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Power quality assessment using smart electrical plugs: a review of voltage disturbances, harmonic monitoring, and appliance performance evaluation

Tole Sutikno[1], Tri Wahono[2], Hendril Satrian Purnama[2]
[1]Faculty of Industrial Technology, Universitas Ahmad Dahlan, Yogyakarta, Indonesia
[2]Embedded Systems and Power Electronics Research Group, Yogyakarta, Indonesia

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ABSTRACT

The increasing use of electronic appliances and power-electronic-based equipment has intensified concerns regarding power quality in residential, commercial, and industrial electrical installations. Conventional smart plugs primarily provide energy measurement and remote switching, but their potential for power quality assessment requires more advanced sensing and signal-processing capabilities. This review examines the application of smart electrical plugs for monitoring voltage disturbances, harmonic distortion, power factor, and appliance operating performance. Research published up to 2023 is considered, including studies on smart metering, power quality monitoring, harmonic estimation, and disturbance classification. Particular attention is given to voltage variations, waveform distortion, nonlinear load characteristics, and the relationship between electrical quality and equipment performance. The review also discusses measurement accuracy, sampling requirements, signal processing, and the limitations of low-cost smart-plug instrumentation. The findings indicate that appropriately designed smart plugs can complement conventional power quality analyzers by providing distributed, outlet-level measurements. However, reliable assessment requires calibrated sensors, adequate waveform acquisition, and measurement procedures consistent with recognized power quality standards. Future development should emphasize affordable high-resolution monitoring, intelligent disturbance detection, and integration with broader energy management systems.

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1. INTRODUCTION

Power quality is an important factor affecting the reliability, efficiency, and operating life of electrical appliances and equipment. Modern electrical installations contain numerous nonlinear loads, including LED lighting, electronic power supplies, computers, variable-speed drives, and inverter-based appliances. These devices may introduce harmonic currents, waveform distortion, and other electrical disturbances into distribution systems. Such conditions can increase losses, produce unwanted heating, interfere with sensitive equipment, and reduce the reliability of electrical installations [1], [2].

Smart electrical plugs provide an opportunity to extend electrical monitoring from distribution panels to individual appliance outlets. Conventional products commonly measure voltage, current, active power, and accumulated energy, while more advanced designs may support additional electrical measurements. Distributed outlet-level measurements can help identify which appliances contribute to unusual consumption or electrical loading conditions. Nevertheless, ordinary energy-monitoring smart plugs should not be assumed to provide complete power quality information because many do not capture voltage and current waveforms at a sufficient sampling rate [3].

This review examines the potential of smart electrical plugs for power quality assessment, focusing on voltage disturbances, harmonic monitoring, power factor, and appliance performance evaluation. It

considers the relationship between smart-plug measurement capabilities and established power quality monitoring methods. Research on smart meters, power quality analyzers, harmonic estimation, and disturbance classification is included to establish the technical foundation for plug-level applications. The central objective is to identify the measurement capabilities required to transform smart plugs from basic energy-monitoring devices into useful supplementary power quality instruments [4], [5].

2. SMART-PLUG ARCHITECTURE FOR POWER QUALITY MONITORING

A power-quality-oriented smart plug requires more than a switching relay and an energy measurement circuit. Its architecture should include voltage and current sensors, an analog signal-conditioning stage, an analog-to-digital converter, a processing unit, and a communication interface. The processing unit calculates electrical quantities and extracts information from sampled waveforms. Depending on its design, the device may transmit measurement results to a local gateway, computer, or cloud-based monitoring platform [3], [6].

The measurement architecture determines which power quality parameters can be assessed reliably. Low-rate measurements of average power and accumulated energy are useful for consumption monitoring but cannot fully characterize short-duration disturbances or detailed harmonic spectra. Waveform-based analysis requires sufficiently fast and synchronized voltage and current sampling, appropriate anti-aliasing filters, and suitable digital signal processing. The measurement system must also be calibrated against reference instruments to establish its accuracy under different load conditions [2], [7].

A distributed architecture can use multiple smart plugs to collect measurements from different appliances and locations. The collected data can be compared to identify load-related disturbances and determine whether abnormal conditions occur at particular outlets or across an installation. Local processing can calculate basic indicators, while a central platform performs historical analysis, visualization, and advanced disturbance classification. This arrangement offers a practical route toward more detailed electrical monitoring without replacing established power quality analyzers [8].

3. VOLTAGE DISTURBANCES AND FLUCTUATION MONITORING

Voltage disturbances can affect the operation of electrical appliances even when their total energy consumption appears normal. Important phenomena include voltage sags, swells, interruptions, rapid voltage changes, flicker, and waveform notching. Voltage sags may occur during short-circuit faults, motor starting, or the energization of large loads, while swells may result from switching events or system operating conditions. These disturbances can cause electronic equipment resets, control-system malfunctions, reduced motor performance, and interruption of sensitive processes [6], [9].

