Optimal Electrical Design of Condenser Graded High Voltage AC Bushings

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ABSTRACT:

The application of Genetic Algorithm for optimal electrical design of high voltage bushing concentric foils in transformers is investigated.
Condenser-bushings contain concentric conductive foils which are isolated against another. By adjusting the number, diameter and length of these cylinders as well as the electrical strength of insulating material between foils, the voltage drop and also electrical stress in the core and along the surface can be affected by variation of partial capacitances between the conducting cylinders. This paper aims to find optimal design of concentric conductive foils for having lower maximum and well-distributed electric stress and also a constant voltage drop for different layers subject to some practical constrains by using Genetic Algorithm optimization method.

1. INTRODUCTION

With the increase of electrical energy demand, the voltage levels of electric transmission system have increased rapidly within recent years. The reliability of equipment and facilities used in power system is an essential precondition of the energy safety transmission. From the literature, as well as field data, it has been established that bushing failure is one of the major reasons for transformer failures [1],[2]. With this background, it has been the theme of this research work to establish an approach for optimal electrical design of high voltage AC bushings in order to minimize the catastrophic failures of bushings and guarantee the longer period of operation.

This paper has been organised in five sections. Introduction has been developed in Section 1. In Section 2, mathematical model of the problem including design parameters, technological and manufacturing restrictions of each parameter has been developed. The mathematical model has been formulated as an optimisation problem and the paper uses the Genetic Algorithm optimisation method for finding the optimum electrical design.

In Section 3, a 145kV oil impregnated paper (OIP) bushing has been designed by this proposed method and the optimum design indices have been compared with a conventional design. Finally, some typical tests have been done on manufactured optimal designed bushing. The tests are according to IEC 60137 Standard which defines necessary tests on high voltage bushings.

2. MATHEMATICAL MODEL OF THE PROBLEM

The electrical design of capacitive grading bushings is one of the important parts of manufacturing of these kinds of bushings. In this step, engineers design the condenser bushings with practical design parameters and with considering the technological constrains. It goes without saying that finding an optimum design has its own importance in this stage. The reason is that it leads to using minimum amount of raw materials and lower cost of manufacturing process along with higher performance of condenser bushings during operation on power transformers. These are very important factors for manufacturing companies.

Capacitive grading bushings contain embedded in their insulation core concentric conductive foils which are isolated against another. By adjusting the diameter and length of these cylinders the electrical stress and voltage drop in the core and along its surface can be influenced by variation of the ratio of the partial capacitances between the conducting cylinders. Because of some manufacturing limitations, this paper suggests the use of the foil configuration; this is shown in Figure 1.

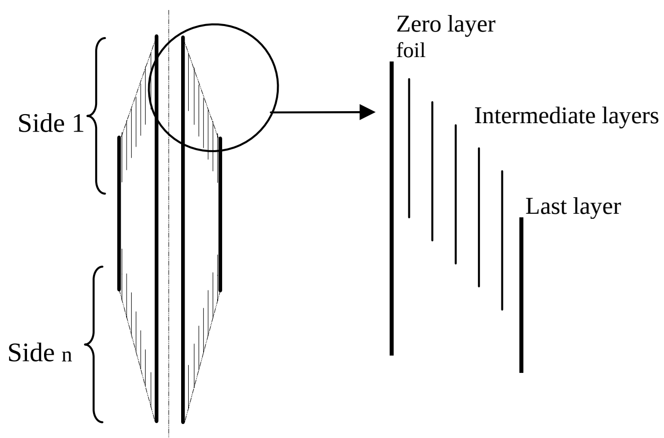

Figure1. Conic-TYP2 foil configuration

The grading of ac-bushing is achieved from the capacitances that are formed between the grading foils and thus determined by the permittivity of the insulating material. The electrical field has to be calculated from the set of equation (1).

$$\oint \vec{E}.d\vec{l} = 0, \quad \oint \vec{D}.d\vec{A} = Q \quad and \quad \vec{D} = \varepsilon \vec{E} \qquad (1)$$

$\vec{E}$: *Vector of electrical stress*

$d\vec{l}$: *Vector of element of integration path*

$d\vec{A}$: *Vector of elemement of area*

$\vec{D}$: *Vector of electrical flux density*

ε : *permittivity*

For the conic-TYP2 foil configuration the above set of equations leads to cylinder capacitors. Voltage drop on each layer can be found by the series-parallel configuration of these cylinder capacitors.

