NATIONAL UNIVERSITY of SCIENCE and TECHNOLOGY
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DOCTORAL SCHOOL of ELECTRICAL ENGINEERING

EXTENDED ABSTRACT
Doctoral THESIS

Electrotechnical methods in monitoring energy conversion systems

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Content

Chapter 1 – Bibliographic Research

Introduction

The Electric Power System includes interconnected installations for producing, transmitting, distributing, and utilizing electrical energy, which are essential for the modern economy. Understanding these systems progresses through formulating laws that describe natural phenomena, and precise measurements are fundamental for their analysis. Accurate measurement of electrical quantities is essential in electrical networks, using measuring instruments that can be connected directly or indirectly, depending on the electrical voltage at which the measurement is to be taken. Measurement transformers allow for precise values in medium and high voltage networks, adjusting measurements according to transformation ratios.

1.1 Presentation of the Doctoral Thesis

In the thesis, the theory of asymmetric and residual power components (theory of Acad. Andrei Țugulea) was fully verified, considering that the author could experimentally verify the theory only regarding the conservation of asymmetric powers. In contrast, residual powers had an order of magnitude comparable to the accuracy class of measuring instruments. Therefore, the verification of residual power balances could not be conclusively performed, as indicated in the paper "Criteria for the definition of the electric power quality and its measurement systems" by A. Țugulea, ETEP 1996 (https://doi.org/10.1002/etep.4450060518) [12]. In this doctoral thesis, the degree of nonlinearity of the utilized consumers allowed the identification of active and reactive residual power circulation through the verification of corresponding power balances. Furthermore, the theoretically demonstrated hypothesis was practically verified, according to which "more deforming" receivers are the source of residual power generation, which is then absorbed by receivers presumed to be "linear" and/or "less deforming".

The thesis explores existing theories regarding reactive power calculation, compares the models of Fryze and Budeanu, and addresses the challenges associated with these theories in modern electrical networks. Additionally, methods for measuring electrical power and energy in complex networks are investigated, including the application of measuring transformers and analyzing the balance between the symmetric and asymmetric components of power flows. The main goal is to provide innovative solutions that improve the efficiency and reliability of electrical energy conversion systems through advanced monitoring and power flow control techniques.

1.2 The Purpose of the Doctoral Thesis

The Doctoral thesis's main objective is to develop and validate advanced methods for monitoring power flows in complex electrical networks, with a particular focus on analyzing and optimizing energy management under nonlinear and unbalanced load conditions. The thesis aims to improve the accuracy of electrical measurements by comparing existing theories, such as those of Fryze and Budeanu, and by applying Tugulea's power theory, validating it experimentally and through numerical simulations. This integrated approach allows for a better understanding of the behavior of electrical networks and the influence of symmetric and asymmetric components on power flows.

1.3 The Content of the Doctoral Thesis

The doctoral thesis is structured into several key chapters, starting with detailed bibliographic research on the existing studies and theories in power flow monitoring in electrical networks. It then presents the disturbances in electrical networks, emphasizing their impact on the system's performance and stability.

Another central point of the thesis is the analysis of the theories for calculating reactive power, comparing Fryze's and Budeanu's models. Subsequently, the theoretical and experimental demonstration of Tugulea's power theory is presented, where the power balance in a network is verified, regardless of disturbances that may arise. These verifications confirm the validity of the theory and the complexity and challenges encountered in analyzing disturbed networks.

Chapter 2 – Research on the Operating Regimes of an Electrical Network: Generation, Transmission, and Distribution of Electrical Energy

Energy systems have evolved significantly over time, with essential technical and economic transformations, and the laws of physics govern their operation. Electrical networks, classified into high and low-voltage networks, play specific roles in the energy infrastructure and require appropriate strategies to ensure the continuity and quality of the energy supplied.

The development of distributed generation and microgrids has changed the traditional structure of distribution networks, enabling local energy production but also creating new challenges for the stability of the network. These changes require advanced monitoring and control solutions to manage fluctuations from renewable sources and improve the efficiency and stability of electrical networks.

2.1. Electrical Networks

Electrical networks are complex systems that ensure the generation, transmission, distribution, and utilization of electrical energy, playing the essential role of delivering energy from production sources to end consumers. The quality of the electrical energy supplied is monitored through a series of indicators, such as voltage, frequency, power factor, and harmonic distortions, which must comply with established standards to guarantee the performance and safety of the users' electrical equipment.

