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Quantum-Enhanced Grid of the Future: A Primer

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ABSTRACT Computing plays a significant role in power system analytics. As mathematical challenges increase and data become the epicenter of modern decision making, substantial progress needs to be made to draw on emerging analytics and computing technologies. Quantum computing is a ground-breaking technology in information processing that can support the global efforts in addressing power system challenges and in further envisioning the grid of the future. However, despite extensive research activities in quantum computing applications in various sectors, its application to power systems has remained mostly unexamined. It is necessary to have an across-the-board view of the quantum computing technology applications in power systems, and in particular, in building the grid of the future. This paper discusses the essential elements of quantum computing and presents a review of issues concerning this technology. The paper further provides an in-depth discussion of the potential of quantum computing in improving analytical and computing capabilities in solving multiple power system problems.

INDEX TERMS Quantum computing, superposition and entanglement, grid of the future.

I. INTRODUCTION

The electric power grid is undergoing unprecedented modernization as a result of the growing proliferation of distributed energy resources, increased reliance on variable renewable generation, and electrification of various sectors such as transportation. These sweeping changes have compelled electric utilities to amplify their monitoring and measurement efforts, through the deployment of advanced metering infrastructure, wide-area measurement, and distribution automation, in turn resulting in the collection of a myriad of data from the entire grid. The significant increase in the volume and variety of collected data ensures better grid observability and further enables enhanced decision making. The enabling component, however, remains to be a robust computational foundation that is capable of converting the collected big data into actionable information.

Computation has been central to power system management for decades. From the earliest efforts in solving network power flow problems to today's use of multi-time-scale and multi-dimensional power systems, advanced computation has served as an indispensable player in a reliable, efficient, and cost-effective operation and control of the grid. There has been extensive research on this topic, including the latest efforts by the U.S. National Academies of Sciences, Engineering, and Medicine to identify the computational needs of the next-generation electric power grid [1].

Given the substantial ongoing transformations, current analytical models may fail to address the needs of the grid of the future. Using existing mathematics on more powerful computers is also not a practical approach to address a broad new class of emerging complexities. An example of this is the growing concerns around uncertainty inclusion in grid operation and planning. As the power system is becoming increasingly reliant on variable renewable generation and intermittent loads, developing forecasts for the state of the system requires different kinds of analytical capabilities. Multi-outage cases in response to the growing frequency and intensity of extreme weather events and natural disasters as a direct result of climate change is another viable example. Therefore, new classes of models, algorithms, and computational tools are required to address the needs of the grid of the future. Quantum computing is an empowering technology that can address many of these challenges while creating the computational foundation for an ever-evolving grid.

The overarching objective of this paper is to provide a review of the quantum computing technology and to explore its prospective applications to power systems. The paper

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further attempts to open a new field of research (on quantum-grid) and to serve as a guide to the power system society for follow on work. In Section II, the basic principles of quantum computing are discussed, including the physics behind it, a brief history of the technology, fundamental elements, and design aspects. Section III identifies and proposes potential quantum computing applications in the power grid. Section IV concludes the paper.

II. QUANTUM COMPUTING

A. QUANTUM TECHNOLOGY

Quantum computing is developed based on quantum mechanical phenomena that describe the nature and conduct of energy and matter at the level of fundamental subatomic particles. A quantum computer operates by controlling the behavior of these particles to achieve desired computation. Quantum computers mark a step forward in computing capacity, which is potentially superior to that of a modern supercomputer by offering extensive efficiency growth. Based on the laws of quantum physics, a quantum computer can achieve enormous processing power over multi-state capacity and can execute multiple functions simultaneously by using possible permutations [2].

The laser is an excellent instance of recognized quantum technology and one that has many similarities with quantum computers in terms of applications analogy. Radiation in the laser is produced by stimulated emission, extracting energy from a transition in an atom. The laser produces a coherent light that is different from the prior technologies, e.g., lightbulbs, in which the light was incoherent, meaning it did not contain photons with the same frequency. There are two points about the laser to consider: (i) the laser was a more advanced technology than prior technologies. It was invented based on the quantum processes, and (ii) although beneficial – integrated within various apparatus from medical devices to toys – the laser couldn't replace lightbulbs for most applications. This is also the case for a quantum computer, a different kind of computer, engineered to control coherent quantum mechanical waves for computation, which will be useful for many applications but at the same time may not completely replace classical computers.

