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Application of Quantum Sensing Technology in Power System Measurements

Tingyu Zhang

Linyi No.1 High School Shandong Province, Linyi, China
Email: zhangtingyu0115@outlook.com

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Abstract

The accuracy of power system measurements directly affects the safe and stable operation of power grids. This study explores the application prospects of quantum sensing technology in power system measurements. The research first analyzes the limitations of traditional measurement techniques, such as electromagnetic interference sensitivity and measurement accuracy bottlenecks. It then introduces the basic principles of quantum sensing, including concepts like quantum entanglement and superposition states. Through theoretical analysis and numerical simulations, the study assesses the potential advantages of quantum sensors in current, voltage, and magnetic field measurements. Results show that quantum magnetometers offer significant improvements in accuracy and interference resistance for current measurements. The study also discusses the application of quantum optical technology in high-voltage measurements, demonstrating its unique advantages in improving measurement dynamic range. However, quantum sensing technology still faces challenges in practical applications, such as technological maturity and cost. To address these issues, the research proposes a phased implementation strategy and industry-academia collaboration model. Finally, the study envisions future directions combining quantum sensing with artificial intelligence. This research provides a theoretical foundation for innovative upgrades in power system measurement technology.

Keywords

Quantum Sensing, Power System Measurements, Quantum Magnetometer, High-Voltage Measurement, Accuracy Enhancement

1. Introduction

As a critical infrastructure in modern society, the safe and stable operation of power systems directly impacts national economic development and social order.

With the rapid advancement of smart grids and ultra-high voltage transmission technologies, power system measurement techniques face unprecedented challenges. Traditional measurement methods are struggling to meet the demands of modern power grids in terms of accuracy, anti-interference capability, and dynamic range [1]. In recent years, the flourishing development of quantum technology has provided new ideas and approaches to address these issues. Quantum sensing technology, leveraging quantum mechanical principles such as quantum entanglement and superposition, has achieved measurement performance beyond classical limits [2]. In power systems, quantum sensors show promise in measuring critical parameters like current, voltage, and magnetic fields. For instance, quantum magnetometers based on atomic spin have demonstrated excellent precision and anti-interference capabilities in current measurements [3]. Quantum optical technology has also shown unique advantages in high-voltage measurements, potentially greatly enhancing measurement dynamic range [4]. However, quantum sensing technology still faces numerous challenges in practical applications, such as technological maturity and cost issues that require further resolution [5]. This study aims to systematically explore the application prospects of quantum sensing technology in power system measurements, analyze its potential advantages and challenges, and propose corresponding implementation strategies. Through theoretical analysis and numerical simulations, this research provides a theoretical foundation and practical guidance for innovative upgrades in power system measurement technology. Additionally, this study explores the convergence of quantum sensing with emerging technologies such as artificial intelligence, laying the groundwork for future intelligent measurements in power systems.

2. Limitations of Traditional Power System Measurement Techniques

2.1. Electromagnetic Interference Sensitivity

Traditional power system measurement techniques often exhibit high sensitivity when faced with complex electromagnetic environments. Various sources of electromagnetic interference in power systems, such as high-voltage switch operations, lightning strikes, and harmonic pollution, can significantly affect measurement results. These disturbances come not only from within the system but also from external environmental factors, such as electromagnetic radiation produced by wireless communication devices and industrial equipment. Conventional current transformers and voltage transformers are prone to saturation and phase shift issues in strong electromagnetic field environments, leading to decreased measurement accuracy [6]. Even with shielding and filtering measures, it is challenging to completely eliminate the effects of electromagnetic interference. Particularly in ultra-high and extra-high voltage transmission systems, the electromagnetic environment is more complex, and the performance of traditional measurement equipment often fails to meet requirements. Furthermore, with the widespread application of power electronic technology in power grids, the increasing switching frequencies pose greater challenges to traditional measurement devices due to high-frequency electromagnetic interference. These factors severely constrain the accuracy and reliability of power system measurements, potentially causing misoperation of protection and control systems, threatening the safe and stable operation of power grids.

