

End-to-End Connectivity of Quantum Resources with EMT Power Grid Simulator

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SUMMARY

Power system operation and planning involve computationally intensive NP-hard problems that challenge conventional computing paradigms. Quantum computing is being evaluated to solve these problems and has shown early promise, offering the potential to solve such problems. There is also work on quantum communication for secure communication in the power grid that can connect to quantum computers. Concurrently, novel electromagnetic transient (EMT) simulators are being developed to model increasingly complex power system dynamics. However, end-to-end integration framework and facilities between quantum computing platforms, quantum communication networks, and EMT simulators remains largely unexplored, creating a critical gap in the in-depth evaluation and expanded research of quantum-assisted power system solutions. This paper presents a novel Quantum Software-in-the-Loop (QSIL) framework that establishes full end-to-end connectivity between quantum computers and EMT simulators through a quantum communication simulation layer (that can also simulate classical communication that is encrypted using quantum algorithms like quantum key distribution), providing a one-of-its-kind capability to perform in-depth research and evaluation of end-to-end quantum solutions for power grids. The proposed architecture leverages SeQUeNCe (Simulator of QUantum Network Communication), an open-source discrete-event simulator that enables detailed, accurate, and highly customizable simulations of photonic quantum networks, to bridge quantum computing resources with power grid simulators. The QSIL setup integrates IonQ quantum computing hardware and SeQUeNCe with next generational EMT simulation platform RE-INTEGRATE as a proof-of-concept demonstration. Experimental results validate the functionality and effectiveness of the proposed architecture, demonstrating its capability to enable quantum-accelerated power system analysis through a fully connected simulation ecosystem.

KEYWORDS – Quantum network, QKD, quantum computing, EMT power grid simulator, RE-INTEGRATE

1 Introduction

Quantum computing is being increasingly explored for NP-hard problems in electric power systems like in electric power systems, including optimal power flow, unit commitment, contingency analysis, restoration, and control-oriented decision making. Many of these problems exhibit combinatorial complexity, high-dimensional search spaces, and stringent timing

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requirements, making them difficult to solve at the scale and speed required by future grid operations. At the same time, the power grid is undergoing a rapid transformation driven by the increasing deployment of power electronics-interfaced resources and loads, including generation plant with inverters, electric vehicle charging infrastructure, battery energy storage, high-voltage dc systems, large industrial loads, and data centers. These devices introduce fast electromagnetic and control interactions that occur on microsecond-to-millisecond time scales, thereby increasing the need for high-fidelity modeling and simulation tools capable of resolving detailed dynamics across large-scale networks.

Electromagnetic transient (EMT) simulation is a critical tool for analyzing such fast dynamics, particularly in power-electronics-dominated systems where traditional phasor-domain models may not capture switching behavior, converter controls, protection interactions, and stability-limiting transient phenomena with sufficient fidelity. However, scaling EMT simulation to large networks with many power electronic devices remains computationally challenging. To address this need, advanced EMT simulation platforms such as RE-INTEGRATE are being developed to provide high-fidelity, scalable, and automation-enabled simulation capabilities. RE-INTEGRATE is being researched upon to support large-scale power-system studies involving many power electronics systems, automated differential-algebraic-equation generation, advanced DAE solvers, and accelerated computation using modern multicore and GPU-based architectures[1]. Such simulators are being researched to enable detailed studies of fast converter-driven dynamics, cascading disturbance mechanisms, and system-wide interactions with greater accuracy and substantially reduced simulation time compared with conventional workflows.

In parallel, prior work has begun exploring the integration of quantum computing resources with real-time power-system simulation environments. In [2], a Quantum-in-the-Loop (QIL) architecture was proposed to connect quantum computing resources with real-time power-system simulation for resilient smart-grid applications. This framework emphasized the use of quantum processors as external computational resources that can receive grid-state information, solve selected optimization or decision problems, and return control or planning signals to a real-time simulation environment. More recently, quantum hardware-in-the-loop concepts were extended in [3], where quantum and quantum-inspired annealing resources were coupled with a real-time digital simulator for power-flow and optimal-power-flow studies. These studies represent important early steps toward evaluating quantum algorithms in realistic grid-simulation environments rather than isolated offline benchmarks.

