SIMPLE METHOD FOR THE CALCULATION OF THE SINGLE-PHASE AUTOMATIC RECLOSING PROBLEMS ON LONG EXTRA HIGH VOLTAGE OVERHEAD LINES

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Received October 1, 1981

The number of the installed transmission lines of 750 kV has increased in the recent years. This voltage level is well suited for lines spanning large distances in low load density areas. The transmission capacity of these lines is equivalent to that of several large generators, therefore their reliable performance is of great importance. 90 per cent of all outages are single-phase line to ground faults on this voltage level. If the line is protected with fast clearing protection, an even higher percentage of faults become line-to-ground faults, since the quick fault clearing prevents single-phase faults to develop into two- or three-phase faults. The elimination of single-phase faults therefore contributes greatly to the reliability of these lines. The device for the elimination of line-to-ground faults is the single-phase reclosing. Its successful application for long extra high voltage lines is of great importance.

The present study deals with the application of the single-phase automatic reclosing for long extra high voltage lines and a method is shown to compute parameters affecting fast clearing for a symmetrical line.

The factors influencing the single-phase reclosing

The automatic reclosing is effective, if it is successful and is realized in a relatively small reclosing time and during the reclosing time the transmission capacity of the line remains relatively large.

The short reclosing time could be realized with three phase reclosing and in this case the probability of the arc extinction is relatively high, but this solution is disadvantageous for stability reasons, since — even for a short period — the power transmission is broken off.

The short reclosing time can not always be realized in the case of single-phase reclosing, since a secondary current is maintained after the fault clearing, which causes a delay in the arc extinction.

The extinction of this arc maintained by the secondary currents is the most critical problem in the application of automatic reclosing. Secondary

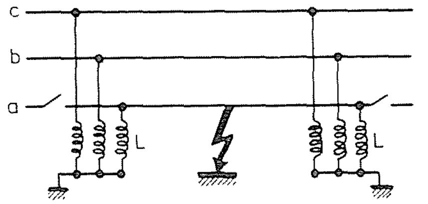

Fig. 1. Long line with shunt reactors, line-to-ground fault cleared in the faulted phase at both ends

current is induced via capacitive and inductive coupling by the unfaulted lines. It maintains the arc after breakers clear the faulted line section.

The most important factors influencing the secondary arc extinction are: the steady-state 50 Hz rms value of the secondary arc current, the steady-state rms value of the power frequency component of the recovery voltage and the frequency and the rate of rise of the transient recovery voltage.
The weather, especially wind velocity affects arc length and extinction. Wind helps arc extinction by cooling, deionizing and by lengthening the arc. To characterize the arc extinction a gradient is defined: the ratio of the recovery voltage (rms value) and the insulator length in the form of kV_{eff}/m. Thomas Reiner [1] gives curves — based on a large number of tests — showing the expected arc time at different kV_{eff}/m values of the gradient, for a range of secondary currents. The direct current component and harmonics appearing in the secondary current could also influence the arc extinction. The duration and magnitude of the preceding line-to-ground short-circuit current is in the order of magnitude of 10 kA. These latter effects will not be considered in this paper.

In the following analysis the magnitude of the secondary current, the recovery voltage considered as power frequency quantity and the transient recovery voltage will be analysed. The faulted line is shown in Fig. 1 after having been tripped by breakers in the faulted phase on both sides. Shunt reactors applied for reactive power compensation are also shown in the Figure.

At lower voltage levels and commonly used line lengths the automatic reclosing is a widely used method for the elimination of single phase line-to-ground faults. In such cases the secondary current is low, in the order of 10—20 A, and the arc will be extinguished in a very short time. At a voltage level of 400 kV and short lines the circumstances are similar. The calculation method of the reclosing performance for short lines was developed by Peterson and David [5]. They modelled the line by its concentrated capacitance, as it is shown in Fig. 2a. The line was assumed symmetrical. Figure 2b is a one line diagram for the case of Fig. 2a and Fig. 2c is its reduced form, showing also a switch "S", which represents the line-to-ground fault. Figure 2d is identical to Fig. 2c except it shows the shunt reactor, as well. This circuit is adequate for the

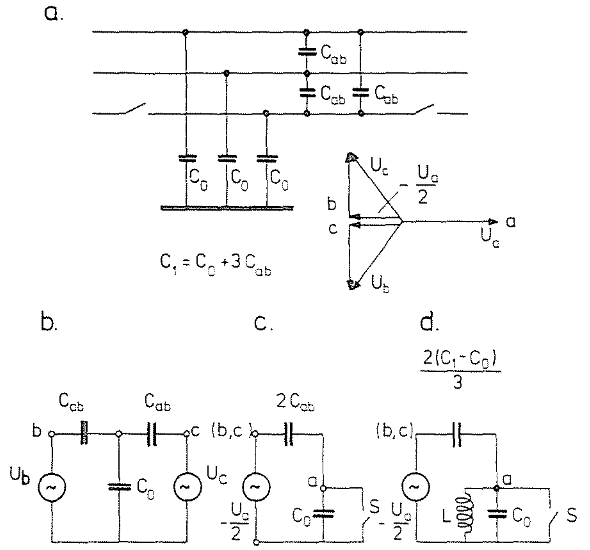

Fig. 2. Long line modeled by its capacitances a) the three-phase system; b) single-phase equivalent with the switch *S* simulating the short-circuit; c) simplified scheme; d) same as "*C*" with shunt reactor banks

calculation of the secondary current and the recovery voltage for short lines and yields approximate estimation of the phenomena on long lines.

