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Hybrid Quantum-Classical Optimization for Energy Distribution using TSP Model

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Abstract: Managing energy distribution efficiently has become an important challenge in modern smart grid systems. This paper proposes a hybrid quantum-classical optimization approach based on the Traveling Salesman Problem (TSP) model. The system combines classical optimization techniques with the Quantum Approximate Optimization Algorithm (QAOA) to determine efficient energy distribution paths while reducing transmission cost and energy loss. Qiskit is used for simulation and implementation. The results indicate improved routing efficiency and demonstrate the potential of quantum computing in handling complex optimization problems in smart grid applications.

Keywords: Hybrid Quantum-Classical Optimization, Traveling Salesman Problem (TSP), Quantum Approximate Optimization Algorithm (QAOA), Smart Grid, Energy Distribution, Qiskit, Quantum Computing.

I. INTRODUCTION

Energy needs are rising fast, meanwhile smart grids keep getting more complex - making it harder to move power efficiently. Old methods tend to fall short once systems grow too big or change too quickly. With today's expanding power networks, smarter computing tools become necessary so flows stay smooth, waste stays low, and expenses don’t climb.

Figuring out the shortest path that visits many places once - called the Traveling Salesman Problem - is a classic challenge tied to real tasks like delivery planning, moving data across networks, or managing power flow. When it comes to smart electricity grids, this idea helps map how energy should move smoothly from point to point. Trouble starts when regular computing approaches try handling larger sets of locations; each added stop multiplies the route options fast. Because possibilities explode so quickly, old-school math techniques slow down drastically. Efficiency drops just when you need it most.

Nowhere near perfect, today's quantum machines are already tackling tough math puzzles faster than old-school computers sometimes can. Instead of waiting step by step, methods like QAOA tap into weird physics - think ghost-like states and linked particles - to test many answers at once. Even with shaky circuits and too few working parts right now, mixing regular software with quantum tricks has begun delivering useful outcomes. Not magic, just steady progress where it counts.

A different kind of math blend - part old, part new - guides how power moves through grids, borrowing ideas from travel route puzzles. Instead of just traditional methods, it slips in a quantum trick called QAOA to reshape path choices. Running inside IBM's Qiskit playground, the setup tests how well these mixed tools behave when faced with real network shapes. Less waste along the wires becomes possible, routes tighten up - not by magic, but by rethinking computation itself.

A. Research Contributions

The major contributions of this research are listed below:

- A hybrid quantum-classical approach is proposed to improve energy distribution efficiency in smart grid systems.
- The Traveling Salesman Problem (TSP) model is used to determine optimized routing paths for energy distribution.
- Quantum Approximate Optimization Algorithm (QAOA) is integrated with classical optimization methods to improve route selection and reduce transmission loss.
- Qiskit is utilized to simulate and implement the proposed optimization framework.
- The study explores the capability of quantum computing in solving complex optimization problems related to smart grids.
- The proposed system demonstrates the potential of hybrid quantum computing techniques for future energy management and intelligent distribution systems.

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II. RELEVANT LITERATURE

A. Paper 1: Hybrid Quantum-Classical Optimization Algorithms for Energy-Efficient Smart Grids (Judijanto et al., 2025)

A mix of quantum and classical computing was tested by Judijanto and team [1] to boost how power moves through smart grids. Instead of relying only on standard models, their method linked new computation styles with older ones, aiming to cut down waste during delivery. Efficiency in directing flow, handling supply needs, and speeding up calculations became central targets. Tests ran under real conditions pointed toward stronger results than those seen with conventional setups. Even so, challenges like route planning using traveling salesman logic, shifting energy loads based on demand, or live tracking across massive networks stayed outside the project's reach.

B. Paper 2: Evolutionary Algorithm for the Traveling Salesman Problem with Innovative Encoding on Hybrid Quantum-Classical Machines (Ravi Saini et al., 2025)

Starting off differently, Ravi Saini and team [2] introduced a mix of quantum-style and standard computing approaches to tackle the Traveling Salesman Problem through a method called Quantum-Inspired Evolutionary Algorithm (QEA). Rather than sticking to one path, they merged regular evolution strategies with ideas drawn from quantum mechanics, aiming for stronger route planning that scales well. What stood out was their use of clever data encoding paired up with access to cloud-hosted quantum systems like those from IBM Quantum and AWS Braket. Testing revealed gains in efficiency - solutions were sharper and handled growth better when stacked against older rule-of-thumb techniques. While progress appeared in optimizing TSP, attention wasn't directed toward linking it with smart grids, live power delivery updates, or flexible energy control setups.

