A COMPARATIVE ANALYSIS OF CLASSICAL AND COMPOSITE INSULATORS BEHAVIOR

Marian COSTEA[1], Ileana BĂRAN[2]

In many papers, the good behavior in operation and benefits offered by a certain type of insulator, classic (toughened glass or porcelain) or composite (fiberglass core and silicone rubber) for overhead lines, is often exaggerated and compared only with the disadvantageous characteristics of the other type of insulator.

This paper present both the advantages and disadvantages of each of the two types of insulators, and also some results of tests performed mainly in the last 15 years in the High Voltage Laboratory of Polytechnic University of Bucharest and conclusions based on theirs data processing.

Keywords: ceramic insulator, composite insulator, high voltage testing, up-and-down method

1. Introduction

The outdoor insulation is an important component of an electric power system. Nowadays the insulators and insulator strings are made of glass, porcelain and non-ceramic materials. The first two types are considered classic insulators and sometimes they are included in the same category: ceramic insulators [1].

The non-ceramic (composite) insulator represents the last acquisition in the field of outdoor insulation; their use begun in the 1960's and knows an explosive development in the last years.

Regarding ceramic insulator, it has a long history being used for the first time in the telegraph lines, beginning of the fourth decade of 19th century and then of the end of this century, for power lines.

The aim of this paper is to present both the advantages and disadvantages of each of the two types of insulators, the information being based on literature and, especially, on the test results obtained in the last 15 years in High Voltage Laboratory of the Polytechnic University Bucharest. Also is presented a method to estimate the confidence region of results obtained by up-and-down procedure used at high voltage impulse testing.

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[1] Assoc. Prof, Power Engineering Faculty, University POLITEHNICA of Bucharest, Romania
[2] Prof., Power Engineering Faculty, University "Politehnica" of Bucharest, Romania

2. Main features of ceramic and non-ceramic insulators

The structure of the two types of insulators is well known. Regarding porcelain and glass insulators, the achieved experience in operation is very long, coinciding practically with the beginnings of the widespread use of electromagnetism applications. Technological progress has led to the constructive shapes of the currently used insulators, through improvements of the design, of the recipe used for obtaining glass or porcelain and also through the improvement of the metal fittings and binders used to achieve the bond between the terminals and dielectric body. Regarding the glass insulators has been considered not only the improvement of insulating features but also the mechanical ones through thermic toughening of glass. Regarding the porcelain insulators, attention was paid to obtain resistant glazes in various weather conditions or special resistive (semiconductor) glazes (the first attempts in the 1940's) for use in highly polluted areas. Moreover, the lifetime of such type of insulators can be increased and their behavior at intense pollution conditions can be improved, approaching it from that of a composite insulator, by coating them with room temperature vulcanizing rubber. The market of glass and porcelain insulators is still dynamic at the moment, with all the disadvantages related to their mass, the assembly and installation costs, and the fragility to mechanical stresses or vandalism. The large lifetime (which can exceed 50 years) was the main reason for maintaining these types of insulators in operation, and, in certain cases, they represents the reliable solution.

Regarding the composite insulators are always highlighted the following qualities:
- a good behavior in natural or industrial polluted areas (a "lotus effect" particularly active, the hydrophobic surface being able to self regenerates after a thermal or chemical stress);
- a mass of approx. 10 times lower than that of a glass or ceramic insulator string, for the same nominal voltage line; it allowed the redesign of the towers and reducing the costs of entire line;
- simplifying of the insulator string assembling and also their installation;
- very good behavior to vandalism;
- high resistance to arcing and also to ultraviolet radiation of the sun;
- high breaking strength of glass fiber core subjected to longitudinal mechanical efforts; this strength can exceed the similar one of the steel having the same diameter;
- silicone rubber can be colored in shades that can reduce the visual impact of overhead lines.

In addition, the improvement of manufacturing technology (we can say that, at this moment, it has clearly matured comparing with the state of 30...40 years ago) and strictly quality control, substantially reduced the rate of

incidents, most of them of mechanical nature, and led to a fall in prices. As consequence an increase in competitiveness was recorded compared with porcelain or toughened glass insulators.

