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114. — COMPARISON OF THE OVERVOLTAGES DUE TO THE DISCONNECTION OF AN OPEN LINE FED BY A TRANSFORMER WITH ISOLATED OR DIRECTLY EARTHED NEUTRAL

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SUMMARY.

An analysis, on the basis of oscillographic records, of the phenomenon of disconnecting an open line shows that the amplitude of the resulting overvoltages depends on the interaction of ignitions and extinctions of the power arc in the circuit breaker. The theoretically highest values occur so infrequently that they are of little practical importance. The most important problem consists in determining the probability of the frequency of occurrence of the various overvoltage amplitudes.

For the same degree of probability, the voltages stressing the transformer are higher when the neutral is isolated than when it is solidly earthed. This fact constitutes a further argument, particularly for operating voltages above 100 kV, *in favour of direct earthing of the neutral point.*

REPORT

INTRODUCTION.

It is well known that the highest overvoltages caused by closing or opening of a circuit breaker are produced :

either by the disconnection of an open-circuited transformer (*fig.* 1 *a*);
or by the disconnection of an open line fed by a transformer (*fig.* 1 *b*).

Although the first overvoltages (disconnection of an open-circuited transformer) are also, to a certain extent, a function of the method of earthing these will not be considered here. Instead, we shall deal with the second type of overvoltage : those which appear at the transformer terminals when the open line which it feeds is disconnected. The numerous possibilities presented by this problem have not been examined in great detail and are, as

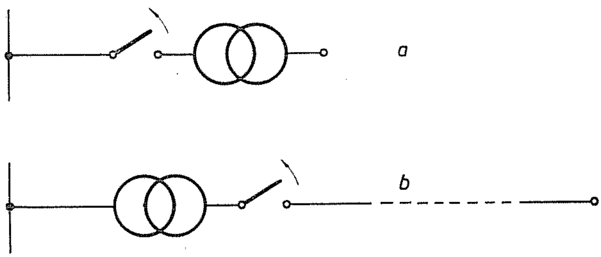

Fig. 1.

will be seen, largely determined by the method of earthing of the neutral point.

In 1943 oscillographic measurements of this type of disconnection were made in Switzerland by the F.K.H. on a 150 kV line fed by a 16 500 kVA transformer with isolated neutral. In 1949 similar tests were carried out on another 150 kV line with a 45 000 kVA transformer the neutral of which was directly earthed. The following analysis of the problem is based on the oscillograms taken during these tests.

CIRCUIT ARRANGEMENT.

In figure 2 a three-phase transformer T which is supplied by a system or a generator G feeds, via circuit breaker D, a line *L* (30-40km) the other end of which is open. The primary side of the transformer (50 kV) is connected in delta, the secondary (150 kV) in star.

The symbols in figure 2 have the following significance :

C_L, the total capacitance of each phase of the line to earth. In reality this capacitance is distributed over the entire length of line. The line may be represented by three sections the capacitance $\frac{C_L}{3}$ of each being taken to be concentrated at its midpoint.

For a line of 30-40 km the value of C_L is about 0.2-0.3 μ F.

C_q, the mutual capacitance between phase conductors. As this is small compared with C_L (10-20 %) it will be neglected for the sake of simplification.

C_T, the capacitance to earth of each transformer terminal to which are to be added that of the breaker bushing, of the connecting leads and of parts of the transformer winding. The value of these capacitances is about 2 000-3 000 pF.

L_L, the inductance of a phase conductor which, with 1.3-1.7 mH : km, becomes 40-70 mH.

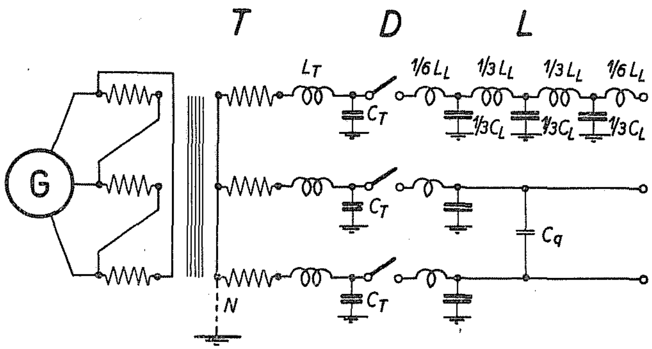

Fig. 2. — Detailed diagram of the circuit condition indicated in figure 1 *b*.

L_T, the inductance of the transformer (due to the leakage field between primary and secondary winding) to which is added that of the generator (or system), reduced to the secondary voltage of the transformer.

We shall neglect the ohmic resistances of the circuit and its losses as well as the arc voltage between the breaker contacts. In so doing, it may be recalled that the factors which are thus neglected tend to damp the oscillations which occur. It may also be noted that, despite its small value, the inductance $\frac{L_L}{6}$ in series with the breaker ensures a certain degree of stability. These arcs are maintained without difficulty as long as their current exceeds several amperes and they can only be extinguished when the current passes through zero. As the line current is essentially capacitive it passes through zero every time when the phase voltage reaches a maximum or minimum.

A. CASE OF A TRANSFORMER WITH DIRECTLY EARTHED NEUTRAL.

For reasons of simplicity this case will be considered first. The neutral N in figure 2 should thus be deemed to be connected to earth by the dotted line.

Neglecting the mutual capacitances C_q the three phases are seen to be identical and completely independent of one another. Whatever happens in one phase may occur equally well in another so that the investigation may be confined to the study of a single phase.

