OVERVOLTAGE AND OVERCURRENT DURING NON-SIMULTANEOUS FAULTS IN TRANSMISSION LINES

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Abstract This paper describes the transient analysis in high-voltage transmission line systems with the specially stress of the overcurent and overvoltage analysis occurring during system operation or non-simultaneous fault conditions. Special attention is given to the current and voltage waveforms at the relaying points, i.e. at the line terminals. This work is concerned with the most severe conditions of fault and shows the possibility of the extremely value of the high frequency- and d.c- components caused by non-simultaneous multi-phase faults, and single and three-pole autoreclosure. The results are compared for the extremaly fault conditions, with faults close to voltage maximum (the worst cases from the point of view of overvoltages) and faults close to voltage zero (the worst cases from the point of view of overcurrent). The study was performed using the MicroTran program [1].

I. INTRODUCTION

In spite of careful design and maintenance, power systems and their elements will always be subject to failurs due to electrical or mechanical breakdown. In order to confine the consequences for such failures to the minimum possible, the defect has to be detected quickly, localized and isolated, respectively measures taken to ensure the continued supply of electrical energy to consumers. These functions are performed automatically by power system protection. For any given fault condition there are a variety factor which influence the transients response by fault conditions. One very important point which emerges is that the sound- and the faulted phase can contain very significant traveling wave components. The magnitude of the transients voltage and current components are significantly affected by the magnitude of the zero-sequence system impedance. Another remerkable aspect of transient analysis is the fact that a single physical component may have different model representations depending upon the context of the problems. This work is concerned with the most severe conditions of fault and shows the possibility of the overvoltages caused by arcing non-simultaneous three-phase faults, and three- and single pole autoreclosure in the different coupled high-voltage line working on the same tower construction.

The article examines :

- a two phase fault in which the fault begins as a single phase line-to ground fault but becomes line-line to ground,
- a three-phase to ground fault in which the fault begins as single-phase fault to ground but becomes the fault between two phases and finally three-phase to ground,
- a three-phase fault in which the fault begins as double line to ground faults but becomes three phase to ground,
- a single and three- pole autoreclosure by transient and solid single- and multi-phase faults. The computation of electomagnetic transients was carried for switching operations and non-simultaneous faults.

II. SYSTEM SIMULATION

The most important of the information about the investigated system related to transmission lines, and the detailed date for synchronous generators and transformers were not needed. The investigated lines were represented as distributed frequency dependent parameter. The part of the transmission system were represented by the equivalents circuit. The choice of the right equivalent method and structure influences the measuring accuracy and exact representation of the current and voltage waveforms. The representation of complex source impedance matrix is very important for the transient analysis. The network equivalent should adequately reproduce the behaviour of the full system. Due to the mathematical formulation of models by simulation program large system composed of networks can be easily represented and identified. Using the parameter identification techniques the optimal reduced model can be obtained to find the fault transient solution for any given power system configuration. The analysed transmission lines were simulated as a distributed-parameter system with frequency-dependence parameter [2]. Overhead line parameters were calculated from the **FdData** program. Faults were applied at the both side of the transmission line **M-H**, consisting of nine phase conductors (Fig.1). The resulting variation of the voltages and currents at the line are simulated. The nonlinear nature of simulating arcing fault transient phenomena has been developed for the primary arc models.

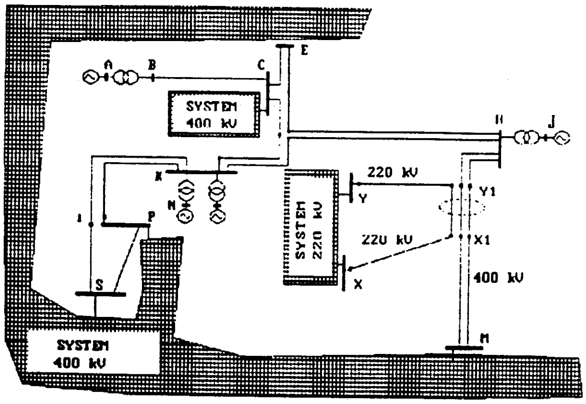

Figure 1 One line diagram of calculated system

The arc hysteresis cyclogram and its piecewise linear approximation are obtained with the nonlinear switched elements.

