Designer-Oriented Electric Field Analysis System for Power Cable Accessories

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Sumitomo Electric has worked on electric field analysis for more than 30 years. A technique for accurate electric field calculation was established, however, it has been conducted by CAE (computer-aided engineering) analysis engineers. It was desired that the analysis be conducted by designers in the process of designing power cable accessories. To transfer the analytical technique from the analysis section to the design section, we have simplified the analysis processes and combined them into a new system. The system allows operators to view analysis results simply by inputting CAD (computer-aid design) data. This paper details the development of the system and the successful technology transfer.

Keywords: power cable accessories, electric field, electric field analysis, finite element method, designer-oriented system

1. Introduction

In power cable accessories, insulators must be able to prevent dielectric breakdown over a long period of time. For this purpose, the electric field generated in each part of an accessory needs to be controlled so that the maximum electric field can remain sufficiently small. Since power cable accessories are composed of multiple insulators with complicated structure, the calculation of the electric field distribution requires numerical simulation using the finite element method or other numerical method.

Sumitomo Electric has worked on the electric field calculation for more than 30 years, and already established the technology to lead solutions with high accuracy. Although this analysis has been conducted by CAE[※1] analysis engineers, it has been desired that the analytical process be conducted by designers. In fact, several attempts have been made for such technology transfer through provision of training for engineers at the design section. However, such attempts have failed because: 1. acquiring new technology took a long period (at least six months); and 2. analysis time (operation time) tended to be long to ensure high accuracy.

Therefore, we have automated all the analysis process and developed the system that is able to display calculated results based on the input CAD[※2] data with simple operation. The technology was transferred to the design section and has been used effectively.

2. Electric Field Analysis

Electric field analysis techniques may be classified into several types based on the operation frequency, physical properties of insulator, and phase difference of the applied voltage. Three types of electric field analysis are used for design of power cable accessories.

Electric field analysis is performed using **Equation (1)**, which is obtained from Maxwell's equations.

$$div\,(\hat{\varepsilon}\boldsymbol{E}) = 0 \quad \cdots\cdots (1)$$

Here $\hat{\varepsilon}$ is complex permittivity ($\hat{\varepsilon} = \varepsilon + \frac{1}{j\omega\rho}$), ε is permittivity, ρ is resistivity, $\boldsymbol{E}$ is the electric field, ω is angular frequency ($\omega = 2\pi f$), and f is frequency. **Table 1** and **Fig. 1** show classifications of **Equation (1)** by application and condition (physical property of insulator and frequency)[(1),(2)].

Usually, electrostatic fields are analyzed by considering the insulator's permittivity only, and the permittivity used here is normally constant, linear analysis is performed. Complex electric field analysis may be classified into two types: one takes into account both permittivity and resistivity (electrical conductivity) to solve the electric field distribution and is used for accessories that uses semiconducting materials, and the other takes into account permittivity only, and is used to analyze insulator's section by applying three-phase alternating voltage. Direct electric field analysis takes into account the insulator's resistivity (electrical conductivity) only. In this case, nonlinear analysis is performed for almost the entire region, where resistivity is dependent on temperature and the electric field.

Table 1. Classification of electric field analysis by application

Type	Required physical properties	Applications
Electrostatic field analysis	Permittivity ε	AC power cable accessories
Complex electric field analysis	Permittivity ε Resistivity ρ (Electrical conductivity σ)	AC power cable accessories ・Accessories using semiconducting materials ・Phases of three-phase alternating voltage are considered
Direct electric field analysis	Resistivity ρ (Electrical conductivity σ)	DC power cable accessories

Note: Electrical conductivity $\sigma = 1/\rho$

Figure 2 shows the percentage of analysis cases by technique that we have performed over the past several years.

At roughly 85%, electrostatic field analysis (particularly for power cable accessories with an ordinary shape) accounts for most analyses performed. This is primarily because power cable accessories are often operated with commercial alternating current, with most such accessories being made up of insulators whose resistivity is sufficiently high.

