Optimization Design of Capacitive Voltage Transformer Grading Ring

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Abstract: High voltage capacitive voltage transformer grading ring plays a key role in improving electric field distribution and reducing maximum electric field strength. The study conducted grading ring optimization design by testing 500kV capacitive voltage transformer, maximum electric field strength of the equipment setting and asymmetric coefficient are selected as objective function; grading ring dimension and location as optimization variables. Optimization design is performed applying simulated annealing optimization strategy to come up with optimal dimension and installation location.

Keywords: Capacitive voltage transformer; Optimization design; Simulated annealing method; Grading ring

Foreword

Capacitive voltage transformer has a wide application as an equipment of measuring and protection in AC power system. Especially in high voltage system, capacitive voltage transformer greatly excels electromagnetic voltage transformer in both economic performance and electrical performance, which is an increasingly evident advantage as voltage level rises. The increase of voltage level will definitely raise electric field strength on exposed live part and generate corona discharge. Both domestic and overseas manufacturers add grading ring outside the equipment in purpose of lowering maximum electric field strength on the equipment surface and improving electric field distribution, in order to prevent or reduce atmospheric corona generation.

There have been studies on the effect of grading rings on improving electric field distribution, whereas no documentation is seen on algorithm of grading ring dimension and location. This article draws the optimization plan of grading ring design by studying 500kV capacitive voltage transformer applying simulated annealing method, maximum electric field strength of the equipment setting and asymmetric coefficient are selected as objective function; grading ring size and location as optimization variables.

1. Electric field numerical calculation

1.1 Algorithm model(as shown on figure 1)

Figure 1 Outline drawing of 500kV capacitive voltage transformer

Apply 500kV capacitive voltage transformer as algorithm model, rated primary voltage is $500/\sqrt{3}$kV, outline drawing as shown on figure 1. Due to the property of axial symmetry, 2 dimension model is applied during calculation, simplified algorithm model as shown on figure 2.

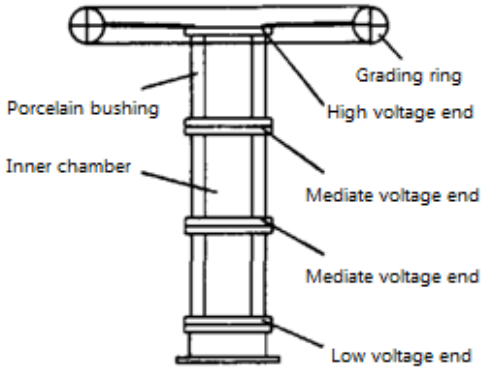

Figure 2 Sketch map of algorithm model

1.2 Calculation method

This study applies finite element method for calculation of electric field numerical value, mathematic model as seen below:

$$\begin{cases} \nabla^2 \varphi = 0 \\ \dfrac{\partial \varphi}{\partial n}\Big|_{s_2} = 0 \\ \varphi|_S = \varphi_0 \\ \varphi|_{s_{1,2}} = 0 \end{cases}$$

Boundary conditions as shown on figure 3.

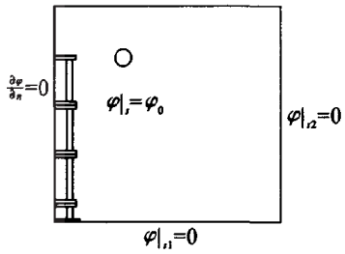

Figure 3 Sketch map of boundary conditions

1.3 Calculation results

Apply finite element software ANSYS to conduct electric field simulation calculation respectively on capacitive voltage transformer with and without grading ring, Figure 4~9 show electric field distribution of both situations, calculation results as shown on table 1.

Table 1 Correlation table of electric field calculation results

Grading ring dimension	Maximum electric field strength E_{max}/(V/mm)	Uniformity coefficient
Without grading ring	7434	18.54
With grading ring (Pipe diameter 100mm, diameter 1000mm)	3183	11.88

Through electric field analysis calculation of capacitive voltage transformers with and without grading ring, it can be concluded that grading ring plays a key role in revising electric field distribution, reducing maximum electric field strength and electric field asymmetric coefficient. Consideration of grading ring design is thus essential while designing capacitive voltage transformer above 500kV voltage level. Optimization design in aspects of number, dimension and installation location of grading ring has significant meaning in corona prevention and transformer electrical performance.

