ON THE ADEQUACY OF SOME POSSIBLE MODIFICATIONS OF THE SEPARATE-SOURCE TEST OF ELECTRICAL EQUIPMENT

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1. Introduction

In an earlier paper [1] the author tried to show that the separate-source test in the present form might be a most dangerous one for the sound insulation. It seems, considering our present knowledge of the properties of insulating materials that some revision of the test procedure as well as of the internationally prescribed values may be a subject for discussion.

The aim of the present study is to contribute a few ideas to this discussion which perhaps may be useful if its necessity will be accepted. The author appreciates quite well that an unjustified reduction of the requirements may bring risks for the safe operation of electrical equipment, but he hopes that the modifications proposed below are not unjustified. It will be useful to consider first the purpose of the voltage test *in general.*

2. Interturn insulation, layer insulation

For apparatus containing coils, as transformers, etc., the interturn insulation can be tested practically *only* with impulse (surge) voltages. At present this fact seems to be accepted generally. The induced-voltage test with twice the nominal voltage is not convenient for testing interturn insulation faults, because the test voltage between turns is of the order of magnitude of 100 Volts maximally which is too small to break down an even very bad interturn insulation. Therefore it may test only for some layer faults if the number of turns per layer is not too small. The induced-voltage test is therefore suitable for testing the insulation between windings of the different phases, between the terminals, etc.

The impulse tests with appropriate voltage are therefore necessary for such transformers, too, which are designed for so-called ,non-exposed' installations, *e.g.* for cable networks. This test is not standardized yet, but in spite of this fact it seems that it will be accepted by the manufacturers as a good quality control method. For the magnitude of the test voltage the crest value of the nominal line-to-line voltage might be considered as an adequate value, naturally only for transformers in non-exposed installations. It will be perhaps useful to give a numerical example. Let us suppose that $N = 2000$ is the number of turns per phase of a transformer with 35 kV nominal voltage. The voltage per turn is therefore, if the high-voltage winding is star-connected, 10 V/turn $\frac{35\,000/\sqrt{3}}{2000}$. The voltage between turns with the proposed impulsetest would be

$$U_{tt} = a\,\frac{35 \cdot 10^3 \cdot \sqrt{2}}{2000} \approx 250 \text{ V/turn}$$

taking for

$$a = \sqrt{\frac{C_{\text{earth}}}{C_{\text{turn}}}}$$

the moderate value of 10. (It lies between 5 and 30.)

If the number of turns per layer is too great and there is a good layer insulation, a lower impulse voltage will also give a good check.

The interturn and the layer insulations of transformers designed for exposed installations are sufficiently tested by the impulse-test provided in most national standards, and in the IEC Recommendations. It seems, however, that if the impulse test prescribed is carried out as a type test only, an impulse test with some reduced amplitude would be very useful also as a routine test.

The problem of the adequate testing of the interturn and of the layer insulations seems therefore, for the time being, to be *solved* by the impulse-test. The idea might occur that with this test the resistance of these insulations against thermal instability, thermal breakdown and breakdown resulting from ionization cannot be examined. This is quite so, but the adequacy of the insulation can be calculated now for the thermal breakdown with reasonable accuracy, the voltages, the temperature distribution, the temperature-dependence of the losses being well-known.

The presence of ionization can be detected also and it can be avoided with adequate dimensioning and with adequate manufacturing technology. It shall be presumed, however, that severe local faults in the insulating wall are not present, but the correctness of this presumption might even be demonstrated by the impulse test.

3. Main insulations

(Insulations between conductors and earth, insulation between primary and secondary windings, etc.)

Here the different kinds of main insulations shall be considered separately.

3.1 *Transformers.*

The separate-source test of the main insulation of transformers with full insulation is carried out with a prescribed voltage of 50 Hz frequency and it lasts one minute The minimum value of the test voltage is about twice the line-to-line voltage or $2\sqrt{3}$-times the line-to-ground which is the service-voltage of the main insulation. The minimum value of the safety factor $2\sqrt{3} = 3.5$ seems to be somewhat exaggerated. The safety factors for 10 kV, 20 kV and 35 kV are 5.6, 3.92, 3.9 respectively, thus even greater than 3.5.

