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Conference Paper

RELIABILITY OF INSULATORS

D. Riviere
Associate IEEE
Sediver
Paris, France

A paper recommended by the IEEE Transmission and Distribution Commit tee of the IEEE Power Group for presentation at the IEEE Winter Powe Meeting, New York, N. Y., January 26-31, 1969. Manuscript submitted October 3, 1968; made available for printing December 4, 1968.

Price: $1.00
(75¢ at meeting)

345 East 47th Street
New York, N. Y. 10017

Litho in USA

Paper No.
69 CP 66 - PWR

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D. Riviere
Sediver
Paris, France

ABSTRACT

This paper deals with reliability tests as a reliable method of predicting long-term performance. First test results appear to warrant further pursuit of this program. Present and future testing program outlined.

INTRODUCTION

All technicians who have checked the quality of insulators, used in high voltage overhead lines, after several years of service, realized that the mechanical or electro-mechanical resistance of some of them had decreased and that others no longer withstood a voltage of even a few KV. The insulation in the strings they comprised had therefore weakened, increasing the probability of flashover and the risk of line drops.[1,2,3]

We shall call "defective" any insulator which, clean and subjected to a mechanical load equal to its rated maximum sustained load, no longer withstands 40% of its guaranteed dry flashover voltage. For example, these would be punctured porcelain or annealed glass insulators or toughened glass insulators with broken skirts.

The proportion between the number of insulators which become "defective" per unit time and the total number of insulators considered will be called "rate of failure".

Experience has shown that this "rate of failure" depends on the type and even on the lot of the insulator considered as well as on the nature and the level of the stresses which it undergoes in service. This "rate of failure" can, all other things being equal, also vary with the age of the insulators.

This "rate of failure" is one of the most important criteria in judging the quality of insulators in service. The reception tests on insulators usually carried out by users [4, 5] do not permit us to be sure that this rate of failure will be sufficiently low and that it will not increase with time.

We therefore suggest the usefulness of perfecting a test which permits prediction of insulator behavior in service. Such a test can give users further security and manufacturers, a potent means of study.

With this aim, we can use principles which have proven their value in other areas. First, we shall review indispensable rudiments of reliability. We shall then show how they can be applied to insulators. Then, we shall see, in the light of the first experimental results obtained, that this method of investigation warrants being further pursued. Finally, we shall indicate the program of tests now under way and those planned.

Rudiments Of Reliability [6, 7]

Experience has shown that the failures which happen to a material can be classified into three categories.

Infancy failures which happen very early in the life of a material and which are due for the most part to faulty manufacture and insufficient routine quality control.

Accidental mishaps. They happen at haphazard intervals, in irregular ways, unexpected, unpredictable. Nevertheless, providing that a long enough period is taken into consideration, they obey, on the whole, several rules, so that the frequency of their appearance is roughly constant.

Wear of the material. They are a symptom of ageing. Often they can be avoided by applying a policy of appropriate maintenance.

The evolution of a material, in the course of time or of a succession of ordeals, can then comprise three successive periods:
-the first, called period of youth or adaptation, during which the majority of failures is of the first category;
-the second, period of useful life during which the majority of failures is of the second category;
-the third, period of wear during which the majority of failures is of the third category.

Let us call h(t) the rate of instantaneous failure, that is to say h(t) dt the probability that a failure will occur in a short interval of time (t, t+dt) or conditional probability of a failure's occurring between t and t+dt, the failure not occurring before the instant t.

In the general example shown above, the variation of h(t) with time will have a general shape shown schematically in Figure 1.

The rate of failure defined in the Introduction as a percentage of insulators becoming defective can also be defined as the probability which an insulator has of becoming defective. It is equally in terms of "probability" that it is preferable to define reliability which is "the probability that an apparatus function correctly during a given time and in precisely defined working conditions".

The mathematical expression of this reliability R(t), function of the time t taken into consideration, is:

$$R(t) = e^{-\int_0^t h(t)\,dt}$$

where e is the base of the neperian logarithms (2, 7, 18, 28...) and h (t) the rate of instantaneous failure which is a function of time respectively decreasing, constant, then increasing during the infancy, the useful life, and the wear periods.

This rate of failure can be determined only for specified operating conditions.

One can devise test conditions which accelerate the degradation of insulators. But we must be sure that the degradation processes be identical to those which appear in service. We would then find the same periods of infancy, useful life and wear as in service, if they exist, but the duration of each of these must be sufficiently short for significant results to be obtained in a sufficiently short time - at the most, several weeks or several months. The rates of instantaneous failure will then be much greater than in service.

