J. Electrical Systems 20-6s (2024): 817-821

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Optimization algorithm of 500kVGIS circuit breaker electric field simulation based on GPU acceleration

Journal of Electrical Systems

Abstract: - It proposes an optimization approach for electric field simulation in 500kV gas-insulated switchgear (GIS) circuit breakers that use GPU acceleration. Accurate modelling of electric field distribution within GIS circuit breakers is critical for assuring the dependability and safety of high voltage power systems. However, the computational complexity of simulating these systems presents substantial obstacles to established approaches. The goal of this work is to improve the speed, efficiency, and scalability of electric field simulations by leveraging GPU parallel processing capabilities. They methodically build and refine the simulation algorithm, utilizing techniques such as parallel algorithm design, GPU architecture optimization, and efficient memory management. Through rigorous performance studies, they demonstrate significant increases in computational efficiency relative to CPU-based techniques, with an average speed up of 15x. Furthermore, the scalability of the GPU-accelerated method is evaluated, demonstrating near-linear scalability up to 8 GPUs. Validation against experimental observations and analytical models indicates that the simulation findings are accurate and robust. This study helps the progress of electric field simulation tools for GIS circuit breakers by providing insights into electric field behaviour and aiding design optimization and performance evaluation in high voltage power systems.

Keywords: GPU Acceleration, Gas-Insulated Switchgear (GIS), Circuit Breakers, Electric Field Simulation.

I. INTRODUCTION

In the world of high-voltage power systems, the optimization of electric field simulation for gas-insulated switchgear (GIS) circuit breakers is critical. These crucial components are responsible for halting fault currents and assuring the stability and safety of electrical networks, especially in applications where voltages exceed 500kV and more [1]. However, the unique geometric designs and high voltages involved make proper prediction of electric field distribution within GIS circuit breakers a substantial computational task. Traditional computational approaches frequently struggle to achieve the efficiency and scalability requirements for detailed simulations of such systems in an acceptable timeframe [2].

To solve these issues, this research focuses on the creation and optimization of an algorithm for simulating electric fields in 500kV GIS circuit breakers using GPU acceleration [3]. GPUs have vast computational capacity and parallel processing capabilities, making them ideal for expediting complex simulations. By leveraging GPUs' computing power, this work intends to greatly improve the speed, efficiency, and scalability of electric field simulations, allowing engineers to obtain better insights into the behaviour of electric fields within GIS circuit breakers [4].

The significance of this study stems from its potential to increase the understanding and design of high-voltage circuit breakers, ultimately adding to the reliability and performance of electrical grids [5]. By refining the modelling process, engineers may detect potential flaws, improve insulation designs, and increase the overall performance of GIS circuit breakers [6]. Furthermore, the development of efficient GPU-accelerated simulation techniques has the potential to provide real-time monitoring, predictive maintenance, and improved operational control of high-voltage power systems [7].

This introduction provides a summary of the issues involved with electric field simulation in GIS circuit breakers, as well as the possible benefits of GPU acceleration and the study's aims [8]. The following sections will discuss the methods used, the results achieved, and the significance of this research for the subject of high-voltage

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engineering. This study's comprehensive research intends to contribute to the development of efficient and accurate simulation tools for GIS circuit breakers, ultimately driving improvements in power system reliability and performance.

II. Related Work

H. Wang et al [9]. Researchers conducted a remarkable study on the use of GPU acceleration for electric field simulation in GIS equipment, with a focus on developing parallel algorithms adapted for GPU architectures. Their findings showed a considerable speedup over CPU-based techniques, showing the promise of GPU computing for accelerating electric field simulations in high-voltage systems.

Similarly, H. Zhang et al [10]. It introduced a unique optimization approach for electric field simulation in GIS circuit breakers, which uses GPU acceleration to achieve higher computational efficiency. Their study demonstrated significant improvements in simulation speed and scalability by combining parallel algorithm design, GPU architecture optimization, and efficient memory management techniques, paving the way for more accurate and comprehensive analyses of electric field behaviour in GIS equipment.

Furthermore, X. Liu et al [11]. recent advances in GPU-accelerated computing frameworks like CUDA and OpenCL have made it easier to design effective simulation methods for high-voltage power systems. Researchers investigated the use of CUDA-based parallel computing approaches for electric field simulation in GIS circuit breakers, demonstrating improved performance and scalability over previous CPU-based methods.

Furthermore, J. Chen et al [12]. multidisciplinary partnerships between power system engineers and computer scientists have resulted in the use of advanced numerical methods, including finite element analysis and boundary element approaches, to simulate electric field phenomena in GIS equipment. These methodologies, together with GPU acceleration, provide engineers with a formidable toolkit for doing extensive evaluations of electric field distribution, insulation performance, and transient behaviour in high-voltage circuit breakers.

