EFFECT OF BUS AND OVERHEAD LINE SECTIONS UPON THE OVERVOLTAGE CONDITIONS OF HEAD STATIONS

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The solution shown in Fig. 1 has become general for the overvoltage protection of substations. The overvoltage protective device of the station (expulsion-tube, co-ordinating spark-gap) is placed at the overhead-line junction, while the transformers to be protected are connected to the station busbar. According to the figure, there is a distance L measured along the line between the transformer and the spark-gap, consequently a higher voltage may arise at the transformer terminal, than the sparkover voltage of the spark-gap. From the point of view of overvoltage protection, the most unfavourable case is, if only a single incoming line is connected to the busbar. (So further on, a distance L will be assumed between the transformer and the protective device, where L cannot be zero, as a consequence of some practical reasons.)

In first approximation the impedance roughly simulating the transformer may be left out of consideration, this being much higher than the surge impedance of the overhead line, assumed to be ideal.

The overvoltage conditions of the station shown in Fig. 1 may be examined by the equivalent circuit of Figs. 2 and 3. Let us suppose the surge wave coming from a great distance. The voltage arising at the transformer terminal (*i. e.* at the open end) may be arrived at by aid of the plotting to be seen in Fig. 4 for different points of the line, that is: *a*) for the transformer terminal; *b*) between the spark-gap and the transformer; *c*) for the location of the spark gap; *d*) at the line end of the spark gap, at a distance y from it and *e*) and *f*) for a more distant point. (The distance-scale of the figures — for saving space — is not true-to-scale.) The entering wedge-shaped wave marked by 1, running along the line is reflected at the transformer terminal with identical amplitude (Curve 2), consequently a resultant wave of double rate-of-rise, and (in the present case) of 1.20-times larger amplitude appears (Curve 3). (The 1.20 value has arisen instead of the double one, because the effect of the spark gap, having operated meanwhile, became perceptible.)

The reflected wave marked 2 returns in a time of $t = 2L/c$ to the spark gap and superimposes the incoming wave (of index 1). In the formula

L is the distance between the lightning arrester and the transformer, c is the wave velocity of propagation 300 m/μsec.

According to this, the shape of the arising surge wave is shown by the curve 5 of Fig. 5c. When the resultant voltage (marked 3) reaches the sparkover voltage U_s of the spark gap, latter is operating, consequently its voltage falls to zero and from the sparkover on, the rest of the resultant voltage starts