Optimum condenser bushing designs can be formulated as an optimisation problem with relevant restrictions. The experience of authors in designing of condenser bushings shows that the best objective function along with practical restrictions can be introduced as follows:

$$Minimise \sum_{k=1}^{DsNo} \left\{ \begin{array}{l} \alpha \times \left[(1-Dev) \times ((\frac{Min}{Max})^{k}_{\Delta U1} - 1) + (Dev) \times (\frac{Max^{k}_{\Delta U1} - MVD}{MVD}) \right] + \\ \beta \times \left[(1-Dev) \times ((\frac{Min}{Max})^{k}_{Erad1} - 1) + (Dev) \times (\frac{Max^{k}_{Erad1} - MRS}{MRS}) \right] + \\ \chi \times \left[(1-Dev) \times ((\frac{Min}{Max})^{k}_{\Delta U2} - 1) + (Dev) \times (\frac{Max^{k}_{\Delta U2} - MVD}{MVD}) \right] + \\ \delta \times \left[(1-Dev) \times ((\frac{Min}{Max})^{k}_{Erad2} - 1) + (Dev) \times (\frac{Max^{k}_{Erad2} - MRS}{MRS}) \right] \end{array} \right\} \qquad (2)$$

$$\begin{array}{l} Such \ that: \\ 1.\ \varepsilon_{Min} \le \varepsilon \le \varepsilon_{Max} \\ 2.\ Nfl_{Min} \le Nfl \le Nfl_{Max} \\ 3.\ D\mathrm{int}_{Min} \le D\mathrm{int} \le D\mathrm{int}_{Max} \\ 4.\ Dext_{Min} \le Dext \le Dext_{Max} \\ 5.\ Lx_{Min} \le Lx \le Lx_{Max} \\ 6.\ Lp1_{Min} \le Lp1 \le Lp1_{Max} \\ 7.\ Sp1_{Min} \le Sp1 \le Sp1_{Max} \\ 8.\ Lp2_{Min} \le Lp2 \le Lp2_{Max} \\ 9.\ Sp2_{Min} \le Sp2 \le Sp2_{Max} \\ 10.\ \Delta U \le MVD \\ 11.\ Eaxl \le MAS \\ 12.\ Foils\ Configuration \\ Must\ be\ Conic-TYP2 \\ 13.\ \alpha + \beta + \chi + \delta = 1. \end{array} \qquad (3)$$

The objective function and its restrictions are explained in the following part of this paper.
The insulation of a capacitive grading bushing is stressed, as shown in Figure 2, radially and axially, where any area above the boundary surface between the insulating material and surrounding medium should be considered as a critical area.

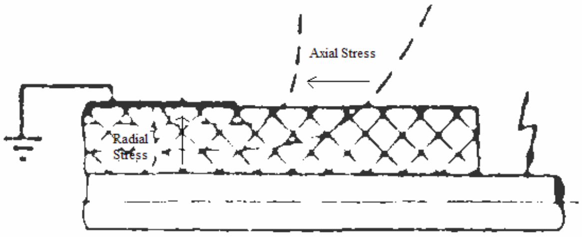

Figure 2. Radial And Axial Stress in high voltage bushings

The radial component of the electric field strength can cause serious breakdown of the insulating material, whilst under certain circumstances, the axial component can lead to surface discharges along the boundary surface. Since the electric strength of the insulating material stressed to breakdown limit is appreciably higher than that of the boundary layer stressed to flashover limit, the axial stress is in general far more critical.