2.1.1. Generation, Transmission, Distribution, and Utilization of Electrical Energy

The energy needs of consumers are met by generating units that continuously regulate active power and frequency to respond to the fluctuating requirements of the network, thereby maintaining stable voltage and a sinusoidal waveform. The energy transfer to consumers is achieved through transformer stations and overhead electrical lines, designed to ensure supply continuity and prevent failures, even under extreme network load conditions.

Electrical networks are designed to operate in a loop, ensuring an energy reserve to protect consumers in the event of a failure. However, disruptive consumers, such as those with nonlinear or unbalanced elements, can negatively affect the stability and quality of electricity delivery, creating voltage fluctuations and instabilities that must be managed with advanced protection and adjustment solutions.

2.1.2. Disturbances and non-symmetry

Electromagnetic interference is any phenomenon that can affect the operation of electrical equipment, disrupt the quality of electrical energy, or influence the health of living organisms. These disturbances can be of various types, such as low-frequency signals propagating through conductors or high-frequency signals propagating through the air. They can include phenomena like flicker, harmonics, voltage fluctuations, voltage drops, or disturbances caused by lightning strikes or network equipment faults.

These interferences can affect not only the reliability of equipment and the stability of networks but also the comfort of users, causing physiological discomfort or damage to electronic devices. Additionally, electromagnetic disturbances can significantly impact the quality of the electricity service. Parameters like frequency, voltage amplitude, transient overvoltages, and voltage dips are essential for maintaining a stable and reliable system.

These interferences can be caused by equipment with nonlinear loads, voltage imbalances, or rapid voltage fluctuations due to industrial or welding equipment. Monitoring and controlling these disturbances is crucial for ensuring quality power supply and preventing severe faults in electrical networks.

2.2. Power Transfer in Electrical Networks

Monitoring the power factor is essential for optimizing the performance of energy operators and reducing energy losses in the network. Managing it becomes a priority, as a low power factor can affect the network's stability and result in financial penalties for consumers who generate additional losses.

2.2.1. Power factor definition

The power factor (PF) represents the ratio between active and apparent power in an electrical system, an essential parameter for evaluating energy efficiency. A PF close to 1 indicates that most of the supplied energy is converted into sound (active) energy, and reactive energy losses are minimal, leading to efficient use of electrical energy.

It can vary depending on the waveform (sinusoidal or non-sinusoidal) and the type of system (single-phase, three-phase, balanced, or unbalanced), and proper management of it is essential for maintaining a stable and efficient energy system.

A low power factor indicates that only part of the supplied energy is effectively used, while the rest is lost as reactive energy. These losses reduce energy efficiency and can overload network equipment, increasing the risk of failures and operational costs.

2.2.2. Methods for optimizing the power factor

Two main approaches are required to improve the power factor: separate analysis of reactive power and the deforming regime of the current, as well as their simultaneous analysis. In the first approach, current distortions are limited through passive filters, and reactive power is compensated. In the second approach, active filters are used to correct both distortions and phase shifts of the current, thus achieving unified compensation and better network performance.

Chapter 3 – Power Flow Monitoring in End-User Consumption Systems

3.1. Power Flow Measurement

The theories of Budeanu and Fryze represent two fundamental approaches to analyzing reactive power, each having significant contributions and limitations. Budeanu's theory, while influential in defining reactive power, has been criticized for an incomplete interpretation of power phenomena. Fryze's theory, on the other hand, brought a more profound understanding by decomposing current into orthogonal components. However, Fryze’s idea of explaining the properties of power solely in the time domain was abandoned, and studies have highlighted both the advantages and limitations of the two theories, depending on the circuit and operational conditions.

In analyzing circuits with non-sinusoidal voltages and currents, Budeanu's and Fryze's theories yield different values for reactive power, highlighting the importance of precisely defining reactive power in such conditions. The differences between these values reflect the limitations of each theory in practical applications, and network disturbances and consumer influences can significantly affect reactive power measurements. These theories are applied differently depending on the analysis requirements and the technologies used for power factor compensation.

3.2. Studied Cases – Measurements, Results, and Discussions

Field measurements were conducted on two distinct categories of consumers to analyze the impact of consumers on power quality, and the results obtained were compared using Budeanu's and Fryze's theories. The equipment used for measurements was a Checkmeter 2.3 genX device, a portable three-phase instrument used for calibrating measurement equipment and obtaining precise measurements of voltage, current, and power.

