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Application of wavelet transformations on microcontrollers for monitoring and optimising energy systems in industrial conditions

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Abstract. The purpose of the study was to analyse approaches to the use of wavelet transformations on microcontrollers to improve the efficiency of control and management of energy systems in industrial environments, and to investigate the possibilities of integrating wavelet transformations into hardware platforms of microcontrollers. The paper considered methods for applying wavelet transformations on microcontrollers for monitoring and optimising energy systems in industrial conditions. The proposed method helps to detect short-term anomalies, voltage and current fluctuations, which contributes to timely detection of energy losses. A discrete wavelet transform algorithm optimised for microcontrollers has been experimentally implemented, which provides anomaly detection accuracy of 94-96% with a signal-to-noise ratio of 40 dB. The analysis showed that the use of Daubechies-type wavelets can increase the sensitivity of the algorithm by 3-4% compared to Haar, while maintaining an acceptable level of computational costs. Optimisation of the implementation allowed reducing the average processing time of a single signal segment to 0.1 seconds on the STM32 microcontroller. In addition, the features of industrial conditions characterised by a high noise level and variable parameters were considered, which further complicates the use of wavelet transformations. The main achievement was the development of an adapted wavelet analysis method that ensures efficient use of microcontrollers for monitoring energy systems with minimal hardware requirements. A new algorithm was proposed that allows optimising the use of computing resources, reducing power consumption without losing the accuracy of signal analysis. The developed method allowed detecting anomalies in a timely manner and optimising energy consumption, which is of practical importance for reducing operating costs and improving the stability of industrial systems

Keywords: industrial solutions; processing algorithms; equipment reliability; resource management; resource efficiency

Introduction

Modern industry is actively moving to the use of energy-efficient systems that provide high productivity with minimal resource consumption. In this context, monitoring and optimisation of energy systems, which

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require accurate and fast methods of real-time data analysis, plays an important role. One of the promising approaches is the use of wavelet transformations for processing signals received from sensors and other measuring devices. Due to its ability to analyse signals in the time-frequency domain, the wavelet transform is a powerful tool for detecting anomalies, assessing the state of systems, and predicting energy parameters. Of particular importance is the implementation of such algorithms on microcontrollers, which are key components of automation and control systems. Microcontrollers provide sufficient computing power to perform complex mathematical operations while remaining compact, cost-effective, and energy-efficient. The use of wavelet transformations in such devices opens up new opportunities for integrating signal analysis methods directly into the hardware platform of energy systems. The relevance of the topic is conditioned by the need of industrial enterprises to improve energy efficiency and reduce equipment maintenance costs. However, their implementation on microcontrollers is associated with a number of challenges, in particular, optimisation of computational algorithms and limited memory resources and power consumption.

The development and implementation of wavelet transform algorithms on microcontrollers for monitoring energy systems was the subject of numerous studies. The academic literature contains papers that analyse certain aspects of this problem, which allows outlining current trends and identifying prospects for further development. The study by M. Karkhaneh & S. Ozgoli (2022) focused on the use of discrete wavelet transform to detect anomalies in industrial power systems. The researchers showed that the use of multilayer wavelet decomposition allows achieving high accuracy of fault identification even under conditions of noise in the signal. Their research also highlighted the importance of optimising computing resources. M.Y. Mazin & Y.O. Onykiienko (2023) considered the problem of limited hardware resources of microcontrollers and proposed an adaptive wavelet transform algorithm that reduces memory requirements without losing analysis accuracy. Their results indicate the prospects of using such approaches in real industrial conditions.

A. Sharma *et al*. (2021) discussed the use of a continuous wavelet transform to estimate the state of electric motors. The researchers emphasised the advantages of this approach for detecting early stages of mechanism wear. They also focused on the need to develop energy-efficient algorithms for embedded systems. J. Gao *et al*. (2021) investigated the use of wavelets for signal analysis in distributed energy systems. Their study demonstrated how the wavelet transform can help to optimise energy distribution and reduce network losses. The paper by N.T. Bui *et al*. (2020) focused on the development of microcontroller systems for real-time signal processing. The researchers proposed specialised hardware solutions for implementing wavelet transform, which can improve the system's performance. L. Peng *et al*. (2022) presented an approach to combining wavelet transformations with machine learning methods for predicting energy consumption. The researchers highlighted the effectiveness of wavelets in isolating relevant features from signals in complex dynamic environments.

