SWITCHING SURGE OVERVOLTAGE ON EHV TRANSMISSION LINES

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Abstract

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Switching Surge Overvoltage on EHV Transmission Line

The effects of Automatic Reclosure, Corona, Ferroresonance, Load Rejection are included in a general review of various problems associated with switching surge overvoltages on extra high voltage (EHV) transmission lines.

Methods of reducing overvoltages are described and their effects on insulation co-ordination considered. The use of Transient Network Analyzer (TNA) and digital computer as aids for transmission line design is illustrated.

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PART I

The Problem of Switching Overvoltage in EHV Transmission Line

INTRODUCTION

The transient overvoltage due to circuit breaker operation in power systems has always been of importance, but in the past attention has been focused on restriking overvoltage when a circuit breaker opens. More recently, due to rising of system voltage to increase the loading capability of a transmission line, maximum transient overvoltage occurs when a long transmission line is energized and re-energized, and reduction of this transient overvoltage has become more important.

Electrical stress in a high voltage transmission line is usually caused by lightning strike, load rejection and switching surge overvoltage. In general, the number of outages caused by lightning strikes decreases as the system voltage increases because of higher insulation level. For transmission lines such as 330 kV and below, system insulation level is mainly governed by lightning[11]. At the present time, there are many extra high voltage (EHV) system (500 kV to 1,000 kV) and there is a possibility that still higher voltage will be used in the future. A 1,100 kV line is now under test[21]. At this order of operating voltages, switching overvoltages can exceed those due to lightning and hence, reduction of switching surges is required.

For the reliable operation of a power system network, it is important to know the conditions under which transient overvoltage may be developed within the system and what is the maximum voltage.

This report will illustrate various problems caused by high voltage switching, various methods employed to determine the magnitude and to control or suppress the switching surge overvoltage in the EHV transmission line.

2. BREAKER SPAN

It is very difficult to design a three phase breaker where the three poles close in simultaneously, mechanically and electrically. In practice, three poles of the breaker never close simultaneously because of the mechanical nature of circuit breaker construction. If the three poles of the circuit breaker close simultaneously and if the system is symmetrical, no zero sequence current will flow. The transient phenomena are not influenced by the zero sequence system or by the ground wire. The transient overvoltages that do occur are mainly governed by the positive sequence system. If the three poles of the breaker do not close simultaneously, there is unbalance in the system as a result of which a zero sequence current flows.

Therefore, the properties of the zero sequence system or the nature of earth return influences the magnitude and shape of the switching surge overvoltage. The magnitude of the switching surge is mainly governed by the damping resistance value of positive and zero sequence system and the phase angle of the supply voltage when closing the circuit breaker. It is very difficult to define the zero sequence impedance and it mainly depends on the configuration of the transmission line tower, ground wire and ground resistivity. Computer programs are now available

to determine zero sequence impedance of a transmission line.[22]

The speed of the positive sequence wave is equal to $\frac{1}{\sqrt{LC}}$ where L and C are positive sequence inductance and capacitance respectively and the speed of zero sequence is equal to $\frac{1}{\sqrt{L_o C_o}}$ where L_o and C_o are zero sequence inductance and capacitance respectively. Therefore, for practical purposes, zero sequence should be included for modelling a transmission line for switching surge overvoltage study.

Zero sequence of a transmission line is frequency dependent, and can be modelled by a non-linear device for transient network analyzer (TNA) study. The extra high voltage (EHV) designer has to investigate the maximum switching overvoltage by varying the breaker poles close and open sequences and the phase angle which the breaker poles close or open. These can perform easily by transient network analyzer (TNA) and the accuracy of the results is mainly dependent on the modelling of a transmission line and source behind the transmission line.

There is no known practical method yet available to reduce the switching overvoltage caused by random closing and opening of breaker poles and the phase angle which breaker poles close or open.

Experiments have been performed on low voltage synthetic breakers and required further research for practical application on high voltage system.

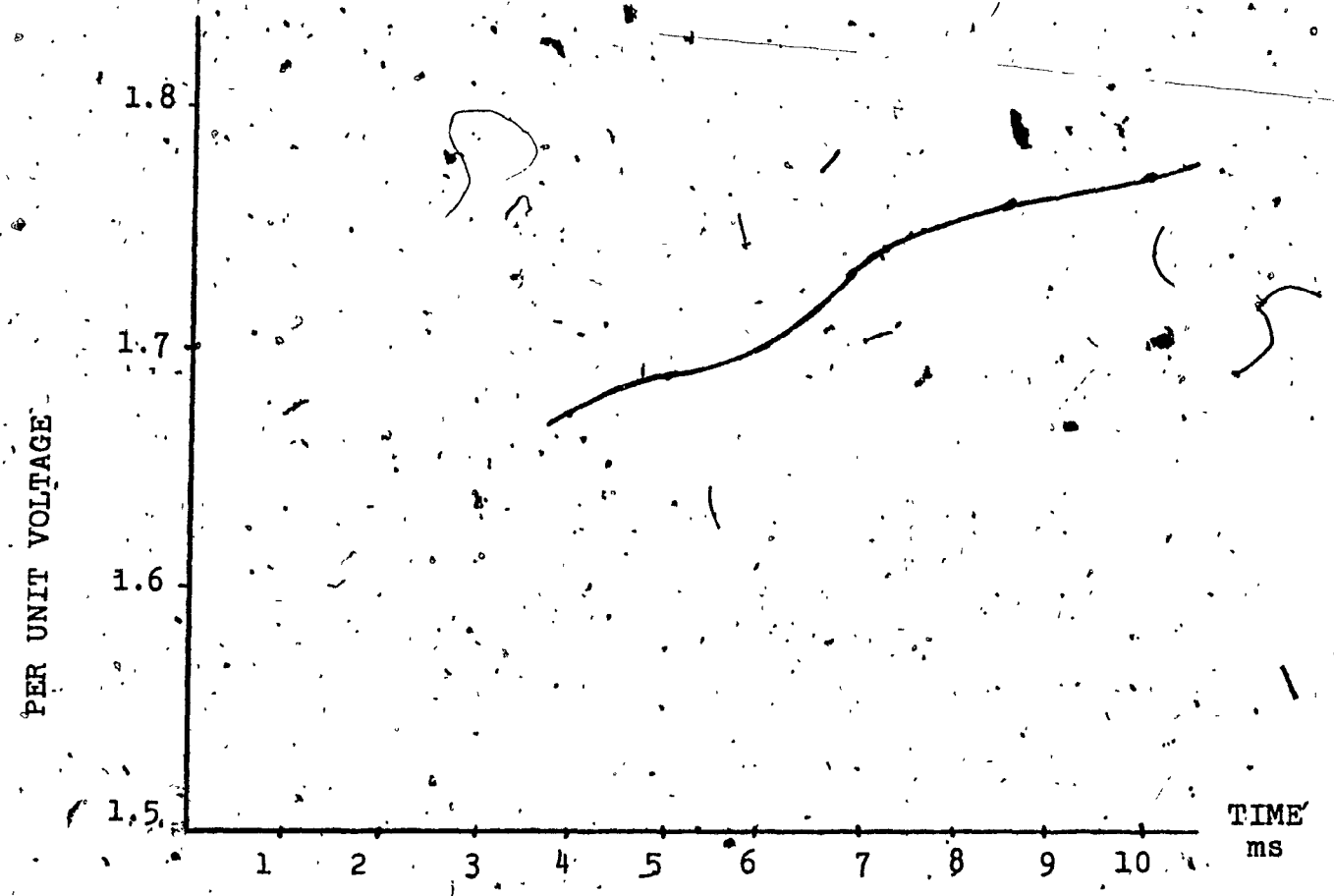

Fig. 2.1 Pole closing span overvoltage
(with 400 ohm Pre-insertion resistor)

3. PROBLEM OF AUTOMATIC RECLOSURE

3.1 Auto-Reclosing After Opening of a Line Without Fault

Automatic reclosure of the line without fault is mainly a switching error or failure of protection system. If this case is considered and if it is presumed that the line is discharged very slowly due to dry weather, absence of shunt reactors, potential transformers, etc., high residual charges are maintained on the three phases as high as 1 to 1.73 per unit if the breaker poles do not open simultaneously and the system is ungrounded.

In practice, the EHV circuit breakers are in most cases equipped with opening resistors. The effect of the circuit breaker opening resistors in reducing the trapped-charge voltage on the line depends upon its resistance, the length of line and the time the resistor is in circuit. The resistance and the time it is in circuit are functions of the circuit breaker design. Opening resistors used are of the order of 400 to 1,000 ohms and the contacts of the resistor break may separate at time of the order of 30 to 60 ms after main break. The time constant of the discharge may be calculated from the resistance and the shunt capacitance of the line. The following example is to show the percentage reduction of the original trapped-charge voltage through a surge resistor.

Let shunt capacitance = 100 micro-farads

Resistance = 1,000 ohm

Time constant of discharge = $100 \times 10^{-6} \times 1000 = 100$ ms

If the resistor is in circuit for 40 ms, the trapped charge will reduce to 67% of its initial value. Based on this assumption, the insulation level of the automatic reclosure to a line without fault will reduce considerably by the inserted resistor in the breaker.

3.2 Single Phase Fault; Single Phase Disconnection, Single Phase Reclosure

The two sound phases which stay closed remain at the voltage of the feeding system. The overvoltages which can be arisen on these phases consist of power frequency overvoltages which are the function of the zero sequence impedance of the system as shown previously of the order of 1 to 1.73 per unit. The fault resistance in the faulty phase is generally sufficiently low for the trapped charge of this phase to be completely discharged immediately after breaker opened. The automatic single phase reclosing conditions are zero charge on the phase of which the fault occurs and power frequency overvoltage of the order of 1 to 1.73 per unit on the other two sound phases as shown previously.