3.2.1. Disturbances in the electrical network for an office building type consumer

An electricity consumer in an office building consists of various electronic equipment essential for daily activities, such as computers, printers, and lighting systems. These devices are interconnected to create an optimal working environment, and the total energy consumption varies depending on the number of devices used and the types of activities carried out. In the experiment, a much more pronounced harmonic spectrum was observed, with the current on the second phase being the most affected by distortions, indicating an asymmetry in energy consumption. The high distortion factor and inter-harmonics suggest a significant power quality disturbance caused by various electrical devices, such as electric heaters and air conditioning units.

3.2.2. Disturbances in the electrical network for a residential complex type consumer

Measurements taken near the transformer station in the residential complex indicated a maximum simultaneous power absorption from the distribution network of 99 kW, with a predominantly inductive behavior of the reactive power. Analyzing the harmonic spectrum, a much higher presence of inter-harmonics was observed compared to the first case, suggesting that the distributor intentionally injects interharmonics to control the equipment in the transformer station. These interharmonics may also be generated by disturbances caused by consumers in the area. A measuring device was installed between the client and the distributor at the boundary point, ensuring an accurate energy evaluation.

Upon analyzing the impact of consumers on the distortion of current and voltage waveforms, it was found that residential equipment, such as household appliances, has a lesser effect on power quality than those in commercial environments. However, careful monitoring remains crucial to optimize energy consumption and prevent power fluctuations that could affect the electrical grid's stability.

Chapter 4 – Experimental evaluation of the effects of imbalance in three-phase networks without a neutral conductor

In recent years, power electronic equipment and alternative energy sources have introduced new challenges in managing electrical grids, placing pressure on the system due to imbalances and harmonic distortions. These imbalanced regimes affect energy efficiency and the stability of networks, causing significant energy losses.

This report applies Tugulea's power theory to an experimental platform to evaluate the impact of phase imbalances and nonlinearity on three-phase networks. The theory allows for separating active, reactive, and distortion power, offering accurate energy billing. The study contributes to improving energy management and efficiency in the face of new technological challenges.

4.1. Experimental circuits

Two models were proposed to simulate power flow in a three-phase circuit and analyze the behavior of electrical networks disturbed by nonlinear components. Experimental Circuit A includes an experimental circuit without a neutral conductor, with a nonlinear element on the first phase of the first disturbing consumer and the third phase of the second disturbing consumer. The nonlinear elements are similar but have different conduction angles. This model highlights the unequal distortion in currents and voltages, essential for analyzing imbalances and circulating power phenomena in the three-phase network.

In experimental circuit B, the configuration of the experimental circuit is slightly modified to introduce more nonlinear elements—two in phases 1 and 2 of the first disturbing consumer and different value capacitors in phase 3, in parallel. For the balanced consumer, three identical capacitors are mounted on each phase, eliminating the distortions induced by the nonlinear elements. This model adds complexity to the electrical network and allows more detailed observation of their impact on the stability and efficiency of the power supply, with the goal of better understanding how power fluctuations can affect the system's overall performance.

4.2. Studied cases – measurements, results, and discussions

The experiments involved using four Janitza UMG 509-PRO network analyzers to simultaneously acquire voltage and current waveforms at various points in the network. Additionally, a Chauvin Arnoux C.A. 8336 analyzer was used to capture screenshots of waveforms and corresponding histograms of harmonic content, which is used for monitoring and analyzing the electrical power quality.

4.2.1. Experimental Circuit A

The measurements are taken at three key points in the experimental circuit. These points include the connection terminals of the experimental circuit, the connection terminals of the first disturbing consumer, and the connection terminals of the second disturbing consumer. Each of these acquisitions is essential for analyzing power flows in a three-phase system, and the disruptive effects of nonlinear consumers are tracked through precise measurements at each connection point.

Data acquisition, performed sequentially at these measurement points, allows for a detailed analysis of the current and voltage waveforms and the harmonic distortions introduced by the nonlinear consumers. For example, in the first acquisition, the waveforms of the measured currents and voltages at the terminals of the experimental circuit show significant distortions, especially in phases 1 and 3, where nonlinear elements are placed. These distortions are quantified by indicators such as total harmonic distortion (THD), which has higher values in the phases influenced by the nonlinear consumers. These observations suggest a considerable impact on the electrical power quality and the system's efficiency, indicating the need for filtering or correction measures to reduce these distortions.

4.2.2. Experimental Circuit B

In the second experiment, where more nonlinear elements are integrated on phases 1 and 2 of the first disturbing consumer, there is a significant increase in the distortion of the waveforms, both for currents and voltages. The total harmonic distortion (THD) values are much higher than the first model, highlighting the significant impact of these nonlinear elements on the circuit. The circuit parameters—resistances and inductances—are different from those of the balanced consumer, allowing for observing their influence on the system's overall behavior.

