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Switching Surges on Transmission System-I

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This report presents the theoretical analyses for the switching surges on transmission system which are perfectly suppressed by lightning arrester.

1. Introduction

It has been recognized for many years that voltage surges of considerable magnitude could be produced under certain system conditions. Many authors have been pointed at the system fault and lightning surges as a source of high voltages. Arresters were therefore designed to withstand all but the most severe lightning surges that nature could produce.

Recently, it has become increasingly evident that lightning arresters were serving a more general purpose, namely, that they were and are serving as overvoltage arresters.(1)(2) They serve to limit overvoltages. It has become apparent also that certain switching surges may be of sufficient magnitude and duration to exceed the discharge capacity of arresters. Therefore, switching surges become an important factor for consideration in the proper design and application of arresters. In a number of installations, it became apparent that lightning arresters were functional more often on switching surge overvoltage than on lightning discharge voltages. Consequently there was a very real need for studying switching surges and the arrester discharges to see what duty was imposed upon the arrester each time its series gap was sparked over by a switching overvoltage.

One of the common type of switching surges is evidently switching a line. It is the purpose of this report to outline the fundamental nature of the mechanism whereby overvoltages may be produced during interruption of transmission circuits and extend the analysis to practical cases, including the effects of long lines and the non-linear characteristics of arrester discharge.

2. Opening or Closing the Switch of Single Phase

The elementary basic circuit is shown in Fig. 1. It consists of a source of generated sinusoidal voltage E, an equivalent inductance L of the generator and transformer, a surge impedance Z of the line, and a switch S, all in series except the arrester located at the sending end of the transmission line.

The function of an arrester is to prevent the flow of power current to ground after having discharged the impulse current. It becomes evident, therefore, that an arrester should have low impedance to surges and high

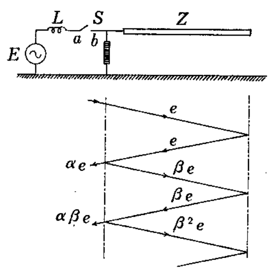

Fig. 1 Reflection lattice for switching surges, when the arrester is located at the sending end.

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impedance to normal power voltage. The arrester, which is used in model stations, possesses the characteristics

$$I_a = f(V_a). \tag{1}$$

An example of the hyperbolic characteristics is illustrated in Fig. 2.[2]

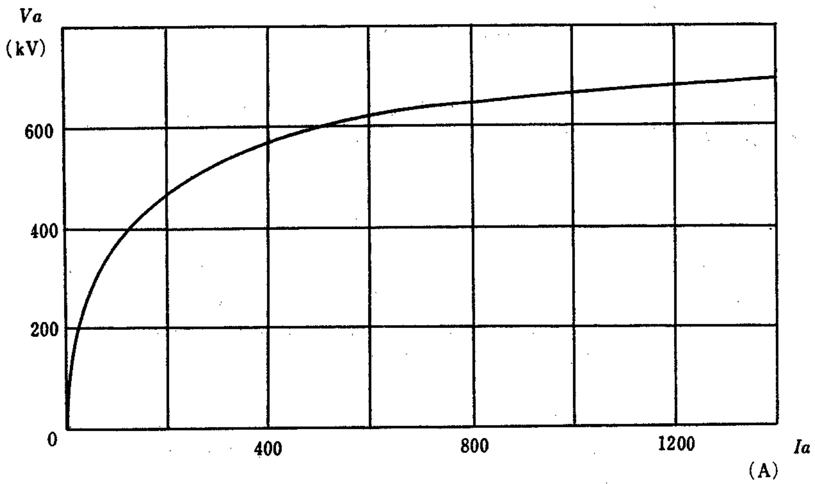


Fig. 2. Arrester voltage-current characteristics.