3.3. Single Phase Fault, Three Phases Disconnect, Three Phases Reclosure

The faulty phase is either partially or completely discharged through the fault resistance as described before. The two sound phases on the other hand are opened at the instant when their voltages are at the maxima and they remain charged at a certain level. This level depends on whether or not opening resistors are used and on the zero sequence impedance of the system. Thus, in the absence of opening resistor and for poorly grounded system, the level of the charges left on the two sound phases can exceed 1.73 per unit as stated before. The initial three phase automatic reclosure conditions are zero charged or partially charged on the fault phase and partially charged or completely charged for the two sound phases if switching surge resistors are not used. Transient overvoltage can be as high as four per unit and will be shown later. High speed single phase automatic reclosing and not three phase automatic reclosing after clearing the fault are the most commonly used by utilities. It can restore the power supply very quickly without re-synchronizing the system.

4. EFFECT OF CORONA ON SWITCHING SURGE OVERVOLTAGE

4.1 Mechanics of Corona

Corona acts as a damping effect on switching surge overvoltage. Very little is known about the mechanism of corona, although attempts have been made to obtain analytical expressions for the effect of corona on switching surge overvoltage and distortion. As the travelling wave moves along the transmission line, it suffers three different changes: the crest of the wave is attenuated and the shape of the voltage and current ceases to be similar. The last two changes that occur together are called distortion. It is theoretically possible to have attenuation without distortion as in the distortionless transmission line where GL = RC [12]

where G = conductance per unit length
L = inductance per unit length
R = resistance per unit length
C = capacitance

Attenuation and distortion is caused by energy losses and by variation of inductance and capacitance along the line. The mechanism of corona loss explained by Skilling and Dykes [5] are as follows:

1. There is a critical electric gradient for air which cannot be exceeded.[24]

2. If the surge overvoltage electric gradient exceeds the critical electric gradient, then the air will be ionized and liberate charges to take up such a position in space that the gradient does not exceed this value.

3. The supply of space charge to the region around the conductor increases as the voltage increases. After the crest of voltage wave has reached the critical level and begins to decrease, the charges return to the wave and build up the voltage in the tail of the wave. Consequently, the wave will shear back as shown in fig. 4.1 and reduce overvoltage in the transmission line.

4. Energy loss and distortion is caused by the exchange of charges between the conductor and corona reservoir.

4.2 Mathematical Model of Corona

Corona distortion has been modelled by Boehne[24] and the explanations are as follows:

1. A travelling wave is divided into a number of laminations corresponding to different voltage levels, and each voltage level is assumed to extend the conducting corona envelope by a proportional amount.

2. Capacitance to ground of transmission line changes proportionately to voltage level but the inductance is unchanged. Hence, in each voltage level there will be a corresponding velocity of propogation. The travelling wave will slip back, clip the crest, flatten the front end and fill in the tail end of the wave.

$$V_i = \frac{1}{\sqrt{LC_i}} \quad \ldots\ldots\ldots\ldots\ldots (4.1)$$

V_i = Velocity at voltage level i

C_i = Capacitance at voltage level i

L = Inductance (constant)

The following mathematical derivation achieves the the same result:

$$W = \frac{1}{2} Ce^2dx + \frac{1}{2} Li^2dx \quad \ldots\ldots (4.2)$$

Energy stored in section dx of the wave at voltage e and current i

$$i = \frac{e}{Z} = \frac{e}{\sqrt{\frac{L}{C}}} = e\sqrt{\frac{C}{L}} \quad \ldots\ldots (4.3)$$

Z = surge impedance

C = capacitance per unit length

L = inductance per unit length

$$W = \frac{1}{2} Ce^2dx + \frac{1}{2} L \left(e\sqrt{\frac{C}{L}}\right)^2 dx$$

$$= \frac{1}{2} Ce^2dx + \frac{1}{2} Ce^2dx$$

$$= Ce^2dx$$

$$\frac{dw}{dt} = 2\,Cedx\,\frac{de}{dt}$$

$$e = f(x,t)$$

$$\frac{de}{dt} = \frac{de}{dx}\frac{dx}{dt} + \frac{de}{dt}$$

$\frac{dx}{dt} = v$ = velocity of propogation

$$\frac{dw}{dt} = 2Cedx\left(V\frac{de}{dx} + \frac{de}{dt}\right)$$

Peek's formula for corona loss [24]

$$W = \frac{172}{10^{13}}\sqrt{\frac{R}{2h}}\left(e - e_o\right)^2 dx \quad \ldots\ldots\ldots\ldots\ldots\ldots (4.4)$$

R = radius ~~of~~ conductor

h = distance above ground

e = peak voltage

e_o = peak critical corona voltage

Let $K = \frac{-172}{10^{13}}\sqrt{\frac{R}{2h}}$

$$W = -k(e - e_o)^2 dx$$

$$\frac{dw}{dt} = -2k(e-e_o)\frac{de}{dt}\,dx$$

Assume other losses are small by comparing corona loss.

(this is true only if $e >> e_o$)

$$\therefore -2k(e - e_o)\frac{de}{dt}\,dx = 2Ce\left(V\frac{de}{dx} + \frac{de}{dt}\right)dx$$

$$-k(e - e_o)\frac{de}{dt} = Ce\left(V\frac{de}{dx} + \frac{de}{dt}\right)$$

$$-k(e - e_o)\frac{de}{dt} - Ce\frac{de}{dt} = Ce\,V\frac{de}{dt}$$

$$-\frac{de}{dt}\left[K(e - e_o) + Ce\right] = CeV\frac{de}{dx}$$

$$\frac{V}{1 + \frac{k(e - e_o)}{C e}} \frac{de}{dx} + \frac{de}{dt} = 0$$

Let $V^1 = \dfrac{V}{1 + \frac{k(e - e_o)}{C e}}$

$$V^1 \frac{de}{dx} + \frac{de}{dt} = 0 \quad \text{.....} \quad (4.5)$$

$$e = f(t - \frac{x}{V^1}) \quad \text{.....} \quad (4.6)$$

The voltage e on the crest of the wave travels at the velocity V^1 which is slower than the velocity V of the wave toe.

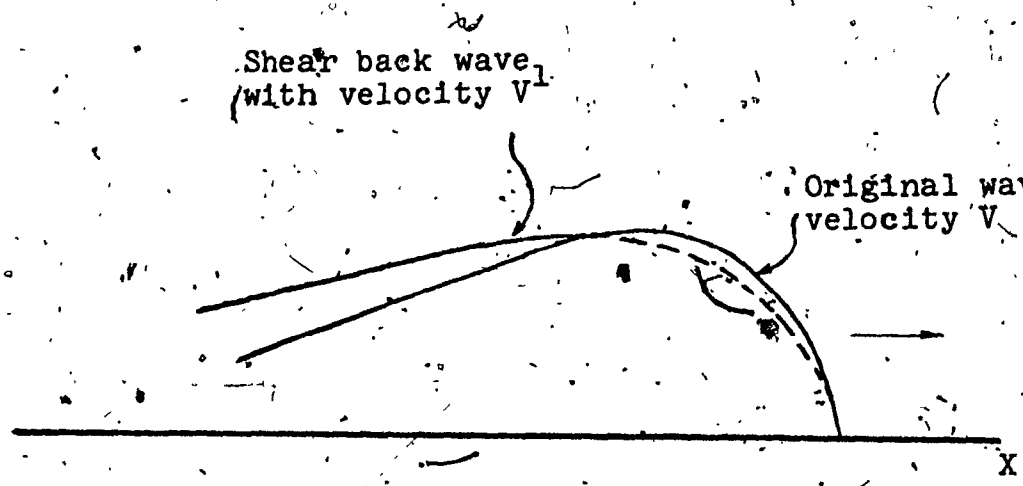

Fig. 4.1 Corona distorted wave

The magnitude of switching surge overvoltage has been reduced by the corona effect as shown in fig. 4.1. EHV designers have not yet been able to include corona effect on switching surge overvoltage studies. This reduced amount of switching surge overvoltage caused by corona effect has been added to the system as an extra safety margin.

5. FERRORESONANCE

5.1 General Review of Ferroresonance

Ferroresonance is oscilliation due to transformer saturation caused by system overvoltage. It frequently occurs in switching of high voltage transmission line or load rejection and occasionally appears in low voltage system as well. Terminal equipment damaged by ferroresonance have been reported by utilities. It is difficult to predict or calculate under what conditions ferroresonance may occur in the system. Many EHV transmission line designers now are using transient network analyzer (TNA) to test various switching modes, system configurations, system voltage and equipment parameters to locate the prime cause of ferroresonance and to ensure that ferroresonance will not occur under normal switching.

5.2 Theoretical Approach to Ferroresonance

Non-linear inductance of the transformer due to iron core saturation is the main cause of ferroresonance. Figure 5.1 is the approximate equivalent circuit of an open circuit transformer with magnetization curve as shown on fig. 5.2.