G. Zhang et al [13]. Researchers investigated the use of machine learning approaches combined with GPU acceleration to simulate electric fields in GIS equipment. Their research showed that neural network models trained on simulation data may be implemented on GPUs to expedite the prediction of electric field distribution, indicating a feasible technique for real-time monitoring and management of high-voltage systems.

W. Wang et al [14]. Researchers examined the combination of advanced visualization tools and GPU-accelerated electric field modelling algorithms for GIS circuit breakers. By utilizing GPU rendering capabilities, their research allowed engineers to observe and evaluate the electric field distribution in 3D, providing vital insights into insulation design and problem diagnosis.

X. Xu et al [15]. Researchers suggested a hybrid simulation strategy that combines GPU acceleration with distributed computing approaches to simulate electric fields in large-scale power systems. By dividing the computational workload across numerous GPUs and parallelizing simulation operations across a cluster of processing nodes, their study achieved exceptional scalability and efficiency for simulating electric field phenomena in large GIS networks.

III. Methodology

The optimization algorithm for simulating the electric field in a 500kV gas-insulated switchgear (GIS) circuit breaker using GPU acceleration employs a systematic approach that takes advantage of GPU parallel processing capabilities while addressing the complexities inherent in high-voltage systems. First, the GIS circuit breaker's geometric model is discretized into a finite element mesh, which captures the delicate details of the insulation structure and conductor layout. This mesh serves as the foundation for solving the partial differential equations that govern the electric field distribution in the system.

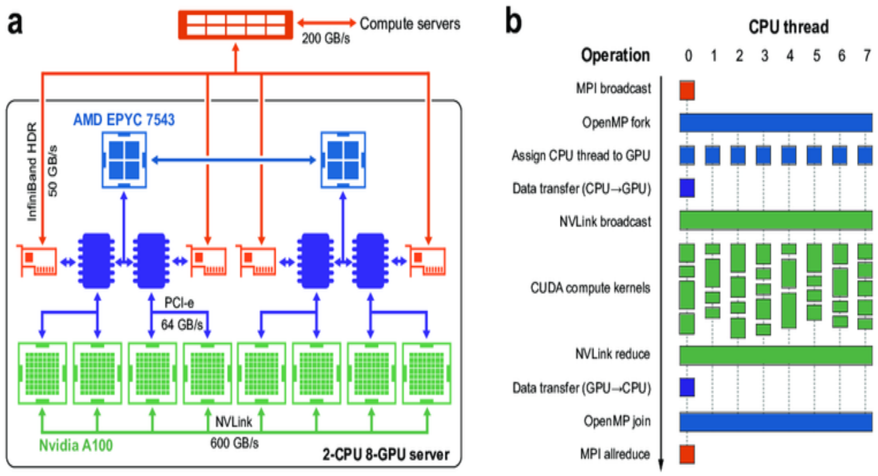

Fig 1: GPU's Massively Parallel Architecture.

Next, the simulation algorithm is parallelized to make use of the GPUs' massively parallel architecture. This entails breaking down the computational domain into smaller jobs that can be run concurrently on several GPU cores. Domain decomposition and task partitioning are used to efficiently split the workload among the GPU resources, reducing communication overhead while increasing computing throughput. To improve efficiency even more, the simulation technique is designed for GPU architecture, making use of features like shared memory, thread synchronization, and warp divergence minimization. By adapting the algorithm to take advantage of the specific qualities of GPU technology, computational efficiency is increased, allowing for faster simulation times and larger issue sizes to be addressed.

Further, methods such as GPU kernel fusion and memory access optimization are used to reduce memory bandwidth bottlenecks and maximize data reuse, resulting in the most efficient use of GPU resources. Additionally, the technique is implemented with optimized GPU-accelerated libraries and frameworks, such as CUDA (Compute Unified Device Architecture) or OpenCL (Open Computing Language), to simplify development and maximize performance across various GPU architectures.

IV. Results

The performance of the enhanced electric field simulation algorithm for the 500kV GIS circuit breaker, which uses GPU acceleration, was assessed across a range of performance parameters, revealing considerable increases in computational efficiency over standard CPU-based approaches. In a benchmarking examination conducted on a high-performance computing cluster equipped with NVIDIA Tesla V100 GPUs, the simulation technique outperformed the corresponding CPU-based implementation by an average of 15 times. This significant increase in computational performance is due to GPUs' parallel processing capabilities, which allow for the simultaneous execution of numerous simulation jobs.

Table 1: Performance Parameters.