1. **Designation of the transient oscillations and their symbols.** — With reference to figure 2 we shall now consider the different circuits capable of oscillation :

a. With the circuit breaker closed (or as long as the arc persists between its contacts); the capacitance of the line (including that of the transformer) with the leakage inductance of the transformer at the frequency

$$f_{01} = \frac{1}{2\pi\sqrt{\left(L_T + \frac{L_L}{2}\right)(C_L + C_T)}} \approx 500 \text{ c : s.}$$

b. With the circuit breaker closed :

On the transformer side : the transformer capacitance with its inductance at the frequency

$$f_{02} = \frac{1}{2\pi\sqrt{L_T C_T}} \approx 5\,000 \text{ c : s;}$$

on the line side : the capacitances (in series) of the external lines with the inherent inductance at the frequency

$$f_{05} = \frac{1}{2\pi\sqrt{\left(\frac{2}{3} L_L\right)\left(\frac{1}{2}\frac{1}{3} C_L\right)}} \approx 4\,000 \text{ c : s.}$$

This latter is almost exactly the fundamental frequency of the oscillations due to the travelling waves which build up as a result of the reflections between the two open ends of the line. It plays only a secondary part; however it is always superimposed on the frequency f_{01} and can be recognized on the oscillograms.

The damping factor (α) of these oscillations, i. e. the ratio between the amplitude of one oscillation with that preceding it by half a cycle is generally between 0.6 and 0.8.

The supply frequency of 5o c : s is represented by f_{50}. Furthermore we introduce :

u_p, $U_p \sqrt{2} \sin (2 \pi f_{50} t)$, the wave shape of the supply voltage to earth (phase voltage) with U_p as its r. m. s. value and $u_{p_{\max}}$ as its crest value. u_p results from the electromotive force induced by the variation of the main transformer field, increased by the inductive voltage drop which produces the capacitive current established in the transformer by the line;

u_T, the wave shape of the voltage to earth of the transformer terminal;

u_L, the wave shape of the voltage to earth of the line at its end on the breaker side. For frequencies between 5o and 5oo c : s this voltage is taken to be the same along the whole line;

u_D, the wave shape of the voltage between the breaker contacts;

u_a, the breakdown voltage between the breaker contacts;

$u_{\max}$, the highest voltage (to earth, instantaneous value) appearing in the course of the disconnection;

U_n, the nominal or line voltage (r. m. s. value);

i_D, the breaker current;

t, the time;

t_0 the start of contact separation;

t_a, the instant at which an arc is produced;

t_1, t_2, t_3, the instants of the first, second and third breakdown, producing an oscillation of the frequency f_{01};

t_e, the instant of arc extinction at current zero;

t'_1, t'_2, t'_3, the instants of the first, second and third passage of current zero of the first oscillation with frequency f_{01} due to breakdown at t_1;

α_{01}, α_{02}, α_{03}, attenuation coefficients of the oscillations of frequencies f_{01}, f_{02}, $f_{03} \ldots$;

p, probability of occurrence;

p_a, » » » of a breakdown;

p_e, » » » of an extinction;

p_I, » » » of a voltage $u_{\max}$ at a single breaker terminal;

p_{III}, » » » of a voltage $u_{\max}$ at one or more of the three poles of a three-phase breaker.

2. **Analysis of the interruption phenomenon.** — The wave shapes of the different voltages during the phenomenon are reproduced in figure 3.

At the instant (t_0) when the breaker contacts begin to separate an arc occurs between them due to their initially very small separation. The arc persists almost until the current passes through zero when u_p reaches its maximum (positive or negative). When the arc is interrupted the suddenly isolated line remains charged and retains the potential acquired whereas the transformer voltage u_T falls to zero by following the sinusoidal voltage u_p. The

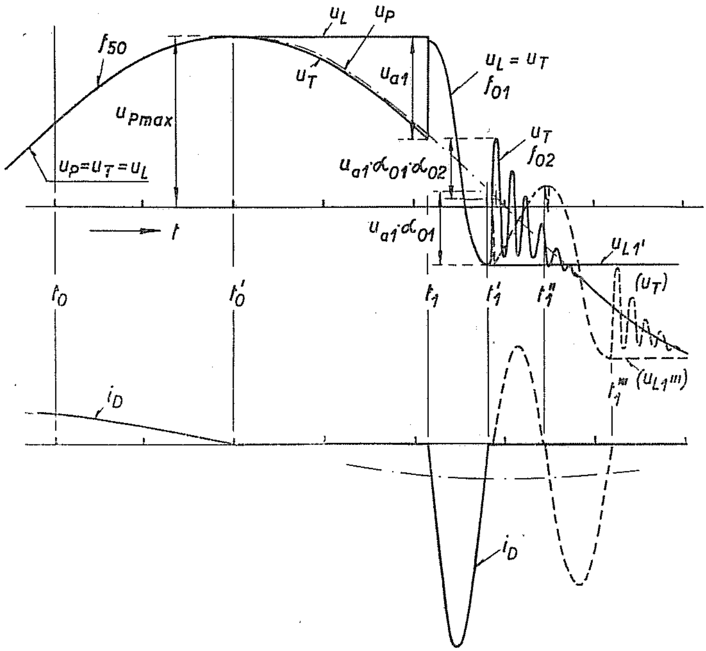

Fig. 3. — Diagram of the voltages after a disconnection with breakdown (t_1) and extinction after the 1st (dotted, after the 3rd) current zero.

voltage u_D across the breaker contacts increases until it causes an arc to strike ($u_D = u_{a1}$). As the transformer capacitance C_T is about two orders of magnitude smaller than that of the line C_L the latter imposes on it rapidly its own potential, but the line can attain the supply voltage only by oscillating about it at the transient frequency f_{01}.

