Digital Simulation for Switching Surges on Transmission System

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This paper describes the effectiveness of the series resistors in the 500_{kV} transmission system. Increased reliability of transmission systems is obtained by using the resistors for the transient voltage appearing across the switches reclosed in high speed. And it is shown by means of the digital computers that the switching surges are perfectly prevented by the resistors.

1. Introduction

One of the principal functions of the high speed reclosing switch with resistors is to reduce the surge voltage produced on the 500_{kV} transmission system. Even the fastest high-speed circuit breakers are not always expected the interruption of currents of all magnitudes. Voltage surges have been investigated in some details in the past, and theories have been developed to explain their occurrence and to predict their magnitude[1]. In general, it was required to so design the protective device that damage to equipments would be minimized from the point of view of switching surges, rather than lightning surges[2].

Influence of switching surges is so vital as to change the characteristics of the phenomena completely, and entirely erroneous results are obtained if they are not considered in system design. There are two reasons, principally, for this standpoint: (1) switching surges have a slow rising wave front with long wave tail and (2) the flashover volt-time characteristics of wires, insulator string and other insulators all follow the typical shapes – the higher the voltage, the shorter the time to breakdown and conversely.

Even the non-restriking circuit breakers are not always expected to produce no surges. If restriking takes place before the line voltage has reached an applicable magnitude, there should be overvoltages, so-called reclosing surges produced of any serious magnitude.

In the study of reclosing surges the effect of the actual voltage destributions along the transmission lines just before a breaker operation can not be neglected[3)–5)]. The initial voltages on the lines escape to ground owing to the law of exponential discharge (attenuation), but ideal lines are easier to operate upon mathematically. This solution

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differs from that of a four-parameter line, only in having no decrement factors. For no-loss lines the reclosing surge voltage may reach approximately quadruple value to the normal voltage to ground and energizing transient is, therefore, severe. Thus their occurrence must be accepted and the system must be designed in such a way that the overvoltage can be limited to a value lower than the value corresponding to the dielectric strength of the insulation being protected. Lightning arresters and series resistors are known as the devices for these purposes. One scheme that has been found highly successful is to provide resistors across the breaker interrupting contacts which remain in parallel with these contacts. After a while the resistors can be switched out as a part of the normal breaker operation. The consequences are especially significant from the standpoint of the overvoltages produced, resistor applications and circuit breaker applications. It is the purpose of this paper to outline the fundamental nature of the mechanism that overvoltage may be prevented to impinge by the series resistors and to extend the analysis to practical cases, including the effects of long transmission lines.

2. Analysis

In order to present the elements of the phenomena, suppose the simple three-phase circuit of Fig. 1. It consists of a source of a generated sinusoidal voltage G, a transformer Tr, circuit breakers P and Q, and transmission lines, all in series. It is relatively easy to study the effects of reclosing in the electric circuit if it is assumed that the power system is neutral-grounded and interruption or reclosing is ideally instantaneous, so that the current flow is completely stopped or rushed. Such assumptions were put into practice in the previous papers[6),7)].

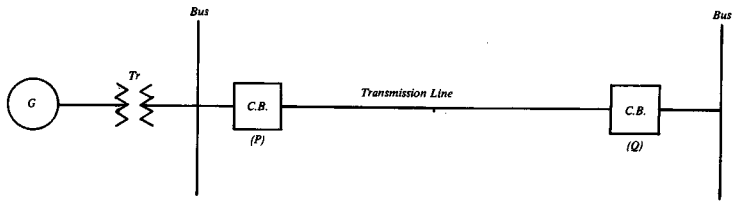

Fig. 1. Representative circuit for ultra high voltage transmission system.

In this circuit, if the circuit breaker Q is opened initially, the flow of the fault current will be stopped. This merely causes the no-load current to flow through the breaker P. This current continues to flow and the system is then normal again except for the fact that the faulted portion has been separated. Thus, if the circuit breaker P is opened ideally, the entire line is charged to a value equal to the crest value of voltage to ground, which remains constant for the moment.

After a fault is removed, the breaker P is reclosed immediately and the line voltages build up. To simulate this condition mathematically, consider the simple single-phase circuit of Fig. 2, in which L is the source inductance. This figure shows an arrangement which was studied in detail with a resistor R across the breaker switch in phase A between t and s.

