National University of Science and Technology POLITEHNICA BUCHAREST

Doctoral School of ENERGY ENGINEERING

DOCTORAL THESIS

Analysis of the power quality aspects of advanced power systems

PhD supervisor
Prof. Dr. Eng. Radu PORUMB

Author
Eng. Mădălina CĂLIN-ARHIP

Bucharest
September 2024

THESIS CONTENTS

Thanks 5
List of abbreviations 6
Summary 7
Introduction 8
The context of the study 8
Main objectives 9
Thesis structure 9
1. Relevant theoretical aspects……………………………………………………10
1.1. Energy Efficiency……………………………………………………………...10
1.2. Quality of Electric Energy……………………………………………………..11
1.3. Energy generation from renewable sources……………………………………13
1.4. Active users (Prosumers)………………………………………………………13
1.5. Smart grids and blockchain……………………………………………………15
2. The impact of distributed sources on electrical networks………………………..16
2.1. General aspects…………………………………………………………………..16
2.2. The influence of distributed sources on the voltage level………………………..17
2.3. The impact of distributed sources on the circulation of powers…………………17
2.4. The influence of distributed sources on the operation of protections……………19
3. Analysis of load GRAPHS……………………………………………………….20
3.1. Mathematical aspects of load graphs……………………………………………..20
3.2. Classification of load curves……………………………………………………...21
3.3. Forecasting methods……………………………………………………………...22
3.4. Statistical correlations…………………………………………………………….23
3.4.1. Pearson's linear correlation coefficient…………………………………………...24
3.5. Abnormal values………………………………………………………………….25
3.5.1. Definition of the term outlier……………………………………………………..25
3.5.2. Methods of detecting abnormal values…………………………………………...26
3.5.3. The LOF algorithm……………………………………………………………….26
3.5.4. Z-score method…………………………………………………………………...28
4. Case studies and results…………………………………………………………..29
4.1. Data acquisition and normalization………………………………………………29

4.1.1. The measurement system used…………………………………………………...29
4.1.2. Modeling the UPB system……………………………………………………..33
4.1.3. Input data analysis……………………………………………………………..37
4.1.4. Analysis of power consumption during a week………………………………..38
4.1.5. Analysis of power consumption during a year………………………………...43
4.2. OFAT- One Factor at a Time…………………………………………………….44
4.2.1. Comparative analysis of power and temperature values……………………….46
4.2.2. Graphic representation of data on the electricity production side………………..47
4.2.3. Graphic representation of data on the electricity use side………………………..49
4.2.4. Daily evolution of the hourly production average………………………………..50
4.2.5. Daily evolution of the hourly average of use……………………………………..53
4.2.6. Representation of comparisons of the distributions of the hourly power values produced and used……………………………………………………………………….55
4.2.7. OFAT parametric analysis of the system…………………………………………62
4.2.8. Analysis of the results……………………………………………………………….64
4.3. Cluster analysis from 2020 to 2021………………………………………………66
4.3.1. Graphic representation of data on the electricity production side………………..66
4.3.2. Graphic representation of data on the electricity use side………………………..69
4.3.3. Graphical representation of common data………………………………………..72
4.3.4. The distances between the centroids……………………………………………...76
4.4. Cluster analysis from 2022-2023…………………………………………………79
4.4.1. Graphical representation of data in clusters………………………………………79
4.4.2. The distances between the centroids……………………………………………...82
4.5. Analysis of abnormal values (outliers)……………………………………………...83
4.5.1. Graphical representation – outlier program……………………………………... 83
4.5.2. Graphical representation – program outlier correlation…………………………85
4.6. Pearson correlation analysis……………………………………………………...86
4.6.1. Analysis period of one week……………………………………………………...86
4.6.2. Analysis period 2020-2021……………………………………………………….87
4.6.3. Analysis period 2022 – 2023……………………………………………………..90
4.7. Results – recommendations………………………………………………………91
5. Conclusions……………………………………………………………………….92
5.1. General conclusions………………………………………………………………92
5.2. Original contributions…………………………………………………………….94
5.3. Prospects for further research…………………………………………………….94
Bibliography 95

Appendix 1 – Results of the data normalization process for the analysis of power consumption during one year [64] 100

Appendix 2 – MATLAB programs 127

KEYWORDS

Active users (*prosumers*), photovoltaic panels, load curve analysis, power *outliers*, voltage *outliers*, OFAT, clusters, correlation, euclidean distance analysis

EXTENDED ABSTRACT

In the last two decades, the evolution of human society has directly influenced the increase in energy demand. Due to the fact that the power system has a structure built over several decades, it presents a wide technological spectrum. This is a vulnerability, because the implementation of new technologies cannot be done without adaptation.

Currently, the field of advanced power systems is in various stages of development. In this sense, the end users of electricity are evolving towards the status of *prosumers* , who will have the ability to produce, store and sell energy through local energy markets, configurable with the help of new technologies.