Based on this fact, this paper includes the radial component of electric strength in the introduced objective function and the minimisation is done only on this component of electric strength. The axial component of electrical strength has been considered as a constraint of the objective function and checked only according to its maximum value.

In the objective function, introduced by Equation (2), there are two terms for each radial component of electrical strength that relates to each other by *Dev* variable. *Dev* variable can be only 0 or 1 according to the value of designed parameters. For each design, the radial electrical stress is calculated and if this value is more than the maximum value, the *Dev* variable takes 1 and the minimisation is done on $(\frac{Max^k_{Erad1} - MRS}{MRS})$ term. In this term, Max^k_{Erad1} is the maximum value of radial stress in the side number 1 of the condenser bushing for design number k (total number of designs is *DsNo*), and also *MRS* introduces the Maximum Radial Stress. In this process, when Max^k_{Erad1} becomes lower than *MRS* then the *Dev* variable takes zero value and the minimisation process is done on the $(\frac{Min}{Max})^k_{Erad1} - 1)$ term. From that point, the minimisation process tries to make the maximum radial stress on side 1 (Max^k_{Erad1}) equal to the minimum amount of it (Min^k_{Erad1}). The reason is that the best exploitation of the insulating material in view of its insulating strength is achieved when the radial stress is kept constant. However, it should be noted that this concept can not be achieved in practical cases. But, this process is attempted in the design phase to achieve an optimum solution, which is considered in this paper in its suggested objective function.

In addition, for optimum utilisation of the dielectric, it is recommended that the capacitive grading be arranged so that the same partial voltage is across two adjacent layers [10]. To meet this condition, similar to radial electrical stress, the objective function includes two terms for representing voltage drop on each layer. These terms relate to each other by *Dev* variable that can accept 0 or 1. The $(\frac{Max^k_{\Delta U1} - MVD}{MVD})$ term minimises the maximum voltage drop on each layer to an amount that is lower than the permitted value, that is *MVD* (Maximum Voltage Drop). When maximum voltage drop for different layers ($Max^k_{\Delta U1}$) becomes lower than the permitted value, *Dev* variable gets a 0 value and the objective function minimises $(\frac{Min}{Max})^k_{\Delta U1} - 1)$ term so that the minimum and maximum voltage drop reach to an equal amount.

In the objective function introduced earlier, the index 1 relates to side 1 of condenser bushing and the index 2 relates to side 2 of condenser bushing. α , β , χ , *and* δ give weight to different design parameters, namely, radial electrical stress and voltage drop on each layers of sides 1 and 2.

Regarding constraints 1 through 12, ε (Circle 1 in Figure 2) shows the permittivity of insulating material that can have a maximum and minimum value according to available insulating materials. *Nfl* describes the number of foils that can be used for making partial cylinder capacitors in condenser bushing and it can vary between two margins according to the experience of design engineer. *Dint* (Circle 2 in Figure 2) and *Dext* (Circle 3 in Figure 2) are the diameter of high voltage conductor and inner diameter of outer porcelain insulator. These two parameters can have minimum and maximum values according to the current level of bushing and the needed volume of oil for solving the produced heat caused by the passing current. *Lx* (Circle 4 in Figure 2), *Lp1* (Circle 5 in Figure 2), and *Lp2* (Circle 6 in Figure 2) are zero layer foil length, intermediate layer foil length of side 1 and 2. The horizontal distances between intermediate foil layers are included by *Sp1* (Circle 7 in Figure 2) and *Sp2* (Circle 8 in Figure 2). *DU* is the voltage drop on each partial capacitors created by partial foils and *Eaxl* is the axial component of radial stress. The maximum permitted values of these variables are *MVD* (Maximum Voltage Drop) and *MAS* (Maximum Axial Stress). Finally, the constraint number 12 points at the Conic-TYP2 configuration of foils (Figure 1). These design parameters have been shown in Figure 3 (This figure is shown after section 4).