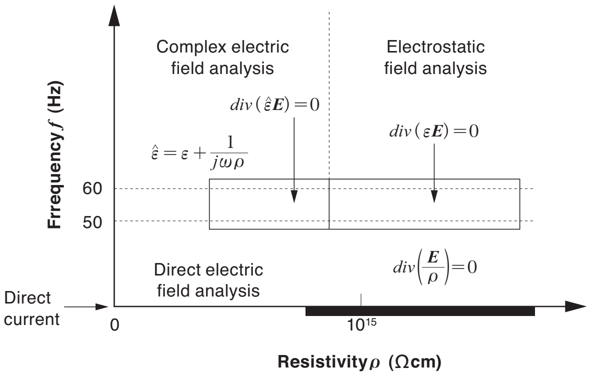


Fig. 1. Classification of electric field analysis

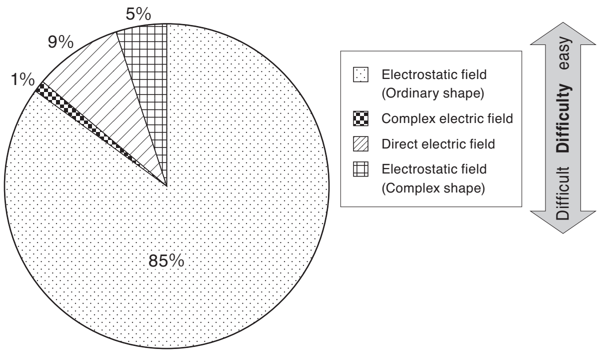


Fig. 2. Electric field analysis by Sumitomo Electric

3. Transfer of Electric Field Analysis Technology

Transferring electric field analysis technology has two objectives, as shown in **Table 2**. The design section expects to shorten the design cycle and reduce costs by incorporating analysis into the design process, whereas the analysis section expects to provide its engineers with more time to develop new analysis techniques.

Table 2. Objectives of transferring analysis technology

Section	Objectives
Design section	To shorten the design cycle and reduce costs by incorporating analysis into the design process
Analysis section	To allow engineers to use their time for development / implementation of new, more advanced analysis technology, rather than merely executing established analysis technology

In order to achieve the aforementioned objectives by transferring analysis technology to the design section, while at the same time addressing the two issues of new technology acquisition and analysis time, a new system has been developed. This system automates the entire analysis process, allowing operators to easily display analysis results. Below are the details of the system.

3-1 Significance of process automation

In order to use electric field analysis for design, it is necessary to achieve high precision in determining and evaluating the values of regions where a high electric field is produced. The electric field distribution and maximum electric field of regions where a high electric field may be produced, such as the electrode surface and insulator interface, are analyzed, outputted, and then used for design. In order to determine such values with high precision, when performing electric field analysis using the finite element method, it is necessary to discretize elements for the electrode surface and insulator interface where a high electric field occurs by cutting thin slices of the element in the normal direction. **Figure 3** shows an example of element discretization for electric field analysis (test electrode model)(2).

Since potential boundary conditions are set for the electrode surface, no electric field is generated within the electrode itself. Because of this, it is not necessary to perform element discretization inside of the electrode. However, element discretization is performed for the entire insulator region. As shown below in **(a)** Overall view, elements are discretized thinly for areas between the high-volt-

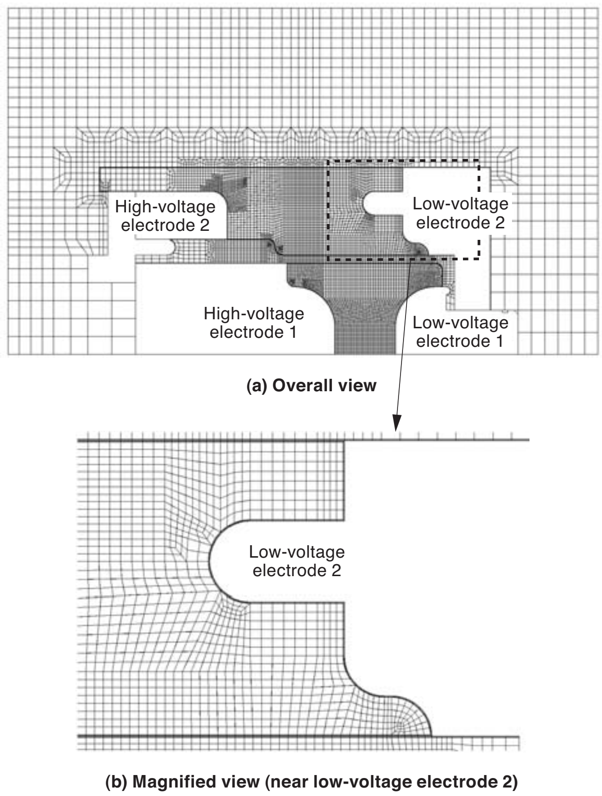


Fig. 3. Element discretization (test electrode)

age electrode and low-voltage electrode where voltage is applied. On the electrode surface and each insulator interface, in particular, a very thin element is created in the normal direction. As an example of thinly discretized elements, from which high-precision results may be obtained, element discretization on a low-voltage electrode is shown in **(b)** Magnified view.

