

## AI DRIVEN POWER QUALITY ANALYSIS IN DISTRIBUTION GRIDS

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### Abstract:

The increasing integration of distributed generation (DG) and power-electronics-based equipment has intensified power quality (PQ) disturbances such as harmonics, voltage fluctuations, and transients in distribution grids. While artificial intelligence (AI) has demonstrated strong potential for PQ monitoring and classification, existing research remains focused mainly on signal analysis rather than intelligent control of renewable energy converters for active PQ enhancement. This review provides a comprehensive synthesis of AI-driven approaches for PQ detection, classification, prediction, and mitigation. A practical low-cost measurement framework is also presented, utilizing an ATmega328 microcontroller interfaced with current and voltage transformers (CT, VT) for PQ data acquisition. The processed parameters are transmitted via ESP8266 Wi-Fi to a cloud platform such as ThingSpeak for real-time visualization and storage. MATLAB further supports data analytics, AI-based classification, and harmonic analysis, enabling improved decision-making for PQ management. By comparing machine learning, deep learning, and hybrid AI models, this study evaluates accuracy, response time, and total harmonic distortion (THD) reduction. The findings highlight a major research gap: the limited use of AI for adaptive control of renewable energy converters to directly enhance PQ. Future directions are proposed toward self-optimizing and intelligent PQ management in evolving smart grids. The system uses a low-cost microcontroller and an open-source cloud platform, reducing system cost by over 60% compared to commercial PQ analyzers. The framework also integrates reinforcement learning for autonomous control actions and explores digital twin technology for virtual PQ prediction before faults occur. This study bridges the gap between theoretical AI models and practical embedded deployment for PQ monitoring. Unlike existing survey papers, this work integrates hardware implementation with intelligent analytics.

### Introduction:

The rapid transformation of modern electrical distribution systems is largely driven by the growing penetration of distributed energy resources (DERs), power-electronics-based interfaces, smart grid technologies, and advanced monitoring frameworks. These developments create both opportunities and challenges for utilities, consumers, and system planners. Among the most critical concerns is the maintenance of acceptable power quality (PQ), as the emerging grid environment is more dynamic, nonlinear, and sensitive to disturbances than conventional centralized power networks. As renewable energy technologies such as solar photovoltaic (PV) inverters, wind turbine converters, and battery storage systems become widespread, the electrical characteristics of distribution networks continue to evolve.

Unlike traditional electromechanical systems, these modern components rely heavily on power electronics, making them susceptible to harmonic distortions, voltage flicker, frequency deviations, and transient switching events. These PQ issues not only degrade consumer equipment performance but also hinder grid stability and operational efficiency. Historically, PQ monitoring and mitigation relied on fixed passive filters, capacitor banks, and basic signal processing techniques. While effective to some extent, these approaches do not offer the adaptability needed to handle rapidly changing loads, nonlinear components, or widespread renewable integration. To address this challenge, artificial intelligence (AI)-based techniques are increasingly being adopted for PQ detection, classification, prediction, and active control. Machine learning (ML), deep learning (DL), and hybrid data-driven signal processing methods have shown the ability to extract complex PQ patterns from raw voltage and current waveforms, achieving high accuracy even in noisy or mixed-event scenarios.

Beyond analysis, AI also opens pathways for autonomous PQ improvement by controlling converters, optimizing reactive power flow, and maximizing system resilience in real time. Despite this progress, a noticeable research gap persists: most existing PQ-related AI studies concentrate heavily on classification tasks, while fewer works explore AI-driven control of renewable energy source (RES) converters for active PQ enhancement. In parallel with methodological advances, there is also a growing interest in practical, low-cost PQ monitoring systems suitable for industrial, academic, and research environments. Microcontrollers like the ATmega328, in combination with Wi-Fi modules such as the ESP8266, enable compact and affordable IoT-based PQ measurement platforms.

By integrating sensors such as current transformers (CTs) and voltage transformers (VTs), these systems can measure real-time parameters including current, voltage, frequency, and harmonic signatures. Cloud platforms such as ThingSpeak allow seamless data transmission, visualization, and storage, while MATLAB provides a powerful environment for signal processing, PQ characterization, harmonic decomposition, and AI model development. This integration of embedded systems, wireless

communication, and computational intelligence supports the creation of scalable PQ analysis frameworks that are suitable for both academic research and field deployment.

