SHORT-CIRCUIT CURRENTS IN CIRCUITS CONTAINING SERIES CAPACITORS

By

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The development of short-circuit currents in circuits containing a series capacitor has scarcely been dealt with in the literature. This may be ascribed to the fact that the protection of the capacitor is, for economical reasons, generally considered inevitable [1]. As the spark-gap protective device by-passes the capacitor, already during the first semi-period of the fault-current, the series capacitor has apparently been supposed to have but a small effect, if any, upon the short-circuit current.

Nevertheless, according to other authors [2] the spark gap may in some instances be omitted. In this case the capacitor obviously remains in the circuit during short circuit and will increase the short-circuit current. The question arises : to what extent? Does this endanger the transmission line, transformer, circuit breaker, etc.? On the other hand, an overvoltage rises even on the capacitor during short circuit. To what extent should the capacitor be oversized in order to endure the overvoltage? The present paper is devoted to these questions.

1. Simplifying assumptions

To simplify computation we make some assumptions adopted in practice. The magnetizing current and the iron loss of the transformers shall be neglected, and the transformer substituted by a series resistance R_{tr} and an inductivity L_{tr}. The capacitance and leakance of the transmission line are also neglected and the transmission line substituted by a series resistance R_t and an inductivity L_t. A pure capacity C, will be substituted for the series capacitor and the losses of the latter neglected. An "infinite" bus is assumed before the feed-side transformer. Consequently, during the whole period of short circuit the voltage of the feed-point shall be of steady value and frequency. We start by examining a three-phase short circuit arising at no-load.

2. Calculation of the short-circuit current

With the assumptions made, the short-circuit loop may be substituted by a simple R, L, C circuit in series, where $R = R_t + \Sigma R_{tr}$ and $L = L_t + \Sigma L_{tr}$. The short circuit is equivalent to the sudden connecting of an alternating voltage (Fig. 1).

For zero starting conditions the integral-differential equation of the circuit with *complex quantities* is:

$$L \frac{d\bar{I}}{dt} + R\bar{I} + \frac{1}{C}\int_0^t \bar{I}\,dt = \bar{U} = U_m e^{j(\omega t + \psi)} . \tag{1}$$

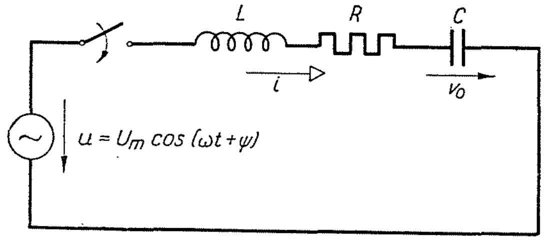

Fig. 1

By *Laplace transformation** the *operational function of the current* may be easily computed:

$$\bar{I}(p) = U_m e^{j\psi} \frac{p}{p - j\omega} \cdot \frac{1}{pL + R + \frac{1}{pC}} . \tag{2}$$

The *time function* $\bar{I}(t)$ may be determined by the generalized expansion theorem [3]. $\bar{I}(t)$ consists of two parts: of the *steady-state component* $\bar{I}_s(t)$ and of the *transient component* $\bar{I}_t(t)$. The steady-state component of the short-circuit current is

$$\bar{I}_s(t) = \frac{\bar{U}}{\bar{Z}} = \frac{U_m e^{j(\omega t + \psi - \varphi)}}{\sqrt{R^2 + (X_L - X_C)^2}} = I_m e^{j(\omega t + \psi - \varphi)} . \tag{3}$$

Let us examine the change of amplitude of the steady-state current in case of different compensations. The terms below are to be introduced:

$k = X_C/X_L$ *the degree of compensation*

$h = R/X_L$ *the resistance — inductive reactance ratio (i. e. R/X ratio)*

* $f(p) = p \int_0^\infty f(t)\, e^{-pt}\, dt$

$I_f = U_m/X_L$ *fictive current.* (The amplitude of the short-circuit current would equal this value if the inductive reactance alone were taken into consideration.)

On the basis of above, the amplitude of the steady-state short-circuit current may be expressed as follows:

$$I_s = I_m = \frac{1}{\sqrt{h^2 + (1-k)^2}} I_f = c_s I_f \tag{4}$$

where c_s means the *correction factor* of the steady-state short-circuit current.

