University POLITEHNICA of Bucharest
Doctoral School of ENERGY ENGINEERING

PHD THESIS SUMMARY

Voltage Stability and Control in Active Distribution Power Systems

Controlul și stabilitatea de tensiune în sistemele electroenergetice de distribuție active

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THESIS CONTENTS

KEYWORDS

distributed generation, voltage control, guideline on distribution power system operation, power flow, graph theory, backward-forward sweep method, current mismatch Newton-Raphson for distribution power system, voltage stability index, sensitivity analysis, singular value decomposition, multi-objective optimization, weighted sum method, optimal allocation of reactive power, Grey Wolf meta-heuristic optimization technology, daily load curve, power losses minimisation, improvement of voltage stability reserve, reducing total voltage deviation

EXTENDED ABSTRACT

The prosperity of a nation is dependent on the safe and secure operation of electric power systems. Global economic and social development involves their expansion in the sense of including an increasing number of load and means that ensure continuity in electric power transmission. From the point of view of voltage stability, it is essential to maintain the voltage profile within acceptable limits, both under normal conditions and after a disturbance in the operation of the system. Otherwise, if the voltage drops below an acceptable value the operation point is unstable and the instability process can evolve rapidly, through a series of avalanche events, until the system collapses. Voltage instability generally occurs in overloaded systems, where the reactive power reserve is insufficient or there is an imbalance in the power flow due to a sudden change of the load operating point. In this context, the analysis of voltage stability is essential in the evolution of power systems.

Economic progress in recent years has a positive impact on the expansion of global power systems, but also includes some negative aspects due to the influence of emissions on the environment that inevitably occur using fossil fuels in electricity production. According to the International Energy Agency, electric power demand and associated emissions will increase by 70% from 2013 to 2040, [1].

To facilitate the minimisation of emissions, programs have been proposed at the international level for the implementation of technologies with a low impact on the environment or for commercial obligations, through which companies owning installations that generate emissions are required to purchase controlled gas emission permits. Thus, the greenhouse effect is reduced, as any quantity released in the atmosphere over the approved one is being subject to the penalty. A system organized by the European Union involves trading of emission allowances by the energy industry and power companies, to reduce emissions by 21% by 2020 and by 43% by 2030, [2]. The third phase of this system is being coordinated with the policy imposed by the Europe 20-20-20 strategy, which aims to reduce greenhouse gas emissions by 20%, increase by 20% the electricity produced from renewable resources and 20% improvement in energy efficiency compared to 1990 levels in all EU countries, [3]. National policies support the process of integrating renewable energy sources, as well as high energy efficiency technologies, such as cogeneration plants, to facilitate a neutral impact in terms of emissions from hydrocarbons commonly used in power plants. As a result, distributed generation sources have become increasingly widespread in medium and low voltage distribution networks, [4].

The doctoral research aims at deepening the concept of voltage stability and its control, at the level of power distribution systems, which become active from the perspective of massive integration of distributed generation. In the context of increasing the complexity of the structure of power networks, but also of fundamental changes in their operation, the aim of the thesis is to propose and implement in an analysis programme, a voltage control method of an active power distribution system, to benefit from the advantages of distributed generation. It aims to ensure voltage stability, dependent on the power flow of the users integrated in the system, taking into account the effects of integrated generators, such as bidirectional power flow, possible overloads of existing elements, uncontrolled change in nodal voltage, and increasing active power losses. Thus, the main objective can be achieved by fulfilling the following aspects:

- Recognition of the particularities of active electrical distribution networks, but also of the characteristics that influence the voltage stability process,
- Identifying the legislative conditions, regulated for the planning and operation of active power distribution networks,
- Identifying the means of controlling the available voltage and the technological and regulated limitations for their use,
- Establishing the mathematical models of the elements of the active distribution power systems (RED-a) and of the control means from the point of view of the analysis of the power flow,
- Evaluating and choosing an algorithm to solve the power flow problem,
- Identification of techniques for investigating voltage stability,
- Choosing means to assess voltage stability,
- Identifying the mathematical model of the optimization problem of the operation of an active power system,
- Evaluating and choosing an algorithm to solve the optimization problem,
- Implementation in an analysis programme of the chosen means and methods,
- Use of test power systems to validate the chosen methods,
- Carrying out simulations to optimize the operation of an active distribution power system,
- Extension of the planning study on an active distribution power system located on the Romanian territory.

The study presented in the thesis is disseminated in six chapters and two annexes useful for arguing the results of doctoral research from the perspective of the study of stability and voltage control in active distribution power systems. In addition, the thesis integrates aspects specific to the chapters "Introduction" and "Conclusions", but also a list of bibliographic resources.