The study by P. Khatua & K.C. Ray (2022) focused on the use of compact wavelets to reduce the computational complexity of wavelet analysis. The researchers argued that such methods can be effective for implementation on microcontrollers with limited resources. F. Bilgili *et al*. (2021) conducted research on the use of wavelet transform for monitoring renewable energy sources. Their results highlighted the possibility of integrating these methods into energy storage and transmission systems. A. Rahmani & A. Deihimi (2020) investigated the use of wavelets to analyse harmonic distortion in industrial power networks. They concluded that microcontrollers with support for wavelet processing can significantly improve the quality of real-time data analysis. A.A. Majhi & S. Mohanty (2024) focused on integrating wavelet transform into Internet of Things (IoT) systems for monitoring energy facilities. The researchers developed an approach that provides efficient signal processing and data transmission in distributed systems.

Considerable attention was paid to the use of wavelet transformations for monitoring the state of machines, predicting energy consumption, and detecting malfunctions. However, the practical implementation of such approaches on microcontrollers requires further research aimed at adapting algorithms to limited computing resources. The lack of unified methods and applied solutions in this area creates a space for innovation. Despite advances in wavelet transform applications for monitoring energy systems, a number of unresolved issues remain, including optimisation of algorithms for microcontrollers with limited resources, integration into real-time systems, and energy efficiency. In addition, the practical implementation of these approaches in complex industrial environments with a high level of interference remains limited, which requires the development of noise-resistant methods and adaptation of existing solutions for effective operation in real-world operating conditions. The purpose of the study was to investigate approaches to using modern signal processing algorithms based on wavelet transformations to improve the accuracy of monitoring and optimise the functioning of energy systems. The paper also considered the advantages, problems, and prospects of using the approach of optimised application of wavelet transformations on microcontrollers for monitoring and managing energy systems, which is an important step towards creating more energy-efficient and sustainable industrial systems.

Materials and Methods

The study was based on the analysis of the fundamentals of wavelet transformations, which are a powerful tool for analysing signals in time-frequency space. This approach can effectively detect anomalies, resource losses, and peak loads in power systems. The research was based on discrete wavelet transform algorithms, which allow decomposing signals into components with different frequency ranges, localising anomalies over time, and evaluating their frequency nature. Haar and Daubechies wavelets were chosen for analysis because they provide a trade-off between speed and accuracy. Haar is characterised by simplicity and low computing costs, which is important for devices with limited resources, while Daubechies provides better processing of complex signals with noise and sudden changes. Their effectiveness was evaluated according to the criteria of anomaly detection accuracy, noise resistance, speed, and computational complexity.

The effectiveness of the algorithm was evaluated according to the following criteria: sensitivity, precision, time detection, and noise resistance. Sensitivity showed the algorithm's ability to correctly detect existing anomalies or important changes in the signal and was calculated as the ratio of the number of correctly detected anomalies to the total number of available anomalies multiplied by 100%. Accuracy characterises the proportion of correctly detected anomalies among all cases that the algorithm has classified as anomalies, and is defined as the ratio of the number of correctly detected anomalies to the total number of detected anomalies multiplied by 100%. Anomaly detection time is the average time required by the algorithm to process a single signal segment, which is calculated as the total processing time divided by the number of processed segments. Noise resistance shows how effectively the algorithm maintains its accuracy in the presence of noise in the signal, and is calculated as the ratio of accuracy on noisy data to accuracy on pure data multiplied by 100%. In addition, the computational load measured in millions of instructions per second (MIPS) was analysed and calculated as the number of instructions for signal processing divided by the processing time in seconds, and the reduction in power consumption, which is defined as the difference between unit and the ratio of the power consumption of the optimised algorithm to the power consumption of the base algorithm multiplied by 100%.

The efficiency of the algorithm was evaluated by analysing the results of its operation on test data sets with different noise levels and typical operating modes of the power system. The study used comparative analysis with conventional methods such as fast Fourier transform and Kalman filtering to evaluate the effectiveness of wavelet transformations in detecting anomalies. Features of using real-time wavelet transformations are related to the need to optimise algorithms for working on microcontrollers. The main requirements include considering limited hardware resources, low power consumption, and the need for rapid anomaly detection. The wavelet transform, Kalman filter, and Fourier transform methods were also used to analyse such signals. These filters were chosen because of their effectiveness in reducing noise and predicting the state of the system in real time.

The algorithms were evaluated using 500 test cases with anomalies, including power surges, harmonic distortion, and impulse noise, and 300 runs in normal operating modes. The input signals were segmented into 500 ms intervals with a sampling rate of 10 kHz. The algorithms were performed on a Swiss-made STM32 microcontroller, and efficiency was evaluated according to the criteria of sensitivity, accuracy, processing speed, and noise resistance at a signal-to-noise ratio of 40 dB. In addition, the computational load and power consumption were analysed, comparing the results obtained with the basic implementation without optimisation.

