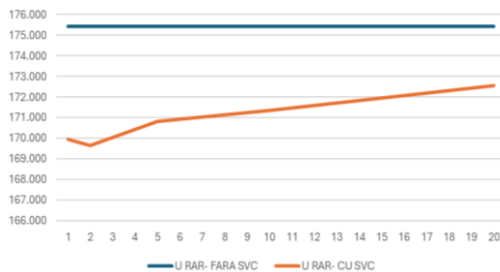


Fig. 6.1.39. Variation of FOB_U as a function of SVC power, compared with the case without SVC

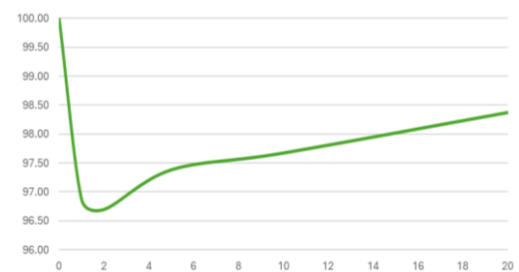


Fig. 6.1.40. Variation of FOB_U as a function of SVC power

The analysis of the results presented in Table 6.1.16 and Fig. 6.1.39 and 6.1.40 highlights the conclusion that the optimal SVC power rating lies within the range of (0.8–2.1) MVar.

The analysis of all results for bus NN110 leads to the following conclusions:

- the minimum value of the lower limit of the optimal range is 0.8 MVar, and the maximum is 1.2 MVar;
- the minimum value of the upper limit of the optimal range is 2.0 MVar, and the maximum is 2.4 MVar;
- the analyses for the other 110 kV buses led to practically similar conclusions;
- in conclusion, it can be stated that the optimal value range for the 110 kV buses is (1.0–2.0) MVar.

The analysis of all results for bus GG220 leads to the following conclusions:

- the minimum value of the lower limit of the optimal range is 4.6 MVar, and the maximum is 5.6 MVar;
- the minimum value of the upper limit of the optimal range is 7.1 MVar, and the maximum is 7.8 MVar;
- the analyses for the other 220 kV buses led to practically similar conclusions;
- in conclusion, it can be stated that the optimal value range for the 220 kV buses is (5.0–7.5) MVar.

For the power system of the Republic of Moldova (PSRM), the dynamic operating condition analyses were performed comparatively, both in the absence and in the presence of SVC devices, for disturbance scenarios similar to those presented for the TEST25 system. Based on the conclusions from Chapter 5, disturbance scenarios were considered in the areas of the 110 kV buses selected at the end of Subchapter 5.2: Zone 1 – Briceni; Zone 2 – Otaci, Soroca; Zone 3 – Kamenka, Rîbnița; Zone 4 – Ungheni; Zone 5 – Cahul, Vulcănești, Ceadar-Lunga.

As an example, the case of a three-phase short circuit on the 110 kV overhead line Vulcănești–Copceac is presented, considering both successful and unsuccessful RAR. The analysis was performed using the NEPLAN software tool [Neplan], with a time step of 0.01 s, and the results are presented over a 15 s interval. The SVC rating is 5 MVar, installed at the Vulcănești bus, Zone 5.

For the case with successful RAR, Fig. 6.9.27 and 6.9.28 present the voltage variation at the buses in the respective area, with and without SVC.

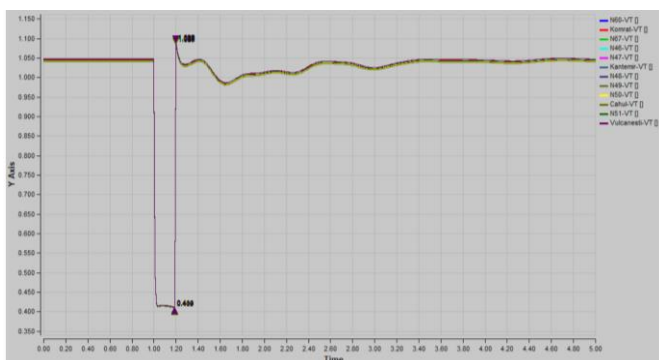


Fig. 6.2.97. Voltage variation in the absence of the SVC

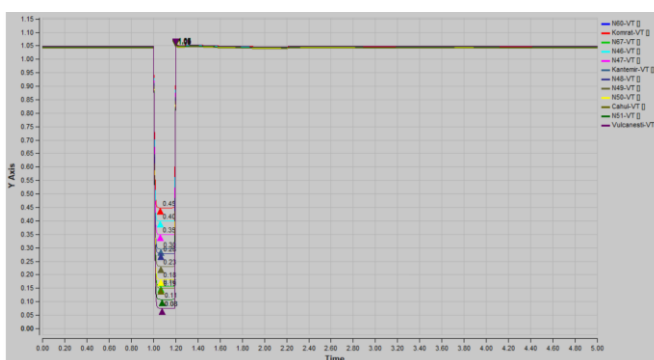


Fig. 6.2.98. Voltage variation in the presence of the SVC

Table 6.2.49 presents a comparative analysis of the sum of squared voltage deviations ($FOBU$), calculated for all buses. It can be observed that the effect of the SVC is positive.