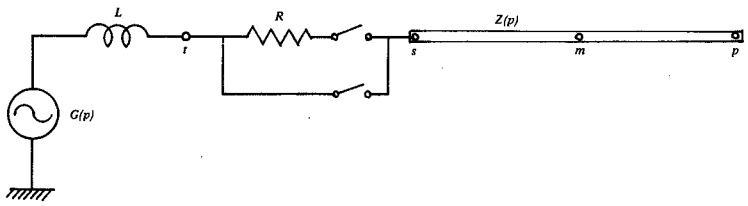

Fig. 2. The equivalent circuit.

Potentials along the line that build up as a result of the suddenly impressed source voltage may be obtained by Bewley's cancellation wave method[8]. The operational expression for the potential at s is

$$V_s(p)=\frac{z(p)\{G(p)-V_0\}}{pL+R+z(p)}+V_0 \tag{1}$$

where $z(p)$, V_0 and $G(p)$ are the surge impedance, the initial voltage on the line and the operational source voltage, respectively. This transient term superimposes on the steady-state term.

When the cancellation wave reaches the far end of the line it reflects therefrom. The successive reflections from the two ends shuttle back and forth, as shown on the lattice of Fig. 3. The resultant voltage at any point at any instant of time is found in the usual way by combining the successive reflection and the steady state wave. In general, then,

$$V_s(p)=G(p)+V_c(p)+\sum_{r=1}^{\infty}\Gamma_r(p)V_c(p)\varepsilon^{-Tp}+V_0 \tag{2}$$

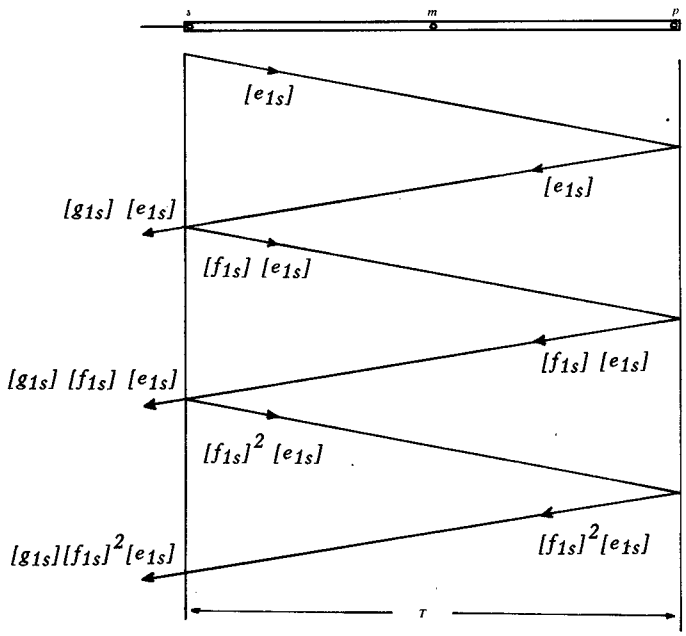

Fig. 3. Lattice for calculating effect of switching.

where $\Gamma_r(p)$ and $V_c(p)$ denote a refraction factor at the generator end due to successive refractions and the reclosing surge appearing at the point s, respectively. Ignoring the line losses, $V_c(p)$ may be taken as

$$V_c(p)=z\{G(0)-V_0\}/(pL+R+z). \tag{3}$$

Thus, the total voltage at the generator end may be written in the matrix form

$$\begin{aligned}[e_{1t}]=[e]+[e_{1s}]+\frac{R}{pL+R+z}[e_\theta] \\ +\sum_{r=0}^{\infty}\frac{p}{p+\mu}[g_{1s}][f_{1s}]^r[e_{1s}]\varepsilon^{-2(r+1)Tp}+[V_0].\end{aligned} \tag{4}$$

At the middle point of the lines and point p, voltages due to reclosing surges are

$$[e_{1m}]=[e]\varepsilon^{-\frac{T}{2}p}+\sum_{r=0}^{\infty}[f_{1s}]^r[e_{1s}]\left(\varepsilon^{-\frac{4r+1}{2}Tp}+\varepsilon^{-\frac{4r+3}{2}Tp}\right)+[V_0] \tag{5}$$

$$[e_{1p}]=[e]\varepsilon^{-Tp}+2\sum_{r=0}^{\infty}[f_{1s}]^r[e_{1s}]\varepsilon^{-(2r+1)Tp}+[V_0] \tag{6}$$

where

$[e]$: generator voltages

$[e_{1s}]$: surges at s due to reclosing

$[e_\theta]$: voltages which would exist across the switch contacts if the breaker were not reclosed

$[f_{1s}]$: reflection coefficients at s

$[g_{1s}]$: refraction coefficients at s

$[K]$: coupling factors of transmission lines.

