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Quantum Computing in Power System Simulation

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Abstract: The concept of quantum computing has been conjectured as the next major breakthrough in computing. The basis of quantum computing, its strengths, weaknesses, and challenges are outlined. The specific application to electric power engineering is discussed.

Keywords: *quantum computing; parallel processing; qubits; superposition; entanglement.*

I. Computing and power engineering

The origins of computing may be traced from the abacus (or earlier), to mechanical adding machines, to modern electronic computers. The concept of electronic computing is based on two main topologies: algorithms, and sequential algorithmic data processing. Modern electronic computing may be traced to von Neumann and Turing [1]. In these topologies and models, engineering tasks are reduced to algorithms that are coded using languages for sequential calculation.

Table 1. Partial listing of main computational algorithms in electric power engineering

Application	*Salient Features*
Algebraic equations, A**x**=**b**	Sparsity; Not easily parallelizable; Core problem in most computations.
Differential / algebraic equations	Computationally intensive; May be time critical.
Real optimization	Often time critical.
Mixed real / integer optimization	Computationally intensive; May be time critical
Eigenvalue / eigenvector	Computationally intensive; Not usually time critical.
Monte Carlo simulations	Computationally intensive; Easily parallelizable

While there have been alternative computational techniques proposed [18], the concept of serial processing using algorithms is dominant in engineering calculation today. In electric power engineering, the main applications requiring significant computational resources are listed in Table 1 with a summary of their salient features.

II. Traditional computing

Traditional computing relies on a unit of binary information called a bit. At any one time, a bit can be either a 1 or a 0. To represent a number in traditional computing, bits are concatenated to form binary numbers; the four-bit binary number, 1101B, is equivalent to the decimal number, 13D. If it is desired to add two numbers, simply add the numbers bit by bit to get a single result. As an example,

$$0001B + 1100B = 1110B. \qquad (1)$$

Adding a second pair of numbers, e.g., 0100B + 0011B = 0111B, requires that the first addition be completed, with the attendant computation time that this entails, before beginning the second addition.

Serial processing refers to calculation in an algorithm that is arranged in series. That is, intermediate results must be obtained sequentially before the final result can be observed. The general concepts of serial computation are depicted in Figure 1. It is often necessary to 'loop' into and out of serial algorithms to obtain desired algorithmic logic, but the concept is mainly serial computation nonetheless. In the example (1) above, note that addition entails first adding 1B + 1B in the least significant bit. If c_0 denotes the carry bit in the 2^0 position, and s_0 denotes the sum bit in the 2^0 position, then

$$s_0(1,1) = 0$$
$$c_0(1,1) = 1$$

where the arguments (operands) (1,1) refer to the 2^0 position of the addends. In the 2^1 position,

$$s_1(0,0,c_o) = 1$$
$$c_1(0,0,c_o) = 0.$$

Both s_k and c_k generally depend on c_{k-1} and therefore this algorithm for addition is sequential.

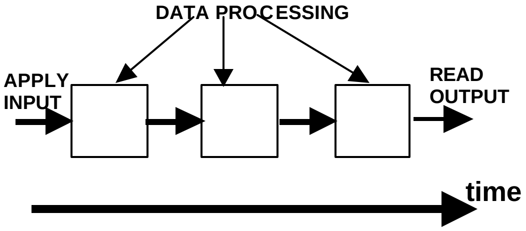

Figure 1. The general concepts of serial computation

III. Quantum computing

In 1982, the renowned physicist R. P. Feynman conjectured as to the potential for a radically different concept in computing [2]. The concept is the use of certain atomic properties at the atomic electronic level for computation. Although Feynman did not implement the concept in hardware, he did lay out the basic concepts, much as Turing did in 1936 for the Turing machine, a hypothetical, serial calculating, algorithmic computer [3]. Deutsch is also credited with embracing the concept of quantum electronic properties for computation [4] -- now known simply as *quantum computing*.