This acceleration of degradation can be obtained:
-either by increasing the frequency of application of the maximum stresses to which insulators risk being subjected in service,
-or by increasing the level of the stresses applied,
-or by simultaneously using both these possibilities.

However, we shall try to use only the first of these three alternatives in order to avoid the appearance of failures different from those which occur on lines.

Reliability Tests Applied To Insulators

In service, insulators are submitted to numerous stresses of very different kinds:

- mechanical stresses
- electrical stresses
- thermal climatic stresses
- stresses of varied ambient conditions due to pollution, rain, snow.
- stresses due to exceptional incidents: heating provoked by flashovers, vandalism, etc.

The failures as we have defined them in the Introduction can be caused by a single one of these stresses, the others playing only a negligible or nil role. It is then easy, through simple tests, to determine the level of each independent stress which can be withstood by the insulator without failure.

The effects of stresses of this nature will have to be studied by appropriate experiments which are not the subject of this paper. That is why we will not make a part of the tests in which we are involved such parameters as pollution, power arcs, vandalism, etc.

On the other hand, during these tests, we shall try to submit insulators to all the stresses which, by their simultaneous action, can coincide with the appearance of "failures", to wit:

- the static mechanical stresses defined by a load S on the insulator,
- the dynamic mechanical stresses defined by an alternating load of amplitude D which is added algebraically to load S,
- thermal stresses defined by periods of ambient cold temperature of Θ_1°F and periods of ambient warm temperature of Θ_2°F,
- electrical stresses at industrial frequency defined by the RMS voltage U applied continuously on the insulator,
- electrical impulse stresses defined by the peak value u of an impulse wave 1.2/40, applied to the insulator at regular intervals.

The rate of failure h will then depend on the parameters which define each of these stresses: S, D, Θ_1, $\Theta 2$, U, u.

The value of each of these parameters should be related, if possible, to the guaranteed values of the new insulator, and chosen in such a way as to represent approximately the maximum level of each of these stresses which an insulator may be called upon to withstand in service. In these conditions, the acceleration of degradation, compared to service conditions, will not be due to the application of stresses having an amplitude greater than in service, but to the continuous application of the maximum stress level and/or to increasing the frequency of their appearance. We can then hope that the deterioration process will be identical to that which may occur in service.

First Test Results

The first tests we made covered a total of 112 porcelain and toughened glass cap and pin insulators of 8 different types which we shall call A, B, C, D, E, F, G, H.

The test method was the following: The insulators are subjected to a cycle of stresses lasting 400 hours. This cycle is repeated until breakage occurs, but to a limit of 13 cycles.

A cycle includes two periods:
-during the first period of 200 hours, the insulators are submitted to mechanical traction stresses of undulating dynamic nature. If P is the M and E rating, the minimum value of the applied load is $\frac{P}{3} - \frac{P}{30}$ and the maximum value, $\frac{P}{3} + \frac{P}{30}$, the period being two seconds. Each cap and pin insulator undergoes a permanent AC voltage of 20 KV RMS. The testing apparati are outdoors so that the insulators sustain natural climatic thermal stresses.
-during the second period of 200 hours, conditions are similar to those in the first periods except for

the mechanical stresses of which the lowest and highest applied load values are: $\frac{6P}{10} - \frac{P}{80}$ and $\frac{6P}{10} + \frac{P}{80}$

At the end of each 400-hour cycle, each insulator is subjected to an electromechanical test: a voltage equal to 90% of the flashover voltage is applied to it; then, maintaining this voltage, it is subjected to an increasing tensile load up to a value of $\frac{8P}{10}$.

Each insulator therefore can have either withstood the test for 5200 hours, or have failed during one of the 13 cycles provided for in the test. This failure can have happened either during the first period or during the second period of the cycle, or during the electromechanical test which ends the cycle. We note each failure by a number between 1 and 13 to indicate the cycle during which it happened, followed by a letter the moment of breakdown, within the cycle. (A is the first period; B, the second; and C, the electromechanical test).

TABLE I

Type of Insulator	No. of Insulators Tested	No. of Insulators Which withstood 5200 hours	Breakdowns
A	4	4	
B	20	20	
C	12	12	
D	12	5	10C-3C-4B-5C-5C-6C-6C
E	12	12	
F	12	12	
G	10	0	1C-1C-1C-1C-2C-2C-2C 2C-3C-3C
H	30	0	1A-1A-1A-1B-1B-1B-1B 1B-1B-1B-1B-1B-1B-1B 1B-1B-1B-1B-1B-1C-2A 2C-1B-1B-1B-1B-1B-1B 1B

All these failures affected the insulator dielectrics which no longer withstood the voltage applied to them. A single insulator of type D, broke in half causing the bottom of the string, of which it was a part, to fall.