The main tendency of the effect of the parameters on the arc extinction can be seen from Fig. 2. The recovery voltage, as the steady-state voltage of the floating line after the extinction of the secondary arc is determined by dividing the voltage $U_a/2$ between the capacitances $2(C_1 — C_0)/3$ and C_0. It is about 15 per cent of the voltage of the unfaulted phases, as it is shown in Fig. 2c. The voltage of the floating phase is the voltage of the point "a" (open switch) in the case without shunt reactor. The larger will be the secondary arc current flowing through the switch after its closure, the higher is the voltage of the point "a", that is the steady-state value of the recovery voltage. The effect of the shunt reactor can be seen in Fig. 2d. The magnitude of the secondary current is not affected by the shunt reactor, since the reactor inserted parallel with the capacitance C_0 is short-circuited by the switch S simulating the secondary short-circuit. The recovery voltage (power frequency component) is intensively influenced by the shunt reactor. At large values of inductances, if the resulting circuit defined by L and C_0 remains capacitive, the insertion of the shunt reactor causes the decrease of the admittance corresponding to the capacitance C_0. The value of $\frac{2}{3}(C_1 - C_0)$ is unchanged in this case, since the admittances of both C_1 and C_0 are equally reduced, the voltage of the floating line will become higher, however, due to the capacitive voltage distribution, since the

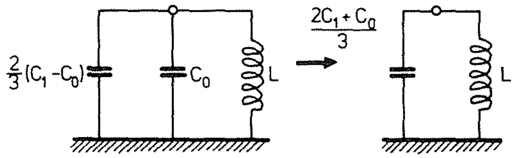

Fig. 3. Kimbark's model for the determination of the eigenfrequency

admittance corresponding to C_0 is reduced by the inductance of the reactor. Thus the insertion of the reactor yields a higher steady-state value of the recovery voltage. Concerning the eigenfrequency it can be stated on the basis of Fig. 2d and Fig. 3 — the latter given by Kimbark [4] — that the insertion of the shunt reactor, i.e. the increase of the number of reactor banks — smaller value of L_S — increases the eigenfrequency of the circuit. When reactors are applied, the eigenfrequency is in the order of magnitude of the power frequency, since the purpose of application of reactors is reactive power compensation. The eigenfrequency is in most cases below the power frequency or is somewhat above it. The transient recovery voltage is the sum of a power frequency component and a component oscillating with the eigenfrequency and these result in a floating wave shape: the amplitude of the voltage of frequency (50 Hz + $+f_S$) varies with the frequency (50 Hz $-f_s$). If the number of reactor banks is not large, the eigenfrequency f_s is below the power frequency and in this case the increase of the number of reactor banks causes the reduction of the frequency difference, which yields the slow increase of the amplitude of the transient recovery voltage. However, the steady-state value of the recovery voltage is higher when shunt reactor is inserted, the time function of the transient recovery voltage has a slowly increasing shape. If the inductance L of the shunt reactor is such, that it produces a resonance frequency near to the power frequency with the capacitance C_0, then the steady-state value of the recovery voltage is equal to $U_a/2$ and the amplitude of the oscillating transient recovery voltage increases exponentially, corresponding to a high time constant, so the voltage increases slowly. If the value of the inductance L is low, the corresponding admittance is large, so on power frequency the parallel circuit of L and C_0 become inductive. This inductance may produce a parallel resonance with the capacitance $\frac{2}{3}(C_1-C_0)$, causing very high recovery voltage. For this reason the overcompensation should be avoided on the networks.

For the reduction of the secondary current Knudsen [3] in 1962 and independently Kimbard [4] in 1964 proposed to insert an inductance parallel to the admittance (C_1-C_0) with equal admittance $\left(\frac{1}{\omega L}-\frac{1}{\omega L_0}\right)$, since the capacitive coupling between the unfaulted phases and the short-circuited phase exists due to the capacitance $\frac{2}{3}(C_1-C_0)$. Thus a parallel resonance is produced with infinite impedance. This means, that the floating phase is no more coupled to the unfaulted phase in this case, so the voltage of the floating phase equals to zero and the secondary current is zero, as well. An inductance of the above properties can be realized by a shunt reactor provided with an additional inductance L_n inserted between the neutral and the ground. The zero sequence inductance L_0 of this arrangement is equal to L_1+3L_n, and the relation $1/\omega L_1 > 1/\omega L_0$ is valid. Obviously, regarding the insulation of the reactor neutral, the fact, that the neutral is not directly grounded must be taken into consideration.

In this way the secondary current can be reduced theoretically to zero, practically near to zero with the neutral reactor, while the recovery voltage also becomes small. The frequency of the transient recovery voltage is not very much affected by the neutral reactor, because L_n is not a large value of inductance.