The switch S is assumed to be originally in a closed position so that a steady-state sinusoidal current flows prior to the initial opening of the switch. The process of building up excessive voltages by the interruption of the current of a connected transmission line is as follows. The switch contact arc is extinguished when the current is passing through zero, and the line is completely charged to one polarity. One half-cycle later the generator voltage has reversed its polarity, but the line voltage remains unchanged, so that double leg voltage is across the switch. If this voltage breaks down the gap between switch knives, a wave travels down the line and reflects. As the reflected wave reaches the switch and the entire line is charged to a value of the arrester impulse spark over voltage, the discharging current flows in the arrester. Actually the effects of the discharging current limit the line voltage to a finite value.

In making a circuit by restrike of arc, the voltage across the switch $(E_b - E_a)$ is nullified or canceled. Therefore the switching operation may be regarded as a cancellation process. A cancellation voltage $(E_a - E_b)$ superimposed on the voltage $(E_b - E_a)$ which would exist if the circuit were not made results in zero voltage across the switch, thereby simulates the closing the switch. This cancellation voltage in series with Z and L will circulate a current and this current will cause a voltage on the line of (writing $\xi = Z/L$)

$$e = (e_a - e_b) \cdot \frac{\xi}{s+\xi} \tag{2}$$

in operational form.[3]

This transient term superimposes on the steady-state terms. When the cancellation wave reaches the far end of the line, it reflects like any other waves, and upon returning to the line gives rise to a new voltage there. In general, then[3]

$$\begin{Bmatrix}\text{Resultant} \\ \text{voltage}\end{Bmatrix} = \begin{Bmatrix}\text{Steady-state} \\ \text{voltage}\end{Bmatrix} + \begin{Bmatrix}\text{Cancellation} \\ \text{voltage}\end{Bmatrix} + \begin{Bmatrix}\text{Successive reflec-} \\ \text{tion voltage}\end{Bmatrix} \quad (3)$$

The steady-state voltages of the generator and line are obviously v_a and e_b, respectively. The reflection and refraction operators at the generator end are

$$\alpha = \frac{2s}{s+\xi}, \quad \beta = \frac{s-\xi}{s+\xi}. \quad (4)$$

With attenuation neglected in the line, the reflected from the open end will be exactly the same as the original wave. This, upon returning to the source, impinges upon the source impedance sL which gives rise to a reflected wave. The amplitude for the r-th reflection is given on the lattice of Fig. 1. Assuming the initial wave to have a unit function, the resultant successive reflection surge at b, as compounded of all reflections, is given by

$$\alpha e\varepsilon^{-2Ts} + \alpha\beta e\varepsilon^{-4Ts} + \alpha\beta^2 e\varepsilon^{-6Ts} + \cdots\cdots$$

in which T is length of transmission line in seconds. The resultant voltage of the line therefore is

$$v = v_0 + e_b + e_0 + \alpha e\varepsilon^{-2Ts} + \alpha\beta e\varepsilon^{-4Ts} + \cdots\cdots \quad (5)$$

where

$$e_0 = (e_a - e_b) \cdot \frac{\xi}{s+\xi} \quad (6)$$

Let the generated voltage be $E_m \sin(\omega t + \theta)$ and the potential of a will then be

$$E_a = E_m \sin(\omega t + \theta) \quad (7)$$

if the switch is opened. And when the current flows in restriking of the arc between the opening contacts of a switch, the normal voltage is

$$V_0 = E_m' \sin(\omega t + \theta - \varphi_0), \quad \varphi_0 = \tan^{-1}(\omega L/Z)$$

where

$$E_m' = E_m Z/\sqrt{Z^2 + \omega^2 L^2}$$

Let the instant of restriking of the arc be $t=0$ and equation (7) will be

$$E_a = E_m \sin\theta \quad (8)$$

With φ_0 being omitted for convenience, the supplied voltage becomes

$$V_0 = E_m' \sin(\omega t + \theta) \quad (9)$$

The recovery voltage transient is given by equation (5), where v_0, e_0 and e are given by equations (9), (6) and (2) respectively. With this substitution, the solution of equation (5) operationally yields