The prospect of streamlining industrial processes, accelerated by the emergence of intelligent command and control systems, will improve the distribution of production resources by enabling engineers to adapt in real time and continuously to system needs. In the future, the most efficient production chains will be identified and used, resulting in cheaper, more reliable and low-carbon final products.

The aim of the thesis is to establish the connection between the power produced by *the prosumers* and the energy use behavior, which can be achieved through the following steps :

- Identification of minimum, average or maximum values of active, reactive, apparent power
- Evaluation of the daily evolution of the hourly average of production and use
- Clustering the data and determining the distances between the resulting centroids
- Detection of power and voltage *outliers*
- Determination and interpretation of the Pearson correlation coefficient

The study presented in the thesis is divided into five chapters and two appendices : one resulting from the data normalization process for the analysis of power consumption during a year and one containing the Matlab programs. The thesis also includes the specific chapters "Introduction", "Conclusions" and "Bibliography".

The first chapter aims to briefly present the theoretical aspects regarding energy efficiency, power quality, energy generation from renewable sources, as well as explaining the notions of *prosumers* and *blockchain* .

By increasing the energy efficiency, the economic competitiveness of the products can be increased, considering that the investment in the development of the generation-transport-distribution infrastructure involves high expenses compared to the investment in increasing the efficiency. At the same time, by reducing the level of environmental pollution, the funds needed in the health system are also reduced [1].

The quality of electricity determines the efficiency of activities in industry or the household sector. May be affected by interference with frequencies up to 10 kHz. They can occur not only in energy system components and supply processes, but also in end-user processes. Permissible deviations from the quality indicators are established on the basis of damage that could occur in the production, transport and distribution systems, as well as in the supply and use of electricity in deviations from the ideal values. Narrowing the frequency spectrum to 10 kHz, there are three categories that define power quality: quality of service supply (long-term power outage), supply voltage quality and commercial quality (supplier – user relationship).

The promotion of electricity production from renewable energy sources was achieved both by Law No. 220 of 2008 , as well as by adopting the Energy Strategy until 2030.

According to the Directive of November 2023 [2], the objective for 2030 regarding renewable energy sources is 42.5%. It is also desired to reach 1% by 2025 and 5.5% for the year 2030 regarding the use of biogas and hydrogen in the automotive sector.

The second chapter presents theoretical information regarding the influence of distributed sources on electrical networks. The valorization of renewable sources can be done following two directions, energy security and sustainable development [3]. Security objectives are achieved by diversifying energy sources and by strengthening energy security by ensuring demand for resources and reducing imported energy resources. The second objective aims at increasing energy efficiency through the rational use of primary resources, promoting the production of energy from renewable sources and reducing the negative impact of the energy sector on the environment [4].

By introducing the distributed sources, the voltage increase after connecting them or the voltage decrease in the case of disconnection is found. Also, the distributed source can cover partially, fully the consumption of the entire network, as well as the injection of the surplus into the electrical network.

Pearson correlation [8] and *outlier* detection methods [9].

Chapter four is intended to explain the case studies, being structured in several sub-chapters. Thus, the method of obtaining, normalizing and analyzing the data used, the OFAT analysis, the analysis of clusters and *outliers , as well as the* Pearson correlation, is presented .

The thesis analyzed data collected from the years 2020 - 2023 recorded in the Faculty of Energy both on the use side and on the production side of electricity . work provides an overview of the behavior of users within the Faculty of Energy in normal operation, but also in the case of special situations, such as the COVID-19 pandemic, which determined the transition of education to the online system.

By carrying out direct measurements carried out at the General Distribution Board, it was possible to identify the different working regimes and at the same time carry out a statistical analysis of the important values of the active, reactive and apparent powers (minimum, average, maximum).

The data analysis using the OFAT method aimed to identify the criticality of certain factors in order to evaluate the quality and efficiency of the analyzed processes. In the first stage, a number of twelve scenarios resulting from the analysis parameters were proposed, namely: semester, the period of data acquisition, as well as the working or non-working character of the day.

From the comparative analysis of the normalized values from the years 2020 - 2021 of power and temperature, the following general conclusion emerged, that in order to obtain high yields of photovoltaic panels, the external temperature must be between 10°C and 25°C.

Also, by means of the graphic representations of the daily evolution of the production hourly average, it was found that the operation interval of the photovoltaic panels in the cold season is between 7 am and 5 pm, reaching some maxima between 11 am and 3 pm, and in the rest of the periods the interval of operation is increased, between 6 a.m. and 7 p.m. The analysis of the work scenarios of the daily evolution of the hourly average used highlighted the energy consumption behavior on non-working days follows the same shape of the load curve, which will allow, in the future , the possibility of implementing some electric charging stations that provide high powers at the weekend compared to the rest of the week.

The superimposition of the production data with the usage data aimed to implement the data in the MATLAB calculation program that would allow a 2D analysis of the dispersion of the common values and a 3D representation of the analyzed parameters (power produced, used and time) from which resulted the presence of three or four clusters and *outliers* depending on the analyzed scenario. It was also concluded that the photovoltaic system can support the load for approximately five hours, which allows the provision of the *load shedding service* .

