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Systematic Analyzation Quantum Computing on Renewable Power System Optimization

Tianle Bu

Fu Foundation School of Engineering and Applied Science, Columbia University, New York, USA
bu20000817@gmail.com

Abstract. While the demand for energy keeps increasing in modern society, the amount of fossil fuel can only decrease. To face the energy crisis that human will face eventually, development in renewable energy need to be made. To achieve the goal of replace fossil fuel, the scale of renewable energy production needs to be increased accordingly as well as the amount of computation need to be done. Power systems are becoming increasingly stressed by high penetrations of variable renewable generation. Some resent study shows how quantum computing can solve traditional problems with speed tremendously exceed conventional computation, which makes quantum computing an ideal candidate for improving renewable power system. This paper synthesizes recent advances in quantum computing on renewable power grid, covering fundamental theory of renewable power and quantum computing, newly quantum computing techniques, and possible implementation strategies. Key challenges of integrating quantum computing into power system is also introduced. Practical pathways for leveraging Noisy Intermediate-Scale Quantum era hardware, identifies critical engineering bottlenecks such as state preparation, error mitigation, and scalable benchmarking is reviewed. A focused comparative evaluation contrasts quantum and classical approaches with respect to performance, scalability, and robustness, and an evaluation framework is illustrated.

Keywords: Renewable Energy, Power System, Quantum Optimization

1. Introduction

Fossil fuel is the main resources for energy supply around the world, according to the U.S. Energy information Administration, 84% of the total energy consumption in the U.S. is provided by fossil fuel [1]. However, the downsides of depending on fossil fuel are clear. First, due to the characteristic of non-renewable, it will fail to satisfy the ever-increasing demand of energy eventually. Second, the greenhouse gas emission from burning fossil fuel shall rise global temperature and cause series environment issues, such as global warming. Renewable energy currently supplies for 8% of total energy consumption [1]. U.S. government has published a new "Nationally Determined Contribution" (NDC) 2024, target to reduce 61-66% green gas emission and a 35% decrease in methane usage by the time of 2035 [2]. To achieve that goal, the production of renewable energy needed to be increased, which would increase the burden of power grid. Examples include overloaded transmission and distribution corridors; reduced grid stability caused by declining

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system inertia; pervasive variability and uncertainty from high renewable penetration; diminished real-time situational awareness; and disruptions and increased volatility in electricity market operations [3]. Quantum computation would be a promising potential solution considering its ability to solve massive scale computational problems, which allows it to handle large volumes of data and outputting commands much faster than conventional computing. For example, the University of Science and Technology of China (USTC) reported a photonic experiment implementing Gaussian boson sampling on a programmable photonic device in 2020. The team reported that their device produced samples for the target distribution in on the order of ~200 seconds, and they presented an estimate that performing the same task on then-state-of-the-art classical supercomputers, which would require on the order of hundreds of millions to billions of years. This experiment has shown the potential and irreplaceable of quantum technology. However, this advantage is specific to particular task instead of overall at the moment. Gaussian boson sampling is a quantum related task, so it is natural that quantum computer handles it better. Therefore, more study needs to be done before the practical usage of quantum computing.

This paper presents a focused synthesis of recent QC developments as they pertain to renewable rich power systems, and proposes a practical evaluation framework to compare quantum, hybrid, and classical solutions. Following sections are included in this paper. A literature synthesis reviews recent studies on the subject. A detailed explanation on the recent breakthroughs. A comparative evaluation is done in the benefits of emphasizes performance, scalability, and engineering constraints relevant to power grid operations. This study aims to clarify realistic potential for QC on renewable rich power grid, and review on the fundamental theories.

2. Literature review

To give a through illustration on the challenges renewable energy is facing, and how some of the recent breakthrough in quantum computation may help address these challenges, the following articles would be reviewed:

Y. Zhou reviewed quantum algorithms, hardware, and networking for power-grid analytics. Static analysis, optimization, security, implementation challenges, and future research directions is included [3].

M. A. Basit reviewed synthesizes grid-integration challenges for renewables. Introduced flexible AC transmission system (FACTS). Simulation through MATLAB/Simulink showing how FACTS enhance voltage and transient stability [4].

M. Schwenzer reviews grid control strategies for renewable integration. Schwenzer contrasted on conventional centralized and emerging decentralized/hierarchical concepts. Impacts on stability, reliability, and scalability are analyzed [5].

M. AbuGhanem reviewed synthesizes Noisy Intermediate-Scale Quantum (NISQ) era progress toward quantum supremacy and surveying leading superconducting and photonic demonstrations. Evaluation of hardware, scalability, and error correction limits was introduced. Concept studies in quantum machine learning, simulation, optimization, finance and drug discovery, was illustrated to argue NISQ devices are essential transitional platforms toward fault tolerant QC [6].

