IJARSCT
International Journal of Advanced Research in Science, Communication and Technology
International Open-Access, Double-Blind, Peer-Reviewed, Refereed, Multidisciplinary Online Journal
ISSN: 2581-9429
Volume 6, Issue 3, September 2026
Impact Factor: 8.2

Advanced Wavelet Transform-Based Signal Processing for Power Quality Disturbance Detection and Improvement

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Abstract : *Power quality has become an important concern in modern electrical power systems because of the increasing penetration of renewable-energy sources, power-electronic converters, nonlinear loads, distributed generation, electric vehicles, and sensitive digital equipment. Voltage sag, swell, interruption, harmonics, transients, flicker, notching, and oscillatory disturbances can adversely affect equipment performance, protection systems, production processes, and overall grid reliability. Conventional Fourier-transform-based techniques are effective for stationary harmonic analysis but have limitations when disturbances are short-duration, transient, or non-stationary. Wavelet Transform, particularly Discrete Wavelet Transform, Continuous Wavelet Transform, Wavelet Packet Transform, Maximal Overlap DWT, Empirical Wavelet Transform, and Dual-Tree Complex Wavelet Transform, provides simultaneous time-frequency localization and multi-resolution analysis. Consequently, wavelet-based approaches have become important for detecting, localizing, characterizing, and classifying PQ disturbances.*

Keywords: Power Quality, Wavelet Transform, Discrete Wavelet Transform, Power Quality Disturbance, Signal Processing, Active Power Filter.

1. INTRODUCTION

Electrical power quality refers to the degree to which voltage, current, frequency, and other electrical characteristics remain within acceptable operating limits for electrical equipment and power-system operation. Modern distribution systems are increasingly exposed to disturbances because of nonlinear loads, inverter-based renewable-energy generation, distributed energy resources, switching operations, electric drives, and rapidly changing loads. These conditions can produce voltage sags, swells, interruptions, harmonic distortion, transients, flicker, notching, and combinations of several disturbances. Accurate detection and classification of these events are essential because disturbance information can be used for protection, equipment diagnosis, power-quality monitoring, and selection of appropriate mitigation strategies.

Traditional Fourier Transform, Fast Fourier Transform, and Short-Time Fourier Transform methods have been extensively used for harmonic and spectral analysis. However, Fourier-based methods have difficulty representing disturbances whose frequency characteristics change rapidly with time. STFT improves temporal information through a moving window but its fixed window creates a trade-off between time and frequency resolution. Wavelet Transform addresses this limitation through multi-resolution analysis, allowing short windows for high-frequency components and longer windows for low-frequency components. Reviews of PQ signal-processing research identify WT, DWT, STFT, S-transform, Hilbert-Huang Transform, and intelligent classification methods as major approaches for disturbance analysis (Mishra 2019; 2020).

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II. ADVANCED WAVELET TRANSFORM TECHNIQUES

1. Discrete Wavelet Transform

DWT is among the most widely applied techniques for PQ disturbance detection because it provides multi-resolution analysis with comparatively low computational complexity. A power waveform can be decomposed into several frequency bands, and disturbance-specific information can be extracted from the corresponding coefficients.

The choice of mother wavelet is important. Daubechies wavelets, particularly db4, are frequently selected because their compact support and shape can provide effective representation of abrupt electrical disturbances. Zhao (2019), for example, used db4-based wavelet analysis in combination with S-transform features and a decision-tree classifier for single and combined PQ disturbances.

2. Continuous Wavelet Transform

CWT provides detailed time-scale information and is useful for visualizing disturbance signatures. It can generate time-frequency representations that are subsequently converted into two-dimensional scalograms. These scalograms can be processed by CNNs and other deep-learning architectures.

Salles and Ribeiro (2023) investigated CWT-generated time-frequency representations combined with deep learning and transfer learning for PQ disturbance classification. Their work illustrates the transition from conventional manually engineered wavelet features toward image-like representations suitable for deep learning.

3. Wavelet Packet Transform

WPT extends conventional DWT by decomposing both approximation and detail components. Consequently, it can provide a more uniform and flexible frequency-band representation. This can be useful when disturbances contain frequency components that do not correspond well with the conventional dyadic decomposition of DWT.

4. Maximal Overlap Discrete Wavelet Transform

MODWT is particularly useful for localization and feature extraction because it avoids some alignment limitations associated with conventional decimated DWT. A 2016 study applied MODWT to ten categories of PQ events, including sag, swell, interruption, harmonics, spike, and notch, and used wavelet coefficients as inputs for SVM and decision-tree classifiers.

5. Empirical Wavelet Transform

EWT adaptively separates a signal according to its spectral characteristics rather than using a predetermined filter bank. This makes it attractive for non-stationary PQ signals containing multiple frequency components. Research has combined EWT-based adaptive filtering with multiclass SVM for recognizing multiple PQ disturbances.