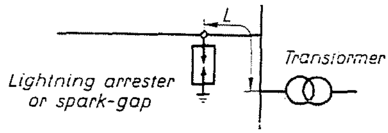


Fig. 1

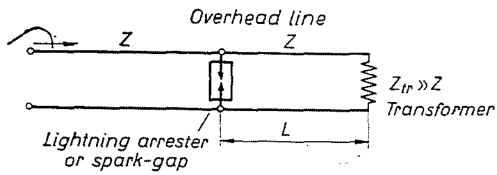


Fig. 2

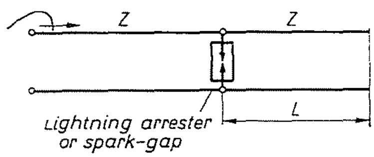
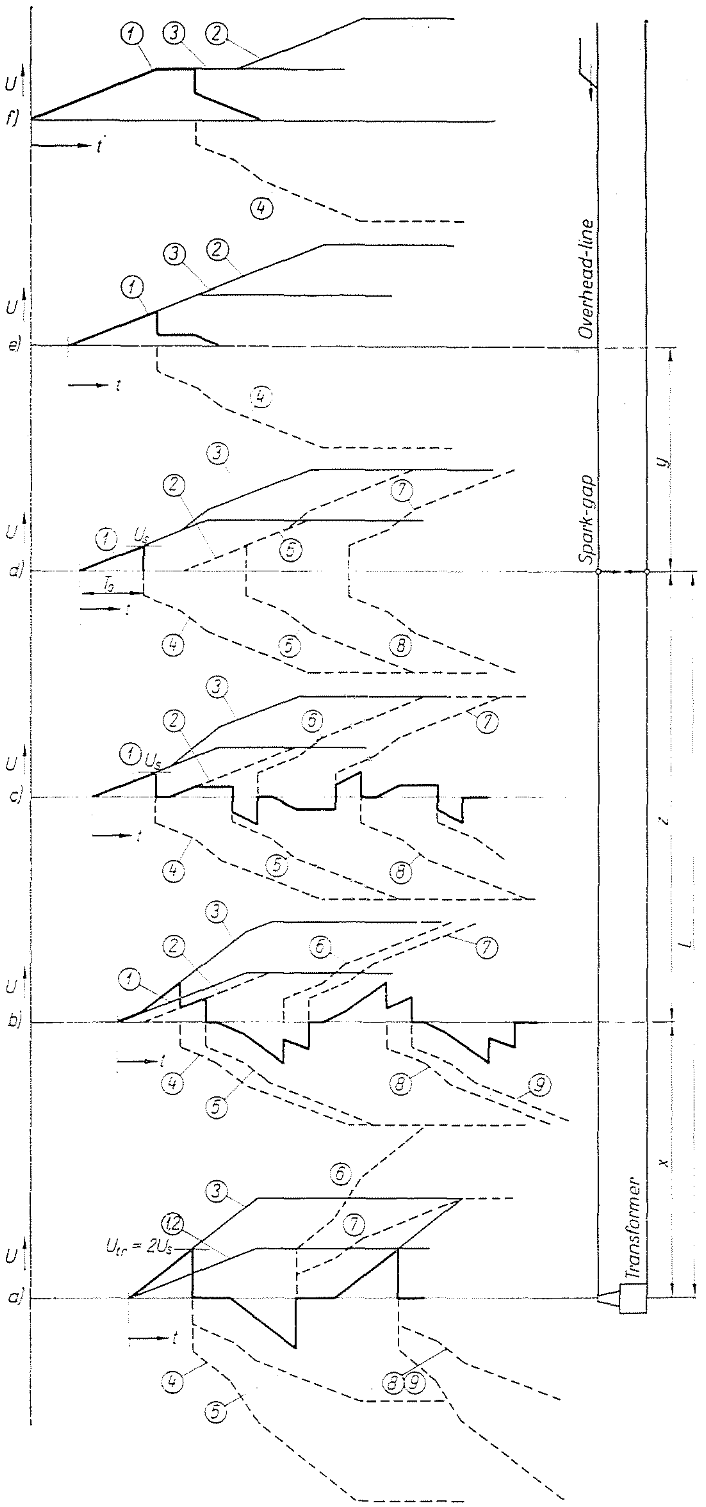


Fig. 3

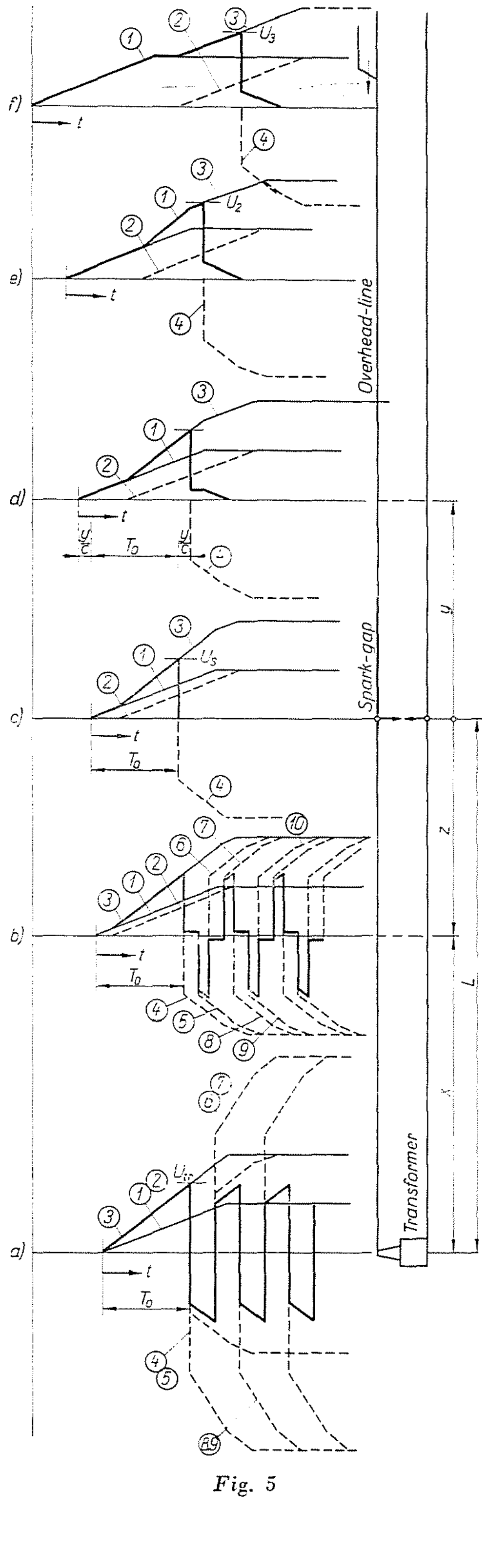
towards the transformer as a wave of negative polarity (curve marked 4). This negative reflected wave arrives to the transformer terminal within a time of $t' = L/c$, where it is reflected with an identical amplitude (5). This wave is added to the voltage already present at the transformer terminal (3) and stops its increase. Thereafter the negative reflected wave (marked 4) again reaches the spark gap (in a time t'), accordingly, the phenomenon described is periodically repeated. At the transformer terminal a voltage of periodical run appears.

