Lightning Surges in Power System

Chapter 6

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Content

1. Mechanisms of overvoltages in power systems due to lightning strikes
2. Surge propagation fundamentals
3. Computation of tower voltage
4. Lightning surge arresters
5. Surge arrester application in a substation and its protection performance

Outcomes

1. Able to describe various mechanisms of overvoltages in power systems due to lightning strikes
2. Able to analyze surge propagation in lines and towers
3. Able to compute tower voltage
4. Able to design lightning surge arresters for substations

1. Mechanisms of overvoltages in power systems due to lightning strikes

Mechanisms of overvoltages in power systems due to lightning strikes
Three Ways to Cause Overvoltages

- The negative charges at the bottom of the cloud induces charges of opposite polarity on the transmission line.
- These are held in place in the capacitances between the cloud and the line and the line and earth, until the cloud discharges due to a lightning stroke.
- Figure 1 shows the problems facing the transmission engineer caused by lightning.
- There are three possible discharge paths that can cause surges on the line.

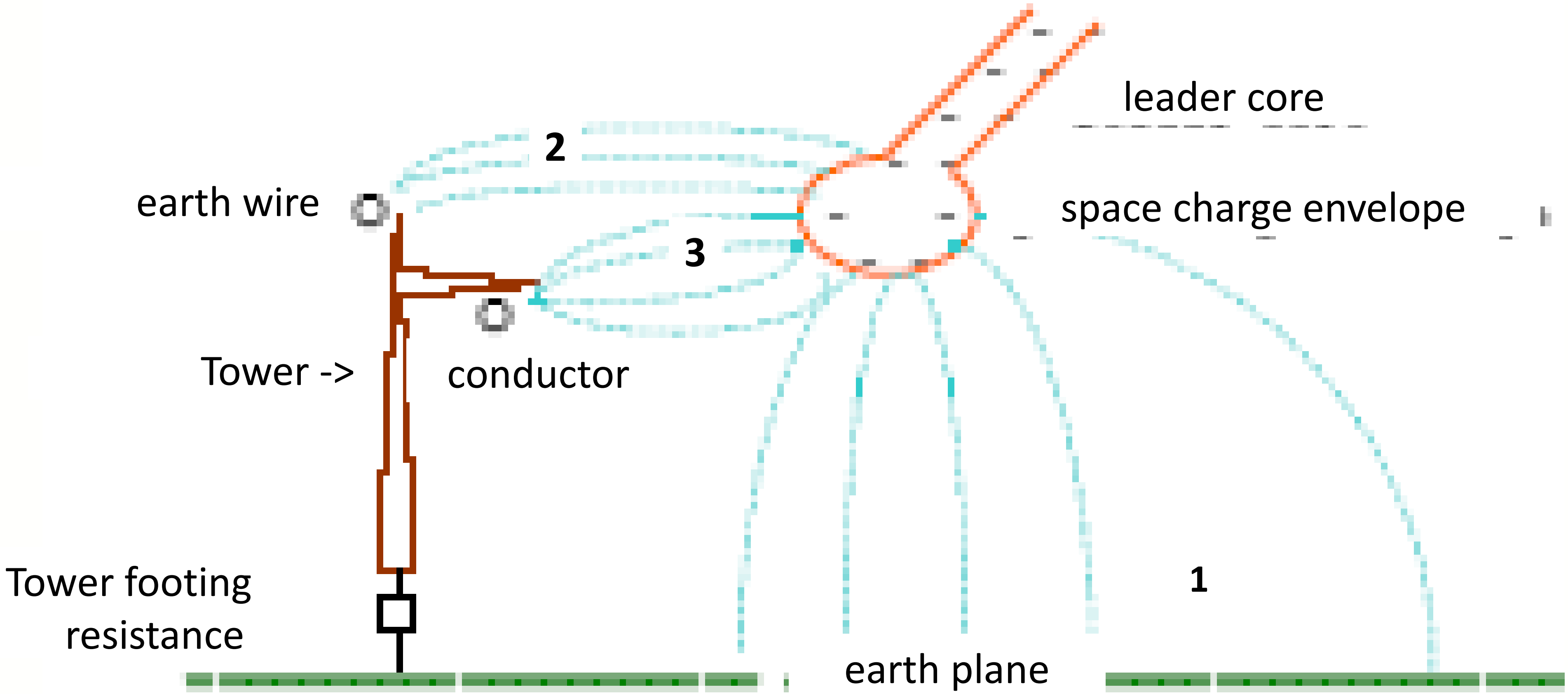


Fig. 1 Geometry of lightning leader stroke and transmission line

First Discharge Path-Induced Overvoltages

(a) In the first discharge path (1), which is from the leader core of the lightning stroke to the earth, the capacitance between the leader and earth is discharged promptly, and the capacitances from the leader head to the earth wire and the phase conductor are discharged ultimately by travelling wave action, so that a voltage is developed across the insulator string.

This is known as the induced voltage due to a lightning stroke to nearby ground. It is not a significant factor in the lightning performance of systems above about 66 kV, but causes considerable trouble on lower voltage systems.