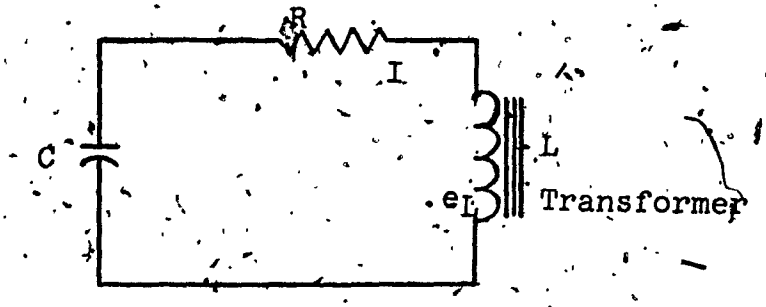

Fig. 5.1 Equivalent circuit

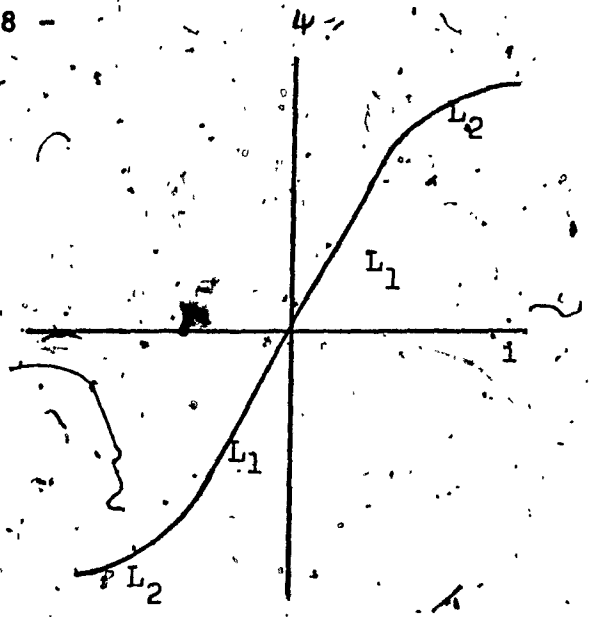

Fig. 5.2 Transformer magnetization curve

i = current

e_L = voltage across inductor

R = resistor

L = inductance

ψ = magnetic flux

C = capacitance

From Fig. 5.2, we have

$$\frac{d\psi}{dt} = e_L \quad \ldots\ldots\ldots\ldots\ldots (5.1)$$

$$\psi = \int_{t_1}^{t_2} e_L dt \quad \ldots\ldots\ldots\ldots (5.2)$$

The transformer iron core will be saturated if the voltage is applied long enough as indicated in equation 2. That is, the 60 H_z transformer cannot be used in 50 H_z system because of saturation of the transformer iron core. If there is overvoltage in the system, due to load rejection or switching, the transformer iron core is also saturated. The inductance drops to very low value when the flux linkage has reached the saturation region. Large current flows through the inductor, transforming all energy stored in the capacitance. $\frac{d\psi}{dt}$ at saturation region is approaching zero. That is, the voltage e_L across the inductor drops to zero. The magnetic field of the transformer collapses, transforming all energy stored in the transformer back to the capacitor in opposite polarity. Negative potential in the capacitor begins to drive the flux linkage curve to downward direction until it reaches the saturated region. The cycle will repeat itself until all energy disappears in I^2R and hysteresis losses.

Unfortunately, losses in the circuit are usually supplied from external sources. Hence, sustained ferroresonance oscillation can occur. These external sources usually are due to capacitive coupling with the parallel transmission.

Standard methods of prevention or minimization include:

1. Increasing the iron core of transformer. (Uneconomical)
2. Varying the system parameters.
3. High speed de-excitation device to reduce system overvoltage caused by switching or load rejection.

6. DYNAMIC OVERVOLTAGE

6.1 General

Dynamic overvoltage is the maximum power frequency overvoltage, usually caused by load rejection, ground fault, Ferranti effect and ferroresonance. It is different from switching surge overvoltage or maximum system voltage. Maximum system voltage is usually 10% higher than rated or nominal voltage allowing for 5% transformer tapping and 5% for generator overvoltage. The duration of dynamic overvoltage, usually a few seconds, is much greater than switching surge overvoltage, usually a few cycles, and its frequency is very close to power frequency. Equipment insulation must be able to withstand maximum power frequency overvoltage, because the lightning arresters' reseal voltage must be set above the level of the overvoltage in order to avoid damaging the arresters.

6.2 Ferroresonance Overvoltage

Ferroresonance oscillation caused by transformer saturation has been explained in detail in Chapter 5 Part I. Oscillation voltage superimposes the fundamental voltage to cause the system dynamic overvoltage.

6.3 Ferranti Rise

The voltage at the receiving end caused by the system reactance rises somewhat higher than the nominal voltage is called Ferranti Rise and is described by the following equation 6.1. This overvoltage can be improved by adding a shunt reactor or series capacitor to the system.

$$\frac{V_2}{V_1} = \frac{1}{\cos BL} \quad \text{.....(6.1)}$$

V_2 = voltage at receiving end

V_1 = voltage at sending end

L = length of transmission line in mile

B = phase constant of the line ($12^{\circ}/100$ mile for 60 H_z system)

6.4 Load Rejection Overvoltage

Load rejection causes the system dynamic overvoltage and the magnitude of the voltage at the receiving end is governed by the following formula. If the load rejected is a substantial portion of the system load, the generator speed will increase and the system becomes synchronously unstable.

$$\frac{V_2}{V_1} = \frac{1}{1 - \frac{X_s}{X_c}} \quad \text{.....(6.2)}$$

V_2 = voltage at receiving end

V_1 = voltage at sending end

X_s = system reactance

X_C = capacitance of the line

6.5 Ground Fault Overvoltage

For a symmetrical three phase to ground fault, there is no voltage rise in the system. For single line-to-ground fault, which very commonly occurs, there is a voltage rise in the other two healthy phases and the magnitude is dependent upon the effectiveness of the system grounding. If the system is ungrounded, line-to-ground voltage of two sound phases becomes line-to-line voltage or 1.73 times higher than nominal voltage.

If the system is effectively grounded, line-to-ground voltage of two healthy phases will rise above their nominal voltage but below line-to-line voltage. Hence, for high voltage system, an effective grounding system is commonly required. [24]

$$\frac{V_b}{V_{LL}} = \frac{\sqrt{3}\, a^2 R - j(Z_1 - Z_0)}{Z_0 + 2Z_1 + 3R} \qquad \ldots\ldots(6.3)$$

$$\frac{V_c}{V_{LL}} = \frac{\sqrt{3}\, a\, R - j(Z_1 - a^2 Z_0)}{Z_0 + 2Z_1 + 3R} \quad \ldots\ldots\ldots (6.4)$$

where V_a = faulted phase voltage

V_b = healthy phase voltage

V_c = healthy phase voltage

a = $-\frac{1}{2} + j\sqrt{\frac{3}{2}}$ phase operator

Z_1 = positive sequence impedance

Z_0 = zero sequence impedance

R = fault resistance

Energization of a Completely Discharged Transmission Line

Among the different types of switching surge transients, the highest switching overvoltage is to energize a high voltage transmission line with open circuit at the remote end. For voltage below 330 kV attention has been focused on the restriking voltage transient occurring when a circuit breaker opens. In order to reduce the capital costs by reducing the system insulation level, transient overvoltage caused by energization of transmission line becomes very important. The voltage at the open circuit receiving end will rise 2.0 per unit due to reflection coefficient of +1. This can be demonstrated by a simple example. For simplicity, assumptions are made as follows:-

1. System linear, therefore, super-position applies.
2. No loss or distortion.
3. Single phase circuit with open circuit at remote end.
4. Completely discharged or no trapped-charge voltage.
5. Infinite sinusoidal source supply $60H_z$ 1.0 per unit.

The power-frequency voltage applied at the sending end is a sinusoid starting with the instantaneous value of the voltage at the instant of closing. If no loss or distortion, the same sinusoid will arrive at the receiving end of transmission line at time $T = L/V$ where L is length of line and v is travelling velocity. If superposition applies, the incident voltage obeys the law of reflection and doubles at the open end of the transmission line because the reflected voltage superimposes to the arrival of incident voltage.

Reflection coefficient $R = \frac{Z_2 - Z_1}{Z_1 + Z_2}$ (See Appendix "A" for proof)

Z_1 = surge impedance of line

Z_2 = surge impedance at discontinuity at the remote end.

$Z_2 = \infty$ For open circuit at the remote end of transmission line.

$\therefore R = +1$

Starting at time T, a reflected wave identical with the incident wave, travels towards the sending end where it arrives at 2T. It is cancelled by a wave of equal magnitude and opposite polarity, because the coefficient of reflection equals to -1 and $Z_2 = 0$ for infinite source of supply. The remaining voltage at the

source terminal is the source voltage. The voltage at the receiving end can be expressed as a series as follows:

$$E_R = 2 \sum_{k=0}^{n} (-1)^k e^{-jSk}$$

where E_R = voltage at receiving end

k = number of arrival times at the receiving end.

$Sk = \frac{2L}{\lambda} 360$ angle of supply

L = length of line

λ = wave length of 60HZ supply

e^{-jSk} = phasor angle of supply

At $k = 0$, then the voltage at the receiving end is 2.0 per unit which is unacceptably high for EHV transmission lines. This can be reduced by insertion of resistors as shown later.

8. Energization of a Transmission Line with Trapped Charge

The problem involved in the energization of high voltage transmission lines, that of voltage doubling at the receiving end of the line has been illustrated previously with assumption that the line being energized was initially discharged completely. This condition does not always hold in practice as an example of high speed automatic reclosing. After de-energizing a transmission line, usually leave a charge or residual voltage remains with the magnitude of up to 1.73 per unit nominal voltage. The restoration of supply to a line in this charged state can result in the appearance of transient overvoltage at the open circuited end of the line, theoretically, of the order of 4.0 per unit. Although in practice, resistance, corona loss and shunt reactors act to limit the magnitude of the transient overvoltages produced by the trapped charged voltage or residual voltage. The maximum transient overvoltage on the line may be expected to occur when the line is energized at a peak of the supply voltage wave with opposite polarity to a trapped charged voltage on the line.

Other factors which may affect the transient voltage are the nature of the ground impedance of the source, non-simultaneous closure of three phases of

the circuit breaker energizing the line, the amount of reactive compensation connected to the line, and losses. The trapped voltage may remain at its initial value for many seconds after the current interruption or longer for high-speed automatic reclosure scheme. The line will discharge eventually through paths across insulators, etc., but the rate at which discharge occurs is governed by the climatic conditions. The time constant of the discharge is usually in the range of 20 - 60 ms for a damped system, but under extreme dry conditions, it may take 5 - 10 minutes to completely discharge. Therefore, it is possible even in the case of manual reclosure to close a line with large trapped charge voltage.

Very often other factors are present which act to accelerate the discharge of the line. The circuit breaker may be fitted with opening resistors, alternatively shunt reactors or voltage transformers may be directly connected to the line, all of which discharges the line to some extent before the reclosure operation takes place. When a line is compensated by shunt reactor, it will discharge through the reactor in an oscillatory manner. The frequency of the oscillation is determined by the reactor inductance and line capacitance and the trapped charge voltage decays at the rate determined

by the losses of the line and the reactor. The transient oscillation frequency is different from the source frequency and, hence, there is always a possibility of reclosing the supply on to a line in opposite polarity of the trapped voltage.

For better understanding of the problem the following will illustrate a simple example with trapped voltage in the transmission line. For simplicity, the transmission is considered lossless, distorionless, and single phase system.