The current of this oscillation is proportional to the breakdown voltage. At the same voltage it is about 10 times as large as the normal capacitive current, in proportion with the frequency ratio $\frac{f_{01}}{f_{50}}$. If the breakdown voltage u_{a1} is very small (smaller than $1/10$ of $u_{p_{max}}$) the current of the oscillation f_{01} remains below the normal capacitive current and the next current zero occurs only near the maximum of the voltage u_p. If, on the other hand, the breakdown voltage is higher (than $0.2\ u_{p_{max}}$) the current passes through zero at about each half cycle of the frequency f_{01} and each time there exists a possibility for the arc to be extinguished. However, it will be seen that the probability of an extinction during the first half cycles is smaller than for the later ones since this chance increases as the amplitude of the oscillation decreases.

If the arc is extinguished at the first current zero (at t'_1) the line voltage u_L which was positive with respect to u_p before the breakdown (at t_1) has become negative and retains its potential after the extinction at t'_1. The voltage u_T at the transformer terminal is at the exact instant of extinction equal to the line voltage u_L and produces a voltage difference u_p of

$$u_{P1'} - u_{T1'} = u_{a1} + \alpha_{01}.$$

As a result, u_T immediately tends to attain the voltage u_p by oscillating about it with the transient frequency f_{02} (about 5000 c : s). It is thus seen that the voltage u_D across the contacts of the breaker increases very rapidly and reaches, shortly after the extinction considered $\left(\frac{1}{2}\right.$ cycle of the frequency $\left.f_{02}\right)$ the maximum value :

$$u_{D_{max}} \approx (1 + \alpha_{02})(u_{P1'} - u_{T1'}) = u_{a1}\,\alpha_{01}(1 + \alpha_{02}).$$

For normal values of the damping coefficients α_{01} and α_{02} (for example each equal 0.7), the voltage $u_{D_{max}}$ reaches therefore a value of $1.19\ u_{a1}$ already $1/10000$ s after arc extinction; i. e. it exceeds the value which $1/1000$ s earlier had caused breakdown. If therefore the voltage $u_D = u_{a1}$ was sufficient to produce breakdown although its rate of rise was comparatively slow — since it was determined by the normal frequency of 50 c : s — there would be little chance for the insulating medium of the breaker to sustain a voltage of about 10-20 % higher amplitude and with a hundred times greater rate of rise. The extinction of the current of frequency f_{01} at the first current zero is therefore likely to be followed immediately (i. e. 20-70μ s later) by a restrike. In view of the post-arc conductivity which reduces the oscillation f_{02} and particularly in view of the large variation of the breakdown voltage of oil, the extinction at the first current zero without immediate restrike will occur fairly exactly in one case out of 5.

3. **Unfavourable cases.** — The maximum voltage to which the transformer is subjected is determined by the interplay between

restriking and extinction in the circuit breaker. The case which is theoretically known to be most unfavourable is that in which restriking occurs regularly at each positive and negative maximum of the voltage u_p and extinction without immediate restriking at each first current zero of the oscillation f_{01} (*fig.* 4). The line assumes therefore a form of resonance and its voltage would reach its maximum when :

$$\left(u_{L_{\max}} + u_{P_{\max}}\right) \alpha_{01} = u_{L_{\max}} - u_{P_{\max}}$$

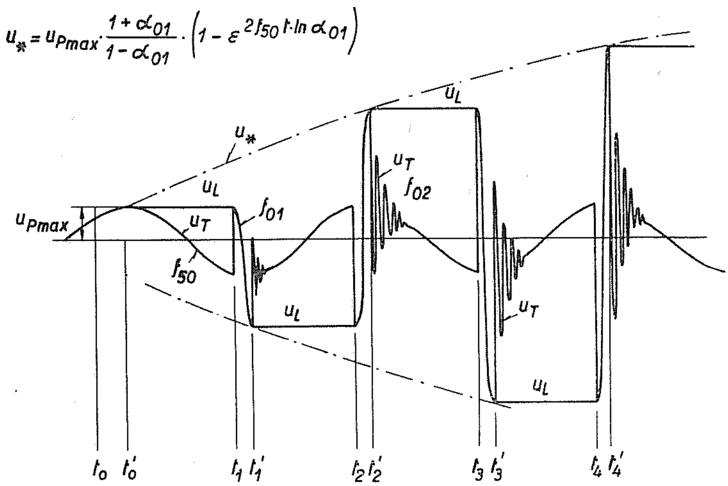

Fig. 4. — The, theoretically,
most unfavourable case of breakdowns and extinctions.

from which

$$u_{L_{\max}} = u_{P_{\max}} \left(\frac{1 + \alpha_{01}}{1 - \alpha_{01}}\right)$$

e. g. for

$$\alpha_{01} = 0.8,$$

$$u_{L_{\max}} = 9\, u_{P_{\max}}.$$

In practice, the chance of this phenomenon occurring is so small as to be deemed almost impossible. In fact, the increase in the dielectric strength of the oil would have to be exactly the same as that of the line voltage if it were to produce breakdown at exactly the maximum of the voltage u_p. Again if extinction at the first current zero occurs in 1 case out of 5 there is little chance of 20 consecutive occurrences. If the probability of a breakdown (p_a) at the necessary instant is taken to be 0.2 and that of extinction (p_e) 0.2, the chance of occurrence of a voltage of $9\,u_{p_{max}}$ which requires 20 consecutive restrikes becomes of the order of

$$(p_a\,p_e)^{20} = (0.2 \times 0.2)^{20} = (0.2)^{40} \approx 10^{-28}.$$

What is therefore of importance is not merely a knowledge of the value of the overvoltage but also of its probability of occurrence.