We note:

1)that insulators of types A, B, C, E and F had no failures during the test. Types A, C, and E are insulators used throughout the world and which appear to satisfy users. Type B is a special model; type F is recent and has not yet proven itself through experience.

2)that none of the insulators of types G and H withstood this test. The insulators of type H, of insufficient quality, are now being replaced on the network using them. Unfortunately we have no precise information on the behavior in service of type G insulators.

3)type D insulators, used widely in many networks, are considered by the users of one such network as having service behavior much inferior to types A and B, because their rate of electrical failure is clearly higher.

All the information we have indeed shows a real correlation between these test results and insulator behavior in service. It will obviously be necessary to the study of this correlation to definitely confirm this fact.

Advantage Of These Tests

In these electromechanical tests during which the mechanical load was brought to 80% of the rating, we considered "defective" any insulator the M and E strength of which had decreased by more than 20%. In order to examine the variation in the rate of failure, with time, we use the 400-hour cycle as a time unit. We shall not examine the results obtained with insulators of type H which had too fast a destruction rate, but only types D and G of which we shall try to liken the law of breakdown as a function of time to a law of Weibull which corresponds to a rate of failure.

$$h(t) = \frac{B}{\eta} \left(\frac{t-\gamma}{\eta}\right)^{B-1}$$

B, η and γ being parameters which can be determined by experience.

One will note that $B < 1$ corresponds to a decreasing breakdown rate

$B = 1$ corresponds to a constant breakdown rate

$B > 1$ corresponds to an increasing breakdown rate

γ is the minimum life span and

η is the characteristic life span.

Reliability is then expressed by

$$R(t) = e^{-\left(\frac{t-\gamma}{\eta}\right)^{B}}$$

We shall determine the parameters γ, η, and B of the experimental laws using a graph of functional scale which can be obtained commercially. Using this graph consists of showing the percentage of cumulative failure (on the ordinate) as a function of time or better, in our case, as a function of the number of cycles (on the abscissa). We then obtain a rectilinear curve when the minimum life span γ is zero. If such is not the case we determine γ by selecting the value for which a horizontal movement of all the experimental points of this same quantity γ shows a straight line; η is then the abscissa of the point of this straight line of which the ordinate is $\frac{e-1}{e}$ i.e. about 63%. B can be read at the intersection of the B axis, shown on the graph, with the parallel on the right shown leading from the encircled point.

TABLE II
Cumulative Percentage of Breakdown as a Function of Cycles

No. of cycles	G	D	D_1	D_2
1	35	0	0	0
2	75	0	0	0
3	95	4.16	8.4	0
4	--	12.50	25	0
5	--	29.2	58.4	0
6	--	46	91.6	0
7	--	46	--	0
8	--	46	--	0
9	--	46	--	0
10	--	54.2	--	8.4

We have shown on Table II the cumulative percentage of failures as a function of the number of cycles sustained by the insulators of types D and G.

We have carried over onto Figure 2 the values corresponding to type G. We note that the 3 points are aligned without a movement of translation; then $\gamma = 0$. We read on this graph $\eta = 1.65$ and $B = 1.8$.

The rate of experimental breakdown is then:

$$h(t)_G = 1.09 \left(\frac{t}{1.65}\right)^{0.8}$$

And the experimental reliability

$$R(T)_G = e^{-\left(\frac{t}{1.65}\right)^{1.8}}$$

We have shown in Figure 3 the values corresponding to type D. We note that the first 4 points are perfectly aligned, but that those that follow are not and that there is no value of γ which permits them all to be aligned. Furthermore, examination of the results shown in Table I shows that 6 of the 12 insulators broke during the first 6 cycles, while the six others sustained the 5200 hours of testing, without failure, except for one which broke during the tenth cycle. We can then believe that the quality of these insulators was not homogeneous and that the quality of six of them was inferior to that of the six others. We shall therefore consider these units as comprising two distinct lots D_1 (the six units broken during the first 6 cycles) and D_2 (the six other units).

Thus, the cumulative percentages of failure as a function of the number of cycles for each of these two D_1 and D_2 are shown in Table II. We have carried over to the graph of Fig. 4 the corresponding points.