In order for element discretization to be performed in the way that is exemplified here, both knowledge and experience are required so that density may be varied after determining which areas require high precision and which areas do not. However, it takes a very long time to acquire such knowledge and experience. When performing element discretization, even experienced engineers require a whole day for a simple shape, and an entire week for a complex shape. Furthermore, it takes a long time before results can be displayed for a complex shape. In the past, engineers at the design section were trained in this technique, but none of them truly mastered it, and so analysis jobs have been left to the Analysis Technology Research Center (ATRC), Sumitomo Electric's analysis section.

As a solution to meeting the given requirements (simple operation, short analysis time), a system that automates the entire electric field analysis process has been developed jointly with the Power Cable Accessories Division of J-Power Systems Corporation (JPS).

Differences in analysis flow between the results of previous analysis by ATRC and those of automated analysis by JPS are shown in **Fig. 4**.

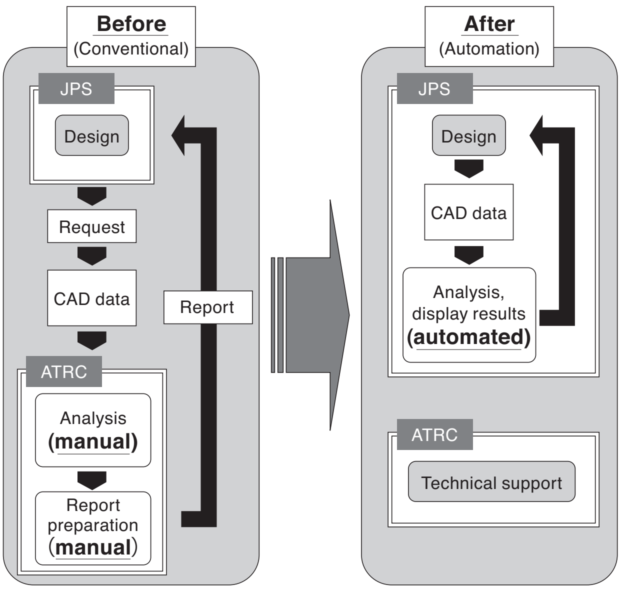


Fig. 4. Analysis flows before and after automation

3-2 Automation method

Before developing an automatic analysis system, it was decided to limit the scope of automated analysis to electrostatic field analysis, for which demand is the highest, and to develop separate systems for other analysis techniques if it becomes necessary to do so.

In the past, ATRC performed electric field analysis by importing shapes from CAD data for design into a general-purpose pre-post software program, setting analysis conditions such as element discretization, physical properties, and boundary conditions on such program, and processing the results display after computation. In order to execute this process automatically to the greatest extent possible, a dedicated software program for specifying boundary conditions and displaying results was developed. It was also decided to fully automate the element discretization process, which used to consume the greatest amount of time and labor.

In order to realize this, authoring software[3] for the automated processing of CAE was used to customize the program so that each process may be executed together in one flow.

3-3 Automatic analysis procedure

Figure 5 shows the analysis execution flow of the newly developed automatic electric field analysis system[2].

The analysis procedure comprises: 1. importing CAD data, 2. setting analysis conditions (physical properties and boundary conditions), 3. element discretization, 4. computation, and 5. displaying results.