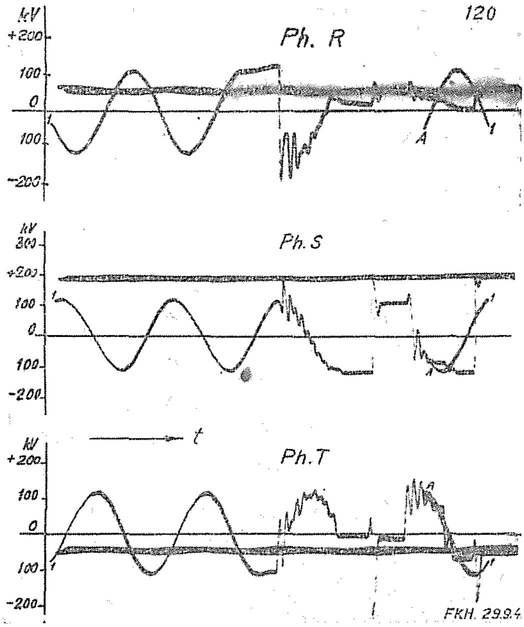

Fig. 5. — Oscillogram of the disconnection of an open line at 150 kV, fed by a 45 000 kVA transformer with directly earthed neutral. Voltages of the three phases on the line side.

As an exact calculation is too involved we shall here confine ourselves, partly, on a summarizing conclusion based on actual test results and, partly, on an estimate of the degree of probability of occurrence of each breakdown.

For the oscillation of frequency f_{01} a damping coefficient $\alpha_{01} = 0.8$ may be adopted.

From a statistical analysis of the oscillograms it appears that the line remains charged after arc extinction with a value equal to, or greater than $0.7\,u_{p_{max}}$ (example *fig.* 5, phase S) in 6 % of the cases. This value will be adopted as starting point for a calculation of the probability of occurrence of higher voltages (*fig.* 6). In order to derive the probability for the crest voltage at t'_3 to be equal to, or greater than — 2.6 $u_{p_{\max}}$ it suffices to know the chance with which breakdown may occur at t_3 while the transformer voltage u_p lies between the values — 0.7 and 1.0 $u_{p_{\max}}$. The chance

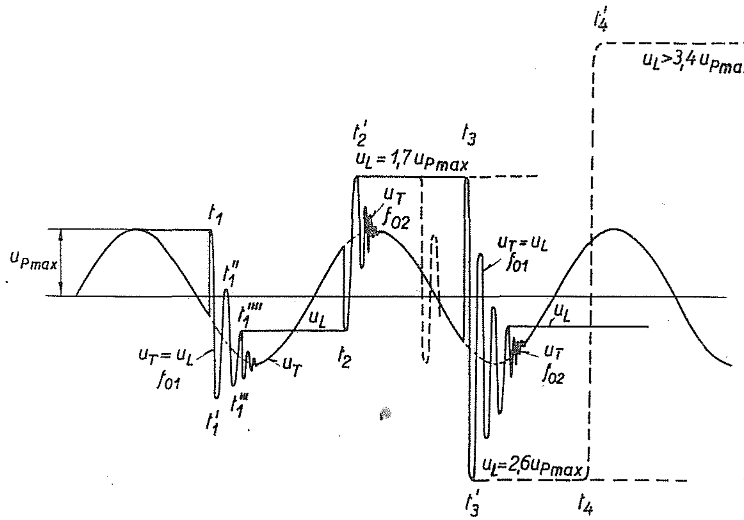

Fig. 6. — Diagram of the voltages after a disconnection which serves as a basis for an estimate of the probability of the over-voltages.

of such a breakdown occurring is estimated as 25 %, since the possibilities are as follows :

50 % without breakdown;
50 % with breakdown;

where the latter 50 % can be further subdivided into

25 % of breakdown between the given voltage limits of u_T (— 0.7 and 1.0 $u_{p_{\max}}$);
25 % of breakdown outside these limits.

The probability of reaching a crest voltage equal to, or greater than 2.6 $u_{p\max}$ becomes therefore

$$p = 0.06\, p_a = 0.06 \times 0.25 = 0.015$$

and the probability of the line remaining charged with that value (extinction at first current zero) becomes

$$p = 0.015\, p_e = 0.015 \times 0.2 = 0.003, \qquad \ldots.$$

As the line voltage increases the chance of a new breakdown 180° later must, of necessity, diminish since the limits between which it must occur become progressively more narrow. This calculation thus gives the following results :

TABLE I.

Probability of a crest voltage being reached equal to or greater than.

1.7 $u_{P_{max}}$	$p_I = 0.3$	$p_{III} = 0.65$
2.6 »	$p_I = 0.015$	$p_{III} = 0.044$
3.4 »	$p_I \approx 0.0004$	$p_{III} \approx 0.001$
4.0 »	$p_I \approx 0.00001$	$p_{III} \approx 0.00003$

The probability p_I is that of the occurrence of the voltage indicated at a single pole of the circuit breaker ; p_{III} that of the occurrence at one or more of the three poles. The relation between these two values is defined by

$$p_{III} = 1 - (1 - p_I)^3$$

and for small values of p_1 this becomes

$$p_{III} \approx 3\, p_I.$$

The values of p_I and p_{III} are plotted in figure 12.

Voltage values the probability of which is below 10^{-4} can be regarded as of no importance.