The 4 experimental points of lot D_1 are suitably aligned; thus $\gamma = 0$, and we read $\eta = 5$ and $B = 4.9$; the rate of failure and the experimental reliability are then respectively:

$$h(t)\ D_1 = 0.99 \left(\frac{t}{5}\right)^{3.9}$$

$$R(t)\ D_1 = e^{-\left(\frac{t}{5}\right)^{4.9}}$$

The straight line which was drawn for lot D_2 is that which would correspond to a constant rate of failure ($B = 1$) taking into consideration the only breakdown which occurred in the tenth cycle and would correspond to a constant rate of breakdown:

$$h\ D_2 = 0.0077$$

and a reliability:

$$R(t)\ D_2 = e^{-\frac{t}{130}}$$

We have therefore just verified that the results obtained could be interpreted thanks to principles of reliability. Unfortunately the small number of insulators tested does not yet permit us to form a definite judgment on the effectiveness of this method. However, the results found prompt us to pursue our investigations.

Conclusions - Program Of Next Tests

The analysis just made of the results of long-term tests which we have made on cap and pin insulators should be viewed with prudence because of the small number of insulators tested.

However, we can conclude therefrom:

1.-that cap and pin insulators, or at least some of them, are susceptible to being affected by ageing which appears by puncture of the dielectric, all the more dangerous as it is often invisible.
2.-that this ageing appears in some types of insulators at a level of stresses equivalent to that which they would have to sustain in service.
3.-that it is possible to perfect a reliability test applicable to overhead line insulators.

We are presently continuing these tests on insulators of Classes 52-3 and 52-5, modifying and simplifying the tests in the following manner:

-test duration: 2000 hours
-applied static load: $S = 0.6T$
(T being the M and E rating)
-dynamic load: $D = \pm \frac{T}{80}$
-thermal stresses: $\begin{cases} \Theta_1 = -60^\circ F \\ \Theta_2 = +120^\circ F \end{cases}$
or $\{$ambient conditions
-electrical stresses at industrial frequency
U = 30 KV
-electrical impulse stresses: not applied.

These tests are applied on insulators of types B, E, F and G.

It would obviously be indispensable to know at the same time the behavior in service of insulators of the types tested. The cooperation of users is therefore indispensable to the compilation of statistics on the number of insulators punctured per year in service. Checking these insulators can be done, for example, by a simple verification apparatus such as the one mentioned in paragraph 242 of section 13 of reference 8 (R and I. E. line-line insulator tester).

Comparing test results and service statistics should enable us to evaluate the practical value of these tests and also to determine by testing the life span of insulators which correspond to a practically suitable quality level.

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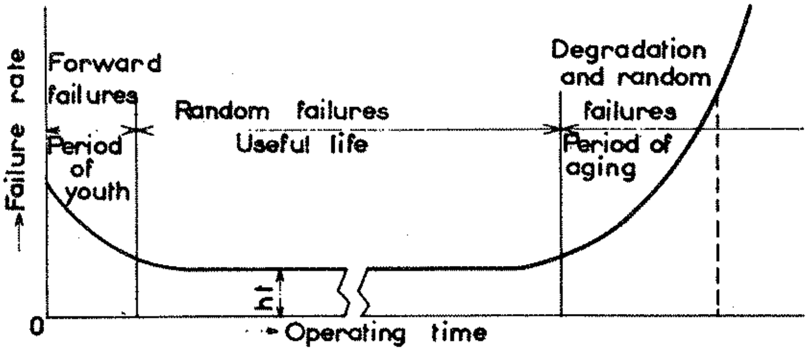

Figure 1.

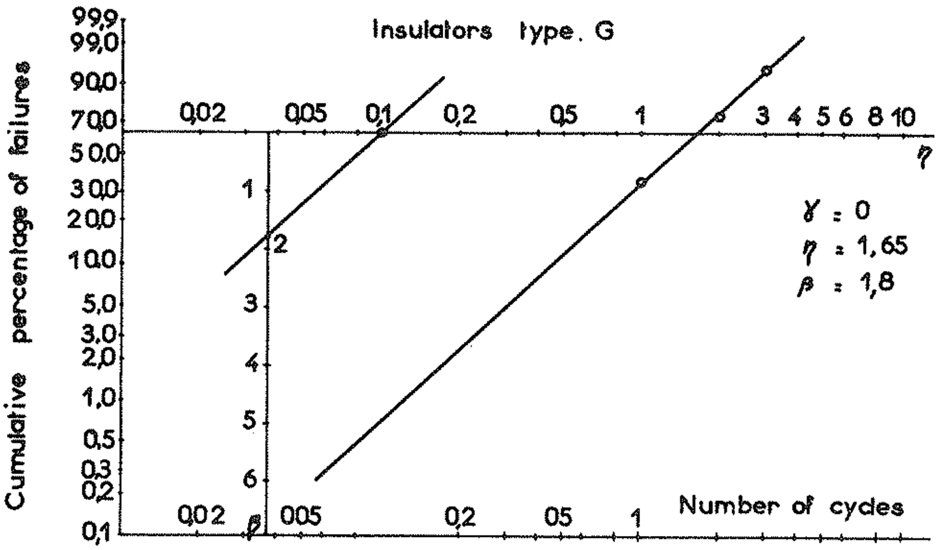

Figure 2.