B. DEVELOPMENT

Quantum information processing has become a vast interdisciplinary field at the intersection of both theoretical and experimental quantum physics and quantum engineering. There are extensive efforts globally to build a quantum computer capable of significantly improving computing power and to support solving problems that classical computers cannot solve [3]. The initial development efforts were started during the 1980s when a few pioneers were inspired to answer several fundamental questions of computer science and information theory with the help of quantum mechanics. Rather than looking at quantum systems as phenomena found in nature, they looked at them as systems that can be *designed* [2]. In 1982, Richard Feynman indicated that quantum mechanical phenomena are capable of being applied to simulate a quantum system more effectively than simulations on today's classical computers [4], [5]. The research in the 1990s illustrated that quantum computers could violate the extended Church-Turing thesis [6] and that there could be an exponential speedup in quantum polynomial-time algorithms for the discrete logarithm and integer factoring problems [7], [8]. The research efforts further indicated that a quantum computer would solve many critical computational problems once built. The general perception was that quantum computing would create the framework for a new computing paradigm. Involvement in this research increased through Shor's algorithm that would exponentially accelerate cryptanalysis, thereby questioning the security of many cryptographic methods [8]. Discussions in [9], [10] present a brief introduction to fundamental concepts of quantum computation, quantum information, and the development of these concepts.

In the last two decades, research and development attempts have produced significant strides in building a working quantum machine, restoring interest in the potential of this technology. One of the first milestones in building quantum computers involved demonstrations of basic analog and digital proof-of-principle systems. In 1997, the first tiny quantum computer was built, but the field took off only when the Canadian startup D-Wave revealed its 28-qubit quantum computer ten years later in 2007 [11]. There is now substantial competition among leaders of this field, including but not limited to Google, IBM, and Honeywell, to build larger and less noisy quantum computers [12]–[16].

Fig. 1 presents the growth of the number of qubits in superconducting (shown as circles) and trapped ion (shown as squares) quantum computers in the past two decades. The same color points have similar two-qubit gate error rates.

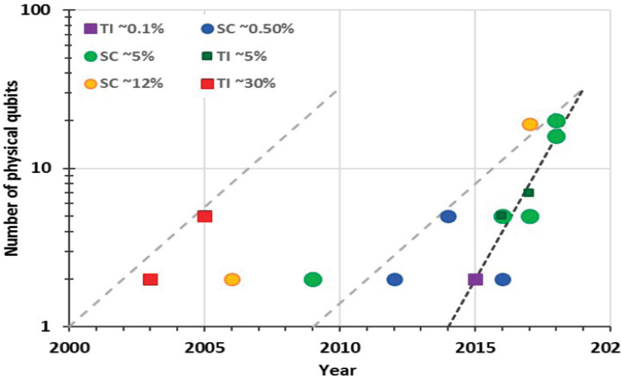

FIGURE 1. The number of qubits in superconductor (SC) and trapped ion (TI) quantum computers versus year [2].

Despite the power of classical computers, there are still applications that are difficult to compute but seem to be simply calculated by the quantum world, primarily around estimating the properties and behavior of quantum systems. Classical computers can simulate simple quantum systems and usually find useful approximate solutions. Still, for more complicated operations, the amount of memory and processes required for the simulation raises exponentially with the size of the system simulated.

C. FUNDAMENTALS

Quantum physics is a theory of the physical world that is probabilistic and with inherent uncertainty. Quantum mechanics precisely predicts an extensive range of observable phenomena that classical physics cannot. The quantum computer utilizes quantum mechanics to execute certain types of computation more effectively than a classical computer [17], [18].

There is a fundamental difference between a classical computer and a quantum computer on how they process information. A classical computer utilizes information by bits. A bit is a basic unit of data that represents a yes-no answer to a question, and mathematically is a binary number which can be either 0 or 1. Classical computers work by converting information to a series of these bits. However, a quantum computer encodes the data by quantum bits or qubits. Like a regular bit, a qubit could be either 0 or 1, but unlike a regular bit, a qubit may also be simultaneously in both states.