In the followings a simple method valid for long transposed overhead lines will be presented for the calculation of the secondary current, the recovery voltage and the transient recovery voltage, taking into consideration both the inductive and the capacitive effects. The method does not take into consideration the effect of steady-state harmonics. The secondary current and the recovery voltage are considered as steady-state quantities, their calculation is carried out by means of phasors. The transient recovery voltage has to be given as function of time, so it must be analysed by its instantaneous values. Consequently, the steady-state and the transient calculations are carried out separately and the relation between them will be given.

The calculation of the secondary arc current and the recovery voltage in the case of long lines

Consider a long overhead line in steady-state condition after the clearing of the circuit breaker in the faulted phase. The short-circuit is considered of zero impedance, the line itself is dealt as a four-pole characterized by its **A**, **B**, **C**, **D** constants (taking into consideration, that $\mathbf{D}=\mathbf{A}$). The shunt reactors can be represented as four-poles with the constants $\mathbf{A}=1$, $\mathbf{B}=0$, $\mathbf{C}=-jY_L$, $\mathbf{D}=1$ (Fig. 4). The parameters of the resultant four-pole will be given by the matrix product of the parameters.

The open circuit breakers at the line ends in the faulted phases represent two series faults, appearing as simultaneous faults, since they are on different points of the same conductor. The short-circuit occurring on a given point of the line will be a third fault — a shunt fault. For the calculation of the

		A	B	1	0
		C	A	$-jY_L$	1
1	0	A	B	$A-jY_LB$	B
$-jY_L$	1	$C-jAY_L$	$A-jY_LB$	$C-2jAY_L-Y_L^2B$	$A-jY_LB$

Fig. 4. The shunt reactors as four-poles connected in series to the line

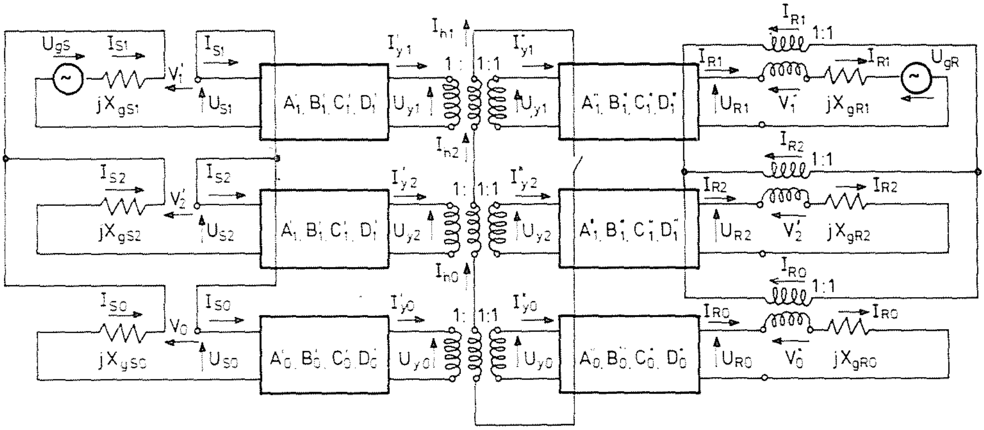

Fig. 5. The analysis of the series faults simulating the open-circuit breakers and the shunt fault simulating the single-phase line-to-ground fault by means of the symmetrical components for the long line

simultaneous faults the symmetrical components will be applied in such manner, that the line will be represented as long line in the positive, negative and zero sequence networks, given by their **A**, **B**, **C**, **D** constants. The positive and negative sequence values of the line constants $\mathbf{A}_1$, $\mathbf{B}_1$, $\mathbf{C}_1$, $\mathbf{D}_1$ and their zero sequence values $\mathbf{A}_0$, $\mathbf{B}_0$, $\mathbf{C}_0$, $\mathbf{D}_0$ are to be calculated from the line parameters r_1, L_1, C_1 for line modes and r_0, L_0, C_0 for ground mode. The short-circuit point is considered as a node, so the long line consists of two sections of length $1'$ and $1''$ $(1=1'+1'')$. The four-poles representing the shunt reactors are added to both line sections, so the four-poles of Fig. 5 are obtained, which are characterized by the resultant constants $\mathbf{A}'$, $\mathbf{B}'$, $\mathbf{C}'$, $\mathbf{D}'$ and $\mathbf{A}''$, $\mathbf{B}''$, $\mathbf{C}''$, $\mathbf{D}''$. It is to be noticed, that $\mathbf{A}'\neq\mathbf{D}'$.

The networks at the receiving end R and sending end S are both represented by a reactance: X_{gS} and X_{gR}. The angle between the ideal voltage sources is the power angle, being positive if U_{gS} leads U_{gR}. The ideal transformers are applied to make possible the correct connection of the four-poles in the case of series and shunt faults.

In the following a summary will be given about calculation results related to reclosing problems on a 750 kV line of legth nearly 500 km. The secondary current and the recovery voltage were calculated on the basis of the model of Fig. 5, taking into consideration different numbers of reactor banks, and different power angles. The initial data of the calculations are:

rated line voltage: 750 kV (433.5 kV phase)
line length: 480 km
line parameters:
$C_1 = 13.246$ nF/km
$C_0 = 9.7192$ nF/km
$L_1 = 0.8967$ mH/km
$L_0 = 1.9537$ mH/km
$r_1 = 0.0149$ ohm/km
$r_0 = 0.1317$ ohm/km.

