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Improving the resilience of urban distribution networks based on intentional islanding strategies

Îmbunătățirea rezilienței rețelelor urbane de distribuție pe baza strategiilor de insularizare intenționată

Author: Eng. Irina-Ioana PICIOROAGĂ

Ph.D. Coordinator: Prof. em. PhD. Eng. Mircea EREMIA

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KEYWORDS

Chapter 1: Key Performance Indicators, Smart Grids, Smart City

Chapter 2: reliability, resilience, vulnerability of power systems

Chapter 3: distributed generation, intentional islanding, standards

Chapter 4: genetic algorithms, linear programming, optimization, particle swarm optimization, reconfiguration, second-order cone programming

Chapter 5: depth first search, optimization model, power imbalance, resilience indicators, security parameters

Chapter 6: economical dispatch, GAMS, island partitioning

SUMMARY

In addition to the accelerated population growth, modern cities face numerous challenges in terms of climate change, acts of terrorism and the increasing frequency of natural disasters. Under these circumstances, the smart cities of the future must be able to adapt quickly to these new threats by developing appropriate resilience strategies [1]. Motivated by the need to solve the most common urban problems, the concept of "Smart City" aims to improve living conditions through efficient management of local resources, whether hardware or software [2]. Within the smart city, the energy, transport, water, public safety and other essential services sectors are managed in such a way as to ensure its proper functioning, while taking into account the maintenance of a clean, economical and secure environment in which citizens can enjoy a high quality living. Overall, the energy infrastructure is probably the most important feature of any city, given the high dependence of other critical infrastructure on it. A prolonged unavailability of electricity eventually leads to the shutdown of all other functions of the city [3].

For the efficient implementation of the smart city concept, the urban administration must adapt its development strategies in line with the new challenges, in order to avoid building a smarter but more vulnerable city. Based on these premises, many current urban development plans propose the incorporation of advanced operating technologies in all basic infrastructures of cities, from transport and administrative services to electricity supply systems. However, account must be taken of increasing the vulnerability of cities to attacks targeting information and communication technology (ICT), as a result of the increasing digital dependence of municipal communities. Therefore, without a thorough understanding of the new risks to which these technologies are exposed, the physical and digital damage can be severe, leading to more and more prolonged disruptions [4].

According to [5], a smart electricity grid pursues three main categories of objectives. A first objective involves the modernization of power systems through automation, infrastructures capable of self-repair, monitoring and

remote control. The second objective focuses on informing and educating users about the use of electricity, by proposing variable tariff systems and alternative power options, in order to make efficient decisions on the quantity and timing of consumption. The third objective is to ensure safety and security in operation, along with the integration of distributed generation, especially the one based on renewable sources. The incorporation of all these solutions lays the foundations for a more reliable, sustainable and resilient energy infrastructure. Under these conditions, a smart electricity grid is the basic structure without which a smart city cannot be built. Therefore, smart cities depend on a smart electrical grid to ensure the efficient conservation, management and supply of electricity to its many functions [6].

In the context of smart urban planning, the energy sector is also a key component in developing resilient and sustainable strategies, given its key role in maintaining most of a city's critical infrastructure, such as medical and emergency services, communication and transport. Characterized by a complex configuration that includes a diversity of critical infrastructures spread over a vast geographical area (transformers, generating units, power lines, etc.), power systems are exposed to many unforeseen dangers. Disastrous events, regardless of their origin (natural disasters, such as floods, hurricanes, storms, or man-made events, such as cyber attacks and acts of vandalism), can have a significant negative impact on the operation of power supply systems. From the 1980s to the present day, both the frequency and intensity of power outages caused by extreme weather conditions have been steadily increasing [7]. Under such drastic changes in natural phenomena, the risk associated with power line failures intensifies, and power transformers (and other components) may be overloaded. Based on these premises, the preparation of appropriate and predictive strategies to increase resilience, as well as corrective plans to mitigate the consequences of such extreme phenomena, is a current concern for global electricity supply companies.

