Comparison between '*cut and try*' approach and automated optimization procedure when modelling the medium-voltage insulator

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Abstract: In this article the comparison between 'cut and try' approach and automated optimization procedure is presented in the example of the medium-voltage insulator modelling. The goal of the research was to define the shape of the insulator, the shape of the capacitive dividers electrodes and the distances between the insulators. Both approaches were based on the numerical analysis performed with the EleFAnT (Electromagnetic Field Analysis Tools) programme tool. Firstly a series of FE analyses were performed when every improvement of the FE model was achieved with traditional 'cut and try' approach. In this procedure the model's modifications were determined by technical directives and our experiences in the field of modelling of similar devices. Secondly the same modelling procedure was carried out using optimization algorithm combined with FEM analysis. A newly developed pre-processor for automatic generation of finite elements' mesh, and genetic optimization algorithm of differential evolution were used together with the existent EleFAnT solver. The results of numerical analyses were confirmed by practical tests on a prototype of the insulator with capacitive divider.

Keywords: High-voltage techniques, Insulators, voltage detector, FEM, optimization.

1 Introduction

In medium-voltage switchgear there is always a need for visible information on the presence of voltage, which brings an additional safety to manipulators, prevents incorrect manipulations and increases operational security. A system for voltage indication in medium-voltage switchgear consists of a voltage indicator and an electronic unit. A voltage indicator, at the same time, performs the role of epoxy post insulator with a built-in capacitive voltage divider. Post insulators are installed in a switching device or in any other input element where voltage is present [1]. Those post insulators with capacitive dividers, manufactured so far, have low capacitance since in the past there have been no limitations. The new IEC 61985 standard defines that a switching device is undoubtedly in a no-voltage state, defined by a voltage indicator, only if it is designed in accordance with the IEC 61243-5, which gives the required capacitance values. The standard requires the capacitance to be between 74 and 88 pF. Therefore, it is necessary to redesign all the existing voltage dividers in post insulators in such a way that the requirements of the standard will be fulfilled, while the external shape of the post insulators remains unchanged.

Furthermore, the optimization of an element, such as a medium voltage insulator is advisable, above all, to reduce electric field strength which has a strong impact on the element's operation and, thus, on the operational reliability of the switchgear unit. This element is of such a nature that any possible unreliability can manifest itself only after a longer period of operation [2]. This is especially true as a result of failing to take into account all physical laws and circumstances during normal operation, and in the case of extraordinary situations (e.g. lightning).

Figure 1a shows the 3D meshed metal construction of the capacitive divider electrode's final elements in the interior and external structure with the mesh and visible materials of the existing post insulator. The metal fitting of the insulator (upper connection) for fastening to the conductive part of the upper side, is elongated with a special electrode of the divider, which has the potential of the conductive part. The metal fitting for fastening the insulator to the earthed part (lower connection) is situated at the bottom of the insulator. An electrically separated cylindrical metal mesh is mounted around this metal connection, which represents the other electrode of the divider.

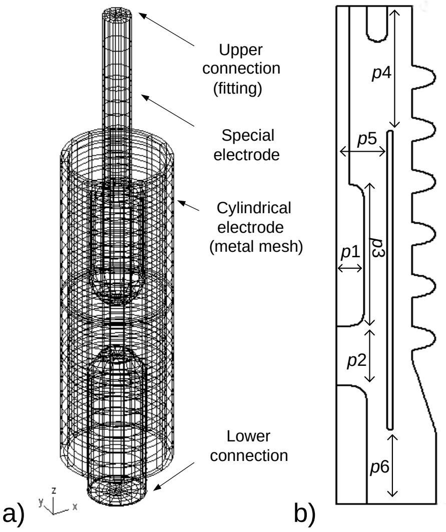

Fig. 1: a) Internal structure of the post insulator model b) setting of parameters for optimization of geometry.

The design process was traditionally accompanied by greater number of prototypes elaboration. Later the use of numerical analyses decreased the number of needed prototypes, but the major design decisions were still dictated by engineers' experiences. This kind of design process is often referred as 'cut and try' approach. On the market there is a constant cost-benefit battle, so this forces manufacturers to reorganize and optimize the processes of switchgear design. In these efforts the following powerful tool is worth consideration – numerical methods combined with optimization algorithms.