Nevertheless, real-time simulator based QIL frameworks are not immune to scalability limitations. As the size of the grid model, the number of power-electronics devices, the required time-step resolution, and the number of scenarios increase, the supporting infrastructure can become increasingly complex and expensive. Large racks of dedicated simulator hardware, specialized communication interfaces, strict synchronization requirements, and high-fidelity data exchange pipelines may be needed to reproduce large-scale grid behavior in real time. Moreover, integrating quantum computers into such highly specialized environments introduces additional challenges, including latency management, data encoding, solver orchestration, quantum job scheduling, result interpretation, and compatibility between quantum-computing workflows and simulator execution timelines. These challenges can limit the rate at which quantum acceleration concepts can be researched and evaluated for realistic power-grid applications.

Therefore, there is a clear need for facilities and software frameworks that can provide end-to-end connectivity between quantum computing resources, quantum communication simulator, and next-generation power-grid simulators. In this paper, this gap is addressed by proposing a

Quantum Software-in-the-Loop (QSIL) framework that integrates IonQ quantum computing hardware with the grid simulator RE-INTEGRATE through a secure classical communication layer enabled by quantum key distribution (QKD), modeled using SeQUeNCe. In the proposed architecture, SeQUeNCe, the Simulator of QUantum Network Communication, is used to represent the QKD-based key-generation and distribution process, while measurement data, simulation states, control instructions, and quantum-computing task information are exchanged over classical communication channels encrypted using QKD-derived keys [4], [5]. The resulting QSIL workflow includes grid-model execution, state extraction, secure classical-quantum data exchange, problem formulation, quantum task submission, classical post-processing, and feed-back into the EMT simulator. By combining RE-INTEGRATE, IonQ quantum computing hardware, and SeQUeNCe-based QKD modeling, the proposed proof-of-concept establishes a fully connected and secure simulation ecosystem for evaluating quantum-accelerated power system operation in realistic high-fidelity EMT simulation environments. The main objective is not only to demonstrate end-to-end connectivity, but also to define the facility-level and framework-level requirements needed for future quantum-enabled power-grid studies.

2 Background

This section provides background and context for the framework developed later. It briefly introduces the framework's components, related software packages, and key concepts.

Quantum Computer: For completeness, relevant quantum mechanics background is briefly summarized. A qubit, or quantum bit, is the basic unit of quantum information that can represent 0, 1, or a superposition of both. The two basis states are the zero $|0\rangle$ (or ground state) and the one $|1\rangle$ (or excited state) [6]. Key concepts in quantum mechanics include superposition, entanglement, and physical realization. In superposition, a qubit can exist in a linear combination of the basis states. In entanglement, multiple qubits become correlated such that the state of one cannot be described independently of the others. Regarding physical realization, qubits can be implemented in various quantum systems such as photons, trapped ions, or super conducting circuits.

The principles of quantum mechanics have been applied in areas such as quantum computing, quantum sensing, and quantum networking. A quantum processor unit (QPU) is the core chip in a quantum computer that uses the principles of quantum mechanics to perform calculations. These calculations are carried out by applying a series of fundamental operations, known as quantum logic gates. There are two types of quantum gates: single-qubit and multi-qubit gates. Single-qubit gates manipulate the state of a single qubit, whereas multi-qubit gates act on two or more qubits, enabling entanglement and complex conditional logic. A quantum back-end is the target system that executes quantum circuits and returns the results, either a physical quantum processing unit (QPU) or a quantum simulator running on classical hardware. With current quantum technologies, QPUs are still hosted in specialized laboratories to preserve the coherence of quantum states [7]. With current quantum technologies, QPUs are housed in specialized