B. — CASE OF A TRANSFORMER WITH FREE NEUTRAL.

In this case the transformer windings as well as the phase conductors which they feed are completely insulated from earth and their potential is so distributed as to make the sum of the electric charges always zero. The only voltage difference between the poles is determined by the electromotive forces induced by the normal frequency variations of the main transformer fields and by the transient oscillations.

As the capacitance of the transformer is very small compared with that of the line the distribution of the voltages at the transformer terminals can readily become asymmetric if only one pole remains connected. This constitutes not only an asymmetry of phases but also of amplitude since the two other phases oscillate about that connected to the line which remains charged with a voltage which may exceed the amplitude of the normal operating voltage.

1. **Designation of the transient oscillations and their symbols.** — According to figure 2 in which the connection between the neutral point N and earth is taken to be interrupted several oscillatory circuits can be distinguished :

1. In the case of simultaneous breakdown of two (or three) poles :

The capacitances of the two lines (in series) with the leakage inductance of two transformer phases in series, at the frequency :

$$f_{01} = \frac{1}{2\pi\sqrt{\left(\frac{C_L + C_T}{2}\right)(2L_T + L_L)}} \approx 500 \text{ c : s.}$$

2. In the case of extinction at three poles :

The capacitances of two transformer terminals (in series) with the leakage inductance of two phases (in series), at the frequency :

$$f_{02} = \frac{1}{2\pi\sqrt{\frac{C_T}{2}\,2L_T}} \approx 5\,000 \text{ c : s.}$$

3. In the case of breakdown of one phase only :

The capacitances of the two other terminals C_T in parallel, in series with that of the connected line (C_L), with the leakage inductance of one phase in series with the other two phases in parallel at the frequency :

$$f_{03} = \frac{1}{2\pi\sqrt{2C_T\frac{C_L}{C_L + 2C_T}\frac{3}{2}L_T}} \approx 3\,000 \text{ c : s.}$$

4. In case of simultaneous breakdown of two poles :

The capacitance of the free terminal (in series with the capacitance of the two other lines in parallel) with the leakage inductance of one phase in series with the two others in parallel, at the frequency :

$$f_{04} = \frac{1}{2\pi\sqrt{C_T\frac{2C_L}{2C_L + C_T}\frac{3}{2}L_T}} \approx 4\,000 \text{ c : s.}$$

5. As in the case of the transformer with solidly earthed neutral, the fundamental frequency of the line itself :

$$f_{05} = 4\ 000 \text{ c : s.}$$

The damping coefficients of these oscillations are the same as in the preceding case A.

The same symbols as in case A are used to designate the various voltages by adding to the respective index the name of the phase (R), (S) or (T).

2. **Analysis of the interrupting phenomenon.** — The phenomenon of disconnecting an open line with a free transformer neutral

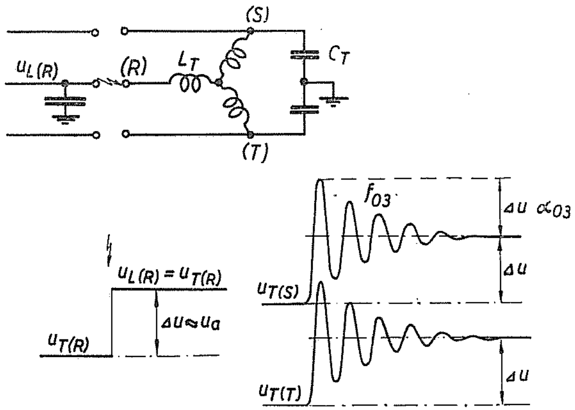

Fig. 7. — Reflection at the terminals S and T of a sudden voltage change Δu impressed on a transformer terminal R after a breakdown.

presents, from the point of view of striking and extinction of the arc, the same characteristics as the case with directly earthed transformer neutral. On the other hand, it differs from it by an interdependence of the phases which complicates the matter. If breakdown occurs at one breaker pole it tends to cause breakdown also at the two other poles. In fact, if after breakdown one transformer terminal is subjected to a sharp potential change the voltage of the entire winding (of the three phases) varies in the same manner. This cannot happen instantaneously but takes place in the other two phases with a frequency of oscillation f_{03} the crest value of which — which may reach almost twice $(1 + \alpha_{03})$ the initial change — tends to produce a breakdown of these poles (*fig.* 7).

For the sake of exemplification we shall consider a simple example involving some of the essential features which occur in practice and this will be done by a step-by-step method. All the damping factors will be taken as o.8.