S. Golestan reviews the integration of QC in power systems, highlighting its potential to solve complex problems like AC/DC power flow, contingency analysis, state estimation, and electromagnetic transients' simulation. It examines recent advancements in applying QC algorithms to these issues, discusses challenges due to NISQ hardware limitations, and suggests future research avenues. The paper emphasizes the promise of QC in handling future energy systems' computational challenges, although large-scale applications remain distant due to current hardware limitations [7].

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F. Feng introduced a quantum power flow (QPF) model, aiming to integrate QC into power system analytics. The QPF combined Harrow-Hassidim-Lloyd (HHL) algorithm and fast decoupled power flow principles to achieve faster and more accurate power flow calculations [8]. Test results demonstrate QPF's potential to outperform classical methods. The model also enables probabilistic power flow analysis, enhancing risk assessment and reliability evaluations. QPF lays the foundation for future quantum-enabled power system optimization despite challenges with quantum circuit depth and noise in current NISQ computers.

M. H. Ullah discussed QC as a transformative technology for addressing computational challenges in smart grid applications. It reviews the potential of QC for optimization, forecasting, power flow analysis, fault management, and cybersecurity in power systems, emphasizing its ability to improve decision-making and efficiency. The paper also outlines advancements in QC hardware, software, and algorithms, comparing quantum platforms and discussing the evolving research landscape. Despite current hardware limitations, QC's potential to revolutionize grid operations, particularly in handling large-scale, complex problems, is highlighted [9].

G. Colucci applies quantum annealing to transmission-network optimization by mapping a graph-partitioning formulation into quadratic unconstrained binary optimization (QUBO). This study aims to show that hybrid quantum approaches yield consistently better objective values than several classical heuristics under fixed time limits. Scalability limits (minor-embedding, hyperparameter tuning) and the need to validate the electricity-sharing variant and compare with industrial classical solvers are noted as future work [10].

U. T. Salman proposed QUIRCY which is a compact two-level quantum–classical framework that couples an HHL-based quantum power-flow solver with a QUBO/QAOA (quantum annealers and variational algorithms) module. Simulations on small IEEE cases show accurate QPF results and potential scaling benefits, while NISQ noise, qubit counts/connectivity, precision/readout overheads, and fault-tolerance requirements remain key practical barriers [11].

3. Technical analyzation

3.1. Conventional renewable power grid

Common renewable energy sources include hydropower, wind, solar, biomass, and geothermal energy. Among these, solar and wind have the greatest potential because they are less geographically constrained; however, their integration is limited by intermittency. Solar PV output is driven by solar irradiance and wind generation by wind speed—both can vary widely during extreme events such as windstorms, and are difficult to forecast even on ordinary days. To solve this limitation, various approach is applied, take variable synchronous machines (VSMs) as an example, it is a converter control strategy that makes inverter-connected distributed generators emulate the dynamic and steady-state behavior of a conventional synchronous machine [4]. VSMs usually uses PID control, one of the best-known control strategies in industrial applications, but it can be difficult to use PID control in a nonlinear system, which most of renewable generations are [5].

Model predictive control (MPC) was introduced to make up for situation PID or any single control method hard to manage. It is a combination of a various advance control method, which predict system behavior and making optimization, and repeat [5]. It is a complex method, and one of the main challenges for MPC today is the real-time computational burden of solving an optimization problem at every sampling step. The problem size grows with horizon length, system dimension, and constraints, while nonlinear or high-dimensional systems further increase complexity.

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3.2. Quantum computing theory

In classical computing, information is encoded in bits that take one of two values: 0 or 1. Logic gates, basic building blocks of computing, are combined into circuits to perform computations. For example, an AND gate accepts two-bit inputs and outputs 1 only when both inputs are 1; otherwise, it outputs 0. An XOR gate accepts two-bit inputs and outputs 1 when the inputs differ (one is 0 and the other is 1), and outputs 0 when the inputs are the same. By wiring these gates together, one can constructs adders that perform binary addition. Compared with conventional computers, QC does not deterministically output full numerical vectors; instead, it prepares and samples quantum states or estimates quantities. The basic unit is the qubit, which unlike a classical bit (0 or 1) can occupy a coherent linear combination $|\psi\rangle=\alpha|0\rangle+\beta|1\rangle$; measurement collapses this state to 0 or 1 with probabilities $|\alpha|^2$, $|\beta|^2$.