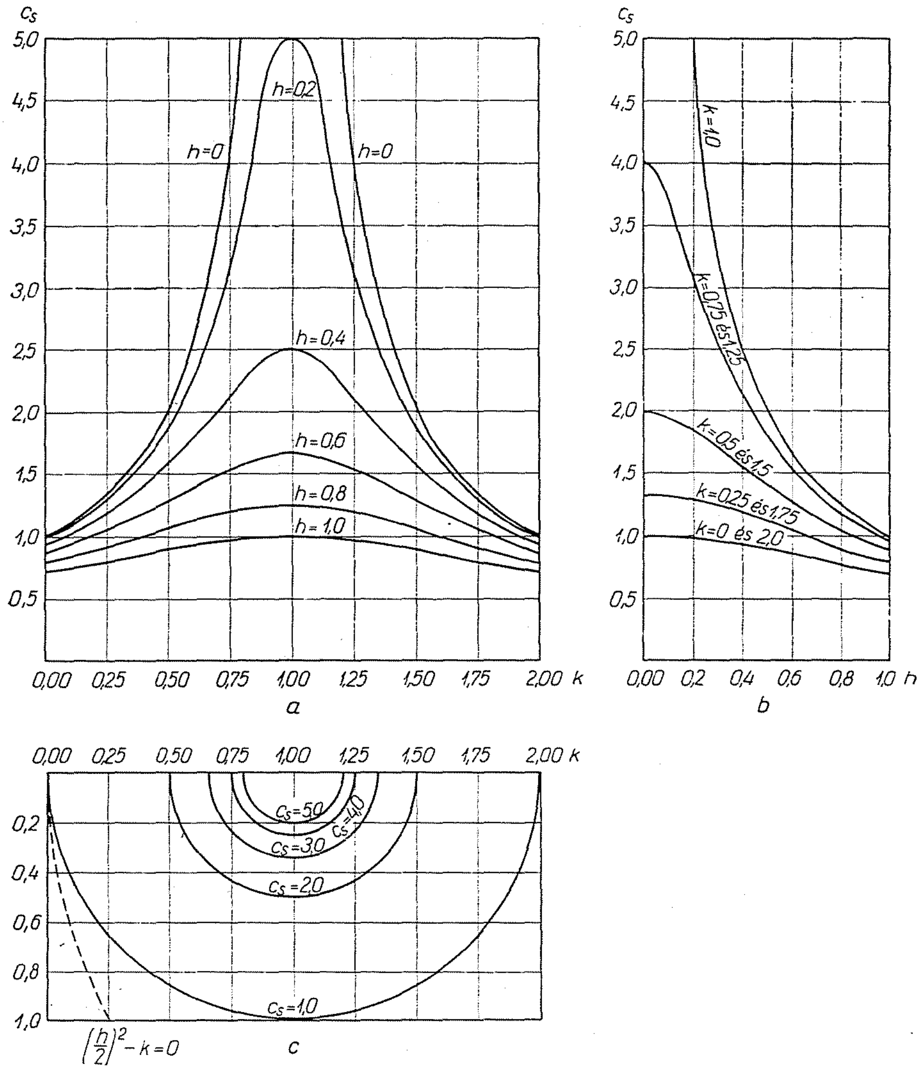

Fig. 2

Figs. 2a, b, c show the coherent values oh h, k and c_s. If the notations

$$\alpha = \frac{R}{2L} = \frac{R}{2X_L}\,\omega = \frac{h}{2}\,\omega \tag{5}$$

$$\beta = \sqrt{\left(\frac{R}{2L}\right)^2 - \frac{1}{LC}} = \omega \sqrt{\left(\frac{R}{2X_L}\right) - \frac{X_C}{X_L}} = \omega \sqrt{\left(\frac{h}{2}\right)^2 - k} \tag{6}$$

$$\nu = \sqrt{\frac{1}{LC} - \left(\frac{R}{2L}\right)^2} = \omega \sqrt{\frac{X_C}{X_L} - \left(\frac{R}{2X_L}\right)^2} = \omega \sqrt{k - \left(\frac{h}{2}\right)^2} \tag{7}$$

are introduced we may write the transient component $\bar{I}_t(t)$ in the following form:

a) In the aperiodic case

$$\bar{I}_t(t) = -I_m e^{j(\psi-\varphi)} \frac{1}{2\sqrt{\left(\frac{h}{2}\right)^2 - k}} \times$$
$$\times \left\{ \left[-\left(\frac{h}{2}\right) + \sqrt{\left(\frac{h}{2}\right)^2 - k} + j\,k \right] e^{(-\alpha+\beta)t} - \right.$$
$$\left. - \left[-\left(\frac{h}{2}\right) - \sqrt{\left(\frac{h}{2}\right)^2 - k} + jk \right] e^{(-\alpha-\beta)t} \right\}. \tag{8}$$