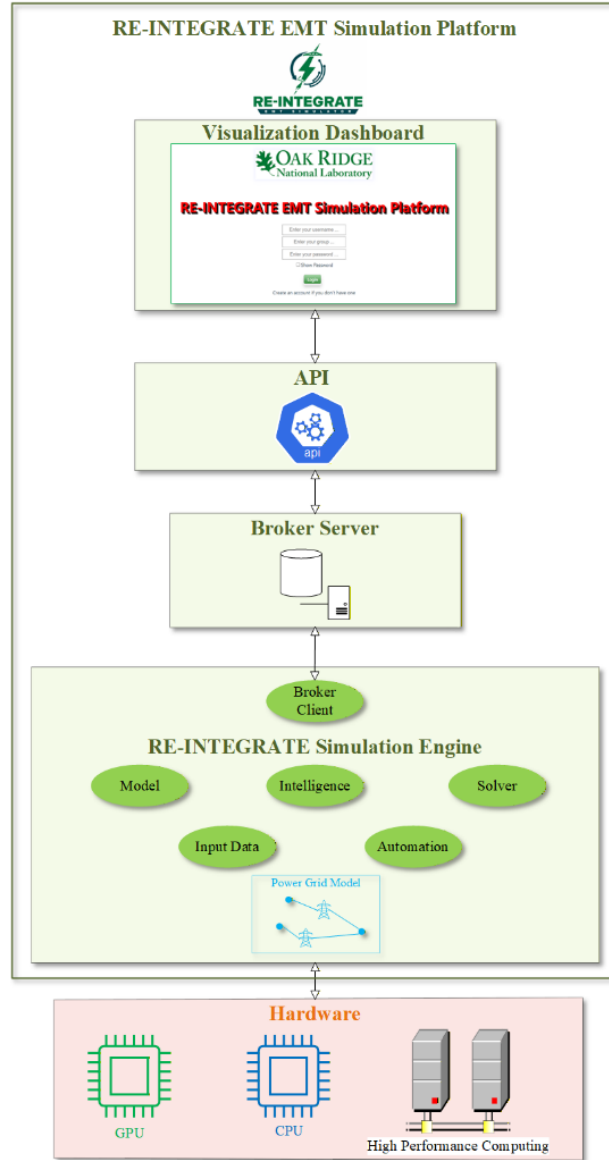


Fig. 1. Illustration of the RE-INTEGRATE EMT Simulator.

laboratories to preserve quantum-state coherence. Consequently, they are typically accessed remotely via cloud interfaces. There are several software development kits (SDKs) for quantum computing, such as IBM's Qiskit, Google's Cirq, and Microsoft's Q#, that enable users to create and run quantum circuits and formulate quantum optimization problems. The Qiskit SDK is a general-purpose, widely used Python toolkit for quantum computing. Distributed as a Python package and supported by QPU vendors such as IonQ, it facilitates the integration of quantum resources.

RE-INTEGRATE EMT Simulation Platform: The RE-INTEGRATE EMT simulator, developed at Oak Ridge National Laboratory, is a next generation EMT modelling and simulation platform [1]. It is designed primarily for classical computers and implemented in C++. The simulator's core engine comprises several modular components: Model, Solver, Intelligence, Input Data Parsing, and Automation. The Model contains detailed component models, including various generators, exciters, governors, power system stabilizers, different types of line models, transformers, and different types of switched inverters. The Solver uses state-of-the-art algorithms

and supports execution on multiple hardware platforms such as central processing units (CPUs) and graphics processing units (GPUs). The Intelligence component detects matrix patterns and performs intelligent reordering. The Input Data Parsing component parses information from multiple files and supports formats such as .raw, .dyl, .dss, and .xml. The input files contain power-system component and network data used in EMT modelling and simulation. The Automation component handles power-grid modelling and automates EMT simulation workflows. The core simulation engine exchanges data with external applications through a Redis-based message broker. A JavaScript-based visualization dashboard provides interactive views of power-grid networks and components, geospatial maps with asset locations, and EMT simulation results, including 3D visualization. The dashboard communicates with an application programming Interface (API) built for the simulator. The API orchestrates core engine workflows, manages connectivity with external applications, and exchanges data with the EMT engine via the message broker. With the core EMT modelling and simulation engine, a range of power-system studies and applications can be conducted, including EMT simulation, fault analysis, and contingency analysis. The simulator has been tested on NVIDIA DGX A100 systems and high-performance computing platforms such as ORNL’s Frontier, demonstrating its ability to be deployed across multiple platforms. Additionally, because the simulator can exchange data with external applications, it can leverage and integrate capabilities from other platforms, such as using quantum computing to solve challenging optimization problems. Fig. 1 illustrates the overview of the RE-INTEGRATE EMT simulation platform.

