UNIVERSITY **POLITEHNICA** OF BUCHAREST
DOCTORAL SCHOOL OF ENERGY

ABSTRACT

PhD THESIS

OPTIMIZING THE OPERATION AND IMPROVING THE QUALITY OF ELECTRICITY IN ELECTRICITY DISTRIBUTION NETWORKS

Author: Ing. Georgiana GUȚU

PhD Coordinator: Prof. dr. ing. George Cristian LĂZĂROIU

Bucharest 2021

Contents

1. INTRODUCTION

The evolution of consumption in urban areas globally leads to an energy transition that is based on saving electricity, increasing energy efficiency, and replacing the use of fossil energy with renewable energy.

Cities are home to more than half of the world's population and consume between 60% and 80% of the world's total energy production. Because energy is responsible for two thirds of total Greenhouse Gas (GHG) emissions, urban areas emit 75% of global CO_2 emissions. As seen in the United Nations projections for up to 2050, if the current urban population growth trend continues, global urbanization will represent 67% of the total population, and cities will demand a more significant amount of energy.

Therefore, guaranteeing the security and quality of the energy supply to provide urban services using the planet's resources will pose an enormous challenge in terms of our ability to manage and restore the natural assets upon which all life depends. The integration of renewable sources has both advantages and disadvantages and their integration into the electricity system is something that must be analyzed in detail in terms of the influence on the network and the quality of electricity.

With the increasing importance of electricity quality in modern power supply systems, the requirements for equipment that can measure both the quality indicators and the level of energy used have increased.

The thesis aims at analyzing the electricity distribution network, in particular the urban network in a metropolitan area, in terms of network development and analysis of electricity quality. On these types of networks can be analyzed the integration of microgrids, storage sources, Smart technologies, charging stations for electric cars, etc.

2. ELECTRICITY QUALITY

2.1. Indicators for evaluating the quality of the electricity supply service

The following indicators are used to evaluate the quality of the power supply service in the electricity distribution networks [1]:

- " *SAIDI* (*System Average Interruption Duration Index*)" [1] for one year as the ratio of the total duration of outages to all discontinued users to the total number of connected users

$$SAIDI = \frac{\sum_{S=1}^{n}(N_S \cdot D_S)}{N_t}, \tag{2.1}$$

- „*SAIFI* (*System Average Interruption Frequency Index*)" [1] calculated as the ratio between the total number of interrupted users in a year, at each of the long-term interruptions, and the total number of connected users in the analyzed system

$$SAIFI = \frac{\sum_{S=1}^{n} N_S}{N_t}, \tag{2.2}$$

- *CAIDI* (*Customer Average Interruption Duration Index*) calculated as the ratio between the total duration of interruptions during a year, for all interrupted users and the total number of interrupted users for each of the long-term interruptions:

$$CAIDI = \frac{\sum_{S=1}^{n}(N_S \cdot D_S)}{\sum_{S=1}^{n} N_S} = \frac{SAIDI}{SAIFI} \tag{2.3}$$

The SAIDI, SAIFI, and CAIDI indicators are the main indicators that define the performance of the distribution network. The decrease of the values of the SAIDI and SAIFI indicators determines the improvement of the quality of the supply service offered to the end-users.

2.2. Electricity supply continuity analysis

Users of the electricity distribution network are supplied by electricity networks of public interest owned by eight licensed distribution operators [2].

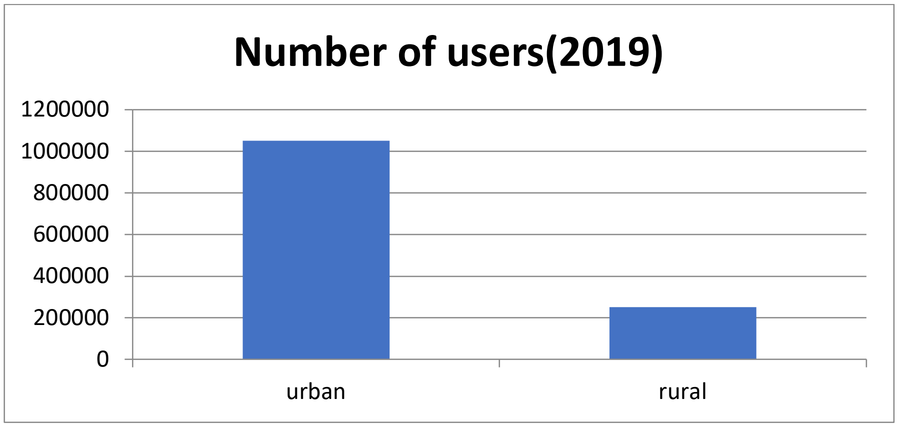


Fig. 2.1. Number of users of E-Distribuție Muntenia (year 2019)

In the urban area, E-Distribuţie Muntenia has the largest number of users (1,052,285) and in the rural area, the largest number of users (829,837) is owned by Delgaz Grid.

If we compare the values of the continuity indicators from 2019 with those registered in 2018, the following conclusions are obtained, considering the average values per country:

– The planned SAIFI remained at the level of 2018 (0.61 interruptions/year);

– Unplanned SAIFI decreased in 2019 (2.9 in / year) compared to 2018 (3.2 in / year);

– Planned SAIDI decreased in 2019 (171 min / year) compared to 2018 (184 min / year);

– Unplanned SAIDI decreased in 2019 (179 min / year) compared to 2018 (224 min / year).

2.3. The quality of electricity in electricity networks in which renewable sources are connected

To eliminate the risk of electromagnetic disturbances when we are connecting renewable sources to the grid, appropriate limitation measures may be taken.

Overload and exceeding the voltage limit, as well as disturbances, can normally occur in the network. These can be in the form of:

- voltage fluctuations,
- harmonics and interharmonics;
- not-symmetry.

Quality indicators must comply with the rules specific to each voltage level.

2.4. Analysis of electricity quality in microgrids

From the perspective of electricity quality, alternating current microgrids are operated in two distinct ways: connected to the grid and isolated. The effects on the quality of electricity are felt especially in the isolated operation but also when the microgrid switches the mode of operation.

The voltage fluctuations, determined by the wind installations, result both in their normal operation and in the operations of connecting the installation to the return of the wind with the speed necessary to restart it.

Voltage fluctuations caused by wind installations can be of two types:

1. Voltage fluctuations in normal operation
2. Voltage fluctuations due to switching

2.5. Monitoring the quality of electricity in smart grids

By monitoring the quality of electricity in a node of the electricity network, the aim is to determine the characteristics of voltage and current curves as well as variations in the frequency of the mains voltage concerning a set of standardized technical indicators [1]. Monitoring the electricity quality indicators and adopting the necessary measures to maintain them at the level prescribed by the quality standards is the obligation of the network operators.

3. URBAN DEVELOPMENT

Introduction

Cities are home to more than half of the world's population [3] and consume between 60% and 80% of the world's total energy production. Because energy is responsible for two thirds of total Greenhouse Gas (GHG) emissions [4], urban areas emit 75% of global CO_2 emissions [5].

Covering this energy demand with the current model based on fossil resources will increase GHG emissions and the consequences of global warming will put the planet's environmental sustainability at risk [6].

Smart cities are analyzed in detail in the literature [7–9]. Energy sustainability is a field of knowledge which has been studied in depth. Similarly, smart cities has attracted the economic interest of the technological, industrial and service sectors as well as governmental and supranational organizations in search of the competitiveness of cities and as a strategy to face climate change [10, 11]. In this sense, there are several methodologies for assessing smart cities (rankings or benchmarking of cities as in the studies [12,13]) and the energy sustainability of cities (see [14]).

3.1. Data on the electricity network

This chapter describes the electricity network owned by E-Distribuţie Muntenia, at the level of the year 2019, given that the largest urban area (Bucharest) is owned by this distribution operator.

Most 110kV lines (91%) are put into operation before the year 2000. If we refer to the medium and low voltage lines approx. 29% have been put into operation in the last 20 years.

According to the information from the ETN Development Plan [15], the Bucharest metropolitan area shows a significant increase in electricity consumption compared to other areas of Romania, as a result of economic development conditions.

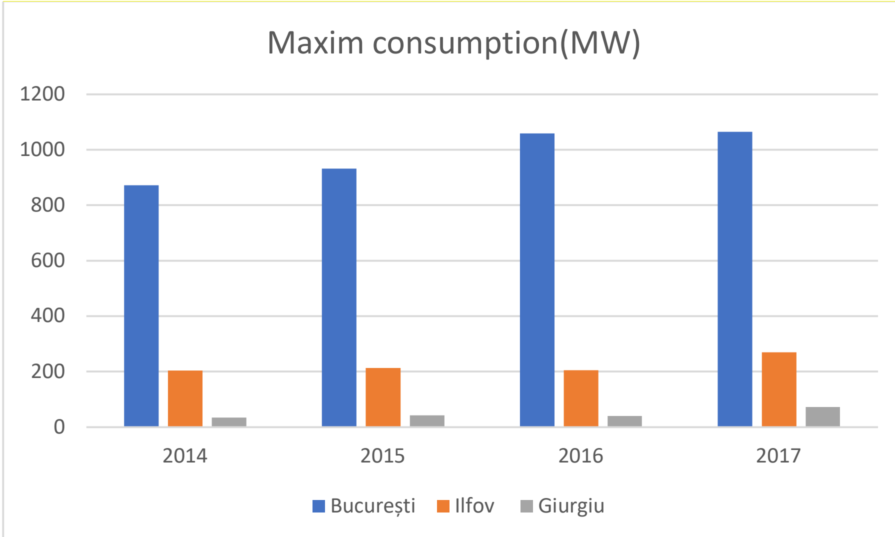


Fig. 3.1. Evolution of maximum consumption (MW) at Metropolitan level

Taking into account forecasts for the increase of consumption in the period 2020-2029, considering an average annual growth rate of power of approx. 3%, the Metropolitan area will reach a consumption of up to 2000MW in 2029. During the summer, the security of supply to consumers decreases, during this period there are total shutdowns for the inspection of heating power plants.