These operators are:

$$[e_{1s}]=\frac{z}{pL+R+z}[K][e_\theta]=\begin{pmatrix} a \\ b \\ c \end{pmatrix}\frac{\xi}{p+\xi} \tag{7}$$

$$[f_{1s}]=\begin{pmatrix} g-1 & g' & g' \\ g' & g-1 & g' \\ g' & g' & g-1 \end{pmatrix} \tag{8}$$

$$[g_{1s}]=\begin{pmatrix} g & g' & g' \\ g' & g & g' \\ g' & g' & g \end{pmatrix} \tag{9}$$

$$[K]=\begin{pmatrix} 1 & \kappa & \kappa \\ \kappa & 1 & \kappa \\ \kappa & \kappa & 1 \end{pmatrix} \tag{10}$$

in which

$$g=2(p+\mu)(p+\eta)/(p+\eta')(p+\lambda) \tag{11}$$

$$g'=-2\xi'(p+\mu)/(p+\eta')(p+\lambda) \tag{12}$$

$$\mu=R/L \tag{13}$$

$$\xi'=z'/L \tag{14}$$

$$\xi=(R+z)/L \tag{15}$$

$$z'=\kappa z \tag{16}$$

$$\lambda=(R+z+2z')/L \tag{17}$$

$$\eta'=(R+z-z')/L \tag{18}$$

$$\eta=(R+z+z')/L. \tag{19}$$

If the generator voltages and the initial line voltages are given as a function of time and all the parameters are known, the overvoltages on the lines are determined by substituting them into the above equations. The details of the solutions for these operational equations will not be undertaken here, but the equations may be solved very easily.

3. Numerical Examples

By way of illustration of the general equations, consider the simple case of reclosing surges that followed a clearance of a 60_{Hz} three-phase-to-ground short circuit on a solidly grounded generator. If the nominal voltage of the system is 500_{kV}, the voltage to ground is

$$E_m=525\times(\sqrt{2}/\sqrt{3})\times1.2\times1.3\simeq 700\mathrm{kV\ crest}\ ^{9)}.$$

The limiting conditons are:

$$V_0=\begin{cases}700_{\mathrm{kV}} \text{ for phases } A \text{ and } B.\\ -700_{\mathrm{kV}} \text{ for phase } C.\end{cases}$$

Typical values of the resistance R, the coupling factor κ, the effective inductance of generators and transformers, L, the phase angle in reclosing, θ, and the line length ℓ are:

R = 0, 400, 600, 800, 1000 and 1200 $_{\mathrm{ohms}}$

κ = 0.25 and 0.4

L = 0.1 and 0.2 $_{\mathrm{Henries}}$

θ = 60° and 90°

ℓ = 50, 150 and 250 $_{\mathrm{kilometers}}$.

Table 1. Maximum surge voltages at poonts t, m and P. Voltages are expressed as ratios of maximum surge to crest voltage to ground, for R = 0 and 400 ohms.

R (Ω)	κ	$\theta°$	Line length (km)	Inductance L = 0.1 (H)			Inductance L = 0.2 (H)		
				Point t	Point m	Point p	Point t	Point m	Point p
0	0.25	60	50	2.93	3.12	3.17	3.0	3.14	3.22
			150	2.39	2.97	3.48	2.6	2.78	3.10
			250	2.23	2.92	3.35	2.14	2.59	3.16
		90	50	3.42	3.6	3.68	3.47	3.56	3.61
			150	2.93	3.52	4.01	3.06	3.41	3.7
			250	2.81	3.51	4.02	2.67	3.24	3.83
	0.4	90	50	3.11	3.27	3.34			
			150	2.66	3.20	3.68			
			250	2.53	3.23	3.64			
400	0.25	60	50	2.04	1.88	1.95	2.22	2.10	2.14
			150	1.96	1.58	1.77	1.96	1.64	1.80
			250	1.94	1.35	1.53	1.94	1.35	1.52
		90	50	2.48	2.17	2.30	2.58	2.38	2.43
			150	2.36	1.78	2.03	2.30	1.82	2.0
			250	2.23	1.59	1.90	2.19	1.53	1.86

Table 2. Maximum surge voltages at points t, m and P. Voltages are expressed as ratios of maximum surge to crest voltage to ground, for R = 600 and 800 ohms.