These safety values were till now justified by two reasons. First, the value of 3.5 is nearly the ratio of the internal overvoltages to the service voltages. The second reason might be that there was no impulse test at the time when these values were prescribed and so it was inteded to demonstrate by the separate-source test the adequacy of the insulation for external overvoltages, too.

These values were justified at the time, but it is not quite sure that they remain justified at present also.

The impulse test is now in general use, therefore proving the impulse strength of the insulation with the 50 Hz separate-source test appears to be superfluous. This fact might influence the *amplitude* of the separate-source test voltages. It seems, that the existing minimum safety (3.5) is enough for *all* nominal voltages up to 35 kV inclusive.

The one minute seems also to be exaggerated. Internal overvoltages of such magnitude last mostly a few periods only. It is also possible that during the one minute a thermal instability occurs in spite of the fact that it is impossible in service. It is also quite possible that at the test voltage internal ionization develops which is not the case at service voltage. This ionization can damage the insulation during the one minute of the test; therefore the stress on the insulation might be quite different from the service stress.

Hence the sound insulation might be unnecessarily damaged by the test. This possibility may have two consequences. First, the designer has to dimension for the test and not for service (which might be uneconomical) and it is also possible that a transformer with damaged insulation and restricted life will be put into service.

This possibility shall now be considered in more detail.

It has been shown that the separate-source test is a very severe one. One might say that far more severe than the standardized impulse test. In this connection the fact should be mentioned that the impulse test voltage is only by 20—30% higher than the protection level voltage which may be considered as the impulse "service voltage" of the insulation. This safety factor is therefore much smaller than the safety factor of the 50 Hz voltages (< 3.5).

For transformers with graded insulation as used in effectively grounded systems (above 35 kV in Hungary) the safety factor seems to be adequate, but the testing time may be considered as being also too long.

The severity of the separate-source test seems to be appreciated generally, because it is known that it should be repeated—according to the existing standards — only with a restricted voltage (70% of the first testing voltage).

But there exists another difference between the separate-source test and the impulse test. The latter will be carried out using control methods of reasonable sensitivity which will show whether or not a fault has occurred during the test. A control of this kind is generally not used in the separate-source test. It is well-known that the current measured by the primary ammeter of the testing transformer or the occurring of sound or smoke are not very sensitive methods for fault-detecting compared with the methods used by the impulse-test (Methods of Hagenguth, Rabus, Elsner, etc.).

3.2. *Generators*

The insulating system of a generator is more simple than that of a transformer, but nevertheless the insulating *material* being a complex one, a control of the separate-source test seems to be necessary here as well. It is true that there is less possibility of a fault during the test than in transformers, because the mica used in the insulation is very resistive against the deteriorating effects of internal ionization and a thermal breakdown in mica itself is not very probable either. Nevertheless, the detection of starting deterioration in the materials used as adhesives (shellac, asphalt compound, glyptal, etc.) is also very interesting. Recent results seem to prove that the life of a generator insulation lasts approximately as long as the life of the adhesive, the bonding material. Therefore, by maintaining ionization for a minute on such voltages (about 4-times service voltage) which never occur in service might damage unnecessarily the generator insulation too.

3. 3. *Cables*

When testing cable insulations, the occurrence of thermal breakdown is also possible, because the test lasts for 20 minutes instead of one. But it is also known that the life of cable insulation is greatly influenced by the slow development of ionized voids, therefore the occurrence of a breakdown during the test is not very probable either. It seems possible, however, that starting faults can be detected here too by appropriate control methods. The control of cable tests is also useful for the sake of the prophylactic tests which are obligatory in some countries; this control gives the primary (first) values for the ionization inception voltage, for the voltage-dependency of the power-factor on this voltage, etc.

After this brief survey of characteristic features of the separate-source test and before putting forward proposals for its modification a few results of the theoretical and experimental work carried out in the field of dielectrics shall be recalled.

For the sake of briefness, mathematical deductions will not be given and the author will restrict himself to mentioning the formulae needed for his purposes.

4. Some properties of an insulation which appear most characteristic of its condition

In an insulation there might always be a *local fault*, a hole, etc. This can be checked by a voltage test only and it is not characteristic for the insulation as a whole. In most cases it results from inadequacy of the manufacturing technology of either the insulation or the materials used for its construction. According to our present knowledge, there exists no other method to detect a local fault than the voltage test. This test is therefore at present an *absolutely necessary* tool for the quality control of insulation. But it is also quite clear, according to our present knowledge of the properties of insulating materials that this test alone gives no adequate information on the general qualities of an insulation and, as already has been mentioned it even may be dangerous for a sound insulation, too.

