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ТЕЛЕКОМУНИКАЦИИ
АВТОМАТИКА И
ИНФОРМАТИКА
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ELECTRONIC
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OF THE REPUBLIC
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Improving the Efficiency of Grounding System Analysis Using GPU Parallelization

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***Abstract*— Safety analyses of the effectiveness of large grounding systems are often hampered by the lengthy computation times. Using even the simplest image models, the evaluation of touch and step voltages can require from several minutes to several hours of computations on modern CPUs. Our analysis shows that substantial reduction of computation times can be achieved by utilizing GPU parallelization. In this paper we provide basic steps in the implementation of GPU parallelization on the simplest equipotential model for grounding analysis in homogeneous earth, and we test the effectiveness of this approach in different scenarios.**

Keywords—ArrayFire; grounding; parallelization; GPU; step voltages; touch voltages; ground potential rise

I. INTRODUCTION

Grounding systems are an important part of industrial and power plants [1]. They should provide proper equipment operation and personnel protection in normal and fault conditions, including lightning. The effectiveness of grounding systems is often evaluated by computer models [2]-[4], during the design of the plant. The image theory-based models are commonly used in practical engineering analysis of grounding grids due to the simplicity of their implementation and the fact that they can provide accurate results for frequencies of up to a few kilohertz [5]-[6]. For analysis of transients in grounding systems and connected equipment, accurate full-wave models are required [7].

Safety analyses of the effectiveness of large grounding grids are often hampered by the lengthy computation times. While image theory based-models are much simpler and computationally more efficient than full-wave models [8], their calculations can take up to several hours when analyzing touch and step voltages on modern CPUs. For analysis in multilayer soil or in case of transient analysis using the full-wave models, the computation times will be increased severalfold.

Computational efficiency can substantially be improved by utilizing parallelization of the models using a GPU. This is a complex procedure since it requires proper optimization and organization of the code, and understanding some limitations imposed by the hardware, related to memory optimization, bottlenecks in the data transfer to and from the GPU etc.

In this paper we provide some basic steps in utilizing GPU parallelization of the equipotential image theory-based model, for analysis of grounding systems in homogeneous earth [8]. This approach can be considered as a simplest example for GPU parallelization of computer model for grounding analysis and also as a first step towards GPU parallelization of the full-wave electromagnetic model [7].

We analyze the effectiveness of this approach by comparing the computation times on CPU and GPU, as a function of the number of mathematical operations required for the analysis.

II. DESCRIPTION OF THE MATHEMATICAL MODEL FOR GROUNDING ANALYSIS

Here we follow the mathematical model described in [8]. We consider a grounding grid made from perfectly conducting wires with radius a, energized by fault current I_f. The grounding grid is divided into n segments, and each segment dissipates leakage current I_k to ground, where k=1..n. Leakage currents are sources of electric scalar potential in their surrounding, so the potential of the k-th segment can be calculated by superposition as:

$$\varphi_k = r_{k,1} I_1 + r_{k,2} I_2 + \cdots r_{k,n} I_n \tag{1}$$

where $r_{k,k}$ and $r_{i,k}$ are self and mutual resistances of segments, respectively. Each $r_{i,k}$ depends on the spatial position and orientation of the k-th and i-th segment, and the electrical characteristics of their environment. Their evaluation for homogeneous earth is described in section III. Following the assumption of equipotential grounding system, we can write the following expression:

$$\varphi_1 = \varphi_1 = \cdots = \varphi_n = U_f \tag{2}$$

where U_f is the potential of the grounding grid with respect to remote neutral earth, when fault current I_f is dissipated.

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Considering the entire grounding grid, the relations between the electric potential U_f and the leakage current from each segment can be written in matrix form:

$$[1]_n \cdot U_f = [r] \times [I] \tag{3}$$

and from Eq. (3), follows:

$$[r]^{-1} \times [1]_n \cdot U_f = [I] \tag{4}$$

where $[1]_n$ is n-element column matrix of ones, $[r]$ is n x n-element square matrix with self and mutual resistances between segments, and $[I]$ is an n-element column matrix with leakage currents from each segment.