The first chapter, "*Means of voltage control in active power distribution systems*", aims to identify their capabilities in the sense of integration into a coordinated voltage control system.

In the context of ensuring the required power demand along with reducing the impact on the environment in the process of its production, the operation of power systems must become flexible enough to integrate current changes. The analysis of voltage stability at the level of active distribution power systems is an essential element from the perspective of increased integration of distributed generation, based on renewable resources, which significantly contributes to changing operating conditions. The identification of the voltage control method, which incorporates the capabilities of these sources, together with the classical means available at the level of distribution power systems is indispensable for the adherence of power networks to the directives imposed by the transformation of traditional grids into smart grid networks.

Thus, following the analysis of the available means, presented in this chapter, it results that in the coordinated voltage control system will be integrated, *distributed generators*, the existing *on-load tap changer* at the power station through which energy is supplied to the distribution network, but also *capacitor banks* integrated in the buses of the grid.

For voltage control, the use of distributed generation is an attractive alternative to maintain safe conditions for the electric power transfer, without additional costs invested in technologies used exclusively for voltage regulation.

By choosing the right means, safe operating conditions can be ensured in the event of a change in the power flow imposed by the energy users integrated in the system.

This chapter also includes the legislative conditions that must be met by both the distribution power system operators and by the means of control integrated in it to ensure the safety and quality of the supplied energy.

The second chapter includes the “*Power flow in active distribution power systems*”, with the aim of identifying an algorithm that corresponds in terms of robustness, performance, and speed to the particularities of power distribution networks. Choosing the right algorithm for evaluating the operating state is important given that the voltage stability analysis depends on the power flow results. Among the available methods analysed in the study, the classic "Backward-Forward Sweep" method and a variation of the bus potential method "Newton-Raphson with current mismatches", were noted.

For the " Backward-Forward Sweep " method, it is proposed an adaptation of the algorithm implemented in the analysis programme, which follows two stages: systematization of input data, by identifying an oriented tree associated with the distribution network, based on graph theory, and establishing the power flow equations, by using the matrix calculus.

The "Newton-Raphson current mismatches" method used in the study was adapted to the specifics of the distribution systems. For this, by using rectangular coordinates, the Jacobian matrix can be divided into diagonal blocks, which can be updated at each iteration and non-diagonal, which remain constant during the iterative process.

Adaptation involves permuting the elements of the diagonal blocks so that they become diagonally dominant, due to the real part of the complex expression of nodal admissions, which can be assessed by the ratio $r / x \geq 1$, specific to distribution networks.

In addition, in this chapter, mathematical models of loads, and distributed generators are analysed, to include, as accurately as possible, their characteristics in the study of the power flow.

Chapter three deals with "*Methods for assessing voltage stability in active power distribution systems*" which shows the state of the systems considered, but also their elements or vulnerable areas.

To plan the operation of an active distribution power system, in compliance with the regulated technical restrictions, it is necessary to identify the proximity between the current operating point and the critical point associated with the onset of the instability phenomenon. For this it is necessary to classify the available evaluation methods. The vulnerability of the power system, from the point of view of voltage stability, depends on the formulation of its evaluation methods. It is therefore noted: the profile of the nodal voltages, which describes the dependence of the loads on the voltage level of the bus through which they are supplied; active power – voltage characteristic, according to which the required power varies in the same direction as the voltage, indicating the stable operating conditions; voltage stability indexes, resulting from the analysis of voltage sensitivity in relation to nodal power and the condition of obtaining a real and positive solution in the power flow equation solution space, on the basis of which sensitive elements and vulnerable areas of the network can be determined, to be strengthened by connecting voltage control means; analysis of the decomposition of the singular values of the Jacobian matrix attached to the electrical network, from which results the degree of stability, so that the voltage stability reserve of the considered system can be specified. For the method based on the decomposition of singular values, the study proposes an adaptation of the classical method, for the case of electrical distribution networks, for which the degree of stability is influenced by both the variation of reactive power circulation and the variation of active power. In addition, the determination of the reduced Jacobian matrix attached to the grid, from which singular values results, includes load coefficients whose values reflect the variation of the bus powers, depending on the load or the distributed generation source connected in that bus.

Based on the results of the voltage stability analysis, both the optimal operating settings of the equipment responsible for voltage control in the network and the need to integrate new devices to improve locally or globally the static stability of the system considered can be identified later.

Chapter four aims at "*Optimal control of reactive power in active power distribution systems using multi-objective meta-heuristic techniques*", in the sense of establishing the voltage control strategy through the management of available control means.