Fig. 2 provides a visual representation of a qubit. The qubit state can be mapped onto a point on the surface of a unit sphere, called a Bloch sphere. The Bloch sphere provides a useful means of visualizing the state of a single qubit, where the north and south poles correspond to the states $|0\rangle$ and $|1\rangle$, respectively. This characteristic, to be able to be in any state between $|0\rangle$ and $|1\rangle$, is called a superposition of states. In other words, at the quantum scale, particles can exist in different states, including positions, energies, or speeds. But because of quantum mechanics, particles can exist across all the possible states at the same time. Entanglement is the other major characteristic of a quantum system that represents the ability of quantum particles to be linked in perfect unison in different spaces. This means when there is a change in one particle, it can impact the other even if great distances separate them.

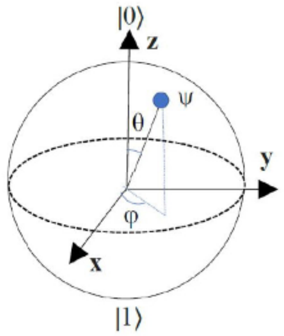

FIGURE 2. **A single qubit represented by Bloch sphere.**

The potential power of quantum computing is in the superposition and entanglement of states, allowing the execution of exponentially many computations in parallel. Superposition and entanglement are fascinating and extremely useful in computing and communications technology. Specific difficult problems that are impossible for classical computers to process can be solved efficiently by a quantum computer because of these two quantum behaviors.

D. DESIGN AND MAIN IT ASPECTS

There are currently two main approaches to implement a quantum computer: analog and digital. Analog methods include the quantum simulation, quantum annealing, and adiabatic quantum computation. Digital quantum computers use quantum logic gates to do computation [19]. Similar to a classical computer that is built from an electrical circuit containing wires and logic gates, a quantum computer is made from a quantum circuit containing wires and quantum gates to process the quantum information. There are three main aspects in quantum computing:

1. How to encode the classical data efficiently into a quantum computer,
2. Processing the quantum data, and
3. Extracting useful information from the processed quantum data.

The following further discusses these aspects under data encoding and algorithms:

1) DATA ENCODING

The first aspect has been an open problem for a long time, but there are few popular ways to encode a classical dataset into a quantum computer. One of the popular methods is called quantum random access memory (qRAM) [20]. In classical computers, the Random-Access-Memory (RAM) is an array of addressed memory that allows access to individual data irrespective of the physical location where it is stored. In light of the rapid development of quantum computers, there has been an increasing need for a quantum counterpart of the RAM (qRAM) to serve a similar purpose for data storage and access. Unlike classical RAMs where multiple memory locations can only be queried individually in sequential order, a qRAM allows accessing multiple memory locations simultaneously by creating a superposition of address locations. The function of a qRAM can be represented as $qRAM\left(\sum_i c_i|i\rangle|0\rangle\right) = \sum_i c_i|i\rangle|d(i)\rangle$, where each i represents an address location, and each $d(i)$ represents the data stored in the qRAM corresponding to the location i. Many quantum algorithms, such as the Harrow-Hassidim-Lloyd (HHL) algorithm, quantum search, principle component analysis, and support vector machine, require an oracle step that functions like a qRAM. Thus the development of a functional qRAM is crucial in closing the gap between theoretical algorithm design and practical implementation. Although various qRAM models have been proposed trying to mimic the architecture of classical counterparts, no physical implementation of qRAM has been realized as of now.

There is another way to encode classical data into the quantum computer, namely, to prepare the desired quantum state containing the classical data in its components with the

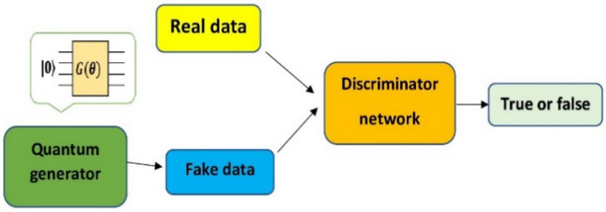

FIGURE 3. Schematic diagram of hybrid QuGAN; quantum generator replaces the generator neural network in GAN.

help of controlled rotation in the quantum Hilbert space, e.g.,

$$\begin{pmatrix} v_1 \\ v_2 \\ v_3 \\ v_4 \end{pmatrix}_{cl} \rightarrow |v\rangle_q = v_1\,|00\rangle + v_2\,|01\rangle + v_3\,|10\rangle + v_4\,|11\rangle.$$

However, in this process, the number of two-qubit quantum gates (e.g., CNOT gates) required to prepare a general 2n-qubit state (with real components) is roughly in the order of 2^{2n}. In general, storing the quantum state of a system with n distinct elements takes about c^n bits on a classical computer, where c is a constant that depends on details of the simulated system and the desired accuracy of the simulation. The main challenge is how to reduce the number of quantum gates (especially two-qubit gates) in the circuit.