According to figure 8 we shall assume that a breaker begins to

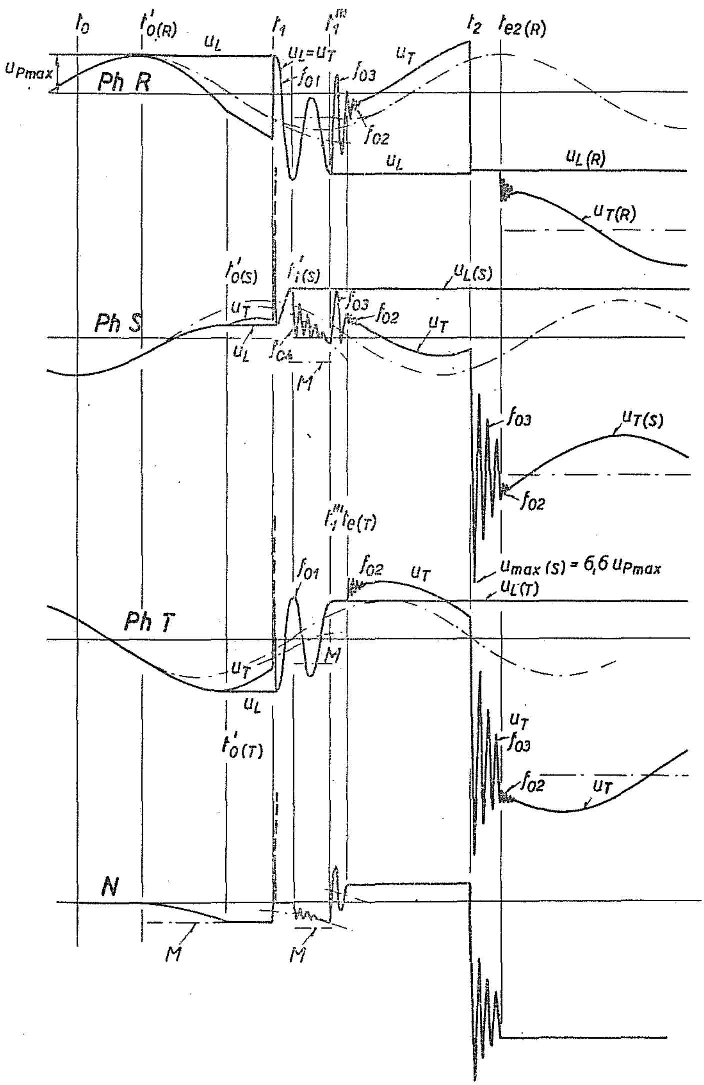

Fig. 8. — Diagram of the voltages during a disconnection producing, at the 2nd breakdown of pole R, a crest reaching at the terminal S 6.6 times the crest value of the phase voltage; transformer neutral insulated.

open its contacts at time t_0. At each pole an arc maintains the current flow and until this becomes zero (first in phase R) the arc persists and the line (R) remains charged with the potential acquired. Since at this instant, the sum of the two other currents must be zero, they become equal with a phase difference of 180° and point M of the vector diagram of figure 9 *a* maintains a fixed potential exactly midway between the voltages of the terminals (S) and (T). To this constant potential M the vectors S′ and T′ have to be added with an amplitude $\pm u_p \frac{\sqrt{3}}{2}$ while the vector R′ assumes $1.5\, u_{p_{max}}$ and the neutral point $0.5\, u_{p_{max}}$.

At the instant t'_0 (S) $= t'_0$ (T) the transformer is separated completely from the line, the three phases of which remain charged each

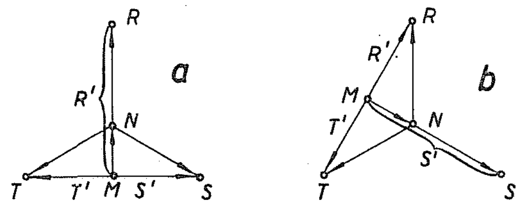

Fig. 9. — Vector diagram of the three phases and the neutral after disconnection of only two phases from the line.

with its respective potential (u_l). The transformer remains charged with the potential M which now corresponds to that of the neutral and about which the voltages u_p of the three phases are distributed.

At the instant t_1 we now assume a breakdown at pole R. The line (R) impresses its potential on the transformer terminal R and subjects it to a sudden voltage rise of $2.2\, u_{p_{max}}$. As the result of coupling this is transferred to the terminals S and T, producing a potential $1.8 \times 2.2\, u_{p_{max}}$ which causes a breakdown of both these phases. The transformer is thus again connected to the line through the three arcs while the three phases tend to resume their normal values u_p by oscillating about these voltages with the frequency f_{01}.

At the first passage of this transient current through zero (at t'_1) only the arc of phase S is extinguished. The line S remains charged with the positive voltage $u_L(S) = 1.3\, u_{p_{max}}$. The sum of the potentials of the two other phases must assume the same value with negative polarity and the midpoint M of the diagram (*fig.* 9 *b*) remains in the middle. Superimposed on this fixed potential M is one half of the voltage vector R-T, the one with $R' = -\frac{\sqrt{3}}{2} u_p$ and the other with $T' = +\frac{\sqrt{3}}{2} u_p$, the lines R and T oscillating about these two values with the frequency f_{01}. Terminal S′ of the transformer attains the voltage of the vector $S' = 1.5\, u_p$, superimposed on the potential of M, by oscillating with the frequency f_{04}.

It may now be assumed that the arc in phase R is extinguished at its third passage trough zero at time t_1, ... If phase T is also extinguished at this instant the three transformer windings assume again their normal voltages after oscillating with a transient frequency f_{02} about the potential which, at this instant, appears at the neutral. In order to present a case which may also occur in practice we may assume that T restrikes immediately after the third passage through zero. The line then impresses its potential on the transformer terminal T and on the whole winding after an oscillation with the frequency f_{03}. The arc may be extinguished at any one passage through zero of the oscillation f_{03}. If we assume that this happens at the third passage [at time t_e (T)] the line becomes completely separated from the transformer, the neutral remains fixed and the phases R and S, being subjected to an excessive potential, equalize each other and with T by means of a transient oscillation of frequency f_{02} about the three respective voltages u_p which are superimposed on the fixed neutral voltage. The lines remain charged with the voltage which they assumed during the extinction of their arcs.