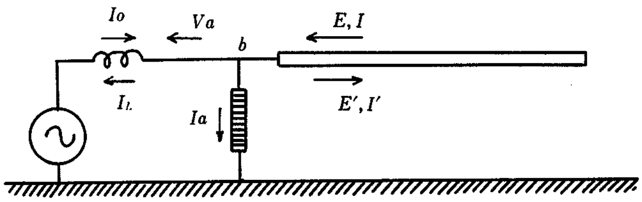
$$\begin{aligned} V = \{&E_m' \sin(\omega t + \theta) + E_b + E_m''(1 - \varepsilon^{-\xi t})\} H(t) \\ &+ 2E_m'' \xi \{(t-2T)\varepsilon^{-\xi(t-2T)} H(t-2T) \\ &+ (t-4T)(1 - \xi \cdot \overline{t-4T})\, \varepsilon^{-\xi(t-4T)} \cdot H(t-4T) + \cdots\cdots\} \end{aligned} \quad (10)$$

where

$$E_m'' = E_m \sin\theta - E_b$$

$$H(t-\delta)=\begin{cases}0, & t<\delta\\ 1, & t\geqq\delta\end{cases}$$

This voltage builds up to serious value in few milliseconds. This merely causes the arrester gap to spark over so that all that happens is that the line current is suddenly transferred to the arrester. This current continues to flow through the arrester until a current zero is reached at which time the arrester seals off and the system is then normal again. As far as the arrester discharge current is concerned, it depends on the initial value and on the system voltage, which is influenced by the successive reflections of the cancellation waves. For the purpose of this analysis, only the limiting case of instantaneous transition will be considered.



Fig, 3. Wave components at a transition point.

Fig. 3. shows a generator and an arrester at the sending end of a transmission line of surge impedance Z. When an incident wave E approaching along the line reaches the transition point, it will give rise to a wave E' reflected back on the line; transmitted current waves I_L and I_a; a potential V_a at the junction b. Assuming that the current I_0 flows into b by the steady-state voltage (V_0+E_b) and cancellation wave E_0, the following equations are self-evident:

$$\left.\begin{aligned} &v_a=v_0+e_0+e+e'+e_b\,, && e=Zi\\ &i-i'=i_a+i_L-i_o\,, && e'=Zi'\\ &v_0+e_0+e_b=sLi_0\,, && v_a=sLi_L \end{aligned}\right\}\qquad(11)$$

Therefore,

$$v_a=v-sZi_a/(s+\xi)\qquad(12)$$
$$e'=v_a-v_0-e_0-e-e_b\qquad(13)$$

If s is sufficiently large, as will usually be true at transient state, the equation (12) may be written

$$V_a=V-ZI_a\qquad(14)$$

Equations (12) and (14) may be solved graphically as in Fig. 4, in which ($V-ZI_a$) is plotted against I_a. Then for any I_a there is a certain V_a, so that V_a and I_a may be obtained directly. It is usually quicker to solve the equations by graphical-tarbular method.(4)(5)

Following the arrester operation, a voltage (and current) surge travels down the line, bring the line voltage down to the arrester discharge voltage. The voltage and current wave are reflected from the open end of the line and

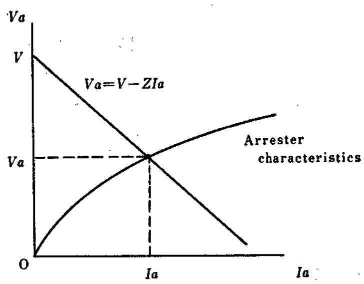


Fig. 4. Graphical solution for arrester circuit.

travel back to the arrester. The reflected traveling wave of current thereupon reduces the arrester current. The degree of reduction depends on the arrester characteristics and may be found by means of Duhamel's theorem.