For single π equivalent circuit such as figure 8.1.

$$V_S = L \frac{di}{dt} + V_R$$

$$i = C \frac{dV_R}{dt}$$

Substituting

$$V_S = LC \frac{d^2V_R}{dt^2} + V_R \quad \text{.....(8.1)}$$

Taking Laplace transform

$$V(s) = LC\, S^2V(s) - S\, V_R(0) + V_R(s)$$

Let $V_S(t)$ = unit step function

Then $V_S(s) = \frac{1}{S}$

Let the transmission initially charged with

$V_R(0) = -1.73$ per unit (Refer to Chapter 3)

$\frac{dV_R(0)}{dt} = 0$

$V(s) - LC\,S^2 V_R(s) + 1.73S + V_R(s)$

$$V_R(s) = \frac{1 - 1.73\,S^2 LC}{LC\,S(S^2 + \frac{1}{LC})}$$

Let $\frac{1}{LC} = W^2$

$$V_R(s) = \frac{W^2}{S(S^2 + W^2)} - \frac{1.73\,S}{S^2 + W^2}$$

$V_R(t) = 1 - \cos wt - 1.73 \cos wt$

$V_R(t) = 1 - 2.73 \cos wt$ .....(8.2)

Let $wt = \pi$

V_R max = 3.73 per unit

With 4 per unit voltage at the open circuit receiving end, the insulation will flash over and will eventually be destroyed. This overvoltage can be suppressed by insertion of resistor to the acceptable level as shown later in Chapter 9 , Part II.

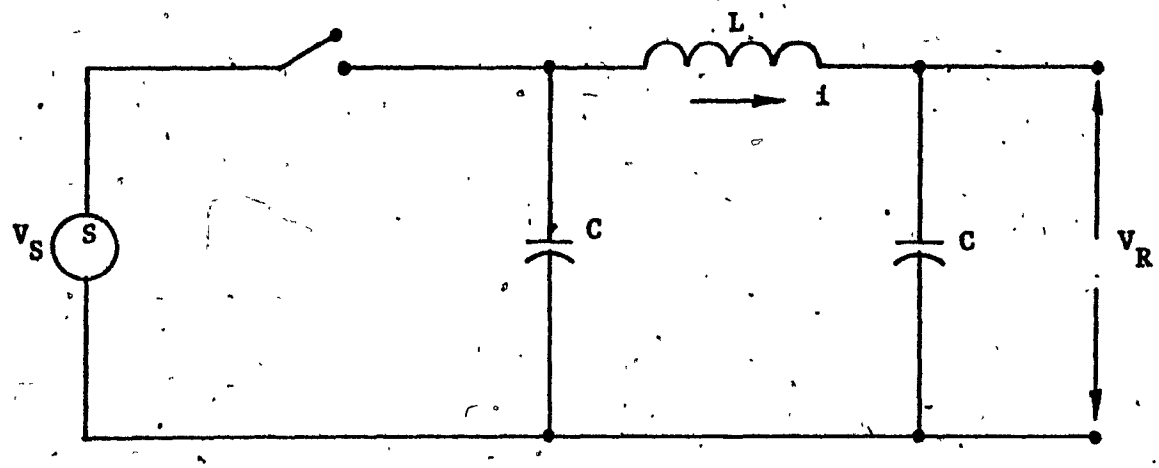

Fig. 8.1 Single π Equivalent Circuits

V_S = Source voltage

V_R = Voltage at open end

C = Capacitance of half of transmission line

L = Inductance of transmission line

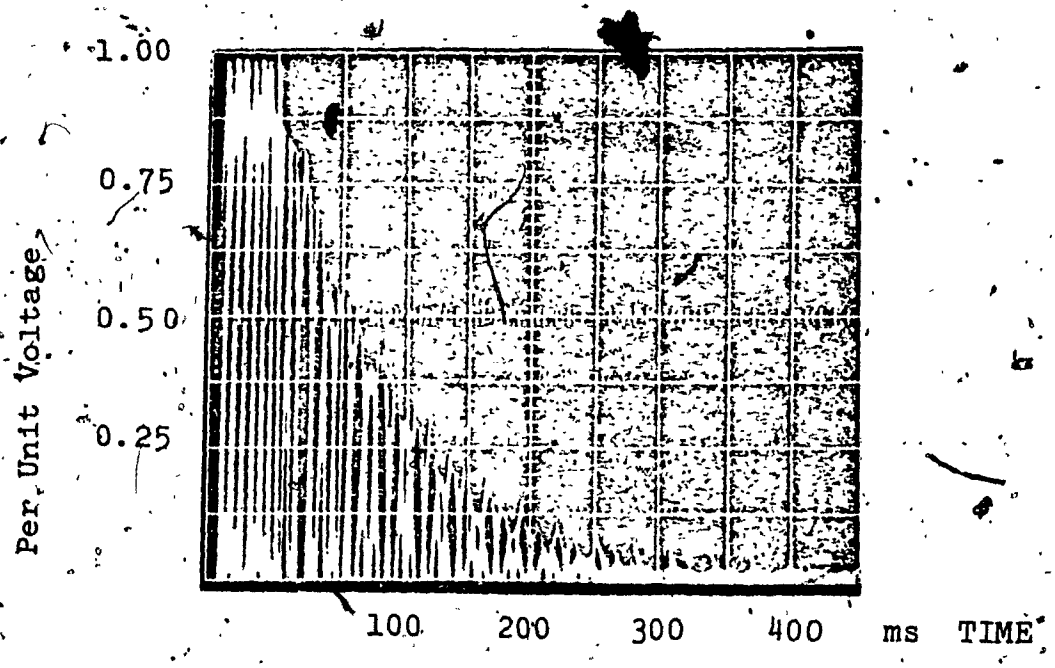

Fig. 8.2 Trapped Charge Decay in Transmission Line

PART II

Methods of Design for Switching Surge Overvoltage Suppression, Prediction and Protection

9. Method of Reduction of Energization Transient Surge Overvoltage

9.1 General

Prior to designing an EHV transmission line, the maximum switching surge overvoltage has to be defined for all equipment insulation rating. This overvoltage level is often specified in the range of 2.0 to 2.5 per unit depending on the system voltage. For 750KV line, the acceptable overvoltage level is approximately 2.0 per unit and below. If the transient overvoltage exceeds this level, additional devices must be used to suppress the surge overvoltage to an acceptable level.

In general, the suppression and control of the switching surge overvoltage in the EHV system can be accomplished by various methods, such as control of the switching angles among the poles of the circuit breakers as described in Chapter 2, Part I; shunt reactors; circuit parameters; configuration, etc. The most economical and commonly used method by utilities is to switch the resistors across the main breaker contacts, as shown in fig. 9.1 and 9.2.

For system voltage of 500KV and below, it normally employs only one stage of resistor as shown in fig. 9.1 and multiple stages of resistor for extra high voltage, 500kV and above, as shown in fig. 9.2

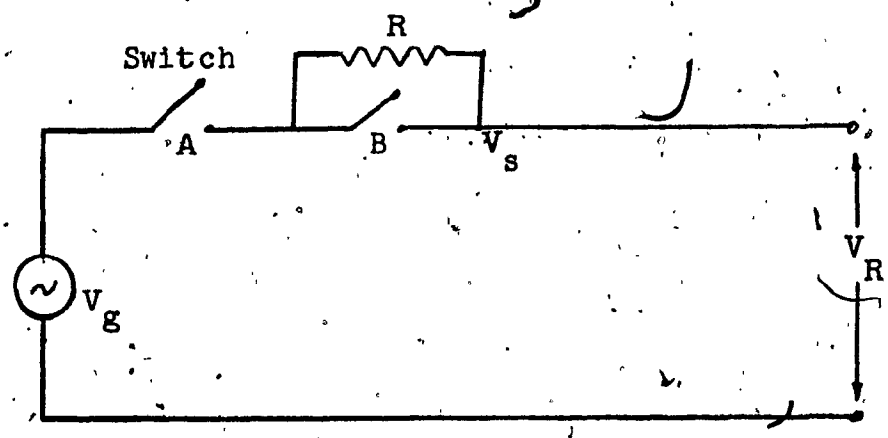

Fig. 9.1 Single Stage Resistor

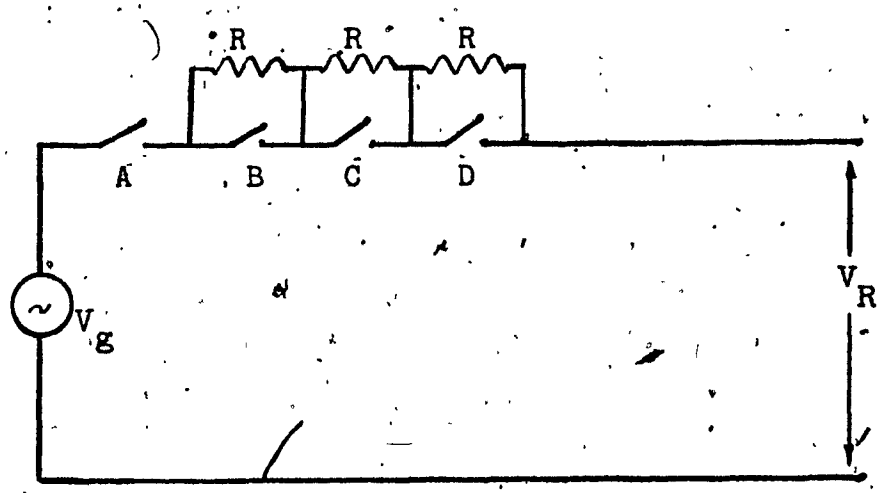

Fig. 9.2 Multiple-Stage Resistor

Initially, the switch B is open and the line is energized through the resistor R by closure of the switch A. After a short time, a few cycles of power frequency, the switch B closes, short-circuiting the resistor as shown in fig. 9.1. The line thus energized in two stages and two switching surges are produced; one due to initial energization through the resistor and the second due to the short-circuiting of the resistor. The operation sequence of multiple-stage resistor is similar.