More recently, adaptive empirical wavelet approaches have been investigated for noisy and non-stationary PQ signals, with the objective of reducing the need for manually specifying signal components and improving robustness to noise.

6. Dual-Tree Complex Wavelet Transform

DT-CWT provides improved shift invariance and can offer a richer representation of transient and oscillatory components. Das (2020) incorporated DT-CWT into a PV-integrated shunt hybrid active filter and used the decomposed frequency information for generating reference signals for PQ compensation.

III. WAVELET-BASED FEATURE EXTRACTION FOR PQ DISTURBANCES

Feature extraction converts raw voltage or current waveforms into a compact representation that can be used for detection and classification. Wavelet coefficients provide multiple opportunities for extracting meaningful features.

Important wavelet-domain features include:

1. Wavelet coefficient energy
2. Relative wavelet energy
3. Wavelet entropy
4. Mean coefficient value
5. Standard deviation
6. RMS value

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7. Variance
8. Kurtosis
9. Skewness
10. Maximum and minimum coefficient values
11. Energy ratios between decomposition levels
12. Time location of maximum coefficient

The wavelet energy at a particular decomposition level can be calculated as:

$$E_j = \Sigma |d_j(k)|^2$$

where dj(k) represents detail coefficients at level j.

The relative energy can be calculated as:

$$RE_j = E_j / \Sigma E_j$$

These measures can distinguish disturbances because different PQ events distribute signal energy differently across time-frequency scales.

IV. WAVELET-BASED DETECTION AND LOCALIZATION

Detection is the first stage in automated PQ monitoring. The purpose is to identify whether a disturbance exists and determine its beginning and ending points. Wavelet coefficients are especially sensitive to abrupt changes, making them suitable for locating disturbance boundaries.

An adaptive-threshold wavelet approach reported accurate segmentation in more than 96% of evaluated signals, demonstrating the usefulness of wavelet detail coefficients for determining disturbance start and end points.

The basic detection process can be represented as:

Measured waveform → Pre-processing → Wavelet decomposition → Coefficient analysis → Adaptive threshold → Disturbance localization

This method can operate independently of the final classifier. Therefore, a practical PQ monitoring system can first detect an event using wavelet coefficients and then classify the event using statistical or machine-learning features.

V. REAL-TIME WAVELET-BASED POWER QUALITY MONITORING

For practical grid deployment, accuracy alone is insufficient. PQ monitoring must also satisfy requirements concerning latency, computational complexity, memory, energy consumption, and hardware implementation.

A 2024 DWT-ELM framework reported 99.69% classification accuracy and was implemented on a Xilinx Zynq-7000 SoC FPGA, with reported latency of approximately 1.5 ms and power consumption of 1.8 W.

Real-time implementation is also supported by wavelet-based disturbance detection approaches designed specifically for distribution systems. A 2023 study developed a wavelet-based disturbance index using power decomposition and demonstrated detection from a single substation measurement point.

These developments suggest that wavelet algorithms can be implemented in embedded monitoring devices, FPGA systems, digital signal processors, smart meters, and intelligent electronic devices.

VI. WAVELET TRANSFORM FOR POWER QUALITY IMPROVEMENT

The term "power quality improvement" extends beyond disturbance identification. Once a disturbance has been detected, an appropriate compensating action should be initiated.

Wavelet-based control can identify harmonic and transient components and separate them from fundamental components. The extracted disturbance information can then be used to calculate reference currents for:

1. Shunt active power filters,
2. Series active power filters,
3. Unified power-quality conditioners,
4. Hybrid active filters,

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5. Dynamic voltage restorers,
6. STATCOM-based compensators,
7. Grid-connected inverter controllers.

Kumar and Bansal (2019) investigated wavelet-based control of a shunt active power filter and evaluated Haar, Symlet, Daubechies, and biorthogonal wavelets. Their hardware-in-the-loop implementation used OPAL-RT hardware and examined harmonic mitigation and power-factor improvement.

Das (2020) developed a PV-integrated shunt hybrid active filter using DT-CWT and adaptive filtering. The study specifically targeted harmonic compensation, reactive-power compensation, and improved performance in renewable-energy-integrated distribution systems.

Table 1. Wavelet Applications in Power Quality Improvement

Application	Wavelet Role	Expected Improvement
Shunt active power filter	Extraction of harmonic/reference-current components	Reduced current THD
Hybrid active filter	Separation of frequency components	Harmonic and reactive-power compensation
PV-integrated filter	Disturbance extraction under variable generation	Improved grid-current quality
DVR	Identification of voltage disturbance components	Improved voltage waveform
UPQC	Joint voltage/current decomposition	Simultaneous voltage and current compensation
STATCOM control	Detection of harmonic/reactive components	Improved voltage regulation
Adaptive filtering	Multi-resolution separation	Better response to non-stationary disturbances
Real-time FPGA control	Fast wavelet decomposition	Reduced detection/control latency

VII. FUTURE RESEARCH DIRECTIONS

Future research should focus on adaptive and intelligent wavelet architectures capable of responding automatically to changing grid conditions. Adaptive mother-wavelet selection could reduce dependence on manually chosen wavelet functions. EWT and tunable-Q-factor wavelet methods offer promising approaches for adapting the decomposition to signal characteristics. A 2024 study investigated TQWT combined with ensemble learning specifically to represent sparse PQ signals in the time-scale domain.