The line constants for the total length in positive and zero-sequence case are:

$\mathbf{A}_1 = 0.8685 + 0.00682$ $\quad$ $\mathbf{A}_0 = 0.792 + j\,0.0429$
$\mathbf{B}_1 = 6.53 + j\,129$ ohm $\quad$ $\mathbf{B}_0 = 0.5434 + j\,247.3$ ohm
$\mathbf{C}_1 = -10^{-5} + j\,1.89\;10^{-3}$ mho $\quad$ $\mathbf{C}_0 = -0.21\;10^{-4} + j\,0.00132$ mho

the inductance of one reactor bank is: $L \approx 6$ H/phase.

The rms value of the recovery voltage along the line is shown in Fig. 6 in the case without shunt reactor, and with $1-1$, $2-1$ and $2-2$ reactor banks at the line ends. The magnitude of the recovery voltage is practically constant along the line and is equal to appr. 50 kV without reactor. The recovery voltage is somewhat lower at the ends of the line than in the middle of it when applying reactors. It is about 100 kV in the case of $1-1$ reactor banks, and it is about 280 kV in the case of $2-2$ reactor banks. Thus the recovery voltage increases with increasing number of reactor banks in accordance with the simplified model of Fig. 2d. The effect of the power angle on the magnitude of the recovery voltage can be seen in Fig. 7, the recovery voltage along the line is shown in the Figure for the cases of $\delta = 0°$ and $\delta = 25°$. The difference between the two curves is small. Related to the currents the calculations have proved that neither the number of reactor banks nor the power angle influences essentially the magnitude of the secondary current. The secondary currents were between

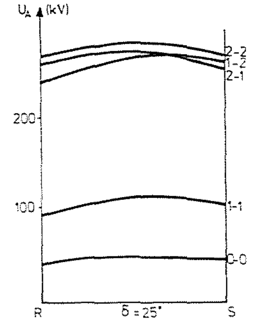

Fig. 6. The rms value of the recovery voltage along the line in the cases of different shunt reactor configurations at a power angle of $\delta=25°$

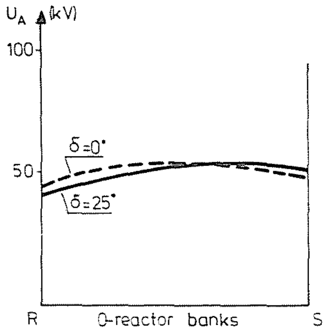

Fig. 7. The rms value of the recovery voltage along the line in the case of $0-0$ reactor sets at power angles $\delta=0°$ and $\delta=25°$

60 A and 93 A. The small values correspond to the case of 2 reactors with a power over 1000 MW, which is not a very important practical case. The higher values were obtained in the case of supplying of both ends, with unloaded line, where there are no stability problems.

Comparing the value of 75 A given by Kimbark independent of the number of reactors and of the place of the short-circuit point to the present calculation results, a difference of $+8$ and -16 per cent was found between the exact calculated values and the approximate values. Considering only the most important practical cases, the deviation was even smaller, for example at $1-1$ reactors with $\delta=0°$ the secondary current obtained is 81 A, at a load of 1200 MW it yielded 70 A.

It is to be mentioned, that the recovery voltage may increase considerably, if larger inductance is inserted, than that foreseen. For example in the case of $2-2$ reactor-banks a tolerance inductance 10 per cent larger cause a recovery

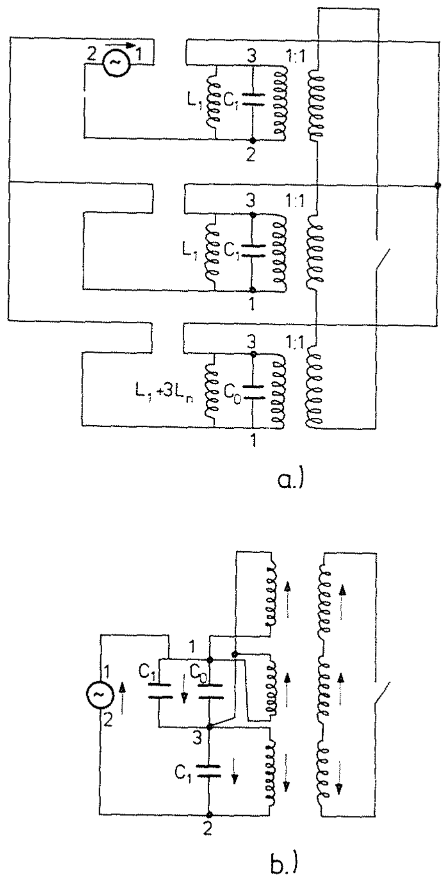

Fig. 8. The consideration of the neutral reactor while modeling the line with its concentrated capacitance, assuming supply on one end

voltage of about 1000 kV. The same thing may occur, if the reactor has the rated value, but the line parameters differ so, as it would have the same effect as the increase of the reactor inductance. In such case the probability of the arc extinction is considerably reduced.