The shape of the voltage curve may be plotted in the same way, if the gap is sparked over by the incoming wave. The run of the voltage curve, in this case, is shown in Fig. 4. The voltage curve periodic run may well be seen in Figs. 4 and 5, as the gap having sparked over reflects — as a short-circuit — the surge wave coming from the transformer with full amplitude in a negative sense. The figures also illustrate that a higher voltage arises at the transformer terminal than at that of the spark-gap.



U
t
a)
b)
c)
d)
e)
f)
U_s
T_0
$U_{tr} = 2U_s$
Overhead-line
Spark-gap
Transformer
x
y
z
L

Fig. 4



f)
e)
d)
c)
b)
a)
t
U_3
U_2
U_s
T_0
Overhead-line
Spark-gap
Transformer
x
y
z
L

Fig. 5

The phenomenon described is influenced by the overhead-line damping, as well as by the fact, that the actual surge wave is not wedge-shaped. As a result of the above two factors, the surge waves composed of broken lines to be seen in the figures, get rounded off, whereby the shape of the voltage curve becomes similar to a sine-wave, further the surge waves formed by the successive reflections, will be damped. Therefore, the highest voltage is always given by the first crest of the surge wave, being practically not influenced by the damping.

The effect of the spark gap located at different distances is shown by the wave-plots of Photo-Table I., illustrating the voltage at the transformer terminal in function of the distance between the spark gap and the transformer. The waves were plotted with the aid of the transient model of the Institute for Electrical Power Research (*Villenki*). One can see the crest voltage arising at the transformer terminal increasing gradually from 100%, which corresponds to the spark gap sparkover voltage, to a value of 188%, if the distance between the transformer and the spark gap is growing from zero to 350 m.

The crest voltage may also be determined by calculation. This also permits examination of the voltage arising within the section between the spark gap and the transformer. Let us first of all examine the case shown in Fig. 5, when the expulsion tube is operated by the incoming surge wave.

The equation of the incoming wave is

$$U(x, t) = \delta t \qquad (1)$$

where δ rate of rise of the wave kV/μsec:

t: time in μsec

x: distance, calculated from the transformer location

The time T_0 elapsing up to the sparkover of the (spread free) spark gap is obtained by putting $t = T_0$, $u(x, t) = U_{sz}$ into equation (1). U_s stands for the impulse sparkover voltage of the gap.

Accomplishing the calculation, we have

$$T_0 = \frac{U_s}{\delta} \qquad (2)$$

To determine the voltage arising between the transformer and the spark gap, respectively, the time of the voltage rise is to be calculated. Putting this value t' into the equation expressing the surge wave, the wave crest voltage is obtained. Examining Figs. 4—5, appears the time of the voltage rise being equal to T_0, *i. e.* the time elapsing up to the sparkover of the gap, namely the surge wave is running between the gap and the transformer with a velocity c, so at any point the voltage rises for a time T_0 with the original rate of rise, while after U_s the negative reflected wave follows. After all, the time of the wave increase will be $t' = T_0$ at every point z.

From the foregoing it follows that the *maximum*, or crest *voltage* may be determined by putting the time of the voltage rise T_0 into the equation.

