Challenge 2 - Optimising Power Distribution Network
TCS Quantum Computing Challenge 2023

Idea Summary

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1 Introduction

The distribution of energy from production units to customers requires a complex grid of distribution networks. These networks consist of pipelines and small sub-stations to deliver, monitor, and moderate power outputs to safe levels to the customers. However, these power grids are often inefficient, leading to inefficient routing of energy and loss of energy during transmission. This increases the overall cost of maintaining the power grid and increases carbon footprint. Through careful planning, advanced technologies, and data-driven strategies, optimization can address challenges such as voltage fluctuations, line losses, and peak demand management. An optimized power distribution network will ensure a seamless and economical flow of energy from production units to end-users while mitigating energy losses and reducing environmental impact. Power grid optimization (PGO) includes minimizing the operational cost of production of energy and finding an optimal route for transmission while ensuring the energy demands of customers are met. An optimized solution needs to take care of various factors including energy demands of customers, power loss of several transmission lines and capacities of several nodes. The number of decision variables grows exponentially with the size of distribution network making it difficult for the classical computers to find an optimal solution. The limitations of current approaches in classical computers motivate us to search for a possible solution with quantum computers. Some known quantum algorithms have leveraged unique properties of quantum mechanics to get measurable advantage over classical computers in several combinatorial optimization problems. Hence finding novel techniques in quantum optimization algorithms will allow us to address the intricacies of optimizing power distribution networks and revolutionize power distribution network management.

2 Problem Statement

The challenge aims to test the potential of quantum computing to address the real-world problem of finding the optimal network topology. A transmission network is provided in the data set - (IEEE 14-bus system with 14 buses, 20 distribution lines, and 5 generators) that must be reconfigured under two possible scenarios.

Scenario 1: For the given network, finding the optimal topology and configuration to reduce the generation cost while ensuring all components of the network operate within the specified limits.

Scenario 2: After network changes (such as the addition of load or reduction in generation at a particular node, breaking of a certain transmission line, a faulty bus, and so on), finding the corrective topology with the least generation cost that ensures efficient power transmission to all parts of the network and that all the components operate within the specified limits.

The scope of the problem is to leverage quantum computing to create an efficient optimisation algorithm that, given any power network, searches through the combination of possible operations such as line switching, bus splitting, and generation re-dispatching to handle the above-mentioned scenarios.

3 Solution Approach

The cost function for power grid optimization (PGO) problem can be formulated as a Mixed Integer Linear Programming (MILP), which comprises of integer, binary and continuous decision variables. The Mixed Integer Linear

Programming (MILP) problem cannot be directly solved on a quantum computer due to the non-binary variables in the problem. The continuous variables in the problem must be converted into a binary variable and the problem along with the constraints have to be formulated as a quadratic unconstrained binary optimization (QUBO).

The novel approach to solve PGO is to discretize the continuous variables and associate binary variables to discretized bins. The cost function and constraints are then reformulated into a QUBO problem, which is then solved using QAOA. This approach uses lesser number of qubits and optimizes the cost function iteratively by reducing the bin size till a desired accuracy is reached. QAOA can avoid problems such as barren plateau problem which is commonly encountered in various optimization algorithms dealing with a large number of decision variables.

The PGO consists of two parts as mentioned above [1] finding the optimal power to be generated based on the demand and [2] optimal path in sending power from generators to the destination. The first and second part can be regarded as an independent problem and efficiently solved using a quantum computer. The first part of the problem contains a cost function which needs to be minimized subject to the constraints given by the power generation limits and for scenario 2, different power transfer scenarios for minimizing the cost of corrective actions like generator redispatch and line switching. The second part of the problem can be regarded as Multi-Vehicle Routing Problem (MVR) in which the sources are the power plants, and the customers are the destination and the optimal path to be found are the transmission lines in which the power has to be transferred.

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4 Results

The problem is solved in two parts 1) determining the optimal power to be generated followed by 2) the optimal path the power is to be transferred from source to destination. Our analysis shows that for a small number of generators, scenario 1 can be solved using both classical as well as Quantum techniques. Also, it has been observed that for a small number of decision variables, classical solver runs the task faster than QPUs. As we increase the number of decision variables, the classical solver is unable to get the optimal solution, but using actual QPUs, we can go beyond 20 decision variables (we could not solve further due to restrictions in the number of qubits available). For scenario 2, we require a minimum of 20 decision variables, hence it cannot be solved efficiently using a classical technique. We solved the same using QPU and the solution satisfies all the constraints in the problem. The entire problem is solved using Quantum hardware IONQ ARIA which contains 24 qubits. The summary of the results is documented in a tabular format below.

	CLASSICAL	**QUANTUM**
Number of bits	Scenario 1 can be solved as it requires less number of bits	Scenario 1 can be solved using quantum algorithm
Speed	For a small number of decision variables, classical solution is faster (**Scenario 1 took 1.51 seconds on local computer**)	For a small number of decision variables the quantum algorithm takes more time than classical algorithm (**Scenario 1 took 17 minutes on a qpu**)
Hardware Requirement	**As we increase the number of decision variables to 15 (more than 15) classical solver is unable to obtain a solution**	**Quantum algorithm can solve more than 15 decision variables** (We went upto 24 variables,solved on IONQ Aria 1)
Quantum Advantage	Hence scenario 2 cannot be solved using BQM formalism	BQM can be solved for higher number of decision variables. Hence we obtained solution for scenario 2 using quantum algorithm.
Scalability	Classically more number of bits with high computing power is required to solve higher bus systems	**Its a matter of qpus in quantum algorithm, scalability is possible, IEEE 8, 30, 118 can also be implemented in our model by slightly modifying our problem statement, (approximately $3N^2$ qubits are required for arbitrary N bus system)**

5 Conclusion

With the current approach, QAOA algorithm executed on QPU gives better optimal results compared to the classical counterpart. Also, the solution approach is generic enough to include variants of the problems in terms of number of generators, buses and lines. With better fault tolerant QPUs in the future, the current model can be more generalized by including more real-world scenarios with slight modifications (considering reactive constraints, power losses in the lines, bus split constraints).

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Links

Solution approach document pdf TCSChallenge2Solutionapproachdocument.pdf
Defense Presentation deck TCSchallenge2defencePPT.pdf
Code Base for scenario 1 scenario_1.ipynb
Code Base for scenario 2 scenario_2.ipynb