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# Quantum Computing Applications in Power Systems

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## SUMMARY

Quantum computing is the research area centered on creating computer technology that uses quantum theory concepts that explain the nature and conduct of energy and matter at the level of the quantum (atomic and subatomic). The development of a practical quantum computer would mark a step forward in computing capacity far greater than that of a modern supercomputer, with considerable increases in efficiency. According to the rules of quantum physics, a quantum computer could achieve enormous processing power through multi-state capacity and execute functions simultaneously using all possible permutations. This paper briefly discusses the basic elements of quantum computing and further explores the potential of quantum computing to improve analytical and computing capabilities in solving power system problems.

## KEYWORDS

Quantum computing, parallel processing, power systems

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## 1. INTRODUCTION

Computing plays a major role in power system analytics. To ensure safe, secure, and economic control and operation of the power system, it is essential to create a systematic modeling structure and to identify performance goals and control/optimization components and their interactions, followed by proper computing to reach the desired solutions. Many prominent techniques have been created over previous decades to solve various power system problems, starting from exact enumeration methods (which proved to be impractical for realistic power systems) [1], to numerical optimization techniques such as priority list methods, dynamic programming, Lagrangian relaxation, branch-and-bound, and mixed-integer programming [2]-[10], and stochastic search methods such as genetic algorithms, evolutionary programming, simulated annealing, and optimization of particle swarms [11]-[17]. Quantum-inspired evolutionary algorithms have also recently been implemented as alternatives to solve some power system problems [18]-[19].

Quantum Computing, a subfield of quantum information science, which depicts the conduct of very small particles, creates the framework for a new computing paradigm. Quantum computing was first introduced in the 1980s to enhance computer modeling of the behavior of very small physical systems and to express the idea that a quantum computer can simulate problems that a classical computer could not. Involvement in this research increased in the 1990s with the advent of Shor’s algorithm that would exponentially accelerate a significant class of cryptanalysis if implemented on a quantum computer, thereby possibly threatening several of the cryptographic methods employed for government and civil communication protection and storage of information [20]. Quantum computing benefits from the subatomic particles’ capacity to exist in more than one state at any moment. Operations can be performed much faster with less energy than classical computers due to the conduct of the tiniest particles. In other words, a quantum computer is a computer that utilizes quantum mechanics to more effectively execute certain types of computation than a classical computer [21]–[24].

When the idea was first proposed and several algorithms were later on developed in the 1990s, nobody was able to build this type of machine. In the last two decades, however, attempts have produced significant strides in building a working quantum machine, rekindling interest in the potential of this technology. The first milestones in quantum computing were demonstrations of basic analog and digital proof-of-principle systems. Small digital computers were accessible in 2017, with dozens of qubits but errors too large to fix. Work in quantum annealing began in 2000s using qubits built with a technology that had lower coherence times but that allowed them to scale more rapidly. So experimental quantum annealers grew to computers with approximately 2000 qubits by 2017 and reached 5000 qubits by D-Wave Systems Inc in 2019.

This paper explores the potential of quantum computing to improve analytical and computing capabilities in solving power system problems. It provides a brief overview of quantum computing and some of its basic elements, and further investigates a power system problem that its solution can be computationally improved using a quantum computer. The rest of the paper is organized as follows: Section 2 presents the basics and principles of quantum computing. Section 3 presents the potential of quantum computing in enhancing the computational performance of solving power system problems. Section 4 concludes the paper.

## 2. THE BASICS AND PRINCIPLES OF QUANTUM COMPUTING

Quantum computing is not a deterministic but probabilistic physical world theory with intrinsic uncertainty. While the dynamics that describe it in a small scale seem counterintuitive, it accurately predicts a wide range of observable phenomena that classical physics cannot. The growth of this area has changed the researchers' understanding of the nature. Very small systems whose behavior cannot be properly approximated by classical physics equations are often referred to as "quantum systems."

Although computer systems today have extraordinary power, there are applications that are difficult for them to compute but seem to be easily computed by the quantum world: estimating the properties and behavior of quantum systems. While classic computers can simulate simple quantum systems today, and often find useful approximate solutions for more complicated ones, the amount of memory that is required for simulation exponentially grows with the simulated system size for many of these problems. In 1982, the physicist Richard Feynman suggested that quantum mechanical phenomena themselves could be more efficiently used to simulate a quantum system than a naïve simulation on an ordinary computer [25,26]. In 1993, Bernstein and Vazirani showed that the extension of the Church-Turing thesis could be violated by quantum computers [27]–a fundamental computer principle that states that the output of all machines is polynomial quicker than a probabilistic Turing computer [28]. Their quantum algorithm provided an exponential speed over a classical algorithm for a computational job called recursive Fourier sampling. Dan Simon provided another illustration of a quantum algorithm that showed an exponential speed for another computational problem [28]. In 1994, Peter Shor demonstrated that in theory, a quantum computer can solve several significant computer challenges considerably more effectively if such a machine is constructed. In particular, he extracted algorithms to quickly factor big integers and solve discrete logarithms, problems that takes even today's biggest computers thousands of years to compute.