The Genetic Algorithm (GA) as a metaheuristic optimisation methodology is proposed to solve the optimal bushing design problem. The main idea of GA is that “the best member of a population has the highest probability for survival and reproduction” [5], [6]. Tools applying GA are reported in the literature to be capable of finding a global optimum for mathematical problems having a multiplicity of local optimum and hard non convexities. GA has also proved powerful in the optimisation process in various power engineering applications [e.g., 7-9]. The genetic optimisation algorithm, as applied to optimum bushing design, observes the following steps:

Decision variables in GA are the nine variables as introduced in constrains of 1 to 9 of equation set 3 with considering the minimum and maximum values. A typical chromosome is shown in Figure 4.

ε	Nfl	Dint	Dext	Lx	Lp1	Sp1	Lp2	Sp2

Figure 4.Chromosome Structure for different designs

The GA needs the definition of an initial population. As previously mentioned, each member of the population in the case of this paper is an individual design of the condenser bushing.

The well known operators for genetic algorithm, namely, crossover and mutation, as explained in the literature on genetic algorithm theory [23-25] are used in this paper, too.

In this step, the original population grows through the addition of new members, which are obtained from the crossover and mutation steps. This enlarged population is ranked with a fitness function defined as follows:

$$Fitness(w_i) = \begin{cases} Obj\,Val(w_i) & If\ w_i\ meets\ all\ constra\,\mathrm{int}\,s \\ B & If\ w_i\ doesnot\ meet\ all\ constrains \end{cases}$$

w_i: A sample chromosome

B: A large number

Obj Val (w_i): Object value for chromosome w_i

It means that if a design satisfies all constraints in Equation set 2, then the objective function for that design should be found; otherwise, a large number will be assigned to that design as its fitness.

A reduction of that enlarged population is made, using the ranking, in order to maintain the original population size. Therefore, a new generation is then determined, as a mixture of some members of the previous population plus some new members resulting from the crossover and mutation steps. Poor bushing designs, which does not satisfy all constrains will be eliminated.

In the following section, the optimum electrical design of a typical bushing is proposed.

3. CASE STUDY (BUSHING 145KV-OIP)

The basic technical specifications of the oil impregnated paper bushing chosen for design are as follows:

System voltage 145 kV

Rated current 1600 A

Impulse withstand voltage 650 kV

Power frequency withstand voltage 275 kV

The practical data for minimum and maximum values of design parameters, as well as design constrains as introduced in Equation set 2, has been collected in Table 1.

Table1. Maximum and minimum values of bushing design parameters

Design parameter	Minimum	Maximum
Epsilon of Oil Impregnated Paper	0.0283	0.0483
No. of foils	20	80
Dint(mm)	40	45
Dext(mm)	100	105
Zero layer length,Lx(mm)	1200	1500
Length of partial foils in side 1, Lp1(mm)	200	500
Length of partial foils in side 2, Lp2(mm)	100	300
Length of steps in side1,Sp1(mm)	10	40
Length of steps in side2,Sp2(mm)	10	40
MVD(kV)	-	3.5
MRS(kV/mm)	-	5.2
MAS(kV/mm)	-	0.4

Table 2 includes GA basic settings in running the developed program for finding the optimum design of bushing.

Table 2. Values of GA settings

GA parameter	Value
Population size	300
Cross over probability	0.9
Mutation probability	0.3
Ending criterion	100
α (p.u.)	0.4
β (p.u.)	0.1
χ (p.u.)	0.4
δ (p.u.)	0.1

The results of optimal design of this bushing and also a conventional design have been given in Tables 3 and 4.