Table 6.2.49. Comparative Values of $FOBU$

$FOBU$	
Without SVC	With SVC
201.43	201.01

Figures 6.2.99 and 6.2.100 present the variation of the angular speed of the rotors of the seven generators in the power system of Moldova, in the absence and, respectively, in the presence of the SVC.

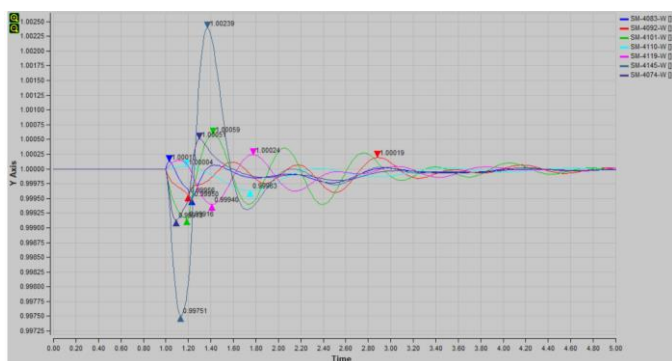


Fig. 6.2.99. Variation of angular speeds in the absence of the SVC

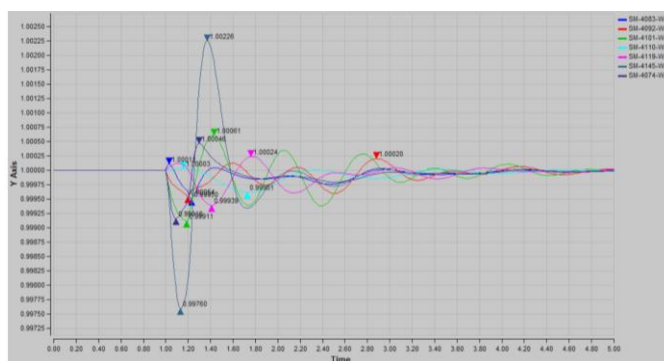


Fig. 6.2.100. Variation of angular speeds in the presence of the SVC

Table 6.2.50 presents a comparative analysis of the sum of squared angular speed deviations (FOB_{ω}), calculated for the 7 SG, with and without SVCC. It can be observed that the effect of the SVC is positive - oscillations are damped more rapidly and the maximum values are reduced.

Table 6.2.50. Comparative Values of FOB_{ω}

FOB_{ω}	
Without SVC	With SVC
2.625×10^{-3}	2.480×10^{-3}

Subsequently, the analyses presented above were repeated for other SVC power ratings within the range of 1–20 MVar. A synthesis of the results regarding the sum of squared voltage deviations ($FOBU$), calculated for all buses of the power system, is presented in Table 6.2.51.

Table 6.2.51. Comparative Values of $FOBU$ for Various SVC Power Ratings

Q_{SVC} [MVar]	$FOBU$	
	Without SVC	With SVC
1	201.43	198.81
2	201.43	198.41
5	201.43	199.42
10	201.43	199.82
20	201.43	201.03

The results presented in Table 6.2.51 are graphically illustrated in Fig. 6.2.101 and 6.2.102.

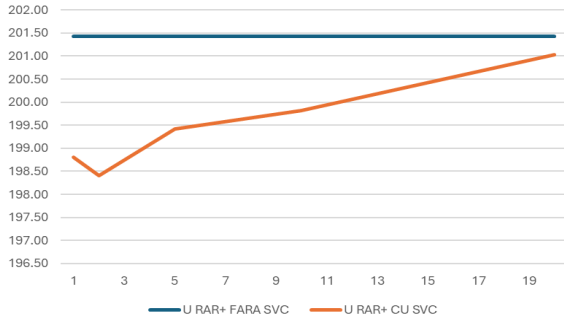


Fig. 6.2.101. Variation of FOB_U as a function of SVC power, compared with the case without SVC

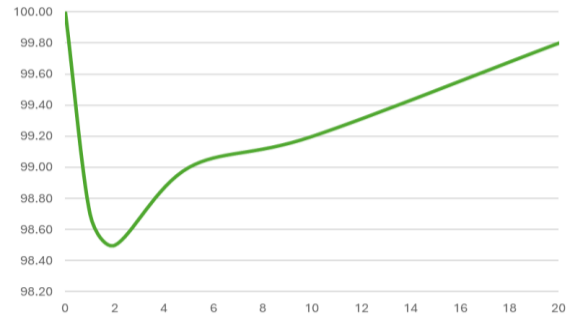


Fig. 6.2.102. Variation of $FOBU$ as a function of SVC power

The analysis of the results highlights the conclusion that the optimal SVC power rating lies within the range of 0.8–2.3 MVar.