It is worth examining the effect of the neutral reactor on the elimination of the capacitive coupling between the floating phase and the unfaulted phases by means of the method of the simulation of series and shunt faults with the aid of symmetrical components. It will be first shown for a simplified case in Fig. 8. The line is supplied of one side through zero impedance, the series impedance of the line is neglected, so the line is modeled by its capacitance being equal to C_1 in positive and negative sequence cases and C_0 in zero sequence case. The phase

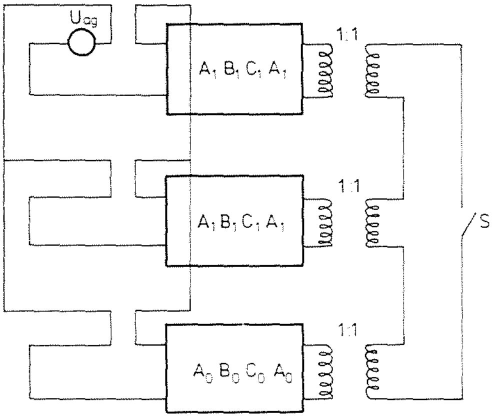

Fig. 9. The model of the long line with supply at one end with the simulation of the open-circuit breakers and ground fault

"a" is broken. The sum of the series connected secondary voltages of the ideal transformer inserted on the short-circuit point gives the recovery voltage U_a on the terminals of the open switch S. The current flowing through the closed switch is the component $I_1 = I_2 = I_0$ of the secondary current. The terminals of the voltage source are numbered, so the connection can be followed on the figure. The point 3 is a fictitious neutral, so the capacitances C_1 and C_0 are connected parallel and they together are connected in series with C_1 (Fig. 8b). If C_1 would be equal to C_0, half of the voltage would appear on the two parallel connected capacitances. The voltage direction on the parallel capacitances in the secondary of the ideal transformer is opposite to the voltage between the points 2 and 3 of the capacitance C_1. Thus the voltage between the switch poles is just equal to zero, and the single phase short-circuit current flowing when closing the switch is zero, as well. The relation $C_1 = C_0$ can be produced by the aid of a reactor provided with a neutral reactor. The zero sequence inductance of such an arrangement is $L_0 = L_1 + 3L_n$. The higher admittance of C_1 (which is obvious from the relation $C_1 = C_0 + 3C_{ab}$) is reduced in this case by an inductance of higher admittance, the lower admittance of C_0 is reduced by an inductance of lower admittance. It can be achieved, that both the recovery voltage and the secondary current should be zero.

A long open-ended overhead line is considered now (Fig. 9), where the condition $\mathbf{C}_1 = \mathbf{C}_0$ is now realized for the line constants. Since there is an open-circuit breaker at the sending end in phase "a",

$$\mathbf{I}_{S1} + \mathbf{I}_{S2} + \mathbf{I}_{S0} = 0 \tag{1}$$

is valid. For an open-ended line with the above conditions

$$\mathbf{I}_{S1}=\mathbf{C}_1\mathbf{U}_{R1}$$
$$\mathbf{I}_{S2}=\mathbf{C}_1\mathbf{U}_{R2} \tag{2}$$
$$\mathbf{I}_{S0}=\mathbf{C}_1\mathbf{U}_{R0}$$

can be written, that is

$$\mathbf{I}_{S1}=\mathbf{I}_{S2}=\mathbf{I}_{S0}=\mathbf{C}_1(\mathbf{U}_{R1}+\mathbf{U}_{R2}+\mathbf{U}_{R0})=0\,. \tag{3}$$

Since $\mathbf{C}_1\neq 0$,

$$\mathbf{U}_R=\mathbf{U}_{R1}+\mathbf{U}_{R2}+\mathbf{U}_{R0}=0\,, \tag{4}$$

which means, that the voltage of the phase "a", being the recovery voltage is equal to zero.

Thus the positive sequence value of the line constant **C** must be equal to its zero sequence value for the elimination of shunt effects in the case of long lines. The value of the inductance L_0 needed must be determined from this assumption.

It has to be emphasized, that the value of neutral reactor inductance needed for compensation varies with the number of shunt reactors on the line. Furthermore, with the application of neutral reactor the longitudinal effects will not be eliminated.

The voltage on the sending end at the terminal of the open circuit breaker on the end of the line can be written as follows:

$$\mathbf{U}_{S1}=\mathbf{A}_1\mathbf{U}_{R1}\,,$$
$$\mathbf{U}_{S2}=\mathbf{A}_1\mathbf{U}_{R2}\,,$$
$$\mathbf{U}_{S0}=\mathbf{A}_0\mathbf{U}_{R0}$$

and

$$\mathbf{U}_S=\mathbf{U}_{S1}+\mathbf{U}_{S2}+\mathbf{U}_{S0}=\mathbf{A}_1(\mathbf{U}_{R1}+\mathbf{U}_{R2})+\mathbf{A}_0\mathbf{U}_{R0}+\mathbf{A}_1\mathbf{U}_{R0}-\mathbf{A}_1\mathbf{U}_{R0}=$$
$$=\mathbf{A}_1(\mathbf{U}_{R1}+\mathbf{U}_{R2}+\mathbf{U}_{R0})+(\mathbf{A}_0-\mathbf{A}_1)\mathbf{U}_{R0}\,. \tag{6}$$

Thus

$$\mathbf{U}_S=(\mathbf{A}_0-\mathbf{A}_1)\mathbf{U}_{R0} \tag{7}$$

which is not zero, but a small value.