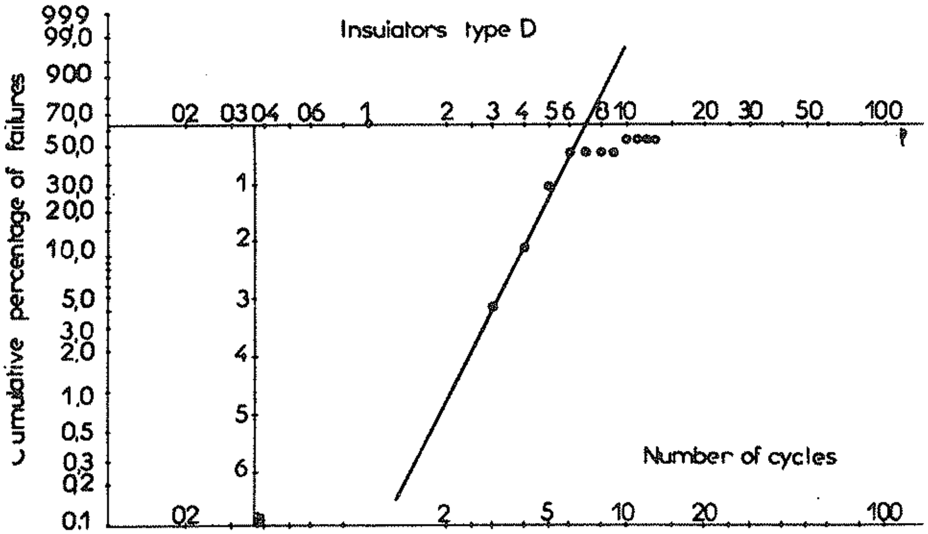

Figure 3.

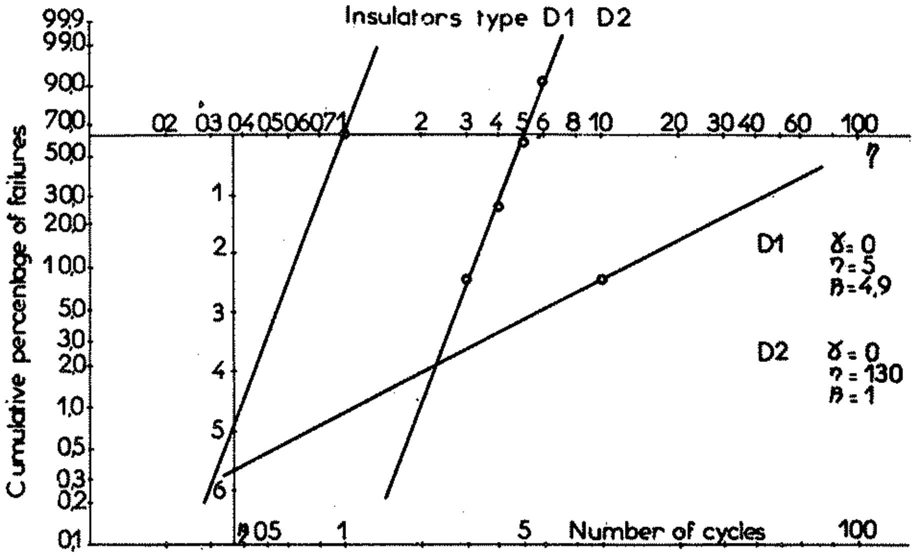
Insulators type D1 D2
Cumulative percentage of failures
99,9
99,0
90,0
70,0
50,0
30,0
20,0
10,0
5,0
3,0
2,0
1,0
0,5
0,3
0,2
0,1
02 03 04 05 06 07 1 2 3 4 5 6 8 10 20 30 40 60 100
η
1
2
3
4
5
6
β 05 1 5 Number of cycles 100
D1 γ = 0
η = 5
β = 4,9
D2 γ = 0
η = 130
β = 1

Figure 4.