The unit of information in quantum computing is called the quantum bit, or qubit for short. This new computing technique uses two properties exhibited by some elementary particles. The first (bizarre) property is that a particle may occupy more that one state at any one time; hence a qubit may be both a 1 and a 0 simultaneously (by Schroedinger) [5-7]. This property is known as *superposition*. Superposition means that with N bits, one can operate on 2^N numbers *simultaneously*; hence with only a few hundred qubits, one can simultaneously represent more numbers than there are atoms in the entire universe. The superposition principle is similar to the concept of parallel computation—that is, computation of several processes simultaneously [5, 8-11, 18]. Superposition implies that high-speed computing can be accomplished—at least on problems that can be converted to a suitable 'parallel' algorithm. If T is the serial execution time of an entire algorithm, T_S and T_P are the execution times of the serial and the parallelizable portion, respectively, then the gain, G, (or speed-up) that can be expected from parallelizing the algorithm by performing N operations in parallel, is

$$G = \frac{T}{T_g + (T_p / N)} \leq \frac{T}{T_g} \tag{2}$$

Because several distinct results are calculated simultaneously, quantum computation of each separate result has the potential of being very fast, assuming a traditional algorithm is simply parallelized using quantum computation. The exciting aspect of quantum computing is that the properties of superposition and quantum entanglement have the potential of allowing new, faster algorithms to be devised.

Because a string of cubits can occupy many states simultaneously [12], and because these states can be processed independently, qubit strings may be interpreted as a complex number; hence each qubit can represent a phasor. This means that quantum computers may be viewed as having an CPU that operates on complex numbers. While complex numbers are not particularly interesting to most of the world, calculations with complex numbers (e.g., phasors), are something fundamental to the way the power community performs analysis / simulations of power system phenomena. Using qubits in an algorithm may allow calculations on multiple versions of a phasor *simultaneously*. Such techniques may be used to advantage when performing contingency analysis, dynamic simulations, Monte Carlo simulations and optimization. References [13-

15, 18] discuss the potential for parallel processing in power engineering, and a few of the main applications are listed in Table 2. These applications are listed because there is a similarity between parallel processing and quantum computing—and some applications of parallel processing will likely carry over to quantum computation.

Table 2. Potential quantum computing applications

Operating tools	Optimal Power Flow
	Unit Commitment
Planning tools	Contingency Analysis
	Dynamic Stability Simulation
	Long/Mid/Short Term Stability Simulations
	Monte Carlo Simulations

The concept of quantum computing effectively results in computation in which a group of complex quantities are processed simultaneously. Simultaneous processing would also entail loading or coding the input data to the 'quantum computer'; some means of processing the group of data; and also having some provision for reading the result. Figure 2 shows the general concept.

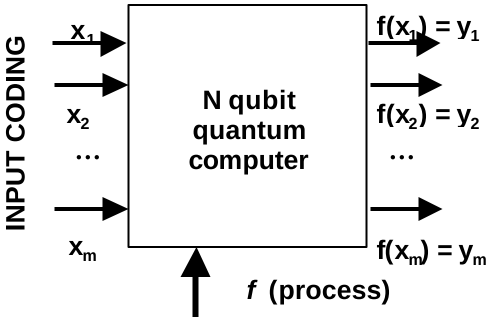

Figure 2. A pictorial of processing a group of complex data, $m \leq 2^N$

IV. Entanglement

There is a second property of particles that is used to advantage in quantum computing. This property is known as entanglement. In the 1930s, there was a disagreement between Albert Einstein and the quantum mechanics community. According to quantum mechanics, certain pairs of particles have quantum states that are linked together. No matter where these particles exist in space, quantum theory dictates that the state of one particle is complementary to the state of the other. The coupling of atomic particles in this way is known as *entanglement*. Albert Einstein, together with his colleagues, Boris Podolsky and Nathan Rosen, claimed that this had to be incorrect, since it necessitated a faster-than-light-speed communication between the particles to maintain complementary states. An experiment verified that quantum mechanics was correct; the experiment also showed that no faster-than-light signal occurred and that the property of entanglement cannot be used for subluminal communication. The entanglement property of Einstein-Podolsky-Rosen (EPR) pairs is used along with probability waves to develop quantum computational algorithms that perform calculations by reinforcing correct quantum states through constructive interference, and destroying quantum states that are not indicative of the problem solutions via destructive interference.