However, the process of strengthening the electricity networks in facing emergency scenarios remains a challenge. While the term "resilience" is increasingly used in research activities, studies are still needed to quantify the concept of resilience in order to be usable in practice. The definition of resilience provided by EPRI (Electric Power Research Institute) specifies three main factors: prevention, recovery and survival [8]. The concept of resilience differs from the notions of reliability and vulnerability, through the objectives addressed that focus on extremely rare situations. These scenarios with a low probability of occurrence that cause the shutdown of multiple components of the system at the same time, affect a significant number of users, and require the implementation of complex restoration strategies. Therefore, resilience highlights the ability of a system to recover from a serious breakdown. However, the intended recovery does not involve a "perfect" restoration and full return of the system to the nominal parameters, but a state of operation considered acceptable for a limited time. Planning for increased resilience of power systems needs to focus on the optimal allocation of local resources, establishing trade-offs between the various components of the system and developing standards based on specific data.

More and more urban projects and studies to increase resilience focus on exploiting the concept of intentional islanding of urban electricity grids. Currently, the main objective of strategies to increase the resilience of power systems is the rapid restoration of power supply services for critical components of the system. The reliability of distribution systems can be significantly improved through distributed generation sources, which are encouraged by the new regulations to participate in the restoration procedure through the island operation mode. The reconfiguration of the electricity distribution network can effectively change the islanding process and thus provide an opportunity to supply more of the required energy and reduce power losses in the system. In the case of emergency operations, the deliberate islanding of distributed generation is a promising solution for maintaining a reliable power supply service in smart distribution networks, given the presence of critical loads and infrastructures that depend on it. However, local generating units cannot always provide power to all users, which is why there is a need to apply shedding procedures, while taking into account some priority criteria assigned to critical loads. Thus, the generation-consumption balance is maintained and a good functioning of the critical users/infrastructures during periods of crisis is ensured by the optimal distribution of the resources distributed in the urban electricity network.

Based on these arguments, *the scope of this thesis* is to develop a new model to increase the resilience and flexibility of electricity distribution networks based on optimal partitioning in intentional islands, using technologies specific to smart grids. The approach presented is based on the full control of existing assets in urban electricity networks in case of emergency scenarios and takes into account practical considerations aimed at improving preparation of power grids and mitigation of risks in such situations.

In the present context, the topic of the doctoral thesis is part of the current concerns regarding the development of smart cities, by strengthening the resilience of their energy infrastructure based on Smart Grid technologies. The sequential model proposed in this thesis is composed of two stages: the optimized intentional islanding process and the optimal management of local resources (distributed generation, electricity storage systems, controllable loads, etc.). The developed model presents originality due to the implementation of modeling equations developed by the thesis author herself and is elaborated with the help of modern and efficient calculation software tools. Using the resilience increasing methodology developed in this study, preventive optimization strategies can be formulated before a major outage, to give operators the opportunity to make the right decision when disruptions occur.

In the first stage of the model, the optimal island partitioning scheme is identified with the help of an algorithm based on the graph theory. Also, in this stage takes place the determination of the optimal settings for the active power generation of the distributed sources and the scheduling of the load shedding, taking into account the security restrictions that minimize the power imbalance between generation and consumption. This is possible by ensuring an adequate control reserve for both active and reactive power. At the end of this stage, the value of the frequency in the islands can be investigated to check the available reserve bands. If these are not sufficient to ensure an adequate value of the frequency, changes may be made to the configuration obtained. Otherwise, the algorithm moves on to the next step.

The second stage deals with aspects related to the proper functioning of the formed islands, ensuring appropriate conditions regarding the voltage level and the other operational parameters (power losses, maximum current through the lines, etc.). In other words, the island partitioning determined in the first stage is checked for feasibility. This partitioning can be corrected, if necessary, to meet the constraints related to the operation of the system. To this end, the calculation of the load flow is incorporated in this stage and optimal measures are taken to manage the power flow and the reactive power reserve, in order to mitigate voltage deviations and avoid exceeding the transfer capacities of power lines.

Given that the model proposed in this paper takes into account key factors regarding the proper operation of distribution systems, such as power balance, prioritization of critical loads, bus voltages and line capacity constraints, it covers the requirements of practical applications.

The doctoral thesis consists of 6 chapters, 5 annexes and a rich bibliographic study, to which are added the *Introduction* and the *Final Conclusions*.