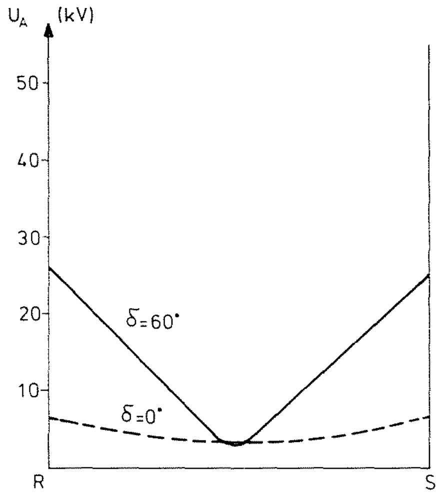

Fig. 10. Recovery voltage along the line with neutral reactor, at load angles $\delta=0°$ and $\delta=60°$

Following this concept, considering supplies on both ends, it is interesting to examine the effect of the realization of the assumption $\mathbf{B}_1-\mathbf{B}_0=0$, supposing that the assumption $\mathbf{C}_1-\mathbf{C}_0=0$ is still valid. In this way the longitudinal effects would also be avoided. This is, however, a theoretical question, since the reduction of the magnitude of B_0 would only be possible by a series zero sequence capacitor, which would be very costly.

In the followings numerical results will be given for the effect of the insertion of neutral reactor having the value calculated from the condition $\mathbf{C}_1=$ $=\mathbf{C}_0$, with the above given line and shunt reactor parameters. The neutral reactor was applied in each shunt reactor neutral. The magnitude of the recovery voltage along the line is shown in Fig. 10 following the secondary arc extinction in the case of supplies at both ends at power angle $\delta=0°$ and $\delta=60°$. The recovery voltage is due to the inductive effect in this case. The recovery voltage in the middle of the line is reduced to a very small value (3 kV) due to the insertion of the neutral reactor, and it is somewhat larger at the line ends because of the inductive effect, but it is still very small related to the case without neutral reactor (at $\delta=0°$ it is equal to 6 kV instead of its previous value of 100 kV, and at $\delta=60°$ it is equal to 26 kV instead of about 100 kV). Even in the case of the largest load the neutral reactor reduced the maximum voltage to one quarter of its formal value. The secondary currents were reduced by an order of magnitude due to the insertion of neutral reactor. In the case of $\delta=0°$ the secondary current was reduced to 3 A in the middle of the line and to 6 A at the end of the line from 81 A being its magnitude in the case without neutral reactor. At large load ($\delta=60°$) in the case of a short-circuit in the middle of the line the secondary current was reduced to 3 A from 69 A, in the case of short circuit at the end of the line it was reduced to 27 A from 78 A being the current in the case without neutral reactor. It can be seen, that in the cases of short-circuits in the middle of the line the secondary current is reduced to the 4 per cent of the value corresponding to the case without neutral reactor. It is reduced to one third in the cases of short-circuit at the end of the line. This tendency corresponds to the decrease of the recovery voltage, described before.

Zero arc resistance was assumed in the calculations. In an actual case an arc resistance corresponding to an arc of 7 – 8 m length is inserted in the circuit thus reducing the magnitude of the secondary current. The expected currents are therefore smaller than the calculated ones. The quick extinction of the secondary arc is more likely with neutral reactor even for high short-circuit currents. The effects of the harmonics of the steady-state performance are not taken into consideration in the above calculations.

The calculation of the transient recovery voltage

The transient recovery voltage is the transient voltage appearing on the faulted phase when the secondary arc is extinguished. The transient recovery voltage can be calculated by injecting the sine shape secondary short-circuit current into the passive network. Generally, the previous steady-state voltage is to be superimposed to the voltage obtained in this way, but in the present case the arc resistance was supposed to be zero, therefore the transient voltage on the faulted point obtained by current injection produces directly the transient recovery voltage. Since the arc extinction occurs at current zero and the direct current component is neglected in this study, the injected current is a sine function starting from zero.

The transient phenomena on the long line are considered as wave phenomenon, the shunt reactors and the impedance of the supply are modeled by inductance. The transient model of the network is shown in Fig. 11. Bergeron's equations are used for mathematical modeling of transient wave phenomenon. Solution of differential equations by means of trapezoidal rule is used for lumped elements [7], taking advantage of the simple network topology.

Single-phase model can not be applied here, since the system is not a symmetrical three-phase one, because a section of the faulted phase is tripped by circuit breakers. The calculations have to be carried out for the entire three-phase system. The wave propagation along the line can not be simply handled with phase quantities because of the coupling between phases. A transformation yielding three decoupled systems is needed. The α, β, 0 transformation is appropriate for this purpose. It is a scalar transformation applicable for continuously transposed lines. The line is considered by its surge