The growing complexity of distribution networks necessitates a more intelligent and holistic approach to PQ management. Conventional mitigation techniques are insufficient for rapidly changing load profiles, sudden disturbances, and high penetration of nonlinear devices. Therefore, modern PQ management demands real-time monitoring, automated decision-making, and adaptive corrective actions. AI-driven methods can contribute significantly by offering predictive capabilities, identifying multiple simultaneous PQ events, and recommending optimal control strategies.

Moreover, the integration of edge computing and IoT-based sensing devices ensures that PQ data is collected continuously, enabling long-term analytics and energy management optimization. This project aims to bridge the gap between theoretical advancements and practical implementation by developing a comprehensive framework for AI-driven PQ analysis in distribution grids. It combines the strengths of embedded hardware, cloud platforms, and MATLAB-based analytics to construct an end-to-end solution for PQ monitoring, classification, and improvement. The ultimate goal is to move towards intelligent power distribution environments where issues can be detected early, classified accurately, and mitigated adaptively through coordinated control of converters and renewable energy resources.

#### **Proposed System:**

##### **1. ATmega328 Microcontroller:**

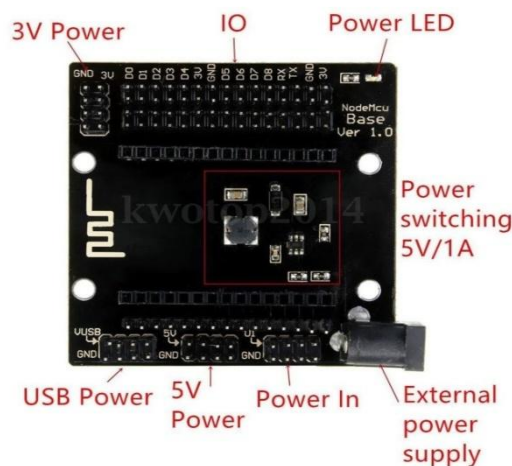
The ATmega328 microcontroller functions as the central processing unit of the PQ monitoring device. It is an 8-bit, low-power microcontroller from the AVR family, widely used due to its stability and ease of programming. The controller interfaces with analog sensors such as current transformers (CT) and voltage transformers (VT) through its 10-bit ADC channels, converting raw analog electrical signals into digital values for processing. It performs essential tasks such as sampling, RMS computation, zero-crossing detection, variation identification, and preparation of data packets for wireless transmission. The microcontroller operates at a clock frequency of 16 MHz, providing sufficient speed for real-time PQ monitoring. Multiple GPIO pins allow interfacing with signal conditioning circuits, LCD modules, and serial communication with the ESP8266 via UART. Its flash memory stores the embedded C program responsible for periodic sampling, filtering, and execution of PQ algorithms. The ATmega328 is selected for its reliability, low power consumption, open-source ecosystem, and seamless integration with the Arduino IDE, enabling rapid firmware development.

##### **2. ESP8266 Wi-Fi Module (NodeMCU Base Board):**

The ESP8266 Wi-Fi module is used for wireless communication and IoT integration. The NodeMCU baseboard acts as a breakout board for the NodeMCU ESP8266 V3 (Lua CH340) Wi-Fi development board. The NodeMCU platform is an open-source IoT development environment that combines firmware and hardware based on the ESP8266 system-on-chip (SoC). It uses the Lua scripting language and allows developers to interact with hardware in a manner similar to Arduino, making it easier for software developers to control hardware devices. The baseboard provides convenient access to all input/output pins of the ESP-12E module and includes an onboard power supply circuit. It also supports USB-based programming and debugging, making it suitable for rapid IoT prototyping and deployment.

#### **Port Description:**

The NodeMCU baseboard exposes multiple pins for interfacing with peripherals, including GPIO, UART, SPI, and ADC pins. It also provides regulated 5V and 3.3V outputs for powering external components.



#### **Note:**

Please pay attention when ordering this board, as this shield is compatible only with the Lua V3 NodeMCU model and not with all NodeMCU boards. If you use a different type of NodeMCU board, the connectors may not match due to differences in width. Therefore, this baseboard is suitable only for the Lua V3 NodeMCU board.

#### **Features:**

- Provides an effective solution for breaking out the pins of the Lua V3 NodeMCU.
- Compact and handy module design.
- Mounting header spacing of 25.5 mm.
- Supports Lua scripting language programming.
- Exposes all I/O ports of the ESP-12E development board.
- Provides access to both 5V and 3.3V power supply pins.