The purpose of comparing signal processing algorithms was to determine the efficiency of using wavelet transformations in industrial settings for monitoring power systems on microcontrollers. The following algorithms were considered in the study: Fourier transform, wavelet transform, Kalman filtering, mean filtering, and Gaussian filtering. The comparison was based on several criteria: signal processing speed, memory usage, noise sensitivity, and the ability to detect short-term anomalies. The processing time was defined as the average time for analysing a signal with a length of 1,024 points, simulating typical operating conditions of power systems. The amount of memory was estimated as the maximum amount of RAM used during algorithm execution. Noise sensitivity was measured by analysing signals with a noise level of 40 dB, which helped to evaluate the resistance of methods to noisy data. In addition, the accuracy of detecting anomalies, in particular pulsed emissions, harmonic distortions, drifts, and random interference, was analysed. Both real signals from industrial power systems and synthetic data simulating anomalous situations were used to evaluate the effectiveness of the algorithms.

Results

Energy efficiency is becoming one of the key aspects in the development of modern industry, especially due to the growing energy costs and requirements for sustainable development. Industrial power systems, which are the basis of production processes, require constant monitoring to ensure their stable and uninterrupted operation. Anomaly detection, equipment health assessment, and energy optimisation are critical to reducing operating costs and minimising environmental impacts.

Conventional signal analysis methods used to monitor power systems often do not provide sufficient accuracy or require significant computational resources. Wavelet transformations, due to their ability to work in the time-frequency domain, allow more efficient detection of even minor changes in signal characteristics, which is important for early detection of malfunctions and improving the efficiency of systems. Microcontrollers, due to their compact size, cost-effectiveness and low power consumption, are widely used in industrial automation systems (Dong *et al.*, 2023).

Modern monitoring and optimisation of energy systems are complex tasks that require the integration of the latest technologies to ensure the efficiency, reliability and sustainability of energy processes. Due to the growing demands on energy consumption and environmental conservation, enterprises and other organisations are actively using modern methods for managing energy resources (Khatua *et al.*, 2020). These methods include the use of intelligent monitoring systems, load forecasting, integration of renewable energy sources, and the use of algorithms to optimise energy consumption.

Modern energy systems use sophisticated intelligent systems for real-time monitoring, collecting data from various sources and providing a prompt response to changes in energy consumption. Power management systems use numerous sensors that measure parameters such as power consumption, voltage, frequency, and other important metrics. This allows providing an accurate picture of the state of energy systems and detecting deviations from normal operation in time. The development of IoT technologies contributes to the integration of a large number of sensors into networks that allow monitoring and automatically adjusting the operation of energy systems. For example, IoT can be used to remotely monitor equipment, detect malfunctions, and even make adjustments to improve efficiency (Marinakis *et al.*, 2020). To reduce environmental impacts and improve energy efficiency, many energy systems integrate renewable energy sources such as solar panels, wind turbines, and geothermal installations. This creates new challenges for optimising energy systems, as renewable energy sources have a fickle production nature. Specialised optimisation strategies that consider changing environmental conditions and economic factors are used to manage such energy (Al-Shetwi, 2022). Such strategies include storing energy (such as in batteries) to equalise consumption peaks, or using smart grids to redistribute energy.

Adaptive control systems are an important area in modern monitoring of energy systems. They can adjust their strategies depending on changes in the external environment or internal parameters of the system. Automation in energy networks allows reducing the human factor, increasing the speed of responses to changes in the network, and ensuring a more reliable and uninterrupted supply of energy. For example, automated systems based on embedded microcontrollers can immediately respond to changes in voltage or power consumption by changing the settings of devices or equipment for optimal operation (Obaid *et al.*, 2019).

Microcontrollers also effectively interact with various peripheral devices through interfaces such as sensors, actuators, relays, which provides the ability to control various aspects of industrial processes. This allows creating integrated and scalable automation systems that can perform multiple tasks in a single controller. One of the advantages of microcontrollers is their ability to save energy (Wu *et al.*, 2021). They consume a minimal amount of energy, which is important for the smooth operation of power systems, and for autonomous devices and remote monitoring systems.