The short-circuit current transient component of the *noncompensated* system is obtained by the substitutions $k = 0$, $\beta = \alpha$:

$$\bar{I}_t(t) = -I_m e^{j(\psi-\varphi)} e^{-2\alpha t} \tag{9}$$

b) In the aperiodic limit case :

$$\bar{I}_t(t) = -I_m e^{j(\psi-\varphi)} e^{-\alpha t} \left[1 - \left(\frac{h}{2}\right) \omega\, t \left(1 - j\,\frac{h}{2}\right) \right] \tag{10}$$

c) Finally, in the periodic case :

$$\bar{I}_t(t) = -I_m e^{j(\psi-\varphi)} \frac{1}{2j\sqrt{k - \left(\frac{h}{2}\right)^2}} \times$$
$$\times \left\{ \left[-\left(\frac{h}{2}\right) + j\sqrt{k - \left(\frac{h}{2}\right)^2} + j\,k \right] e^{(-\alpha+j\nu t)} - \right. \tag{11}$$

$$-\left[-\left(\frac{h}{2}\right)-j\sqrt{k-\left(\frac{h}{2}\right)^2}+jk\right]e^{(-a-j\nu t)}\Bigg\}.$$

This formula is simplified in case of $R = 0$ and $h = 0$;

$$\bar{I}_t(t) = -I_m e^{j(\psi-\frac{\pi}{2})} \cdot \frac{(1+\sqrt{k})e^{j\nu t}+(1-\sqrt{k})\,e^{-j\nu t}}{2} \tag{12}$$

Here simply $\nu = \omega\sqrt{k}$.

2. Comparison of the short-circuit currents

Now that the time functions are known the short-circuit currents can be compared. Comparison will be effected on the basis of the peak value of the short-circuit current.

It is advisable to keep the complex quantities and to employ a method of graphic design for the determination of peak currents. The steady-state component $\bar{I}_s(t)$ is represented by a vector of constant length rotating with angular velocity ω. The transient component $\bar{I}_t(t)$ may be represented by two vectors of different lengths [see Expressions (8) . . . (12)]. In both cases the initial value of the resultant vector is zero, the short-circuit current starts from the zero value. To determine the peak current for different times, we draft the resultant of the three (in case of $k = 0$, two) vectors and find that of the greatest absolute value.

When drafting, the factor $e^{j(\psi-\varphi)}$ involved in both steady-state component and transient component may be abandoned as a factor not influencing the absolute value of the vectors, but determing only their starting position. On the other hand, the factor I_m figuring in all components, may be taken as a factor of unit length. In this case drafting will not give the greatest peak value, but only a *peak factor* c_t. Knowing the peak factor, we may express the short-circuit peak current as follows:

$$I_c = c_t I_s = c_t I_m\,. \tag{13}$$

In Fig. 2*c* the limit curve $\left(\frac{h}{2}\right)^2 - k = 0$ is also shown. It may be read from the figure that the most important cases for practical purposes fall within the territory of $k > \left(\frac{h}{2}\right)^2$. Consequently, for the realization of the design we shall use first of all the periodical solution given by Eq. (11) and, for comparison, the solution regarding the noncompensated case given by Eq. (9).

The design for case e. g. $k = 0{,}5$; $h = 0{,}2$ and $k = 1{,}5$; $h = 0{,}2$ is shown in Figs. 3*a* and *b*. The thick line is the diagram of the three current vectors, the dotted circle is the diagram of the steady-state component and the dotted spiral line is the diagram of the resultant of the two transient components. Time segments are marked on the diagrams.

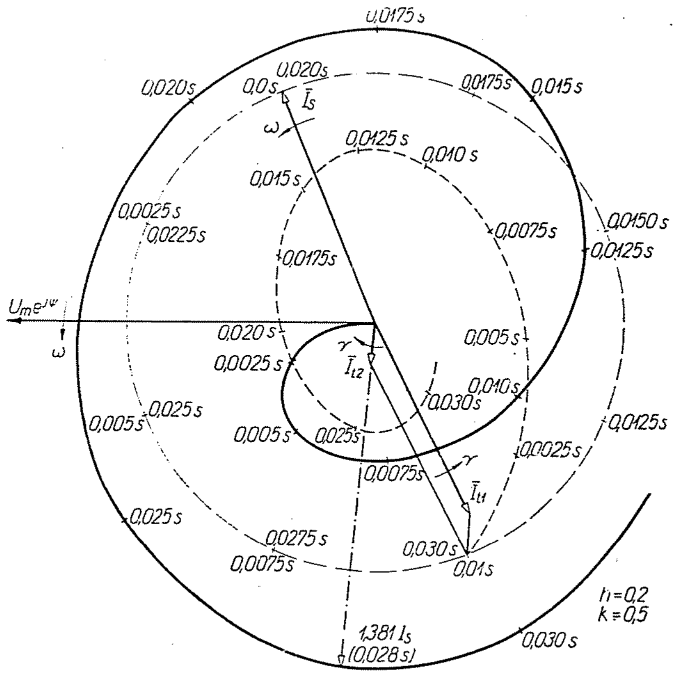

Fig. 3a

Table 1a

Values of the peak factors c_t

k \ h	0,2	0,4	0,6
0,0	1,552	1,316	1,188
0,25	1,55	1,347	1,235
0,50	1,381	1,175	1,081
0,75	1,139	1,033	∼ 1,0
1,0	∼ 1,0	∼ 1,0	∼ 1,0
1,5	1,355	1,107	1,03
2,0	1,67	1,37	1,20

The results of the drafting are shown in Table 1. Table 1*a* sums up the peak factors and Table 1*b* shows the time the short circuit takes to attain the greatest peak current in the most unfavourable case, *i. e.*, when the greatest short-circuit peak current has indeed developed. Near the maximum value, the resultant diagram deviates but slightly from the arc of a circle. Hence, the peak factor may be determined with suffiecient accuracy though the space of time with less precision. Fig. 4 gives the peak factors c_t, int he function of h, with different k parameters.