SeQUeNCe Quantum Network Simulator: As quantum computing continues to advance, interest in quantum networks has grown rapidly in recent years. However, building practical quantum networks remains highly challenging, and current efforts are still largely limited to small-scale testbed demonstrations [8,9]. To support the design, evaluation, and optimization of such systems, several quantum network simulators have been developed [7]. The Simulator of QUantum Network Communication (SeQUeNCe) developed at Argonne National Laboratory (ANL) [4] is a comprehensive, customizable, and scalable discrete-event simulator for quantum networks. SeQUeNCe is open source on GitHub [10] and is in active development. It comprises five modules: hardware models, entanglement management protocols, resource management, network management, and applications. Users can modify these modules to add functionality and prototype and test new protocol schemes. The simulator’s highly reconfigurable architecture simplifies integration while maintaining fidelity. Instead of focusing on gate-by-gate computation inside a single processor, SeQUeNCe emphasizes the end-to-end dynamics of quantum communication protocols, where timing, contention, and probabilistic physical processes are central: photon emission and transmission, channel attenuation, quantum noise (bit flip and phase flip), coupling inefficiencies, detector behavior, and the heralded success or failure of entanglement generation all occur stochastically and must be coordinated with classical messages that arrive with finite latency. In SeQUeNCe, users can construct networks with quantum routers, repeaters, and end nodes equipped with components such as photon sources, beam splitters, Bell-state measurement modules, and quantum memories characterized by finite coherence times and imperfections, then run protocols for entanglement generation, swapping, purification, and routing/scheduling to study achievable entanglement rates, fidelities, and delays. Because it is event-driven, the simulator can efficiently capture asynchronous interactions among many network elements, who attempts entanglement with whom, when memories expire, when classical acknowledgments return, how resource reservation affects throughput, providing a realistic view of performance bottlenecks and trade-offs under different hardware assumptions and control policies. This feature makes SeQUeNCe useful for designing quantum repeater architectures, evaluating protocol stacks that blend quantum operations with classical control, and comparing strategies for scaling quantum networks toward applications like

quantum key distribution, distributed sensing, and eventually distributed quantum computing, all while allowing researchers to sweep parameters and network topologies in a reproducible software testbed.

3 Framework

This section presents a framework for integrating quantum resources, including QPUs and quantum networks, with the RE-INTEGRATE EMT simulator. This is representative of a real-world grid connected to quantum computer through a quantum communication network. IonQ's QPUs are used in this research and the quantum network is modelled using the SeQUeNCe simulator. It is noted that the previous section provides background and context, and it briefly introduces the platforms and tools used in this framework. The task is to design and implement a seamless connectivity architecture to connect SeQUeNCe, RE-INTEGRATE, and IonQ's QPUs through its API.

IonQ's QPUs are cloud-deployed and offer two backend types: a quantum simulator running on classical hardware and real quantum computing systems. These resources provide a platform for solving hard problems that are infeasible for classical computers and are accessed via an API for job submission and result retrieval. IonQ's cloud platform supports the Python-based Qiskit SDK. Jobs are submitted via an API, and the qiskit and qiskit_ionq packages must be installed to use the Qiskit SDK. IonQ offers several hardware QPU types with different qubit counts, such as IonQ Forte with 36 qubits and IonQ Aria with 25 qubits. IonQ's quantum simulators also include multiple options, such as the Ideal Simulator (a noise-free state vector simulator), the Aria 1 Noise Quantum Simulator, and the Harmony Noise Quantum Simulator. Submitting a job requires an IonQ API key; backend settings can be configured at submission time.

The IonQ backends used in this work are shared resources. Jobs enter a queue on submission, and their start and finish times vary with system load and queue length, making execution latency and result timing unpredictable. As the technology matures, more QPUs are expected to become available, improving throughput, reducing turnaround times, and increasing the number of QPUs involved.

A simulated quantum network with two nodes, named Node 1 and Node 2, is established using the SeQUeNCe quantum network simulator. The created quantum network is to connect the RE-INTEGRATE EMT simulator with IonQ's QPUs. Node 1 receives processed data from the RE-INTEGRATE EMT simulator through the Redis message broker and a storage layer, with the data stored in CSV format. The data structures exchanged with the RE-INTEGRATE EMT simulator are flexible and depend on the specific EMT application and study. An example of data format output from the RE-INTEGRATE EMT simulator and sent to Node 1 is $[P, Q, V, f, \theta]$, where P, Q, V, f , and θ represent active power, reactive power, voltage, frequency, and voltage angle at a bus, respectively.

Node 1 sends the data received from the RE-INTEGRATE EMT simulator to Node 2 via the established classical network that is quantum encrypted. There are several QKD protocols available for this communication that is simulated through SeQUeNCe. QKD is a secure, physics-based method for two parties to generate and share a random cryptographic key, using quantum mechanics to ensure confidentiality. In this work, the BB84 protocol, the most fundamental QKD protocol, is used. The quantum network linking Node 1 and Node 2 uses photons to transmit information. If an eavesdropper attempts to measure these photons, the measurement collapses their quantum states and introduces detectable noise that reveals the intrusion. This

feature results from the no-cloning theorem in quantum mechanics. It ensures secure data exchange over quantum networks and enables the detection of intrusion attempts. This feature is important because power systems are critical infrastructure, and their data is typically transmitted over private networks. Consequently, there are numerous cybersecurity research efforts focused on protecting power systems.

