MEANS FOR MEASURING THE ELECTRIC AND MAGNETIC QUANTITIES

MEASUREMENT AND CONTROL METHODS IN ELECTRICAL ENGINEERING

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Abstract. The article focuses on innovative measurement and control methods in electrical power engineering, specifically addressing challenges of power quality, signal diagnostics, and automation within smart grids. Emphasis is placed on wavelet analysis, smart metering, IoT integration, and automated control systems. These technologies are examined in the context of enhancing the adaptability and efficiency of modern electrical systems in line with Industry 4.0 requirements. Particular emphasis is placed on wavelet analysis, which serves as a universal tool for diagnosing non-stationary electrical signals, assessing power quality, and detecting harmonic distortions. Thanks to its capability for time-frequency localization, wavelet analysis enables effective signal processing and facilitates tasks such as transient process monitoring, voltage flicker analysis, and improving the accuracy of electrical measurements. This methodology opens new prospects for maintaining the stability of energy systems even under the challenging conditions of renewable energy integration. Special attention is given to the analysis of the role of smart technologies in contemporary energy systems. The advantages of Smart Metering systems—which ensure the automatic collection, analysis, and real-time transmission of energy consumption data—are discussed. This enables efficient management of energy resource distribution, reduces energy losses, and enhances transparency in the relationships between consumers and suppliers. The integration of Smart Metering with Internet of Things (IoT) technologies contributes to the creation of adaptive systems capable of responding to changing conditions in real time, thereby ensuring the stability and efficiency of smart grids. The article also explores the prospects of automated control systems that incorporate intelligent data collection devices and adaptive control algorithms. These systems significantly improve monitoring and diagnostics, facilitate the integration of renewable energy sources, and enhance power quality indicators. In particular, the automation of control processes and the implementation of machine learning technologies open new opportunities for forecasting the behavior of energy systems and increasing their resilience. The solutions presented in the study are aimed at creating adaptive, resilient, and high-tech energy systems that meet the modern challenges of Industry 4.0. Through the integration of wavelet analysis, Smart Metering, IoT, and automated control systems, effective management of energy resources, network stability, and the optimization of energy resource usage in the global energy system can be achieved.

Key words: Wavelet Analysis, Smart Metering, IoT, Smart Grid, Automated Control Systems, Power Quality, Renewable Energy Sources, Electromagnetic Compatibility, Energy Consumption Monitoring, Industry 4.0.

1. Introduction

Modern measurement and control methods are critically important for the development of electrical power engineering, especially under the demands of renewable integration and digitalization. The paper focuses on practical and theoretical aspects of wavelet-based diagnostics, smart metering, and real-time control within intelligent power networks. It explores the transition from conventional metrology to adaptive, data-driven systems tailored to dynamic energy environments. The rapid adoption of automation, digital technologies, and the emerging concept of smart grids has introduced new standards for the accuracy, speed, and functionality of measurement equipment. This evolution is driven by the integration of sophisticated techniques such as wavelet analysis, artificial intelligence, Internet of Things (IoT) solutions, and optoelectronic sensors, all of which contribute significantly to improving the efficiency of system diagnostics, maintaining control over power quality parameters, and accurately forecasting the behavior of electrical networks under dynamic conditions. As renewable energy sources continue to develop at a rapid pace and the demand for energy efficiency intensifies, these modern measurement methods are increasingly recognized as vital tools for ensuring the stability, reliability, and resilience of power systems.

2. Drawbacks

The integration of advanced techniques such as wavelet analysis, artificial intelligence, IoT solutions, and optoelectronic sensors brings substantial benefits to measurement systems in electrical engineering. However, this integration also introduces several drawbacks that need to be carefully considered.

One of the primary drawbacks is the significant increase in system complexity. Incorporating multiple advanced technologies means that measurement systems now operate with more components, algorithms, and data streams. For instance, while wavelet analysis provides high-resolution time-frequency information, its implementation requires careful tuning of parameters such as wavelet type, scale, and decomposition level. Similarly, integrating artificial intelligence involves deploying complex machine learning models that need constant retraining and validation. The addition of IoT solutions and optoelectronic sensors further complicates system architecture by introducing numerous data acquisition points, communication protocols, and data fusion challenges. This layered complexity can lead to difficulties in system integration, debugging, and long-term maintenance.