Currently, the supply of the Bucharest and Ilfov areas is done through 3 electric transmission stations located on the outskirts of Bucharest.

In the next period, it is necessary to develop the electricity network following the economic development of the analyzed area. This can be implemented by the realization of at least one power injection transmission station in the electricity distribution network.

3.2. Existing energy situation and development plans

The national electric power system is provided by the “Investment Plan of CNTEE Transelectrica SA” [15] refurbishments and developments of the transmission network.

To solve some problems encountered in operation, it was proposed to carry out the following projects in the next period:

- flexibility of the 220 /110kV Fundeni substation to increase the safety in the supply of consumers from the North-East area of Bucharest and installation of a new autotransformer 220 /110kV;

- installation of a new 400 / 110kV transformer in Bucharest South station.

In the longer term, it is necessary to analyze the opportunity of ample actions for the development of the electric transmission network:

- construction of 400kV or 220kV injection stations realized in the centers of gravity of consumption, correlated with the distribution network, and

- closing a 400kV loop (ring) for the Bucharest area, on the eastern area, by making a new transmission station in one of the Otopeni, Tunari, or Voluntari locations (northeast area of Bucharest) and building a power line 400kV from Domneşti power station to 400 / 110kV Bucharest South power station.

Regarding the E-Distribuţie Muntenia network, a series of investments in the 110kV network are foreseen, consisting of new 110kV / MT substations, increasing the capacity of the transformation units in some 110kV / MT substations, new 110kV LECs, or LEC replacements 110kV old with some with higher carrying capacity.

3.3. Analysis of the area in terms of the need for reinforcement

For the analysis of the static regimes of a Metropolitan area, normal operating regimes but also operating regimes are followed, so that it is considered that [16]:

- the group with the highest installed power is stopped,

- the balance is restored by loading proper power; loading is performed in the order of production costs (in ascending order they are: lignite power plants, coal power plants, hydrocarbon power plants) in remote areas of the national power system.

<u>Analysis of the stationary regime area</u>

Considering the minimum production in the Bucharest area (exclusive operation of thermal power plant Bucharest West with an available power of 112 MW), the consumption can be supplied from the Dobrogea area (considering wind sources) or from Oltenia (considering thermal sources and hydroelectric power plants).

Following the implementation of the regimes with N elements in operation, it resulted that there are no overloads on the network elements and the permissible voltage limits are followed.

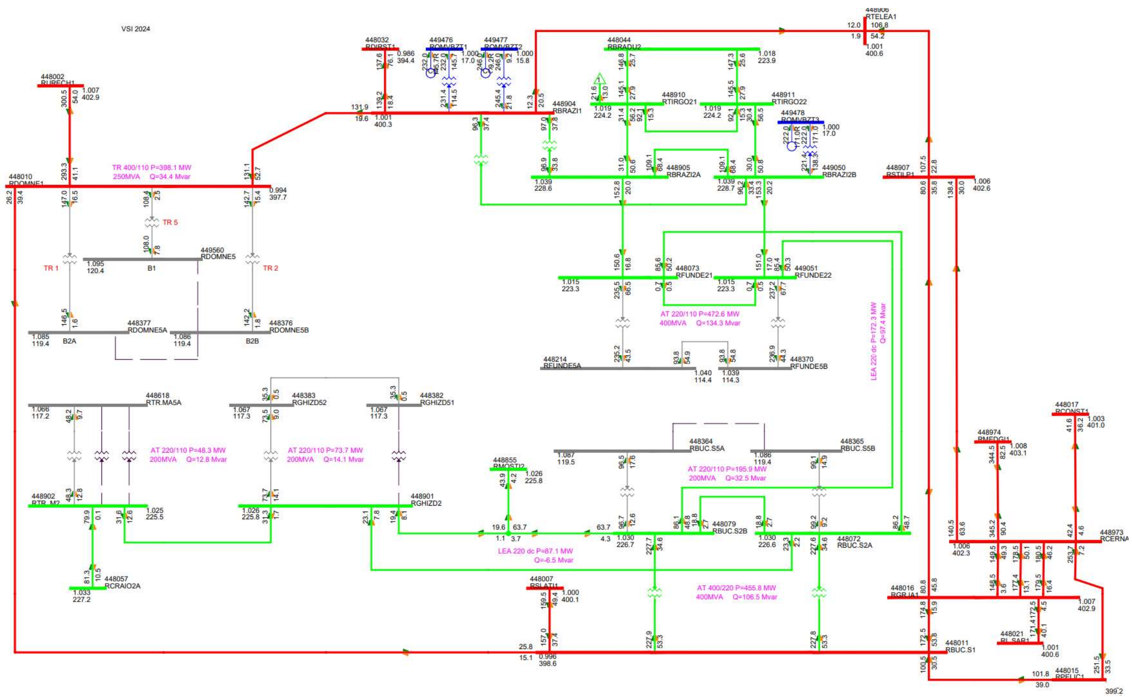


Fig. 3.2. Diagram of the electric transmission network

Following the implementation of the regimes with N-1 elements in operation, it resulted that this regime is not respected because there are overloads on the network elements.

From the analysis of the Bucharest Metropolitan area, it resulted that in various consumption hypotheses, for different stages of development, the existing transformation units in the three injection stations do not answer the N-1 criterion elements in operation.

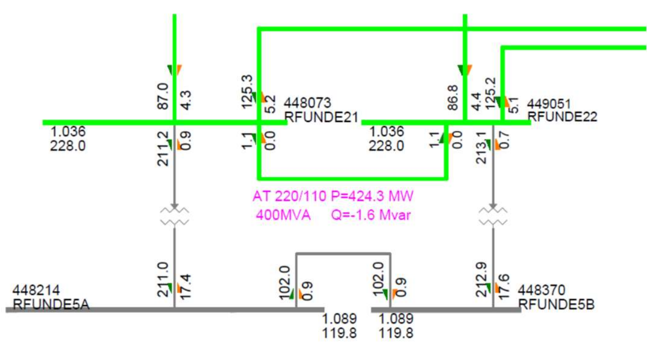


Fig. 3.3. Substation Fundeni, winter peak

The figure above shows that in the regime with N elements in operation, the two autotransformers from the 220 / 110kV Fundeni station are transited by more than 400MVA. In this 110kV area, there is no power plant to supply some users. In the event of a 220 / 110kV autotransformer fault, the remaining autotransformer will overload.

To solve some problems encountered in operation, it is necessary to make the following investments in the next period:

- installation of a new autotransformer unit in Fundeni station;
- installation of a new 400 / 110kV transformer unit in Bucharest South station.

ANALYSIS OF THE STEADY-STATE STABILITY CASES

The calculations were performed for the characteristic level of winter peak, analysis stage 2020, 2024 and 2029.

The analized 110kV deficitary area contains:

- The consumption of E-Distribuţie Muntenia besides stations 220/110kV Fundeni, 400/220/110kV Bucureşti Sud and 400/110kV Domneşti;
- The consumption of E-Distribuţie Dobrogea from station contained between station Mostiştea and station Lehliu Gară;
- The consumption of CEZ besides stations 220/110kV Ghizdaru, Turnu Măgurele and 400/110kV Domneşti.

The total consumption of the area analyzed is **1660,7MW** in stage 2020, **1766,3MW** in stage 2024, **1920,4MW** in stage 2029.

According to the „Technical Standars of the power transmission network" [17] and „PE 026/92" [16], „the power transmission network must ensure a steady-state stability margin of minimum 20% in Case with N operational elements and of minimum 8% in Case with N-1 operational elements." [17].

In order to determine the critical operating condition and the operating condition with steady-state stability standardized margin for a deficitary section the initial steady-state operating condition was worsened in succesive steps by increasing the power consumed in the respective area.

In all the cases with N and N – 1 operational elements the standardized margin operating condition of 20% in the Case with N elements and 8% in the Case with N-1 elements is accomplished.

ANALYSIS OF THE TRANSIENT STABILITY

Hypotheses

Check the conditions of transient stability in case of the most difficult short-circuit requests for power plants in the analysis area:

- TPP Bucharest West,

- TPP Bucharest South,
- TPP Grozăveşti
- TPP Progresu

The critical times will be determined in complete configuration for each plant in the analyzed area.

For this purpose, the transient regimes caused by three-phase short circuits appeared on the connecting lines of the stations where the power plants in the area are connected, in the area of 110kV bars of Bucharest Sud, Bujoreni, Progresu, and Grozăveşti stations.

The main electrical sizes whose development is monitored, in the transitory scheme, in order to determine whether that scheme is stable or not, are the following: relative or absolute internal angles of generators, active powers defbited by them, the voltages at their terminals, as well as those of the bus bars of the substations in the area.

<u>The hypothesis considering AT3 220 /110kV Fundeni and the transformation unit 400 / 110kV Bucharest South</u>

The synthetic calculation results are presented in the table 3.1.