Additionally, qubits can be entangled, meaning the state of one qubit can depend on the state of another qubit even if they are far apart. This characteristic substantially improved communication security which is critical to power grid. This also allows for faster problem-solving, especially in complex tasks like simulating molecules or optimizing large systems. Quantum computers perform calculations by manipulating qubits with quantum gates, and once the calculation is done, collapsing it to a single outcome (either 0 or 1) [6]. The power of QC comes from doing many calculations at once due to superposition and entanglement, which can solve specific problems much faster than classical computers.

However, substantial challenges limit near-term impact. Current devices are NISQ machines: qubit counts, coherence times, gate fidelity and connectivity are constrained, and deep circuits become impractical due to decoherence and accumulated error [6]. Quantum random-access memory (qRAM) and scalable error correction remain largely unrealized; many quantum algorithms lose their advantage if state preparation, readout or conditioning costs are included. Hybrid and variational approaches such as VQE and QAOA reduce depth and show promise on NISQ hardware, but their ultimate advantage versus improved classical methods is still an open question [7]. Overall, QC presents a transformative theoretical model with targeted speedups, yet realizing those gains requires significant advances in hardware, error correction, and algorithm engineering.

3.3. Quantum approach for power system optimization

Quantum methods help optimization in power systems by recasting hard, discrete decision problems into forms quantum devices can handle, typically QUBO/Ising models, and then exploiting quantum hardware's different search dynamics. QAOA can explore many candidate solutions simultaneously (superposition) and use tunnelling-like moves or parameterized circuits to escape local minima, often providing better approximate solutions under tight time limits [10]. This can reduce wall-clock time for large combinatorial searches or improve solution quality when classical heuristics struggle, especially for highly constrained, high-dimensional instances.

However, integrating quantum technology into grids faces practical limits. One of the main challenges is the fragility of qubits, noise and short coherence times make deep circuits unreliable. current devices offer limited qubit counts and sparse connectivity, so embedding realistic grid models blows up resource needs.

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4. Recent breakthroughs and performance comparison

4.1. Recent advances

To avoid deep quantum loops (which amplify noise), researchers propose hybrid schemes that perform the parts that need quantum parallelism on the quantum device while leaving iterative bookkeeping, state preparation, or result aggregation to classical CPUs. Recent studies have been focusing on this principle.

QPF proposals suggest parameterizing expensive routines only once and offloading other tasks to classical processors to shorten quantum circuits [8]. QPF expresses the fast-decoupled, which is a classical method of computation. P–θ (active power to phase) and Q–V (reactive power to magnitude) updates as normalized quantum states and leverages Hermitian constant-Jacobian submatrices so phase estimation can produce solution states for voltage magnitude and angle updates. Further, parameterize the expensive quantum phase estimation steps only at the initial iteration to reduce repeated circuit cost [8]. To put it succinctly, QPF only uses quantum method on finding the solution, which is the most time-consuming procedure for classical computer, and leave everything else such as preparing system matrices, updating mismatches, controlling the iterative loop to classical part. Technically, the methods combine specific encodings, circuit primitives, and classical coordination. In QPF the network linearization produce coefficient matrices B' (describing how θ affect P) and B'' (describing how V affect Q) that are engineered to be sparse and Hermitian so they can be spectral-decomposed on a quantum register [8]. The input mismatch vectors are amplitude-encoded as normalized quantum states, quantum phase estimation (QPE) extracts eigenvalue information, controlled rotations implement reciprocal weighting, and inverse QPE un-computes ancilla (measurement of an ancilla flag yields the post-selected solution state for Δθ and ΔV). To limit quantum resources, Feng et al. parameterize QPE/inverse rotations only once and reuse the parameters across iterations, thereby lowering circuit depth for NISQ runs [8].

A complementary strand encodes combinatorial allocation and topology decisions as QUBO and applies QAOA to search large discrete spaces. Achieving this by mapping transmission partitioning into a QUBO with auxiliary binary variables for real-valued constraints and then solving with hybrid D-Wave solvers [10]. Building on these components, Salman et al. propose QUIRCY, a two-level integrated pipeline: an HHL-based QPF at level one and a QUBO/QAOA placement optimizer at level two [11]. Level one is responsible to provide a fast simulation, which can rapidly compute voltages and flows for a given grid configuration. Level two work on optimization, finding the best or potentially best solutions from base one level one simulation result.