Real-time signal processing systems play an important role in today's industry, providing fast and accurate data analysis for operational decision-making. The main elements of such systems work in a coordinated manner, forming a single architecture for signal processing. At the first stage, data is collected using sensors and sensors that convert physical parameters into electrical signals. These signals undergo preprocessing, such as amplification or filtering. Then they are converted to digital format by analogue-to-digital converters, which allows working with them on digital devices. Microcontrollers or digital signal processors are the core of a system where key calculations are performed to analyse, monitor, or optimise signals. RAM is used for temporary data storage, and digital filters ensure that signals are cleared of noise. Communication interfaces allow data to be exchanged with other systems, and output devices such as displays or actuators display results or perform appropriate actions. Table 1 summarises the main components of the system, their functions, and their role in ensuring efficient real-time signal processing.

Table 1. Key components and functions of a real-time signal processing system

Component	Description	Function
Detectors and sensors	Devices that measure physical or electrical parameters (temperature, pressure, voltage, current)	Collecting input data from the environment for further processing
Preamp	Amplifier that increases the signal strength from the sensor to the required level	Ensuring the correct signal strength for the analogue-to-digital converter
Analogue-to-digital converter	Converts an analogue signal to a digital one for processing by a microcontroller or digital signal processor	Converting an analogue signal to a form suitable for digital processing

Table 1. Continued

Component	Description	Function
Microcontroller or digital signal processor	Central processing element that performs analysis, filtering, and optimisation algorithms	Digital signal processing, system management, and real-time algorithm execution
RAM	Temporary storage of input data and intermediate results during processing	Providing fast access to computing data
Permanent memory	Storage location for firmware, configuration parameters, and signal processing programmes	Saving algorithms and basic system parameters
Digital filters	Algorithms or hardware that remove noise or unnecessary frequency components of the signal	Improving signal quality and ensuring the correctness of further analysis
Communication interfaces	Means of data transfer between system components (UART, SPI, I2C, Ethernet, etc.)	Organisation of communication between sensors, processors, and other modules
Output devices/ actuators	Elements that display processing results or execute commands (displays, relays, motors, etc.)	Transmitting results to users or performing control actions based on the processed data

Notes: UART – Universal asynchronous receiver/transmitter; SPI – Serial Peripheral Interface
Source: developed by the authors based on I.I. Samborsky *et al.* (2021), Y.O. Ushenko *et al.* (2021)

These components play a key role in ensuring continuous and efficient operation of the real-time signal processing system. Collecting accurate data using sensors is the basis for making correct decisions, while preamps provide the necessary signal strength for further processing. The analogue-to-digital converter converts analogue signals to digital ones, which allows using modern processing algorithms. Microcontrollers and digital signal processors perform calculations with minimal latency, which is crucial for dynamic processes. Due to the continuous improvement of components and the introduction of innovative technologies, the architecture of systems for real-time signal processing is constantly evolving. Current research focuses on integrating machine learning, IoT, and cloud computing to create more adaptive and energy-efficient solutions. In the future, such systems can become a key element for building "smart" industrial and household solutions that can provide autonomy, high accuracy, and scalability (Bharany *et al.*, 2022).

An algorithm consisting of several stages was developed to optimise wavelet transformations on microcontrollers. First, the input signal is divided into small blocks (segments) to identify time intervals in which significant changes are observed. This preliminary analysis allows performing calculations only for relevant sections of the signal, which reduces the number of mathematical operations. Next, adaptive quantisation of the wavelet transform coefficients is performed, which reduces the memory requirements of the microcontroller without losing important information. Then the optimal wavelet function is selected: for signals with sharp transitions, the Haar wavelet is used, which provides speed of calculations, and for analysing complex and noisy signals, the Daubechies wavelet, which gives a more accurate result. The algorithm also provides for a multi-level schedule, where detailed processing is performed only at key levels, which further reduces power consumption. Analysis of the noise characteristics showed that it is advisable to use smoothed wavelets, such as Daubechies, for noisy data, while the Haar wavelet is more effective for sharp changes. The power consumption of the microcontroller was also taken into account. Table 2 shows comparative results using Haar and Daubechies wavelets, demonstrating a trade-off between computational speed and analysis accuracy, and an overview of alternative approaches to signal analysis.

Table 2. Overview of alternative approaches to signal analysis

Criteria	Haar	Daubechies
Sensitivity	92.3%	95.1%
Precision	88.7%	92.5%
Detection time	118 Ms	147 Ms
Noise resistance	84.2%	91.8%
Computing load	0.8 MIPS	1.2 MIPS
Reduce energy consumption	27%	30%

Source: developed by the authors based on their own research and O.A. Mohamed *et al.* (2017), Y.M. Yan *et al.* (2019), J. Lefebvre *et al.* (2020)

As can be seen, the Haar wavelet demonstrates higher performance (118 Ms per segment), which makes it suitable for applications where fast real-time analysis is important. At the same time, the Daubechies wavelet provides better sensitivity (95.1%) and noise resistance (91.8%), which allows working more efficiently in conditions of complex signals with a high level of interference. The computational load of the

Daubechies algorithm is higher (1.2 MIPS vs. 0.8 MIPS in Haar), but it provides more accurate analysis, which can be critical for tasks of predicting peak loads and detecting minor anomalies. The use of both approaches in a hybrid system will optimise the signal analysis process depending on specific operating conditions.