However, silicone rubber insulators have also weaknesses. Of these the following could be mentioned:
  − low strength at transverse mechanical efforts (shear forces);
  − they requires careful handling during the transport and assembly operations; the scratching on rubber surface diminishes the dielectric features;
  − they need adequate storage conditions, the rodents attacking silicone rubber; on the other hand it could be mentioned their fragility in the attack of some birds (starlings, parrots, etc.);
  − the silicone rubber is also sensitive to the attacks of fungi or other inferior plants (such as moss or lichen); their deposition on the surface of insulator, in wetlands, will led to water retention and then compromise the dielectric features;
  − the reduced mass of the insulator favors conductors' galloping under the action of wind or during sudden ice downloading; to reduce this probability it is necessary to add counterpoise at the bottom of insulator string.
  − regarding the use on DC overhead lines: there is still hesitation, because the lack of data/experience on their behavior over time at this specific type of stress [2]; it could be mentioned that there no IEC standard regarding the use of composites in DC power lines.
  − about live working: large reluctant to work on overhead lines equipped with composite insulators because of the risk of sudden fracture. Before starting the work, the identification of hidden defects must be carry out by measuring the electric field distribution along the string;
  − a study on the aging of composite insulators showed that after 15 years of a 400 kV overhead line operation in a coastal marine area [3], the hydrophobicity of coating (measured by contact angle of water droplets to the surface) decreased significantly especially on the sunny side of insulator.
  − the fiberglass cord can fracture under the action of mechanical and electrical stresses in the presence of water: corona discharge produce nitric acid in the presence of moisture, favoring the corrosion processes [4]; the water penetration to the fiberglass core may occur during manufacturing, transportation or installation operations but the improper handling (especially by bending isolator) is the main cause.

3. Results of dielectric tests

Regarding the insulators behavior during laboratory tests at impulse voltages, several particularities are worth mentioning. Thus, according to

IEC 60060-1 [5] and IEC 60383-2 respectively, the recommended method for determining the 50% disruptive discharge voltage (U_{50}) is "up-and-down". Knowing U_{50} and based on the recommended values of the relative standard deviation, z*, the withstand voltage (statistical withstand voltage) U_{10} can be calculated using the relation: $U_{10} = U_{50}(1 - 1.3z^*)$. In the case of composite insulators the number of voltage levels necessary to determine U_{50} is sometimes too high, and the first consequence is the increasing of the test duration. As known, in the procedure "up-and-down" the applied voltage to the object under test is increased or decreased with a small voltage step, ΔU, depending of the previous event: withstand respectively disruptive discharge. The 50% disruptive discharge voltage will be determined according to the relation:

$$U_{50} = \left(\sum_{k=1}^{m} n_k U_k \right) / \sum_{k=1}^{m} n_k \qquad (1)$$

where m is the number of significant voltage levels (which can be taken into account according the rules set by IEC 60060-1) and n_k - the number of applied voltage impulses on k level, at which corresponds, as average, the voltage U_k.

In the last 15 years, in the HV laboratory of Politehnica University of Bucharest were tested different types of composite insulators produced by local companies or of abroad. There were tested insulators and insulator strings for transmission overhead lines (110, 220 and 400 kV), for distribution (20 kV) or AC electric traction (25 kV). Were performed dielectric tests at power frequency voltage, standardized lightning (LI) and switching impulse (SI) and also for determining the radio interference voltage (RIV).

When up-and-down method was applied in order to find 50% disruptive discharge voltage, the number of voltage levels ranged from 2 to 10, as shown the table 1.

Table 1

Number of levels necessary to calculate U_{50} in "up-and-down" method

Standardized voltage impulse	Polarity	No. of analyzed cases	Numbers of levels in "up-and-down" method								
			2	3	**4**	5	6	7	8	9	10
SI	+	7	-	-	**4**	2	1	-	-	-	-
	−	7	-	-	**4**	2	1	-	-	-	-
LI	+	22	1	6	**11**	2	1	-	-	-	1
	−	21	-	**9**	7	5	-	-	-	-	-

Some conclusions could be drawn from this, regarding the most likely number of voltage levels necessary to calculate the U_{50}: in the case of SI, under artificial rain, almost 50% of the cases requires four voltage levels; in the case of LI of positive polarity, also four levels are necessary in 50% of experiments, while for the negative polarity, in most cases 3 levels could be sufficient.

The ratio between 50% disruptive discharge voltage at negative and positive polarity respectively (U_{50}^{-}/U_{50}^{+}) is not always higher than unity. For the SI, it ranging (in our test results) from 1.06 to 1.23, but there was one case (400 kV insulator string) it was equal to 0.82. Regarding LI, this ratio was between 1.002 and 1.19, and in two cases (110 kV insulator strings), it has 0.96 and 0.97 respectively.