Another important direction is the development of lightweight deep-learning models. Instead of using computationally expensive architectures, wavelet preprocessing can reduce the dimensionality of raw signals and provide informative representations to compact neural networks.

Edge computing and FPGA implementation are also likely to become increasingly important. Wavelet-based detection can be placed close to sensors so that disturbances are detected with low latency and compensation can be initiated quickly.

Future systems should also integrate synchronized measurements from multiple locations. Combining wavelet-based local analysis with wide-area measurements could improve disturbance localization and help distinguish local disturbances from network-wide events.

Finally, future studies should emphasize real-world datasets. Although synthetic datasets are useful for controlled evaluation, field measurements contain noise, parameter variation, overlapping events, and disturbances that may not perfectly follow theoretical models.

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VIII. CONCLUSION

Advanced Wavelet Transform-based signal processing provides a powerful framework for detecting, localizing, classifying, and mitigating power-quality disturbances. Unlike conventional Fourier analysis, wavelet methods provide multi-resolution time-frequency information and are therefore particularly appropriate for non-stationary electrical events. DWT offers an attractive balance between accuracy and computational efficiency, while CWT provides detailed time-frequency representations, WPT enables flexible frequency decomposition, MODWT supports localization, EWT provides adaptive decomposition, and DT-CWT offers advanced time-frequency characteristics for filtering and control.

The research published between 2010 and 2025 demonstrates a clear progression from conventional wavelet-based disturbance detection toward hybrid wavelet-machine-learning and wavelet-deep-learning architectures. Wavelet-derived features have been successfully combined with decision trees, SVMs, neural networks, LSTM networks, CNNs, ELMs, and ensemble methods. Recent studies report high classification accuracy under noisy conditions and demonstrate real-time implementation using FPGA platforms.

REFERENCES

1. Coelho, R. de A., Dantas, K. M. C., Lima, É. M., Brito, N. S. D., Dantas, K. de V. O., & Zacarias, R. (2023). Real-time wavelet-based distribution systems disturbances detection. Electric Power Systems Research, 220, 109325.
2. Das, S. R., Mishra, A. K., Ray, P. K., Mohanty, A., Mishra, D. K., Li, L., Hossain, M. J., & Mallick, R. K. (2020). Advanced wavelet transform based shunt hybrid active filter in PV integrated power distribution system for power quality enhancement. IET Energy Systems Integration, 2(4), 331–343.
3. Kumar, R., & Bansal, H. O. (2019). Hardware in the loop implementation of wavelet based strategy in shunt active power filter to mitigate power quality issues. Electric Power Systems Research, 169, 92–104.
4. Mahmoudi, A., Hosseinian, S. H., & Doroudi, A. (2010). A new and fast method for detection of power quality disturbances using wavelet transform. 2010 First Power Quality Conference. IEEE.
5. Mishra, M., Routray, A., & Sadhu, P. K. (2019). Power quality disturbance detection and classification using signal processing and soft computing techniques: A comprehensive review. International Transactions on Electrical Energy Systems, 29(1), e12008.
6. Salles, R. S., & Ribeiro, P. F. (2023). The use of deep learning and 2-D wavelet scalograms for power quality disturbances classification. Electric Power Systems Research, 214, 108834.
7. Sipai, U., Jadeja, R., Kothari, N., Trivedi, T., Mahadeva, R., & Patole, S. P. (2024). Performance evaluation of discrete wavelet transform and machine learning based techniques for classifying power quality disturbances. IEEE Access, 12, 95472–95486.
8. Wang, Y., et al. (2019). Detection and classification of disturbances in the islanded micro-grid by using wavelet transformation and feature extraction algorithm. The Journal of Engineering.
9. Xi, X., et al. (2023). Classification of multiple power quality disturbances based on continuous wavelet transform and lightweight convolutional neural network. Energy Science & Engineering.
10. Zhao, W., Shang, L., & Sun, J. (2019). Power quality disturbance classification based on time-frequency domain multi-feature and decision tree. Protection and Control of Modern Power Systems, 4, 27.
11. Ismael, M. R., Abd, H. J., & Homod, R. Z. (2024). An algorithm for the classification of power quality disturbance signals using a tunable-Q-factor wavelet transform and ensemble learning methodology. Electrical Engineering, 106, 5253–5265.
12. Kumar, (2016). Localization and classification of power quality disturbances using maximal overlap discrete wavelet transform and data mining based classifiers. IFAC-PapersOnLine, 49(1), 437–442.