It is advisable to use the Haar wavelet for operational monitoring of network parameters and rapid detection of sudden changes, which is critical for protection and automatic control systems. The Daubechies wavelet is optimal for detailed signal analysis, especially when predicting voltage and current deviations, and detecting weak anomalies that may precede accidents. It is recommended to use a hybrid approach: Haar – for preprocessing and rapid response, and Daubechies – for detailed analysis of historical data and accurate forecasting. This strategy will minimise the power consumption of computing resources, while ensuring high control accuracy.

The Haar wavelet provides high computing speed due to simple arithmetic operations, making it efficient for real-time signal processing. However, its limited ability to accurately reproduce complex signal details reduces the accuracy of analysis, especially in the presence of noise or smooth changes. The Daubechies wavelet, by contrast, uses more complex functions, which improves recognition of small fluctuations and anomalies, but increases computational complexity. Thus, the choice between these wavelets depends on specific requirements: Haar is suitable for fast filtering and preprocessing, while Daubechies is more efficient for detailed analysis of noisy signals.

Signal processing is the basis for numerous engineering applications in fields such as telecommunications, radio electronics, medicine, and many others. The signals that need to be processed can be very diverse in their characteristics: they can be periodic or continuous, clear or noisy, static or dynamic. Choosing the right algorithm for signal processing depends on many factors, such as signal type, accuracy requirements, processing speed, and application specifics.

In order to choose the most effective algorithm for a particular task, it is necessary to understand the advantages and disadvantages of each of them. Some methods, such as the Fourier transform, are well suited for periodic signals and allow obtaining spectral information. However, wavelet transform or Kalman filtering is more suitable for analysing variable or complex signals, which can process information in time and frequency simultaneously, while preserving the local characteristics of the signal.

Other methods, such as linear regression or the principal component method, are often used to predict and reduce the dimension of data, but they may be less effective when working with high-frequency or unstable signals. For low-noise signals, simple algorithms such as medium filtering or Gaussian filtering may be sufficient, as they effectively reduce interference, but may cause some useful signal characteristics to be lost. Table 3 provides a comparison of the main signal processing algorithms, their advantages, disadvantages, and applications, which will help to visualise the key aspects of each method and make the right choice for specific tasks.

Table 3. Comparison of signal processing algorithms

Algorithm	Fourier transform	Wavelet transform	Kalman filtering	Filtering by average	Gaussian filtering
Description	Algorithm for converting signals from time space to frequency space allows getting the signal spectrum	Algorithm for decomposing the signal into a set of wavelets allows considering both time and frequency characteristics	Algorithm that combines prediction and correction to get the best estimate of the system state	Algorithm that replaces each input point with an average value in its vicinity	Filtering algorithm that uses the Gaussian function to blur the signal
Advantages	Processing speed, efficiency for periodic signals	Suitable for processing heterogeneous signals, effective for localised changes	Good performance with noisy signals, real-time efficiency	Easy to implement, effective for reducing noise in signals	Reduces noise well, preserving most of the useful information
Disadvantages	Poor signal processing with non-constant characteristics (time instability)	High computational costs, complexity of choosing a wavelet function	Necessary to accurately model processes, for complex systems – difficult configuration	Degrades the signal, especially with a high amplitude of changes	Poor adaptation to signals with different rates of change
Application areas	Acoustics, radio electronics, sound processing, spectral analysis	Image processing, medical signals, financial analysis, seismology	Navigation systems, robotics, economic forecasts	Image processing, audio signals, medical data	Image processing, video, audio, data visualisation

Table 3. Continued

Algorithm	Fourier transform	Wavelet transform	Kalman filtering	Filtering by average	Gaussian filtering
Processing time (signals)	0.08 s (for 1,024 points)	0.1 s (for 1,024 points)	0.12 s (for 1,000 measurements)	0.02 s (for 1,024 points)	0.03 s (for 1,024 points)
Memory (KB)	40-60)	150-250	50-70	20-40	30-50
Noise sensitivity	High	Moderate	High	Average	Low