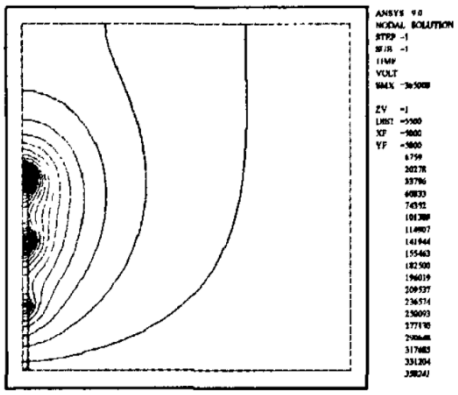

Figure 4 Distribution diagram of equipotential line (without grading ring)

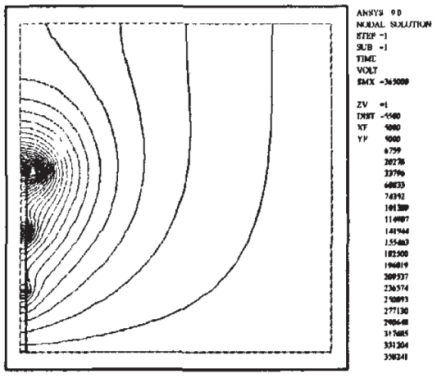

Figure 5 Distribution diagram of equipotential line (with grading ring)

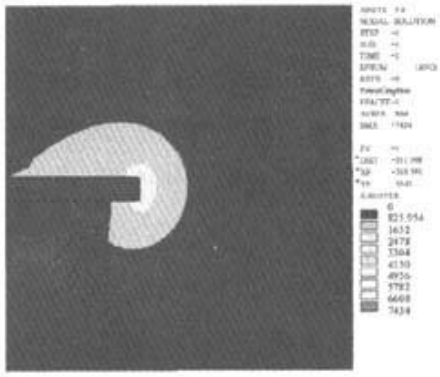

Figure 6 Electric field strength distribution at high voltage end (without grading ring)

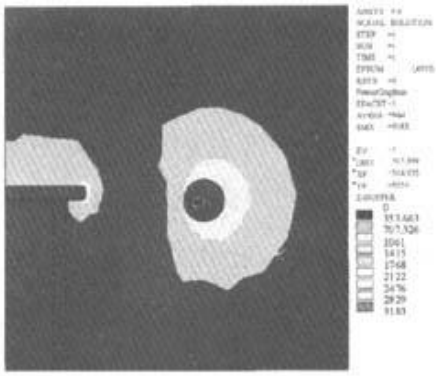

Figure 7 Electric field strength distribution at high voltage end (with grading ring)

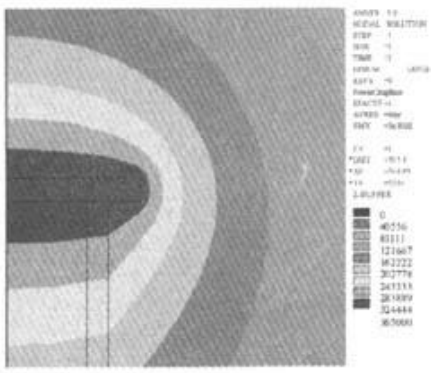

Figure 8 Potential distribution at high voltage end (without grading ring)

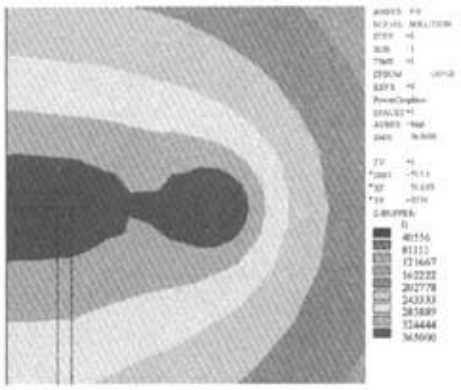

Figure 9 Potential distribution at high voltage end (with grading ring)