Table 3.1. Critical fault removal time calculation

Bus	**Critical fault removal time**		**Fault removal time**	**Stability reserve**	**Restrictive generators**	**Remarks**
	t_{stable}	$t_{unstable}$				
	[ms]			**[ms]**		
Bucureşti Sud 110 kV - 1	270	275	150	125	G3	-
Grozăveşti 110 kV	190	195	150	45	VT4	-

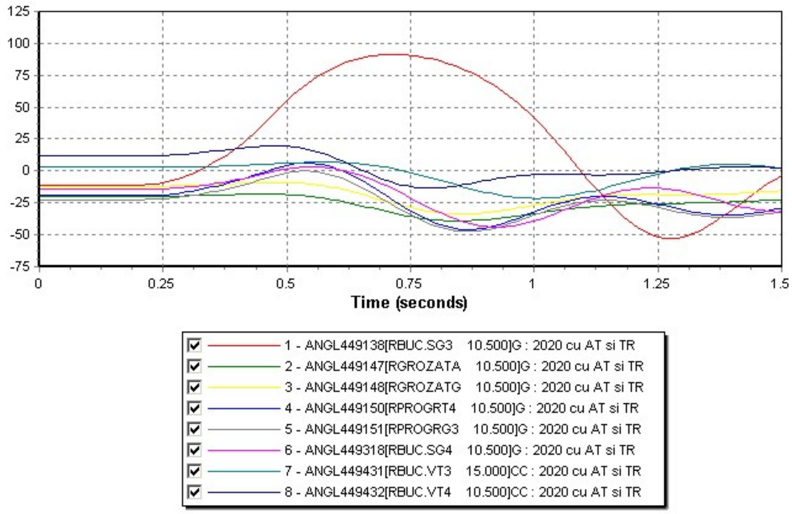


Fig. 3.4. Three-phase short circuit near the **110kV Bucharest Sud** 1 substation, eliminated in 270ms
The hypothesis considering the additional transformation units from Fundeni and Bucharest South
STABLE (critical time)

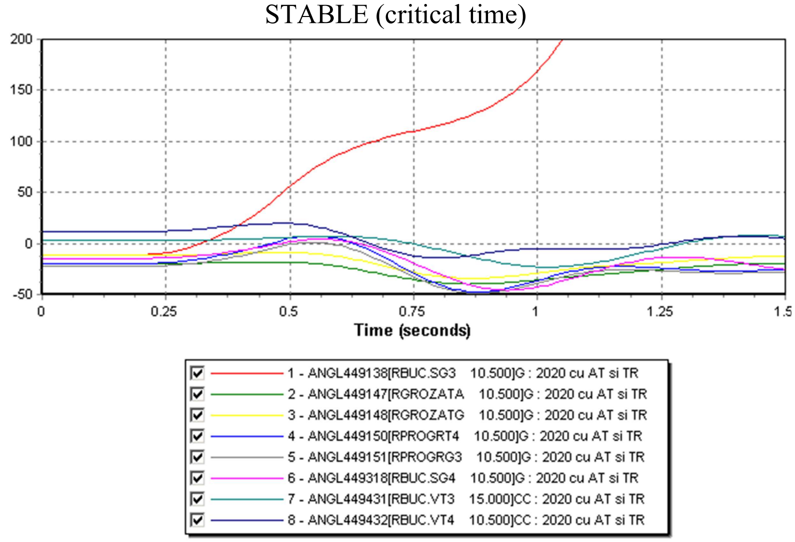


Fig. 3.5. Three-phase short circuit near the **110kV Bucharest Sud** 1 substation, eliminated in 275ms
The hypothesis considering the additional transformation units from Fundeni and Bucharest South
UNSTABLE (critical time)

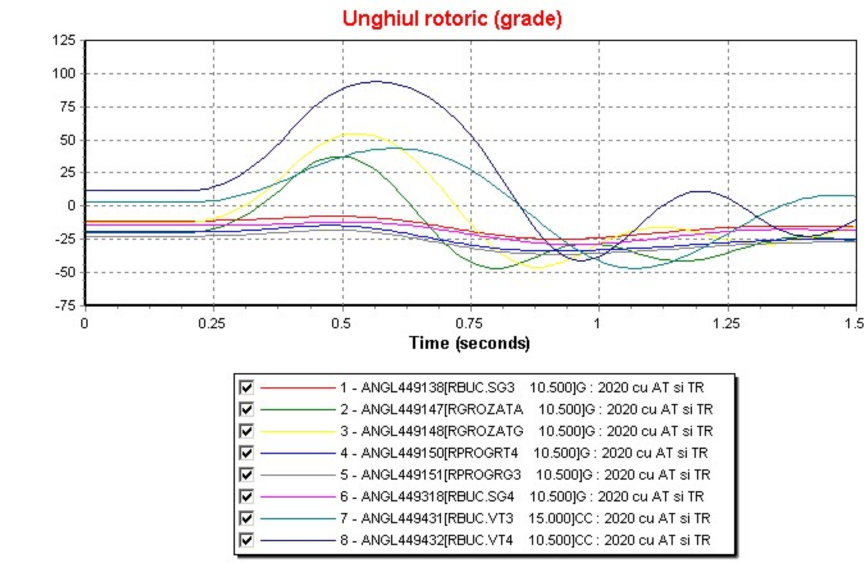


Fig. 3.6. Three-phase short circuit near the **110kV Grozăveşti** substation, eliminated in 190ms
The hypothesis considering the additional transformation units from Fundeni and Bucharest South
STABLE

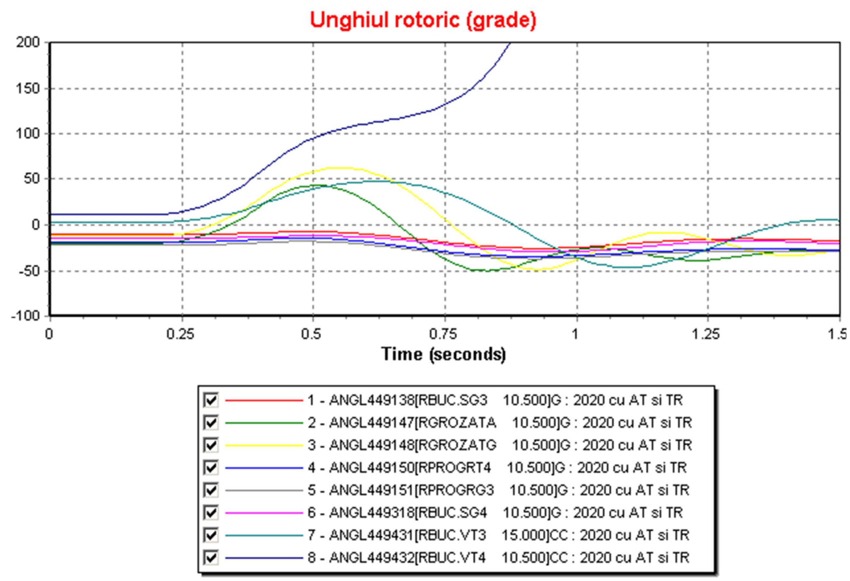


Fig. 3.7. Three-phase short circuit near the **110kV Grozăveşti** substation, eliminated in 195ms
The hypothesis considering the additional transformation units from Fundeni and Bucharest South
UNSTABLE

The dispatchable groups in the Bucharest area have a critical fault elimination time longer than the fault elimination duration of the networks connecting these groups to the national electric system and as a result, they are not in danger of losing their stability.

Checking short-circuit currents

The value of the maximum three-phase short-circuits currents, two-phase with earth and single-phase in the 110kV, 220kV, and 400kV buses belonging to ETN and EDN in the Bucharest metropolitan area was determined following "PE 134/1995 Normative regarding the calculation methodology of short-circuit currents in electrical networks with voltage over 1kV "[18].

As a first step, the calculation of the maximum short-circuit currents is performed by applying all the requirements regarding the national electric system modeling, including the connection of the coupling from the ETN and EDN 110 kV stations.

The calculation of the maximum short-circuit currents in the 110kV substations in the Bucharest metropolitan area, in the hypothesis of closing all the coupling in the 110kV substations, highlights particularly high values, exceeding the 40kA limit.

The most efficient measure for the decrease of the maximum short-circuit currents in EDN 110kV in the Bucharest metropolitan area is to opening of some couples in the 110kV stations and the opening of the 110kV lines according to the normal operation diagram.

3.4. Measurements performed on characteristic levels in consumption nodes

3.4.1. Equipment used

Fluke 434 is a three-phase energy quality analyzer.

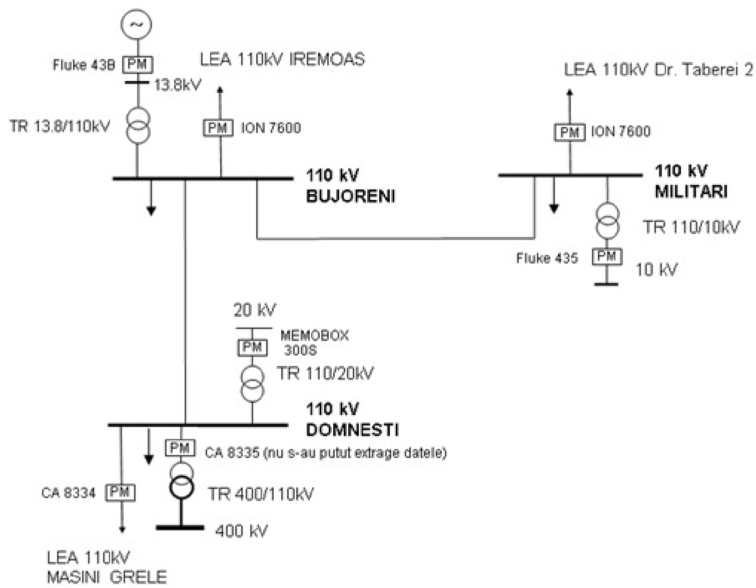
The **Fluke 435** has the same technical features as the Fluke 434 but has a larger data storage memory.

C.A 8334 is a compact, three-phase, shock-resistant electrical analyzer. The ergonomic design and simplicity of the user interface make its use pleasant and intuitive.