R (Ω)	κ	$\theta°$	Line length (km)	Inductance L = 0.1 (H)			Inductance L = 0.2 (H)		
				Point t	Point m	Point p	Point t	Point m	Point p
600	0.25	60	50	1.93	1.7	1.77	2.08	1.84	1.86
			150	1.92	1.41	1.54	1.93	1.43	1.54
			250	1.92	1.12	1.29	1.92	1.09	1.26
		90	50	2.3	1.9	1.99	2.44	2.06	2.14
			150	2.26	1.5	1.70	2.24	1.51	1.67
			250	2.12	1.5	1.52	2.1	1.5	1.5
800	0.25	60	50	1.90	1.56	1.60	2.0	1.62	1.65
			150	1.91	1.26	1.40	1.92	1.26	1.36
			250	1.92	1.0	1.10	1.90	1.0	1.06
		90	50	2.24	1.74	1.84	2.33	1.85	1.91
			150	2.20	1.5	1.5	2.18	1.5	1.5
			250	2.06	1.5	1.5	2.05	1.5	1.5
	0.4	90	50	2.17	1.60	1.67			
			150	2.13	1.5	1.5			
			250	2.0	1.5	1.5			

Table 3. Maximum surge voltages at Points t, m and p. Voltages are expressed as ratios of maximum surge to crest voltage to ground, for R = 1,000 and 1,200 ohms.

R (Ω)	κ	$\theta°$	Line length (km)	Inductance L = 0.1 (H)			Inductance L = 0.2 (H)		
				Point t	Point m	Point p	Point t	Point m	Point p
1,000	0.25	60	50	1.87	1.43	1.46	1.94	1.46	1.48
			150	1.90	1.13	1.26	1.90	1.12	1.23
			250	1.90	1.0	1.0	1.89	1.0	1.0
		90	50	2.22	1.64	1.70	2.26	1.70	1.74
			150	2.15	1.5	1.5	2.17	1.5	1.5
			250	2.03	1.5	1.5	2.02	1.5	1.5
1,200	0.25	60	50	1,86	1.31	1.33	1.90	1.33	1.34
			150	1.89	1.0	1.13	1.90	1.0	1.01
			250	1.89	1.0	1.0	1.89	1.0	1.0
		90	50	2.19	1.51	1.57	2.20	1.55	1.60
			150	2.12	1.5	1.5	2.11	1.5	1.5
			250	1.99	1.5	1.5	1.99	1.5	1.5
	0.4	90	50	2.14	1.5	1.5			
			150	2.07	1.5	1.5			
			250	1.94	1.5	1.5			

It is often possible to obtain the results for a given problem by assuming the various circuit conditions for an entirely different one. This possibility is illustrated in Tables 1, 2 and 3, in which the variation shown as overvoltages indicates the range in the shape of the reflected and transmitted waves caused by different circuit conditions. A large number of specific cases calculated from general equations are given, of which some representative examples are produced in Figs. 4 to 6 inclusive. The overvoltages at points p, m, and t are plotted as a function of time. Tables 1, 2 and 3 mentioned above summarize the results of these curves with respect to the maximum voltages developed in this paper.

(1) It becomes clear from Fig. 4 that the resistor added to the line reduces the high voltages and absorbs excess vars produced under these conditions. It has a great influence on building up of overvoltages at points m and s; the larger the resistor's value, the lower the overvoltages. However it is important to recognize the fact that the impinging surges at point t are not much dependent on the value of the resistor. This is because the surge impedance of the source is in series with the resistor.

Generally speaking, in order that the resistor may be most efficient, its value should be chosen adequately. If the resistor is on the generator side, then the apparatus can not be subjected to more than three times normal line-to-neutral. So far as overvoltages are concerned, the effect of series resistance is not critical. That is, there is no particular critical value that eliminates the possibility of overvoltages. As the amount of resistance is increased, systems become more prolific as far as the production of overvoltages. Thus, one scheme that is expected to be successful in this very desirable object is to provide