Therefore, if as a quality control this test is used *only* no knowledge on the general quality and condition of the insulation is obtained. The measurement of leakage resistance by low voltages cannot give adequate information. This shortcoming has been already appreciated for the quality control of cable insulation and a tg δ measurement is being inaugurated. This measurement can be used in cable testing also for the control of the test, because here the time for the balancing of the Schering-bridge is available. This is, however, not possible in the oneminute separate-source test prescribed for generators and transformers. It is naturally possible to carry out different useful quality control measurements, but these will take time and therefore they will not be popular as routine tests. It would be best to find a control method for the *general conditions* of the insulation which can be applied simultaneously with the unavoidable routine test for local faults, the voltage test.

The properties characterizing the quality of an insulating material and to a certain degree also an insulation, are the insulating (leakage) resistance, the dielectric losses, their temperature and voltage dependencies and the ionization inception voltage.

In the practice of prophylactic testing it turned out that the absolute magnitude of the resistance or of the losses is not so interesting as their change with the time of service. It seems possible to forecast this change to a certain amount from the change of the losses with temperature and with voltage and from the magnitude of the ionization inception voltage.

The separate measurement of the resistance with a high d. c. voltage may be interesting, too, but the losses caused by the leakage resistance being a component of the total losses, measurement of the total losses only might be sufficient. It is also known that an insulation with losses can be represented in the simplest way as an ideal capacitance in parallel with two resistances (Fig. 1). The first of the resistances (R_l) represents the leakage (conducting) losses, the second one (R_d) the dielectric losses due to the different kinds of polarization. R_l can be determined also by direct resistance measurement, while R_d has a fictive value, given by the dielectric losses. Both resistances have a common property: they are more or less voltage-dependent, non-linear. The consequence of this fact is that with a sinusoidal voltage the loss current contains higher harmonics. Recent and also earlier research work shows that the shape of the loss current is characteristic for the general properties and for the state of the insulation [2]. The capacitive current which is not so interesting here, is in most cases much more important than the loss current, therefore it shall be compensated in order to bring into evidence the shape of the loss current. This is easily carried out with the Schering bridge. The bridge is balanced only for the ground-harmonic, in our case for 50 Hz. Therefore in the diagonal of the bridge balanced for the capacitance only, a CRO (cathode ray oscilloscope) will show the shape of the loss current and in the completely balanced bridge its higher harmonics will appear on the screen. The ionization in voids or on the surface of the insulation results in high-frequency oscillations which will appear as well in the oscillogram of the loss current or in the shape of the balanced current. It is also known that the frequency of the pulses is somewhat characteristic for the shape and the number of the voids [3].

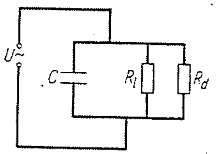

Fig. 1

The facts mentioned above permit the conclusion that the shape of the loss current may be characteristic for the general condition of the insulation. It should be mentioned that the variation of the loss current with time at a given voltage can also be of interest. In order to prove this statement it is necessary to recall some recent results in the field of electrical breakdown theories. It seems that the criterion of *all* types of 50 Hz breakdown (pure electrical breakdown, thermal breakdown of solids and liquids and in some respect the avalanche breakdown of gases, too) can be formulated as follows: the breakdown is always an instability and it occurs if a voltage of such magnitude is reached that the current flowing through the insulation or the losses developing in this will grow monotonously with time, even if the voltage remains the same. Therefore the registration of the losses as a function of time *may* show that a breakdown is developing. It is naturally not always possible to have enough time to appreciate this development and to take off the voltage before the breakdown occurs, but in many practical cases there exists a probability for doing so. It is not easily done in the case of thermal breakdown. The time dependency of the overtemperature and also of the losses is given by the formula (4)

$$\tau = k_1 \ln \frac{1}{1 - k_2 t},$$

where τ is the overtemperature in centigrades, t the time in seconds, k_1 and k_2 known constant values for a given insulation.