7600 ION™ Electricity Analyzer-Controller - Power Measurement. 7600 ION™ is configured by the manufacturer to perform all basic functions for power monitoring. 7600 ION™ has the flexibility and computing power needed to monitor the supervised power supply system.

3.4.2. Measurements

The diagram of the Domneşti area with the marking of the points where the measurements were made and of the devices used is presented in figure 3.8.



PM - measuring points, LEA 110kV=OHL 110kV

Fig. 3.8. Diagram of the Domneşti area with the marking of the points where the measurements were made and of the devices used

The voltage levels were adjusted by:

→ the variation of the reactive power on group 1 (135MW) TPP Bujoreni in the limits +80MVAr and -17MVAr, which, together with the regulation of the plots in the 400 / 110kV Domneşti station led to a voltage interval on IREMOAS OHL between 121.5kV and 123.5kV ;

→ variation of plots at TR 400 / 110kV 250MVA from Domneşti station (from plot 9 to plots 8 and for maximum voltage on plot 12); the reactive power produced by the group was also adjusted on each stage;

→ in the 110 / 20kV Domneşti station and in the 110 / 10kV Militari station, the curves P = f (U) and Q = f (U) was obtained - for each of the situations mentioned above, by switching the plots of the respective transformers.

The monitored interval for samples was the one in practically constant load between 15 and 16.00.

3.5. Conclusions

The analyzed area, formed by the Municipality of Bucharest, Ilfov, and Giurgiu counties, includes 400kV and 220kV networks belonging to CNTEE Transelectrica, respectively 110kV and medium voltage networks belonging to E-Distribuţie Muntenia.

For a development characteristic of a 2029 stage, it is necessary to develop a 400 / 110kV Grozăveşti substation, in the consumption center of the Bucharest area. Disadvantages of this variant specify the difficulty of installing 400kV cables from the 400kV stations Domneşti and Bucureşti Sud to the center of Bucharest.

The 400 / 110kV substation Grozăveşti corresponds to the situation when a new 400 / 110kV substation is needed in the consumption center of Bucharest, next to an existing 110kV substation with multiple connections with other 110kV substations and double bar at 110kV.

The 110kV Bucharest area operates radially, and the distribution operator has developed the network to meet the requirements of users. The uncertainty of the development of the classic sources connected in the 110kV network can lead to difficulties of the transmission network in the safe power supply of the users. The development of the short-term transmission network involves the installation of additional transformation units and in the long term, it is necessary to build a power injection station in the consumption center.

4. OPTIMIZING THE OPERATION OF A MICROGRID

4.1. Market models for microgrids

4.1.1. Introduction

This chapter provides an overview of possible market models for microgrids.

Depending on the operational model, there are two major markets: the bulk market and the retail market. These two different markets can function by interacting with each other through a common fund and/or through bilateral transactions.

4.1.2. Internal markets and business models for microgrids

Monopoly model of the distribution system operator

In a microgrid that follows the monopoly model of the distribution system operator, the distribution system operator is part of a vertically integrated utility, so that it not only owns and operates the distribution network but also fulfills the function of the distributor to sell electricity to the final consumers.

Liberalized market model

In liberalized markets, microgrids can be driven for many reasons (economic, technical, environmental, etc.) by different stakeholders (suppliers, operators, consumers, etc.). Suppliers are best suited to maximize the value of the share of accumulated energy resources accumulated in liberalized local energy markets, ie they are best suited to the participation of commercial microgrids.

The pro-consumer consortium model

A pro-consumer consortium microgrid is most likely encountered at times when the retail price of electricity is high and/or the level of financial support for microgeneration is high.

4.1.3. Control functions of a microgrid

The control system of a microgrid includes the control functions that define the microgrid as a system that can be managed alone, can operate isolated or connected to the network, can connect/disconnect from the distribution network, and can provide ancillary services.

The microgrid control system operates in the following situations [19]:

• Operation in networked mode,

• Operation in isolated mode,

• Automatic transition from one operating mode to another (this ensures the power supply to users in case of faults in the distribution network or case of planned interruptions),

• Reconnecting and resynchronizing the network when switching from one operating mode to another,

• Optimization of active and reactive power generated and consumed,

• Ancillary services, network support, and energy market participation.

4.1.4. Hierarchical structure of the real-time balancing market with the participation of microgrids

At the level of the electricity distribution network, microgrids containing distributed sustainable sources (such as demand response, distributed renewable sources, and storage systems) are economically dispatched by the distribution operator.

The balancing market is functional in every interval of less than one hour (for example 5-15 minutes) to constantly ensure the stability of the system by balancing any imbalance. This service is performed by the carrier (TSO) who uses the bidding sources for this system service to minimize total costs.

4.2. Optimization analysis within a microgrid

4.2.1. Introduction

In this chapter is analyzed an efficient method for optimally operating microgrids by minimizing the functioning costs, under grid-connected and islanding modes, accounting for intermittent production of photovoltaic systems and critical load supply.

The islanding operation can occur during periods with excessive load and insufficient generation. The optimization model is tested over a period of 24 hours.

The purpose of the problem is to achieve an optimized scheduling of microgrid grid-connected and in islanding operations for a 24 hour time horizon, with 15 minutes time slots, minimizing costs considering generation and demand operational constraints. The 15 minutes analysis allows to investigate the microgrid operation under sudden changes in renewable energy sources production, i.e. shadowing occurrence of photovoltaic installation within the microgrid.

4.2.2. Description of the analyzed microgrid

The microgrid has local generation units (photovoltaic units), fueled thermal engine, battery energy storage systems, critical and interruptible loads. The microgrid controller can acquire or sell energy with the mains supply.

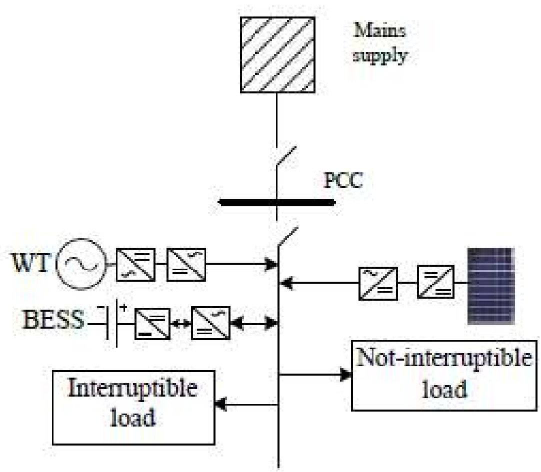


Fig. 4.1. Schematic structure of the considered microgrid

The recorded power production curve for a 300 kW photovoltaic plant (PV) is illustrated in Fig. 4.2., for a summer day.

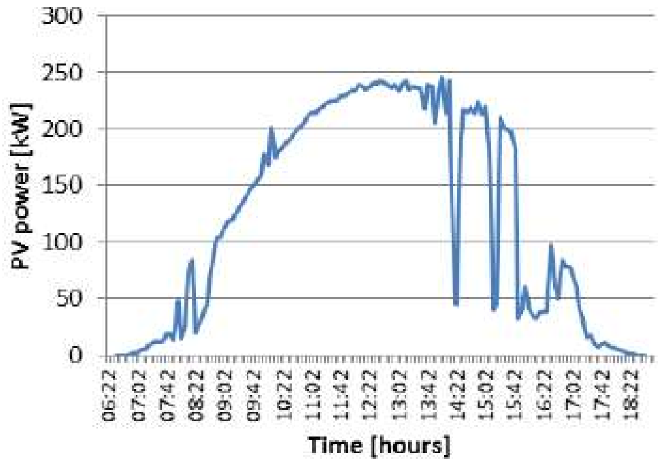


Fig. 4.2. Recorded production curve of PV system.

Initial, the forecasted photovoltaic production is considered perfectly accurate. The cost of operating these photovoltaic generating units is usually very low and will be considered zero

Classical back-up source is used within the scheme as a dispatchable unit (ThE) [20]. The cost function of this classical unit is a quadratic function of the amount of energy $E_{ThE}(t)$, at each time period t, with a cost function expressed as:

$$C_i\left(E_{ThE,i}(t)\right) = a_i \cdot E_{ThE,i}^2(t) + b_i \cdot E_{ThE,i}(t) + c_i \text{ ,} \forall i \in S_{ThE}, \quad t = 1,\ldots,24 \tag{4.1}$$

where a_i, b_i, and c_i are the cost function coefficients for each unit within the set of classical units S_{ThE}, expressed in Euro/MWh.

The output power state of the classical unit is modeled with the help of a binary variable $u(t)$ (equal with 0 if the unit is off, and 1 if the unit is on):

$$u_i(t)\cdot P_{ThE,i}^{\min} \le P_{ThE,i}(t) \le u_i(t)\cdot P_{ThE,i}^{\max} \text{ ,} \forall i \in S_{ThE}, \; t = 1,\ldots, 24 \tag{4.2}$$

where $P_{ThE,i}^{min}$ and $P_{ThE,i}^{max}$ are the minimum and maximum output powers of the classical unit i.

The startup cost C_i^{SU} and shutdown cost C_i^{SD} associated with the classical fueled unit are expressed with the constraints

$$\begin{aligned} &C_i^{SU}(t) \ge S_i^U \cdot \left(u_i(t) - u_i(t-1)\right), \forall i \in S_{ThE}, \; t = 1,\ldots, 24 \\ &C_i^{SU}(t) \ge 0, \forall i \in S_{ThE}, \; t = 1,\ldots, 24 \end{aligned} \tag{4.3}$$

$$C_i^{SD}(t) \geq S_i^D \cdot (u_i(t-1) - u_i(t)), \forall i \in S_{ThE}, \ t = 1,..., 24$$
$$C_i^{SD}(t) \geq 0, \forall i \in S_{ThE}, \ t = 1,..., 24 \tag{4.4}$$

where S_i^U and S_i^D are the actual costs of turn on/off of the classical unit.