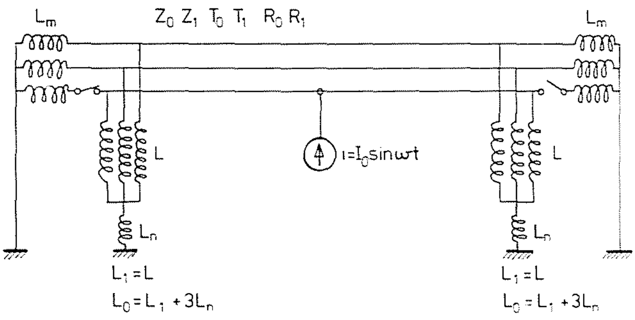

Fig. 11. Network model for the calculation of electromagnetic transients

impedances $Z_\alpha = Z_\beta = Z_1$ and Z_0, and by its travel times $T_\alpha = T_\beta = T_1$ and T_0 corresponding to each mode. The model of series resistances is applied for the modeling of the attenuation along the line. This can easily be built into Bergeron's mathematical model and it is a very good approximation for the present system with an eigenfrequency of near to 50 Hz. The frequency of the oscillations is near the power frequency, therefore the frequency dependence of the parameters is negligible, and constant resistances can be taken into consideration, R_1 for the line modes and and R_0 for the ground mode. The internal impedance of the supply network can be modeled by inductances in each phase. The shunt reactors can be characterized by their modal inductances $L_\alpha = L_\beta = L_1$ and L_0. If neutral reactor is inserted $L_0 = L_1 + 3L_n$, without neutral reactors $L_0 = L_1$.

Bergeron's equations are applied for the lines, which can be expressed in the form below for each mode in the case of lossless line:

$$i_t = Y u_t - d \tag{8}$$

where d is the past history constant (of current dimension) calculated from the previous values of voltages and currents:

$$d = Y u_{t-T} + i_{t-T} \tag{9}$$

and T is the travel time of the line for a certain mode. The attenuation will be considered by series lumped resistances, which yields the modified equation

$$d = h_1 d' + h_2 d'' \tag{10}$$

where d' and d'' are the past history constants corresponding to both ends of the branch in question. The calculations of d' and d'', respectively are to be carried out according to the following formula:

$$d' = Yu_{t-T} + hi_{t-T}. \tag{11}$$

Trapezoidal rule is applied for the computation of the differential equations of the internal network impedance and for the reactors. The result of integration is arranged in a form similar to the Bergeron's equation. For each phase:

$$i = \frac{\Delta t}{2L} u - d_L \tag{12}$$

where d is a past history constant (of current dimension) calculated from the preceding time step $t - \Delta t$

$$d_L = -\frac{\Delta t}{2L} u_{t-\Delta t} - i_{t-\Delta t} \tag{13}$$

In three-phase system the voltages and currents must be column vectors of the phase quantities and the inductance has to be a matrix, in equation (13) the inverse of the matrix has to be used.

The nodal equations corresponding to line branches have to be solved for phase quantities, therefore equation (8) must be transformed from modes to phase quantities. The sum of branch currents is computed for a given node considering that $\sum i = 0$. The column vector of the instantaneous values of the nodal voltage is computed as:

$$\boldsymbol{u} = \boldsymbol{Y}_n^{-1} \cdot \boldsymbol{SD} \tag{14}$$

where $\boldsymbol{SD}$ is the column vector of the sum of the past history constants. It is a phase quantity, and is associated with nodes. The matrix $\boldsymbol{Y}_n$ is the nodal admittance matrix. Its diagonal contains the sum of the equivalent wave admittances of the lines terminating on the given node. The past history values of the line branches must be calculated first in modal quantities because of the different values of the velocity in the line and ground modes, but in equation (14) the past history values must be phase quantities. Therefore, the modal values of the past history constants have to be transformed in each time step to phase quantities. Equation (14) must be solved for each time step Δt. It is not difficult, since the matrix $\boldsymbol{Y}_n^{-1}$ does not depend on time, only the values of $\boldsymbol{SD}$ are changing. The calculated voltage must be transformed to modal quantity for the computation of the past history values. The currents in the line branches must also be computed with these voltages. The currents of the inductive branches are calculated directly from phase quantities.

The model of the problem is a switching on analysis, which means now a current injection on the passive network, so the initialization of the past history values means in the present case setting equal to zero. To save computer storage for each time step, past history values have to be shifted back retaining only the values corresponding to the last needed number of time steps.

The following input data were used for the transient calculations of the sample problem:

$$Z_1 = 260 \text{ ohm} \qquad Z_0 = 448 \text{ ohm}$$

$$T_1 = 1.6 \text{ ms} \qquad T_0 = 2 \text{ ms}$$

$$R_1 = 7.14 \text{ ohm} \qquad R_0 = 63.1 \text{ ohm}$$

The time step used is $\Delta t = 0.2$ ms. The number of time steps corresponding to the travel time is obtained by rounding, which causes error — very small however — in the calculations. The values above of T_1 and T_0 are rounded off values. The inductances of the shunt reactors are: $L_1 = 6H$, $L_0 = 10.6H$, which latter involves a neutral reactor of $L_n = 2.2H$, determined from assumed the line constants of $\mathbf{C}_1 = \mathbf{C}_0$ for the case of 2 shunt reactor banks/phase. The current injected is the current having flown before the extinction of the secondary arc, its rms value is obtained from the previous steady-state calculations.