Another stage of the research turned to cluster analysis. From the analysis of the data from 2020 – 2021, it was concluded that the number of scenarios can be halved, resulting in six scenarios that were implemented in the MATLAB calculation program in order to determine the optimal number of clusters. The graphic representation of the data for the three cases (of three, four or five clusters) allowed the identification of the time zones of production, respectively use, as well as *outliers* . Although, from the images presented in the thesis, it was observed that increasing the number of clusters from three to five would allow a thorough analysis of the data, after calculating the Euclidean distances between the resulting centroids, it was concluded that for the analyzed databases, the optimal analysis solution remains the three-cluster one, thus minimizing analysis errors. At the same time, we came to the conclusion that the presented *outliers* actually represent normal values taking into account the users within the faculty, namely the operation of the laboratories, which causes the increase in consumption for a short period of time.

In the cluster analysis of 2022 – 2023, the number of scenarios was significantly reduced to two, where the entire database was divided into working and non-working days. And in this case, following the analysis of Euclidean distances, the optimal solution of dividing into three clusters resulted. Also, for this last set of data, with the help of the MATLAB program, we created an algorithm to identify abnormal power and voltage values, which allowed observing the behavior of the electrical distribution system in the presence of the local electricity generation system.

All analyzed databases were subjected to the process of determining the Pearson correlation coefficient. This allowed the drawing of some general conclusions regarding the existence of correlations between working and non-working days, correlations between the values recorded between semester I and II, as well as the correlation between voltage and power determined for the last data set. Thus, these data can provide an analysis tool for those who have information only on the voltage side and who need to know the degree of correlation with the presence of distributed sources, implicitly *prosumers* . This allows them to have the possibility of increasing or decreasing the voltage level or restoring the degree of connection of the network using other connections.

SCIENTIFIC CONTRIBUTIONS

Included in the research study are personal contributions related to ensuring the quality level of electricity

1. Documentation of specialist articles on:
    a. Important theoretical aspects regarding the efficiency and quality of electricity
    b. Impact of distributed sources on power grids
    c. Load curve analysis indicators and forecasting methods
    d. Methods of detecting abnormal values
2. Analysis of multiple data sets to obtain relevant data that provides information on common characteristics between electricity production and use
3. Progressive turn-by-turn analysis of influencing factors – OFAT
4. The influence of photovoltaic panels on energy efficiency from the perspective of prosumers
5. Data implementation in the MATLAB calculation program regarding:
    a. 2D dispersion analysis and 3D representation of the analyzed parameters
    b. Identifying the optimal number of clusters
    c. Detection of abnormal power and voltage values
6. Establishing the Pearson correlation coefficient for all analyzed databases
7. Dissemination of study results in international conferences such as UPEC 2019, ISFEE 2020, UPEC 2020, MPS 2021, ICATE 2021, UPEC 2022, UPEC 2024, but also EMERG, Sustainability 2021 magazines, the Scientific Bulletin of the Polytechnic University of Bucharest

BIBLIOGRAPHY

[1] Nicolae Golovanov, Radu Porumb, Cornel Toader, Nicolae Mogoreanu,, Energy efficiency. The environment. Modern economy, Agir Publishing House, 2017.

[2] ***, [Interactive]. Available: https://www.europarl.europa.eu/factsheets/ro/sheet/70/energia-din-surse-regenerabile. [Accessed 15 07 2024].

[3] Alexandra Mânzat, Cristina Daniela Deac, "The opportunity of using solar energy in Romania," in *the 12th multidisciplinary National Conference - with international participation "Professor Dorin Pavel - the founder of Romanian hydropower"* , Sebeș, 2012.

[4] ***, "Government Decision no. 1069 of September 5, 2007 (HG 1069/2007) regarding the approval of Romania's Energy Strategy for the period 2007-2020 published in Official Gazette 781 of November 19, 2007 (M. Of. 781/2007)".

[5] N. Golovanov, I. Ionescu, N. Mira, P. Postolache, C. Toader, Electrical energy consumers, Bucharest: Agir Publishing House, 2009.

[6] L., Stoyanov, Z., Zarkov, I., Draganovska, V., Lazarov, "Methods for Energy Production Estimation from Photovoltaic Plants: Review and Application," in *International Conference on High Technology for Sustainable Development (HiTech)* , Sofia, Bulgaria, 2018.

[7] DR Chandra, MS Kumari, M. Sydulu , "A detailed literature review on wind forecasting," in *International Conference on Power, Energy and Control, ICPEC* , India, 2013

[8] A. Ayadi, O. Ghorbel, A. M. Obeid, M. Abid, „Outlier detection approaches for wireless sensor networks: A survey,” *Computer Networks,* vol. 129, pp. 319-333, 2017.

[9] H. Wang, M. J. Bah and M. Hammad, „Progress in Outlier Detection Techniques: A Survey,” *IEEE Access,* vol. 7, pp. 107964-108000, 2019.