A. Line Parameter Calculation

A series of analyses are used to develop criteria for designing accurate transmission line models to be used for transmission line behavior under short-circuit conditions. It was shown that a good line model must include the effect of frequency dependent parameters in order to accurately predict overvoltages and increase of the peak current that occur under fault conditions. In distributed, frequency dependent transmission line models the distribute nature of R, L, C is taken fully into consideration. The impedance and admitance matrices for this model are calculated from the geometry of the transmission line and from electrical constants. Fig. 2 shows the configuration of the four typical power lines, which consisted of :

- simple circuits and two ground conductors (**A**),
- double circuits and one ground conductor (**B**),
- double circuits and two ground conductors (**C**),
- double circuits and the simple circuit with another voltage level (**D**) working on the same tower construction with one ground conductor.

As shown in Fig. 3 the positive and zero sequence resistance calculated (for all lines shown in Fig. 2) from the geometry of line depend strong on the frequency.

The most marked parameter behavior variations with frequency occur in the neutral inductance which begins to drop and the zero sequence resistance which begins to rise with low frequencies.

Therefore a good line model have to be include the effects of parameter variations with frequency to be used for predicting power transmission line behavior under switching operation. In MicroTran-program it is at disposal the best transmission line model for

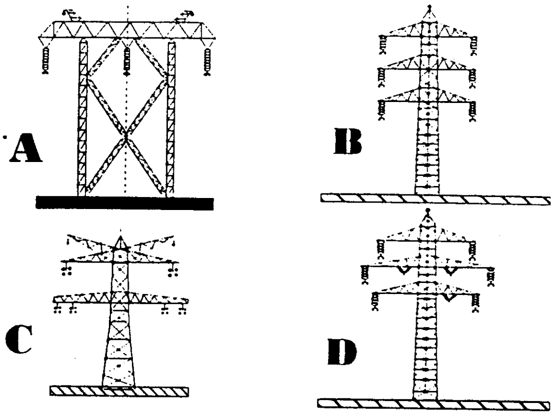

Figure 2 Typical tower configuration used by calculations

the calculation of electromagnetical transients - "Marti-model".

In this model the rational function approximation of the characteristic impedance $Z_c(\omega)$ produces directly the values of **R** and **C** in the R-C network.

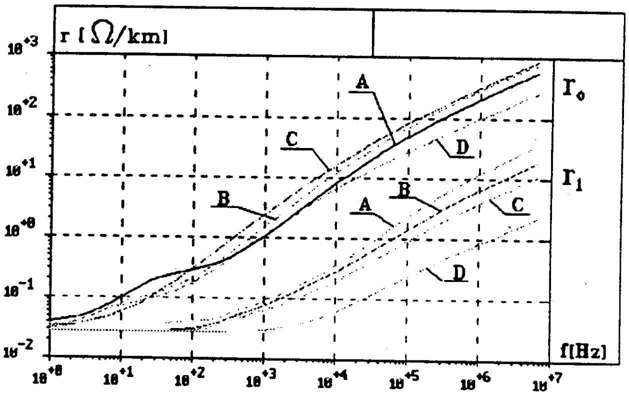

Figure 3 Zero sequence resistance and inductance for the lines shown in Fig. 2

B. Fault model

The modelling of non-simultaneous arc fault is extremely important in relation of the simulation of primary and secondary arcing. The arcing fault representation includes a high-order voltage-current nonlinearity. A number of studies have obtained the voltage-current arcing characteristic. Typical of the results of the investigation which has been carried out under laboratory conditions [3], is the arc voltage/current characteristics as shown in Fig. 4.

An adequate representation of the arcing-fault characteristic would be modified seventh-order power or with normalised function. This is very easy to obtain in MicroTran program with piecewise characteristics. However the arcing-fault conditions can be simulated to a good degree of accuracy with a correctly chosen resistor for most practical applications. The most influence of the arc length variation are wind velocity. The primary arc current is quickly reduced following clearance at the end of faulted line.