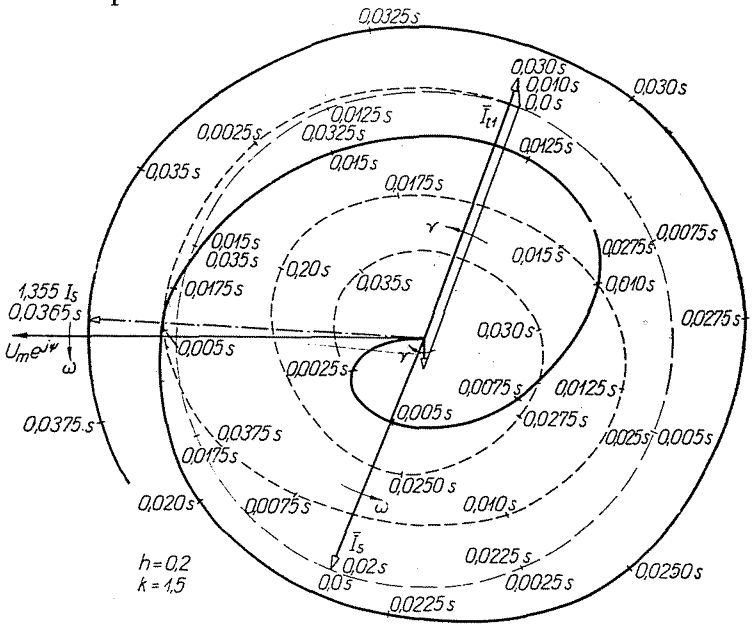

Fig. 3b

Table 1b

Time in sec from the short circuit up to the development of the highest peak current

k \ h	0,2	0,4	0,6
0,0	0,009	0,00838	0,00791
0,25	0,0195	0,0185	0,0175
0,50	0,028	0,028	0,0275
0,75	0,0565	0,0475	?
1,0	?	?	?
1,5	0,0365	0,0370	0,0375
2,0	0,0175	0,0175	0,0175

Knowing the factors c_s and c_t, the greatest short-circuit peak current may be computed with the formula

$$I_c = c_s\, c_t\, I_f = I_f\,. \tag{14}$$

Fig. 5 shows the *resultant factor* $c = c_s c_t$, in the function of h, with different k parameters.

Making use of factor c, the short-circuit currents may be compared according to different degrees of compensation and different ratios of R/X. To make comparison easier the $\sqrt{2}$-times, as well as the 2-times value of c_0 in the non-

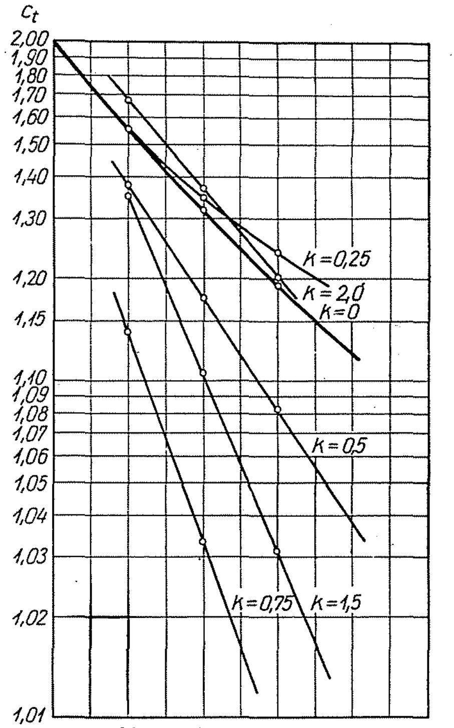

Fig. 4

compensated system (curves $\sqrt{2}\, c_0$ and $2\, c_0$) are plotted on the figure (dotted line). Employment of terms c, c_t and c_s for the comparison of short-circuit currents is shown by an example.

4. Example

Let us compare the short-circuit currents of the system shown in Fig. 6. Calculations were made in relative units referred to a basic voltage of 22 kV and to a basic power of 2 MVA. Results of the calculation are shown in Table 2.