Data acquisition is done at three essential points: at the terminals of the experimental circuit, at the first disturbing consumer (with nonlinear elements), and at the balanced consumer, which contains only linear elements. Compared to the previous model, the total harmonic distortion analysis shows an intensification of distortion in phases 1 and 3, which aligns with the high THD values. The differences observed between the waveforms of the currents and voltages reflect the substantial impact of nonlinear elements on the quality of the energy distributed in the network.

Chapter 5 – Laboratory platform for demonstrating the Tugulea power theory applied to network models with neutral conductor

Asymmetric and distorted waveforms represent significant challenges to energy efficiency and the stability of electrical systems. Phase imbalances and harmonic distortions can lead to considerable energy losses and put additional strain on equipment in electrical networks. Therefore, managing these conditions becomes essential for ensuring a stable and reliable power supply to consumers, reducing their negative impact on the overall performance of electrical systems. Thus, studying these effects is crucial for optimizing the design and operation of modern electrical networks to prevent energy losses and improve the quality of the supplied power.

This paper explores the impact of deforming and asymmetric regimes on energy efficiency through an experimental circuit. Using a neutral conductor in the circuit configuration can accurately assess the influence of imbalances and distortions on the system, considering its role in stabilizing voltages and reducing adverse effects. The experiment seeks to highlight how nonlinear elements and harmonic distortions influence the transfer of active and reactive power, creating additional losses and disrupting the stable operation of electrical networks. These observations will contribute to a deeper understanding of how asymmetric and deforming regimes affect electrical systems, offering valuable perspectives for improving energy management in electrical infrastructures.

5.1. Experimental circuits

As part of the study on the importance of the neutral conductor in a circuit with unbalanced electrical loads and nonlinear elements, two distinct experimental models were proposed to analyze its behavior under various conditions. In Experimental Circuit A, a disturbing consumer has two nonlinear elements installed on phases one and two, while capacitors are mounted in parallel on phase three. The second consumer is balanced, without nonlinear elements, highlighting the circulation of electric power between consumers due to imbalances and harmonics generated by the nonlinear elements.

Experimental Circuit B focuses on two distorted consumers with nonlinear elements that introduce imbalances and higher-order harmonics. A nonlinear element is installed on the first phase of the first consumer, and another is placed on the third phase of the second consumer, with capacitors added to phase three of the first consumer and an inductor on phase two. Both models allow the study of these imbalances' effect on the circuits' performance and efficiency.

5.2. Studied cases – measurements, results, and discussions

The experiments were based on four Janitza UMG 509-PRO network analyzers, which allowed the simultaneous acquisition of voltage and current waveforms at critical points in the network, accurately evaluating the circuit's behavior under nonlinear and unbalanced load conditions. To perform a detailed analysis of higher-order harmonics and generate corresponding histograms, a Chauvin Arnoux C.A. 8336 network analyzer was used, which allowed the identification of harmonic distortions caused by the nonlinear elements in the network.

5.2.1. Experimental Circuit A

Measurements for the first experimental model were taken at three essential points, selected to support the determination and analysis of power flow according to Tugulea’s theory. The first acquisition point is located at the connection terminals of the experimental circuit to the three-phase source. In contrast, the second and third points are placed at the terminals of the disturbing and balanced consumers. These locations allow for detailed monitoring of variations and effects of currents and voltages in the tested circuit, providing crucial information about the influence of nonlinear and balanced loads on the electrical network.

Measurements taken at these points indicate the presence of significant distortions in currents and voltages, especially near the disturbing consumer, where nonlinear elements cause imbalances and harmonic distortions. Analysis of the waveforms and harmonics reveals a considerable impact on power flow, and the harmonic distortion values reflect differences in network behavior depending on the load configuration. These measurements are essential for understanding the interaction between loads and for correctly applying Tugulea’s theory in evaluating the performance of the electrical network under conditions of imbalance and distortion.

5.2.2. Experimental Circuit B

In the case of model two of the experimental circuit, where nonlinear elements are distributed individually for each consumer, both groups of loads act as disturbing sources. This creates a complex dynamic in the electrical network, where each disturbing consumer influences the supply voltages and currents, generating significant harmonic distortions. In this configuration, the combined effects of the two disturbing sources are amplified, and the current and voltage waveforms are modified in distinct ways, depending on the characteristics of each consumer. The configuration offers an opportunity to study how two disturbing sources interact in a three-phase system and their cumulative impact on the electrical network.