9.2 Insertion of Resistor to Reduce Switching Surge Overvoltage

Determination of the optimal resistor size to reduce switching surge overvoltage for the single phase case can be illustrated as follows. The transient effect of energization through a resistor and shorting the resistor are determined by assuming that the transient from energization through a resistor has been damped out before shorting the resistor. The overvoltage at the open end of an ideal complete discharged line energized through a resistor from an infinite bus can be calculated using the standard travelling wave method as follows:

$$V_R = \frac{2Z}{Z + R} V_g \left[U(t - T) - MU(t - 3T) + M^2U(t - 5T) \cdots\cdots\right] \quad \cdots\cdots\cdots (9.1)$$

(See Appendix "B" for proof)

$$M = \frac{Z - R}{Z + R}$$

R = Resistor across switch

Z = Surge impedance $Z = \sqrt{L/C}$

V_g = Source voltage

V_R = Voltage at open circuit receiving end

$T = \frac{e}{V}$ time in second

V = Velocity $V = \frac{1}{\sqrt{LC}}$

e = length of transmission line

L = inductance per unit length

C = capacitance per unit length

U (t - T), U(t - 3T), U(t - 5T) ..... delayed step function

The solution for transmission line with trapped charged voltage V_T where V_T can vary from 0 to 1.73 per unit as described in Chapter 9, Part I.

$$V_R = V_T + \frac{2Z}{Z + R}(V_g - V_T)\left[U(t - T) - MU(t - 3T) + M^2U(t - 5T) \cdots\cdots\right] \quad \cdots\cdots (9.2)$$

Prior to short circuiting the resistor, the maximum voltage at the open circuit receiving end for the duration between one travel time and the next travel time is as follows.

$$V_R = V_T + \frac{2Z}{Z + R}(V_g - V_T)\,U(t - T) \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (9.3)$$

where $U(t - 3T)$, $U(t - 5T)$ ..... = 0

The voltage across the resistor after the energization transient has damped out is

$$V_C = \frac{R}{R + X_e}\,V_g$$

where X_e = the impedance of the tranmission line

$$= \frac{(jwL - \frac{2}{jwC})\,\frac{2}{jwC}}{jwL - \frac{4}{jwC}}$$ for single π equivalent circuit.

Prior to short circuiting the resistor across the switch, the voltage at the resistor terminal is

$$V_S = \frac{X_e}{X_e + R}\,V_g \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (9.4)$$

The voltage at the receiving end

$$V = V_S\,\frac{1}{\cos BL}$$

$\frac{1}{\cos BL}$ = Ferranti Rise (see Chapter 6)

If the resistor is short circuited, a wave, with magnitude of V_C travelling down, will double when reaching the open receiving end. The total transient overvoltage for shorting the resistor will be as follows.

$$V_R = V_S \frac{1}{\cos BL} + 2 V_C$$

$$V_R = V_S \frac{1}{\cos BL} + \frac{2R}{R + X_e} V_g$$

$$V_R = \frac{X_e}{X_e + R} \frac{V_g}{\cos BL} + 2 \frac{R}{R + X_e} V_g$$

$$V_R = \frac{V_g}{X_e + R} \left(\frac{X_e}{\cos BL} + 2R \right) \quad \cdots\cdots\cdots\cdots\cdots (9.5)$$

The function of overvoltage at the receiving end versus the magnitude of resistor is plotted in fig. 9.3 for energization through a resistor with trapped charge -1 per unit and short-circuiting the resistor separately.

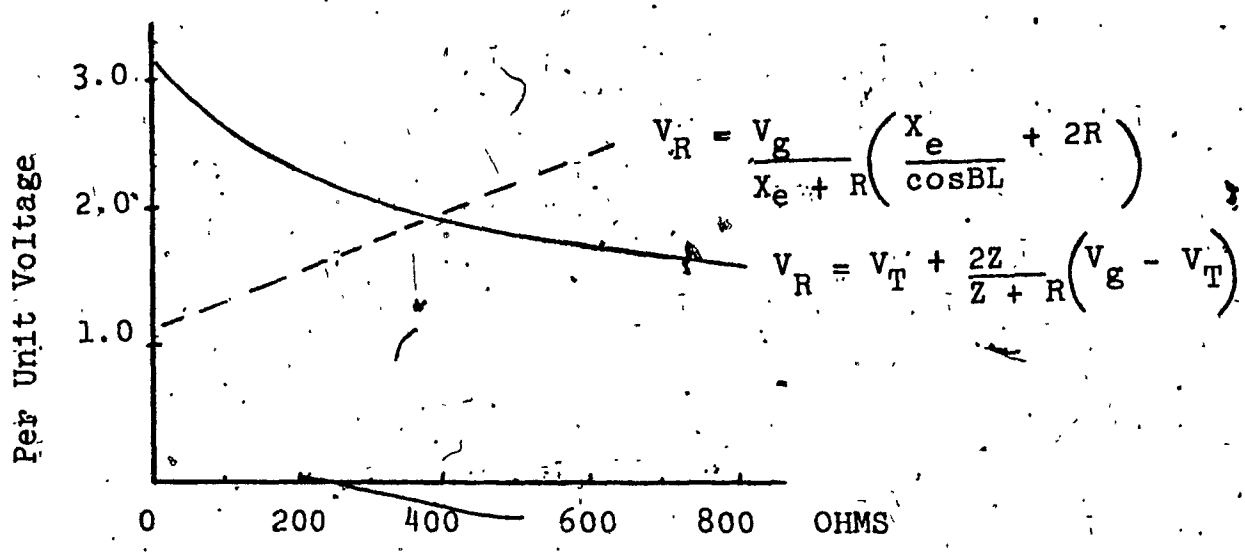

Fig. 9.3 Overvoltage vs Resistor

Dotted line Short Circuit Resistor

Solid line Energized through Resistor

The solid line indicates the transient overvoltage per unit when energized through a resistor versus insertion resistor and the dotted line indicates the transient overvoltage when short-circuiting the resistor versus the resistor. In order to optimize the resistor for two stages of switching, two curves must meet in one point which is approximately at 400 ohms. The maximum transient overvoltage will be approximately 2.0 per unit for energizing a transmission line through a resistor and short-circuiting the resistor which is economical for EHV design.

10. Overvoltage Protection and Insulation Co-Ordination

10.1 Overvoltage Protection

There are two commonly used overvoltage protection devices, rod gap and surge diverter. Both rod gap and surge diverter are connected in parallel with equipment to be protected by lowering or discharging the dangerously high surge voltage.

The discussion will focus on surge diverters only because they have reached a high degree of perfection and are commonly used for EHV protection.

Rod gaps are inferior but still have lots of application in industries for medium and low voltage system owing to their cheapness.

For proper protection, the surge diverter must perform as follows;

1. It must not spark over, under dynamic overvoltage as described in Chapter 6 Part I or surge diverter would be destroyed as its thermal capacity is small. Duration of dynamic overvoltage is relatively long.
2. Their voltage time curve must lie below the withstand insulation level of the protected equipment.
3. It must be able to discharge high energy surges without changing their characteristic or being damaged.

4. After discharging a surge, it should be resealed to maintain the system voltage. Otherwise, it will cause outage.

10.2 System Insulation Co-Ordination

The cost of power apparatus is approximately proportional to the basic impulse level (BIL) for a given rating and the insulation level is mainly dominated by switching surge overvoltage for high voltage system. In order to minimize the capital cost, switching surge overvoltage has to be reduced to an acceptable level as described in Chapter 10, Part II and protective devices have to be provided to guard against excessive switching surge overvoltage.

For simplicity, assume the system voltage is 500kV with acceptable switching surge overvoltage of 2 per unit. There is a small probability that the switching surge overvoltage exceeds 2 per unit which would be protected by the lightning arrester or surge diverter as shown in fig. 10.1 co-ordinating curve. The arrester operates over a certain voltage range, depending on air contamination, temperature, etc. The upper limit is given by the maximum switching surge protection characteristic voltage specified by manufacturer and its lower limit is normally 20% below the upper limit. A 440 kV arrester has impulse

sparkover voltage 1050 kV (specified by manufacturer).

The transformer BIL (basic impulse level) must be selected in order to have safety margin of 20% above the impulse sparkover voltage. This safety margin is mainly dependent upon the arrester location in respect to equipment to be protected.

Lightning arrestor impulse sparkover voltage 1050 kV (Given by manufacturer)

Transformer BIL = 1.2 x 1050 = 1260 kV

It is normally used by industries that the transformer basic switching surge withstands (BSL) is 83% of the transformer BIL level. The transformer BIL is tested with sharper wave front than transformer BSL.

Transformer BSL 1260 x 0.83 = 1046 kV

Maximum lightning arrester switching surge sparkover voltage (BSL) of a 440 kV is 940 kV (specified by manufacturer).

Safety margin $(1046 - 940)/940 = 12\%$

From the insulation co-ordination curves, there will be a slight possibility the lightning arrester may sparkover during three poles reclosing to a trapped charged transmission line.