At Node 2, the received data is stored in another storage layer, where it is processed and subsequently sent to quantum computing resources via the IonQ API through job processing and submission. It is noted that the messages sent from Node 1 and received at Node 2 may contain errors due to the inherent nature of quantum encryption errors and may require further processing to correct errors.

After the QPU completes the submitted job, the returned results are processed and sent back to the RE-INTEGRATE EMT simulator. Data from the QPU may require additional processing before being forwarded to the RE-INTEGRATE simulation platform. The data structure also depends on the specific application and study. For example, in a unit commitment application, the QPU returns each generator's operational status (on/off) and its scheduled output. All data are sent to the RE-INTEGRATE EMT simulator will go to the Redis message broker.

A Workflow Manager is developed to orchestrate job submission, queuing, processing, and data exchange. It maintains the job queue, monitors job status, processes returned data, and coordinates downstream tasks. These capabilities are encapsulated in a Workflow Manager package that communicates via the Redis broker to receive updates and dispatch work. Fig. 2 illustrates the proposed end-to-end connectivity framework that integrates the RE-INTEGRATE EMT simulator with quantum resources.

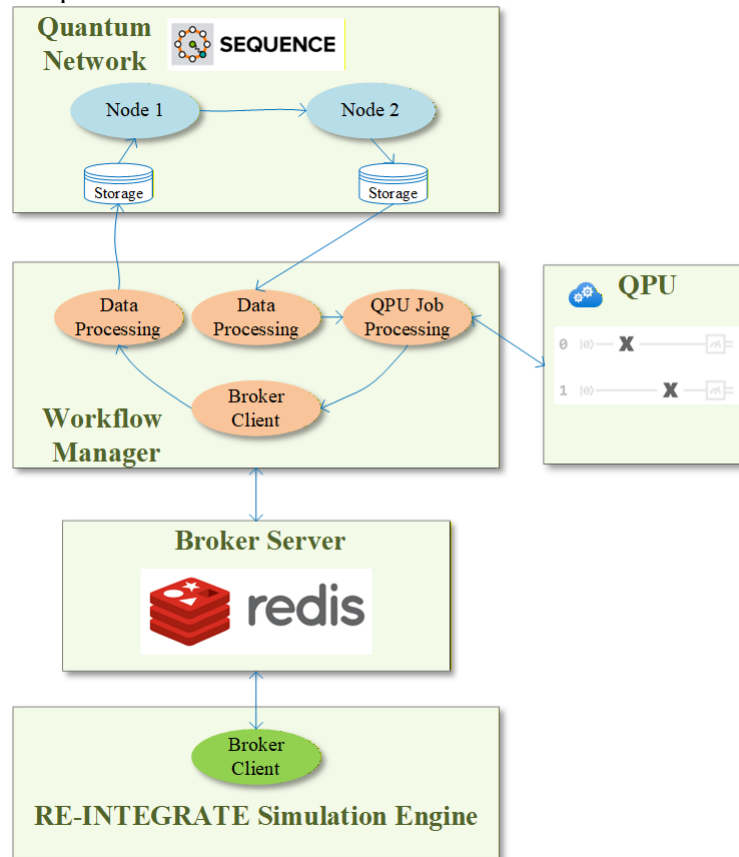


Fig. 2. End-to-end connectivity framework integrating the RE-INTEGRATE EMT simulator with quantum resources.

4 Simulation Results

The previous section introduced a secure data-exchange framework that connects the RE-INTEGRATE EMT platform to quantum resources. The framework establishes a quantum-secured communication channel to quantum processing units (QPUs), enabling RE-INTEGRATE EMT to offload subproblems that are computationally hard or infeasible for classical machines. In this section, we design and specify test cases to validate the framework.