The fault current I_f dissipated through grounding system equals the sum of leakage currents from all segments:

$$I_f = [1]_n^T \times [I] \tag{5}$$

and therefore Eq. (4) can be written as:

$$[1]_n^T \times [r]^{-1} \times [1]_n \cdot U_f = [1]_n^T \times [I] = I_f \tag{6}$$

Then the grounding resistance R_g of the grid can be evaluated as:

$$R_g = \frac{U_f}{I_f} = \frac{1}{[1]_n^T \times [r]^{-1} \times [1]_n} \tag{7}$$

while the grid potential U_f and the leakage currents from each segment $[I]$, for a given fault current I_f are calculated as:

$$U_f = R_g I_f = \frac{I_f}{[1]_n^T \times [r]^{-1} \times [1]_n} \tag{8}$$

$$[I] = [r]^{-1} \times [1]_n \cdot U_f = \frac{[r]^{-1} \times [1]_n}{[1]_n^T \times [r]^{-1} \times [1]_n} I_f \tag{9}$$

Once the leakage currents from each segment are evaluated, the potential at any point M can be evaluated as:

$$\varphi_M = r_{M,1} I_1 + r_{M,2} I_2 + \cdots r_{M,n} I_n = [r_M] \times [I] \tag{10}$$

where $r_{M,k}$ can be thought of as mutual resistances between the k-th segment and the point M, described in section III.

III. EVALUATION OF SELF AND MUTUAL RESISTANCES

Following the assumption that leakage current density is uniform over the entire length L_k of the k-th segment, the potential φ_M at any point M in a homogeneous environment with specific resistivity ρ can be calculated as [9]:

$$\varphi_M = \frac{I_k}{L_k} \frac{\rho}{4\pi} \ln \frac{r_1 + r_2 + L_k}{r_1 + r_2 - L_k} \tag{11}$$

The parameters r_1 and r_2 are the distances between segment endpoints and the point M, as illustrated in Fig. 1.

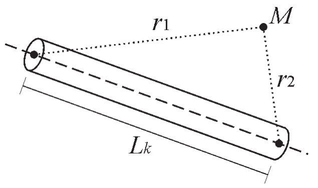

Fig. 1. Geometry parameters for calculating potential at point M

The simplest method of calculating mutual resistance $r_{i,k}$ between two segments in homogeneous medium is to calculate the potential $\varphi_{i,k}$ at the i-th segment's midpoint, due to leakage current I_k from k-th segment. The mutual resistance depends solely on the specific conductivity of the medium and the position between two segments:

$$r_{i,k} = \frac{\varphi_{i,k}}{I_k} = \frac{\rho}{4\pi L_k} \ln \frac{r_1 + r_2 + L_k}{r_1 + r_2 - L_k} \tag{12}$$

If both segments are in conductive half-space, which is a typical assumption for grounding analysis, then the influence of the air-earth interface can be considered by the contribution of reflected image of the source segment, from the interface between upper and lower half-space, (see Fig. 2):

$$r_{i,k} = \frac{\rho}{4\pi L_k} \left(\ln \frac{r_1 + r_2 + L_k}{r_1 + r_2 - L_k} + \ln \frac{r_{1i} + r_{2i} + L_k}{r_{1i} + r_{2i} - L_k} \right) \tag{13}$$

When the self-resistance $r_{k,k}$ is evaluated, the potential $\varphi_{k,k}$ is calculated at the surface the k-th segment, and near its midpoint.

IV. IMPLEMENTATION OF THE GPU PARALLELIZATION

A. Considerations

Over the last two decades GPUs have become widely available in consumer as well as developer computers. Despite this, GPU software development adoption has had a slow rise, which is mainly attributable to the difficulty in programming GPUs.

Currently, there are a number of programming platforms and languages for parallel programming, which cover a range of different approaches. Choosing the right approach for a certain application depends on the nature and complexity of the problem and requires analysis of the pros and cons of each approach.

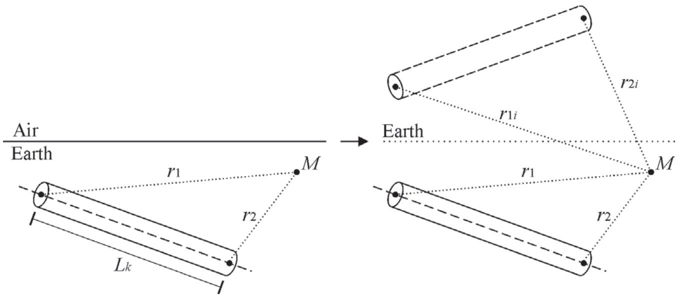

Fig. 2. Equivalence for modeling the influence of the air-earth interface in calculating potentials at point M within earth