Examining Fig. 4 it may be seen that until T_0 is shorter than $\frac{2x}{c}$ this being the time necessary for the wave running from point x up to the transformer and back from it, the spark-gap chops the original incoming wave, consequently if $T_0 \leqq \frac{2x}{c}$, T_0 must be substituted into equation

$$U = \delta t$$

describing the incoming wave to determine the crest voltage.

After substituting, the maximum voltage yields

$$U_{\max} = T_0 \delta = \frac{\delta U_s}{\delta} = U_s$$

Accordingly, after the spark gap the maximum voltage is the same at all points and equals the gap sparkover voltage, where

$$T_0 \leqq \frac{2x}{\delta} \tag{3}$$

To facilitate the calculation, the equation may be transformed by writing — with the symbols of Fig. 4 — instead of x the distance measured from the spark gap, $x = L - z$. Here L means the distance between the spark-gap and the transformer, z that between the spark gap the respective point, measured from the spark gap. After the substitution

$$T_0 \leqq \frac{2(L - z)}{c}$$

From this inequality the distance z, inside of which the crest voltage is constant in function of the distance and equal to the gap sparkover voltage may be determined. Marking by Z the critical value z, accomplishing the calculation

$$Z = L - \frac{c}{2} T_0 = L - \frac{c U_s}{2\delta} \tag{4}$$

According to equation $z = L - x$, to the critical value Z also belongs a value X, this being the critical distance measured from the transformer:

$$X = \frac{cU_s}{2\delta} \tag{5}$$

Within the distance, X the voltage is given by the superposition of the entering and the reflected wave, consequently the equation of the voltage-curve yields

$$U(x, t) = \delta t + \delta\left(t - \frac{2x}{c}\right) = 2\delta\left(t - \frac{x}{c}\right) \tag{6}$$

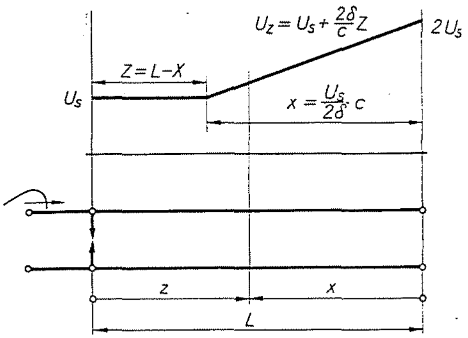


Fig. 6

Putting t instead of T_0 when determining the voltage crest

$$U_{\max}(x) = 2\delta\left(T_0 - \frac{2x}{c}\right) = 2U_s - \frac{2\delta}{c}x = 2\left(U_s - \frac{\delta}{c}x\right) \tag{7}$$

It can be seen that the crest voltage is not constant within the interval between the transformer and X, but increases linearly with the distance reduction.

The crest voltage arising at the transformer terminal is arrived at by substituting zero into x

$$U_{tr} = 2U_s$$

Accordingly, the crest voltage is constant within the section $Z = L - X$ after the spark-gap, while from this place on it rises linearly up to the value $2U_S$. The variation of the crest voltage between the transformer and the spark-gap, in function of distance, is illustrated in Fig. 6.

Thereafter, let us examine the case shown in Fig. 5, when the gap is operated by the reflected wave. In this case the voltage is determined by the sum of the incoming wave and the reflected wave.

$$U(x, t) = \delta t + \delta \left(t - \frac{2x}{c}\right) = 2\delta \left(t - \frac{x}{c}\right) . \tag{8}$$

To obtain the time T_0 elapsing up to the gap sparkover, let us put $t = T_0$, $x = L$, $U(x, t) = U_s$ and solve the equation for T_0:

$$T_0 = \frac{U_s}{2\delta} + \frac{L}{c} . \tag{9}$$

For determining the crest voltage arising within the section spark-gap — transformer, let us write into equation $t = T_0$ and instead of $x = (L - z)$.

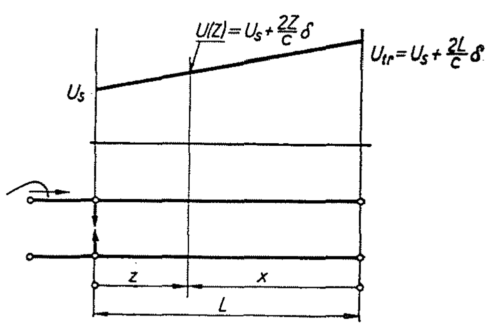


Fig. 7

Accordingly

$$U(z) = U_s + \frac{2z}{c} \delta . \tag{10}$$

It appears that in that case the crest voltage rises linearly with the distance measured from the spark gap.