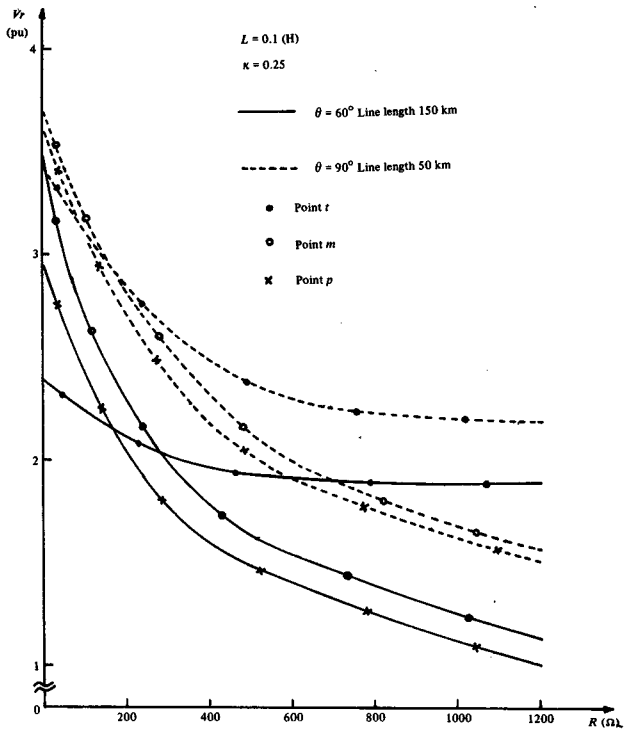

Fig. 4. Effect of series resistors for switching surges.

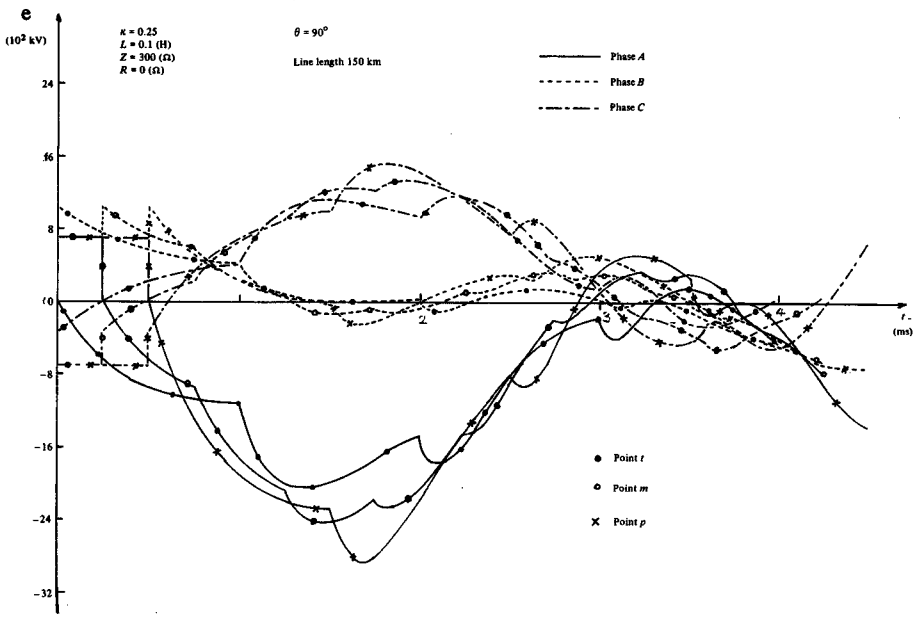

Fig. 5. Overvoltages due to reclosing for system without series resistor.