There is another approach for data encoding known as the generative adversarial network (GAN), which can generate artificial data with the same statistics as the real data used as the training set. For example, a GAN trained on real photos can generate artificial pictures that look like authentic photos to human observers. GAN consists of two parameterized components: a generator and a discriminator, which contest against each other in an ''adversarial'' manner. The generator is trained on real data to produce artificial data that mimics the distribution of the real data. In contrast, the discriminator is trained to distinguish the real data from artificial data. By giving enough capacity to these two components, which means both have sufficient power in representing functions, the training process will reach an equilibrium where the generator reproduces the real data distribution. At the same time, the discriminator cannot tell the difference between real and artificial data. A quantum version of the GAN, the quantum generative adversarial network (QuGAN), was proposed in 2018 [21], [22]. The QuGAN developed quickly with both simulations and experiments recommended for applications, including probability distribution modeling, quantum state approximation, missing data inference, and price estimation in finance.

2) ALGORITHMS

The second and third main aspects of quantum computing described in the previous section, i.e., processing and extracting the quantum data, involve various quantum algorithms. There are different classes of quantum algorithms. The first class of algorithms bases on quantum versions of the Fourier transform (QFT). These algorithms transform a set of N complex numbers into a set of complex numbers, which, of course, has a significant number of applications in most branches of science. Factoring and discrete logarithm are two instances of algorithms in this class. The fast Fourier transform takes about $N\log(N) = Nn$ steps to Fourier transform $N = 2^n$ numbers and has an exponential computational time saving on a quantum computer by using approximately $log^2(N) = n^2$ steps. This outcome looks to direct that quantum computers can compute the Fourier transform of a vector of 2^n complex numbers much faster, which would be significantly advantageous in an extensive range of applications. Examples of the quantum algorithm that uses QFT are the HHL algorithm for solving systems of linear equations [23] and Shor's algorithm for prime factorization [24].

The second class of algorithms focuses on quantum search, for example, Grover's search algorithm [25]. These algorithms attempt to figure out a component of a given search space answering a known property while assuming no previous information about the structure of the data in it. Classically, this problem needs around N operations, where N is the size of the search space. However, the quantum search algorithm can solve it by applying around $\sqrt{N}$ operations.

More recent types of quantum algorithms that are gaining attention for eigenvalue calculations and solving systems of linear equations are the Variational Quantum Eigensolver (VQE) [26] and Variational Quantum Linear Solver (VQLS) [27]. These algorithms leverage the variational principle. However, there is no concrete proof that these algorithms have significant advantages over their classical counterparts.

Finally, the deep learning with the neural network has shown great potential in solving real-world problems like media recommendation, speech recognition, and medical diagnosis. With the availability of more capable quantum computers, the quantum neural network has shown the potential to outperform the classical neural network. Currently, there are two main challenges for implementing the quantum neural network. The first one is the implementation of nonlinear activation functions, e.g., *ReLU* or *tanh*, on the quantum computers, because most quantum gates are implemented only linearly. The other one is the scaling of the number of hidden layers of the quantum neural network. With the emerging quantum technology, various quantum neural network models have been proposed for implementing quantum deep learning on quantum computers [28]–[30].

Although most of the works on quantum computing focus on gate-based universal quantum computers, there is ongoing algorithm development work on quantum annealing as well. Quantum annealing bases on calculating the extremum of some unknown function in a quantum mechanical way. A practical example of a quantum annealer is D-Wave's quantum computer. Quantum annealing computing machines can theoretically solve problems that are QMA-complete, where QMA (Quantum Merlin Arthur) is the quantum analog of the complexity class NP. There are various classes of problems or algorithms into which the quantum annealer can embed, such as the restricted Boltzmann machine (RBM) algorithm, discrete combinatorial optimization problems, and finding the ground state energy for Ising/spin type Hamiltonians.