2. Simulated annealing method

During optimization design, selection of appropriate optimization method directly influences optimization efficiency. This article selects simulated annealing method as optimization strategy. Simulated annealing is a modern optimization method presented in accordance with solid annealing process, Due to similarity between general combinatorial optimization problems and annealing process of matter, optimization process is simulated with annealing process to solve combinatorial optimization problems. In comparison with traditional optimization method, the special optimization searching mechanism determines that this method is capable of accepting target function value under non-optimal status with certain probability, thus has the merit of global optimization.

Traditional simulated annealing method has flaws of blind search and slow searching, this study applied flowing modifications to improve searching performance.

2.1 Determine the appropriate searching domain

Proper selection of feasible domain is crucial by reason that traditional simulated annealing method is featured with large searching space, multiple target, long optimization process even to an unacceptable extent. This article

put a reasonable limit on searching domain according to characteristic of optimization problems, greatly reduced optimization space and time, and improved efficiency.

2.2 Select rational termination criterion

In the aspect of termination criterion selection of optimization process, certain requirements on accuracy is applied according to actual engineering need, which reduces rigorous requirements on global solutions and makes optimization process more rational and feasible.

2.3 Intellectualization of optimization solution

Traditional simulated annealing mechanism has the defect of repetition and blind searching. In respond to this problem, this article added memory device to the optimization process that intellectually memorizes searched intervals, the system will automatically skip searched intervals to avoid unnecessary recalculation.

3. Grading ring optimization design

Optimization design of grading ring helps to change electric field distribution on transformer surface, optimization includes rational design and installment of grading ring. This article applies improved simulated annealing method (mentioned above) on grading ring optimization design, grading ring size and location are selected as optimization variables, maximum electric field strength of the equipment setting and asymmetric coefficient are selected as objective function, calculation of objective function applies finite element method.

As drawn from the stated calculation results of 500kV capacitive voltage transformer electric field value, a one-grading-ring structure falls short to meet the requirement of atmospheric corona discharge prevention, therefore, a two-grading-ring structure should be applied.

3.1 Mathematical model

Figure 10 is the 500kV grading ring design variable sketch map, variables are defined as h_1, h_2, D_1, D_2, φ_1, φ_2.

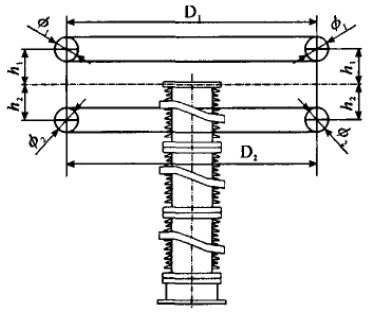

Figure 10 Grading ring design variable sketch map

Optimization objective function concerns maximum electric field strength of calculating field and asymmetric coefficient, optimization design of grading ring can be concluded as the following non-linear programming problem:

$$\left.\begin{array}{ll} & \min\{f(x)=E_{max}+k\} \\ s.t & h_1-h_2\geqslant\phi_1+\phi_2 \\ & D_1\geqslant D \\ & D_2\geqslant D \\ & E_{max}<3\ 000 \end{array}\right\}$$

Among which, $X = [h_1\ h_2\ D_1\ D_2\ \varphi_1\ \varphi_2]^T$ represents column vector of optimization design variable, D represents outer diameter of porcelain bushing that connects hardware fittings, criterion of program termination is $s = \{f(X_{i+1}) - f(X))\} < \varepsilon$, $\varepsilon = 10^{-2}$. Assume atmospheric breakdown field strength is 3000V/mm, in prevention of operative corona generation, program termination is not allowed when optimization process $E_{max}>3000$, therefore optimization process proceeds which efficiently guarantees rationality of optimization results. In addition, practical processing conditions will be considered while deciding step length of optimization design variables.