For the case with unsuccessful RAR, Figures 6.2.103 and 6.2.104 present the voltage variation at the buses in the respective area, in the absence and, respectively, in the presence of the SVC.

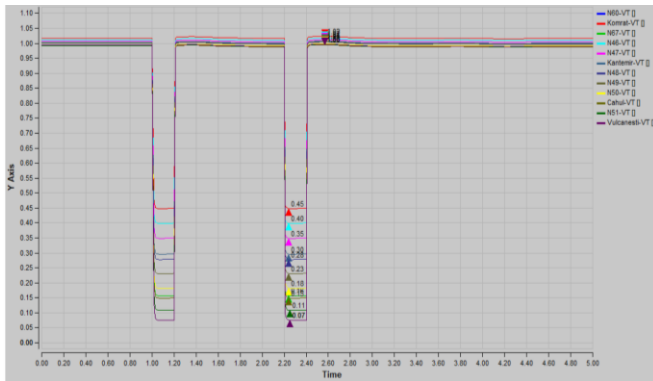


Fig. 6.2.103. Voltage variation in the absence of the SVC

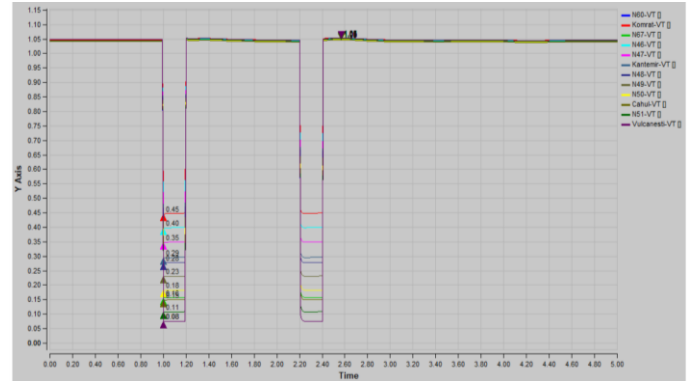


Fig. 6.2.104. Voltage variation in the presence of the SVC

Table 6.2.52 presents a comparative analysis of the sum of squared voltage deviations (FOB_U), calculated for all buses of the power system. It can be observed that the effect of the SVC is positive – oscillations are damped more rapidly and the maximum values are reduced.

Table 6.2.52. Comparative Values of FOB_U

FOB_U	
Without SVC	With SVC
434.82	423.11

Fig. 6.2.105 and 6.2.106 present the variation of the angular speed of the rotors of the seven SG in the RM power system, with and without SVCC.

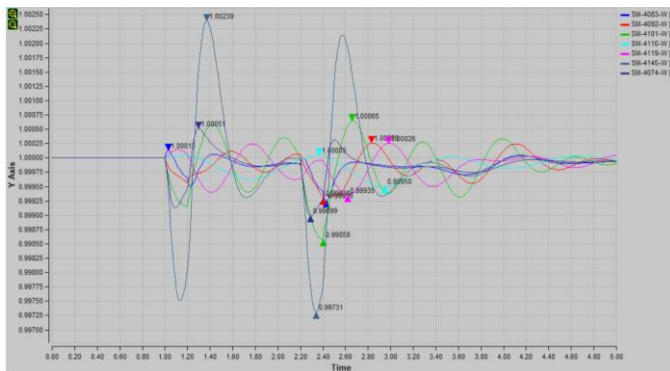


Fig. 6.2.105. Variation of angular speeds in the absence of the SVC

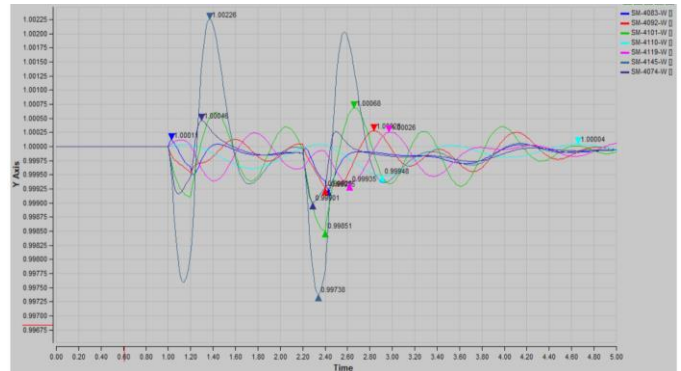


Fig. 6.2.106. Variation of angular speeds in the presence of the SVC

Table 6.2.53 presents a comparative analysis of the sum of squared angular speed deviations (FOB_{ω}), calculated for the seven generators, in the absence and, respectively, in the presence of the SVC. It can be observed that the effect of the SVC is positive.