At one end, there are platforms that require fairly detailed knowledge of the hardware architecture and which usually use a C-based programming code, that sets out the programming details in explicit parallel fashion. A market leader is CUDA (Computer Unified Device Architecture), a massively parallel computer platform and programming language. OpenCL is another widely adopted open-source framework, which provides wider support for different devices, but has slightly worse performance when compared to CUDA. At the other end, there are platforms which allow the user to make use of their own original non-parallel code, but to include instructions, typically pragmas, in the code which enable it to be compiled in parallel form using an appropriate compiler. Examples are OpenMP and OpenACC. The aim of these platforms is saving the user from spending a large amount of effort in understanding hardware details and corresponding programming code. In between are platforms like ArrayFire and Thrust which are C-based libraries of flexible constructs and subroutines which carry out commonly occurring parallel calculations. These platforms are not mutually exclusive and can be used as part of a CUDA application.

B. ArrayFire Library

For this application, the ArrayFire library approach was chosen, because it offers a back-end that manages memory optimization, cross-platform support for a wide range of devices and does not require writing separate kernels. ArrayFire is a GPU matrix library used for rapid development of general purpose GPU (GPGPU) computing appplications within C, C++, Fortran, and Python. ArrayFire contains a simple API and provides full GPU computation capability on CUDA and OpenCL capable devices. It revolves around a single matrix object (array) which can contain floating point values (single- or double-precision), real or complex values, and boolean data. ArrayFire arrays are multidimensional and can be manipulated with arithmetic and functions. Additionally, ArrayFire provides a parallel FOR-loop implementation, “gfor”, which arbitrarily executes many instances of independent routines in a data parallel fashion.

The original code implementing the equipotential model for grounding system analysis described in the previous section was refactored using the ArrayFire library and its matrix-oriented approach. This was done with the goal of accelerating the calculations, which, for large systems, could take up to several hours to complete. It is important to note that the memory allocation and optimization, as well as the optimization of the parallel execution of the operations is handled entirely by the ArrayFire library’s backend.

C. Code Structure

The algorithm that implements the equipotential model for grounding system analysis is straightforward and is shown in Fig 3. The most compute-intensive step in the algorithm is the highlighted step “Calculate Ground Potential Rise”. This owes to the fact that this step consists of executing several mathematical statements a number of times equal to the product of number of segments and number of grid points. This, as can be seen in the following section, can amount to a very large number of operations. The performance benchmark is addressed only to this section of the code.

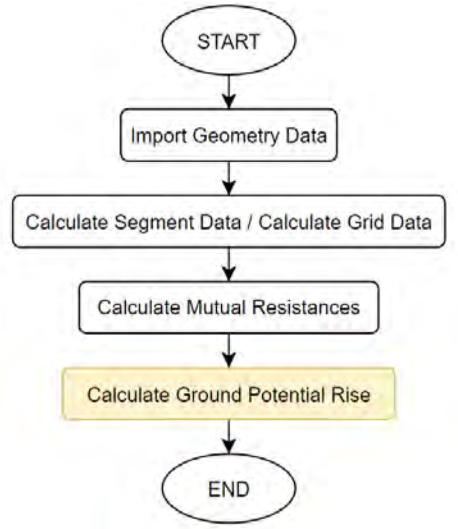

Fig. 3. Equipotential model calculation algorithm

V. PERFORMANCE BENCHMARK

In order to assess the performance of the parallelized GPU code, tests were carried out for grounding analysis of systems containing different numbers of segments as well as grids containing different numbers of points on a predefined geometry. Tests were run for every combination of segments and grid points presented in Table 1. The values in the column “Grid Points” correspond to the values in the column “Grid Step” for the analyzed geometry. The term “Grid Points” is for regularly distributed points on the earth surface, where surface potentials for estimating step and touch voltages have been evaluated.

A. Used Hardware

The benchmarking of the parallelized code was carried out by direct comparison between the execution times of the original code run on a commercial grade CPU and the parallelized code run on a GPU.

TABLE I. NUMBER OF SEGMENTS AND NUMBER OF GRID POINTS USED IN THE PERFORMANCE BENCHMARK

Segments	Grid	
	Grid Step	**Grid Points**
1,000	2 m	28,860
2,500	1 m	115,440
5,000	0.5 m	461,136
7,500	0.25 m	1,841,819
10,000		

The CPU that was used is an Intel Core i5-8265U CPU with a base frequency of 1.6 GHz. The used GPU is an

NVIDIA GeForce MX150, with a base clock speed of 1469 MHz and 384 CUDA cores used for parallel processing. Both the used CPU and GPU are commercially available for personal computers and are classified as mid-range units.