The transient recovery voltage *vs.* time is shown in Fig. 12 as result of calculations. Figures 12 a, b, c correspond to cases without neutral reactor, with different number of shunt reactor banks for the case of short-circuit in the middle of the line and for power angle $\delta = 0°$. The curves show that with 1—1-reactor banks without neutral reactor the maximum value of the voltage is significantly smaller, than that in the case of $1-2$ or $2-2$ reactors. This is in accordance with the results obtained in the steady-state calculations for the recovery voltage. The frequency of the envelope curve of the voltage is considerably higher in the case of 1—1-reactor banks, than in the case of 2—1 banks. With $2-2$ banks of reactors there is an overcompensation, the eigenfrequency is higher, than the power frequency. The frequency of the transient recovery voltage does not decrease with increasing number of shunt reactor banks. It can be seen in Figs 12a, b, c that the initial rate of rise of the transient recovery voltage varies little with the number of reactors.

The insertion of neutral reactor reduces the maximum value of the transient recovery voltage. The curve of Fig. 12d shows the voltage as function of time for a line shorted in the middle. The calculations result in very small secondary current. Thus the application of the neutral reactor designed for the given configuration of shunt reactor results in really favourable conditions for arc extinction. Arc extinction can not be assumed for other number of reactor banks. It seems reasonable to use for reclosure such method, which recloses

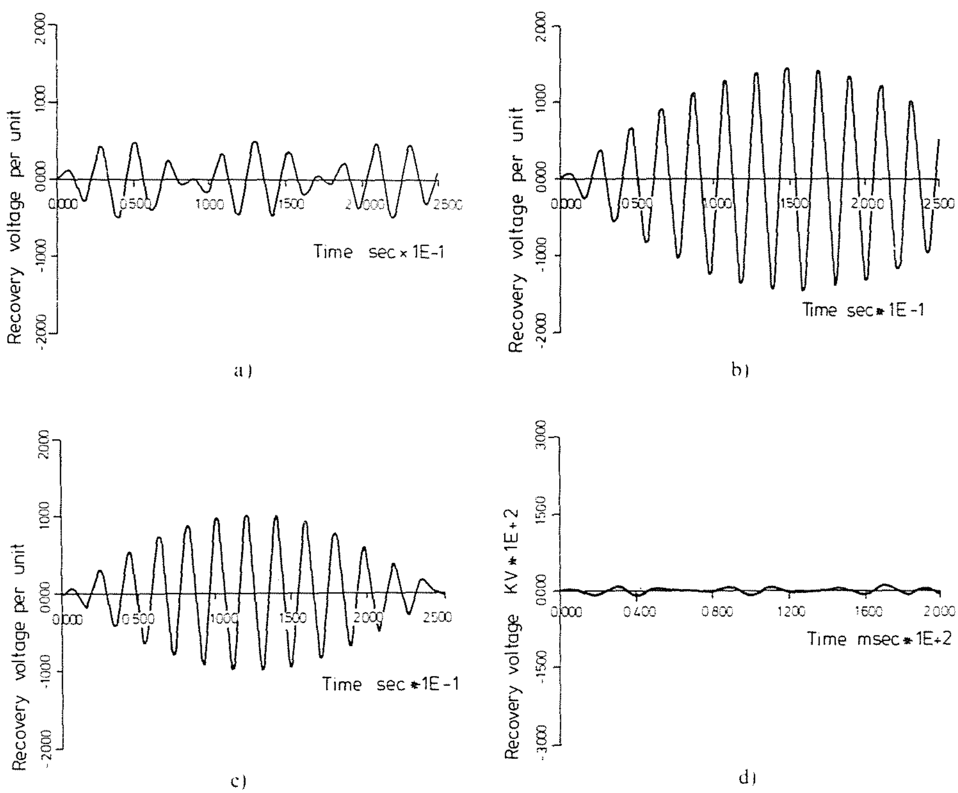

Fig. 12. The transient recovery voltage *vs.* time, $U_{ref}=750\cdot\sqrt{2}/\sqrt{3}$ kV; a) 1—1-reactor banks, without neutral reactor; b) 1—2-reactor banks, without neutral reactor; c) 2—2-reactor banks, without neutral reactor; d) 1—1-reactor banks, with neutral reactor

when the arc is extinguished. By means of this adaptive reclosing method the reclosing time is expected to be considerably reduced.

The steady-state value of the recovery voltage is not sufficient for the characterization of the circumstances after the arc extinction, the time function of the transient recovery voltage is of importance. After all, the magnitude of the secondary current flowing during the existence of the arc and the transient recovery voltage as function of time are essential from the point of view of the arc extinction. The arc extinction depends on the fictitious product of the secondary arc current and the recovery voltage.

It must be emphasized that all the above calculations were carried out on a very small computer with low computing cost.

The authors wish to express their gratitude to K. Petri for programming the steady-state calculations.

Summary

In the case of long extra high voltage overhead lines the application of the single-phase automatic reclosing is of great importance. The present study proposes a simple method for the calculation of the most interesting parameters (the secondary arc current, recovery voltage) influencing the successful reclosing. The method applies the symmetrical components for the steady-state analysis and the α, β, 0 components for the transient calculations using the Bergeron's equations. The method is adequate to describe both the inductive and the capacitive effects, while the previous methods of Knudsen and Kimbark had taken into consideration only the capacitive effects.

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