Should a short circuit behind the step-down transformer take place the results obtained show I_s to increase by 2,06 and I_t by 1,68, in case of $X_C = 10{,}76\%$

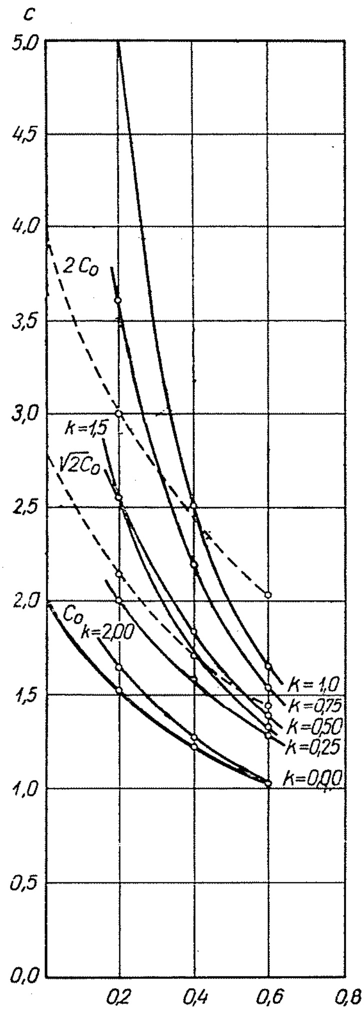
c
5,0
4,5
4,0
3,5
3,0
2,5
2,0
1,5
1,0
0,5
0,0
0,2
0,4
0,6
0,8
2 Co
k=1,5
√2Co
Co
k=2,00
k=1,0
k=0,75
k=0,50
k=0,25
k=0,00

Fig. 5

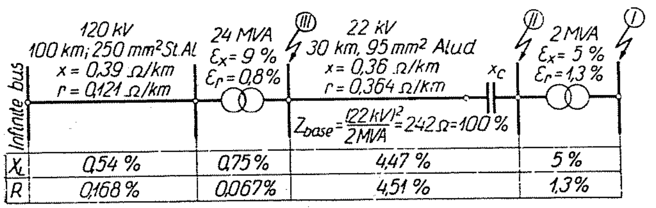
Infinite bus
120 kV
100 km; 250 mm² St.Al
x = 0,39 Ω/km
r = 0,121 Ω/km
24 MVA
εx = 9 %
εr = 0,8 %
III
22 kV
30 km, 95 mm² Alud
x = 0,36 Ω/km
r = 0,364 Ω/km
II
xc
2 MVA
εx = 5 %
εr = 1,3 %
I
Zbase = (22 kV)²/2 MVA = 242 Ω = 100 %
XL 0,54 % 0,75 % 4,47 % 5 %
R 0,168 % 0,067 % 4,51 % 1,3 %

Fig. 6

($k = 1$), while in case of $X_C = 5{,}38\%$ ($k = 0{,}5$), the increases of I_s will be 1,52 and that of I_t will be 1,37 as compared to the noncompensated case. If the short circuit takes place at the receiving end of the transmission line, in case of $X_C = 10{,}76\%$ I_t increases by 1,08, I_t by 1,05, in case of $X_C = 5{,}38\%$, I_s increases by 1,59 and, I_t by 1,42 as against the noncompensated case. But even these increased currents are considerably smaller than the short-circuit peak current, resp. the steady-state current arising at the sending end of the transmission line.

Table 2.
Calculation of the short-circuit currents

Place of the short circuit	R %	X_L %	X_C %	h	k	c_s	c_t	c	I_f p. u.	I_s p. u.	I_c p. u.
I.	6,045	10,76	10,76	0,562	1,0	1,77	1,0	1,77	9,3	16,46	16,46
I.	6,045	10,76	5,38	0,562	0,5	1,31	1,097	1,433	9,3	12,18	13,32
I.	6,045	10,76	0,00	0,562	0,0	0,86	1,22	1,05	9,3	8,0	9,77
II.	4,745	5,76	10,76	0,824	1,87	0,81	1,09	0,882	17,35	14,05	15,3
II.	4,745	5,76	5,38	0,824	0,935	1,19	1,0	1,19	17,35	20,64	20,64
II.	4,745	5,76	0,00	0,824	0,0	0,75	1,12	0,84	17,35	13,0	14,6
III.	0,235	1,29	—	0,182	0,0	0,98	1,58	1,55	77,5	76,0	120,0

5. Further generalizations

The above calculation started from a three-phase short circuit arising at no-load. The results obtained may be generalized for asymmetrical short circuits too. Thus e. g. in case of a two-phase short circuit the terms c_s and c_t remain unchanged, only the fictive I_t current will increase to its $\sqrt{3}/2$-times value. Therefore a three-phase short circuit is more unfavourable than a two-phase one.