2.2. Measurement Accuracy Bottleneck

Traditional power system measurement techniques have approached their physical limits in terms of accuracy [7]. Taking current measurement as an example, commonly used current transformers typically have accuracy classes of 0.2 or 0.5, meaning full-scale errors of about 0.2% or 0.5%. Although accuracy can be further improved through advancements in materials and structural design, the room for improvement is very limited. Similarly, voltage transformers face accuracy bottlenecks, especially in wideband and large dynamic range measurements. As power grids continue to expand in scale and complexity, the demands for measurement accuracy are constantly increasing. For instance, in new power systems with large-scale renewable energy integration and flexible DC transmission, higher precision measurements are required to support advanced control and protection strategies [8]. However, traditional measurement techniques face issues such as rapidly rising costs and declining reliability when attempting to improve accuracy. Moreover, traditional measurement methods often struggle to simultaneously achieve high accuracy and wide range, frequently necessitating trade-offs between the two in practical applications. These limitations severely hinder the development of power systems towards higher efficiency and intelligence.

2.3. Insufficient Dynamic Response Capability

The increasingly complex dynamic characteristics of modern power systems demand higher requirements for the dynamic response capability of measurement techniques. Traditional measurement techniques often fall short in rapidly changing transient processes [9]. For example, in power system transient analysis, it is necessary to accurately capture rapid changes on millisecond or even microsecond scales. However, traditional electromagnetic transformers are severely limited in their dynamic response speed due to magnetic hysteresis effects. Although optoelectronic transformers have shown some improvement in this aspect, they still struggle to meet the measurement needs of ultra-high-speed transient processes. Furthermore, in power system fault diagnosis and protection, fast and accurate measurements are crucial for timely fault isolation and preventing fault expansion. The insufficient dynamic response capability of traditional measurement techniques may lead to delayed action of protection devices, increasing the risk of system collapse. As the proportion of new energy generation continues to increase, the dynamic characteristics of power systems are becoming more complex and variable, further intensifying the demand for measurement techniques with high dynamic response capabilities. Particularly in new power systems such as microgrids and smart distribution networks, rapid load fluctuations and the randomness of distributed energy resources pose higher challenges to the dynamic performance of measurement systems. The limitations of traditional measurement techniques are increasingly evident in these emerging application scenarios, urgently requiring new technological breakthroughs to meet the dynamic measurement needs of modern power systems.

As shown in Figure 1, electromagnetic interference sensitivity, measurement accuracy bottleneck, and insufficient dynamic response capability constitute the three main challenges of traditional measurement techniques. These limitations interact with each other, collectively constraining the further development of power system measurement technology. Overcoming these limitations requires new technological breakthroughs, and quantum sensing technology offers potential solutions.

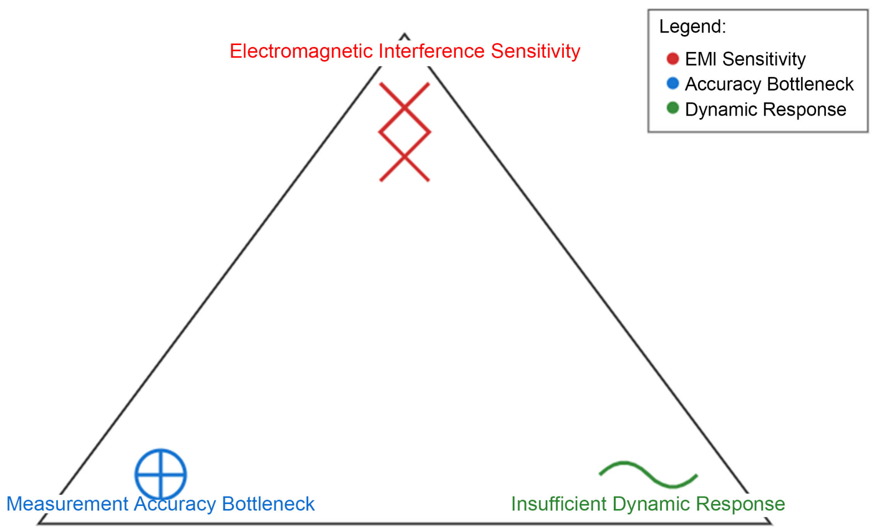

Figure 1. Major limitations of traditional power system measurement techniques.