4.1 Case 1

This test case verifies functional correctness by validating the simulated quantum network, job submission from the RE-INTEGRATE EMT simulator to QPUs, result retrieval, and error handling. Information is transmitted from the RE-INTEGRATE EMT simulator to Node 1, which forwards it to Node 2 over the simulated quantum encrypted network. The message format is $[t, P, Q, V, f, \theta]$, where t denotes time; the remaining quantities are as defined previously. At Node 2, a job is submitted to a cloud-based QPU. The probability that a transmitted qubit experiences no polarization error is set to 0.99999, approximating an ideal channel. The Phase A bus voltage of Bus 1 in the IEEE 39-bus benchmark system, generated by the RE-INTEGRATE EMT simulator, is transmitted. Fig. 3 shows the voltages at Node 1 and Node 2, which are in agreement. Fig. 4 shows a job submitted to and completed on an IonQ simulated QPU. This indicates the successful connectivity between power grid simulation, quantum communication simulation, and a quantum computer.

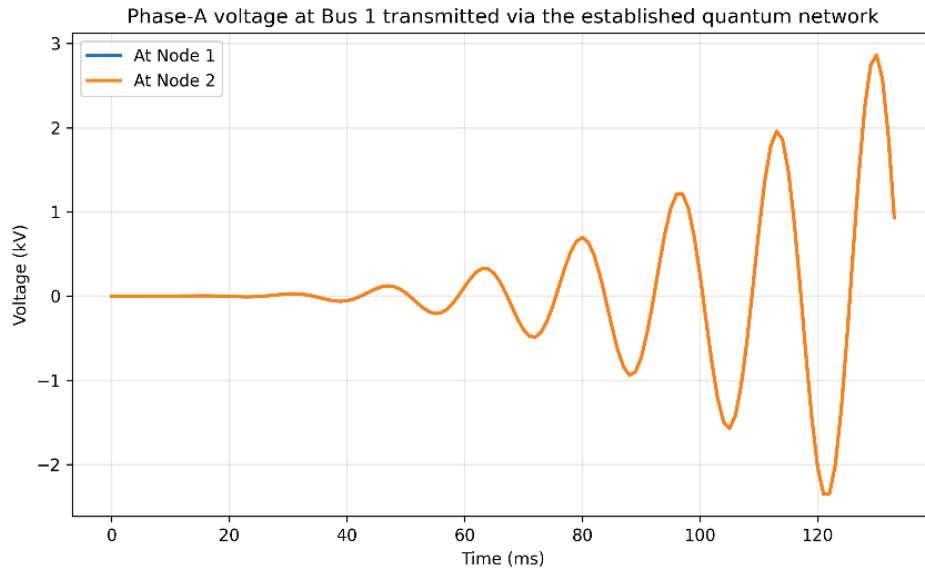


Fig. 3. Voltage transmitted over the simulated quantum network.

Status	✓ completed
Backend	simulator
Type	circuit
Noise Model	ideal
Circuits	1
Cost	\$0.00
Requested	2026-02-15 18:51:02 EST
Completed	2026-02-15 18:51:03 EST
Predicted	00:00:00.008

Fig. 4. Information for a job submitted to and completed on the IonQ QPU.

4.2 Case 2

In this test case, the probability that a transmitted qubit experiences no polarization error, which is referred to as the polarization fidelity, is varied. The tested values are 0.97, 0.975, 0.98, 0.985, 0.990, 0.995, 0.9875, and 0.99999. Values sent from Node 1 and received at Node 2 are compared to compute the error rate. Using the same message format as in Case 1, a total of 131 messages is transmitted. Fig. 5 shows the calculated error rates: as the polarization fidelity increases, the error rate decreases; however, a nonzero error remains even when the polarization fidelity is equal to 0.99999 (nearly ideal). Therefore, error-handling strategies are recommended for QKD encryption whenever the polarization fidelity is less than 1.