The storage battery energy systems are increasingly deployed in the existing distribution networks. Their flexibility and potential to smooth the output power of renewable energy sources determined the widespread within the distribution networks. The state-transition equation for the energy level $E_{BESS,i}(t)$ with finite capacity, for each storage unit i at any time t, is:

$$E_{BESS,\,i}(t) = E_{BESS,\,i}(t-1) + P_{BESS,\,i}^{chg}(t) \cdot \eta_{conv,\,i}^{chg} \cdot 1 - \frac{P_{BESS,\,i}^{dischg}(t)}{\eta_{conv,\,i}^{dischg}} \cdot 1 \tag{4.5}$$

$$E_{BESS,\,i}^{\min} \leq E_{BESS,\,i}(t) \leq E_{BESS,\,i}^{\max}, \forall i \in S_{BESS}, \ t = 1,..., 24 \tag{4.6}$$

Where one hour represent the period of time, $P_{BESS,i}^{chg}(t)$ and $\mathrm{P_{BESS,i}^{dischg}(t)}$ are, respectively, the charging and discharging powers of each storage unit i, limited by certain upper bounds ($\mathrm{P_{BESS,i}^{chg,max}}$, respectively $P_{BESS,i}^{dischg,max}$) expressed as::

$$0 \leq P_{BESS,\,i}^{chg}(t) \leq P_{BESS,\,i}^{chg,\,\max}, \forall i \in S_{BESS}, \ t = 1,..., 24 \tag{4.7}$$

$$0 \leq P_{BESS,\,i}^{dischg}(t) \leq P_{BESS,\,i}^{dischg,\,\max}, \forall i \in S_{BESS}, \ t = 1,..., 24 \tag{4.8}$$

$\eta_{conv,i}^{chg}$ şi $\eta_{conv,i}^{dischg}$ are the conversion efficiencies that accounts for the energy losses associated with the charging and discharging processes, and are lower than 1.

It is considered that there is no transfer constraint between the upstream grid and the microgrid.

For minimizing the microgrid operating costs, it is considered that the interruptible load can be reduced during periods with high electricity prices in the upstream grid or when the microgrid is in islanding operation state.

The load curtailment has a high penalty cost for the microgridInterruptible loads represent a certain percentage of the total demand within the microgrid.

The power demand $P_{crit\_l,i}\ (t)$ of the critical load i from the set of critical loads S_{crit_l} is constrained to be::

$$P_{crit\_l,\,i}^{\min} \leq P_{crit\_l,\,i}(t) \leq P_{crit\_l,\,i}^{\max}, \forall i \in S_{crit\_l}, \ t = 1,...,24 \tag{4.9}$$

while the power demand $P_{inter\_l,\,i}\ (t)$ of the interruptible load is bounded by:

$$0 \le P_{inter\_l,i}(t) \le P_{inter\_l,i}^{\max}, \ \forall i \in S_{inter\_l}, \ t = 1,...,24 \tag{4.10}$$

4.3. Energy management model

4.3.1. Perfectly known photovoltaic production

The optimization model for minimizing the operation costs (Cost) during the 24 hours operation mode can be formulated as:

$$[MIN]Cost = \sum_{t=1}^{24} \begin{bmatrix} \sum_{i \in S_{ThE}} [C_i(E_{ThE,i}(t) + C_i^{SU}(t) + C_i^{SD}(t)] + \\ \sum_{s \in S_{RES}} \Pi_{PV,s}(t) \times P_{PV,s}^{curt}(t) \times \tau \\ + \sum_{j \in S_{crit\_1}} \Pi_{crit\_1,j}(t) \times E_{crit\_1,j}(t) - \Pi_{el}(t) \times P_{exch}(t) \times \tau \end{bmatrix} \tag{4.11}$$

where π_{PV_curt} is the penalty cost associated with the PV curtailed power P_{PV_curt}, π_{crit_l} is value of lost load E_{crit_l}; π_{el} is the electricity market price, and $P_{exch}(t)$ s the amount of power exchanged with the upstream grid in time period t.. The power exchange is positive when the power is flowing towards the mains supply, or negative if the power is going towards the microgrid.

The energy balance constraint ensures, for each time frame, that the sum of total generated energy is equal to the total load, plus the energy exchanged with the upstream grid:

$$\sum_{i \in S_{ThE}} E_{ThE,i}(\tau) + \left(\sum_{s \in S_{RES}} P_{PV,s}^{fcast}(t) - \sum_{s \in S_{RES}} P_{PV,s}^{curt}(t) + \sum_{i \in S_{BESS}} P_{BESS,i}^{disch}(t) \right) \bullet \tau =$$

$$= \sum_{j \in S_{crit\_1}} E_{crit\_1,j}(\tau) + \sum_{k \in S_{inter\_1}} E_{inter_1,k,r}(\tau) + \left(\sum_{i \in BESS} P_{BESS,i}^{chg}(t) + P_{exch}(t) \right) \bullet \tau \tag{4.12}$$

The forecasted PV production value $P_{PV,i}^{fcast}(t)$ ais accurately known, while the outputs at each time moment t are the variables $E_{ThE}(t)$, $E_{crit\_1}(t)$, $E_{inter\_1,k}(t)$, $P_{ThE,i}(t)$, $C_i^{SU}(t)$, $C_i^{SD}(t)$,$P_{PV,i,}^{curt}(t)$, $P_{BESS,i,}^{disch}(t)$, $P_{BESS,i,}^{chg}(t)$, $E_{BESS,i}(t)$ and $P_{exch}(t)$.

4.3.2. Stochastic scheduling model

During microgrid operation, the forecasted values of PV production in practice cannot be accurately predicted. The magnitude of errors depends on the accuracy of the forecast programs [21, 22]. Hence, the microgrid energy balance cannot be fulfilled under different PV productions. For overcoming this possibility, an optimization models is formulated considering the uncertainties in PV production.

For each uncertainty of PV production, a certain probability of occurrence $\lambda \geq 0$ is assigned, and the sum of probabilities for all set of scenarios n_{sc} is equal to 1.

The stochastic optimization model minimizing the operation costs can be formulated as:

$$[MIN]Cost = \sum_{t=1}^{24} \left[-\Pi_{el}(t) \times P_{exch}(t) \times 1 + \sum_{r=1}^{n_{sc}} \lambda_r \bullet \left[\begin{array}{l} \sum_{i \in S_{ThE}} \left[C_i\left(E_{ThE,i,r}(t)\right) + C_{i,t}^{SU}(t) + C_{i,r}^{SD}(t) \right] \\ + \sum_{s \in S_{RES}} \Pi_{PV\_curt,s,r}(t) \times P_{PV\_curt,s,r}(t) \times 1 + \\ \sum_{j \in S_{crit\_1}} \Pi_{crit\_1,j}(t) \times E_{crit\_1,j,r}(t) \end{array} \right] \right] \tag{4.16}$$

for each scenario r from the set of all considered scenarios.

The energy balance constraint (4.17) ensures that, for each time period t and for each PV production scenario r, the sum of total generated energy by classical unit, photovoltaic scenario production and battery discharge equals the sum of load demand, battery charging and exchanged energy with the upstream grid.

$$\sum_{i \in S_{ThE}} E_{ThE,i,r}(\tau) + \left(\sum_{s \in S_{RES}} P_{PV,s,r}^{stoc}(t) - \sum_{s \in S_{RES}} P_{PV,s,r}^{curt}(t) + \sum_{i \in S_{BESS}} P_{BESS,i,r}^{disch}(t) \right) \bullet \tau =$$

$$= \sum_{j \in S_{crit\_1}} E_{crit\_1,j,r}(\tau) + \sum_{k \in S_{inter\_1}} E_{inter\_1,k,r}(\tau) + \left(\sum_{i \in BESS} P_{BESS,i,r}^{chg}(t) + P_{exch}(t) \right) \bullet \tau \tag{4.17}$$

For each PV production scenario, the variables of the optimization model are determined.

4.4. Case studies

Two case studies were analyzed [23]:

1. Optimal energy scheduling for minimizing microgrid operation costs under perfectly known photovoltaic production;;
2. Optimal energy scheduling for minimizing microgrid operation costs under uncertainty of photovoltaic production..

The 2 case studies were analyzed in hypothesis A (operating interconnected with the upstream grid) respectively in hypothesis B (operating in islanding state).

In table 4.1 are presented important characteristic data of all units within the simulated microgrid illustrated in figure 4.5. The operation costs of renewable energy sources and battery storage are considered to be negligible in the case studies. The thermal engines are supplied with gas, with fast turn on/off capabilities. The load demand is composed of the critical load 60%, and the interruptible load 40%. Critical load curtailment costs are set to 50 Euro/kWh. The electrical energy prices represent an important parameter that can greatly influence the optimized operation of the microgrid. The electricity prices are typical average values on the day-ahead market, on a 24 hour interval.

Table 4.1. Characteristic data of units

Component	**Value**
Photovoltaic plant	300 kW
Battery energy storage system	200 kW
- minimum storage level	40 kW
- conversion efficiency	0,9
Engine capacity	600 kW
- engine cost function coefficients	(0,03; 1; 1,3)
Maximum demand	800 kW

Each of the energy management models presented in section 3 are tested in three cases defined as:

Case I: optimal energy scheduling for minimizing microgrid operation costs under perfectly known photovoltaic production;

Case II: optimal energy scheduling for minimizing microgrid operation costs under uncertainty of photovoltaic production.