3. Basic Principles of Quantum Sensing Technology

3.1. Quantum Entanglement Principle

Quantum entanglement is one of the most mysterious and powerful phenomena in quantum mechanics and is also a core principle of quantum sensing technology. When two or more particles are in a quantum entangled state, their quantum states cannot be described independently but must be considered as a whole [10]. This means that measuring one particle immediately affects the state of other entangled particles, even if they are far apart. In quantum sensing, quantum entanglement is ingeniously used to enhance measurement sensitivity. By creating entangled photon pairs or atomic ensembles, measurement precision beyond classical limits can be achieved. For example, in quantum-enhanced magnetometers, using entangled states can significantly improve the signal-to-noise ratio of magnetic field measurements. Quantum entanglement can also be used to realize distributed quantum sensing, achieving higher precision field distribution measurements in space through the collaborative work of multiple entangled sensors. This has potential application value in large-scale monitoring of power systems. However, maintaining quantum entangled states is extremely fragile and susceptible to environmental disturbances leading to decoherence. Therefore, how to effectively utilize and protect quantum entanglement in practical application environments is one of the important challenges facing quantum sensing technology.

3.2. Quantum Superposition State

Quantum superposition state is another fundamental concept in quantum mechanics, describing how a quantum system can simultaneously exist in multiple different states. Unlike classical systems, quantum systems can exist in a linear combination of multiple possible states before being measured. This characteristic provides unique advantages for quantum sensing. In quantum sensors, by placing the quantum system in a superposition state, multiple physical quantities or multiple parameter spaces can be simultaneously detected. For example, in quantum magnetometers, the superposition state of atomic spin can be used to simultaneously measure the intensity and direction of magnetic fields. Quantum superposition states can also be used to implement quantum parallel processing, greatly improving measurement efficiency [11]. In power system measurements, this means that more information can be obtained in a single measurement, such as simultaneously measuring the amplitude and phase of currents. However, quantum superposition states face challenges similar to quantum entanglement, namely how to maintain quantum coherence in complex real-world environments. How to effectively extract useful information from quantum superposition states is also a key issue that quantum sensing technology needs to address.

3.3. Quantum Decoherence

Quantum decoherence refers to the process of quantum state information loss due to the interaction between quantum systems and the environment [12]. This is a major obstacle to realizing quantum sensing, as it destroys quantum entanglement and superposition states, thereby reducing the performance of quantum sensors. In power system environments, various noise sources such as thermal fluctuations and electromagnetic interference can lead to quantum decoherence. However, a deep understanding of quantum decoherence also provides opportunities for developing new quantum sensing strategies. For example, through carefully designed quantum error correction codes and dynamic decoupling techniques, quantum coherence time can be significantly extended, improving the stability and reliability of quantum sensors. Furthermore, some quantum systems exhibit exceptional robustness to specific types of environmental noise, providing new ideas for designing interference-resistant quantum sensors. In power system measurements, understanding and controlling quantum decoherence processes is crucial for achieving high-precision and high-stability quantum sensing. For example, when designing quantum magnetometers for current measurements, consideration must be given to minimizing the impact of external magnetic field fluctuations on quantum states. At the same time, the quantum decoherence process itself can be used as a sensitive means of environmental detection, which may find applications in power system environmental monitoring. Overcoming the challenges of quantum decoherence is not only key to realizing practical quantum sensors but also provides unique opportunities for developing new measurement methods.