C. Paper 3: Hybrid Quantum-Classical Optimization Algorithms for Energy-Efficient Smart Grids (Milad Rahmati, 2025)

A new method by Milad Rahmati [3] mixes quantum and classical computing to boost energy efficiency in smart grids. Instead of relying only on classic models, it uses quantum tools alongside standard solvers to refine how power moves through networks. This setup targets smarter control over supply flows, smoother routing, and quicker reactions when usage shifts. Tests indicated faster problem solving and sharper outcomes than older strategies offered. Even so, the design skipped routes based on traveling salesman logic, live adjustments during peak load changes, plus deep looks into long-distance flow paths across big networks.

D.Paper 4: Travelling Salesman Problem in the Classical to Quantum Era: A Comparative Review of Algorithms and Computational Complexity (Istiyak Amin Santo et al., 2025)

Starting off with Istiyak Amin Santo and team [5], they looked at how traditional, quantum, and mixed strategies tackle the Traveling Salesman Problem. While examining techniques like QAOA, VQE, and quantum annealing, attention shifted toward their efficiency and ability to scale up.

Surprisingly, the work pointed to hybrid quantum-classical methods as useful for tough optimization tasks. Still, real-world tests - like those involving smart grids or power networks - were missing entirely.

E. Paper 5: Hybrid Quantum-Classical Optimisation of Traveling Salesperson Problem (Christos Lytrosyngounis et al., 2025)

Starting off, Christos Lytrosyngounis and team introduced a mix of quantum and traditional computing tactics to tackle the Traveling Salesman Problem through QAOA. Instead of relying only on quantum processes, their method linked standard algorithms with emerging quantum tools to refine path selection and boost result accuracy. It turned out these mixed strategies performed stronger than fully quantum alternatives when optimizing routes. Tests showed promise even though today's quantum devices still face constraints. While gains were made in how fast optimal paths could be found, attention stayed narrow - mainly aimed at TSP cases without extending into power network coordination, live electricity balancing, or smarter energy control systems.

F. Paper 6: Quantum Local Search for Traveling Salesman Problem with Path-Slicing Strategy (Chen-Yu Liu et al.,2024)

Chen-Yu Liu and team [1] introduced a mix of quantum and classical computing to tackle the Traveling Salesman Problem, relying on quantum-guided searches along with segmenting routes. Breaking big route plans into manageable chunks helped speed up solutions while lowering processing demands. Results pointed toward sharper routing outcomes and more effective use of available resources when stacked against standard approaches. Still, the work centered mostly on improving paths, leaving out connections to smart power networks or live electricity flow evaluation.

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III. COMPARATIVE ANALYSIS OF EXISTING SYSTEMS

Table I presents a structured comparison of the reviewed AI-assisted penetration testing and repository security analysis systems.

TABLE I. COMPARISON OF EXISTING RESEARCH ON AI-BASED VULNERABILITY ANALYSIS SYSTEMS

Ref.	Year	Technique Used	Smart Grid Integration	Real-Time Optimization	Key Limitation
[1] Judijanto et al	2025	Hybrid Quantum-Classical Optimization	Yes	Limited	No TSP-based routing
[2] Ravi Saini et al..	2025	Quantum-Inspired Evolutionary Algorithm	No	No	No energy management
[3] Milad Rahmati	2025	Hybrid Smart Grid Optimization	Yes	Limited	No adaptive routing
[4] Istiyak Amin Santo et al.	2025	Comparative Quantum & Classical Review	No	No	Mainly theoretical analysis
[5] Christos Lytrosyngounis et al.	2025	QOQA-based Hybrid Optimization	No	Limited	No smart grid integration
[6] Chen-Yu Liu et al.	2024	Quantum Local Search	No	No	No real-time energy analysis

IV. GAP ANALYSIS

Based on the review of the six studies, the following critical gaps are identified in the existing literature.

A. Lack of Integrated Optimization Frameworks

One way some scientists work is by looking at power grids that think for themselves. Another path takes them toward finding better paths between places using math tricks. Rarely do they mix these two ideas into one setup where old-style computers team up with new quantum kinds. Hardly any papers show this double approach running together in such a linked system.