2 The 'cut and try' approach

The approach to the modelling of the indicator was based upon a good knowledge of the problem itself and by means of a numerical analysis in the programme package EleFAnT [3], developed by the IGTE of Graz Technical University (TUG). It was first necessary to choose proper settings up and shapes of the capacitive divider's electrodes and, after that, to calculate capacitance through energy in the dielectric material and by means of electric field computation to check dielectric strengths in all critical parts. The IEC standard requires the capacitance to be between 74 and 88 pF.

The design process of the switchgear element began with the selection of shape, and the positioning of the capacitive voltage detector's electrodes which was mainly based upon experiences. This phase was followed by calculating the capacity on the basis of the energy in the dielectric. Electric field computation was then used for verifying that the electrical field strength was kept below the values of dielectric strength at all critical points. The selection of electrodes and necessary computations were repeated until all the requirements were met. This procedure is very time consuming, especially the necessary preparation of new models for each individual computation. The most time consuming is the inputting of geometry into the programme package, where the initial mesh of finite elements consists of a certain number of rectangles in x and y directions. A model of the modelled structure is obtained by moving their sides and by using various parabolic functions.

3 Optimization procedure

This new approach to the modelling of voltage detector's electrodes is based on an optimization process. The objective of the optimization is to reduce electrical field strength at the edges of electrodes and at critical points, i.e. at those places where an electrical field crosses from the insulator into the air, with the condition of meeting the required values of capacity.

The choice of optimization algorithms depends on the level of complexity of the optimization problem, shape of the cost function, constraints, accuracy of the solution, and computation time. Traditional optimization methods (e.g. gradient methods) are suitable for optimization of simple systems since they yield the solution in a relatively short period of time. The weakness of these methods is that the obtained solution is not necessarily the optimal one (local instead of global minimum).

The current practice is that for the analysing and planning of complex systems, including problems from the field of electric power engineering, almost exclusively new optimization procedures, based on examples from nature (evolution methods), are used. Evolution could be described as an optimization process, the main characteristic of which is that the solution is not sought after using the pre-defined (deterministic) paths, and that a set of simple objects is treated at the same time.

A. Differential evolution method (DE)

The differential evolution method is a relatively new optimization algorithm, presented by Price and Storn [4]. It is based on the origins of new populations in the evolution of mankind.

The basic algorithm (Figure 2) consists of an entire parametrically-written model of the insulator ($p1$-$p6$), mesh generator, solver of the EleFAnT