The time for breaking down can be expressed very roughly by the formula (5)

$$t_b = \frac{k_3}{\left(\frac{U}{U_{\mathrm{lab}}}\right)^2 - 1}.$$

Here t_b is the time until the breakdown, U the applied voltage, U_{lab} the voltage at which the thermal lability occurs (the thermal breakdown voltage), k_3 a known constant. As is known from literature, [6]

$$U_{\mathrm{lab}} = k_4 \sqrt{\frac{A}{k\, p_{\vartheta_a}}}\, \varphi(c).$$

Here A is the thermal conductivity of the insulation, k and p_{ϑ_a} are given by the equation

$$p_{\vartheta_a} = p_{\vartheta_0}\, e^{k(\vartheta_a - \vartheta_0)},$$

where p_{ϑ_0} is the specific loss at the reference temperature ϑ_0,

$$p_{\vartheta_0} = \frac{f(\varepsilon \operatorname{tg} \delta)_{\vartheta_0}}{18.10^{11}} \frac{W}{cm^3} / (W/\mathrm{cm})^2$$

ϑ_a is the ambient temperature of the insulation, *i.e.* the temperature of the conductor being in contact with it. $\varphi(c)$ is the Fok-function, its argumentum c being dependent on cooling conditions and having a maximum value of 0.662. If the cooling conditions are bad, *e.g.* the thickness of the insulation is great, the lability voltage becomes independent of this thickness. The value of the lability voltage for this case is

$$U_{\mathrm{lab}} = 0.938 \sqrt{\frac{A}{k\, p_{\vartheta_a}}}\ \mathrm{kV}$$

with A in W/cm, °C and p_{ϑ_a} in $\mathrm{W/cm^3/(kV/cm)^2}$; k is a numerical constant of the order of $10^{-2}/°\mathrm{C}$.

The formulae given above have been got from a greatly simplified substituting arrangement, namely from a parallel-plate condenser and therefore they shall be considered, as has been mentioned, as a rough approximation. Nevertheless, the values calculated from this coincide comparatively well with the few experimental results as was pointed out, *e.g.*, by A. ROTH [7].

It is perhaps possible to summarize what has been said above as follows:

i) The registration of the loss current during the voltage test may show the ionization inception voltage, and the eventual variation of it during the testing time,

ii) The shape of the loss current or of its upper harmonics can be characteristic for the condition of a given insulation.

iii) The eventual variation of the loss current can be seen and permits to conclude whether a deterioration of the insulation is starting,

iv) This kind of control requires no extra time.

5. Proposals for the modification of the present test procedure

After all these preliminaries we shall now proceed to the proposals mentioned earlier. It seems opportune, for the time being, to carry out the modifications of the separate-source test in two steps.

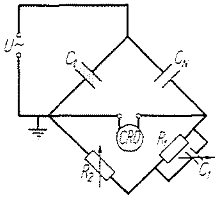

Fig. 2. C_t insulation to be tested, C_N normal capacitance, R_1 R_2 measuring resistances, C_1 measuring capacity

At first, the present prescriptions relating to the test voltages and the test time might be maintained, but an adequate control method shall be introduced. For this purpose, the registration of the loss current in the diagonal of an entirely balanced or partly balanced Schering bridge can be proposed (Fig. 2). This method is not new, it was first proposed for another purpose by GEMANT in 1930 [8].

The test procedure for generators and transformers should then be the following:

1. The bridge is balanced for the capacitive current at a voltage which will not damage the insulation for a couple of minutes necessary for the balancing, say at 50—60% of the testing voltage. This is not necessary for cables because there is time enough during the test for the balancing.

2. Then, a CRO connected in the way shown in Fig. 2 will registrate the magnitude and the shape of the loss current (I_l),

$$I_l = I_c \operatorname{tg} \delta = UC\omega \operatorname{tg} \delta.$$

The bridge may also be balanced for the ground harmonic of the loss current, using an adequate zero-indicator. Then the upper harmonics of the loss current will be seen only.