4. A method to estimate the confidence region of results obtained by up-and-down procedure

As was previously mentioned the up-and-down procedure in the impulse voltage tests is the recommended one. But which is the confidence degree of the obtained results using this method?

An illustration of such a test diagram is given in the table 2, the equipment under test being a composite post insulator ICS 24/3 type (rated voltage 20 kV) subjected at standard lightning impulse (LI), positive polarity.

Table 2

The test diagram for an MV composite insulator using "up-and-down" method

n_k / U_k	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21
151	0												0								
156		0		0				0		0		0		0		0				0	
161			1		0		1		1		1				1		0		1		1
166						1												1			

U_k (kV) : crest value of the test voltage; n_k : rank of the applied test voltage

Such a test can be summarized in the following test diagram:

Number of levels   1 .... i .... m

Test voltage U_1 ...... U_i .... U_m

Number of flashovers $N_{f,1}$ ..... $N_{f,i}$ ...... $N_{f,m}$ with $N_f = \sum_{i=1}^{m} N_{f,i}$

Number of withstands $N_{w,1}$ .... $N_{w,i}$ ..... $N_{w,m}$ with $N_w = \sum_{i=1}^{m} N_{w,i}$

The probability of obtaining the whole set of results relative to all levels

is:

$$P_R = \prod_{i=1}^{m} \frac{N_i}{N_{f,i} N_{w,i}} P^{N_{f,i}} \left(1-P\right)^{N_{w,i}} \qquad (2)$$

Assuming that the true representation of the failure probability $P(U)$ is a function $\Phi\ (X;\ A,\ B,\ C,...)$ it can be seen that the above expression depends on parameters A, B, C,… and on the results N_f and N_i

Choice of interpolating function and parameter estimation

The function $\Phi(U; U_{50}, Z)$ assumed for interpolating $P(U)$ was a modified Weibull function:

$$\text{probability distribution} \rightarrow \Phi(U) = \Phi[y(U)] = 1 - 0.5^y$$

$$\text{standardized variate} \rightarrow y = [1 + (U - U_{50})/K_0 Z]^{\alpha}$$

$$U \geq U_0 = U_{50} - K_0 Z \quad \alpha = 1.39/\ln(K_0/(K_0 - 1))$$

According to the principle of maximum likelihood it is presumed that the function that gives the "best fitting" to the experimental results is the one to which corresponds the maximum probability of obtaining these results. In other terms, for a given set of results R and a given value for the parameter K_0 (usually in the range 2 to 5), the best estimation of the parameters U_{50} and Z will be the values $U_{50,M}$ and Z_M which maximize the likelihood function (L) in equation (3).

$$L(R; U_{50,M}, Z_M) = K \cdot P_R(R; U_{50,M}, Z_M) = L_{MAX} \tag{3}$$

The maximum likelihood estimators for U_{50} and Z cannot be obtained as explicit functions of the observed data, but using an optimization procedure.

Test for goodness of fit

In order to check if the interpolating function $\Phi(X)$ and the most likely values of the parameters fit sufficiently well the results, which is we have to test the hypothesis $H_0 : P(U) \equiv \Phi(U; U_{50,M}, Z_M)$ against $H_1 : P(U) \neq \Phi(U; U_{50,M}, Z_M)$.

The procedure can be summarized in the following steps:

- Calculation of the probability of obtaining the results assuming that H_0 is true.
  $$P_R = \prod_{i=1}^{m} \frac{N_i!}{N_{f,i}! N_{w,i}!} (P)^{N_{f,i}} (1 - P)^{N_{w,i}} \tag{4}$$

- Calculation of the maximum possible value of the probability of obtaining the results using:
  $$P_{R,MAX} = \prod_{i=1}^{m} \frac{N_i!}{N_{f,i}! N_{w,i}!} \left(\frac{N_{f,i}}{N_i}\right)^{N_{f,i}} \left(\frac{N_{w,i}}{N_i}\right)^{N_{w,i}} \tag{5}$$

- Calculation of the quantity $g = P_R / P_{R,MAX}$, which clearly lies between 0 and 1 being 1 when H_0 is rigorously supported by the results. It was proved, [6], that the distribution of the test statistic i.e. $-2\ln(g)$ tends asymptotically to the chi-square distribution with ν degree of freedom, where $\nu = N_{level} - N_{param}$, N_{level} is the number of test voltage levels and N_{param} the number of estimated parameters (in this case 2).