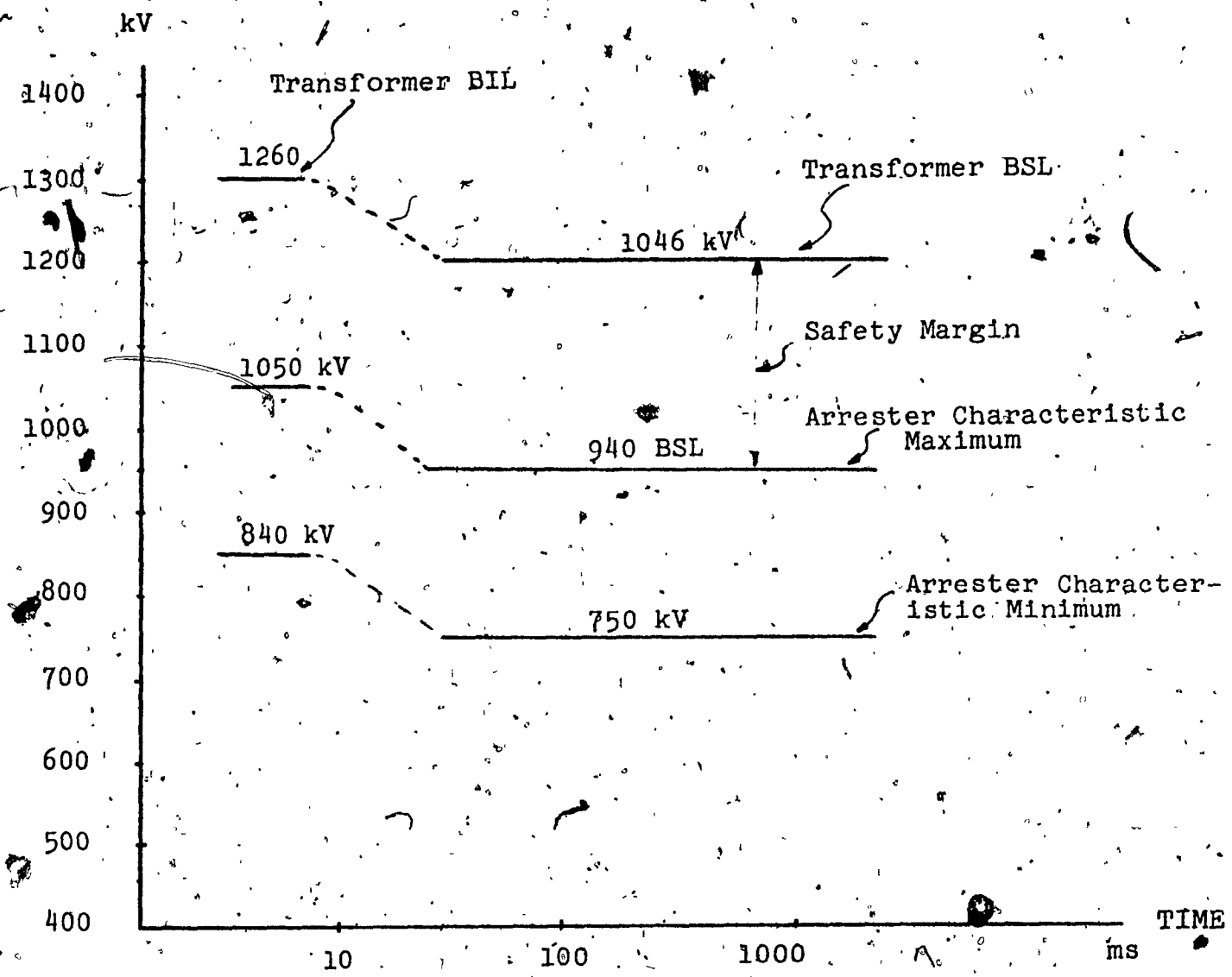

Fig. 10.1 Insulation Co-Ordination Curve

11. TRANSIENT NETWORK ANALYZER (TNA)

11.1 General

The Transient Network Analyzer (TNA) is a three phase analog system, with each element of the actual system represented by a model counterpart. It is commonly used by EHV designer to investigate the problems of switching overvoltage because of its versatility. The most difficult thing in using the Transient Network Analyzer is to model the system, such as transformers, generators, transmission lines, lightning arrester, etc. with non-linear or frequency dependent parameters such as resistors, capacitors and inductors.

11.2 Generator Modelling

In order to obtain an accurate result from TNA, the modelling of the generator should include the voltage regulator and governor characteristics so as to respond to similar disturbances in the system. However, the response of the governor and voltage regulator (not static exciter) are relatively slow so that for approximation, mechanical power input to the generator is constant. The generator can be represented

either by its sub-transient reactance x''_d or transient reactance x'_d depending on applications which can be obtained from manufacturers. The approximate model of the generator is shown in fig. 11.1.

11.3 Transformer Modelling

Precise modelling of the transformer is very difficult. It requires that the magnetic characteristics such as saturation curve and losses match with the corresponding real transformer as close as possible. Transformers can be simulated by means of their short-circuit reactance.

For approximation, the transformer is assumed to be an ideal transformer having a small short-circuit reactance and a large open-circuit reactance. With transformer ratio 1:1, one can simulate the transformer for transient network analyzer as shown in fig. 11.1.

11.4 Transmission Line Modelling

Transmission lines are simulated in Transient Network Analyzer by connecting in cascade of τ sections or π sections of the positive and zero sequence impedance of the line as shown in fig. 11.1. The positive sequence components L, C, and R can be calculated relatively easily.

The zero sequence components are more complicated for the high voltage transmission lines. The values of the zero sequence reactance and resistance can vary within wide limits, depending on the tower configuration, the nature of the earth wires and the conductivity of the ground. The distance of current penetration into the ground is frequency dependent and hence both inductance and resistance of the zero sequence are frequency dependent quantities.

These effects can be included in the model by careful design of the coils by selecting the core material and by matching the air gaps of the cores. By suitably connecting coils in series with additional parallel and series resistors, it is possible to simulate the frequency dependent resistance of the zero sequence of the transmission line.

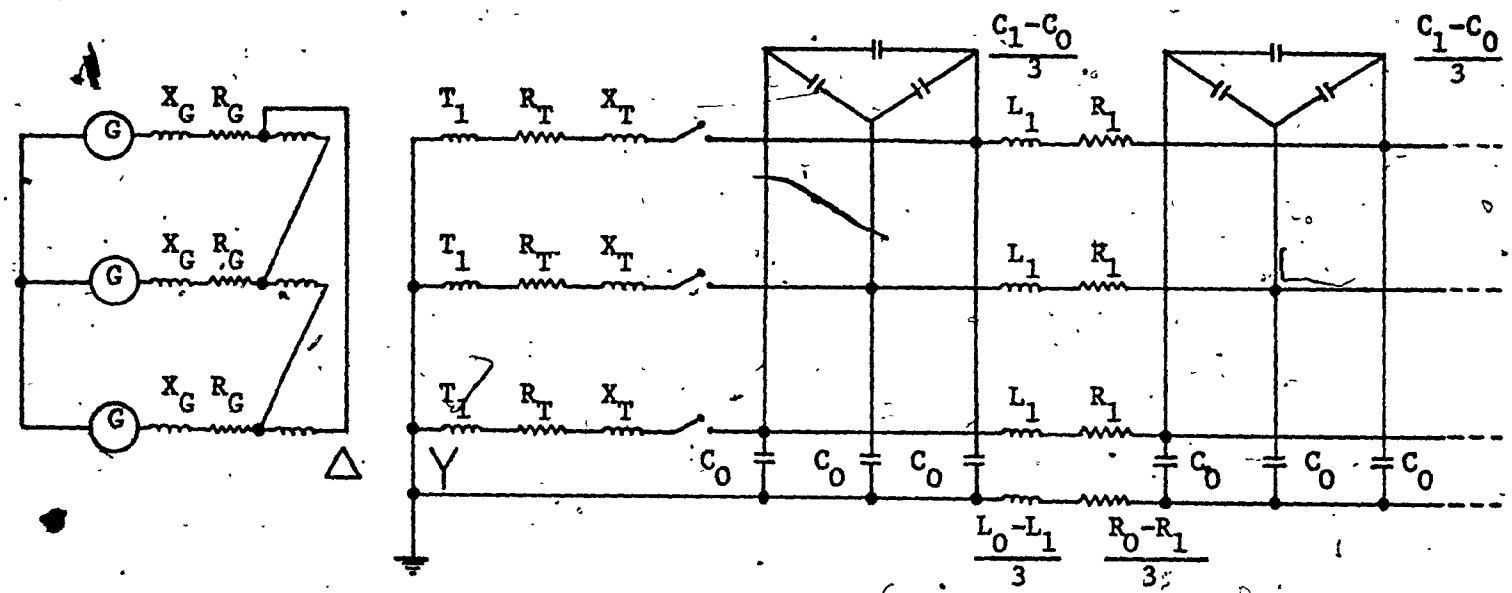

Fig. 11.1 Generator Transformer and Transmission Line Modelling

$L_1R_1C_1$	Inductance, resistance, and capacitance of positive-sequence system of Line
$L_0R_0C_0$	Inductance, resistance, and capacitance of zero-sequence system of the Line
G	Generator
X_GR_G	Reactance and resistance of generator
T_1	Model Transformer
X_TR_T	Reactance and resistance of transformer

12. Digital Computer Solution for Transient Switching Surge Overvoltage

The application of the digital computer to power system transient overvoltage studies has been developed to investigate the large systems which the transient network analyzer cannot handle. The advantage of the digital computer is its ability to process a vast amount of data in an extremely short time. The computer is also capable of storing, retrieving, and matrix operation of large volumes of data. Transient studies using the lattice diagram theory are well suited for digital computer. This program capable of accommodating any specified input wave shape, real or complex line termination and any system configuration.

The unit step input voltage proceeds through the discontinuity and generates a new wave equal to the reflection coefficient at the instant when it reaches the junction. The new wave emanates from the junction in both directions and the sum of the original wave and newly generated waves represent the total response at the discontinuity as shown in fig. 12.1.

The solution is simple in concept but it requires large computer memory to store all the data.

For better understanding, it is best to illustrate by a simple example with unit step input signal and single phase system as shown in fig. 12.2.