E. GENERAL APPLICATIONS

A quantum computer has the theoretical potential to solve some of the problems that no classical computer could currently solve. Quantum computation, quantum information, quantum communications, and quantum sensing are some of the major fields of quantum science and technology. Quantum computing, in particular, could contribute significantly in the areas of finance, cybersecurity and cryptography, forecasting, drug design, and molecular modeling, aerospace, and weather services, to name a few researched applications.

Quantum computing has swiftly advanced in recent years due to substantial development in hardware and algorithms, carrying quantum computers closer to their imminent commercial utility [31]–[33], [40]. This *quantum advantage,* which could demonstrate a disruptive rather than incremental innovation, is what makes quantum computing so exciting and motivates the commercial interest in this field.

As an example, drug discovery is a promising area of application for quantum computers [34], [35]. Quantum computing methods are becoming popular in computational drug design and development mainly because high accuracy is required to estimate binding affinities. It is expected that the use of quantum computing methods will keep growing in all phases of computer-aided drug design and development [36]. Computational enzymology is increasingly integral to understanding mechanisms of enzyme-catalyzed reactions. Combined quantum mechanics/molecular computing methods are also crucial in this field [36]. A range of computing methods is available in [37], which can be used for molecular dynamics simulations to achieve highly accurate electronic structure methods. Studies have further shown applications that explore how quantum computing methods can contribute to the practical development and implementation of drug and catalyst design [38], [39].

III. QUANTUM COMPUTING APPLICATIONS IN POWER GRIDS

Building the grid of the future requires solving problems that haven't yet been addressed or challenges that are yet to appear. Quantum computing is a promising technology that will support the efforts in building a more resilient, reliable, safe, and secure grid of the future. Many prominent techniques have been created over previous decades to solve various power system computational problems. Examples range from exact enumeration methods (which proved to be impractical for realistic power systems), to various numerical optimization techniques and stochastic search methods [42]–[48]. Quantum-inspired evolutionary algorithms have also been recently implemented as alternatives to solve some power system problems [41], [49], [50].

The grid is going through a significant transformation to the point that the current computational technology may not be adequate to address the needs of a modernized grid. The most notable change is observed in the role of the distribution grid and customers in system design and management. Transmission and distribution systems were frequently operated as distinct systems but are becoming more of an integrated system. The underlying hypothesis was that at the substation, the transmission system would supply a prescribed voltage, and the distribution system will supply the energy to individual customers. However, as various types of distributed energy resources, including generation, storage, electric vehicles, and demand response, are integrated into the distribution network, there may be distinct interactions between the transmission and distribution systems. Distributed generation's transient and small-signal stability problems are one instance that changes the energy system's dynamic nature. Therefore, developing more comprehensive models that include the dynamic relationships between transmission and distribution systems, and relevant computational tools that can solve such models will be essential in the future. Furthermore, better scheduling models are needed to design viable deployment and use of distributed energy resources.

The new grid architectures include multi-scale systems that temporarily range between comparatively quick transient dynamics of stability-level and slower goals of optimization, thus presenting distinct mathematical and computational difficulties to current techniques and procedures. They also consist of nonlinear dynamic systems, where the practice today is to use linear approximations and large-scale complexity, making it hard to fully model or fully comprehend all the nuances that might happen during off-normal system circumstances. The tendency to embed sensing/computing/control at a component level is further becoming a necessity. Consequently, interconnected system models become critical to support communication and exchange of data between distinct layers of the system. Sophisticated mathematics will then be required to design computational methods to help decision-making in different time scales, whether they are quickly automated controls or design instruments for planning.

A. OPTIMIZATION, PLANNING, AND LOGISTICS

Optimization problems are omnipresent in power grids. Some of the most significant applications of optimization in power grids include scheduling, such as economic dispatch, power flow, unit commitment, as well as long-term resource planning. Planning and scheduling problems are often NP-hard, and as the number of tasks to plan and schedule increases, the number of solutions increases exponentially. These problems are very challenging and hard to solve. Quantum computers can solve discrete combinatorial optimization problems using the properties of quantum adiabatic (QA) evolution [51]. A machine learning heterogeneous computing stack is proposed in [52] that combines QA and classical machine learning, allowing the use of QA on problems more substantial than the hardware limits of the quantum device.