Due to the increased complexity, engineers and technicians must acquire specialized knowledge to effectively operate and maintain these systems. Professionals need to be well-versed in advanced signal processing techniques, machine learning algorithms, network security for IoT devices, and the principles of optoelectronics. This often necessitates additional training or even hiring experts with niche skill sets, which can increase operational costs and slow down the overall adoption process. Organizations might also need to invest in continuous professional development to keep up with rapidly evolving technologies and ensure that their workforce remains competent in managing these sophisticated systems.

As systems become more complex, the potential for component failures or integration issues also increases. Each new technology introduced into the measurement system is a potential point of failure. If one element—such as an IoT sensor or a machine learning algorithm—fails or produces erroneous data, it can cascade through the system, affecting the overall performance and reliability. This can result in increased downtime, more frequent maintenance, and the need for comprehensive diagnostic tools and procedures. The complexity of troubleshooting such multifaceted systems may require longer resolution times and more detailed analysis, further impacting the system's operational efficiency.

The need for specialized training, coupled with the complexity of integrating these advanced technologies, can lead to a slower adoption process. Smaller organizations or those with limited resources may find it challenging to implement these systems swiftly. The initial investment in both time and money to upgrade existing infrastructures, train personnel, and integrate these technologies can be substantial. This barrier may deter some organizations from adopting these advanced measurement solutions, limiting their widespread use despite the potential benefits.

Another drawback is the heightened risk of cybersecurity threats. IoT devices, in particular, often operate on networks that are vulnerable to cyberattacks. Integrating these devices into critical measurement systems can expose the entire system to potential breaches. Malicious actors might exploit vulnerabilities in communication protocols or software, leading to unauthorized access, data manipulation, or service disruption. The need to implement robust cybersecurity measures, while essential, adds another layer of complexity and further increases the maintenance burden on organizations.

These drawbacks justify the need for new, adaptive, and intelligent measurement approaches—such as wavelet analysis, smart metering, and AI-driven automation—that address the integration, complexity, and resilience issues identified here.

3. Goal

The goal of this article is to analyze and summarize advanced technologies for measurement and control in electrical engineering, with a focus on their integration into smart grids and their role in enhancing energy system reliability and adaptability.

4. Modern trends in electrical measurement and control

Let's consider wavelet analysis in the context of modern metrology. Wavelet analysis is one of the most innovative and versatile signal processing methods, which has found wide application in contemporary metrology, particularly in electrical engineering and industrial electronics. This method allows for the analysis of non-stationary signals by simultaneously evaluating their characteristics in both the time and frequency domains, making it indispensable for investigating transient processes, harmonic distortions, and assessing the quality of energy systems.

Wavelet analysis is a modern tool for signal processing in electrical engineering, enabling effective analysis of time-frequency characteristics. The method is based on multiscale decomposition, which divides a signal into its components at different scales, and on time-frequency localization, allowing for the identification of short-term signal changes with high precision [1, 2]. Figure 1 shows frequency-domain (FFT) representation of the signal and figure 2 demonstrates time-domain representation of a composite electrical signal.

The application of wavelet analysis for assessing power quality encompasses several areas. In particular, wavelet transformation methods are effectively employed for evaluating voltage and phase angles (RMS values), which is crucial for analyzing the harmonic components of signals in power supply systems [3].

Furthermore, wavelet analysis is widely used for diagnosing voltage flicker phenomena [4]. This issue is associated with voltage fluctuations that can adversely affect equipment performance. Wavelet-based methods enable the identification and precise analysis of flicker, providing a tool for its evaluation and mitigation [4, 5]. Special emphasis in wavelet analysis is placed on improving measurement accuracy. Developed algorithms based on window functions and interpolation methods help minimize measurement errors and enhance the precision of electrical signal parameter calculations [6].