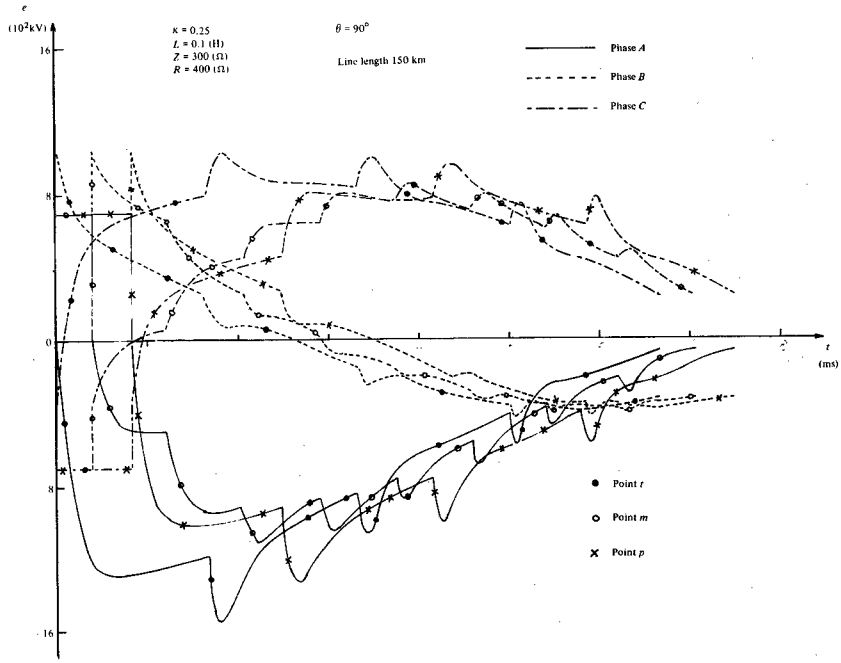

Fig. 6. Overvoltages due to reclosing for system with series resistors.

arresters at the sending ends of the line.

(2) Fig. 5 and 6 show a comparison of overvoltages obtained on the same system with different phases. The maximum crest reclosing voltage was obtained for phase A. Though the mutual coupling is present in the three phase line, there exists a very little coupling between phases and then the voltages in phases B and C are smaller than that in phase A. Thus phases make difference in the magnitudes of voltage or in the region in which high voltages are encountered.

(3) The reclosing angle θ is defined as that a value of $\theta = 90°$ corresponds to the time at which the voltage on phase A is a maximum. Values of θ from 60° to 90° indicate the application of reclosing before the voltage is reached to a crest value. Builds up of the voltage are always higher for $\theta = 90°$ than for $\theta = 60°$. From the preceding analyses there appears to be a plausible explanation for reclosing surges: severe surges depend not so much upon a combination of angle θ and a line length as upon a voltage across contacts of a circuit breaker at reclosing time.

(4) The effect of varying the coupling factor κ is also illustrated in the above Tables. It is believed that this covers the practical range of κ and shows that the phenomenon is not critical to a practical value of κ. Obviously, if κ is 0.2, and if there is exists a little coupling between phases, a little disturbance of the type under discussion would be expected.

(5) Tables 1, 2 and 3 indicate that overvoltages are to be expected over a range of the line length from 50_{km} up to 250_{km}, when source inductances are in practical range.

The maximum value of V_r (ratio of maximum surge to crest voltage to ground) obtained is 4.02, and an increase in line length is shown to increase V_r. Thus, under system conditions corresponding to these, voltages of the order of twice in comparison with those normally expected may exist at the terminals of the sending-end transformer.

However, for the cases of $L = 0.1$ Henries the voltage cuased by reclosing are not greatly different from those of $L = 0.2$ Henries. This reason is that the resistor will be effectively in series with line surge impedance, if the reactance of the source is sufficiently small compared with that of resistors.

(6) It has been shown by this study that the effectiveness of a given resistor used in this manner to control reclosing surge overvoltages depends on the length of line being switched in that particular phase. If a resistor is connected to long line, it should be more effective in reducing overvoltages for shorter line, although the potential is slightly increased at the receiving end of the line. This fact has an additional significance in that the effectiveness of a resistor in power system does not always depend upon the microfarads of capacitance equivalent to the line being switched off.

(7) From the standpoint of overvoltages, devices of their reducing that should be satisfactory are: (a) arrester located at the sending end, which has little chance of arrester failure due to surges of the type discussed here; (b) high-speed circuit breaker that makes it possible to clear an arc between the contacts momentarily without producing overvoltages.

4. Conclusions

It must be emphasized that the resistors brought about a substantial reduction of voltage in all cases of this report, and the higher their values, the greater the percentage of reduction. The results obtained in this paper cannot always be generalized to make them applicable to all system. Some general principles and effects have been discussed in order to show the trends in voltage surge severity which may be expected, but in particular instances it may be advisable to study the system in question, rather than to estimate the probable effects from general data. This is particularly true in evaluating quantitatively the effects of resistors in reducing the magnitude of voltage surges.

Furthermore, it may be well to enumerate some of the factors that have not been considered in the preceding analysis in spite of its importance. Among these factors are the following:

(1) Characteristics of circuit breakers on each phase.
(2) Effects of shortening the series resistors after the surges are slightly overcome[10]).
(3) Effects of arresters.
(4) Attenuations and distortions of waves traveling along the transmission lines.
(5) Corona loss.

It should be remarked that some of these factors can be included simply by continuing the analysis, but to cover all cases analytically becomes far too laborious. Of course, in a case of this kind much time is saved through the case of transient analyzer

with reference to the theory included in this paper.

Acknowledgement

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