It is easy to apply the generalization to the single-phase earth-fault (if the resistance R_0 and the inductivity L_0 are considered constant, independently of the frequency), as the positive-, negative- and zero-sequence network must be series-connected. In this case:

$$h = \frac{2R + R_0}{2X + X_0} \quad \text{and} \quad k = \frac{3\,X_C}{2X + X_0}\,.$$

As generally

$$\frac{R_0}{X_0} < \frac{R}{X} \quad \text{and} \quad X_0 > X$$

we may count upon smaller values of h and k than in case of a three-phase fault. The current I_f will also be smaller since $2\,X + X_0 > 3\,X$. Owing to the fact that with the decrease of h and k the terms c_s, resp. c_t may either increase or decrease, no general statement can be made as to whether a three-phase fault or a single-phase earth-fault is less favourable. In any case conclusions concerning the three-phase fault can invariably be applied to the single-phase earth-fault, too. The generalization, however, cannot be applied to a two-phase earth-fault, since in this case the negative- and zero-sequence network must be parallelly connected.

We have hitherto examined only such short circuits as may arise at no-load. It remains to find out the character of the influence of the initial load.

The load current at the moment of short-circuit is assumed to be

$$\bar{I}_0 = \frac{U_m e^{j\nu}}{\Sigma \bar{Z}} \tag{15}$$

where $\Sigma \bar{Z}$ comprises the load impedance too. The initial voltage of the capacitor is

$$\bar{V}_0 = -j X_C \bar{I}_0 . \tag{16}$$

The Laplace-transform of the short-circuit current in this case is :

$$\bar{I}(p) = U_m e^{j\nu} \frac{p}{p - j\omega} \frac{1}{Z(p)} + \bar{I}_0 \frac{pL}{Z(p)} + \bar{I}_0 j X_C \frac{1}{Z(p)} \tag{17}$$

where $Z(p) = pL + R + \frac{1}{pC}$.

The time function of the first term on the right-side had been determined previously: Eq. (8) ... (22). The time function of the second term for the periodic case :

$$\bar{I}_0 \frac{\left[-\left(\frac{h}{2}\right) + j\sqrt{k - \left(\frac{h}{2}\right)^2}\right] e^{(-\alpha + j\nu)t} - \left[-\left(\frac{h}{2}\right) - j\sqrt{k - \left(\frac{h}{2}\right)^2}\right] e^{(-\alpha - j\nu)t}}{2j\sqrt{k - \left(\frac{h}{2}\right)^2}} \tag{18}$$

The time function of the third term on the right-side is

$$\bar{I}_0 \frac{jk\left(e^{(-\alpha + j\nu)t} - e^{(-\alpha - j\nu t)}\right)}{2j\sqrt{k - \left(\frac{h}{2}\right)^2}} \tag{19}$$

By this the full solution, considering (3) and (11) is:

$$\bar{I}(t) = I_m e^{j(\psi-\varphi)} e^{j\omega t} - (I_m e^{j(\psi-\varphi)} - \bar{I}_0) \frac{1}{2j\sqrt{k-\left(\frac{h}{2}\right)^2}} \times$$
$$\times \left\{ \left[-\left(\frac{h}{2}\right) + j\sqrt{k-\left(\frac{h}{2}\right)^2} + jk \right] e^{(-\alpha+j\nu)t} - \right.$$
$$\left. - \left[-\left(\frac{h}{2}\right) - j\sqrt{k-\left(\frac{h}{2}\right)^2} + jk \right] e^{(-\alpha-j\nu)t} \right\}. \quad (20)$$

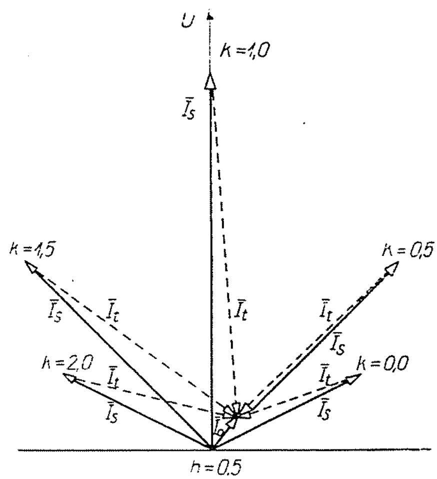

Fig. 7

The steady-state component of the short-circuit current is not influenced by the initial load, but the transient component is changed by it. Fig. 7. shows the vector of the load-current $\bar{I}_0$, the steady-state short-circuit current $\bar{I}_s$ and of the resultant transient component $\bar{I}_t$, for the initial time, with different degrees of compensation k. The transient components are, generally, smaller than in case of faults arising at no-load and exceed this value at very great over-compensation only. As the angle between $\bar{I}_s$ and the resultant vector $\bar{I}_t$ is still close to 180°, the factor c_t under the effect of the initial load generally decreases. In other words, the fault caused at no-load will be more unfavourable.

6. Conclusions

We have studied the increase of the short-circuit current caused by the series capacitor, provided it remains in the fault loop during the whole length of the short circuit. The short-circuit currents of the compensated and noncompensated systems may be compared by means of the correction factor c_s, the peak factor c_t and the resultant factor $c = c_s c_t$.