These combined approaches directly target the principal practical barriers identified in the literature. Circuit depth and repeated expensive subroutines are ameliorated by Feng et al.'s single-time parameterization of QPE/rotation, which reduces per-iteration quantum cost and thereby mitigates decoherence exposure on NISQ devices [8]. Encoding strategies such as Hermitian/sparse reformulation and auxiliary binary expansions reduce qubit requirements and translate domain structure into compact quantum representations. As Colucci et al. and Salman et al. demonstrate; these encodings make problem instances more amenable to existing hardware or hybrid annealer pipelines [10, 11]. Hybridization is critical in recent studies: it minimizes quantum runtime, enables off-line parameter tuning, and leverages classical robustness while still capturing quantum sampling or state-preparation benefits. However, this approach magnifies typical quantum–classical overhead, which is one of the main challenges of putting these theories into practice. State preparation, measurement noise, and data transfer delays can quickly dominate run-time. Moreover, each sub-

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solver has different qubit and connectivity requirements forcing frequent re-embedding and careful qubit-resource scheduling.

4.2. Comparative evaluation

Traditional power system algorithms, such as iterative power flow solvers and linear/nonlinear programming, have underpinned renewable integration to date. These methods for grid analysis and control providing high-precision solutions, but they often in a cost of substantial longer runtimes when repeated under high uncertainty which is the situation renewable power grid optimization often facing [4]. Classical numerical methods exploit sparsity and decades of algorithmic engineering to solve realistically sized networks (hundreds to thousands of buses), but their per-instance cost grows with system dimension and with the need to repeatedly evaluate scenarios under high renewable penetration, which can make real-time or near-real-time operation computationally burdensome [3].

Quantum approaches recast key subproblems into forms that quantum hardware can address, and they therefore offer fundamentally different scaling behavior in idealized settings [11]. In particular, quantum linear-system algorithms such as HHL promise polylogarithmic dependence on system dimension for well-conditioned, sparse matrices, which implies asymptotic speedups over classical direct solvers in those restricted regimes [8]. Similarly, quantum annealing and gate-model variational methods (e.g., QAOA) operate by searching many candidate solutions in superposition or by exploiting quantum sampling dynamics, and several studies report better objective values or faster attainment of good-quality solutions under fixed time budgets compared with selected classical heuristics on benchmark instances [10, 11].

Despite these theoretical advantages, practical performance is strongly controlled by implementation costs and device limits [6, 7, 11]. Most quantum proposals require data encoding (for example, amplitude encoding for HHL), controlled phase-estimation primitives, or auxiliary variables to convert inequality constraints into QUBO form. These steps add state-preparation, measurement, and embedding overheads. Feng et al. explicitly mitigate repeated expensive subroutines by parameterizing costly QPE/rotation steps once and reusing parameters across iterations to lower per-iteration circuit cost, but even with such optimizations NISQ device noise, finite coherence times, and limited qubit counts constrain the absolute problem size and precision attainable in practice [8].

On solution fidelity and reliability, classical methods retain an advantage. They deliver deterministic, numerically stable results given sufficient compute and are supported by mature verification and convergence theory [3, 9]. Quantum outputs are inherently statistical and require sampling and error-mitigation to reconstruct classical solution vectors, so achieving the same numerical precision can be time-intensive. Nonetheless, QUIRCY's HHL-based module, for example, produced voltage and flow estimates comparable to classical fast-decoupled solutions on the test cases shown [11]. Likewise, Colucci and colleagues reported that hybrid annealing pipelines achieved lower objective values than several classical heuristics under constrained time limits on their partitioning problems, indicating that quantum or hybrid approaches can match or exceed classical solution quality in specific problems [10].

Finally, feasibility and near-term deployment considerations favor hybrid approach. Classical solvers are immediately deployable, scale to operationally sized grids, and have predictable runtimes. On the other hand, quantum methods, are limited by current NISQ hardware and by unresolved system-level engineering requirements [9, 11]. Therefore, the most pragmatic near-term path identified across the literature is a hybrid architecture in which quantum components are

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applied selectively to the most computationally intensive subproblems while classical methods retain control for verification, refinement, and large-scale orchestration [8-11].

5. Conclusion

This paper synthesizes recent developments in QC as they apply to core power-system challenges and assesses how these emerging approaches compare with established classical methods. The analysis shows that near-term, NISQ-aware hybrid architectures can offer pragmatic improvements for certain optimization and sampling tasks, particularly where classical solvers face severe time or scaling constraints. At the same time, substantive limitations remain. State-preparation overheads, error rates, and precision costs constrain direct replacement of mature classical tools. Comparative evidence indicates that classical algorithms remain the reliable workhorse for today's operational systems while quantum or hybrid schemes can deliver targeted value on specific, computationally intense subproblems when properly engineered. In short, the following conclusion is drawn: quantum computing is a promising complementary technology for power-system optimization, but broad operational advantage requires coordinated advances in algorithms, hardware, and system integration.

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