- Selection of the value $P_{R,\lim}$ - a sufficiently low, arbitrary value of the probability (usual values being 0.1, 0.05 and 0.01).

- Determination of $\chi^2_{\lim}$ by solving the equation $P_R(\chi^2_{\lim}) = 1 - P_{R\ \lim} = C$

- Determination of $g_{\lim} = \exp\!\left(-\chi^2_{\lim}/2\right)$
- Acceptance of H_0 if $g > g_{\lim}$, that is if $P_R(g) > P_{R,\lim}$.

It must be noticed that $P_R(g)$ can be regard as an index of goodness of fit.

Confidence region

The most likely values of the parameters ($U_{50,M}$ and Z_M) represents only a point in the parameters' space, in this case the plane $\{U_{50}, Z\}$. We must therefore consider the possibility that another point, different from ($U_{50,M}$ and Z_M) may be the "true point" in spite the fact that its likelihood is lower than $L_{\max}$. The hypothesis that a point (U_{50}, Z) may be the "true point" cannot be rejected unless the corresponding value of the likelihood ratio becomes smaller than a critical value:

$$a = \frac{L(R;U_{50},Z)}{L(R;U_{50,M},Z_M)} = \frac{L(R;U_{50},Z)}{L_{\max}} \le a_{\lim} \tag{6}$$

The critical value is determined knowing that the quantity $-2\ln(a) = \chi^2(\nu)$ follows a chi-square distribution with $\nu = N_{param}$ degrees of freedom. Given $P_{R,\lim}$ we have $P_R\!\left(\chi^2_{\lim}\right) = 1 - P_{R\ \lim} = C$ and $a_{\lim} = \exp\!\left(-\chi^2_{\lim}/2\right)$. In the plane $\{U_{50}, Z\}$ the locus

$$C2: \quad L(R;U_{50},Z) = a_{\lim}L_{MAX} \tag{7}$$

divides the plane in two regions: one containing all the points associated to the condition $a < a_{\lim}$ and the other containing the points for which $a > a_{\lim}$.

The last one can contain the "true point" and therefore defines the confidence region for the parameters, with a confidence $C = 1 - \Pr_{\lim}$. As an example, the confidence region computed for the up-and-down test quoted above is represented in figure 1.

5. Conclusions

The paper presents both the advantageous properties and the disadvantages of the classical insulators (made of glass or ceramic) and the composite ones (with fiber glass core and rubber silicone sheds). It is too early to affirm that the dispute between the two types of insulators it's over. Total replacement of the classical insulators in overhead lines by the composite ones, in any type of pollution areas and for any type of thermal, chemical, mechanical or biological aggression, it is difficult to be predicted.

Rather, these types will coexist, enabling designers to opt for one of solutions depending on the specific characteristics of the area crossed by the line.

Even in the theoretical case where the replacement of conventional insulators will be total, it could be assumed that the test procedures for composite

insulators will be adapted (as they have been adapted for power cable insulation), the final aim being, firstly to not be overstressed the insulation during tests, and secondly to obtain results with higher degree of confidence and reproducibility.
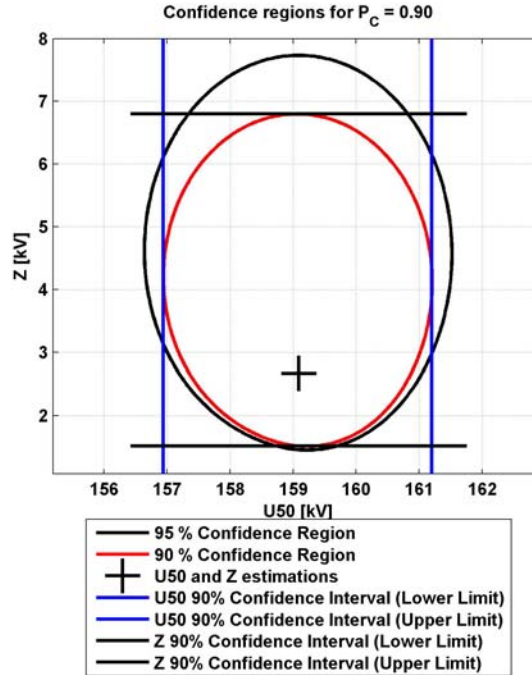

Fig. 1. Evaluation of the amount of uncertainty in the estimation of the interpolating function parameters using confidence regions

R E F E R E N C E S

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