The critical instant for the transformer occurs at t_2 because if an arc is produced at pole R and if the dielectric strength between the contacts of the other breaker poles is sufficiently high the terminals S and T are subjected to the highest stresses. In fact, the occurrence of an arc at t_2 raises the potential of terminal R suddenly by a value Δu to about $3.5\, u_{p_{max}}$. This sudden potential change causes the other two terminals S and T to undergo a potential reduction of $(1 + \alpha_{03}) \times \Delta u = 1.8 \times 3.5\, u_{p_{max}} = 6{,}3\, u_{p_{max}}$. By superposition on the instantaneous value of the 50 cycle voltage of each terminal ($-\,0.3\, u_{p_{max}}$ for phase S and $+\,0.6\, u_{p_{max}}$ for phase T) the crest value reaches a voltage to earth of $-\,6.6\, u_{p_{max}}$ at terminal S and $-\,5.7\, u_{p_{max}}$ at terminal T.

Such crest values may be sufficient to produce flashover of the two transformer terminals thus causing a double earth fault. As the transformer remains supplied from the system on its primary side there exist a probability — which is only little less than that of the occurrence of these crest values — of a short-circuit of the total power available.

If the terminals S and T and the breaker pole succeed in withstanding these crest values phase R is extinguished after several oscillations with frequency f_{03} but the entire transformer remains charged with a voltage of $3.6\,u_{p_{max}}$:

This example in which the interaction between breakdowns and extinctions was intentionally simplified so as to render it possible to explain the individual steps gives an idea of the number of possible variations.

Figure 10 shows an oscillogram of a disconnection resembling

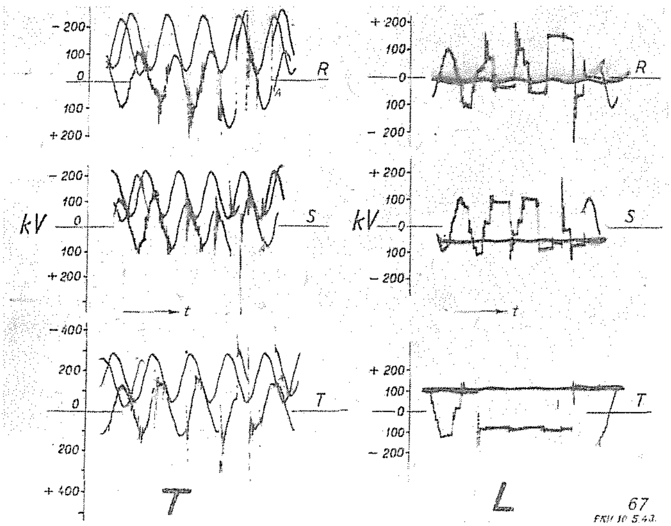

Fig. 10. — Oscillogram of the disconnection of an open line at 150 kV fed by a 16 500 kVA transformer with insulated neutral. T, voltages on transformer side; L, voltages on line side.

the example analysed. The crest values of the voltage reach 4.6 and $4.0\,u_{p_{max}}$; it should be noted that breakdown at pole T of the breaker was caused by the voltage $4.6\,u_{p_{max}}$.

The calculation of the probability of occurrence of these crest values is not easy but experience shows that high values occur comparatively infrequently. The oscillogram of figure 10 was the result of one case out of a total of 21 three-phase disconnections.

3. **Resume of the analysis.** — For the sake of greater clarity the picture may be simplified by considering only two phases and by plotting the potentials of line and transformer by their positions

(heights) as has been done in figure 11. It is known that the transformer may cause each pole of the line to be charged with a value exceeding $u_{p_{max}}$ (in 6 % of all cases about 1.7 $u_{p_{max}}$) (*fig.* 11 *a*).

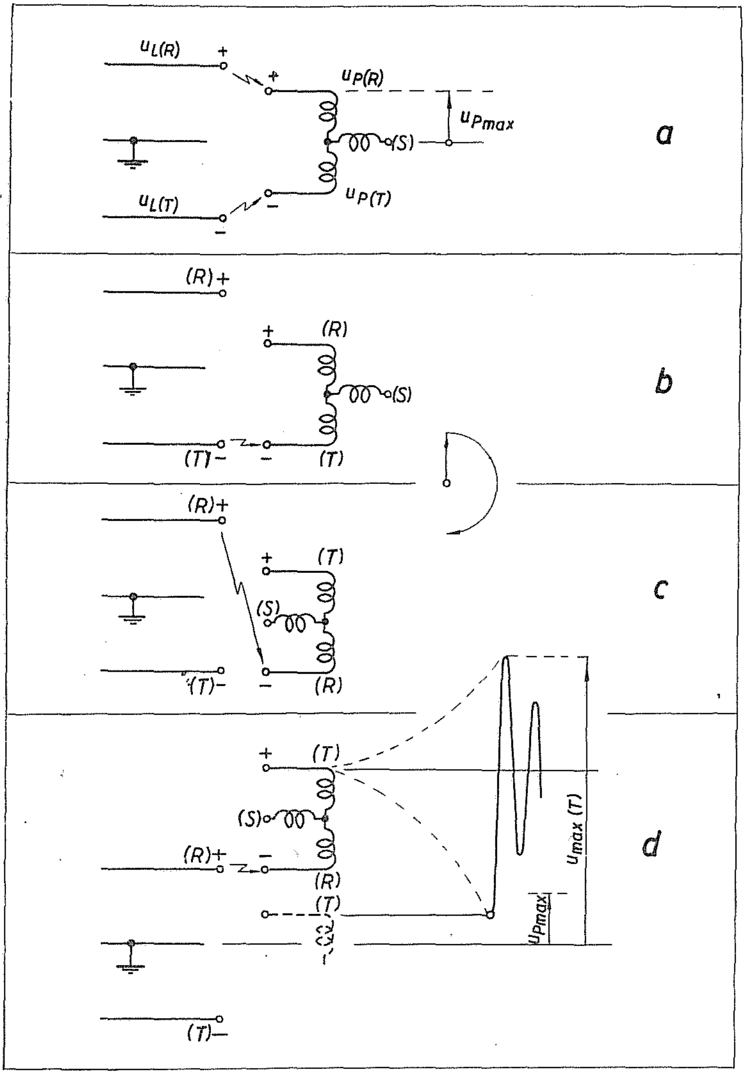

Fig. 11. — Simplified diagram indicating, in a summarizing manner, the development of the phenomenon which produces crest voltages of about 6 times the crest value of the phase voltage.