An important aspect in analyzing model two is the significant difference between the parameters of the components used for the first and second disturbing consumers. These differences are not limited to the values of resistances and inductances but also include variations in the conduction angles of the nonlinear elements, which significantly impact the circuit's behavior. Different conduction angles influence how consumers interact with the network, generating specific harmonic distortions for each phase. This diversity in operating parameters adds complexity to the analysis, requiring a detailed evaluation of the combined effects on the circuit's performance and stability and the quality of the supplied electrical power.

5.2.3. Software simulation

The method for solving the proposed problem is based on a combination of practical experiments and numerical simulations using OrCAD X, an advanced electrical circuit analysis software. This combined approach is essential for validating Tugulea’s power theory, applied to network models with a neutral conductor in unbalanced circuits with nonlinear elements. OrCAD PSpice, the simulation component of the Cadence package, allows for a detailed analysis of transient phenomena, harmonic distortions, and circuit stability. Using this software, it is possible to simulate circuit behavior under variable conditions, confirming experimental results and providing a deeper understanding of the effects of nonlinearities on electrical networks.

Numerical simulations complement practical experiments, allowing for the rapid and controlled acquisition of additional results. In this process, detailed electrical schematics include electrical loads with different characteristics, allowing precise analysis of the influence of nonlinearities on the distribution of current and voltage in the circuit. Moreover, the voltage-current characteristics of the electrical loads are implemented in the simulation environment, which enables the correlation of experimental measurements and numerical simulations. This approach ensures rigorous validation of the theory. It provides a solid foundation for understanding the behavior of electrical circuits with nonlinearities and imbalances, highlighting the applicability of Tugulea's power theory in real electrical networks.

Chapter 6 – Conclusions

In industrial electrical networks, nonlinear loads, such as high-power motors and welding equipment, generate harmonics that significantly distort voltage and current waveform. These distortions directly impact energy efficiency, leading to significant losses and reducing system stability. Furthermore, these harmonics can cause overheating of equipment, shortening their lifespan and leading to premature failure of components. As a result, the network's efficiency is affected, and the risks of additional maintenance and repairs are higher, generating extra costs for operators and consumers.

At the same time, phase imbalances in electrical networks, such as amplitude deviations or 120° angles, exacerbate these problems. These non-symmetry not only contribute to distortions but also induce energy losses and reduce the overall stability of the network. Considering these imbalances and nonlinearities, these disruptive effects highlight the need for stricter control of power flow. By using advanced measurement and simulation methods, it is possible to optimize power flow management, improving the performance of electrical networks and preventing damage to connected equipment.

The doctoral thesis focuses on developing and implementing advanced electrotechnical methods for monitoring power flows in electrical networks, aiming to optimize the management of electrical energy under conditions of complex, nonlinear, and unbalanced loads. The research addresses a detailed analysis of electrical phenomena through both practical experiments and computer-assisted simulations, placing special emphasis on validating the power theory of Țugulea. This approach contributes to improving the accuracy of measurements and developing high-performance technical tools that can support real-time monitoring of energy flows.

Additional confirmation of the theoretical validity and experimental results was obtained through the power balance of symmetric, asymmetric, and residual powers, carried out through the numerical simulation of circuits physically implemented in the laboratory using the Spice software package. The practical values of the voltages and currents provided by this simulation allowed the development of a calculation program capable of decomposing the signals into Fourier series (for higher harmonics) and into symmetric components (direct, inverse, and, if applicable, homopolar— for the fundamental harmonic).

Based on these components, the powers corresponding to the theory of symmetric, asymmetric, and residual components were determined, with power balances being verified with deviations of less than one percent in most cases—this theoretical and practical validation of the theory developed by Acad. Andrei Țugulea opens the perspective for accurate measurement and fair billing of active and reactive energy at the terminals of three-phase consumers. By exclusively registering the components corresponding to the symmetry powers absorbed by the linearly balanced consumers, the influence of the components associated with asymmetric and residual powers is eliminated.

The latest edition of the IEEE 1459-2010 standard, dedicated to “Definitions for the measurement of electric energy in sinusoidal, nonsinusoidal, balanced, or unbalanced conditions” [23], highlights the following conclusion: “There is still no generalized power theory that can provide a simultaneous basis for energy billing, electrical power quality assessment, detection of major waveform distortion sources, and theoretical calculations for the design of attenuation equipment, such as active filters or dynamic compensators.”