Quantum algorithms may also open a new avenue for efficient exploitation of existing information in support of solving hard computational problems, such as Global Optimization Problems (GOP). The GOP formulation finds the absolute minimum/maximum of an objective function over the range of its variables. Sometimes, an optimization problem is not specified in the analytic form and needs to be evaluated pointwise by a computer program. An efficient solution to a class of continuous GOP by using quantum algorithms is proposed, and the impact of quantum algorithms and additional information in decreasing the complexity of a class of GOP are presented in [53]. An example of this application is the Security-Constrained Unit Commitment (SCUC). Even small improvements in the solution of the SCUC problem result in millions of dollars in savings in optimal generation scheduling, which will accordingly benefit end-use customers.

B. FORECASTING

Forecasting is an essential field of study in power grids. From traditionally conventional methods of forecasting loads to the most recent advances in solar and wind generation forecasting, power grids have been heavily involved with methods of predicting the future behavior of its players. Quantum computers can provide a compelling means to help with forecasting in power grids.

There are several examples of quantum computing applications in forecasting. A hybrid intelligent method using Quantum-behaved Particle Swarm Optimization (QPSO) is proposed in [54] to improve financial price forecasting and financial pattern extraction. This is applied to the Foreign Exchange Market, the largest global market today where currencies are traded; this method utilizes historical market data and chart patterns to predict market trends further based on an Adaptive Network-based Fuzzy Inference System (ANFIS). The results show that the proposed quantum-based method is useful for financial price forecasting. A quantum computing-based financial prediction model is proposed in [55], which tackles the NP-completeness problem and outperforms the real-coded genetic algorithm on a problem due to the optimal or near-optimal obtained weighted-values.

The quantum-enabled forecasting can further provide the capability to take societal factors into account. As an example, the potential impact of adiabatic quantum computation is investigated in predicting the 2016 Presidential election in [56]. The forecast model outcomes illustrate a significant performance improvement compared to the best in class election modeling group, which could be a new technique to bring to the broader conversation of modeling in future election forecasts. References [57], [58] discuss the quantum computation application in financial problems and provide an overview of current approaches and potential prospects, including forecasting, that can be leveraged to solve some of the power grid problems. References [59], [60] discuss applications to load forecasting.

C. WEATHER PREDICTION

Today’s weather simulators play an essential role in society by providing advanced warnings of natural climate variations on seasonal, annual and decadal time scales. An accurate weather prediction is also of significance in power grids to provide better preparation and an expedited restoration before and after weather events. This is becoming ever more important as the frequency and intensity of extreme weather events are increasing [61].

The use of Quantum neural networks is analyzed as a weather prediction tool in [62], [63], and the effect of quantum computing to achieve efficient computation in forecasting is further provided. Experimental outcomes disclose that quantum computing based models have better forecasting performance than other machine learning-based forecasting models applied in classical computers. Discussions in [62], [64] determine the feasibility and practicality of using Quantum neural networks as a weather prediction tool. The results show a significant accuracy compared to the traditional neural network models.

D. WIND TURBINE DESIGN

It is shown that quantum computers can be helpful in aerospace design, and this can be leveraged in designing wind turbines for applications in power grids. A summary of quantum computing methods and their contributions to aerospace applications is introduced in [65]. It is shown in [66] that quantum computing has the potential to be at least a million times faster than the current fastest supercomputer, and such potential power would be more than adequate for all computational and control power for large-transport category airplanes [66]. A quantum computing model in computational fluid dynamics (CFD) is proposed in [67] for basic research and aerospace application to highlight the significant impact of quantum computing application in fluid dynamics. Wind turbines can be designed using quantum computing and based on the methods developed for aerospace. For example, quantum-based CFD calculations can investigate lift and drag forces on wind turbine blades for various scenarios, to improve the accuracy of the relevant methods [68], [69].

E. CYBERSECURITY

The evolution of legacy power grids to smart grids was, in most part, due to the increasing deployment of information and communications technologies. The grids of the future will heavily rely on fast and reliable communications. As a result, cybersecurity has emerged as a serious concern, and there has been extensive work to improve cybersecurity in smart grids.