Table 6.2.53. Comparative Values of FOB_{ω}

FOB_{ω}	
Without SVC	With SVC
5.569×10^{-3}	5.246×10^{-3}

Subsequently, the analyses presented above were repeated for other SVC power ratings within the range of 1–20 MVar. A synthesis of the results regarding FOB_U , calculated for all buses of the power system, is presented in Table 6.2.54.

Table 6.2.54. Comparative Values of FOB_U for Various SVC Power Ratings

Q_{SVC} [MVar]	FOB_U	
	Without SVC	With SVC
1	434.82	386.47
2	434.82	385.69
5	434.82	387.64
10	434.82	388.43
20	434.82	390.78

The results presented in Table 6.2.54 are graphically illustrated in Fig. 6.2.107 and 6.2.108.

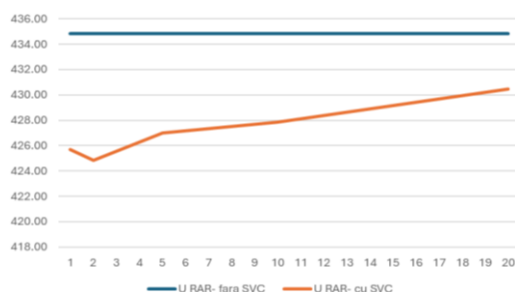


Fig. 6.2.107. Variation of FOB_U as a function of SVC power, compared with the case without SVC



Fig. 6.2.108. Variation of FOB_U as a function of SVC power

The analysis of the results highlights the conclusion that the optimal SVC power rating lies within the range of 0.7–2.3 MVar.

The analysis of all results leads to the following conclusions:

- the minimum value of the lower limit of the optimal range is 0.7 MVar, and the maximum is 1.2 MVar;
- the minimum value of the upper limit of the optimal range is 1.9 MVar, and the maximum is 2.6 MVar;
- the analyses for other disturbance scenarios and for other 110 kV buses led to similar conclusions;
- in conclusion, it can be stated that the optimal value range for the 110 kV buses of the Moldova power system is (1.0–2.0) MVar.

Chapter 7 contains the general conclusions of the thesis and a systematic presentation of the author's original contributions, as well as highlighting the directions and perspectives offered by this work for the continuation of research and the application of the obtained results and experience. The developed calculation methodologies are of general applicability, providing an efficient tool for electricity transmission and distribution system operators.

The annexes provide a some detailed elements and results related to the applied part (Chapters 5 and 6), including databases for the case studies and details on the obtained results.

The results presented in the doctoral thesis have been and will continue to be utilized within contracts concluded between Politehnica University of Timișoara, the Research Center for the Power System Analysis and Optimization, and PPC electrical networks Banat, Muntenia Sud and Dobrogea, DEER Electrica Muntenia Nord, Transilvania Nord and Transilvania Sud, DEO Oltenia, Delgaz Grid Moldova, Transelectrica, Electroechipament Industrial Reșița, Romproiect Electro Cluj-Napoca, MD Electric Timișoara, and Eurotulip Tg. Jiu [UPT2019–UPT2025b]. Moreover, the establishment of the doctoral thesis topic was also motivated by the interest expressed by transmission and distribution operators regarding FACTS-type equipment.

Additionally, a portion of the results obtained within the doctoral thesis have been published or are in the process of being published. Notably, of the five papers published, two are ISI WEB of Science indexed [Barbulescu2021], [Luputi2024], and three are indexed in other international databases [Simo2018], [Bittenbinder2021], [Salinschi2021].

The theoretical and practical analyses carried out within the doctoral thesis, as well as the results presented, open a range of perspectives and directions for the continuation and further deepening of research in the field of the doctoral thesis:

- the application of the developed methods to the Romanian power system or to specific areas of the National Power System;
- the application of the developed methods to the 110 kV networks of distribution companies in Romania;
- conducting studies similar to those in the thesis for other types of FACTS devices;
- implementing metaheuristic techniques for the optimal placement and sizing of FACTS devices.

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