- Enables easy connection with peripheral modules.
- Includes an onboard 5V / 1A DC-DC step-down converter circuit.
- Equipped with an onboard power indicator.
- USB power output is available only for NodeMCU V3.

### 3. NodeMCU:

NodeMCU is an open-source IoT platform that includes both firmware and hardware components. The firmware runs on the ESP8266 Wi-Fi System-on-Chip (SoC) developed by Espressif Systems, while the hardware is based on the ESP-12 module. The term “NodeMCU” typically refers to the firmware rather than the development kit itself. The firmware uses the Lua scripting language and is based on the eLua project. It is built on the Espressif Non-OS SDK for the ESP8266 and incorporates several open-source libraries such as Lua-cjson and SPIFFS. NodeMCU provides an interactive Lua-based programming environment for the ESP8266 Wi-Fi SoC. In addition, the development board includes a CP2102 USB-to-TTL converter for programming and debugging. It is breadboard-friendly and can be conveniently powered through a micro USB port.

### 4. Features:

- Wi-Fi Module: ESP-12E module, similar to ESP-12 but with additional GPIO pins.
- USB Interface: Micro USB port for power supply, programming, and debugging.
- Headers: Dual 2.54 mm 15-pin headers providing access to GPIO, SPI, UART, ADC, and power pins.
- Control Buttons: Reset and Flash buttons for easy operation.
- Power Supply: Operates at 5V via micro USB input.
- Dimensions: 49 mm × 24.5 mm × 13 mm.

### 5. Arduino-like Hardware I/O:

NodeMCU provides an advanced API for hardware interfacing, significantly reducing the complexity involved in configuring and controlling hardware peripherals. The programming style is similar to Arduino but supports interactive execution using Lua scripts, making development faster and more flexible.

### 6. Node.js-style Network API:

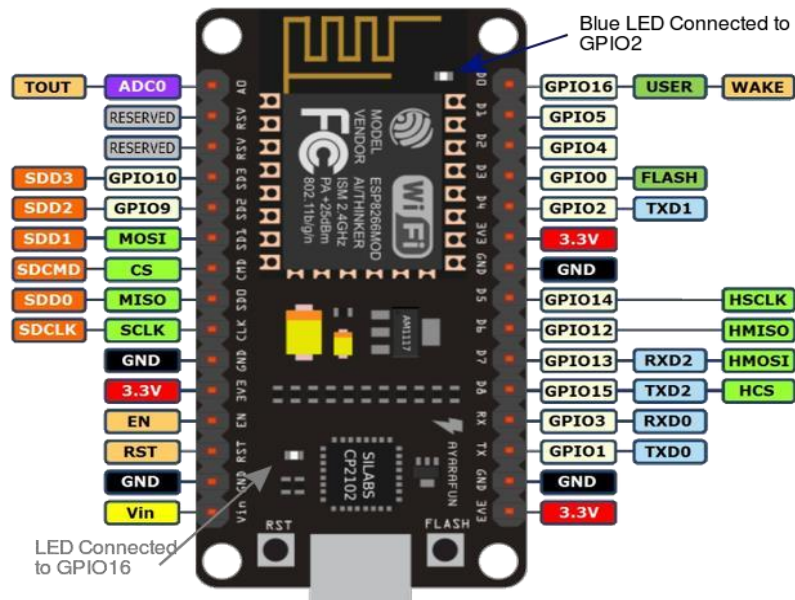
The platform offers an event-driven network API inspired by Node.js, enabling efficient development of network-based applications. This approach allows developers to write lightweight and responsive code suitable for resource-constrained microcontrollers.

### 7. Low-Cost Wi-Fi Solution:

The ESP8266-based NodeMCU module is an affordable Wi-Fi-enabled microcontroller, typically costing less than \$2. It provides an economical solution for IoT application development and rapid prototyping.

### 8. Development Kit:

The NodeMCU development kit integrates multiple functionalities, including GPIO, PWM, I2C, 1-Wire, and ADC, into a single compact board. When combined with NodeMCU firmware, it offers a powerful and efficient platform for rapid IoT system development.



### Important Notes (ESP8266 / NodeMCU Power Requirements):

- The ESP8266 chip requires a 3.3V power supply and should not be powered directly with 5V like typical Arduino boards.
- The NodeMCU ESP-12E development board can be supplied with 5V via the micro USB port or Vin pin, as it includes an onboard voltage regulator.
- The I/O pins of the ESP8266 operate at a maximum of 3.3V logic level. Hence, they are not 5V tolerant, and direct connection to 5V signals may damage the device.