In power systems, maintaining the conditions of static stability and, implicitly, a desired profile of bus voltages generally depends on the reactive power flow, but at the level of distribution networks the active power flow has a significant contribution on voltage stability. But the active power is dependent on the conditions imposed by the users integrated in the network, so that the voltage control is performed, mainly, through devices capable of controlling the reactive power, which can improve, locally, the power factor. In addition, this measure has the effect of increasing the power transited through the network elements, but also reducing the voltage drops and active power losses, including those of the transformer connected to the power supply station of the distribution network.

Thus, it is necessary to allocate the optimal reactive power, as a control strategy to maintain the economic and technical conditions of operation of an active power distribution system. This optimal distribution results from the coordinated adjustment of the reactive power of the distributed generators, of the operating stages of the capacitor banks and of the number of the operating tap of the on-load tap changer. These elements constitute the control variables of an optimization problem that aims to obtain minimum losses of active power through the network elements (ΔP), while maintaining a maximum stability reserve, based on the voltage stability index (VSI), resulting from the decomposition of singular values, and a level of the bus voltage profile around a reference value (TVD). In this sense, given the different objectives to be met, it is necessary to formulate a multi-objective optimization problem.

Subsequently, ways of solving the mathematical model of the optimization problem are investigated, but also the establishment of the criteria for choosing the most efficient algorithm for solving it. The choice of the algorithm depends on the accuracy of the results obtained, but also on the running time until the solution is identified. In the case of the complex mathematical model of the problem, I opted to use a meta-heuristic method inspired by aspects of real life, such as the hierarchical organization of a pack of wolves, according to which members communicate with each other to adjust their position according to common experiences of the group, when moving through the search space.

This algorithm has been adapted for the case of solving the optimal distribution of reactive power at the level of a distribution power systems and included in an analysis programme.

Chapter five, "*Case studies and results*" is structured in several subchapters associated with studies to validate the means implemented in the analysis programme, but also to plan the optimal operation of an active power distribution system, located in Romania.

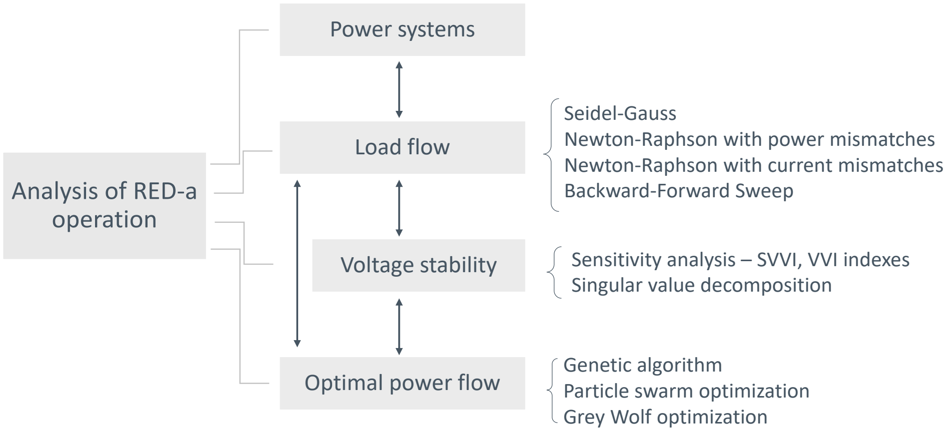

Fig. 1. The analysis programme structure

Thus, the theoretical aspects of the first four chapters are included in an analysis programme, called "Analysis of RED-a operation", used to identify the optimal operation of distribution power systems. The programme is implemented in the MATLAB© environment, version R2021b and is structured in four modules, shown in figure 1.

The results obtained from the analysis programme are useful for choosing the algorithm for solving the power flow, determining the influence of voltage control means on the operating conditions of the electrical distribution networks, choosing the method for evaluating the stability reserve and the proximity of the system operating point, the limit of instability, but also for choosing the algorithm to solve the problem of optimal allocation of reactive power.

Table 1. Multicriteria optimization analysis

	Mono-objective			**Multi-objective**		
	ΔP	VSI	TVD	ΔP and TVD	ΔP, VSI and TVD	
					Initial	Restriction
ΔP [pu]	**0,5002**	0,5019	0,6365	0,5675	0,5428	**0,5485**
VSI [-]	0,9553	**0,9561**	0,9379	0,9499	0,9524	**0,9519**
TVD [pu]	0,3057	0,2967	**0,0107**	0,0226	0,0719	**0,0596**
No. of switches	2	1	**7**	5	5	**1**
U_{med} [pu]	**1,0794**	**1,0782**	**1,0025**	1,0159	1,0360	**1,0321**

From the case studies, represented by simulations of some electrical networks established in the scientific literature, it was possible to validate the proposed adaptations for the power flow methods used, the voltage stability assessment methods and the algorithms for solving the optimization problem. Thus, it is possible to plan the optimal operation of a distribution system located in Romania, for a period of one day, for which the loads operate in accordance with a standardized load profile. The system integrates four distributed generation sources and two capacitor banks.