The concept of simultaneous processing of data occurs in a quantum computer at the microscopic scale. This is an important difference from the concept of parallel processing, which occurs at a macroscopic scale. Whereas a parallel processor may be envisioned as a complex coded algorithm (e.g., a power flow study) acting on several data (e.g., several loading conditions), the quantum computer acts on a scale of AND and OR gates. Therefore the impact of quantum computing is expected to be on the arithmetic processor (e.g., math co-processor). A second distinct area of impact relates to inherent speed. Modern microprocessors operate up to about 2.0 GHz (clock speed), but quantum computers have the potential of being much faster (e.g., several orders of magnitude). A third area of impact relates to size: if Moore's law eventually reaches a maximum point,

$$\textit{Number of transistors per IC} = K2^{1.7Y}$$

where *Y* is the number of years after 1976, then one would expect an ultimate limit to microprocessor size (as measured by number of transistors) for conventional computation. Because of the size of quantum dots, it is expected that the number of computationally active elements in a processor will increase beyond conventional limits, once quantum processors become available.

V. Quantum data processing

The coding of data as quantum spin and flip at the atomic level is the basis of quantum computing. Processing those data is likely to be by application of magnetic fields to the qubits. Entanglement has implications on the accuracy of recovering processed data. That is, the measurement of quantum states may cause the state to be altered. The idea of errors is not unique to quantum computing: errors due to roundoff in conventional computing have been accommodated and accounted for by error correcting codes and fault tolerant computing. The concept of fault tolerant quantum computing appears to have been solved [16].

A quantum computer, like a conventional computer, will likely be constructed of a collection of gates. A primitive quantum gate has been constructed in which one qubit can be made to change the state of another qubit. This is termed a controlled NOT gate (or CNOT gate). In [1], a brief description of a two-qubit CNOT gate is given in which data is stored as electron spin. The spin is coded externally by magnetic fields. One qubit of the CNOT gate can be made to control the spin in the second qubit. The gate was implemented at near absolute zero with state of the art magnetic sensing technologies.

VI. New computing paradigms for power engineering

The power engineering community has always been a leader in numerical computation. Sparsity programming, which is used in many disciplines today, grew out of research into a faster means of performing large-scale power-system simulations, specifically, the power flow problem. General concepts of computing technologies and applications may be envisioned as a hierarchy as shown in Figure 3. At the lower levels of the hierarchy are the bases of computing. At these lower levels one finds 0,1 bit storage in conventional digital computers. At intermediate levels of the hierarchy, algorithms are used to accomplish desired tasks—building on the foundations at the lower levels of the hierarchy. Attributes such as speech recognition and other intelligence occur at the higher levels of the hierarchy. In the case of quantum computation, present technology is located at the very bottom of the computational hierarchy. That is, present efforts concentrate on coding numbers, reading numbers from qubits, and elemental (e.g., gate level) quantum processing. At this level of hierarchy, it is difficult to assess the response of quantum computers at the algorithmic and paradigm levels. One is tempted to use analogies with conventional computing—but these analogies may be fraught with inaccuracy.

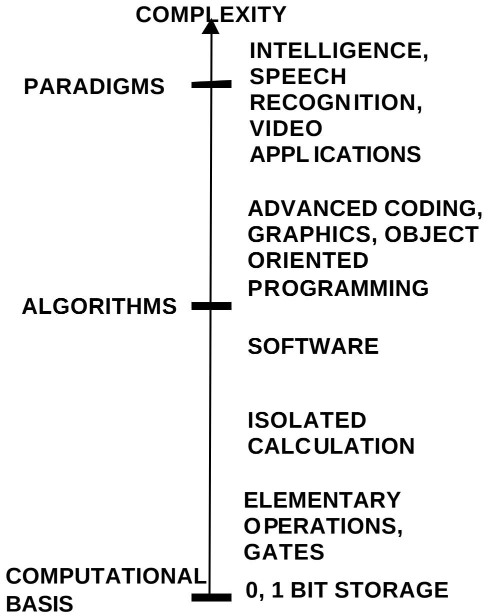

Figure 3. Computational hierarchy

The main issues of input / output should be mentioned in connection with quantum computers. Because information is stored (or coded) in qubits, namely as quantum phenomena (e.g., spin), input coding may be difficult. Also, measurement of the quantum phenomena may have implications beyond the usual consideration in electrical circuits. For example, the Heisenberg uncertainty principle may limit certain output measurements. Also, the speed at which input coding and output measurements are done may be the ultimate limit of a quantum computer. In the power area, on-line control may require large amounts of data to be read in the millisecond time frame, and the input information rate may be high.