Chapter 1, entitled "*The Smart City concept*", aims to present the main aspects of smart cities, addressing issues such as the characteristics and performance indicators that define it, as well as current trends and challenges it faces. Also, in this chapter is highlighted the essential role of smart grids in the context of implementing this concept, being presented the specific Smart Grid solutions that can participate in the development of resilient smart cities.

Carrying out an analysis of the characteristics and performance indicators for smart cities, focused on energy and environmental aspects, it was concluded that ensuring the continuity of the electricity supply service is a high key performance indicator, along with reducing greenhouse gas emissions. greenhouse effect. To improve these indicators, smart grids are the basic solution, given the built-in technologies that allow a rapid restoration of electricity supply, but also the integration of renewable energy sources. For these reasons, the research presented in this doctoral thesis, entitled "*Improving the resilience of urban distribution networks based on intentional islanding strategies*", focuses on increasing the operational safety of urban distribution systems in emergency situations based on Smart Grid technologies, which include among distributed renewable energy sources.

In addition to daily problems, urban electricity networks are increasingly facing disastrous events due to extreme weather events, but more recently human attacks (acts of terrorism or vandalism). Therefore, Chapter 2, entitled "*The concept of resilience of urban electricity networks*" is dedicated to exploring the notion of resilience of energy systems. The chapter describes both the dangers to which electricity networks are exposed and the measures that can be taken to reduce their vulnerability. At the same time, this chapter presents the structure of a resilience analysis framework, which allows the evaluation of multiple strategies that increase the resilience of power systems to make appropriate decisions on the application of strengthening measures.

Chapter 3, "*Island mode operation of electricity distribution networks*", presents the regulation framework that justifies the use of resilience growth strategies based on the intentional islanding of electricity distribution networks proposed in this paper.

Given the need to develop an optimization model that responds quickly and efficiently to the problems and scenarios analysed, in Chapter 4, "*Optimization methods used to solve problems specific to electricity distribution networks*", several optimization methods were evaluated frequently. used to solve the problem of reconfiguring the electrical distribution networks. Following the analysis of four optimization methods in terms of computational performance (computing time) and efficiency of identifying the global optimal solution, the calculation method used in the elaboration the optimal island partitioning model was chosen. Therefore, in order to develop a fast algorithm to restore the power supply service by optimally partitioning the distribution systems in the islands, they were evaluated in terms of computational performance four commonly used optimization methods, namely the linear programming problem and the quadratic programming problem (deterministic methods), respectively the genetic algorithms and the particle swarm method (meta-heuristic methods). Following this analysis, the quadratic programming problem proved to be the best results, being further used in the study to develop the model for increasing the resilience of distribution systems.

Chapter 5, "*The mathematical model for resilience improving based on optimal partitioning in islands*", is dedicated to the presentation of the proposed model for developing strategies to increase the resilience of electricity distribution networks based on the intentional islanding process.

Given that most previous studies in the literature on increasing resilience based on the island operation of distribution systems do not consider aspects of the frequency value in the formed islands, the methodology developed in this work introduces new security constraints. In order to apply these restrictions regarding both the values of the frequency and of the bus voltages, it was necessary to investigate the power imbalance between generation and consumption in the islands obtained. In this sense, an original model was developed to determine the connections of the generators in the obtained islands, which serves to calculate power imbalances. Once the values of these imbalances have been determined, the proposed methodology takes measures to reduce them on the basis of the existing control bands available in the formed islands, in order to ensure the best possible functioning of the system, even during emergency conditions. It should be noted that the optimal island partitioning model takes into account the reserve power margins necessary in the islands, thus meeting the requirements of intentionally islanding operation.

Chapter 6, "*Case studies and results*", is the main application part of the study. This chapter presents the results obtained from the implementation of the proposed model of optimal partitioning in islands of the distribution network. In addition to highlighting the benefits of the islanding strategy in terms of restored loads, achieved by testing the model on two well-known test networks and a real distribution network, the study also includes an analysis of optimal management of local resources during a prolonged interruption of 24 hours, applied in two scenarios that shape the two main types of risk to which modern electricity networks are exposed (natural disasters and cyber attacks).