Source: developed by the authors based on S.V. Zabolotnii (2010), M. Vetterli *et al.* (2014), A.O. Popov (2019)

The analysis of the algorithms demonstrated different approaches to signal processing, each with its own advantages and disadvantages. However, focusing on the methods that are alternatives to wavelet transforms, the Fourier transform and Kalman filtering should be highlighted, as they are widely used to analyse dynamic signals in industrial systems. The fast Fourier transform provides fast and efficient signal analysis in frequency space, but its disadvantage is the limited ability to process signals with unstable characteristics that change over time. This makes it less suitable for analysing industrial power systems where both time and frequency must be processed simultaneously. Kalman filtering, while effective for handling noisy signals, requires precise mathematical modelling of processes, which makes it difficult to use it for systems with dynamically changing characteristics. Unlike these methods, wavelet transformations offer a unique advantage: the ability to localise anomalies in both time and frequency. This is especially important for signals with rapid changes or unpredictable deviations typical of industrial systems. In real-world conditions, where computing resources may be limited, wavelet transform problems involve high computational costs and the choice of the optimal wavelet function.

Wavelet transformations play an important role in improving energy efficiency and extending the service life of equipment in power systems. Their main advantage is the ability to significantly improve control and optimisation of energy use (Shilpa & Puttaswamy, 2025). The use of wavelets for multi-level signal analysis helps to detect low-amplitude anomalies and fluctuations in energy systems that indicate inefficient use of energy. This facilitates a timely implementation of measures to optimise the operation of systems, reducing power consumption without losing performance. In addition, wavelets effectively identify small fluctuations that can cause additional energy losses, which allows quickly eliminating such shortcomings and reducing overall energy costs. Due to their application, it is possible to optimise equipment settings, ensuring a reduction in energy consumption without reducing operational efficiency. In addition, this technology allows more accurately predicting energy needs, contributing to more efficient resource planning and reducing costs during periods of low energy consumption (Pacheco *et al.*, 2024).

As for the durability of equipment, wavelet transformations contribute to monitoring the state of technical systems and early detection of anomalies, such as overload or wear. Analysis of electrical and mechanical signals helps to identify problems that can lead to breakdowns or shorten the service life of equipment. Wavelets can also identify vibrations, corrosion, or other mechanical defects, allowing taking timely measures such as calibration or replacement of components, thereby extending the service life of the equipment (Badihi *et al.*, 2022). It is also important that the use of this technology helps to reduce dependence on the human factor in the process of monitoring and managing energy systems, which minimises the likelihood of errors and increases accuracy. The use of wavelet transformations allows detecting overloads or overheating in time, which can prevent serious breakdowns and thereby extend the service life of the equipment. Based on the aforementioned capabilities, wavelet transformations significantly improve the energy efficiency and durability of equipment in industrial power systems, reducing maintenance costs and improving the overall stability of the system.

Discussion

The results of the study show that the use of wavelet transformations for monitoring industrial power systems is a promising approach that can significantly improve the accuracy of diagnostics and efficiency of equipment. Energy efficiency is a key factor in modern industrial processes, especially given the need to reduce energy costs and minimise environmental impacts (Mikhailova *et al.*, 2024). In this context, the proposed method of signal processing based on wavelet transformations, implemented on microcontrollers, is a practical tool for ensuring the sustainable development of industry. V. Veerasamy *et al.* (2020) investigated the use of wavelet transformations for signal analysis in industrial power systems, but paid more attention to the use of stationary wavelet transformations. Their results confirmed that this approach improves diagnostic accuracy, but system efficiency decreases due to high computational complexity. Compared to the current study, the results confirm the overall prospects of wavelet transformations, but the use of adaptive algorithms in the current study significantly reduced computational complexity, which differs from the researchers' approach.

X. Han *et al.* (2019) investigated the use of wavelet transformations for temperature monitoring in industrial heat transfer systems. They found that second-order adaptive wavelets provide temperature analysis accuracy with an error of up to 1.2%. Similar to the current study, they also emphasised the importance of choosing the optimal wavelet base for specific signals. Current study focused on voltage and power monitoring, and their research focused exclusively on temperature changes. S. Kováč *et al.* (2021) investigated the use of second-order adaptive wavelets for temperature analysis in industrial heat transfer systems. Their method provided fairly good accuracy even in environments with high noise levels. The researchers stressed the importance of choosing the right wavelet base to maximise the efficiency of signal analysis, which confirms the practicality of the approach. Together with the current study, there is an emphasis on adapting wavelet transformations to high noise conditions. However, the researchers focused exclusively on monitoring temperature changes, while the current study was based on voltage and power analysis. In addition, the current results additionally solved the problem of optimising algorithms for working on limited hardware resources of microcontrollers. This highlights the variety of applications of wavelets in industrial tasks.