1. Conclusions regarding the steady-state short-circuit current may be read from the correction factor c_s (Fig. 2). The more complete the compensation, the more the amplitude of the steady-state short-circuit current at a given ratio of R/X deviates from that of the steady-state short-circuit current in the noncompensated system. At a small degree of compensation, as well as at a great overcompensation the deviation is smaller than at a compensation around 100%. The effect of the ratio R/X must be taken into account too ; at a small h value deviation is considerable, at a medium h value it is already smaller and at a very great h value it is insignificant.

2. Conclusions regarding the transient component may be drawn by using factor c_t (Fig. 4). The peak factor c_t to a certain extent changes opposite to the correction factor c_s. At a small degree of compensation and at a very great overcompensation the factor c_t is somewhat greater than the factor c_{t0} of the noncompensated system. Approaching full compensation, the effect of transients decreases, the peak factor c_t comes near to 1. It may also be stated that with an increase of the ratio R/X, the factors c_t themselves considerably decrease, though the deviations are but slightly influenced by the change of h.

3. Conclusions regarding the short-circuit peak current may be drawn by using factor c which includes also the effect of both factors c_s and c_t. The short-circuit peak current of the compensated system may be many times greater than that of the noncompensated system,especially in case of a very small R/X ratio and at a degree of compensation near to 1. Nevertheless, from $R/X = h = 0{,}4$, even in case of $k = 1{,}0$, no peak current of more than twice the noncompensated case arises (see Fig. 5). At a small degree of compensation (about $k = 0{,}25$), the greatest short-circuit peak current in the compensated system is about $\sqrt{2}$-times that of the noncompensated system, within the range of $R/X = 0{,}2$—$0{,}6$. When $R/X = 0{,}6$, the peak current will not be greater than $\sqrt{2}$-times, even at $k = 0{,}5$.

4. All these comparisons referred to short-circuits arisen at identical points of the compensated and noncompensated system, e. g. at the receiving end. If we compare a short circuit at the receiving end of the compensated transmission line with that at the sending end of the noncompensated system, circumstances become even more favourable in the compensated system from the point of view of both steady-state short-circuit current and short-circuit peak current (see "Example").

5. The above conclusions obtained by assuming a three-phase fault can readily be generalized for cases of a single-phase earth-fault and of a two-phase fault, while the two-phase earth-fault necessitates a separate study.

6. Consideration of the initial load does not affect greatly the above conclusions. Generally, a short circuit caused at no-load is the most unfavourable.

(With the exeption of the case of great overcompensation, but practically this is not important).

7. Summing up the above we may state that from the point of view of short-circuit current the series capacitor need not be provided with a protection and by-passed in every case. Although the short-circuit current of the compensated system is always greater than that of the noncompensated system, this increase is not considerable, especially at greater h and smaller k values. For the transformer, the transmission line, the circuit breaker, etc. this increased short-circuit current does not seem very dangerous, as they must endure even the faults arisen before the series capacitor (e. g. the sending end of the transmission line).

7. Overvoltages on the capacitor in series during short circuits

As demonstrated above, the increase of the short-circuit current caused by the capacitor is no great danger to the elements of the system, i. e. the transformer, the transmission line, the circuit breaker, etc. The next question to be examined is, whether the capacitor itself can endure the short-circuit current.

Again the most simple case, the three-phase fault arising at no-load will be studied.

The Laplace-transform of the capacitor voltage may be written in the following form:

$$\overline{V}(p) = \overline{I}(p)\frac{1}{pC} = U_m e^{j\psi}\cdot\frac{p}{p-j\omega}\,\frac{1}{p^2 LC + pRC + 1}\,. \tag{21}$$

Making use of the expansion theorem, the time function of the capacitor voltage e. g. for the periodic case:

$$\begin{aligned}\overline{V}(t) = {} & U_m e^{j\left(\psi-\frac{\pi}{2}\right)}\frac{k}{h+j(1-k)}e^{j\omega t} - \\ & - U_m e^{j\left(\psi-\frac{\pi}{2}\right)}\frac{k}{h+j(1-k)}\,\frac{1}{2j\sqrt{k-\left(\frac{h}{2}\right)^2}}\times \\ & \times\left\{\left[-\left(\frac{h}{2}\right)+j\sqrt{k-\left(\frac{h}{2}\right)^2}-j\right]e^{(-\alpha-j\nu)t} - \right. \\ & \left. -\left[-\left(\frac{h}{2}\right)-j\sqrt{k-\left(\frac{h}{2}\right)^2}-j\right]e^{(-\alpha+j\nu)t}\right\}\end{aligned} \tag{22}$$

(By means of the substitutions used for the calculation of the short-circuit current the solution can be written for the other cases, too.)