Table 3 Decision variables using a conventional design and an optimum design by GA

	Epsilon	Nfl	Dint	Dext	Lx	Lp1	Sp1	Lp2	Sp2
Conventional	0.0283	22	42	106	1300	315	30	130	15
Optimum	0.0283	26	40	104	1497	305	15	197	10

Table4. Percentage of improvement of Performance Indices (Objective Value) using a conventional design and also an optimum design by GA

		(Min/Max – 1)	Average	STD
Erad1	Conventional	0.42	2.67	0.45
	Optimum	0.08	2.66	0.07
	% improvement	33.88	0.21	37.37
Erad2	Conventional	0.54	2.64	0.62
	Optimum	0.10	2.62	0.09
	% improvement	44.19	1.11	53.21
DU1	Conventional	0.43	3.81	0.66
	Optimum	0.09	3.22	0.10
	% improvement	34.08	15.42	55.59
DU2	Conventional	0.55	3.81	0.91
	Optimum	0.11	3.22	0.12
	% improvement	44.52	15.38	78.47
Erad1(2)	Maximum Radial Stress in Different Layers of side 1(2)			
DU1(2)	Voltage Drop on Different Layers of Side 1(2)			
STD	Standard Deviation			

It is clear from Table 4 that the proposed method for optimum bushing design is very satisfying with regard to the essential technological limitations.

In the case of a (Min/Max – 1) index, the *Erad1* has an improvement of 33.88%, *Erad2* an improvement of 44.19%, *DU1* an improvement of 34.08%, and *DU2* an improvement of 44.52%. Regarding the Average, one can see 0.21%, 1.11%, 15.42%, and finally 15.38% improvement in Erad1, Erad2, DU1, and DU2, accordingly. By comparing the standard deviation of *Erad1*, *Erad2*, *DU1*, and *DU2*, it is obvious that in the case of optimum design the deviation of data around the average has decreased considerably.

For easier comparison, Figure 5 shows maximum radial electrical stress for each capacitive layer and Figure 6 shows voltage drop on each capacitive layer in both conventional and optimum design.

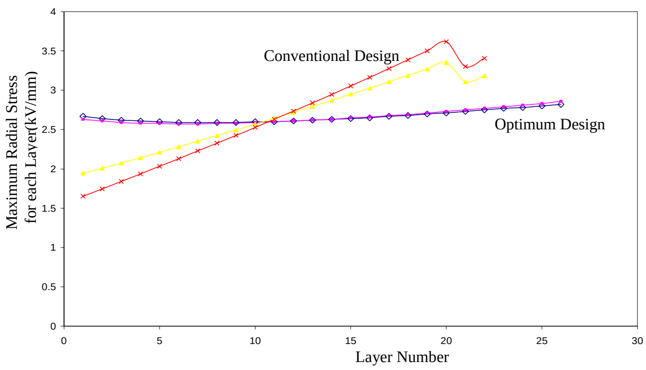

Figure 5 Maximum Radial Electrical Stresses for Each Capacitive Layer for conventional and optimum design

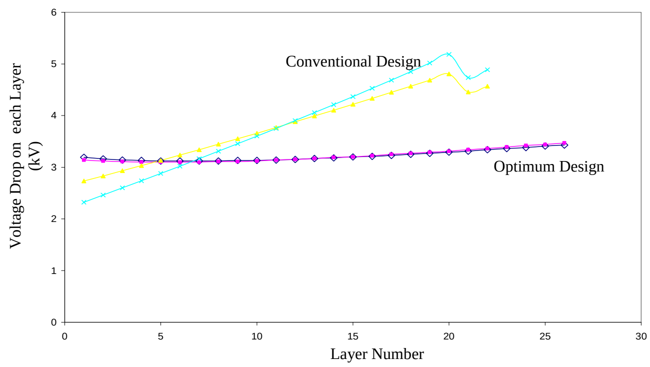

Figure 6 Voltage Drop on Each Capacitive Layer for conventional and optimum design

According to the Figures 5 and 6, a nearly constant electrical radial stress and also voltage drop (in case of different layers) have been achieved using the proposed method.

In order to validate the performance of the proposed algorithm in a practical case, an OIP 145 kV bushing was manufactured according to the design proposed in this paper. The results of power frequency test, tap test, and partial discharge test were according to the IEC 60137 standard.

4. CONCLUSIONS

High voltage bushing breakdown is one of the major contributors to the transformer failures. Since the electrical design of the HV bushings is the most important part of their manufacturing process, finding an algorithm for the design of bushings in an optimum way is very important.