Case I. The photovoltaic production is perfectly known, and is given by the forecasted production values illustrated in figure 4.6. In this case, there is no constraint of transfer capacity between the microgrid and the upstream grid.

Hypothesis A. The microgrid is operating during the 24 hours analysis horizon interconnected with the upstream grid.

The electricity price follows the daily typical curve. During periods when the electricity price is low, i.e. during the night, the microgrid is purchasing energy from the upstream grid to supply the load. In addition, the storage energy system is charged in this period.

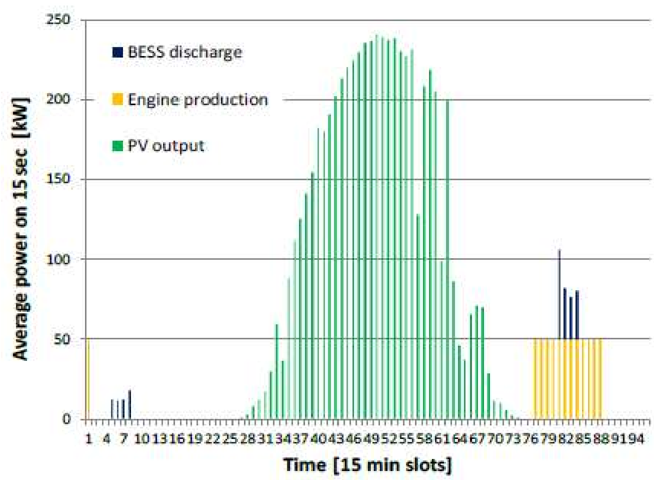


Fig. 4.3. Resulting generation schedule within the microgrid*, case I*, *hypothesis A*

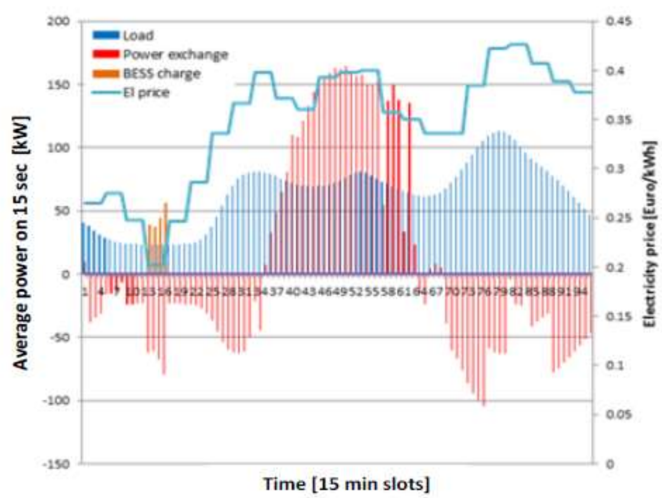


Fig. 4.4. Resulting consumption schedule within the microgrid, *case I*, *hypothesis A*

Hypothesis B. A fault occurring in the upstream grid determines the disconnection of the microgrid. The microgrid is operating in islanding state during the time interval t = 64–80 (i.e. between hours 16:00 and 20:00).

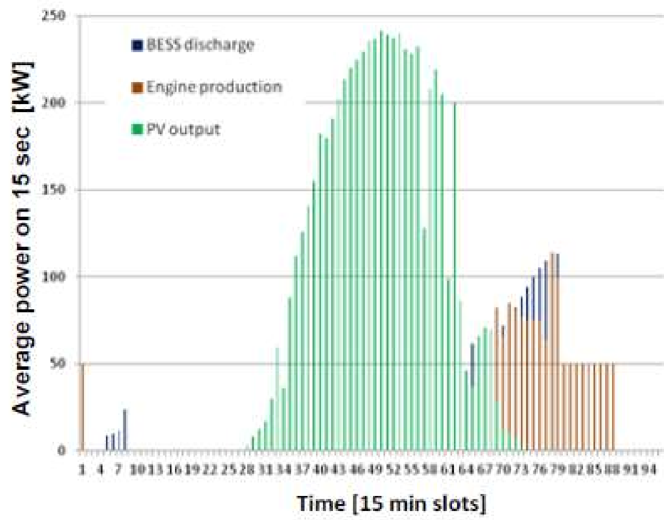


Fig. 4.5. Resulting generation schedule within the microgrid, *case I*, *hypothesis B*

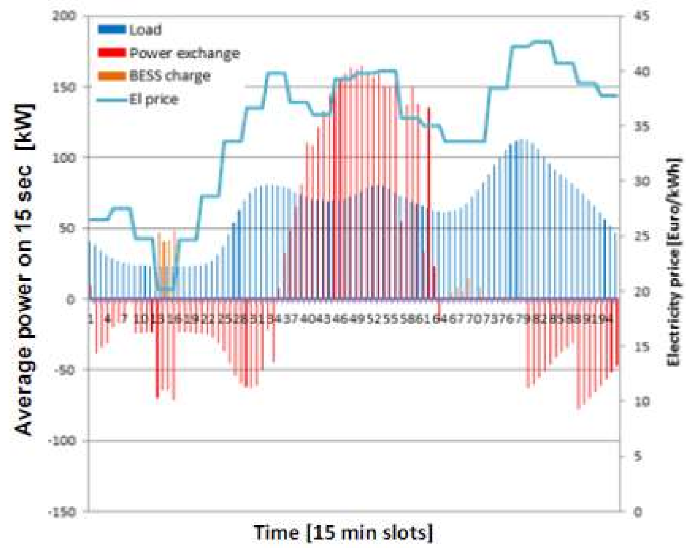


Fig. 4.6. Resulting consumption schedule within the microgrid, *case I*, *hypothesis B*

During the islanding operation, the upstream grid is no more offering support to balance the microgrid demand., the thermal engine is switched on and is maintained in operation between hours 16:00 and 20:00.

Case II. In this case, the photovoltaic production is assumed that cannot be accurately forecasted. For considering the production errors, 20 production scenarios are generated to test the microgrid operation in each scenario. The generated scenarios and the forecasted values of PV production, for a production period between t = 26 and t = 74 (i.e. between hours 06:30 and 18:30), are illustrated in Fig. 4.7. From these 20 scenarios, for reducing the computational burden, by applying mathematical manipulation [24].

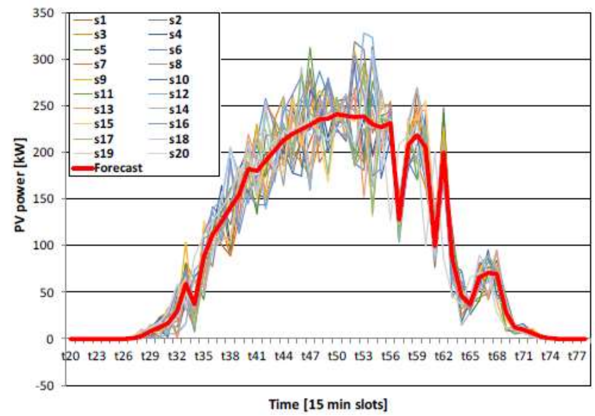


Fig. 4.7. Generated scenarios and forecasted values of PV production

Hypothesis A. The microgrid is operating during the 24 hours analysis horizon interconnected with the upstream grid. The exchanged energy with the upstream grid is settled such that to minimize the microgrid operational costs function of the electricity market price and before the PV production scenarios are occurring.

During midday, for scenarios where the PV production is low and the electricity price is high the thermal engine can be switched on. At time instant t = 79, when the electricity price is highest, the thermal engine is turned on and the storage system is fully discharged such that to sell energy to the upstream grid. At time instant t = 13, when the electricity price is lowest, the storage system is fully charged.

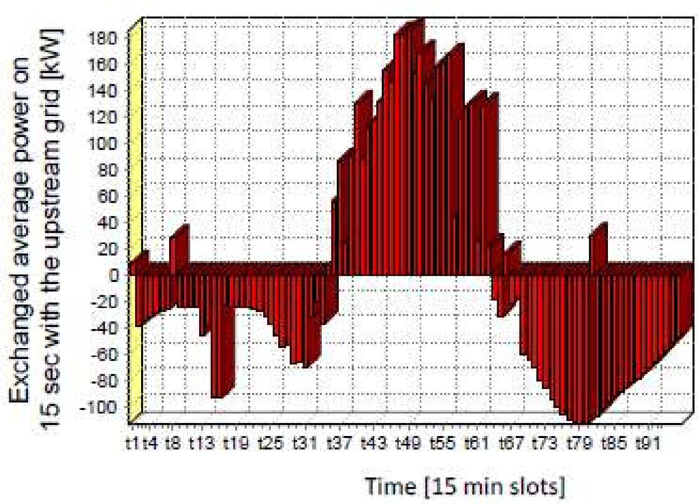


Fig. 4.8. Resulting exchanged energy with the upstream grid, *case II*, *hypothesis A*

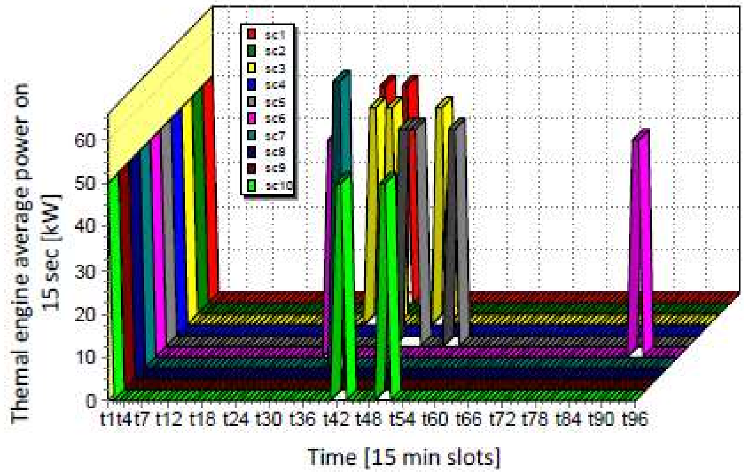


Fig. 4.9. Resulting thermal engine production schedule, *case II*, *hypothesis A*