A first assessment from the point of view of the voltage stability of the analysed system can be made based on the voltage index, resulting from the analysis of the decomposition of singular values, for the base power flow case, whose value is 0.7672, but also from the maximum possible overload, this being about three times higher than the nominal load.

From the analysis of the results of optimizing the operation of the real distribution system, presented in table 1, it is observed that the voltage level necessary to meet the objectives ΔP and VSI is located near the upper limit, which is 1.1 pu, its average value being about 7% higher than the value of reference, considered 1 pu. Following the multi-objective optimization, it is 3.21% higher than the reference value, given that the VSI index improves at 0.9519, indicating a much stable system compared to the base case.

By identifying the optimal settings of the reactive power settings of the existing distributed generation sources in the network, but also of the steps of some capacitor banks, it is possible to establish the minimum number of taps that needs to be switched to satisfy the required conditions. Thus, the number of switches, associated with the achievement of the single objective, TVD was reduced from seven to a single switch during the analysed day, to meet all three objectives, ΔP, VSI and TVD.

SCIENTIFIC CONTRIBUTIONS

Throughout the doctoral research, personal contributions are included in connection with ensuring the voltage stability of active power systems, in the context of distributed generation.

1. Research of the scientific literature to identify trends in:
   - The evolution of distribution power systems to "smart grids",
   - The influence of distributed generation on the operation of power systems,
   - Means and methods of voltage control, in the conditions of optimal operation from a technical and economic point of view of the distribution power system,
   - The regulations imposed by European and national network codes.
2. Analysis of four load flow algorithms, to identify the most efficient and suitable one, for the particularities of active distribution power system. In addition, a new approach of the Backward-Forward sweep method is proposed, using graph theory and matrix calculation, based on the dependence of bus voltages and current flow. In addition, an original adaptation of the Jacobian matrix from the Newton-Raphson method with current mismatches is performed, by reversing the elements of the diagonal terms, to avoid the singularity of the matrix due to the high r / x ratio.
3. Synthesize the strategies for assessing voltage stability to identify the vulnerable areas of the distribution power system to decide the voltage control solution that can increase the voltage stability reserve. In addition, in the reduced Jacobian matrix, of the singular value decomposition method, there are integrated load variation coefficients that take in consideration the diversified load characteristics specific to distribution level
4. Examine the performances of three meta-heuristic optimization algorithms, to identify the optimal distribution of reactive power flow, and adapting the Grey Wolf meta-heuristic optimization technology for the multi-objective optimization problem.
5. Implement in an analysis programme, developed in the MATLAB environment, of modules that aim to:
   - Analyse the operating point through the four algorithms presented,

- Evaluate voltage stability, based on VVI, SVVI indexes, and Singular Value Decomposition method, considering only the reactive power flow case, only the active power flow case and both active and reactive power flow case,
- Solve the multi-objective optimization problem with three different meta-heuristic algorithms.
- Introduce the mathematical model of the optimal allocation of reactive power problem.

6. Approach an original strategy for planning the operation of an active distribution power system with characteristics specific to Romanian power systems, starting from the analysis of the voltage profile, stability assessment and multi-objective optimization considering a minimum number of switching of the tap changer.
7. Dissemination of the results of studies on the chosen topics, through publications in international conferences: CIEM 2019, CIEM 2021, ISFEE 2020, EPE 2020, UPEC 2019, but also in international journals The Scientific Bulletin of the Polytechnic University of Bucharest and Energies.

BIBLIOGRAPHY

[1] J. Campillo, „From passive to active electric distribution networks," Mälardalen University Press Dissertations, Västerås, Sweden, 2016.

[2] European Comission, „ Report from the Commission to the European Parliament and the Council. Report on the functioning of the European carbon market," Bruxelles, January 16th, 2020.

[3] R. Marcin, S. Dalia and B. Yuriy, „EU Carbon Emissions Market Development and Its Impact on Penetration of Renewables in the Power Sector," Energies, vol. 12, no. 2961, 2019.

[4] ANRE, „Report on the functioning of the green certificates market," Energy Strategies and Promotion of Renewable Energy and Cogeneration Service, 2005.