Following the results presented, the following conclusions can be distinguished:

- The optimal partitioning of electrical distribution systems in intentional islands has major benefits in maintaining the operation of critical electrical loads, by supplying them during interruptions in acceptable ranges of the operational parameters, obtained through the proper operation of distributed resources.

- Based on the resilience indicators, three methodologies for power supply restoration during an interruption were evaluated, namely the reconfiguration process, the optimal partitioning in islands without security constraints, respectively the optimal partitioning in islands with security constraints. Two scenarios were analysed in this regard, which model the main types of events that cause prolonged interruptions (natural disasters and human attacks). In both cases, the restoration procedure based only on reconfiguration recorded the lowest values of the indicators, the percentage of restored electrical loads being much lower than in the case of intentional islanding. Regarding the two methodologies based on islanding, the resilience indicators show close values, higher in the case without security constraints. In order to keep the imbalance between generation and consumption as low as possible (by applying security constraints), the second islanding procedure uses a higher amount of load shedding, resulting in a lower percentage of restoration loads, but a frequency closer to the nominal value. However, the differences between the values obtained for the resilience indicators by the two islanding processes are insignificant, given the benefits of the frequency values in the islands through security constraints.

- Proper coordination of distributed resources in urban electricity grids, including distributed generators, energy storage devices and controllable loads, allows critical infrastructures to "survive" during a prolonged outage under acceptable operating conditions, in terms of bus voltages and frequency.

The main contributions of this paper include:

i. *Carrying out bibliographic studies* on:
   - The concept of "Smart City" - Investigating the characteristics and performance indicators that define this concept in order to identify the current concerns about the urban infrastructure development;
   - The role of smart grids in implementing the concept of smart city;
   - Measures and strategies to strengthen urban electricity grids in the light of current concerns about increasing the resilience of power systems to natural disasters and human attacks;

ii. *Analysis of the computation performance of four optimization methods* commonly used in solving problems specific to power systems (linear and quadratic programming, genetic algorithms and the particle swarm optimization), in order to identify the most efficient calculation method;

iii. *Development of a rapid method of restoring the power supply service* in smart distribution systems considering the prioritization of critical loads;

iv. *Development of a novel methodology for determining the power imbalance* in the formed network islands, in order to monitor and manage key operating factors, such as voltage level and frequency;

v. *Development of a sequential model of optimal partitioning in intentional islands* in order to maximize the loads restored after a major interruption, which also takes into account the security constraints on voltage and frequency values (due to generation-consumption imbalance);

vi. *Implementation of new indicators* to quantify the resilience of distribution systems for developing the suitable resilience strategies for each type of scenario;

vii. *Development of an optimal management model for the distributed resources operation* (distributed generation sources, energy storage systems and controllable electrical loads) in island conditions, in order to ensure adequate functional parameters for critical users of an urban electricity distribution network during an extended interruption;

viii. *The research dissemination* by publishing numerous articles at national and international conferences: The Academic Days of A.S.T.R. - ZASTR2017, Constanța, International Conference and Exposition on Electrical and Power Engineering - EPE2018, Iași, International Symposium on Fundamentals of Electrical Engineering - ISFEE2018 and International Symposium on Advanced Topics in Electrical Engineering - ATEE2019, Bucharest, IEEE PowerTech Milano 2019, International Universities Power Engineering Conference - UPEC2019, Bucharest, International Conference on Energy and Environment - CIEM2019, Timișoara, and international magazines: the UPB Scientific Bulletin, Series C: Electrical Engineering and Computer Science, 2020.

In order to continue the studies presented in this PhD thesis, the following research directions are proposed:

- A multi-criteria approach for the optimization problem, by introducing a multi-objective function based on a series of appropriately weighted terms, which may include reducing bus voltage variations, minimizing the number of switching operations required, economic aspects of source generation cost, improving environmental aspects (emission reduction) etc.;
- Dynamic analysis of the islanding process in terms of frequency and voltage stability;
- Extending the analysis on real urban electricity networks in future smart cities from Romania;
- Elaboration of a guide of recommendations regarding the measures to increase the resilience of the urban distribution networks adapted to the meteorological phenomena specific to Romania.

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