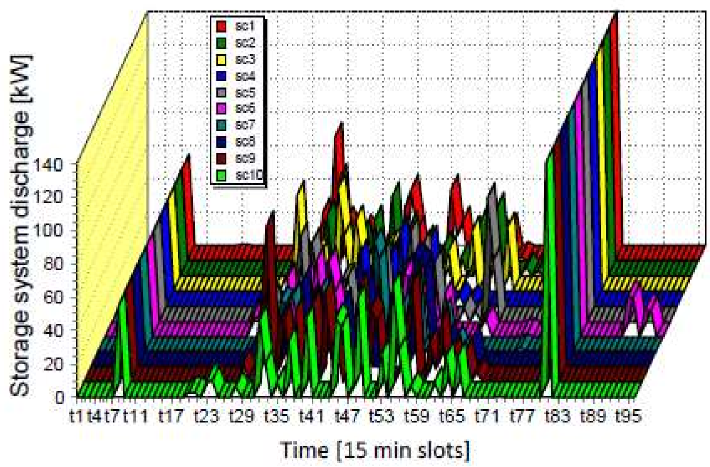


Fig. 4.10. Resulting storage system discharging schedule, *case II*, *hypothesis A*

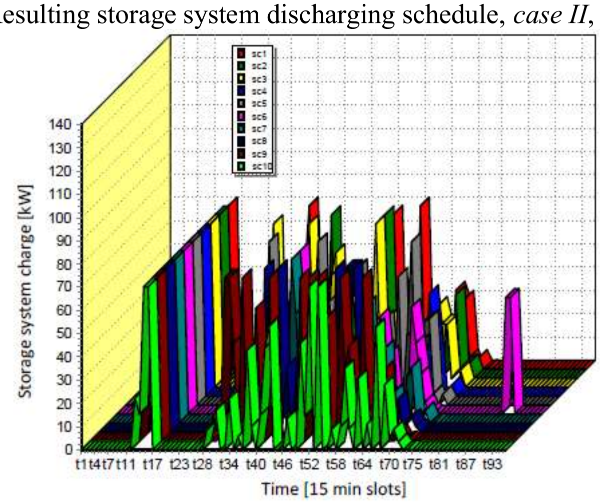


Fig. 4.11. Resulting storage system charging schedule, *case II*, *hypothesis A*

Hypothesis B. After a fault occurrence in the upstream grid, the disconnection of the interconnection breaker between the microgrid and the upstream grid is achieved.

The microgrid is operating in islanding state during the time interval t = 64–80 (i.e. between hours 16:00 and 20:00). The minimum demand for the 24 hours horizon is considered to be equal as in *case II*, *hypothesis A*.

The storage energy system is discharging such that to balance the load demand and to obtain the maximum revenue from selling energy to the upstream grid. During the 24 hours the number of cycles of discharge-charge is higher than in hypothesis A. This can lead to the storage system lifecycle decay and additional costs for the microgrid.

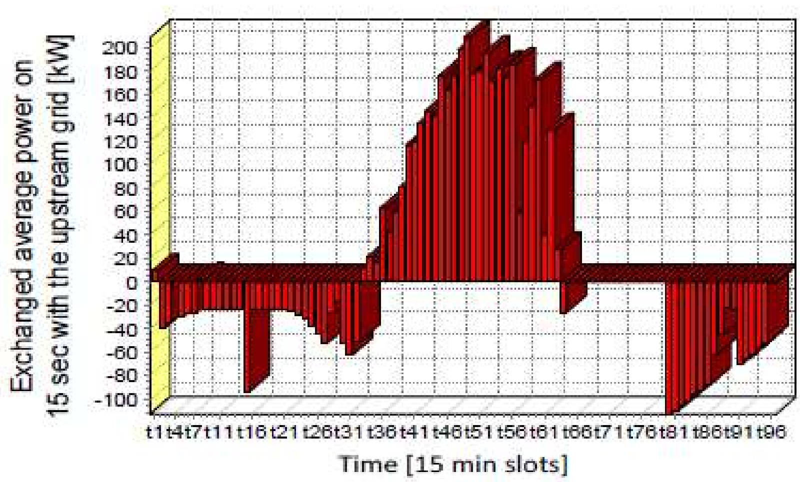


Fig. 4.12. Resulting exchanged energy with the upstream grid, *case II*, *hypothesis B*

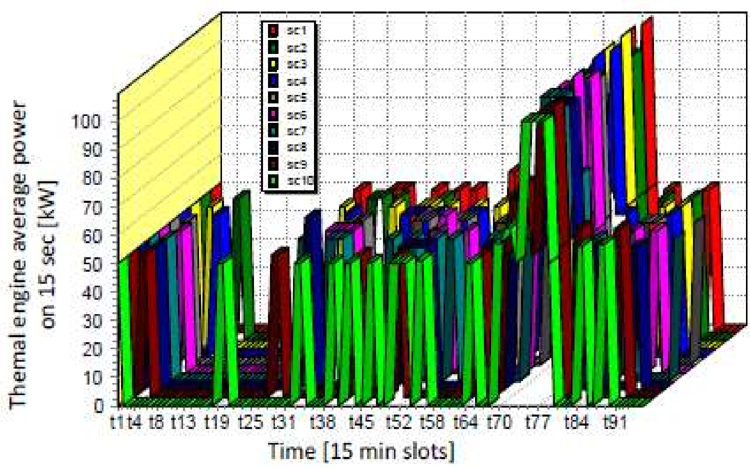


Fig. 4.13. Resulting thermal engine production schedule, *case II*, *hypothesis B*

Figure 4.14 illustrates the variation of objective function Cost. It can be clearly observed that the uncertainty of PV production infeeds on the microgrid operation involving addition costs and passing from a negative value (profit) to positive ones (expenses).

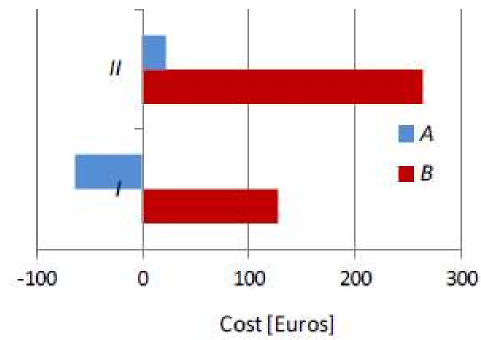


Fig. 4.14. Objective function *Cost* variation

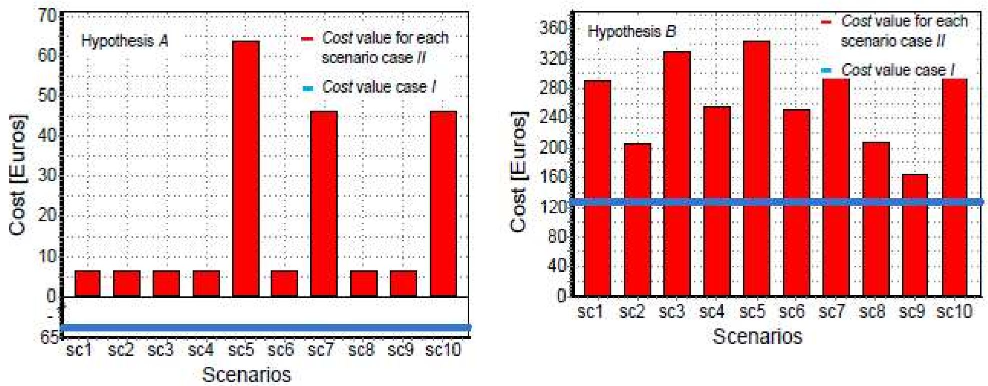


Fig. 4.15. Variation of objective function *Cost* values for each scenario, for *case I* (in blue) and *case II* (in red), under *hypothesis A* (left) and *hypothesis B* (right).

5. CONCLUSIONS

5.1. General conclusions

The doctoral thesis entitled „*OPTIMIZING THE OPERATION AND IMPROVING THE QUALITY OF ELECTRICITY IN ELECTRICITY DISTRIBUTION NETWORKS*” is part of the current concerns of participants in the energy sector to find the best solutions for end-users, using distributed energy sources and a high degree of security in the power supply.

- A solution to reduce the environmental impact of electricity production is the use of distributed energy sources (renewable energy sources and storage systems) near the place of consumption.
- The integration of distributed sources in existing energy systems influences their operating principles, their use having advantages and disadvantages.
- The large-scale integration, considering also the desideratum of the European ecological pact, of these sources in the electric power systems requires the detailed analysis of their impact on the operation of the system and the quality of the electric energy.
- Optimizing the operation of these sources in existing networks and Smart Grids requires consideration of the intermittent nature of these systems.
- Urban population growth and urban development require the selection of the best measures for the supply and integration of low-impact sources for the transformation of existing cities into "Smart Cities".
- The quantification of security in the power supply of end-users is done by using a set of indicators established by international standards.
- The increase in the number of equipment using process informatics has determined the need to take measures to reduce the economic damage that may occur in the case of non-power supply.
- Cities are a key element for global sustainable development and need to become smart as soon as possible to reduce the costs associated with infrastructure investments by optimizing energy systems, increasing energy efficiency, and continuity of supply.