B. Obtained Results

For the presented combination of number of segments and grid points, the execution times of the CPU and the parallel GPU codes are shown graphically in Fig. 4 and Fig. 5 respectively. Table II shows the factors by which calculation times are decreased for each combination. Furthermore, Fig. 6 shows a comparison between execution times for the CPU and GPU codes on a single case of a grounding system containing 10,000 segments as a function of the grid points density.

It can easily be seen from the obtained benchmarking results that the GPU code outperforms the CPU code by a large margin. It can be concluded that the parallelized GPU implementation of the equipotential model for grounding system analysis generally provides for a 35-fold decrease in calculation times on the given hardware. Also, it can be observed that the improvement of calculation speeds increases for larger numbers of segments.

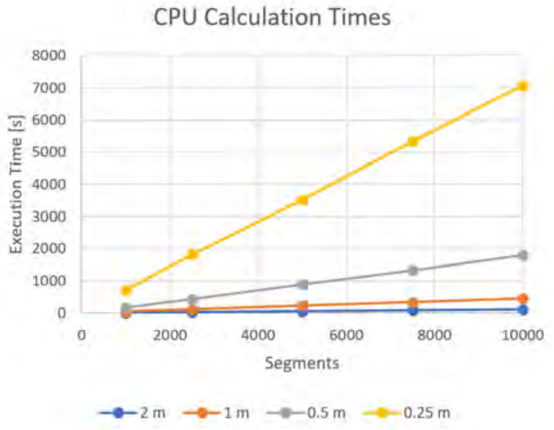

Fig. 4. Execution times of the CPU code

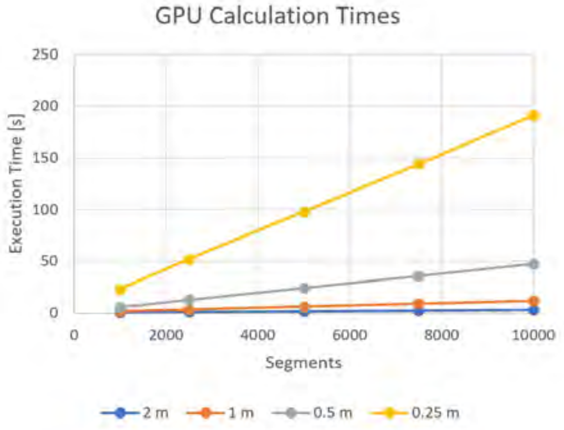

Fig. 5. Execution times of the parallelized GPU code

TABLE II. SPEED INCREASE FOR DIFFERENT NUMBER OF SEGMENTS AND GRID POINTS

Grid Step Segments	2 m	1 m	0.5 m	0.25 m
1,000	27.7	32.0	31.3	31.5
2,500	36.1	35.5	34.8	35.0
5,000	36.4	36.5	37.2	36.1
7,500	36.8	37.5	37.6	37.1
10,000	37.0	37.4	38.2	36.9

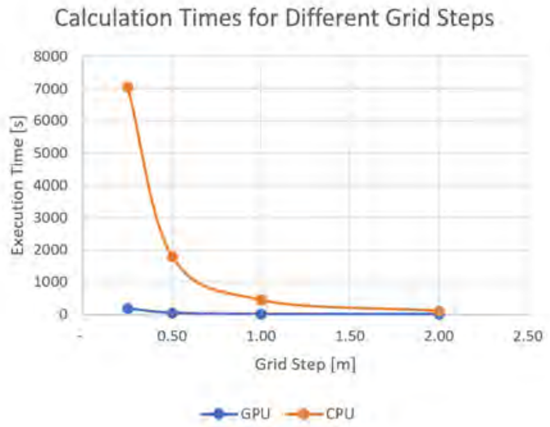

Fig. 6. Execution times of the CPU and GPU codes for 10,000 segments and different grid steps

VI. CONCLUSION

This paper presented the approach chosen for GPU parallelization of an equipotential model for grounding system analysis. The original code developed for CPU was refactored using the ArrayFire library and achieved a 35-fold decrease in computation time on GPU. In practice, calculations that could take up to several hours, now can be conducted in just several minutes using the parallelized code. It is important to state that the used GPU is a mid-range class unit, and using a more powerful GPU would yield substantially shorter calculation times.

This paper presented the first step in the parallelization of a simple computer model for grounding system analysis. Further work in this area will include testing the performance of the parallel code on more powerful GPUs, parallelization of the two-layered earth model for grounding system analysis and eventually parallelization of the full-wave electromagnetic model for grounding analysis in multilayered soil.

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