(Electromagnetic Field Analysis Tools) program package [3], and differential evolution (DE) optimization algorithm [5].

```
Begin
  Initial parametric model geometry and materials with $x_n$ parameters
  Create initial population of size $NP$ ($i$=1,...,$NP$)
  $k$=1
  Evaluate members of the population with regard to the objective function $f_i^{(k)}(x)$
  While the stopping criterion is not reached Do
    For $i$=1 to $NP$ Do
        $k$=$k$+1
        Create vector of mutated descendants $v_i^{(k+1)}$
        Execute differential crossover $x_i^{(k+1)}$
        If ($|(x_i^{(k+1)} - x_i^{(k)}| > max\_difference$) Then
          Meshing of geometry (specially for switchgear)
        else
          re-distribution of existing finite elements
        Endif
        Preparation of the model in the pre-processor
        FEM solver of the EleFAnT program package
        Calculation electrical field strength
        Evaluate quality $f_i^{(k+1)}(x)$ with regard to the objective function
        If ( $f_i^{(k+1)}(x) < f_i^{(k)}(x)$) Then
          Descendant becomes new parent $x_i^{(k+1)} = x_i^{(k+1)}$
        else
          Descendant is covered by the parent $x_i^{(k+1)} = x_i^{(k)}$
        Endif
    End
   End
End
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Fig.2: Pseudo-code of the entire optimization algorithm for the design of insulation elements

In the design process it was necessary to fulfill two criteria. The first function f_E evaluates the magnitudes of electric field strength at the boundaries between the dielectrics, the second f_C describes the capacitance value. Thus, in every step of the optimization, the qualities of two cost functions are valuated, i.e. cost function of capacitance and cost function of electric field. The minimum of the cost function for electric field strength was set at 90 % of the dielectric strength of air (2.7 MV/m) due to the relatively low value for the dielectric strength of air and the possible impact of external factors (e.g. moisture, dust, etc.) on this dielectric strength. Both objective functions were analytically given by bell shaped fuzzy sets (Figure 3) and merged into a unified cost function $f(x)$ that was used in the optimization algorithm:

$$f(x) = w_C f_C(x) + w_E f_E(x) \tag{1}$$

where w_C and w_E are the weights of individual quantities.

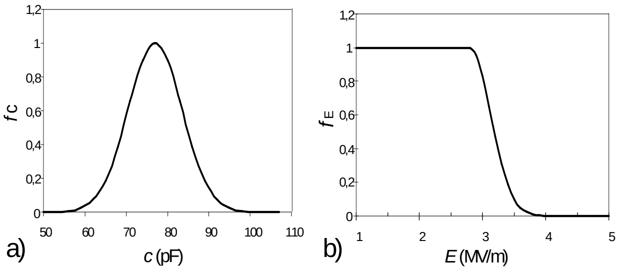

Fig. 3: a) Cost function describing the capacitance value, b) cost function describing the magnitudes of electric field strength

4 Results

The numerical computations were performed under the presumption of withstand voltage of 125 kV. The maximum permissible value of electrical field strength for air amounts to 3 MV/m and for epoxy insulation to 30 MV/m.

A. Results Of The 'Cut and Try' Approach

The results will be presented on the basis of numerical analysis in 2D and 3D space. Both results were obtained by the use of the EleFAnT programme package. 2D optimization was made first, due to the axial symmetry of the insulator and with this related simplification of computation. The results obtained were subsequently checked by 3D computations (Figure 4), both for individual insulators and for the set of the three phase system's three-post insulators.

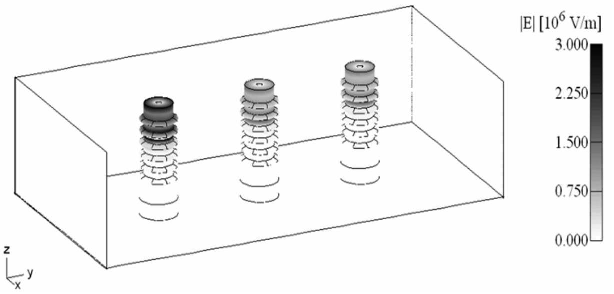

Fig. 4: Electric field strength on the surface of post insulators for three-phase system

The position of the inner electrodes and external insulator shape that was obtained using 'cut and try' approach is represented in the Figure 7b.

B. Results Of The Optimization Procedure

The optimization procedure began with the initial values, given in Table 1. In each step the capacitances were determined by numerical computation from energy in epoxy insulation, and electric field strength values were checked for being below the values of dielectric strength.

Table 1: Optimization set values

Parameter	*p*1	*p*2	*p*3	*p*4	*p*5	*p*6
Initial value (mm)	8	30	42	40	18	35
Optimized value (mm)	11.1	20.2	63.3	59.4	20.3	39.1