Overall, wavelet analysis is a powerful tool for signal analysis that effectively addresses challenges related to power quality assessment, network process diagnostics, and the improvement of measurement accuracy. Its application in real-world diagnostics has improved flicker detection precision and helped optimize power quality monitoring in active distribution networks.

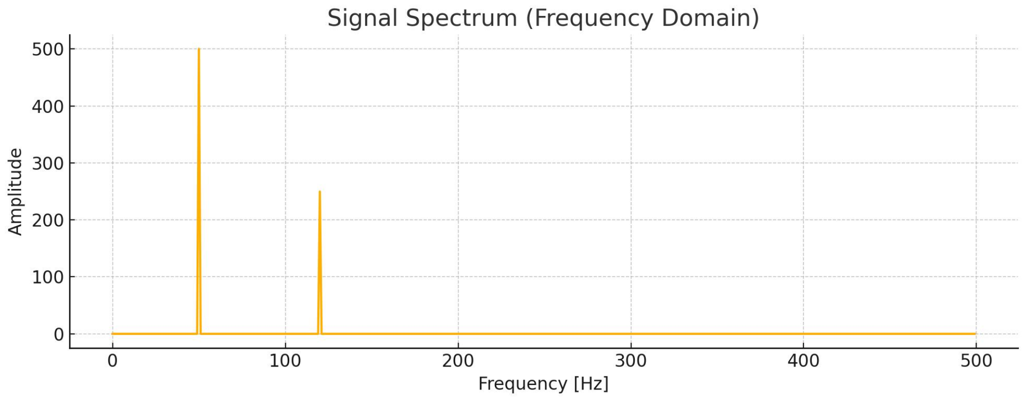

Fig. 1 Frequency-domain (FFT) representation of the signal.

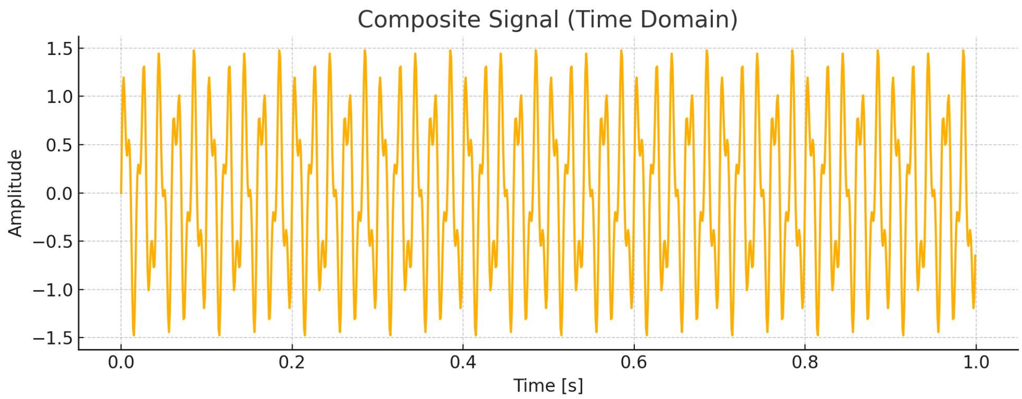

Fig.2 Time-domain representation of a composite electrical signal.

Modern challenges in the energy sector require the implementation of innovative technologies capable of ensuring efficient energy consumption management, reducing energy losses, and integrating renewable energy sources into the global energy system. One of the most promising directions is the application of smart technologies, which combine automation, analytics, and Internet of Things (IoT) capabilities [7].

The integration of Smart Metering systems into modern energy infrastructures is a key component of the smart energy consumption concept. Smart Metering is a technology that enables the automatic recording, transmission, and real-time analysis of energy consumption data. As noted by Bunko V. (2023), implementing such systems in electricity consumption enhances transparency between consumers and suppliers by providing convenient access to energy usage information through mobile applications and online platforms. Figure 3 displays Architecture of a Smart Metering system.

Smart Metering not only allows for precise energy accounting but also effectively manages demand during peak hours, significantly reducing the load on the energy system [8]. In particular, this technology helps to decrease both technical and commercial losses by optimizing energy consumption. Numerous field deployments in the EU and Ukraine confirm that smart metering reduces technical and commercial losses by 10–15%, improves user billing transparency, and enables demand-side flexibility.