The crest voltage arising at the transformer terminal is got by the substitution $z = L$:

$$U_{tr} = U_s + \frac{2L}{c} \delta . \tag{11}$$

From the foregoing it follows that the voltage rises linearly within the section gap — transformer, starting from U_s up to the value U_{tr}. The variation of the voltage crest in function of the location is shown in Fig. 7.

From the equation yielding the voltage at the transformer terminal also the separation distance of the spark gap may be approximately determined, if the equation is solved for L and instead of U_{tr} the transformer impulse sparkover voltage is written

$$L = \frac{U_{tr} - U_s}{2\delta} . \tag{12}$$

As proved by the two cases examined in detail, the case discussed in Fig. 4 occurs, if the *distance* between the spark gap and the transformer *is large*, expressed in formula, if $T_0 < \frac{2L}{c}$, while the case examined in connection with Fig. 5 takes place, if this *distance is small*, that is, if $T_0 > 2L/c$. In practice, exclusively the case shown in Fig. 5 may be met with, as the distance between the transformer and the protective device is chosen so small, that it is operated by the wave of usual rate of rise only after having been reflected from the transformer. In this case, however, the voltage as per Fig. 11 arises at the transformer — this being lower, than would arise, if the incoming wave had had operated the protective device. Nevertheless, considerable stresses may arise also in the case discussed in connection with Fig. 5. *E. g.* with a spark gap placed at a distance of 10 m, if the incoming wave rate of rise is $\delta =$ $= 500$ kV/μsec and the spark gap sparkover voltage is $U_s = 110$ kV(20 kV rated voltage) a voltage of

$$U_{tr} = U_s + \frac{2L}{c}\delta = 110 + \frac{2 \cdot 10}{300} 500$$

$$U_{tr} = 143 \cdot 3 \text{ kV}$$

arises at the transformer terminal, exceeding by 30% the gap sparkover voltage and this voltage rise may endanger the transformer insulation. For reducing the stresses, the spark gap shall be located so that this voltage rise should not exceed the impulse sparkover voltage of the transformer. If this cannot be assured, it is desirable to provide also the transformer terminal with a spark gap. In some cases, however, this cannot be realized, in such times the arising stresses may be reduced by connecting a line of suitable length to the bus, in conformity with the arrangement of Fig. 1, transforming thereby the head station into a through-station (Fig. 8). By this it can be realized that according to Fig. 4 the protective device is operated by the incoming wave and the voltage crest shown in Fig. 6 is being established.

In the substation layouts to be met in practice, in several cases a bus section is connected to the transformer (Fig. 10), which may exert a similar protective effect, if suitably dimensioned. In the following the protective effect of the bus, or line section will be examined, or rather the length of the bus- and line section will be determined, respectively, making the head station into a through-station. The length l' of the overhead line must be chosen so that no higher voltage arises at the transformer terminal, than the sparkover voltage of the spark gap.

The equivalent circuit of the connection of Fig. 8 may be seen in Fig. 9. If the impedance representing the transformer is — as before — neglected, then Fig. 9 is led back to Fig. 2 with the difference, that now the object to be protected is not at the end of the line, but in the middle of it. If we do not want the voltage at the transformer terminal should surpass the gap sparkover

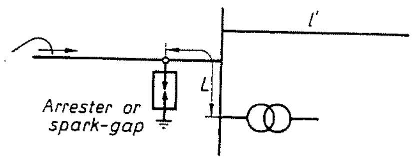


Fig. 8.

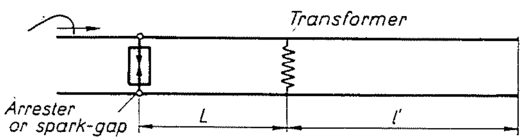


Fig. 9.