Power engineering problems are dominated by some of the following attributes:

- Very large static (and dynamic) databases
- Occurrence of complex numbers
- Real time data received in the 10 ms time frame
- Operator intervention
- Importance of security
- Potential for serious problems associated with errors in calculation.

These issues are at the upper end of the hierarchy shown in Figure (3). It appears that the present status of quantum computing is focused on producing high speed, parallel processing arithmetic processors. How these processors may be configured at the algorithmic level is unknown, but many experts expect a significant increase in processing speed. If this speed materializes, the applications at the upper end of the computational hierarchy would become realizable.

The road map to learning about, implementing, and utilizing quantum computing in power engineering appears to be organized as:

- Understanding the quantum storage process and input coding / output measurement at the microscopic level. This includes learning more about the use of entanglement, superposition and constructive/destructive interference. This is at the lower end of the hierarchy in Figure (3).
- Development of arithmetic processors, and the selection of the number of qubits required for arithmetic processing [17].
- Conceptualizing standard and non-standard algorithms for use with quantum processing
- Apply quantum concepts to power engineering problems to take advantage of computational speed and to minimize the problems of quantum computing idiosyncrasies. The objective is to identify candidate power system simulation / analysis algorithms that may benefit from quantum computation. Many power system computation problems can be handled satisfactorily by traditional computing engines. The algorithms identified will be those that are either so time-complex, or algorithmically complex that the solution procedure is currently problematic. An example of a time-complex algorithm is power system dynamic simulations that include the entire range of dynamic models: short-term, mid-term and long-term. Transient and long-term dynamics simulations cannot be done in real time for even modest-sized practical power system models. An example of an algorithmically complex problem is the mixed integer optimization of a large control area. If detailed models of a large control are needed, there is currently no way for traditional computers to perform the complex optimization in an appropriate length of time.
- At the upper end of the hierarchy, candidate algorithms might be selected for ultimate testing and implementation.

VII. The impact of results in power engineering

It is expected that new, fast quantum computer algorithms will have significant impact on power system simulation and analysis. Exactly what the impact will be will depend on the algorithms that result from research in this area. The current problem areas, as seen in California with deregulation, relate to operating the power system in a secure fashion while on the verge of collapse. The results of this research may help in developing high-speed system-wide control algorithms that may allow power system operation, under operating conditions that would be considered as marginally unstable today.

The following question often arises: how long will it be before we see practical quantum computers? In 2002, the elementary implementation of qubits as quantum spin has been accomplished, and multiple-qubit configurations as quantum dots have been implemented. Elementary logic gates have also been implemented. Issues of input coding and output measurement have been addressed and demonstrated at the most elementary levels. The implementations to date have all been done near absolute zero in highly controlled laboratory environments; although some contemporary research promises to build solid state quantum computers that rely on ions imbedded in a silicon matrix to store quantum information, a design which may not require extreme conditions. The implication of these remarks is that quantum-computing technology is at the very bottom of Figure (3). Estimates of the expected time to reach the algorithmic level range from five to fifty years. No estimates of time required for power engineering applications are available, but it is clear that applications are more likely in the long term than in the short term.

VIII. Conclusions

Quantum computing is a term that refers to the coding of complex data in atomic structure. The basic element is termed a qubit, and elementary gates and input / output using qubits have been constructed near absolute zero in a laboratory environment. Data processing using qubits has been demonstrated at the most elementary level. It appears that a special kind of parallelism may be used to effect many computations simultaneously. The long term applications in engineering in general and power engineering in particular are unclear: however several power engineering applications lend themselves to parallelism. No estimates of time required for power engineering applications are available, but it is clear that applications are more likely in the long term than in the short term.

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