As shown in Figure 2, quantum entanglement, quantum superposition state, and quantum decoherence are the three core concepts of quantum sensing technology. Quantum entanglement enables non-local correlations between particles, quantum superposition states allow systems to exist in multiple states simultaneously, while quantum decoherence describes the process of quantum state interaction with the environment. These principles collectively form the theoretical foundation of quantum sensing technology, providing possibilities for breaking through the limitations of traditional measurement techniques.

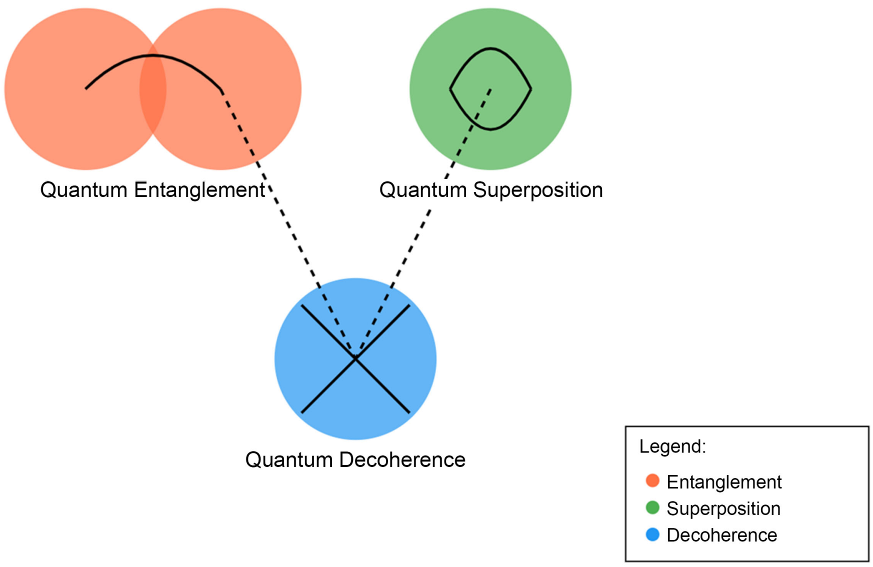

Figure 2. Basic principles of quantum sensing technology.

4. Applications of Quantum Sensing Technology in Power System Measurements

4.1. Application of Quantum Magnetometers in Current Measurement

Quantum magnetometers utilize the sensitive response of quantum systems to magnetic fields, achieving ultra-high precision magnetic field measurements. In power systems, quantum magnetometers can indirectly measure current by measuring the magnetic field around conductors, offering significant advantages with this non-contact measurement method. The sensitivity of quantum magnetometers is far higher than traditional magnetometers, capable of detecting extremely weak magnetic field changes. For example, quantum magnetometers based on nitrogen-vacancy (NV) centers can achieve magnetic field resolution at the nanotesla level, enabling precise measurement of very small current changes. Quantum magnetometers possess an extremely wide dynamic range, allowing simultaneous measurement of large and small currents without changing sensor configurations. This characteristic is particularly important in power systems, where large currents in main lines and small currents in branch lines often coexist. Quantum magnetometers also demonstrate strong resistance to external electromagnetic interference, benefiting from the inherent properties of quantum systems and advanced quantum control techniques. In practical applications, quantum magnetometers can be used for current monitoring in high-voltage transmission lines and condition diagnosis of substation equipment. However, applying quantum magnetometers to power systems still faces challenges, such as maintaining quantum state stability in complex electromagnetic environments and achieving sensor miniaturization and cost reduction.

4.2. Application of Quantum Optical Technology in High-Voltage Measurement

Quantum optical technology provides new solutions for high-voltage measurements. Traditional high-voltage measurement methods, such as capacitive and resistive voltage dividers, face issues of accuracy degradation and insulation difficulties in ultra-high and extra-high voltage systems. Quantum optical technology utilizes quantum properties of light, such as the Pauli blocking effect or electro-optic Kerr effect, to achieve precise measurements of high voltages. For instance, quantum electric field sensors based on Rydberg atoms can directly measure electric field strength, thereby deriving voltage values. This method not only offers extremely high measurement accuracy but also enables wideband measurements, applicable to various high-voltage systems from DC to AC. Another advantage of quantum optical technology is its inherent electrical insulation properties, greatly simplifying the design of high-voltage measurement systems. Furthermore, quantum optical sensors can transmit measurement signals remotely through optical fibers, providing significant safety advantages in high-voltage environments. However, applying quantum optical technology to practical high-voltage measurement systems still faces technical challenges, such as maintaining quantum state stability in strong electric field environments and improving system interference resistance.