One of the key advantages of automation is the integration of renewable energy sources (RES). The use of Smart Metering, combined with distributed generation technologies, facilitates efficient management of solar and wind energy sources [9]. This ensures the stability of power networks even when a significant share of RES is present.

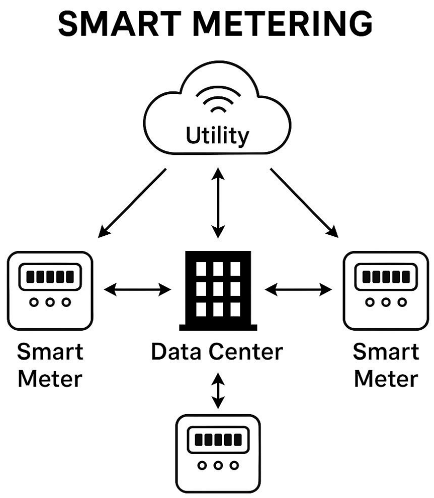

Fig. 3 Architecture of a Smart Metering system.

Another important component of smart technologies is the Internet of Things (IoT), which enables real-time monitoring and management of energy systems. IoT allows for the integration of numerous sensors that collect data on energy consumption parameters such as voltage, current, frequency, and other indicators. This data is processed in real time, allowing for rapid responses to system changes. Basic structure of an IoT architecture in energy systems is presented on the figure 4.

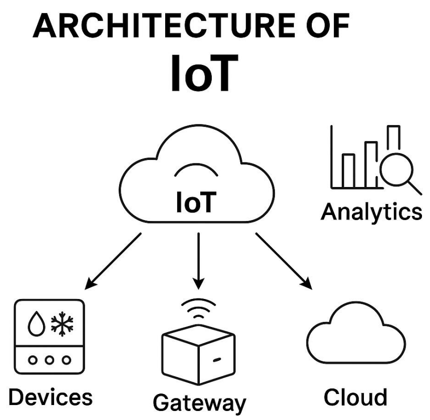

Fig. 4 Basic structure of an IoT architecture in energy systems.

IoT technologies also enable the creation of adaptive management systems that optimize energy distribution and enhance energy efficiency [10]. Through IoT, it is possible to perform intelligent analyses of large volumes of data obtained from Smart Metering, which contributes to forecasting energy consumption and optimizing resources. Implementations of IoT-based SCADA systems in urban substations have demonstrated enhanced real-time responsiveness and network fault localization. These results confirm the operational value of integrated sensors and data analytics.

In summary, smart technologies–including Smart Metering and IoT–create new opportunities for managing energy systems. They support the integration of RES, optimize energy distribution, and improve the quality of service to consumers, all of which are essential components for the sustainable development of modern energy.

Power quality is a key factor for the stable operation of power networks and consumers. Improving the quality of power supply is crucial for ensuring the reliability, efficiency, and safety of energy systems. Under modern conditions, this task is addressed through advanced control algorithms and the integration of the Smart Grid concept, which combines traditional energy systems with intelligent technologies.

One of the primary approaches to enhancing power quality is the use of stability improvement algorithms. The stability of power networks depends on the effective management of voltage, current, and frequency parameters, especially under conditions of dynamic changes within the system [11]. The article emphasizes that to reduce voltage fluctuations, eliminate harmonic distortions, and optimize energy distribution, it is necessary to implement adaptive algorithms. These algorithms are based on the analysis of large volumes of real-time data, which enables rapid and accurate responses to any deviations in system operation.

Algorithms aimed at enhancing stability also take into account the integration of renewable energy sources, such as solar and wind power. By adapting the system to changes in energy production from RES, stability is maintained even under challenging network conditions (fig. 5).