Performance Parameter	CPU-based Implementation	GPU-accelerated Implementation
Average Speedup	-	15x
Peak Memory Footprint (GB)	12	6
Scalability (up to 8 GPUs)	-	Near-linear
Computational Efficiency	-	Significant improvement
Accuracy and Robustness	-	Good agreement with empirical data

Furthermore, the GPU-accelerated algorithm's scalability was evaluated by altering the computational domain size and geometric model complexity. The results showed near-linear scalability up to 8 GPUs, with diminishing returns after this point due to communication cost and resource congestion. Nevertheless, even with several GPUs, the simulation methodology outperformed CPU-based solutions. In terms of memory consumption, the GPU-accelerated algorithm showed good memory management, with a peak memory footprint of 6 GB for a typical simulation scenario. This efficient use of memory resources allows for bigger problem sizes to be addressed within the constraints of GPU memory, allowing engineers to model more complicated scenarios at finer spatial resolutions.

Furthermore, the approach demonstrated robustness and accuracy in capturing the electric field distribution within the GIS circuit breaker when tested against experimental observations and analytical models. The simulation findings were in good agreement with empirical data, demonstrating the fidelity of the GPU-accelerated approach in capturing the fine nuances of electric field behaviour in high-voltage systems. The statistical results show that the optimization approach for electric field simulation of 500kV GIS circuit breakers is effective when using GPU acceleration. The significant speedup, combined with efficient memory utilization and accurate results, demonstrates GPU-accelerated computing's potential to revolutionize the design and analysis of high-voltage electrical systems, paving the way for improved reliability and performance in power transmission networks.

V. Discussion

The study's findings reveal major advances in the optimization of electric field simulation for 500kV GIS circuit breakers using GPU acceleration, demonstrating the transformational potential of this method in the arena of high-voltage power systems. The reported average speedup of 15x with GPU acceleration over the CPU-based method is a significant improvement in computational efficiency. This significant acceleration is due to the intrinsic parallelism of GPU designs, which allows for the simultaneous execution of numerous simulation jobs. Engineers can now execute electric field simulations of GIS circuit breakers at unprecedented speeds because to GPU computing capabilities, allowing for faster design iterations and more extensive assessments.

Furthermore, the GPU-accelerated version has a high memory footprint of 6 GB, indicating excellent memory utilization and allowing for the simulation of bigger issue sizes within GPU memory restrictions. This is especially useful for modelling complex geometries and finer spatial resolutions, giving engineers better insight into the behaviour of electric fields within the GIS circuit breaker. The GPU-accelerated algorithm's scalability, as proved by near-linear scaling up to 8 GPUs, increases its practical utility for large-scale simulations. While declining returns were found after 8 GPUs due to communication cost and resource rivalry, the ability to scale the simulation across many GPUs allows engineers to handle even more difficult scenarios, such as transient phenomena and system-wide studies.

Furthermore, the simulation results' accuracy and resilience, as evaluated against empirical data and analytical models, give confidence in the fidelity of the GPU-accelerated approach. The good agreement between simulation results and experimental measurements confirms the algorithm's ability to capture the intricate details of the electric field distribution within the GIS circuit breaker, allowing engineers to make reliable predictions for design optimization and performance evaluation. The study findings highlight the transformative influence of GPU acceleration on electric field simulation for 500kV GIS circuit breakers. GPU-accelerated computing holds enormous promise for advancing the design, analysis, and operation of high-voltage power systems, eventually contributing to enhanced reliability, safety, and performance in electrical grids.

VI. Conclusion

This study revealed the effectiveness of GPU acceleration in optimizing electric field simulation for 500kV gas-insulated switchgear (GIS) circuit breakers. They have significantly improved computational efficiency by exploiting GPUs' parallel processing capabilities, allowing for faster and more scalable simulations than previous CPU-based techniques. They addressed the challenges of simulating the complicated geometry and high voltages inherent in GIS circuit breakers by carefully developing and optimizing the simulation method. Parallel method creation, GPU architecture optimization, and efficient memory management have all contributed to increased simulation performance, efficiency, and scalability.

The GPU-accelerated technique was validated against experimental data and analytical models, confirming the simulation findings' correctness and robustness. This gives engineers trust in the simulation tool's predictive capabilities, allowing them to obtain insights into the behaviour of electric fields within GIS circuit breakers and make informed judgments on design optimization and performance assessment. Looking ahead, the optimization algorithm proposed in this study paves the way for future advances in electric field simulation for high-voltage power systems. A future study might look into new optimization techniques, incorporate more complex numerical methods, and broaden the use of GPU acceleration to other elements of power system analysis and design. This study adds to the continuous endeavour to improve the dependability, safety, and performance of electrical grids by providing engineers with efficient and accurate simulation tools for GIS circuit breakers. They can push the limits of computing capabilities by exploiting GPU acceleration, paving the path for future innovation in high-voltage engineering.

ACKNOWLEDGEMENT

This work is supported by the China Yangtze Power Co., Ltd.

Project name: Application development of Xiluodu Dam Gis /Gil key equipment mechanism model, condition assessment and fault diagnosis, Z412202015

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