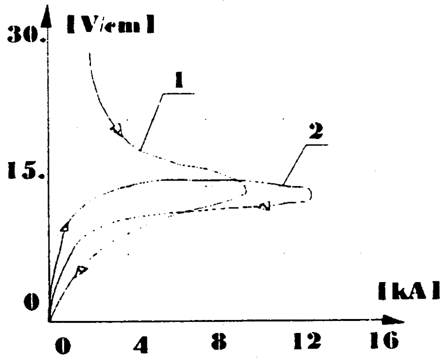

Figure 4 The first (1) and second (2) half cycles of the volt/ampere arc characteristic

The voltage and current are characterised by an initial relatively high-noise period of duration, during which time significant high-frequency oscillations occur. Of the experimental investigation carried out on power system arcing faults, the arc representation based on the nonlinear voltage-current characteristic has been developed for various types of faults (phase-phase, phase-ground etc.), which could be classified as heavy-current. In these case the arc path is relatively short in region of a few meters. The flashover takes place across an insulator to earth or flashover occurs from one phase conductor to another phase conductor. When a flashover takes place from a phase conductor to rapidly growing or falles trees, the arc path can be relatively long, several metres or more. In these case the arcing-voltage gradient is many times greater, compared with the heavy-current arc. The range of possible arc length variation is extremely large. For the purposes of most studies, it is useful to define a reasonably realistic variation between the extremes, and this is adopted here by using (1)

$$
\begin{aligned}
l(t) &= l_o \quad && for\ t < 100\ ms \\
l(t) &= 10\ t\ l_o \quad && for\ t \geq 100\ ms
\end{aligned}
\tag{1}
$$

where :
l_o = initial arc length

C. Network equivalent simulation

In electromagnetic transient studies related to complex power systems nearly always only the respective element of the system is represented precisely, whereas the remaining part is replaced by simplified equivalent networks. It concerns also transient analyses performed for power system protection purposes, e.g. when the fault current and voltage waveforms at transmission line terminals are determined, the line is modelled exactly, while all the rest of the power system at both line ends are represented by simple generation sources. It is evident that the simulation of extremely extensive and complex network configurations will call in question the accurate modelling of each network element. However, it is beyond any doubt that the reduction of the network leads to some inaccuracies of the obtained computed results. It is therefore important to find a compromise between the accurate and reduced network representation for each transient fault analysis, according to the analysed case and the foreseen utilization of the results. Among various equivalent networks applied in reduced systems one of the most frequently used is such an arrangement where the remaining power system with reference to the transmission line being under study is a lumped impedance determined from the given short-circuit level at the line terminals (Fig.5).

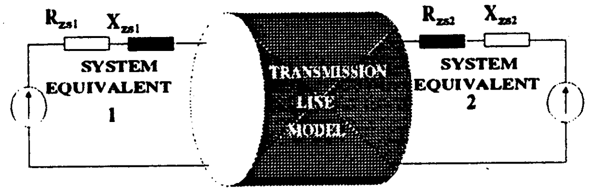

Figure 5 Sample of equivalents networks

This impedance, usually calculated for the rated frequency, is obviously not a satisfactory represenation of complex network configurations, particulary when fast transients with high-frequent components either in the currents or voltages are analysed. It is however well known that the parameters of transmission lines are of distributed nature and therefore highly dependent on the frequency. Thus, the equivalent impedances which assume constant parameters cannot adequately simulate the response of the power system over the wide range of frequencies that are present in transient signals. For this work several equivalent networks of power systems containing mostly transmission lines have been analyzed [4]. Simple and complex faults have been simulated and current/voltage waveforms at relaying points (i.e. line terminals) determined. The effectiveness of parameter identification for reduced networks depends upon various factors, such as : initial values of the parameters, model structure, number of parameters, objective function i.e. number of relative minimums, etc.