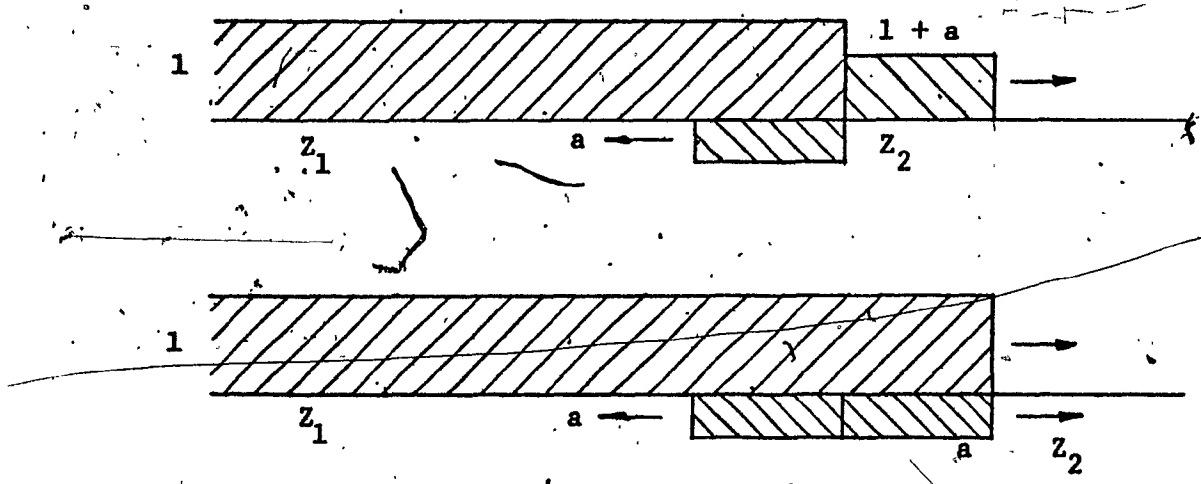

Fig. 12.1 Reflected and Refracted waves

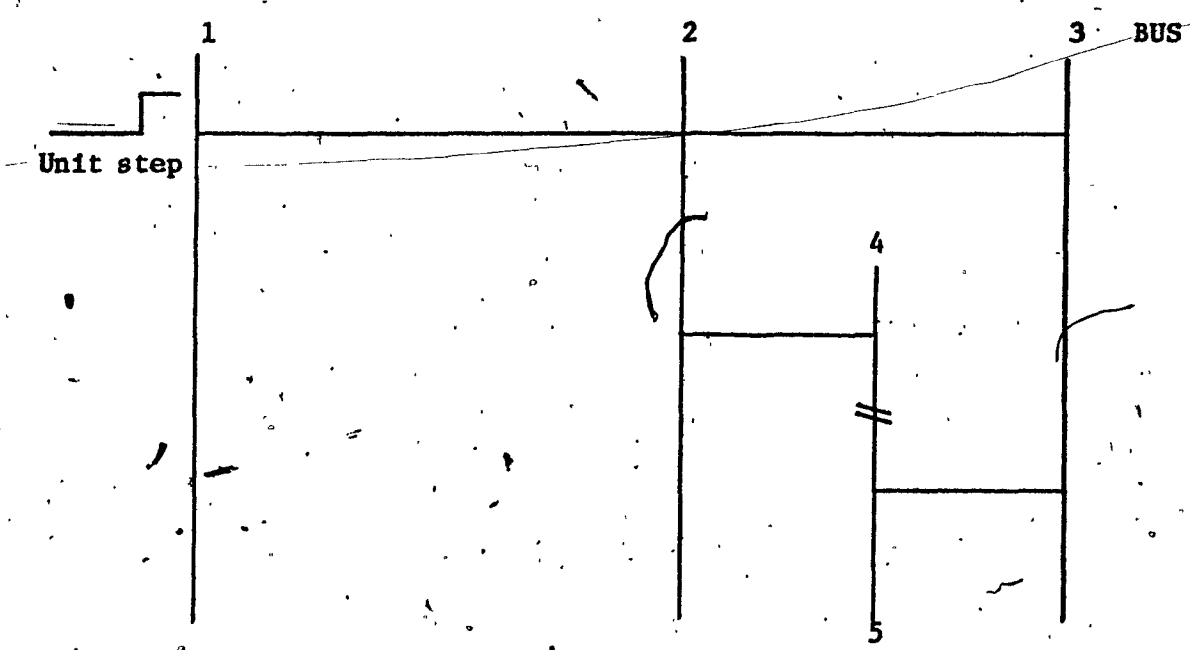

Fig. 12.2 One Line Diagram of Five Bus System

The unit step input wave generated in bus no. 1 will arrive at no. 2, 3, 4 and 5 bus at times equal to travelling times from bus no. 1 to each of these buses. Since many of these analyses must be made before the solution is reached, it is convenient to describe the travelling time array as shown in fig. 12.3 for the system under study.

From Bus \ To Bus	1	2	3	4	5
1	0	T_{12}	T_{13}	T_{14}	T_{15}
2	T_{21}	0	T_{23}	T_{24}	T_{25}
3	T_{31}	T_{32}	0	T_{34}	T_{35}
4	T_{41}	T_{42}	T_{43}	0	T_{44}
5	T_{51}	T_{52}	T_{53}	T_{54}	0

Fig. 12.3 Travel Time Array

The travel time array is symmetrical about the main diagonal since the travel time from no. 1 to no. 2 bus is the same as from no. 2 to no. 1 bus. The main diagonal is zero since the travel time for any bus to itself is zero. The travel time array will be used to determine the time of arrival of all response waves on an absolute time scale, at each bus in the system during computer execution.

A similar array for reflection coefficients can be defined to establish the magnitude of response waves as shown in fig. 12.4.

From Bus \ To Bus	1	2	3	4	5
1	0	A_{12}	A_{13}	A_{14}	A_{15}
2	A_{21}	0	A_{23}	A_{24}	A_{25}
3	A_{31}	A_{32}	0	A_{34}	A_{35}
4	A_{41}	A_{42}	A_{43}	0	A_{45}
5	A_{51}	A_{52}	A_{53}	A_{54}	0

Fig. 12.4 Reflection Coefficient Array

At any location, the magnitude of response waves to the original wave, or to any other response wave is determined by multiplying the incident wave by the appropriate entry in that row of the reflection coefficient array corresponding to the bus being considered. The reflection coefficient array is not symmetrical since interchanging subscripts implies arrival at a different bus. The main diagonal of the array must be assigned a value of zero since there is no reflection at its point of origin.

The results of all these vents are recorded in a voltage register for incoming waves and input signal table for reflected waves which specifies voltage at various buses at specific times. Once the wave enters in the particular location it remains its value or superimposes to other waves in that location until the program is finished. It is convenient to tabulate all arrival waves and reflected waves at all buses in the table forms as voltage register and input signal table respectively as shown in figs. 12.5 and 12.6.

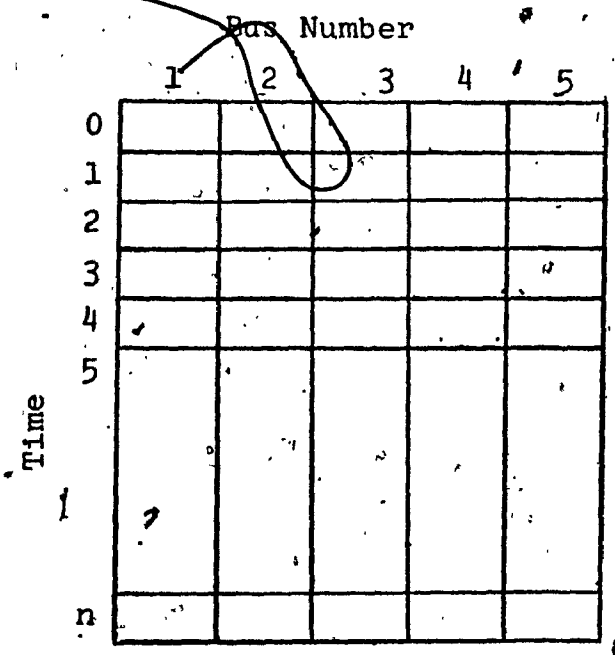

Fig. 12.5 Voltage Register

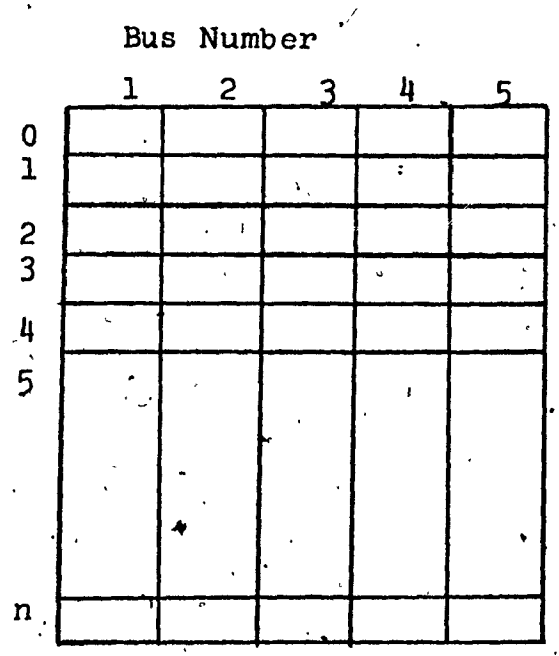

Fig. 12.6 Input Signal Table

The reflected waves are tabulated in input signal tables similar to voltage registers as shown in fig.12.6 . Systematic selection of input signals from the signal table will result in a semichronological build-up of entries in the voltage register for all buses. The input signal in any given row in the signal table produces the new input signals for the following rows of the input signal table and the corresponding row in the voltage register.

If there is a loop in the system such as buses 4 and 5 as shown in fig. 12.2 is not splitted, then it will have infinite number of travelling times in the loop and the time array is meaningless. The splitting of the buses 4 and 5 to create a tree network to permit application of the similar procedure as described before.