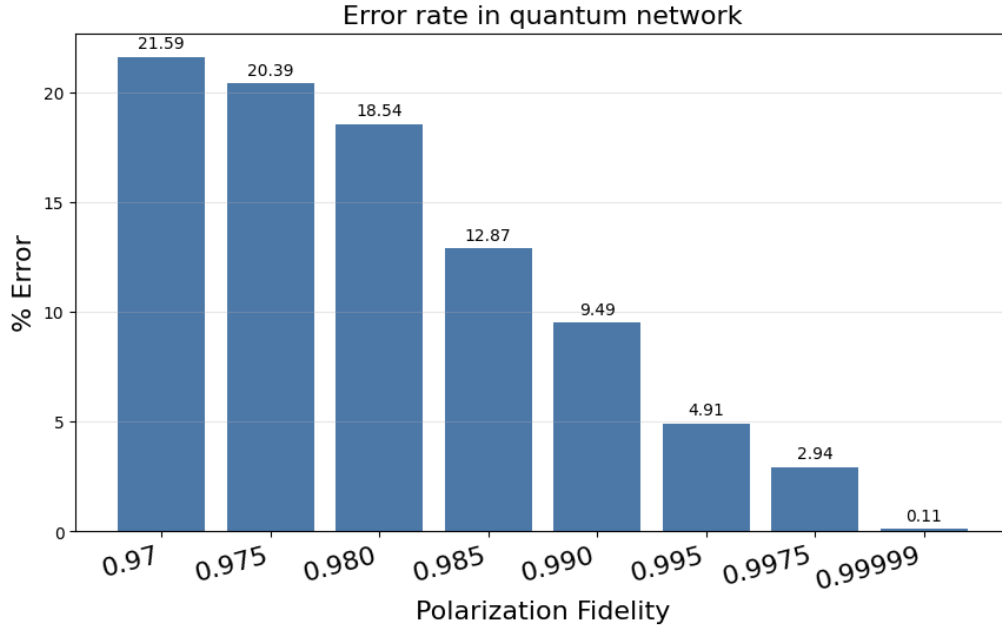


Fig. 5. Error rate with different polarization fidelity.

5 Conclusion

This paper presents an end-to-end connectivity framework that links the RE-INTEGRATE EMT simulation platform, which is a next-generation EMT simulator, to quantum resources. The framework includes a simulated classical network that is encrypted using QKD built with the SeQUeNCe simulator and integrates an IonQ QPU. Through this setup, research on the impact of quantum computing and encryption methods on the power grid can be performed. Simulation results are presented to validate the framework. Future work will extend the framework to additional applications, such as unit commitment.

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BIBLIOGRAPHY

- [1] P. R. V. Marthi, S. Gangopadhyay, K.-C. Hsu, J. Choi, N. Ray Chaudhuri, and S. Debnath, "RE-INTEGRATE EMT simulation software: Dae solvers and automation," in 2025 IEEE Power Energy Society General Meeting (PESGM), 2025, pp. 1–5.
- [2] S. Chanda, M. Mohanpurkar and R. Hovsapiian, "Architecture for Quantum-in-the Loop Real-Time Simulations for Designing Resilient Smart Grids," 2023 13th International Symposium on Advanced Topics in Electrical Engineering (ATEE), Bucharest, Romania, 2023, pp. 1-6, doi: 10.1109/ATEE58038.2023.10108354.

- [3] Z. Kaseb *et al.*, "Quantum Hardware-in-The-Loop for Optimal Power Flow in Renewable-Integrated Power Systems," in *IEEE Transactions on Power Systems*, doi: 10.1109/TPWRS.2026.3696764.
- [4] X. Wu, A. Kolar, J. Chung, D. Jin, T. Zhong, R. Kettimuthu and M. Suchara. "SeQUeNCe: A Customizable Discrete-Event Simulator of Quantum Networks", *Quantum Science and Technology*, 2021.
- [5] X. Wu *et al.*, "Simulations of Photonic Quantum Networks for Performance Analysis and Experiment Design," *2019 IEEE/ACM Workshop on Photonics-Optics Technology Oriented Networking, Information and Computing Systems (PHOTONICS)*, Denver, CO, USA, 2019.
- [6] A. S. Cacciapuoti, M. Caleffi, F. Tafuri, F. S. Cataliotti, S. Gherardini, and G. Bianchi, "Quantum internet: Networking challenges in distributed quantum computing," *IEEE Network*, vol. 34, no. 1, pp. 137–143, 2020.
- [7] O. Bel and M. Kiran, "Simulators for quantum network modelling: A comprehensive review," *Computer Networks*, vol. 263, p. 111204, 2025.
- [8] J. Chung *et al.*, "InterQnet: A Heterogeneous Full-Stack Approach to Co-Designing Scalable Quantum Networks," in *IEEE Transactions on Quantum Engineering*, vol. 7, pp. 1-21, 2026, Art no. 4101021.
- [9] M Alshowkan, B.P. Williams, P.G. Evans, *et al.*, "Reconfigurable Quantum Local Area Network Over Deployed Fiber", *PRXQuantum*, vol.2, p. 040304, 2021.
- [10] SeQUeNCe, <https://github.com/sequence-toolbox/SeQUeNCe>