Smart plugs equipped with suitable voltage sensors can provide distributed observations of voltage variations at individual outlets. Such measurements can help establish whether an appliance is exposed to abnormal supply conditions and whether disturbances occur repeatedly during particular operating periods. However, detecting short-duration voltage events requires waveform acquisition and event-triggered recording rather than occasional voltage readings. A device that reports only average or slowly updated RMS voltage may miss important disturbances [3], [10].

Voltage fluctuation and flicker assessment require specific measurement procedures. Flicker is associated with changes in voltage magnitude that can produce visible variations in lighting intensity, while rapid voltage changes may occur during switching of loads or equipment. Standardized flicker assessment uses dedicated measurement methods and indices, including short-term and long-term flicker severity. Smart plugs may contribute to identifying the appliances associated with these events, but they should not be considered compliant flicker meters unless their measurement design and validation support the required procedures [11].

4. HARMONIC MONITORING AND WAVEFORM DISTORTION

Harmonic distortion is a major power quality concern because nonlinear loads draw current that is not purely sinusoidal. Common sources include switch-mode power supplies, LED drivers, electronic chargers, rectifiers, and variable-speed motor drives. Harmonic currents can increase conductor and transformer heating, contribute to voltage distortion, and create additional losses in electrical installations. Their effects depend on harmonic magnitude, frequency, network impedance, and the interaction of multiple connected loads [12], [13].

Smart plugs can potentially support harmonic monitoring when they measure voltage and current waveforms with adequate resolution. Digital signal processing, particularly Fourier-based methods, can be

used to estimate harmonic components and calculate total harmonic distortion. More advanced methods can employ wavelet transforms, time-frequency analysis, and artificial intelligence to identify changing or transient harmonic patterns. However, the reliability of these calculations depends on sensor bandwidth, sampling synchronization, window selection, spectral leakage, and measurement calibration [7], [14].

The accuracy of smart-meter harmonic measurements is an important consideration when low-cost devices are used for power quality research. Kuwałek and Wiczyński examined problems associated with total harmonic distortion measurements performed by smart energy meters, demonstrating that measurement limitations must be considered when interpreting reported harmonic indicators [2]. Research on smart-meter data has also demonstrated that existing metering infrastructure can support estimation of voltage harmonic distortion under appropriate conditions [15]. These findings suggest that smart plugs may complement network-level harmonic monitoring, although their measurements should be validated before being used for compliance decisions.

5. POWER FACTOR AND APPLIANCE PERFORMANCE EVALUATION

Power factor provides information about the relationship between active power and apparent power in an electrical installation. Under sinusoidal conditions, it is commonly associated with the phase relationship between voltage and current. Under nonsinusoidal conditions, however, harmonic distortion also affects power quantities and the interpretation of power factor. Consequently, a smart plug should distinguish displacement power factor from true power factor when nonlinear appliances are being evaluated [5], [16].

Appliance performance can be evaluated by examining electrical parameters together with operating behavior. A motor-driven appliance may exhibit changes in current, power factor, and harmonic content as its mechanical load changes, while electronic appliances may produce characteristic current waveforms associated with their power converters. Abnormal variations can provide indications of changing operating conditions, but they do not necessarily establish a specific equipment fault. A meaningful diagnosis should therefore combine electrical measurements with equipment specifications, operating states, and, where appropriate, independent condition sensors [12], [16].

Table 1 summarizes the main power quality parameters that may be monitored through appropriately designed smart plugs. It also identifies the measurement requirements and potential relevance to appliance performance. The table distinguishes routine energy-monitoring functions from advanced waveform-based assessment. This distinction is essential because the presence of a voltage or current reading in a smart-plug application does not automatically indicate that the device can measure harmonics or short-duration disturbances.

Table 1. Power quality parameters and potential smart-plug applications

Parameter	Electrical phenomenon	Measurement requirement	Potential application
RMS voltage	Undervoltage and overvoltage	Accurate voltage sampling and RMS calculation	Identification of abnormal supply levels
Voltage sag and swell	Short-duration voltage decrease or increase	High-speed waveform capture and event recording	Assessment of supply disturbances affecting appliances
Voltage fluctuation and flicker	Repeated or rapid voltage variation	Suitable time resolution and flicker-processing method	Identification of fluctuating loads
Current harmonics	Distorted current waveform	Synchronized current waveform sampling	Identification of nonlinear appliance behavior
Voltage harmonics	Distorted supply voltage	Adequate voltage sensor bandwidth and spectral analysis	Assessment of local voltage distortion
Total harmonic distortion	Combined harmonic content	Reliable spectral estimation	Comparison of waveform distortion over time
Power factor	Relationship between active and apparent power	Accurate voltage-current measurement and power calculation	Evaluation of electrical utilization
Active and reactive power	Real and non-active power flow	Synchronized voltage-current acquisition	Appliance operating and loading assessment

6. SIGNAL PROCESSING AND INTELLIGENT POWER QUALITY ASSESSMENT

Signal processing converts measured electrical waveforms into indicators that can be interpreted by monitoring systems. Fourier analysis is commonly used to determine harmonic components and calculate distortion indices, while short-time Fourier and wavelet transforms are useful for examining time-varying disturbances. These techniques provide complementary information because some power quality events are periodic, whereas others occur briefly or change over time. Their selection should therefore depend on the disturbance type, sampling capability, and required processing speed [6], [7].