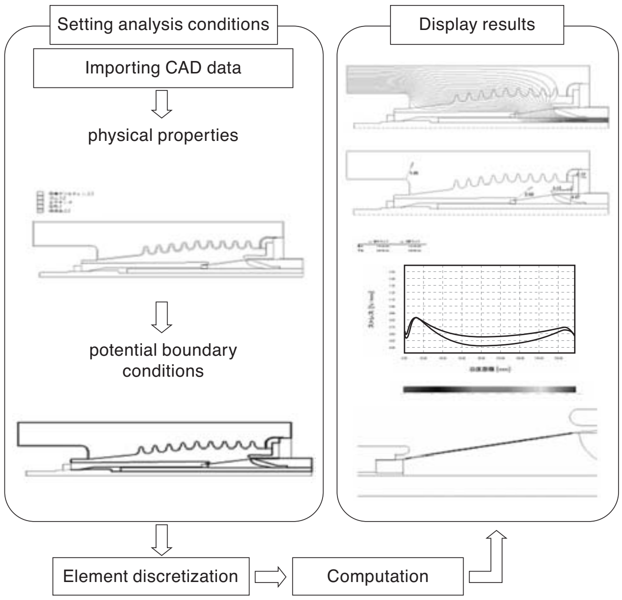


Fig. 5. Analysis flow of the automatic analysis system

In order to perform element discretization using CAD data for design, it is necessary to specify accurately the regions where element discretization is performed, and thus the entire region of CAD data for input must be closed. However, it often happens that the open region and discontinued lines exist in CAD data for design (See **Fig. 6**). As a result, a software program that is separate from the one for setting conditions has been developed so that designers may make modifications using the CAD software.

Specification of physical properties and boundary conditions and display of analysis results were made simpler, as each insulator region may be specified by clicking with the mouse using a GUI※3.

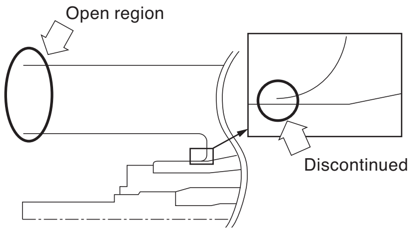


Fig. 6. CAD data for design not suitable for analysis

3-4 Example applications

As an example application for the automatic analysis system, a model of an electrode with an insulator support bar is shown in **Fig. 7**[4]. Comprising an insulating round bar with a ring-shaped electrode, this model has an axisymmetric three-dimensional shape rotated around the z-axis. **Figure 7** illustrates its symmetrical section. For such a shape, wherein the insulating round bar and electrode are enclosed in the atmosphere around them, analysis is conducted by regarding the surrounding atmosphere as an analytic region and performing element discretization for the atmosphere.

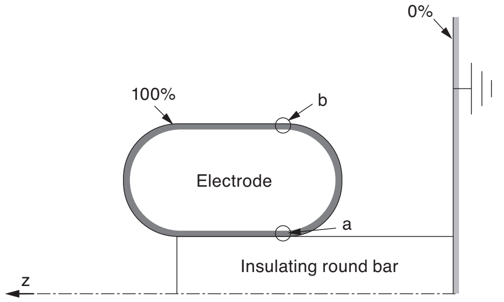


Fig. 7. Electric field analysis model (electrode with insulator support bar)

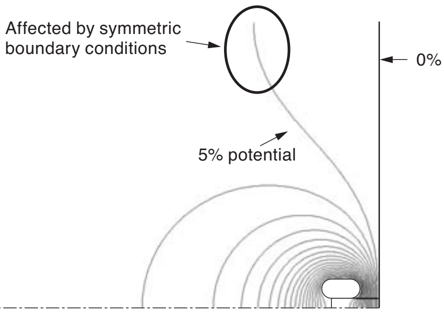
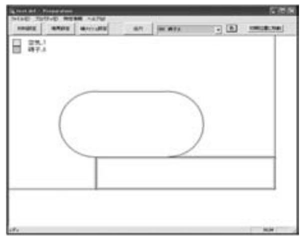
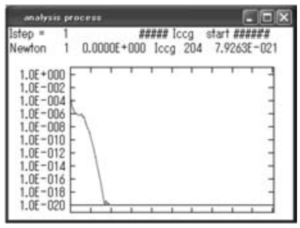
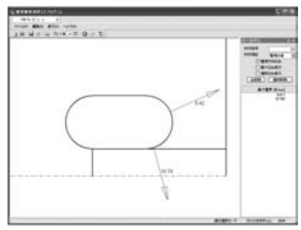
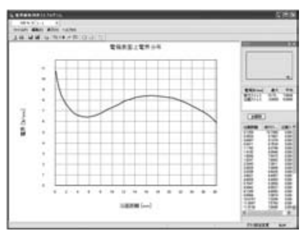


Fig. 8. Equipotential lines (contour lines in 5% potential intervals)

For analysis using the finite element method, it is necessary to set boundary conditions for the ends of the analysis region. In this system, potential boundary conditions and symmetric boundary conditions are used. Potential boundary conditions are set for the surface of high-voltage electrode and the ground, and the electric field distribution of each area is analyzed based on the voltage distribution between the two. Symmetrical boundary conditions, on the other hand, are set for all boundaries other than the electrode surface, for which potential boundary conditions are set.