This paper proposed an effective method for finding optimum electrical design of capacitive grading bushings. The proposed method finds the best values of decision variables in the design of a capacitive grading bushing according to a technological objective function and by using genetic algorithm (GA) as a powerful metaheuristic optimisation method. The results of applying this method to a typical 145kV OIP bushing are very promising.

The authors are doing similar research work for finding the α, β, χ, *and* δ parameters of the objective function by using Artificial Neural Network concepts.

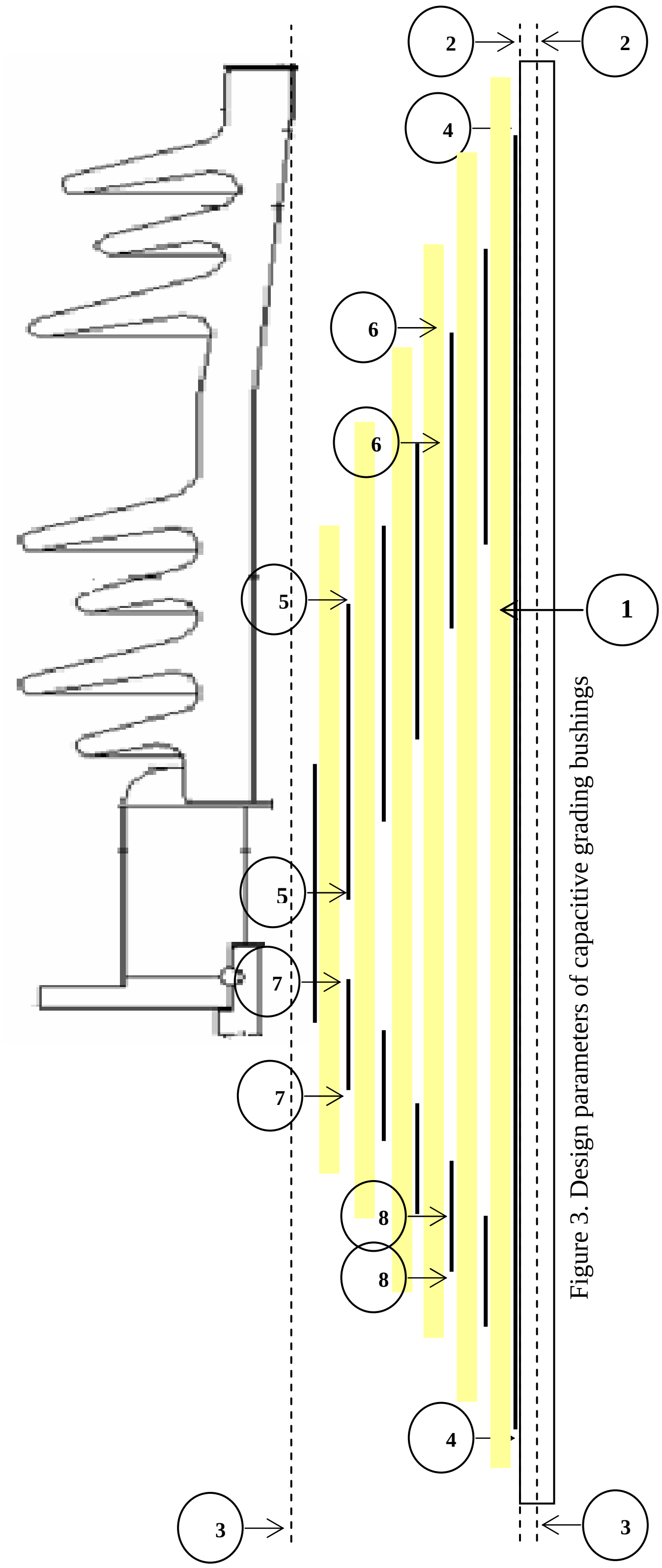

Figure 3. Design parameters of capacitive grading bushings

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