### 9. Current Transformer (CT) Sensor:

The current transformer (CT) sensor is used to measure the current flowing through the distribution line. It operates on the principle of electromagnetic induction, where the primary conductor induces a proportional current in the secondary winding.

This allows safe measurement of high currents without direct electrical contact. The CT is connected to a burden resistor, which converts the induced current into a measurable voltage signal. This voltage is then fed into the ATmega328 analog-to-digital converter (ADC). A rectification and filtering circuit ensures that the output signal remains within the acceptable 0-5V ADC range. The CT sensor enables monitoring of load current behavior, detection of sudden current variations, identification of overload conditions, and evaluation of harmonic distortion through digital signal sampling. A high-quality CT is essential for capturing accurate waveforms and maintaining measurement reliability during transient PQ events such as voltage sags, swells, and switching surges.

#### **10. Voltage Transformer (VT) Sensor:**

The voltage transformer (VT) sensor is used to step down the grid voltage to a safe and measurable level suitable for the microcontroller's ADC. It provides electrical isolation between the high-voltage distribution line and the sensing circuitry, ensuring both operator safety and system protection. The VT outputs a scaled AC voltage, which is then processed through a rectifier and signal conditioning circuit to produce a stable signal within ADC limits. Accurate voltage measurement is crucial for power quality monitoring, as voltage disturbances such as sag, swell, flicker, and harmonic distortion directly affect system performance. The VT sensor also supports the calculation of key electrical parameters, including power, energy, frequency, and phase angle.

#### **11. Signal Conditioning Unit:**

Both CT and VT outputs require proper conditioning before being fed into the ADC of the microcontroller. The signal conditioning unit consists of the following components:

- Voltage dividers
- Burden resistors
- Precision rectifiers
- Low-pass filters
- Offset circuits (to convert AC signals into a measurable 0-5V DC equivalent)

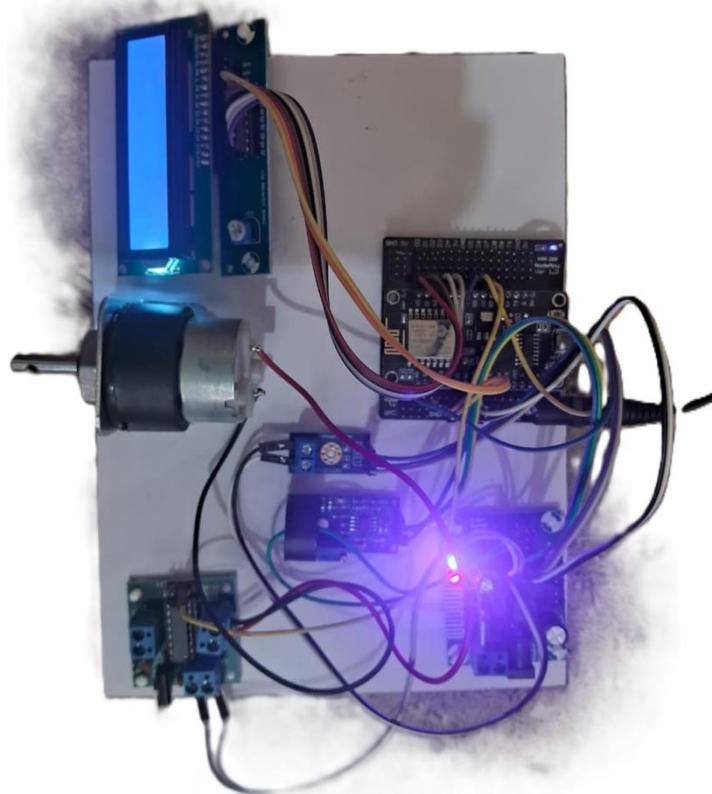
These components ensure that the incoming analog signal is clean, noise-free, and within the safe input limits of the microcontroller. Proper signal conditioning is essential for accurate PQ detection and helps prevent ADC saturation or waveform distortion during measurements.