In addition, the transformer terminal at which the arc is interrupted last has, at the moment of extinction, the same potential as the line (phase T, *fig.* 11 *c*). Half a period of 50 c : s later the transformer has changed polarity (*fig.* 11 *c*). A breakdown of pole R at this

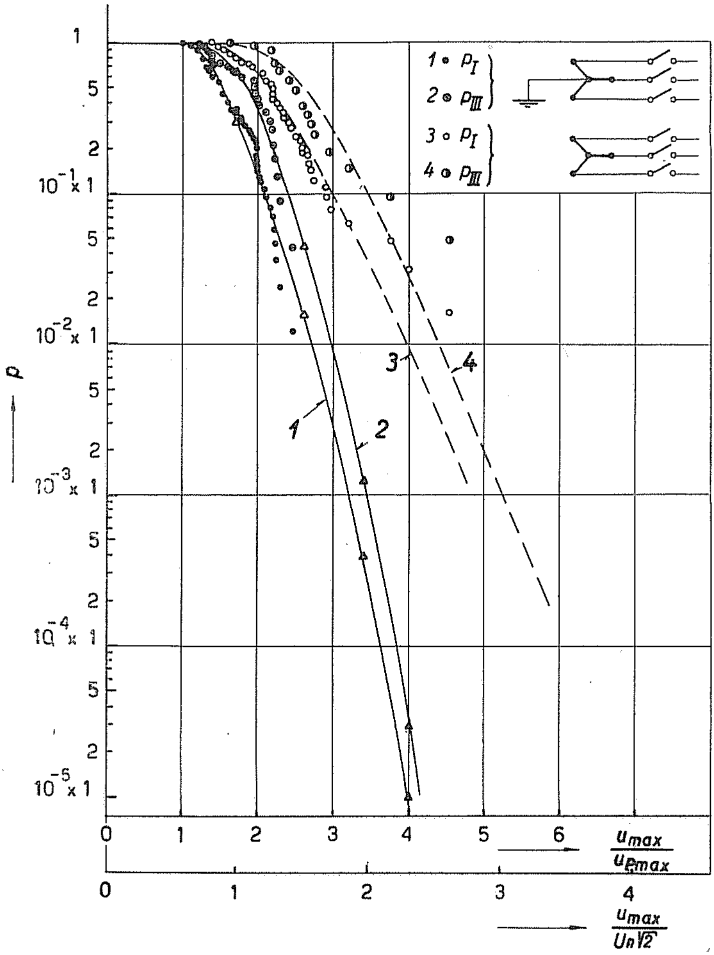

Fig. 12. — Probability of occurrence of a maximum voltage $\left(\frac{u_{\max}}{u_{p\max}} \text{ or } \frac{u_{\max}}{U_n\sqrt{2}}\right)$ equal to, or greater than the value indicated on the abcissa.

Curves 1 and 3 : voltage at one pole.
» 2 » 4 : voltage at one or more poles.
» 1 » 2 : transformer neutral directly earthed.
» 3 » 4 : transformer neutral isolated.

instant subjects this transformer terminal to a sudden voltage rise equal to the potential difference between the lines R and T. This sudden change causes roughly twice that value at the terminals S and T and is super imposed on the instantaneous voltage values of these bushings (*fig.* 11 *d*). This produces in phase T a crest voltage of about $6\,u_{p_{max}}$ to earth.

C. — COMPARISON BETWEEN THE TWO CASES OF NEUTRAL EARTHING.

The foregoing analysis of the disconnection of an open line fed by a transformer shows that in the case of an isolated neutral point the transformer is subjected to crest voltages 1.4-1.8 times higher than in the case when the neutral is directly earthed. With free neutral, crest voltages of 6 times normal phase voltage can be reached (3.5 times the nominal line voltage). With directly earthed neutral the crest values do not exceed 3.5 to 4 times the crest value of the phase voltage (2 to 2.3 times that of the line voltage).

Figure 12 shows the probability of occurrence of these crest values in the different cases. The points shown in that figure are derived from measurements with the exception of those shown as triangles which were calculated for the case of directly earthed neutral (table I).

It can be seen that in the case of a free neutral only the transformer is subjected to higher stresses whereas those occurring on the line are practically the same in both cases. Again, the overvoltages stressing a transformer with free neutral and those occurring on a transformer with directly earthed neutral point have approximately the same ratio as the highest normal frequency voltages which may occur in these two cases $\left(\frac{\text{line voltage}}{\text{phase voltage}}\right)$.

In systems operating below 100 kV the difficulties caused by higher overvoltages can be compensated by the advantages inherent in a system with insulated neutral (or with an arc suppression coil). In such system it is also comparatively easy to combat these overvoltages by adopting a sufficiently high safety factor for the insulation. On the other hand, on systems operating above 100 kV the cost of insulation may become preponderant and may compel the safety factor of the insulation to be limited to the minimum. The existence of the overvoltages studied which are higher with free neutral are a further argument in favour of direct earthing of the neutral point, particularly as the difficulties inherent in the operation of an arc suppression coil also increase with very high operating voltages.

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