Thus, the subsequent voltage impressed to the arrester due to successive reflections is for open-end line,

$$\begin{aligned} V = & \{ E_m' \sin (\omega t + \theta) + E_b + E_m'' (1 - \varepsilon^{-\xi t}) \} H(t) \\ & + 2 E_m'' \xi \{ (t - 2T) \varepsilon^{-\xi (t-2T)} H_1(t-2T) \\ & + (t - 4T)(1 - \xi \cdot \overline{t-4T}) \varepsilon^{-\xi (t-4T)} \cdot H_1(t-4T) + \cdots\cdots \} \\ & + P(t-2T) \cdot H(t-2T) \end{aligned} \tag{15}$$

in which

$$P(t) = 2 \int_\tau^t E'(t-\nu)(\nu - \xi \cdot \varepsilon^{-\xi \nu})\, d\nu$$
$$H_1(t-\delta) = H(t-\delta) - H(t-\tau)$$

τ denotes the time when the reflected wave E' starts from b.

The arrester potential just before breakdown of the gap is plotted from equation (10) and it after arrester discharging is obtained from equation (15). Thus V_a, I_a and E can be easily seen from above equations.

The process of building up excessive voltages by the interruption of the charging currents of a connected transmission line, when the arrester is located at the open end, will be easily known by applying the above method.

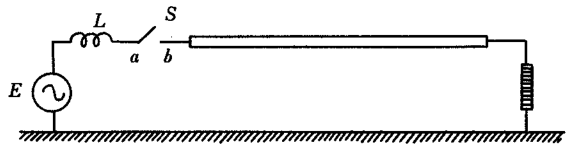


Fig. 5. When the arrester is located at the receiving end.

3. Effect of Neutral Grounding in Three-phase System

As far as the production of overvoltages is concerned, the isolated-neutral system is under suspicion. The switching operation itself may lead to undesirable overvoltages. There are at present very few isolated-neutral system above 33kV in this country.

So far as overvoltages produced by switching are concerned, the effect of neutral grounding impedance is important for three-phase transmission system. It is clear, however, from studies made on laboratories, that the solidly grounded system is least productive of overvoltages. As the amount of neutral impedance is increased, system become more prolific in production of overvoltages.

This chapter is included, in order to show characteristics of high-voltage neutral-grounded system. It was assumed for this study that at the time of switching, all the lines or generators were being previously connected.

Since this investigation is concerned with the effect of arresters on switching surges, and with the nature of the discharge of the switching surge through the arrester, high switching surge voltages were assumed to appear in three cases, in the system.

Case I. In one of the three lines arc restrikes.

Considering waves going in only one direction, there is, in general,

$$\left.\begin{aligned} E_1 &= Z_{11} I_1 + Z_{12} I_2 + Z_{13} I_3 \\ E_2 &= Z_{21} I_1 + Z_{22} I_2 + Z_{23} I_3 \\ E_3 &= Z_{31} I_1 + Z_{32} I_2 + Z_{33} I_3 \end{aligned}\right\} \tag{16}$$

where Z_{rr} and Z_{rs} denote the self and mutual surge impedance of the lines, respectively. This equation applies under the condition that arc restrikes in one of the lines. If one line, say No. 1, restrikes, then $I_2=0$, $I_3=0$. Substitute these values in (16), or else by inspection

$$\left.\begin{aligned} E_2 &= \frac{Z_{12}}{Z_{11}} E_1 \\ E_3 &= \frac{Z_{13}}{Z_{11}} E_1 \end{aligned}\right\} \tag{17}$$

If E_2 and E_3 are taken as the incident wave E of the successive reflection surge, given by equation (5) in previous chapter, then the induced surges on the other lines will be immediately calculated from equation (17). For the successive reflection waves, it must be noticed that the line terminals on the generator side are open, too.

Thus, the arrester voltages connected to these lines can be obtained in previous method.

Case II. In two lines arc restrikes.

In this case $I_3=0$ and (16) reduces to

$$\begin{aligned} E_1 &= Z_{11} I_1 + Z_{12} I_2 \\ E_2 &= Z_{21} I_1 + Z_{22} I_2 \\ E_3 &= Z_{31} I_1 + Z_{32} I_2 \end{aligned}$$

Solving these simultaneous equations, there is

$$E_3 = \frac{(Z_{22} Z_{31} - Z_{21} Z_{32}) E_1 + (Z_{11} Z_{32} - Z_{12} Z_{31}) E_2}{Z_{11} Z_{22} - Z_{12} Z_{21}}$$

This equation may be the incident wave of the successive reflection waves.