Neglecting the transient part for the the time being, let us deal with the steady-state component. Its absolute value is :

$$V_s = U_m \frac{k}{\sqrt{h^2 + (1-k)^2}} \tag{23}$$

Let us compare the amplitude V_s of the capacitor voltage established by the steady-state short-circuit current with the amplitude V_0 of the nominal operating voltage of the capacitor,

$$V_0 = I_0 X_C = I_0 X_L k \tag{24}$$

To eliminate the load current I_0 let us write the approaching form of the voltage drop in the noncompensated system :

$$E = \varepsilon U_m \approx I_0 (R \cos \Theta + X_L \sin \Theta) = I_0 X_L (h \cos \Theta + \sin \Theta) \tag{25}$$

where cos Θ is the power factor at the sending end of the transmission line.

The division of the above two expressions yields :

$$V_0 = \frac{\varepsilon U_m k}{h \cos \Theta + \sin \Theta} \tag{26}$$

and considering (23)

$$\frac{V_s}{V_0} = \frac{h \cos \Theta + \sin \Theta}{\varepsilon \sqrt{h^2 + (1-k)^2}} \tag{27}$$

Introducing the impedance angle φ_0 of the short-circuit loop for the non-compensated case

$$\cos \varphi_0 = \frac{h}{\sqrt{h^2+1}} \quad \text{and} \quad \sin \varphi_0 = \frac{1}{\sqrt{h^2+1}}, \tag{28}$$

the quotient of the capacitor voltages may be written as follows :

$$\frac{V_s}{V_0} = \frac{\cos(\Theta - \varphi_0)}{\varepsilon} \cdot \frac{\sqrt{h^2+1}}{\sqrt{h^2 + (1-k)^2}} \tag{29}$$

Let us examine the smallest value of the above quotient : The power factor is, generally, between 0,9 and 0,5 corresponding to $\Theta = 26°$ and $\Theta = 60°$, resp. In practice $0{,}2 < h < 1{,}0$ and thus $79° > \varphi_0 > 45°$.

Let us consider three cases in detail:

1. $h = 0,2$; $\varphi_0 = 79°$ and $\Theta = 26°$; i. e. $\cos(\Theta - \varphi_0) = \cos 53° \approx 0,6$;
2. $h = 0,6$; $\varphi_0 = 59°$ and $\Theta = 26°$; i. e. $\cos(\Theta - \varphi_0) = \cos 33° = 0,84$;
3. $h = 1,0$; $\varphi_0 = 45°$ and $\Theta = 60°$; i. e. $\cos(\Theta - \varphi_0) = \cos 15° = 0,97$.

For these cases, with different degrees of compensation k, computing the value of

$$\cos(\Theta - \varphi_0) \frac{\sqrt{h^2 + 1}}{\sqrt{h^2 + (1 - k)^2}} \tag{30}$$

it can be stated that except the extreme case of $h = 0,2$, $k = 2,0$, the factor in question is greater than 0,75, moreover, most often greater than 1.

The percentage voltage drop of the noncompensated system is certainly smaller than 30% : $\varepsilon < 0,30$. This means that even in a very favourable case

$$V_s > (2,5 \div 3)\, V_0$$

The output of the capacitor in case of identical reactance is proportional to the square of the voltage. Consequently, if the series capacitor is not by-passed during fault, it must be oversized at least 6—9 times, which would lead to an uneconomical solution. This unfavourable situation is somewhat improved by the fact that the capacitor may be overloaded for a short time, which, however, leads to an abbreviation of lifetime.

The above proportion would be even worse by taking into consideration the transients. Comparing the transient short-circuit current $\bar{I}_t(t)$ Eq. (11) and the part of the capacitor voltage Eq. (22) in braces, a deviation can be noticed. This seems to require a detailed study of the transient component of the capacitor voltage which, however, could be omitted since the examination of the steady-state component has revealed the necessity of providing the series capacitor with a protective device during short-circuit.

8. Conclusion

We can conclude that the weakest link in the short-circuit loop is the capacitor itself. While the other elements of the network endure even the short-circuit current of the compensated system, the voltage arisen on the capacitor is a multiple of the working value. In most cases it is more economical to design the capacitor for the working voltage and to install a special protective device.

Literature

(1) Electrical Transmission and Distribution Reference Book. Westinghouse 1950.
(2) ELSNER H.: Schutz von Seriekondensatoren gegen externe Störungen und interne Defekte. Bulletin S. E. V. 1952. No. 6. p. 214.
(3) KOVÁCS, K. P.—RÁCZ, I.: Váltakozóáramú gépek tranziens folyamatai. (Transient processes of a. c. machines.) Akadémiai Kiadó 1954.

Summary

Short-circuit currents arising in power systems compensated by series capacitors and overvoltages of series capacitors are discussed. The aim of the investigation is to answer the question, whether or not the series capacitor in a short-circuit should be by-passed with a protective device in every case.

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