As demonstrated in this doctoral thesis, the theory of symmetric, asymmetric, and residual components developed by Acad. Andrei Țugulea significantly responds to the objectives mentioned earlier regarding active energy. The same statement holds for the reactive energy associated with Budeanu’s reactive power (Q_B), provided it is reintegrated into the standard above, which, in turn, adopts non-active power—defined as the square root of the difference between the apparent power and active power squared.

In contrast to this model, Budeanu's reactive power, having positive or negative values, can indicate the actual direction of energy transfer associated with circuit elements that have storage capability. Additionally, it allows the identification of the components related to the imbalances and nonlinearities of consumers in the network, which can be recorded and billed separately.

6.1. Results

The power theory of Țugulea, validated through experiment and simulation, provides a solid theoretical foundation for understanding the impact of power flow non-symmetry on electrical networks. Studies show that these non-symmetry can cause significant losses, leading to overheating of equipment and increased operational costs. These effects highlight the need for more precise control measures to ensure the stability and efficiency of electrical networks, particularly in the face of disturbances and imbalances.

Experimental results and simulations confirm the theory's validity, demonstrating that the power balance remains consistent even under conditions of imbalance and nonlinearity. Comparing the measured data with those obtained through software simulation reinforces the validity of the conclusions and shows how advanced modeling methods can support the optimization of complex electrical networks. Thus, the combined experimental and numerical approach provides a practical framework for managing power flows and improving network performance, with significant applications in analyzing electrical networks with various configurations.

6.2. Original contributions

The research significantly contributes to monitoring and managing energy flows in complex electrical networks, highlighting the effects of disturbances and imbalances. Key achievements include the development of an experimental model for analyzing power quantities, which enables detailed monitoring of energy flows in networks with distorting loads. Additionally, the study compares Fryze and Budeanu's formulas for calculating reactive power, clarifying the impact of these differences on reactive power management in networks in Romania [26,27].

Another critical aspect of the research is identifying the impact of harmonics and imbalances on electric power quality, providing directions for filtering and balancing solutions. The power theory of Țugulea was validated experimentally and through numerical simulation, demonstrating its effectiveness in assessing energy losses and identifying sources of disturbance. These theoretical and practical contributions provide a valuable foundation for improving the performance and stability of electrical networks, supporting the development of more precise monitoring and management technologies [24,25,27].

6.3. List of original publications

I. M. Mîndreanu, A. M. Morega, Monitoring power flow in end-user consumption systems, 13th International Symposium on Advanced Topics in Electrical Engineering (ATEE), (2023).

I. M. Mîndreanu, R. M. Ciuceanu, I. V. Nemoianu, Experimental assessment of consumer

unbalance and nonlinearity effects in three-phaze networks without neutral conductor, Roum. Sci. Techn. – Électrotechn. et Énerg., Vol. 69, 3, pp. 287–292, (2024).

I. M. Mîndreanu, R. M. Ciuceanu, I. V. Nemoianu, Demonstrating the symmetry and non-symmetry components balance in grids whith neutral conductor, Roum. Sci. Techn. – Électrotechn. et Énerg., Vol. 69, 4, pp. 413–418, (2024).

I. M. Mîndreanu, R. M. Ciuceanu, I. V. Nemoianu, Power Flow Balance – Simulations and Experiments in Electrical Networks, Roum. Sci. Techn. – Électrotechn. et Énerg., Vol. 70, 1, pp. xxx–xxx, (2025) DOI: 10.59277/RRST-EE.2025.70.1.9. (article accepted for publication, scheduled to appear in issue 1 of 2025)

6.4. Perspectives

The future research perspectives focus on further developing methods for monitoring and controlling electric power flows, particularly in complex networks and industrial equipment with nonlinear loads. Development directions include integrating advanced monitoring technologies into smart grids, enabling rapid and efficient management of disturbances, and using artificial intelligence algorithms to automate the real-time correction of imbalances. Furthermore, the research will explore more efficient active harmonic filtering and balancing solutions and optimize reactive power pricing for more efficient resource usage.

Additionally, future studies will address the impact of imbalances on the durability of equipment, contributing to the development of more resilient devices to network disturbances. Another critical area will be the analysis of disturbances in hybrid networks and renewable energy sources to optimize their performance. These studies will support the development of more stable, sustainable, and intelligent electrical grids capable of responding to challenges posed by disturbances and imbalances, ensuring a constant quality of energy provided to consumers.

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