RESULTS OF CALCULATIONS

A. Switching overvoltages

The magnitude of a switching overvoltage for a given operation depends on the point on the voltage or current wave when switching occurs. As example of the typical switching surge waveshapes are : fault initiation, fault clearing and line energising. Corresponding to the great variety of initiating events the switching surges are of a great variety of shape, magnitude and duration. The magnitude and waveshape of transients depend on many factors : the length of line switched, the electrical characteristics of source and the system configuration, etc. The sudden occurence of fault on a power transmission line causes a propagation of traveling waves which are reflected at any node. This reflection caused by fault produce the high frequency (h.f.) transient that can easily be recorded at the begining or end of line. This h.f. components have to be obtained with high degree of accuracy for the high-speed distance protection as well as for system insulation. Although the computer study was performed on the full system the objective was limited to investigation of h.f. components on unfaulted 220 kV transmission line due to non-simultaneous faults in the 400 kV line worked on the same tower construction. As indicated in Figure 1, the 220 kV transmission line were added to the existing 400 kV tower construction between point X1 and Y1. The 400/220-kV interconnection and the part of the transmission system were represented by the equivalents circuit. The non-simultaneous three phase to ground and the simply double phase faults were simulated were simulated on the end of the 400 kV line (point H) and the voltage on the unfaulted 220 kV transmission line was monitored at the beginning of this line (point X). The 400 kV and 220 kV transmission line system between points X1 and Y1 work on the same tower construction. The 400 kV transmission line system is made up of a double circuit overhead line with boundle conductor and the 220 kV line work as a simple circuit. It is however well known that the parameters of transmission lines are of distributed nature and therefore highly dependent on the frequency. The initial voltage angle has a large effect upon the magnitude of the h.f. components but has no effect upon the fraquency or damping constant. For different fault types originating with the same fault location, slightly different fault frequencies are produced. The first and most prominent h.f. component along with other frequency components are seen to be inversely proportional to the location of the fault. Electrical transient caused by the non-simultaneous fault occurence are proving troublesome. The series of studies has revelated that the magnitude of h.f. components is most heavily effected by the fault position, the fault instant, the source-sequence impedance ratio z_0/z_1, the type of fault and the time difference. It's shown that on lines under non-simultaneous faults very severe transient conditions can exist. The fault sequence may lead to a considerable increase of the overvoltages. Therefore for the detection technique utilizing the h.f. transient as well several other technique the precise nature of this information is required. The results are compared for the extremaly fault conditions, with faults close to voltage maximum and faults close to voltage zero. For any given fault condition there are a variety factor which influence the transients response by fault conditions. The results of investigation indicate that high overvoltages on the unfaulted 220 kV line will appear as a consequence of non-simultaneous faults on the 400 kV line. Figure 6 shows the voltages obtained at the beginning of the line 220 kV (bus X) for an ***a-b-c-to-ground*** fault at point Y1. The magnitude of overvoltages on unfaulted 220 kV transmission line is particulary high in this case for the phase C (2.6 per unit based on the maximal nominal value) and for the phase A (2.4 per unit). These overvoltages, which are of oscillatory nature can results in outage of this unfaulted line.

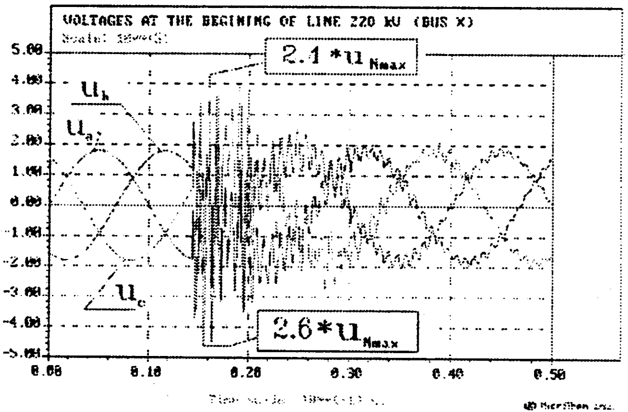

Figure 6 Transiensts at the begining of the unfaulted line

It is important to note that the overvoltages in the unfaulted line may have effect on relay performances. The relatively high level of this distortion produced on the line following faults can produce a slowing of relay responses at this line and unnecessary operation of the relay at unfaulted line. Comparison of the curves indicates that the increase in overvoltage due to non-simultaneous closure is not constant with source inductance but varies throughout the range. The situation is summated by the contours of Fig. 7 which show the increase in overvoltage due to non-simultaneous closure expressed as a percentage of the overvoltage obtained with simultaneous closure. The calculations were carried out for the system which is shown in Fig. 1. It were investigated : - the system response for three-phase simultaneous fault, - the system response for single phase fault. Example of the results of calculation of current and voltage transients are shown in Fig. 8.