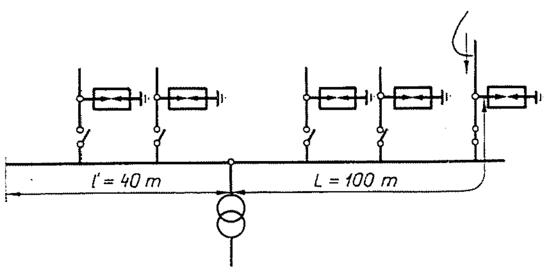


Fig. 10

voltage, l' must be chosen so that the case discussed in Fig. 4 takes place and the transformer should be within the section Z.

To satisfy this condition, the length of line of the overhead line starting from the bus must be longer than the distance X, consequently

$$1' > X = \frac{cU_s}{2\delta} \tag{13}$$

Should this condition be fulfilled, at any distance L between spark gap and transformer no higher voltage than the sparkover voltage of the spark gap will arise at the transformer terminals, if the voltage of the incoming wave is higher, than the gap sparkover voltages. *E. g.* in the above example, by a line length of $l' = \frac{300.110}{2.500} = 33$ m it may be realized, that the maximum voltage at the transformer should not be 143.3 kV, but 110 kV, so the stress could be reduced by roughly 30%.

If the voltage of the incoming wave is lower than the gap sparkover voltage, the wave enters without operating the spark gap, and then, arriving to the line end, it is reflected. The reflected wave, the incoming wave superimposed, operates the spark gap, whereby a negative reflected wave is starting, which arrives to the transformer terminal in a time $\frac{L}{c}$ in order to stop the voltage rise. Consequently, the voltage may rise at the transformer terminal for a time of $\frac{2L}{c}$, so the crest voltage arising at the transformer terminal yields

$$U_{tr} = U_s + \frac{2L}{c} \delta . \tag{14}$$

Accordingly, in this case the crest voltage arising at the transformer terminal is not influenced by the line section l'.

Nevertheless, this case is very rarely met with in practice, the voltage of the lightning strokes into the overhead line generally exceeding the sparkover voltage, therefore, the protective effect of the line section joining the transformer must be, as a rule, taken into consideration.

Examining equation (13) expressing the necessary line length l', it appears, that the minimum line-length converting the substation into a through-station is directly proportional to the spark gap sparkover voltage and *inversely proportional* to the incoming waves rate of rise. This means, that in case of a wave with small rate-of-rise, a higher additional line length is obtained.

The travelling wave rate-of-rise to be considered is furnished by the available lightning statistics. When calculating the gap separation distance, the travelling wave rate-of-rise is generally taken as 500 kV/ μsec.

It follows, however, from the formula, that the smaller the rate-of-rise of the lightning stroke wave is, the longer overhead line is necessary.

Therefore, in addition to the travelling wave rate-of-rise of 500 kV/ μsec, also for rates of rise 300 kV/ μsec and 100 kV/ μsec the line lengths to be employed, have been calculated.

Considering the sparkover voltage of standard spark gap, for the minimum length of line, for different rated voltages, the following values have been obtained.

According to calculations not to be detailed here, from a practical point of view it is generally sufficient to determine the length l by assuming a wave of rate of rise $\delta = 500$ kV/sec.

Table I

Rated voltage U_n	Spark gap sparkover voltage U_s	Necessary length of line m		
		$\delta = 500$ kV/μsec	$\delta = 300$ kV/μsec	$\delta = 100$ kV/μsec
10	65	19.5	32.5	97.5
20	110	33	55	165
30	150	45	75	225
35	170	51	85	255
60	265	19.5	132.5	398
120	415	124.5	207	622
220	760	228	380	1140

Considering, however, Table I it may be seen that the necessary line lengths are always shorter than a span. Moreover, it may occur that in case of a favourable layout (e. g. Fig. 10) *the bus itself may be long enough* to provide the station, in the above sense, with through-station characteristics and should exert the above-mentioned protective effect. Nevertheless, the bus length is generally not sufficient; examining the usual station arrangements, as a rule, smaller bus lengths are available.

At the same time, calculations show that the voltage arising at the transformer terminal may also decrease in that case. It seems to be practicable to examine the influence of the busbar length numerically too. Be L the distance between transformer and spark gap, and a busbar of length l' be connected to the transformer terminal, according to Fig. 11. Latter may be led back to Fig. 9. In accordance with the former deductions, the voltage variates within the section between the spark gap and the line end as shown in Figs. 12, or 13. The case to be seen in Fig. 12 takes place if $L + l' > \frac{cU_s}{2\delta}$. The case illustrated in Fig. 13 occurs if $L + l' < \frac{cU_s}{2\delta}$.