The cost function as a function of the number of steps is shown in Figure 5. The graph shows the convergence course of the cost function towards the optimal result. For each iteration step, the objective function had as many values as there were population numbers. To plot the presented course, the average objective function values within one iteration were considered. The optimization was performed with the following values of optimization coefficients: size of population *NP*=24, scaling factor *F*=0.8 and crossover constant *CR*=0.6.

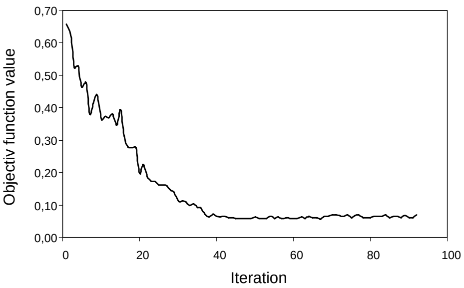

Fig. 5: Schematically presented optimization procedure.

The most significant parameters of the changeable geometry, that influence the shape of the electric field strength and the capacitance value, are the height of the upper electrode (*p*3) and the height of the cylindrical mesh (*p*4). The outcome of both cost functions depending on these two parameters is presented in Figure 6. To obtain the presented results in Figure 6, all other parameters (*p*1, *p*2, *p*5 and *p*6) were constant (for these parameters their optimal values presented in Table 1 were chosen).

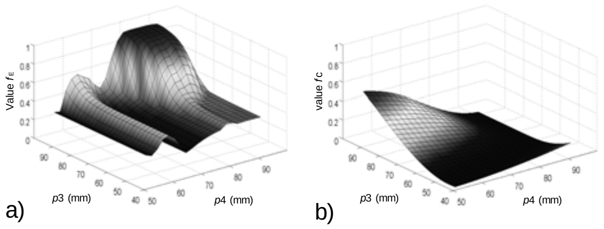

Fig. 6: Dependence of both cost functions from parameters *p*3 and *p*4.

From Figure 6 it can be clearly seen that, in spite of only two considered parameters (*p*3 and *p*4), cost functions are rather complex, containing several local maximums and minimums. The results of the research confirmed that the differential evolution optimization method is more than appropriate for solving such problems.

Figure 7 shows the distribution of electric field strength inside the insulator and in the air around it, for three cases. The first case is for the initial geometrical parameters of the voltage detector's electrodes. The second case represents the most favourable result obtained by ‘cut and try’ method and the third case represents the outcome of the optimization procedure.

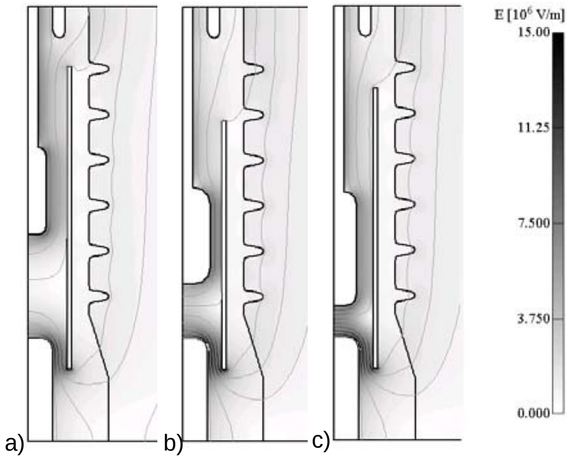

Fig. 7: Distribution of electric field strength for (a) initial voltage detector's geometrical parameters, (b) results obtained by ‘cut and try’ method, (c) results obtained by optimization procedure.

In Figure 8 the comparison between results obtained by ‘cut and try’ approach and optimization procedure are shown. The graph shows the electric field strength in the boundary-line between epoxy resin and external air.

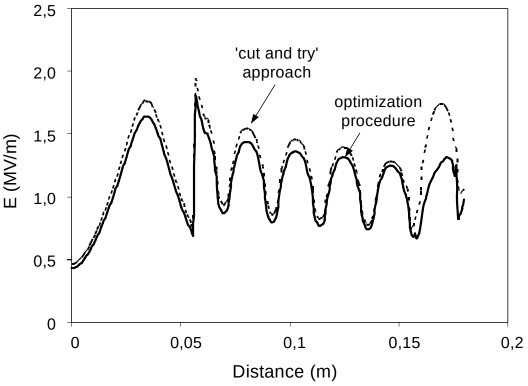

Fig. 8: The electric field strength in the boundary-line between epoxy resin and external air.

5 Conclusion

The results of the presented study show that using classical ‘cut and try’ approach the design process is rather time consuming and limited by engineer’s knowledge of the problem. Nevertheless, using this approach all requirements for electrical field strength and capacitance were fulfilled.

On the other hand the optimization approach proved to be faster and very accurate. Better final results were obtained using this procedure than classical ‘cut and try’ approach (Figure 8). In the process of optimization, the length of the metal mesh electrode and the thickness of the special electrode were increased. This caused a decrease in the distances between individual metal parts inside the insulator. The performed electric field computations showed that the electric field strength after the modelling process did not exceed the dielectric strengths in any part of the insulator.

A prototype voltage indicator was manufactured. Tests were performed for partial discharges, lightning impulse, and power frequency withstanding voltage. All performed tests were successful, consequently confirming the results of our theoretical work. Capacitance was also established by these measurements. The test result was, with an accuracy of 5 pF, close to the calculated capacitance. From the results of the numerical analysis on the basis of the finite element method and its comparison with measurement results, it is possible to conclude that the modelling of axially symmetrical switchgear elements with 2D analysis can be performed with a high level of accuracy.

Based on these results the conclusion can be drawn that the differential evolution optimization algorithm combined with FEM analysis proved to be quick, reliable and completely applicable for electromagnetic computations and is, therefore, preferred over the standard design procedures.

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