One of the main advantages of the proposed approach is the ability of wavelet transformations to operate in the time-frequency domain, which detects even minor changes in the characteristics of signals. This allows detecting malfunctions early and predicting potential hardware failures. The use of wavelet transformations in combination with adaptive filtering algorithms helps to effectively deal with high noise levels, which is typical for industrial conditions. A.A. Ogaili *et al.* (2024) focused on the use of wavelet transforms for early detection of turbine failures. Their study showed that time-frequency analysis can detect even microscopic changes in the signal spectrum, but the high sensitivity of the technique led to a significant number of false positives in noisy environments. However, in contrast to the authors' research, the current results demonstrate efficiency in noise control through the integration of adaptive filtering algorithms, which allowed avoiding false positives.

The microcontrollers used as the basis for implementing the technique have shown high efficiency due to their compact size, low power consumption, and ability to process data in real time (Malinovskyi *et al.*, 2024). However, implementing complex algorithms on devices with limited resources required significant optimisation. The study suggests a number of optimisation approaches, including reducing the computational complexity of algorithms and efficient memory usage. These measures ensured stable operation of the system even in real industrial conditions. J. Konecny *et al.* (2024) analysed the possibility of using microcontrollers to implement wavelet transformations in industrial settings. They noted that the limited resources of such devices limit their suitability for complex tasks. The researchers suggested using the Field Programmable Gate Array to overcome these limitations. The current study focused on optimising algorithms for microcontrollers, which allows achieving more stable operation without switching to more expensive Field Programmable Gate Array solutions.

The industrial conditions in which the proposed system was tested were characterised by a high level of electromagnetic interference, significant fluctuations in network parameters, and a large amount of data for analysis. The results showed that the developed system can adapt to changes in the environment, while maintaining high monitoring accuracy. This confirms the practical suitability of the methodology for use in real-world operation. P. Gangsar & R. Tiwari (2020) conducted testing under conditions that simulate the effects of electromagnetic interference. Their results showed that most signal analysis methods lose accuracy due to significant fluctuations in signal parameters. The methods developed by the authors to compensate for interference partially solved this problem, but required a large amount of data for training. The current study shows that the proposed system demonstrates stability even in noisy industrial environments, which indicates greater adaptability compared to the researchers' approaches. A. Mannelli *et al.* (2021) examined the effect of wavelet coefficients on equipment energy consumption in renewable energy systems. Their method reduced the frequency of maintenance of generators by 20%. It was confirmed that wavelets effectively detect signals that are difficult to identify by conventional methods. Their results were related to energy from renewable sources, while the current study focused on classical industrial power systems.

The study results revealed certain challenges associated with the integration of the proposed solution into existing energy systems. For example, ensuring compatibility between new and legacy system components required additional effort. In addition, further improvement of the system requires the integration of IoT technologies, which will increase scalability and provide remote monitoring capabilities. K.H. Azmi *et al.* (2022) analysed the integration of modern diagnostic systems into outdated power grids. They emphasised the complexity of adapting equipment due to outdated data transfer protocols, but suggested using converters to ensure compatibility. Compared to the current study, the results confirm the need to adapt to legacy components, but the proposed solutions consider not only the protocols, but also the adaptation of the algorithms themselves to existing equipment. T. Ahmad & D. Zhang (2021) investigated the integration of the latest diagnostic technologies into outdated power grids that use obsolete approaches.

The researchers focused on the problems caused by the limited functionality of old data transfer protocols that do not meet modern requirements. To solve this problem, the researchers proposed the use of converters that act as a connecting link between modern monitoring equipment and existing networks. This helped to ensure compatibility without the need for a radical update of the entire system.

An important aspect is the potential integration of the developed system with renewable energy technologies. In particular, the possibility of effective monitoring of the operation of solar or wind power plants, where the variability of energy consumption significantly depends on external factors, opens up new prospects for implementation. This requires further adaptation of algorithms to variable conditions and integration with energy storage facilities. M.Z. Khoker *et al*. (2020) investigated the possibility of monitoring the operation of solar stations using wavelet analysis. Their results showed that algorithms need to be regularly adapted to variable operating conditions, such as light and temperature. The current study also points out the potential for integrating the developed systems with renewable energy sources. However, the current findings cover integration with energy storage facilities, which was not considered by the researchers.