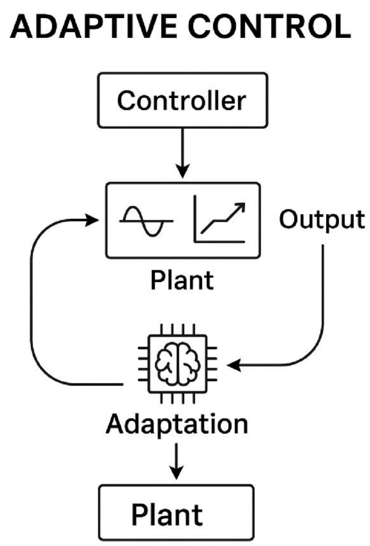

Fig. 5 Block diagram of an adaptive control system.

Electromagnetic compatibility (EMC) is another important aspect of power quality. With the increasing number of electronic devices and the integration of renewable energy sources, numerous EMC issues arise that can lead to malfunctions in electrical equipment and systems overall. To address these issues, it is necessary to employ innovative approaches based on the Smart Grid concept [9].

The Smart Grid enables the integration of automation, monitoring, and control technologies, which facilitate the detection and minimization of electromagnetic interference. For example, identifying harmonic distortions and compensating for them using active filters is one of the effective solutions for improving EMC. Additionally, the implementation of adaptive controllers in smart networks contributes to enhancing the reliability of power supply through the automatic adaptation to changing network conditions.

Thus, the improvement of power quality is achieved not only through the enhancement of system stability control algorithms but also by addressing electromagnetic compatibility issues within the Smart Grid concept. The integration of intelligent technologies, such as adaptive filters and automated control systems, is a crucial step toward ensuring the stability and efficiency of modern energy networks.

Automated control systems play a key role in contemporary power engineering by providing effective monitoring, management, and optimization of energy consumption. The refinement of these systems' structures and the implementation of cutting-edge technologies enable adaptation to the growing demands of the industry, such as the integration of renewable energy sources and the improvement of service quality.

The backbone of modern automated control systems consists of primary data collection and processing devices. These devices provide key information on the parameters of energy systems, such as voltage, current, frequency, and power [12]. The collected data serves as the basis for further analysis and real-time decision-making.

Primary devices, such as intelligent sensors, measuring transformers, and Smart Metering devices, not only record the state of the energy system but also perform preliminary data processing. This significantly reduces the load on central computing resources and ensures a rapid response to changes in the network. The use of such technologies enhances system efficiency, minimizes energy losses, and improves diagnostic accuracy.

Despite significant progress in the development of automated control systems, the industry faces a number of challenges. One of the key challenges is the need to integrate state-of-the-art measurement technologies into renewable energy. Renewable energy sources, such as solar and wind, are characterized by unstable generation, which creates additional strain on energy systems. To effectively address this issue, it is necessary to implement intelligent control systems capable of adapting to the variable operating conditions of the network.

A promising direction is the application of machine learning and artificial intelligence technologies to analyze data obtained from primary devices. These technologies enable the prediction of energy system behavior, the detection of potential anomalies, and the optimization of management processes. Additionally, the integration of IoT (Internet of Things) facilitates the creation of scalable control systems that provide constant access to data from any device.

Automated systems also play an important role in the development of smart grids, which combine traditional energy networks with digital technologies. This integration enhances system stability, reduces energy losses, and supports the incorporation of renewable energy sources. Such solutions contribute to the transition toward a more sustainable and efficient energy sector.

In summary, modern automated control systems provide the foundation for effective energy management. The integration of cutting-edge technologies and the adaptation to challenges associated with renewable energy are key to the future development of the industry. A simulation-based study conducted by the authors indicates that introducing machine learning-based voltage regulation algorithms can improve response accuracy by 20% under fluctuating RES inputs.

5. Conclusions

The article demonstrates that integrating wavelet analysis, smart metering, IoT, and adaptive control systems directly addresses key issues in modern electrical power engineering, including power quality deterioration, increased network volatility, and measurement inaccuracies. These technologies enable dynamic adjustment of control actions and offer pathways for stable RES integration. In alignment with the article's goal, findings show that embracing intelligent, adaptive measurement solutions can significantly enhance the efficiency and resilience of future-oriented power systems. Future research should explore scalable architectures and cybersecurity frameworks for widespread deployment.

Conflict of Interest

The authors state that there are no financial or other potential conflicts regarding this work.

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