Examining the figures one recognizes that in the case shown in Fig. 13 the voltage arising at the transformer terminal is independent of l', the crest voltage being determined by the spark gap — transformer distance, L. As a consequence of this, the condition

$$l' > \frac{U_s c}{2\delta} - L = X - L \tag{15}$$

must be fulfilled for l' to reduce the voltage at the transformer terminal.

Should this condition be satisfied, the crest voltage arising at the transformer terminal yields

$$U_{tr} = U_s + \frac{2\delta}{c}(X - l') \tag{16}$$

where $X = \frac{cU_s}{2\delta}$, if $X < l'$. If $X < l'$, then, according to the aforesaid, the voltage rise does not appear at the transformer terminal.

To evaluate the results obtained, let us determine *e. g.* the effect of the bus of a 120 kV station, to be seen in Fig. 10. The spark gap — transformer

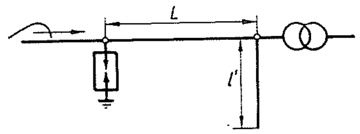


Fig. 11

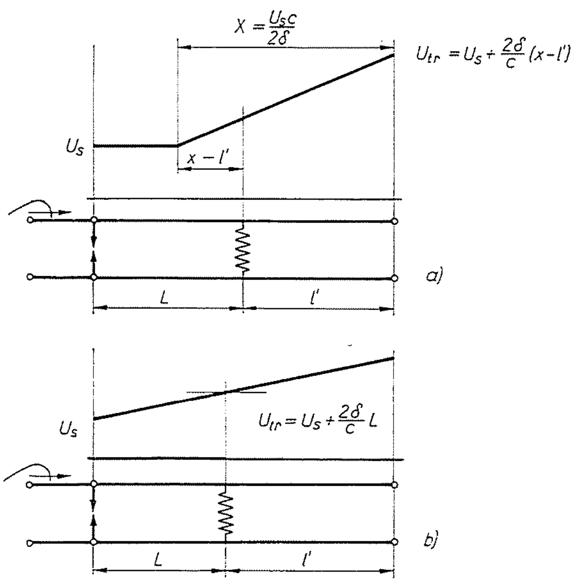


Fig. 12

distance is $L = 100$ m, the bus section $l' = 40$ m. In that case a voltage of 695 kV arises at the transformer terminal, adoption of a standard spark gap assumed as well as an incoming wave of rate-of-rise 500 kV/μsec. If l' is neglected, a voltage of 748 kV arises at the transformer terminal. From the numerical example it appears, that in the given case the stresses were reduced by the bus-section, consequently its effect must be considered when calculating the separation distance.