Figure 8 shows the equipotential lines that were generated through the analysis. The 5% potential line in the figure is affected by the symmetrical boundary conditions and bends at right angles toward the boundary. When using the finite element method to perform numerical analysis for a problem concerning an open system like the one in this model, analysis results are more or less affected

Table 3. Operation / Display screen shots of the automatic analysis system

Process	Operation / Display status
(1) Importing CAD data	Select a file to import data
(2) Setting conditions	
(3) Element discretization	Fully automated
(4) Computation	
(5) Displaying results	 **(a) Maximum electric field vectors on the electrode**  **(b) Electric field distribution on the electrode (Plotted between a and b in Fig. 7)**

by boundaries. If, however, a large atmospheric region is allowed, as in this model, the electric field on the insulating round bar and electrode will hardly be affected.

Table 3 shows screen shots illustrating how permittivity was set for the insulating round bar and the atmosphere in the automatic analysis system, how potential boundary conditions were set for the electrode and grounding, and the analysis results.

4. Conclusion

Electric field analysis of power cable accessories has been automated by combining all of the processes into one sequence of software program. To view analysis results, one has only to import shapes from CAD data prepared by a designer and specify physical properties and boundary conditions for each area by using a dedicated GUI. **Figure 9** shows an example of the time required for each process.

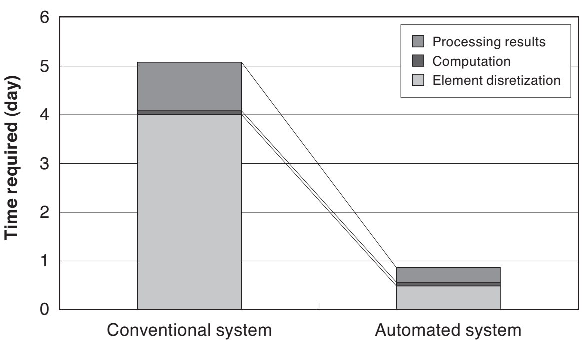


Fig. 9. Comparison of analysis time

By automating and simplifying processes that once consumed a great amount of time and labor for analysis, the total time required has been reduced to less than one fifth, and the software program is now easy to use for designers.

For processes that require manual operations, dedicated software programs were developed separately, thus making it easy to learn how to use the software. JPS has begun using such software, and they have given positive feedback regarding its usability. So far, the software has been used for a greater number of analyses than originally expected, and about ten times more analyses have been performed compared to when the same analysis was performed manually by CAE analysis engineers at ATRC. The fact that such a large number of analyses were able to be made can be attributed to several factors: 1. for accessories for which such analysis was performed in the past, precision checks, including comparisons with previous analysis results, are conducted every time the design function performs analysis using the automated system, 2. the number of analyses performed by the JPS Power Cable Accessories Division has shown an increase (it has become easier for designers to approach optimal design as they repeat analysis while checking the results to modify shape and other conditions), and 3. JPS sections other than the Power Cable Accessories Division that have not often performed such analysis (Quality Assurance, Manufacturing, etc.) have begun to perform it more frequently. Particular mention must be made of 3, as other JPS sections used to find it difficult to perform analysis because of the time and cost involved, but are now free from such restraints. The new automated system has thus helped them to spread the analysis technology throughout the organization.

Technical Term

※1 CAE : Computer-aided engineering : Simulation using a computer for preliminary examination of product design / manufacturing and process design. Also called numerical analysis.

※2 CAD : Computer-aided design : The use of computer technology for the design of objects. Often refers to a drawing system using a computer.

※3 GUI : Graphical user interface : A user interface that, by frequently displaying information through graphics, allows most basic operations to be conducted using a mouse or other pointing device.

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(References (2)-(4) are written in Japanese.)

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