When any wave arrives at a split bus, a wave of equal magnitude must be added to the input signal table for its companion bus at the arrival time. Similarly for the reflected wave at the split bus, it must be entered into the input signal table for the companion bus. The reflection coefficients must be calculated with the loop closed. The computer execution flow chart is shown in fig. 12.7

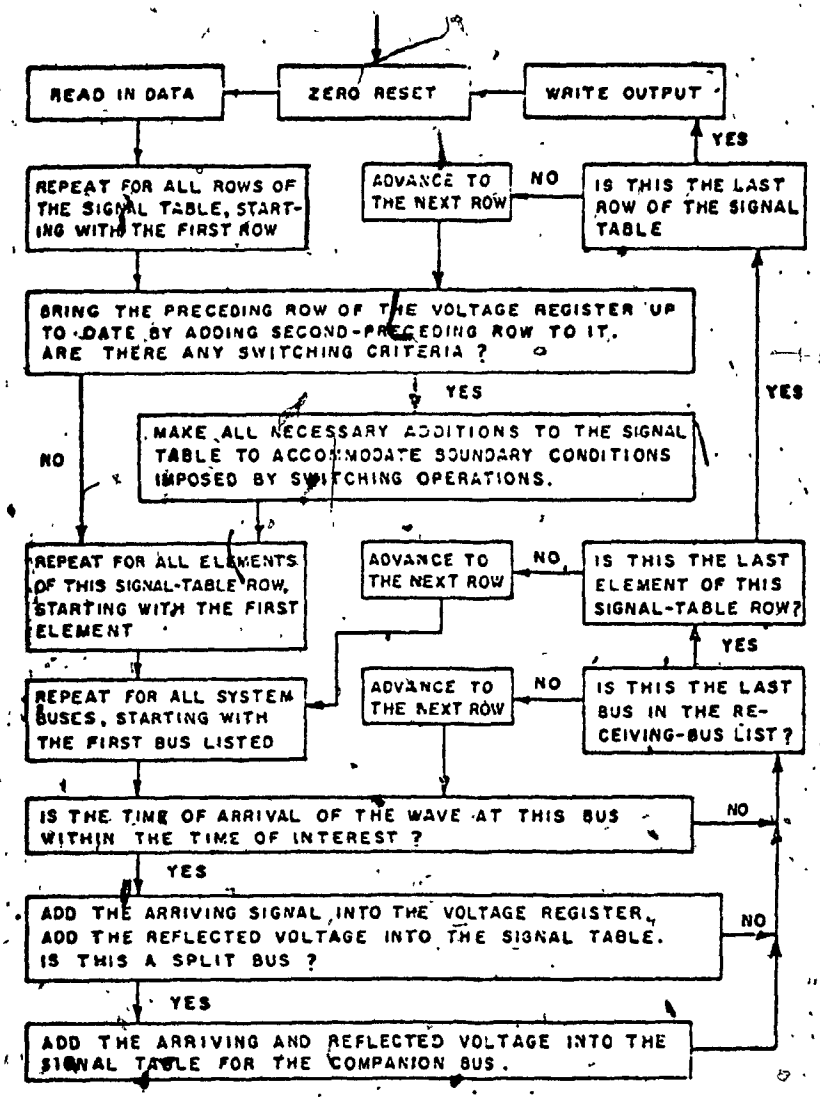

Fig. 12.7 Computer Flow Chart

DISCUSSION

Maximum switching surge overvoltage has been investigated and occurs when energizing an opened circuit transmission line with trapped charge. High speed three phase automatic reclosing after clearing a line-to-ground fault, which is very common operation, allows utilities to avoid permanent interruption of power supply, but leaves the transmission line with fully trapped charge. The dynamic overvoltage in the un-faulted phase becomes a trapped charge which is superimposed on the incident incoming wave to cause the system overvoltage. Caution must be taken to allow the trapped charge to decrease to an acceptable level prior to closing the breaker. This can be done by using a voltage sensing device to control the closing coil of the circuit breaker.

Switching surge overvoltage can be reduced by the insertion of single or multiple stage of resistors as described. This will reduce the insulation level of the transmission line design. If the switching surge overvoltage is suppressed to a very low level, then the power frequency overvoltage has to be considered. That is, there will be an optimal point at which the switching surge is not critical and the power frequency overvoltage becomes dominant. Power frequency overvoltage on which the rating of the lighting arrester is based, can be reduced by a synchronous condenser or shunt reactor with a high saturation characteristic to absorb the excessive reactive power when the system voltage is rising. Hence for reliability and economical design of a transmission line, optimazation

of both switching surge and power frequency overvoltage factors are necessary.

The magnitude of switching surge overvoltage for a given system can be determined by either a digital computer or transient network analyser. The critical flashover voltage for a given system depends on the shape of the wave front as well as the magnitude of the switching surge overvoltage. For any given system the critical time-to-crest impulse wave has to be pre-determined and then simulated in a digital computer by approximation of multiple unit step functions in order to obtain an accurate result.

Appendix "A"

Reflection coefficient

The travelling wave reaching the discontinuity will be reflected and refracted and super-imposed on each other.

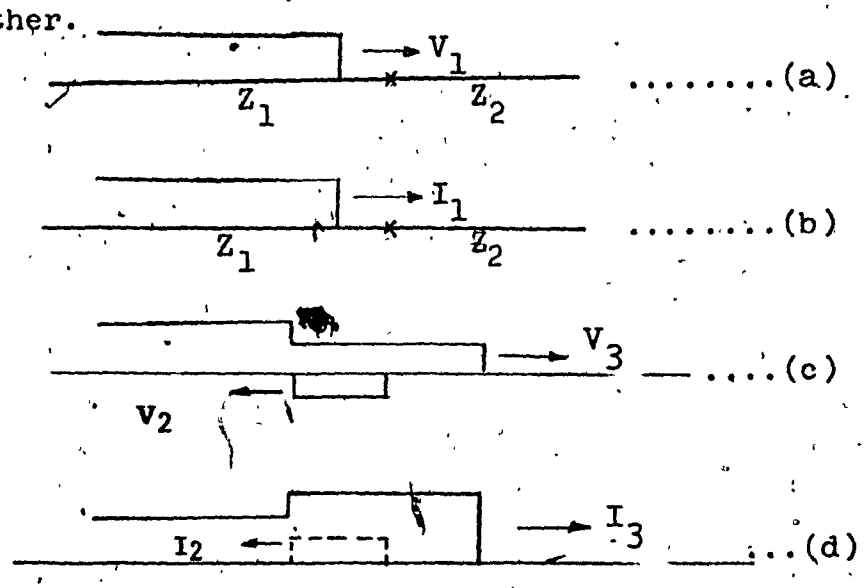

Fig. A.1 Travelling Wave

$$V_1 + V_2 = V_3 \quad .....(A1.1)$$

$$I_1 + I_2 = I_3 \quad .....(A1.2)$$

$$I_1 = \frac{V_1}{Z_1}$$

$$I_2 = -\frac{V_2}{Z_1}$$

$$I_3 = \frac{V_3}{Z_3}$$

$$\frac{V_1}{Z_1} - \frac{V_2}{Z_1} = \frac{V_3}{Z_2} = \frac{V_1 + V_2}{Z_2}$$

$$\frac{V_1}{Z_1} - \frac{V_1}{Z_2} = \frac{V_2}{Z_2} + \frac{V_2}{Z_1}$$

$$V_2 \left(\frac{Z_1 + Z_2}{Z_1 Z_2}\right) = V_1 \left(\frac{Z_2 - Z_1}{Z_1 Z_2}\right)$$

$$\frac{V_2}{V_1} = \frac{Z_2 - Z_1}{Z_1 + Z_2} = R \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots (A1.3)$$

= reflection coefficient

Appendix "B"

Lattice Diagram

The travelling wave reaching the open circuit receiving end will be reflected back and forth along the transmission line.

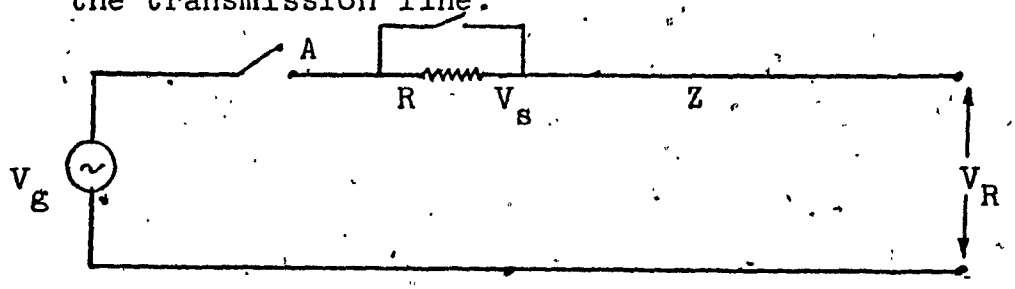

Fig. B.1 Single Stage Resistor Circuit

Reflection coefficient at resistor R $= \frac{R - Z}{Z + R}$

$$= -\left(\frac{Z - R}{Z + R}\right) = -M$$

Transient voltage after breaker A closes $= \frac{Z}{Z + R} V_g$

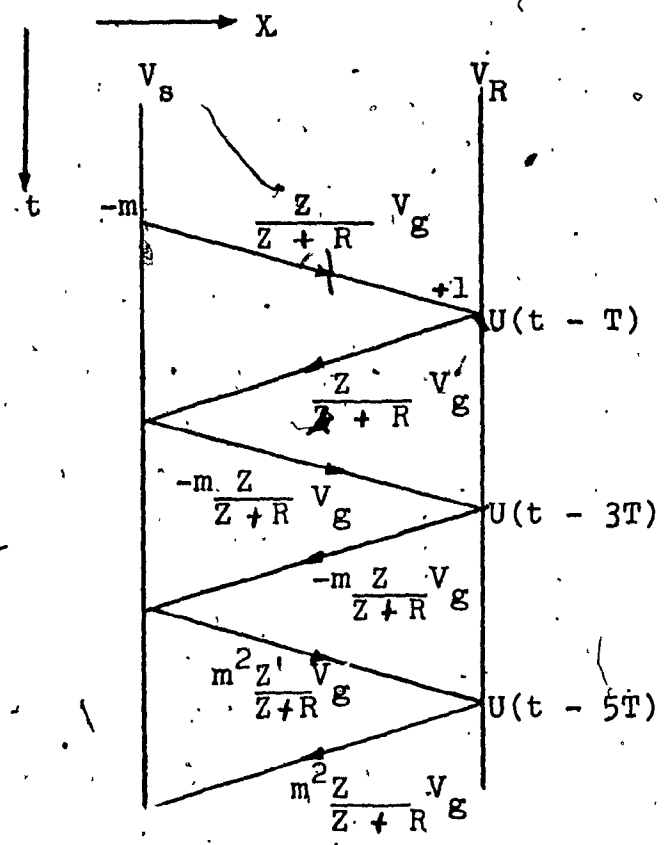

Fig. B.2 Lattice Diagram

$$V_R = \frac{2}{Z + R} V_g \left[U(t - T) - MU(t - 3T) + M^2 U(t - 5T) - \cdots \right]$$

.....(B1.1)

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