It is perhaps worth while mentioning that the bridge earthing should be placed on the diagonal, too, because most oscilloscopes have no symmetrical input. This way of earthing is more convenient also because then it is not necessary to isolate the tested object from the ground. The voltage proposed for the balancing is a very cautious value. If it is supposed that the one minute is the time necessary for breakdown at the testing voltage (which is an exaggerated supposition) then the time for breakdown at 50% of this voltage is, as a minimum,

$$[t]_{Ut/2} = [t]_{Ut} \frac{\left(\frac{U_t}{U_{\text{lab}}}\right)^2 - 1}{\left(\frac{U_{t/2}}{U_{\text{lab}}}\right)^2 - 1}.$$

If $U_{\text{lab}} \approx 1.5\ U_{\text{ph}}$, where U_{ph} is the phase voltage (the service voltage) and the testing voltage is, as mentioned before

$$U_t \approx 3.5\ U_{\text{ph}},$$

then

$$\frac{[t]_{Ut/2}}{[t]_{Ut}} = \frac{\left(\frac{3.5}{1.5}\right)^2 - 1}{\left(\frac{1.75}{1.5}\right)^2 - 1} \approx \frac{4.4}{0.35} = 12.5.$$

3. Then, the voltage is risen to the testing value. Naturally, the balancing of the bridge will be upset, but nevertheless it will be seen far better if some change of the loss current and so of the state of the insulation occurs during the testing time, than from the primary ammeter used now as a control device. The ionization inception voltage can also be seen, if ionization occurs.

4. After the test the voltage is reduced to the value at which the bridge has been balanced and so it is seen whether the losses and the shape of the current have remained the same. If something is changed in an irreversible way, it may show that the condition of the insulation has been affected by the test.

With a self-balancing bridge the procedure is far more simple and exact. It may be hoped that apparatus of this kind will be used in the future for the control of this test.

The introduction of this control (or some better one, suggested by others) may be considered as the *first step*, to collect experiences. It gives no extra risks and nevertheless it is quite certain that it provides *some* information. If it will turn out, as the author is convinced, that the voltage test used now is in fact too severe, and might occasionally damage sound insulation, too, then the *second step* might be made.

The test procedure may be altered as follows:

i) The testing voltage remains the same, but the time of the test with this voltage will be diminished, say to 10 seconds.

ii) Before the application of this test voltage the loss current shall be recorded, at an appropriate lower voltage. After the 10-sec test the loss current shall be recorded again at the same reference voltage, in order to show the eventual variations in magnitude and in shape.

iii) After this procedure another, lower testing voltage is applied, the magnitude of the latter being open to discussion, and it is maintained for 10—15 minutes. During this time it is possible, and necessary, to record the loss current in order to detect the eventual changes in it. As reference voltage mentioned in ii) this lowered testing voltage may be used, too. It is worth while to mention that the proposed method may be used with some modification also for the induced voltage test of transformers with graded insulation.

The possible advantages of the foregoing proposals will now be summarized.

The first alternative brings no risks, the control method does not alter in any way the influence of the testing procedure on the insulation. It takes practically no extra time. For the control measurements no new instruments or equipment are needed, the Schering bridge and the CRO are both commonly used now in the practice of high-voltage testing technique.

If the connexions are made reasonably ionization-free, the ionization inception voltage is easy to determine. According to some research work it is also possible to tell from the shape of the oscillograms whether the ionization occurs in voids or on the surface of the solid insulation.

This oscillographic method shows whether the loss current or its harmonics do change in the testing time. If no self-balancing bridge is available no exact results are got, but in spite of this they may be very useful as comparative values, the main thing being that the values should *not change* during the testing time.

For the reproducibility of the measurements a sinusoidal voltage is needed because the harmonics of the voltage will influence the shape of the loss current, too. However, this seems no serious objection against the use of the proposed method because in most testing plants the testing voltage is supplied by generators. By the way, a sinusoidal voltage is prescribed for the common separate-source test, too.

It is not to hope for the time being that characteristic reference values could be given, the behaviour of the insulation shall be judged from the shape of the obtained curves. This method is therefore somewhat similar to the electrocardiographic method used in medical practice. The final solution of the separate-source test problem seems to be the second step, the introduction of two testing voltages with two testing times.

It is quite appreciated by the author that a couple of another methods for the control of the separate-source test may be proposed. Therefore the essential of the proposals presented above is that *some* control method shall be used, and that the method proposed by the author shall be used only if his colleagues will not propose a better one.

Summary

The author tries to demonstrate that the separate source test in its present form is too severe and may damage the sound insulation, too. It is also a deficiency of the present testing procedure that no control method is used to show, whether a fault occurred in the testing time. He proposes that the bridge out-of-balance current shall be registered by a CRO. He puts forward also some tentative proposals for the possible modification of the testing procedure, the testing voltages and the testing time.

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