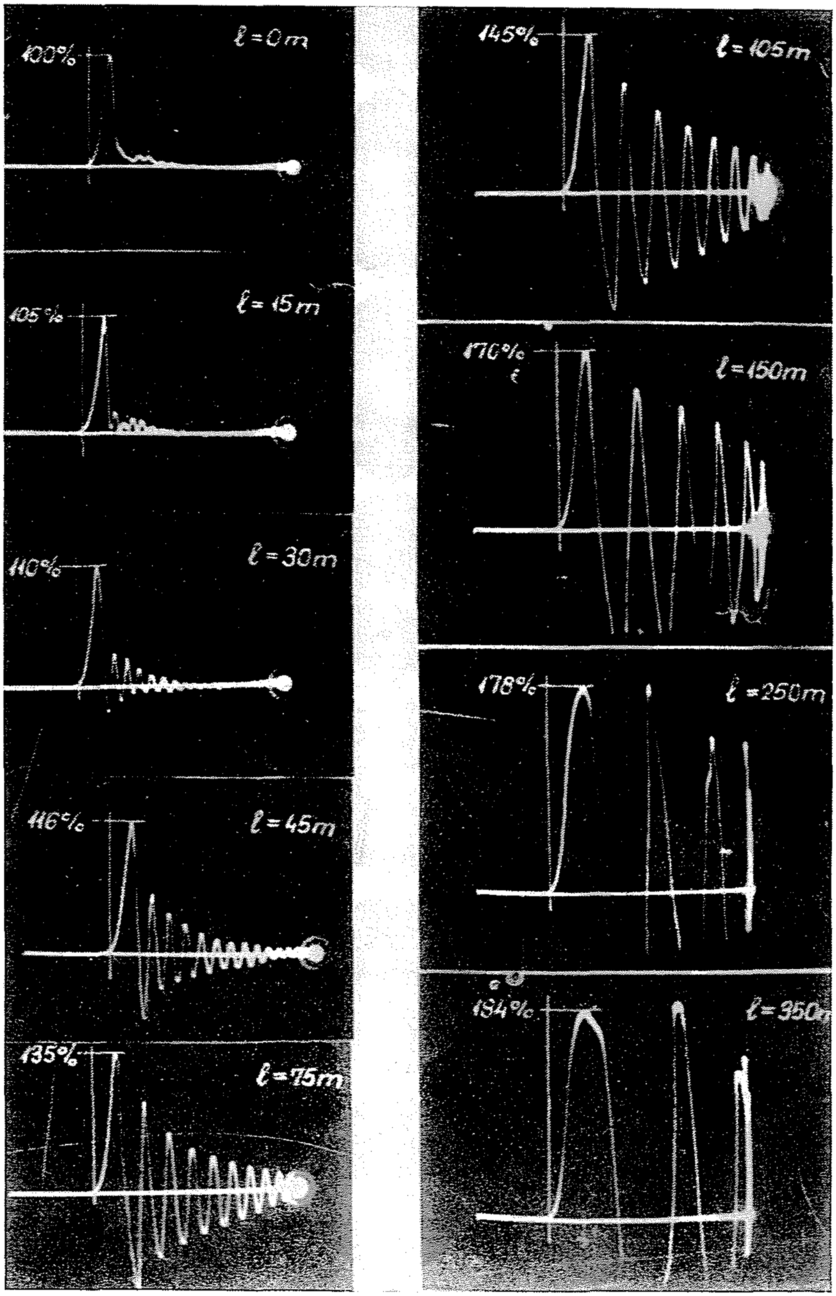

100%
ℓ=0m
105%
ℓ=15m
110%
ℓ=30m
116%
ℓ=45m
135%
ℓ=75m
145%
ℓ=105m
170%
ℓ=150m
178%
ℓ=250m
184%
ℓ=350

Fig. 13

Finally it must be pointed out that similar considerations may also be made in case of lightning arresters, though because of the residual voltage, conditions are more complex. Authors wish to examine this problem in a subsequent paper.

Summarizing the results obtained it may be stated, that in case of head stations

1. the formulae calculating the separation distance merely on the basis of the reflections taking place within the line section between the protective device and the transformer — leaving out of consideration the bus and other line sections — give more unfavourable results than occur in reality.

2. When determining the separation distance of the gap the protective effect of the bus sections, and short leads must also be considered.

3. If the spark gap of U_s sparkover voltage is located at a certain distance L from the transformer, then in case of an incoming wave of δ rate-of-rise, U_{tr} always equals $U_s + \frac{2L}{c}\delta$, accordingly exceeding U_s. By connection a suitable line section of $l' = \frac{cU_s}{2\delta}$ — being generally short — it may always be attained that the transformer stress be $U_{tr} = U_s$. This decrease in stress may be considerable.

4. The efficiency of the connected line section l' is especially high in case of incoming waves with a large δ rate-of-rise.

Summary

In the present study the overvoltage conditions of head stations are examined. It is proved that when determining the location of expulsion tubes, the protective effect of the bus-sections and leads (of 10—15 m) must be considered too. Consequently, the usual formulas expressing the separation distance — neglecting the bus and other line sections — give more unfavourable stresses than occur in reality.

It is known that if the spark gap of an impulse sparkover voltage U_S is placed at a distance L from the transformer, then in case of an incoming wave of a rate-of-rise δ, a voltage of $U_{tr} = U_S + \frac{2L}{c}\delta$ will always arise at the transformer terminal, being higher, than the voltage U_S. By connecting a conductor of suitable length, which is at least $l' = \frac{cU_S}{\delta 2}$, a transformer stress of $U_{tr} = U_S$ may be attained, which is the same as if the gap were placed on the bus of the transformer. The stress reduction got in this way may be considerable.

Finally the calculation results of the study are justified by a numerical example.

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