4.3. Application of Quantum Sensing Networks in Power Grid State Estimation

Quantum sensing networks connect multiple quantum sensors through quantum entanglement or classical communication links, forming a collaborative measurement system. This networked quantum sensing approach offers unique advantages in power grid state estimation [13]. Quantum sensing networks can utilize quantum entanglement to achieve distributed measurements, simultaneously acquiring system state information through multiple spatially distributed sensors, thereby improving the spatial resolution and coverage of measurements. Quantum sensing networks can leverage quantum computing technology for real-time data processing and analysis, greatly enhancing the speed and accuracy of state estimation. For example, quantum machine learning algorithms can more effectively extract useful information from massive measurement data, achieving precise estimation and prediction of power grid states. Quantum sensing networks can also use quantum key distribution technology to protect the security of measurement data, which is particularly important in smart grids. However, implementing large-scale quantum sensing networks still faces numerous challenges, such as how to maintain quantum entanglement in complex power system environments and how to design efficient quantum network topologies.

5. Challenges and Prospects of Quantum Sensing Technology in Power System Measurements

5.1. Technological Maturity and Engineering Challenges

Although quantum sensing technology has shown enormous potential in laboratory environments, it still faces challenges in technological maturity and engineering aspects for practical applications in power systems. Most quantum sensors currently require strict environmental control, such as extremely low temperatures or high vacuum conditions, which significantly differ from the complex on-site environments of power systems. For example, magnetometers based on Superconducting Quantum Interference Devices (SQUIDs), while highly sensitive, typically require liquid helium cooling, which is difficult to implement in actual power systems. The stability and reliability of quantum sensors need further improvement. Power systems require measurement equipment to work stably over long periods, and the long-term stability of many current quantum sensors cannot meet this requirement. Additionally, the calibration of quantum sensors is a significant challenge. Traditional calibration methods may no longer be applicable, necessitating the development of new quantum metrology standards (Bao et al., 2020). In terms of engineering, how to achieve miniaturization, cost reduction, and mass production of quantum sensors are urgent issues to be resolved. These challenges require interdisciplinary collaboration, combining knowledge from quantum physics, materials science, electronic engineering, and other fields to gradually overcome.

5.2. Compatibility with Existing Power Systems

Introducing quantum sensing technology into existing power systems faces compatibility challenges. Existing power system measurement standards and specifications are primarily based on traditional technologies and may not be fully applicable to quantum sensors. For example, new standards need to be established for quantum magnetometer current measurement methods to ensure the comparability and consistency of measurement results. The data formats and communication protocols generated by quantum sensors may be incompatible with existing systems, requiring the development of new data interfaces and processing algorithms. The introduction of quantum sensing technology may necessitate adjustments to existing power system control and protection strategies. For instance, leveraging the high precision and fast response characteristics of quantum sensors could enable more advanced fault detection and isolation schemes, but this would require corresponding control system upgrades. Another important issue is how to gradually introduce quantum sensing technology without affecting the normal operation of power systems. This may require designing transition schemes, such as quantum-classical hybrid measurement systems. Achieving seamless integration of quantum sensing technology with existing power systems requires systematic planning and long-term efforts.