Case III. In all lines arc restrikes.

It is immediately apparent that the circuit in this case is identical with that of single phase and that the analysis of the foregoing section applies directly if, for E, the values of E_1, E_2 and E_3 are substituted, respectively. Therefore, for all line restrikes one would expect from equation (15) the arrester voltages.

Thus it appears from these theoretical considerations that switching in grounded-neutral systems may be productive of overvoltages.

4. Numerical Examples

In this chapter cases will be considered similar to the foregoing Fig. 1 and Fig. 5 but with the line being assigned certain specific length so that reflections can be taken in account. As a numerical example, take the following :[2]

$T=0.5$ ms

$Z=470\ \Omega$

$E_m=424\ \text{kV}\ (1.3\times\frac{400}{\sqrt{3}}\times\sqrt{2}\ \text{kV})$

$\omega=120\pi$

$L=0.122\ \text{H}$

$E_b=-400\text{kV}$

The discharge voltage of an arrester having the characteristics of Fig. 2 is assumed to be 750 kV.

If the arc restrike is timed so that it is completed instantaneously $t=0$, arrester discharges occur at $t=0.59$ ms, when $\theta=90°$. Wave shapes calculated on these assumptions are shown in Fig. 6. In this figure, the values corresponding to no-loss transmission line are plotted in solid curve and those corresponding to the line of attenuation factor $0.9^{(6)}$ in dotted line. Chain line illustrates the case for overhead lines of $T=2.1$ ms.

When the arrester is located at a receiving end, arrester discharges occur at 0.66 ms, and the voltages are plotted as a function of time in Fig. 7.

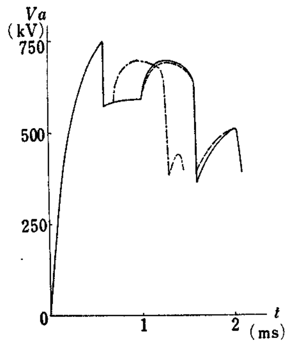


Fig. 6. Potentials of arrester, connected to the sending end.

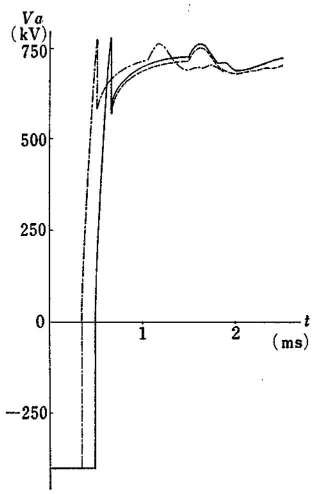


Fig. 7 Potentials of arrester, connected to the receiving end.

5. Conclusions

As a result of extensive calculations and theory the following conclusions have been established concerning the arrester:

(1) As the curves of Fig. 6 indicate, the transient voltage appearing at the station bus is substantially less than 750kV, when the arrester is connected to the source. At 1 ms, the bus voltage is at its maximum instantaneous value of about 700kV. This peak voltage is only twice normal line voltage, because the arrester voltage has been reduced before arriving of the reflected wave.

(2) When the arrester is connected with the open end of the line, the arrester voltage resulting from switching surges will exceed 700kV and sustain its value during several milliseconds.

Thus, discharge duty imposed upon arrester in the open end may be particularly severe, compared with arrester in the sending end.

(3) The factors of surge attenuation and transmission line length can be neglected as results of numerical calculations.

In this paper, fundamental examples are analyzed. Though it is more complex on real system, calculation can be executed by means of the above-mentioned methods.

Furthermore, the laboratory setup manufactures for trial a surge analyzer, so that the results can be obtained very easily and directly, in the case that circuit constants, time of breaker restriking and etc. vary numerically.

It will be reported in next chance as for this device.

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