- Smart urban infrastructures must become sustainable and focus on the well-being of the population, by providing affordable services.
- Energy needs in cities must be optimized following local characteristics, the particularities of the territory, and the requirements of the urban population.
- A synergy must be achieved between investments in the expansion of power systems, in the use of renewable sources, and storage systems / electric vehicles. The development of these sectors will lead to a wide range of benefits for smart cities.

The thesis aims at analyzing the electricity distribution network, in particular the urban network in a metropolitan area, in terms of network development and analysis of electricity quality.

The values recorded for SAIDI and SAIFI (unplanned outages) at the level of E-Distribution Muntenia do not fall within the average values obtained in advanced European countries. From this point of view, it can be concluded that in the Bucharest area the end-users are affected by unplanned interruptions, which occur as a result of wrong procedures or improper operation of the electricity network. A fault in a transmission transformer station can lead to a large area not being supply and disruption of the work schedule of large companies.

The implementation of microgrids can lead to increased security in the supply of electricity to final consumers, taking into account that a microgrid can also operate isolated from the distribution network.

From the perspective of electricity quality, the effects on electricity quality are felt especially in isolated operation but also when the microgrid switches the mode of operation. Changing the operation of the microgrid changes the type of control of renewable sources causing voltage stability problems.

The analysis carried out on the supply area of the Bucharest area led to the conclusion that it is necessary to develop the electricity network following the economic development. This can be implemented by the realization of at least one power injection transmission station in the electricity distribution network. The new station will be connected to the existing stations by making electrical cables.

Regarding the additional transport circuits, the Bucharest Metropolitan area does not require additional transport circuits, neither for bringing power to the area nor for transferring power inside the area if we take into account the reinforcements already provided in the “CNTEE Transelectrica Development Plan”.

For a development of the consumption of the Metropolitan area in the next 10 years, a new 400 / 110kV substation in the consumption center of Bucharest, next to an existing 110kV substation with multiple connections with other 110kV substations and double bar (for example 110kV Grozăveşti substation) would solve the problem transmission network. The distribution network must also develop in line with increasing consumption.

All conclusions presented are verified by calculations of stationary regimes, static stability, transient stability, and short-circuit verification.

The optimization model developed follows an efficient method for optimally operating microgrids by minimizing the functioning costs, accounting for intermittent production of photovoltaic systems and critical load supply.

The microgrid has local generation units (photovoltaic units), fueled thermal engine, battery energy storage systems, critical and interruptible loads. The purpose of the problem is to achieve an optimized scheduling of microgrid grid-connected and in islanding operations for a 24 hour time horizon, with 15 minutes time slots, minimizing costs considering generation and demand operational constraints.

5.2. Personal contributions

The following personal contributions of the author can be noted in this thesis:

- Analysis of continuity indicators in electricity supply, SAIDI and SAIFI for the E-Distribution operator Muntenia, in the years 2015-2019; from the analysis of these indicators it can be concluded that in the Bucharest area end users are affected by unplanned interruptions, which occur as a result of wrong procedures or improper operation of the electricity network,
- Implementation of the electricity network of the Bucharest area, modeling the existing sources in the area and of the consumptions in the network nodes, using a specialized calculation program,
- Development of simulations of stationary regimes with N and N-1 elements in operation in the 110kV area belonging to E-Distribuţie Muntenia,
- Because of consumer sensitivity to long-term outages, operating scenarios with N-2 elements in operation have been developed, representing operating regimes

with an element withdrawn from operation for inspection and an element is accidentally taken out of operation,

- Dynamic modeling of conventional generators and tracking of transient regimes that occur after a short circuit,
- Analysis of the maximum short-circuit currents on 110kV areas with a proposal to disconnect the network in case the admissible currents are exceeded,
- Identifying and proposing necessary reinforcement solutions in the supply network of the Bucharest Metropolitan area,
- Determining the static consumption characteristics of the active and reactive power achieved by using measurements from stations with significant consumption. The problem is particularly current after major system failures due to voltage collapses resulting from failure to take into account the regulatory nature of the load.
- Development of a mathematical model to optimize the operation of microgrids connected to the network and isolated over 24 hours (at intervals of 15 minutes), to minimize the overall costs of the microgrid taking into account the constraints of generation and demand.
- Implementation in GAMS of the components of a microgrid, composed of a photovoltaic system, a heat engine, an electrochemical storage system, interruptible and critical loads.
- Proposing and developing a deterministic model for the renewable and storage network and analyzing it in different operating regimes,
- Considering the intermittent nature of production from renewable sources, a stochastic mathematical model has been proposed and developed,
- Starting from real data recorded for a photovoltaic installation, 20 photovoltaic production scenarios were generated and based on mathematical methods, 10 relevant scenarios were selected and the possibility of each scenario was determined,
- The minimization of the operating costs of the microgrid has been achieved by considering the operation connected to the network and isolated,
- The elaborated case studies analyzed the minimization of the operating costs of the microgrid when the production of the photovoltaic source is known and a stochastic optimization model with intermittent production of the photovoltaic

source. Each case study analyzed 2 operating hypotheses: connected to the network and isolated operation.

- Elaboration of comparative analyzes of the variation of the objective cost function in the analyzed cases, resulting in the fact that the uncertainty of the production of the photovoltaic source leads to additional costs and determines the transition from profit (negative value) to expenses.

5.3. Future developments

- Extending urban development studies to other smart cities in Romania,
- Using a robust optimization mathematical model for microgrids with renewable sources,
- Optimal location of storage systems and charging stations for electric buses in Bucharest,
- Analysis of the quality of electricity in the Bucharest network with the gradual increase of the share of the installation with renewable sources with the converter in the production of the city of Bucharest,
- The zonal transformation of the supply of Bucharest in continuous voltage networks by creating positive energy clusters.

SELECTIVE BIBLIOGRAPHY

[1] Hermina Albert, Ștefan Gheorghe, Nicolae Golovanov, Radu Porumb, Luminița Elefterescu – Calitatea energiei electrice Contribuții, Rezultate, Perspective, Editura Agir, București, 2013.

[2] https://www.anre.ro/ro/energie-electrica/rapoarte/rapoarte-indicatori-performanta

[3] United Nations. World Urbanization Prospects: The 2018 Revision, Key Facts. 2018. doi:(ST/ESA/SER.A/366).

[4] OECD/IEA, IRENA. Perspectives for the Energy Transition: Investment Needs for a Low-Carbon Energy System. 2017.

[5] United Nations Environment Programme (UNEP). 21 Issues for the 21st Century - Results of the UNEP Foresight Process on Emerging Environmental Issues. vol. 2. Nairobi, Kenya: 2012. doi:10.1016/j.envdev.2012.03.005.

[6] IPCC. Global Warming of 1.5°C. vol. 265. 2018th ed. Geneva: 2018.

[7] EIB, UPM. Assessment Methodology for Smart City Projects - Application to the Mediterranean Region (ASCIMER). Luxembourg: 2017.

[8] Sustentable Citiess Index. Sustainable Cities Index 2016. Arcadis Glob 2016:10.

[9] World Health Organization. The Rise of Modern Cities. Hidden Cities Unmask Overcoming Heal Inequities Urban Settings 2010:3–10.

[10] Caragliu A, Del Bo C, Nijkamp P. Smart Cities in Europe. J Urban Technol 2011;18:65–82. doi:10.1080/10630732.2011.601117.

[11] Bakici T, Almirall E, Wareham J. A Smart City Initiative: The Case of Barcelona. J Knowl Econ 2013;4:135–48. doi:10.1007/s13132-012-0084-9.

[12] IESE Business School. IESE Cities in Motion Index 2014. Pamplona: 2014.

[13] JLL and The Business of Cities. The Universe of City Indices 2017 Decoding - Decoding City Performance. Chicago: 2017.

[14] International Telecommunications Union. United for Smart Sustainable Cities (U4SSC). Geneva: 2019.

[15] https://www.transelectrica.ro/ro/web/tel/planului-de-dezvoltare-ret-2020-2029

[16] PE 026/92, Normativ pentru proiectarea sistemului energetic național.

[17] CODUL TEHNIC al Reţelei Electrice de Transport. Revizia I. Aprobat prin Ordinul ANRE nr. 20/27.08.2004.

[18] PE 134/1995 Normativ privind metodologia de calcul al curenţilor de scurtcircuit în reţelele electrice cu tensiunea peste 1kV.

[19] IEEESTD-P2030-7-D9 Draft Standard for Specification of Microgrid Controllers

[20] *G.C. Lazaroiu, V. Dumbrava, S. Leva, M. Roscia*, “Virtual power plant with energy storage optimized in an electricity market approach,” In: International Conference Clean Electrical Power, 2015, pp 1–6.

[21] *A. Alqurashi, A. Etemadi, A. Khodaei*, “Treatment of Uncertainty for Next Generation Power Systems: State-of-the-Art in Stochastic Optimization,” Electr Pow Syst Res, **vol. 141**, 2016, pp. 233–245

[22] *M. Brenna, A. Dolara, F. Foiadelli, L. Gafaro, S. Leva, M. Longo*, “Solar energy exploitation for charging vehicles,” UPB Sci Bull-Series C, **vol. 77**, Issue 1, 2015, pp. 277-284.

[23] Virgil Dumbravă, George Cristian Lăzăroiu, Sonia Leva, **Georgiana Balaban**, Mihaela Teliceanu, Mihai Tîrșu - Photovoltaic production management in stochastic optimized microgrids, UPB Sci. Bull., Series C, Vol. 79, ISS. 1, 2017

[24] *J. Dupacova, N. Growe-Kuska, W. Römisch*, “Scenario reduction in stochastic programming: An approach using probability metrics,” Math Program., **vol. 95**, 2003, pp. 493–511.