5.3. Integration of Quantum Sensing and Artificial Intelligence

The integration of quantum sensing technology and artificial intelligence brings new opportunities for power system measurements. Artificial intelligence algorithms can be used to optimize the performance of quantum sensors. For example, machine learning methods can achieve adaptive calibration and noise suppression of quantum sensors, improving measurement accuracy and stability. Quantum machine learning algorithms can more effectively process the massive data generated by quantum sensors. In power grid state estimation, quantum-classical hybrid algorithms have the potential to significantly improve computational efficiency and accuracy. Artificial intelligence technology can help realize intelligent management of quantum sensing networks, such as automatically adjusting sensor configurations and optimizing data transmission paths. However, the integration of quantum sensing and artificial intelligence also faces some challenges. For instance, how to design new machine learning models suitable for quantum data, and how to achieve efficient data sharing and analysis while protecting quantum information privacy. In the future, with the development of quantum computing technology, it is expected to realize end-to-end quantum sensing-computing systems, providing powerful support for the intelligent operation of power systems.

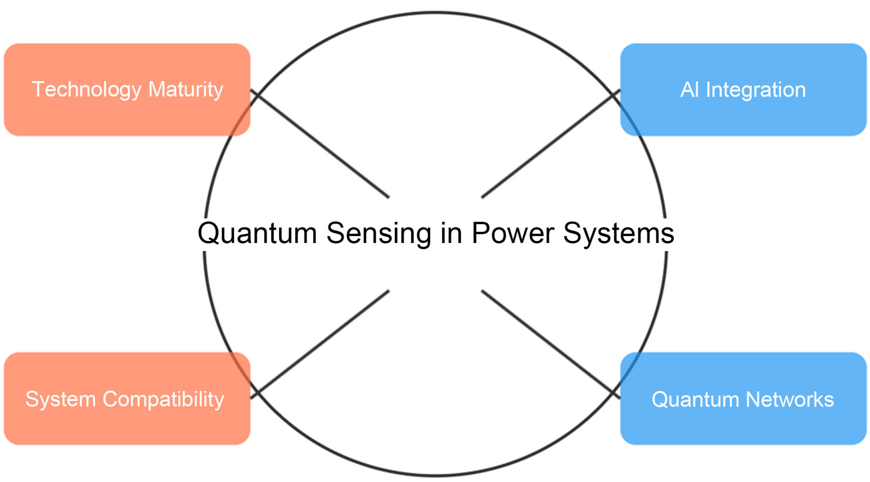

Figure 3. Challenges and prospects of quantum sensing technology application in power system measurements.

As shown in **Figure 3**, technological maturity and system compatibility are the main challenges, while integration with artificial intelligence and the development of quantum networks are important future directions. These challenges and opportunities collectively shape the application prospects of quantum sensing technology in power systems.

6. Conclusion

Quantum sensing technology brings revolutionary opportunities for power system measurements, potentially breaking through the bottlenecks of traditional measurement techniques to achieve higher precision, wider dynamic range, and stronger anti-interference capabilities. This study systematically analyzes the application prospects of quantum sensing technology in power system measurements. The research finds that the greatest challenge in applying quantum sensing technology to power systems lies in maintaining quantum coherence in complex field environments. Unlike laboratory conditions requiring strict environmental control, power substations present harsh conditions with strong electromagnetic interference, wide temperature fluctuations, and mechanical vibrations that can easily destroy quantum states. For example, SQUID-based quantum magnetometers require ultra-low temperatures (-269°C) to maintain superconducting states, making field deployment extremely difficult. Despite these challenges, technologies such as quantum magnetometers, quantum optical sensors, and quantum sensing networks have demonstrated significant potential in current measurement, high-voltage measurement, and power grid state estimation. The integration of quantum sensing with artificial intelligence further expands its capabilities, enabling adaptive calibration and intelligent noise suppression. Through industry-academia collaboration and continued technological innovation, quantum sensing technology shows promise in enhancing power system measurement capabilities. The research findings provide theoretical guidance for future power system measurement upgrades and suggest focusing development efforts on quantum decoherence protection methods and room-temperature quantum sensing technologies. With ongoing advancements in quantum science and engineering, quantum sensing technology is expected to play an increasingly important role in ensuring reliable and efficient power system operation.

Conflicts of Interest

The author declares no conflicts of interest regarding the publication of this paper.

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