B. Limited Real-Time Energy Optimization

Most modern setups tweak performance just for fixed scenarios, yet fail when conditions shift on the fly. Live tracking plus instant path adjustments? Still rare in today's methods.

C. Scalability Issues in Quantum Computing

Although hybrid quantum-classical methods improve optimization performance, current quantum hardware still faces limitations such as noise, restricted qubit availability, and computational complexity. These challenges affect large-scale practical implementation.

D. Insufficient Intelligent Routing Mechanisms

Most routing optimization models do not include intelligent adaptive routing strategies based on transmission conditions and energy demand variations. Efficient energy-aware route selection remains an area that requires further improvement.

E. Limited Practical Smart Grid Implementation

Several reviewed systems are mainly simulation-based and lack real-world deployment in smart grid environments. Practical implementation, large-scale testing, and integration with intelligent energy management systems are still limited in current research.

V. PROPOSED SYSTEM DESIGN

A. System Overview

Fixing these gaps begins with a new setup - one mixing regular math methods, travel route puzzles, plus quantum-style problem solving, all working inside a single control space. Instead of sticking to old models, it combines standard number

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crunching with TSP logic and QAOA rules shaped through quantum-inspired steps. Efficiency jumps when power routes get smarter, cutting down wasted electricity along with daily running fees. Running on tools built in Qiskit, the method tests blended strategies using digital quantum mimics tailored for live grid networks.

B. System Workflow

The proposed workflow follows a structured sequence:

- Smart grid node and transmission data are collected.
- The energy distribution network is represented using the TSP model.
- Preprocessing techniques are applied to organize routing and energy demand data.
- Classical optimization methods generate initial routing solutions.
- QAOA is applied to explore optimized routing combinations.
- Qiskit simulation is used for implementing the hybrid optimization process.
- Optimized energy distribution paths are generated.
- Routing efficiency and transmission loss analysis are displayed through the system dashboard.

C. AI and Quantum Components

Quantum Component: QAOA Optimization Engine
This module uses the Quantum Approximate Optimization Algorithm (QAOA) to identify optimized routing paths for efficient energy distribution.

Classical Component: Energy Routing Engine
This module performs classical routing analysis and manages energy distribution within the smart grid network.

D. Key Parameters

The proposed system incorporates the following major features:

- Smart grid network integration
- TSP-based routing optimization
- Hybrid quantum-classical optimization
- QAOA-based route analysis
- Qiskit simulation framework
- Energy distribution optimization
- Transmission loss reduction
- Intelligent routing mechanism
- Routing efficiency analysis
- Smart grid optimization dashboard

VI. EXPECTED OUTCOMES AND BENEFITS

A. Improved Energy Distribution Efficiency

The proposed hybrid optimization framework is expected to improve energy distribution efficiency by identifying optimized routing paths using the Traveling Salesman Problem (TSP) model and QAOA-based optimization techniques.

B. Reduction in Transmission Loss

The system is expected to reduce transmission losses and operational cost through efficient route selection and intelligent energy distribution mechanisms within smart grid networks.

C. Enhanced Smart Grid Optimization

The proposed framework supports better energy management, routing analysis, and computational performance by combining classical optimization methods with quantum computing techniques.

D. Support for Future Quantum-Based Applications

The system demonstrates the potential of hybrid quantum-classical approaches for solving complex optimization problems and supports future research in smart grid and energy management applications.

VII. CONCLUSION AND FUTURE WORK

A fresh mix of quantum and classic computation shapes how power moves across smart grids, built on TSP patterns alongside QAOA tools. Instead of relying only on traditional math, it taps into quantum-style processing to sharpen path choices, lower wasted flow during transfer, while lifting overall control of electricity use.
Quantum computing might soon tackle tricky challenges in managing power flows across intelligent networks. Through

simulations built with Qiskit, hybrid methods show they can work effectively when applied to today's electricity setups. One step ahead might involve adding live power tracking into the model. Instead of fixed paths, dynamic rerouting could adjust on the fly. Large networks tied to intelligent grids may shape how it scales up. On top of that, smarter calculations using quantum methods could refine outcomes. When built on actual quantum devices, results might shift toward higher efficiency. Progress here leans on testing ideas where theory meets working machines.

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