The results of the study were analysed in the context of modern approaches to monitoring and optimising energy systems. It was established that the use of wavelet transformations on microcontrollers can significantly improve the accuracy of diagnostics and efficiency of equipment operation, even in difficult industrial conditions. The advantages and challenges of integrating the developed solutions into existing energy networks, in particular, compatibility with outdated systems and prospects for use in renewable energy, were considered. The results obtained confirmed the practical value of the proposed approaches and opened up new areas for further research.

Conclusions

This study analysed the use of wavelet transforms on microcontrollers for monitoring and optimising energy systems in industrial environments. The main attention was paid to the urgency of the problem of energy efficiency, which is a critical factor in modern industry due to the increase in energy costs and the need to reduce environmental impact. The study emphasised that the stable and uninterrupted operation of industrial power systems requires constant monitoring to detect malfunctions early, assess the condition of equipment, and reduce operating costs. Conventional signal processing methods were analysed and it was found that they often have limitations, in particular, insufficient accuracy or high computational complexity, which makes them difficult to apply in real time.

Considering the specifics of industrial conditions, such as high noise levels, significant parameter fluctuations, and the complex structure of power networks, the study focused on adapting wavelet transform algorithms to such conditions. For this purpose, it was proposed to reduce the number of decomposition levels, select optimal wavelet functions, and introduce adaptive approaches to signal processing. The study also developed an approach to reducing the power consumption of microcontrollers by using energy-efficient operating modes and adaptive management of computing resources depending on the characteristics of signals. Experiments have shown that optimised wavelet transform algorithms ensure the accuracy of anomaly detection while reducing power consumption.

Optimised wavelet transformations on microcontrollers provide improved accuracy in detecting anomalies and predicting peak loads in real time, which is critical for power systems. The use of Daubechies wavelets provided 95.1% sensitivity and 92.5% accuracy with high noise resistance, while Haar demonstrated a faster processing time (118 Ms vs. 147 Ms) due to easy calculations. Optimisation of the algorithm by reducing the number of operations, using fixed arithmetic and adaptive scaling of the schedule has reduced power consumption by 27-30% without loss of accuracy, which makes this approach effective for implementation in industrial environments. A limitation of the study was the dependence of the results on the specific conditions of industrial power systems and the limited computational capabilities of microcontrollers. Further research should focus on expanding methods for adapting algorithms for different types of power networks and improving their implementation on the latest microcontrollers with larger resources.

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Conflict of Interest

None.

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Застосування вейвлет-перетворень на мікроконтролерах для моніторингу та оптимізації енергетичних систем у промислових умовах

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Анотація. Метою дослідження був аналіз підходів до використання вейвлет-перетворень на мікроконтролерах для підвищення ефективності контролю та управління енергетичними системами у промислових середовищах, а також вивчення можливостей інтеграції вейвлет-перетворень в апаратні платформи мікроконтролерів. В роботі були розглянуті методи застосування вейвлет-перетворень на мікроконтролерах для моніторингу та оптимізації енергетичних систем у промислових умовах. Запропонований метод дозволяє виявляти короткочасні аномалії, коливання напруги та струму, що сприяє своєчасному виявленню втрат енергії. Експериментально реалізовано алгоритм дискретного вейвлет-перетворення, оптимізований для мікроконтролерів, який забезпечує точність виявлення аномалій на рівні 94-96 % при співвідношенні сигнал/шум 40 дБ. Аналіз показав, що використання вейвлетів типу Daubechies дозволяє підвищити чутливість алгоритму на 3-4 % у порівнянні з Haar, зберігаючи прийнятний рівень обчислювальних витрат. Оптимізація реалізації дозволила зменшити середній час обробки одного сегмента сигналу до 0,1 с на мікроконтролері STM32. Окрім цього, враховано особливості промислових умов, які характеризуються високим рівнем шуму та змінними параметрами, що додатково ускладнює використання вейвлет-перетворень. Основним досягненням була розробка адаптованого методу вейвлет-аналізу, який забезпечує ефективне використання мікроконтролерів для моніторингу енергетичних систем при мінімальних апаратних вимогах. Запропоновано новий алгоритм, що дозволяє оптимізувати використання обчислювальних ресурсів, знижуючи енергоспоживання без втрати точності аналізу сигналів. Розроблений метод дозволяє своєчасно виявляти аномалії та оптимізувати енергоспоживання, що має практичне значення для зменшення експлуатаційних витрат та покращення сталості роботи промислових систем

Ключові слова: промислові рішення; алгоритми обробки; надійність обладнання; управління ресурсами; ефективність ресурсів