Artificial intelligence can improve the automatic detection and classification of power quality disturbances. Support vector machines, decision trees, artificial neural networks, and deep-learning models have been investigated for distinguishing events such as voltage sags, swells, harmonics, and transients. These methods can learn patterns from measured or simulated electrical signals and may reduce the need for manually defined decision thresholds. However, model performance depends on representative training data, suitable feature extraction, and validation using actual electrical measurements [9], [17].

Smart plugs could use these techniques to associate disturbances with individual appliances or operating periods. For example, a monitoring platform may identify a device that repeatedly produces high harmonic current or operates with an unexpectedly low power factor. Such information can support maintenance investigations, appliance comparisons, and decisions about load management. Nevertheless, AI-based classification should be treated as a diagnostic aid rather than definitive evidence of equipment failure or standards noncompliance [14], [17].

7. MEASUREMENT STANDARDS, ACCURACY, AND PRACTICAL LIMITATIONS

Power quality measurements require consistent definitions and procedures to make results comparable. IEEE Std 1159 provides guidance on monitoring electrical power quality phenomena, while IEEE Std 1459 establishes definitions for measuring electric power quantities under sinusoidal and nonsinusoidal conditions. These standards are relevant when designing measurement algorithms and interpreting power, apparent power, and power factor. A smart plug intended for power quality applications should be evaluated against the measurement requirements appropriate to its intended use [4], [5].

Measurement accuracy is one of the most important limitations of low-cost smart plugs. Sensor errors, limited sampling rates, waveform clipping, phase mismatch, and poor calibration can produce misleading estimates of harmonic distortion and power factor. Santos et al. examined the accuracy of several commercially available smart plugs and highlighted the need to assess their performance when loads change rapidly [3]. This issue is particularly important for electronic loads because their current waveforms may contain sharp transitions and high crest factors that challenge simplified measurement circuits [18].

Another limitation concerns the distinction between appliance-level measurements and installation-level power quality compliance. A smart plug measures conditions at its own connection point, whereas harmonic limits and other compliance requirements may apply at the point of common coupling. Measurements from one outlet cannot automatically establish the overall power quality condition of an electrical installation. Smart plugs should therefore be used as supplementary monitoring devices, while certified power quality analyzers remain necessary for formal assessments and investigations requiring standardized measurement procedures [8], [12].

8. RESEARCH GAPS AND FUTURE DIRECTIONS

Further research is needed to establish reliable measurement performance across different smart-plug designs and appliance categories. Comparative testing should evaluate voltage and current accuracy, harmonic estimation, power factor, transient response, and long-term measurement stability. Test conditions should include resistive, inductive, and nonlinear loads, together with rapidly changing operating states. Publicly documented test procedures and reference measurements would improve the reproducibility of future studies [2], [3], [18].

Future smart plugs may integrate higher-resolution measurement circuits, embedded signal processing, and AI-based event classification. Edge processing could identify abnormal electrical patterns locally and transmit only relevant indicators or events to a central platform. Multiple smart plugs could also be combined to compare appliance-level measurements with aggregate measurements at the distribution panel. This approach could improve source identification and help distinguish local appliance behavior from disturbances originating in the supply network [8], [15], [17].

Research should also investigate how power quality indicators relate to appliance efficiency, reliability, and service life. Long-term measurements could help establish whether repeated voltage disturbances or harmonic emissions are associated with increased operating temperatures, degraded performance, or premature equipment failure. Such investigations should include independent temperature, vibration, or operational measurements when appropriate. The ultimate objective is to develop smart-plug systems that provide dependable electrical information for both energy management and equipment condition assessment [19], [20].

9. CONCLUSION

Smart electrical plugs have the potential to support distributed power quality assessment by providing electrical measurements at individual appliance outlets. Their most valuable applications include monitoring voltage variations, identifying harmonic-producing loads, evaluating power factor, and observing changes in appliance operating characteristics. However, these functions require more advanced measurement capabilities than those found in many conventional energy-monitoring smart plugs. In particular, reliable harmonic and disturbance analysis requires appropriate waveform sampling, sensor calibration, and validated signal-processing methods.

The literature indicates that smart meters, power quality monitoring systems, and intelligent disturbance-classification methods provide a strong technical foundation for developing advanced smart plugs. Nevertheless, outlet-level measurements cannot replace installation-level power quality assessments or certified instruments used for formal compliance testing. Future development should focus on measurement accuracy, standardized validation, intelligent event detection, and integration with broader energy management platforms. With these improvements, smart electrical plugs can become useful supplementary instruments for understanding appliance performance and improving electrical system monitoring.

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