Classical computers work by converting information to a series of binary digits, or bits, and operating on these bits using integrated circuits (ICs) containing billions of transistors. There are only two feasible values for each bit, 0 or 1. Computers process the data by manipulating these so-called binary images, creating stunning visual worlds in games and films, and offering the web-based services upon which many are dependent. A quantum computer also reflects data as a series of bits or qubits. Like a normal bit, a qubit could be either 0 or 1, but unlike a regular bit that can only be 0 or 1, a qubit may also be simultaneously in both states. This ability to be simultaneously in all possible binary states results in the potential computation power of quantum computing when expanded to many qubits' systems.

### The State of a Single Qubit:

An imaginary sphere can be thought of as a qubit. A classical bit can be a qubit at any stage on the sphere in two times – at either of the two poles of the sphere. The qubit state can be mapped onto a point on the surface of this unit sphere (called a "Bloch sphere"), where the north and south poles correspond to the states $|0\rangle$ and $|1\rangle$, respectively, as shown in Fig. 1.

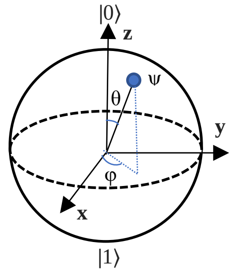

Fig. 1. Bloch sphere represents the set of all possible states for a single qubit.

The state of a single qubit can be represented by:

$$|\psi\rangle = k_0|0\rangle + k_1|1\rangle \tag{1}$$

where

$$|0\rangle = (1,0)\ and\ |1\rangle = (0,1) \tag{2}$$

The probability condition below restricts the values that $k_0$ and $k_1$ can take.

$$|k_0|^2 + |k_1|^2 = 1 \tag{3}$$

We can account for this constraint by setting the magnitude of $k_0$ to $cos\ \theta/2$ and the magnitude of $k_1$ to $sin\ \theta/2$, since:

$$\left(\sin\frac{\theta}{2}\right)^2 + \left(\cos\frac{\theta}{2}\right)^2 = 1 \tag{4}$$

Accounting for the phase component of a complex number means:

$$k_0 = e^{i\alpha}\cos\frac{\theta}{2} \quad \text{and} \quad k_1 = e^{i(\alpha+\varphi)}\sin\frac{\theta}{2} \tag{5}$$

$\theta$ gives the latitude and $\varphi$ gives the longitude of the quantum state on the Bloch sphere. As a result, the state of a qubit can be represented using three independent real numbers ($\alpha$, $\theta$, and $\varphi$):

$$|\psi\rangle = e^{i\alpha}\left(\cos\frac{\theta}{2}\ |0\rangle + e^{i\varphi}\sin\frac{\theta}{2}\ |1\rangle\right) \tag{6}$$

It turns out that the global phase $\alpha$ has no physical significance, and a single qubit can be fully described by two real numbers $0 \leq \theta \leq \pi$ and $0 \leq \varphi \leq 2\pi$.

Based on the characteristics of a qubit, with $N$ qubits a total of $2^N$ numbers can be operated simultaneously. This property is called superposition which is similar to the concept of parallel computing in classical computers. This implies that a computer that uses this property can store much more data while using less energy than a classical computer.

Consider a classical computer that operates on a three-bit register. If the exact state of the register is not known at a given time, it is described as a probability distribution over 8 ($=2^3$)

different three-bit strings, i.e., 000, 001, 010, 011, 100, 101, 110, and 111. If there is no uncertainty about its state, then it is in exactly one of these states with a probability of 1.

The status of a three-qubit quantum computer is defined likewise by an eight-dimensional vector $(k_0, k_1, k_2, k_3, k_4, k_5, k_6, k_7)$. The coefficients $k_i$ are complex numbers, and it is the sum of the absolute values of the coefficients $\sum_i |k_i|^2$ which must equal to 1. For each $i$, the absolute value squared, i.e., $|k_i|^2$, provides the probability that after a test the system will be discovered in the $i$-th state. However, the phase difference between any two coefficients (states) reflects a significant parameter, because a complex number encodes not only a magnitude but also a direction in the complex plane. This is a basic distinction between quantum computing and probabilistic classical computing.

If the three qubits are evaluated, a three-bit string will be observed. The likelihood of evaluating a given string is the squared magnitude of that string's coefficient. Therefore, evaluating a quantum state illustrated by complex coefficients $(k_0, k_1, k_2, k_3, k_4, k_5, k_6, k_7)$ gives the classical probability distribution of $(|k_0|^2, |k_1|^2, |k_2|^2, |k_3|^2, |k_4|^2, |k_5|^2, |k_6|^2, |k_7|^2)$. It could be further said that the quantum state "collapses" to a classical state as a result of making the measurement.