Quantum computers can easily make traditional methods of cryptography obsolete. Discussions in [70] highlight the importance of quantum cryptography in ensuring the future of data security. Quantum cryptography can support secure computation. In [71]–[73], existing solutions and possible quantum cryptography applications are introduced and showed how quantum computing could substantially perform dense coding and teleportation over the Internet. In [74], the implications of quantum computing in modern cryptography are explained, and a basic post-quantum algorithm in cryptography is introduced. The symmetric and asymmetric cryptographic schemes and public key encryption schemes affected, symmetric schemes affected, and their impact on cryptography are discussed in [75]. A quantum cryptography model, which deals with different quantum key distribution methods and mathematical-based solutions, such as lattice-based cryptography, multivariate-based cryptography, hash-based signatures and code-based cryptography, is provided in [76], [77].

F. GRID SECURITY

Linear problems are pervasive in nearly all fields of science and engineering. There are many examples of linear problems in power systems, such as linear approximation for a dynamic stability problem or a DC power flow for steady-state system operation. The classical computers solve a linear system of equations in at least $O(N)$ steps. However, it is proved that using quantum computing, the solution can be obtained in $O(\log N)$ quantum operations [78]. This is a significant advantage of quantum computing as it is much less sensitive to the size of this linear problem compared to its classical counterparts. This turns into a more substantial benefit when the size and the frequency of solving the power flow problem become larger, such as in the grid security problem. The power flow problem should be solved repeatedly to ensure the physical security of the grid by identifying the impact of component outages on other components and, accordingly, on system violations. A quantum computer can, therefore, be an enabling technology to effectively address this problem considering the growing time requirement with the problem size.

G. GRID STABILITY

One of the crucial aspects of power grid stability is to estimate and analyze the real-time oscillatory modal properties of the power grid. The installation of phasor measurement units (PMUs) across the power grid is becoming increasingly useful for this task. When the number of PMU channels grows, the computational time of many PMU data-based algorithms is dominated by the computational burden in processing large-scale dense matrices. The size of the matrix grows quadratically with the number of PMU channels. The challenge is to do this computation in real-time so that large-scale power outages can be predicted and avoided using several Petabytes of data generated every day. The real-time analysis is only possible for a handful of PMU channels. It is important to develop fast algorithms that can process all available PMU data together to detect and to locate the likely cause of any oscillatory problems in the observed PMU measurements.

Quantum computing can solve the grid stability problem significantly more efficiently and by analyzing more PMU data in real-time. Theoretically, quantum algorithms with exponential speedup for singular value estimation (SVE) of a given matrix have been proposed by Rebentrost *et al.* [79]. Although this relies on the quantum random access memory (qRAM) [20], which works well in theory, there is no practical implementation of it yet. Secondly, the quantum algorithms for the phase estimation subroutine rely on exponentiating the matrix. Decomposing the exponential of a product of two matrices in terms of the individual matrices is a challenging task. However, the introduction of the idea of block encodings [80] and the theorems proving the existence of fast SVE algorithms using block encodings highlights that the above is possible by efficiently computing the exponential of a Hermitian matrix within the block-encoding framework, and thereby allowing for efficient singular value computation.

It is worth noting that none of the proposed power system problems are yet being implemented on a quantum computer to examine the computation time and the fidelity of the results. Therefore, we cannot compare the quantum solution with the classical solution at this point. Moreover, considering the currently limited resources for quantum computing, there is no one-to-one comparison with classical computing on the implementation side. This is a subject to be investigated once the technology, and its applications, have further progressed.

IV. CONCLUSION

Quantum computing applications are currently growing across the globe. Various challenges and concerns around quantum computing require a comprehensive study on this topic. This paper briefly discussed the essential elements of quantum computing and further explored the potential of quantum computing to improve analytical and computing capabilities in solving power grid problems. The power grid is evolving ever more rapidly, not only to embrace new technologies but also to adapt to the changing climate as it drives the world to decrease its use of carbon-based fuels to slow down the warming trend. Quantum computers would provide much-needed processing power by the grid of the future through multi-state capacity and executing functions simultaneously using all possible permutations. The next steps should include the application of quantum computing to the mentioned problems and identifying the particular challenges and opportunities.

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