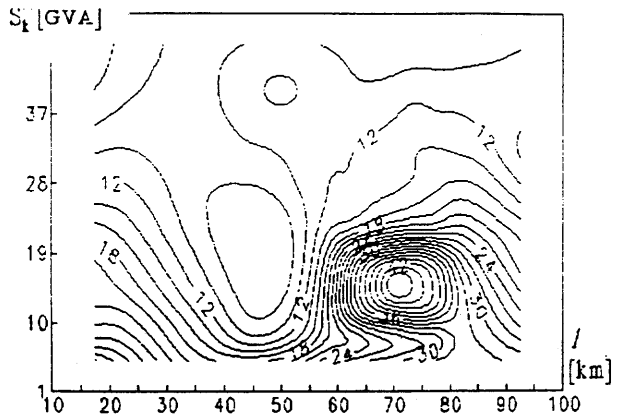

Figure 7 Comparison of overvoltages factors

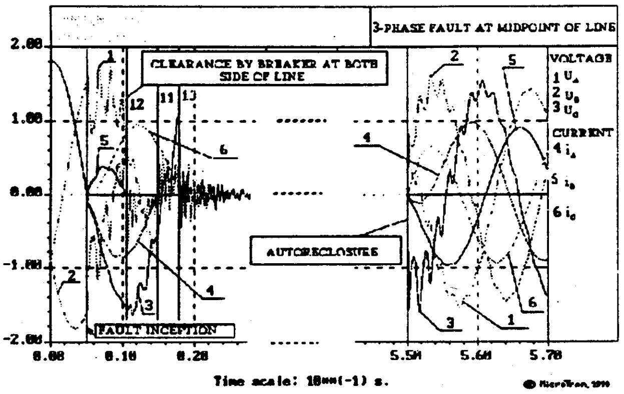

Figure 8 Voltages waveform under autoreclosure conditions

The single-phase *a-earth* fault inception was at zero prefault *a-earth* voltage. The clearance by breaker on the both side of the line was 65 ms after fault. Final of fault was 250 ms after arc transition. Autoreclosure at both end of the line was 460 ms after fault inception. The results reveal the importance of taking account of prefault circuit loading in design studies and the important part that the transient components of voltage and current plays in the process of secondary-arc extinction. It is evident that, a simple calculation of the steady-state arc current and voltage does not provide a reliable guide as to the minimal dead time for corectly autoreclosure. The computational studies must take into consideration the effect of fault position and circuit loading and effect of sequence impedance ratio. The primary arc current is quickly reduced following clearance at the end of faulted line. The voltage and current are characterised by an initial relatively high-noise period of duration, during which time significant high-frequency oscillations occur. The example results of the maximum voltage p.u. from test calculations for some of the worst conditions from the point of view of overvoltages are given in Table 1. The critical conditions are :

- non-simultaneous 3-phase fault at the end of the line,
- autoreclosure after successful fault clearance,
- autoreclosure after unsuccessful fault clearance (long-term fault).

The latter type of fault is the worst case as shown the comparison of overvoltages value in the Table 1.

Table 1 Overvoltages p.u. by non-simultaneous faults

Type of faults	3-phase-earth fault		3-phase successful autoreclosure		3-phase unsuccessful autoreclosure	
line length [km]	S	N	S	N	S	N
10	1.02	1.69	1.96	2.35	2.30	2.68
30	1.03	1.76	1.94	2.21	2.28	2.79
50	1.08	1.71	1.92	2.24	2.34	2.58
70	1.16	2.02	1.89	2.34	2.38	2.89
100	1.25	1.90	1.85	1.97	2.40	2.48
250	1.32	2.21	1.33	2.17	1.12	2.23

B. Overcurrents

For standard valid at present in many countries for calculating the peak short-circuit currents in the network are based on the assumption that a three-phase fault begins in all three phases simultaneously. Using the most severe conditions it is shown [5] that by non-simultaneous fault the current may become greater. It can be observed in practice that, under the same non-simultaneous fauts conditions, the fault current may not pass through zero for some considerable time (Fig. 9), and this phenomenon may result in serious damage to a circuit breaker attempting to interrupt the fault current.