3.2 Optimization results

This article applies APDL language on programming based on ANSYS software, figure 11 shows the sketch map of optimization design flow diagram,

optimization results applying revised simulated annealing optimization strategy as shown on table 2, figure 12 and figure 13 show electric field strength distribution before and after optimization as well as equipotential layout.

As seen from the optimization result, maximum electric field strength reduced greatly after optimization, declined to 2642V/mm, lower than atmospheric breakdown field strength, no corona generation was detected during normal operation, asymmetric coefficient was lowered, criterion of practical engineering can be satisfied.

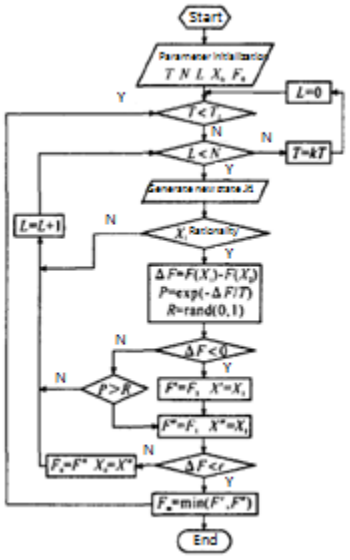

Figure 11 Optimization design flow diagram

Table 2 Comparative table of optimization results

	Design variable/mm						E_{max}/(V/mm)	f(x)
	h_1	h_2	D_1	D_2	Φ_1	Φ_2		
Before optimization	100	100	1000	1000	100	100	3136	3153
After optimization	155	255	1500	1250	120	150	2642	2653

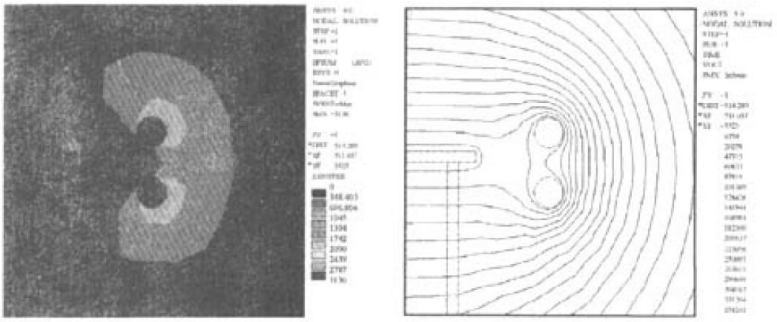

Figure 12 Electric field strength and equipotential distribution before optimization

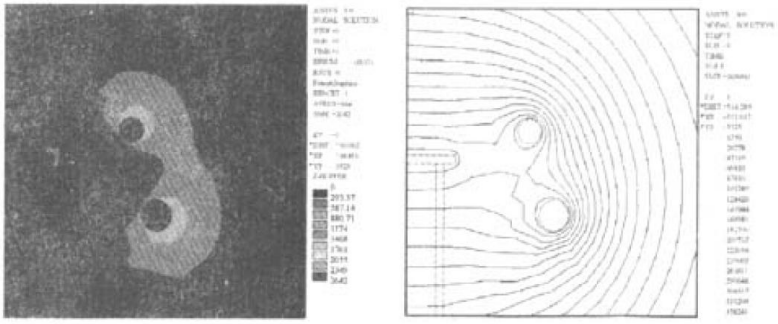

Figure 13 Electric field strength and equipotential distribution after optimization

4. Conclusion

Uniformity of the whole electric field should be given thorough consideration while designing capacitive voltage transformer, even

inter-electrode and the field domain electric field distribution as much as possible, appropriate grading ring design and layout is outstandingly crucial. This study utilized capacitive voltage transformer as test object and came up with electric field distribution within calculating region via numeric calculation and analysis of electric field, optimization design based on design variables of grading ring size and location was conducted applying simulated annealing optimization method, optimization started from arbitrary initial state and eventually came up with optimal dimension of grading ring, analysis result provides guidance for insulating design. Optimization calculating result shows that grading ring design proposed by this article is in accordance with the demand of practical engineering.

As voltage level rises, revising grading ring dimension and location isn't enough, a proper increase in grading ring number and installation tiers is necessary.