Depending on which basis is chosen for a space, an eight-dimensional vector can be specified in many different ways. The computing basis is known as the basis of bit strings. Other possible bases are unit-length, orthogonal vectors and the eigenvectors of the Pauli-x operator. For instance, the state $(k_0, k_1, k_2, k_3, k_4, k_5, k_6, k_7)$ in the computational basis can be written as:

$$k_0|000\rangle + k_1|001\rangle + k_2|010\rangle + k_3|011\rangle + k_4|100\rangle + k_5|101\rangle + k_6|110\rangle + k_7|111\rangle$$

where, e.g., $|010\rangle = (0,0,1,0,0,0,0,0)$ (7)

Based on the abovementioned definition of a qubit, a quantum computer can be seen as a physical system that comprises a collection of coupled qubits that may be controlled and manipulated in order to implement an algorithm such that measurement of the system’s final state yields the answer to a problem of interest with a high probability.

## 3. POTENTIAL OF QUANTUM COMPUTING IN ENHANCING THE PERFORMANCE OF THE POWER SYSTEM

Quantum computers work on entirely distinct principles to current computers, making them suitable for solving specific mathematical issues, such as finding very large prime numbers. Since prime numbers are so essential in cryptography, it is probable that many of the mechanisms that maintain our internet data safe could be rapidly cracked by quantum computers. Because of these potential issues, scientists are already attempting to create technology that is resistant to quantum hacking, and on the flip side of that, it is feasible that cryptographic quantity-based systems would be much safer than standard analogues [3]. Another potential application of quantum computing is in power systems as many problems are formulated, simulated, and analyzed based on complex numbers, or phasors. Qubits can be interpreted as complex numbers, therefore a quantum computer may work on multiple versions of a phasor in a power system problem simultaneously. This is an idea still to be investigated.

In the late 1960s and early 1970s, the first digital analytical instruments for power system applications emerged. In this period, the first power flow and transient stability algorithms, the first optimization algorithms for power flow and generation scheduling, the first supervisory control and data system, and the first energy management system with state estimation and contingency assessment were all created. With the faster evolving computer hardware and software these tools improved over the next four decades, but by and large the methodology and algorithms did not change much. Overall, there have been incremental rather than transformative improvements in energy engineering analytical instruments since the 1970s [29].

In the early period of power engineering analytics, the main reason for the burst of creativity was the entry of many new people into the power engineering community who brought previously unknown mathematical techniques to solve existing problems. Incremental improvements in grid analytics cannot handle the changes taking place in the grid today. New mathematical methods need to be developed and implemented for power grid analytics to make the necessary transformation adjustments. Quantum computing's advanced mathematical and computational capability is precisely what the power system needs to experience revolutionary adjustments at this stage in time.

In addition to the need for advanced analytics, the grid is going through significant changes and modernization. Transmission and distribution systems that were frequently operated as distinct systems are becoming more of an integrated system. The basic hypothesis was that at the substation the transmission system will supply a prescribed voltage and the distribution system will supply the energy to individual customers. Historically, there has been very little feedback between these systems beyond the operator of the transmission system to know the amount of power to be delivered and the operator of the distribution system to know what voltage to expect. 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. One instance is the distributed generation's transient and small-signal stability problems that change the general energy system's dynamic nature. Developing more comprehensive models that include the dynamic relationships between transmission and distribution systems will be essential in the future. Furthermore, better scheduling models are needed to design viable deployment and use of distributed energy resources. It is critical to create such models with other types of distributed energy resources and responsive demand policies to promote the implementation of nondispatchable generation, such as solar.

It is relatively simple to acknowledge that distinct grid architectures present distinct mathematical and computational difficulties to current techniques and procedures based on the previous description of representative power grid architectures. These new architectures include multi-scale systems that temporarily range between comparatively quick transient dynamics of stability-level and slower goals of optimization. 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 be then required to design computational methods to support different decision-making time scales, whether they are quickly automated controls or design instruments for planning.

As an example, consider a linear problem to be solved. Linear problems are very common in nearly all fields of science and engineering. There are many examples of linear problems in power systems such linear approximation for a dynamic stability problem as discussed above, or a DC power flow for a coordinated transmission-distribution system operation and control. 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 [30]. For example, if a linear problem requires 100,000 ms (or 1.67 min) to be solved in a classical computer, it would take a quantum computer just 5 ms to solve this problem. This is a huge improvement in the computation time which is more discernible as the size increases. If this problem becomes 10 times larger, the classical computer would require 1,000,000 ms (or 16.7 min) to solve this problem, i.e., an increase of 10 times in the computation time, while the time required by the quantum computer increases by just 1 ms to 6 ms. 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, thus offering potentially significant benefits in addressing the ever growing computational needs of the power system.

## 4. CONCLUSION

The power system is evolving ever more rapidly, not only in order to embrace new technologies, but also in order to adapt to the changing climate as it drives the world to decrease its use of carbon-based fuels to slow down the global warming trend. Thus, all power engineering research roadmaps call for new analytics to plan and operate the rapidly changing power grid. Analytics generally relate to the computer-based tools that are used to design transmission and distribution systems and to develop associated real-time control systems. The growing number of active players, such as distributed energy resources and prosumers, and the resultant complexity calls for revisiting the traditional computing methods and investigating innovative approaches that can address the needs of a modernized power grid. Quantum computing offers such capability and thus it is logical to conduct comprehensive research on this emerging technology as an enabler and supporter of the green, reliable, resilient, and secure grid of the future.

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