#### **12. Power Supply Unit:**

The entire hardware system requires a stable and regulated power supply for reliable operation. A 5V DC supply is provided for the ATmega328 microcontroller and associated components, while the ESP8266 requires a dedicated 3.3V regulator due to its sensitivity to voltage fluctuations. A combination of a step-down transformer, rectifier, filter capacitors, and voltage regulators such as 7805 and AMS1117-3.3 is used to maintain a constant output voltage. To enhance system reliability and safety, protective components such as over current protection circuits, fuses, and heat sinks are incorporated to prevent damage from electrical faults or overheating.

#### **13. ThingSpeak Cloud Integration (Hardware Support):**

The hardware system is designed to communicate seamlessly with cloud platforms for real-time monitoring and data analysis. The ESP8266 Wi-Fi module transmits the sampled PQ parameters to a ThingSpeak channel using HTTP protocols. For effective cloud integration, the system ensures proper timing intervals, correct API configuration, and reliable data transmission. This enables continuous data logging, remote visualization, and further analysis of power quality parameters.



### **Discussion:**

The proposed AI-driven power quality (PQ) monitoring system demonstrates a practical and cost-effective approach to addressing the growing challenges in modern distribution grids. By integrating embedded hardware such as the ATmega328 microcontroller with IoT communication through the ESP8266 module, the system achieves real-time acquisition and transmission of electrical parameters. The use of current transformer (CT) and voltage transformer (VT) sensors, combined with an efficient signal conditioning unit, ensures accurate measurement of voltage and current waveforms. These measurements enable the identification of PQ disturbances such as harmonics, voltage sags, swells, and transients. Compared to conventional PQ analyzers, the proposed system significantly reduces cost while maintaining acceptable accuracy for academic and industrial applications.

The incorporation of cloud-based platforms enables continuous monitoring, remote accessibility, and long-term data storage. This enhances the capability for trend analysis and supports predictive maintenance strategies. Furthermore, MATLAB-based analysis provides a strong framework for implementing machine learning (ML) and deep learning (DL) models for classification and pattern recognition of PQ disturbances. One of the key observations is that while AI techniques are highly effective in detecting and classifying PQ issues, their application in real-time control and mitigation remains limited. The proposed framework attempts to bridge this gap by suggesting the integration of reinforcement learning and intelligent control strategies for adaptive PQ improvement. However, certain limitations exist. The use of low-cost sensors and microcontrollers may introduce measurement inaccuracies under extreme conditions. Additionally, the system's dependency on internet connectivity for cloud communication may affect real-time performance in remote or unstable network environments. Despite these challenges, the system provides a scalable foundation for future smart grid applications.

### **Conclusion:**

This study presents a comprehensive framework for AI-driven power quality analysis in distribution grids, combining embedded systems, IoT communication, and advanced data analytics. The proposed system effectively monitors key PQ parameters using low-cost hardware components such as the ATmega328 microcontroller, ESP8266 Wi-Fi module, CT and VT sensors, and signal conditioning circuits. The integration of cloud platforms enables real-time data visualization and storage, while MATLAB-based tools support advanced analysis, including harmonic detection and AI-based classification. The results highlight that the system can serve as an efficient alternative to conventional PQ analyzers, offering significant cost reduction without compromising essential functionality. A major contribution of this work lies in identifying the research gap between PQ analysis and active control. While most existing studies focus on detection and classification, this work emphasizes the need for intelligent control of renewable energy converters to enhance power quality dynamically. Overall, the proposed system demonstrates the feasibility of developing an intelligent, scalable, and cost-effective PQ monitoring solution suitable for modern smart grid environments.

### **Future Scope:**

The proposed system opens several avenues for further research and development:

- **AI-Based Adaptive Control:** Integration of reinforcement learning algorithms for real-time control of inverters and converters to actively mitigate PQ disturbances.
- **Digital Twin Technology:** Development of virtual models of the distribution system to simulate and predict PQ issues before their occurrence.
- **Edge Computing Integration:** Deployment of AI models directly on embedded devices to reduce latency and dependency on cloud processing.
- **Advanced Sensor Accuracy:** Use of high-precision sensors and calibration techniques to improve measurement accuracy under dynamic grid conditions.
- **Scalability to Smart Grids:** Expansion of the system for large-scale deployment in smart cities and utility-level grid monitoring.
- **Cyber security Enhancements:** Implementation of secure communication protocols to protect data transmission between hardware and cloud platforms.
- **Integration with Renewable Energy Systems:** Direct control of solar PV inverters, wind converters, and battery storage systems for real-time PQ improvement.
- **Mobile and Web Applications:** Development of user-friendly dashboards for monitoring and control through smart phones and web interfaces.

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