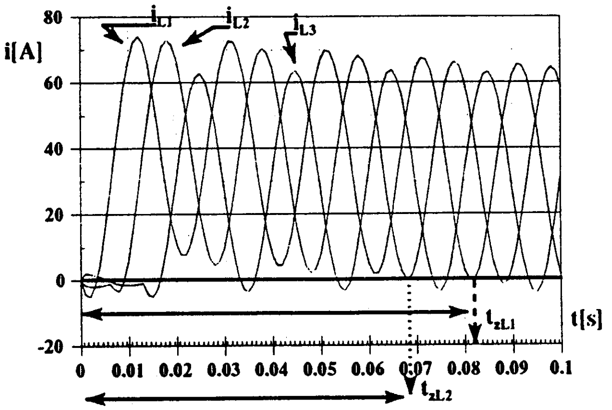

Figure 9 Delayed current zeros under non-simultaneous faults conditions

Extensive series of studies have revealed that the magnitude of d.c. component is most heavily affected by the fault position, the fault instant, the source-sequence, impedance ratio, the type of fault and the time difference. In order to obtain the maximum possible values of peak short-circuit currents the factor k_u used in this paper can be defined by :

$$k_u = \frac{i_{n\text{-max}}}{i_{s\text{-max}}} \qquad (2)$$

where :

$i_{n\text{-}max}$ - the maximum possible peak of non-simultaneous short-circuit current,

$i_{sn\text{-}max}$ - the peak value of the a.c. component of three phase short-circuit current.

The calculation were made with the angle α of the first short-circuit phase varying in the range of 0 ... 359° and the current initiations Δt_1 and Δt_2 (from the beginning of the one-phase fault) of the second and third phases in the range of 0 ... 20 ms. The results of calculations recorded in Table 2 are given for the highest d.c. component conditions with $X_0/X_1 = 0.5$ or $X_0/X_1 = \infty$.

Table 2 Time to current xero t_z and factor k_u for the first short-circuit phase by non-simultaneous 3-phase to ground fault

R_1/X_1	k_{sz}		t_z[s]	
	$X_0/X_1 =$ 0.5	$X_0/X_1 =$ ∞	X_0/X_1 =0.5	$X_0/X_1 =$ ∞
0	2.68	2.36	▨	▨
0.01	2.54	2.32	0.1794	0.1014
0.02	2.49	2.28	0.099	0.0605
0.03	2.45	2.24	0.0596	0.0405
0.04	2.41	2.20	0.0584	0.0398
0.05	2.37	2.17	0.039	0.0214
0.06	2.34	2.13	0.0383	0.0206
0.07	2.30	2.10	0.0378	0.0201
0.08	2.27	2.06	0.0374	0.0198
0.09	2.24	2.03	0.037	0.0195
0.1	2.23	2.00	0.0197	0.0193
0.12	2.14	1.94	0.0186	0.0191
0.15	2.05	1.86	0.0178	0.0191

Fig.10 shows the increase in the peak short-circuit currents in the first phase as a function of time difference Δt_1 and Δt_1. It is evident, that the peak short current in many cases is greater as for the simultaneously fault. The results are shown for the worst possible in practice case when R/X = 0.07 by non-simultaneous 3-phase fault.

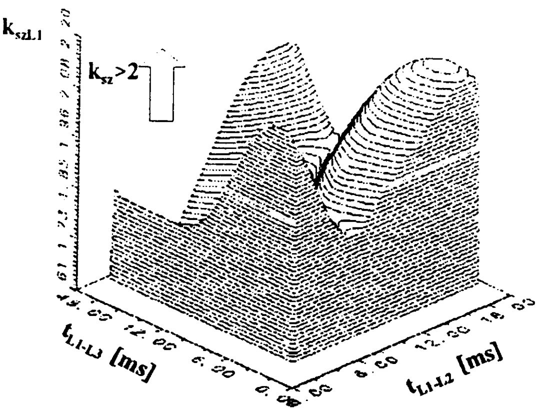

Figure 10 Increase of the short-circuits peak value by non-simultaneous fault

The same results were received for the second and third faultet phases.

IV. CONCLUSIONS

It's shown that on lines under non-simultaneous faults the fault sequence may lead to a increase of the peak currents and the magnitude of overvoltages. Based on the study results it's evident that the critical overvoltage is appeared at non-faulted busbar by non-simultaneous worst conditions. Using MicroTran program it is shown that all transients in high voltage system can be determine and the most severe conditions can be modelled without risk and with very flexible possibility to determine the performance of electrical equipment in the h.v.line under all posible fault conditions.

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