Second Discharge Path-Backflashover

(b) The second discharge path (2) is between the lightning head and the earth conductor.

- It discharges the capacitance between these two.
- The resulting travelling wave comes down the tower and, acting through its effective impedance, raises the potential of the tower top to a point where the difference in voltage across the insulation is sufficient to cause flashover from the tower back to the conductor.

- This is the so-called back-flashover mode.

Third Discharge Path-Shielding Failure

(c) The third mode of discharge (3) is between the leader core and the phase conductor.

- This discharges the capacitance between these two and injects the main discharge current into the phase conductor, so developing a surge voltage across the insulator string.
- At relatively low current, the insulation strength is exceeded and the discharge path is completed to earth via the tower.

- This is the shielding failure or direct stroke to the phase conductor.

Third Discharge Path-Shielding Failure

- The protection of structures and equipment from the last mode of discharge by the application of lightning conductors and/or earth wires is one of the oldest aspects of lightning investigations, and continue to do so.
- Overhead ground wires are provided on transmission lines to intercept direct strokes of lightning and thus keep it off the phase conductor, and to reduce the surge current and hence the overvoltage on a phase conductor by having currents induced in it.

Protection/Shielding by overhead ground wires

- The proportion of lightning flashes capable of causing sparkover of line insulation decreases as the system voltage increases.

- This is due to the fact that the magnitude of the overvoltage caused by lightning strokes are almost independent of the system voltage.
- Of course there is a slight dependence as the height of the towers also increase with the increase in voltage and a taller tower is more liable to a lightning strike.

- For a given magnitude of lightning overvoltage, the per unit value based on system voltage decreases as the system voltage increases.

Protection/Shielding by overhead ground wires

- Thus as the system voltage **increases**, there are **lesser** number of flashovers caused by lightning.
- Not only does the **tall** tower attract more lightning strokes, but also it requires a much better earth-wire coverage for a given degree of protection.

2. Surge propagation fundamentals

- From previous deliberations, lightning overvoltages can be introduced in the electrical power systems by either direct strike to the phase conductor (or shielding failure), backflashover, or induced overvoltages due to the strikes at nearby objects.

- In this section, we will look at the surge or wave propagations inside the electrical system.

- A current or voltage surge can be propagated in conductors or transmission lines. Usually, an impulse surge contains a very fast rising at the front of the wave (in the order of us). The fast rising impulse surge propagates in a conductor similar to a travelling wave in a transmission line. Due to this, the conductor through which it travels is considered as a transmission line with its own so called surge impedance (or travelling wave impedance, that is the impedance seen by the travelling wave as it travels through the conductor which now acts as a transmission line).

- Usually the surge travels at the speed of light or a fraction of the speed light depending on the transmission line.

- The surge impedance of the conductor or the transmission line is given by

$$Z_{surge} = \text{sqrt}\,(L/C)$$

where
L is the equivalent inductance per unit distance of the conductor/transmission line, and
C is the equivalent capacitance per unit distance of the conductor/transmission line

- Interestingly, when calculated, Z above is a real number in ohm.

Surge Characteristics

- Surges behaves similar to a travelling wave, that is, it can get attenuated or damped (hence attenuation factor) when it travels or propagate in a transmission path. It can also be reflected back (in opposite direction to its propagation direction) when it sees a discontinuity. For example, consider a **transmission line 1** with $Z_{surge} = \mathbf{Z_1}$ is connected to **transmission line 2** with $Z_{surge} = \mathbf{Z_2}$ at point Y.

- The reflection coefficient is given as

$$\alpha = (Z_2 - Z_1) / (Z_2 + Z_1)$$

- An incident surge v_i originally travels from point X, will get reflected at point Y, and the reflected wave is given as

$$v_r = \alpha\, v_i$$

Surge Characteristics

- The incident wave can also be transmitted into the transmission line 2 and the transmitted wave is given as

$$v_t = \beta\, v_i$$

wWhere is the transmission coefficient given by

$$\beta = 2Z_2 / (Z_2 + Z_1)$$
$$= \alpha + 1 \qquad (1)$$

- The above equation (1) shows that the transmitted wave or voltage is equal to the sum of the incident wave and reflected wave.

$$v_t = v_r + v_i$$
$$= (\alpha + 1)v_i \qquad (2)$$

Surge Characteristics

- Equation (2) shows that the voltage at the point of discontinuity can be found by either

$$v_y = v_t$$

or

$$v_y = v_r + v_i = (\alpha + 1)v_i$$

Exercises:

For the following discontinuity points as seen by a surge or travelling wave, determine α and β.

1. A conductor having a surge impedance of 600 ohm is connected to a conductor having a surge impedance of

(a) 350 ohm.

(b) 600 ohm

2. The end of a transmission line having a surge impedance of 600 ohm is terminated by a resistor with a value of

(a) 600 ohm;

(b) 1200 ohm

(c) 300 ohm

(d) 0 ohm

(e) very large resistor (teraohms)

3. **A** 100m **coaxial transmission line** having a shorted conductor to shield at 50m.

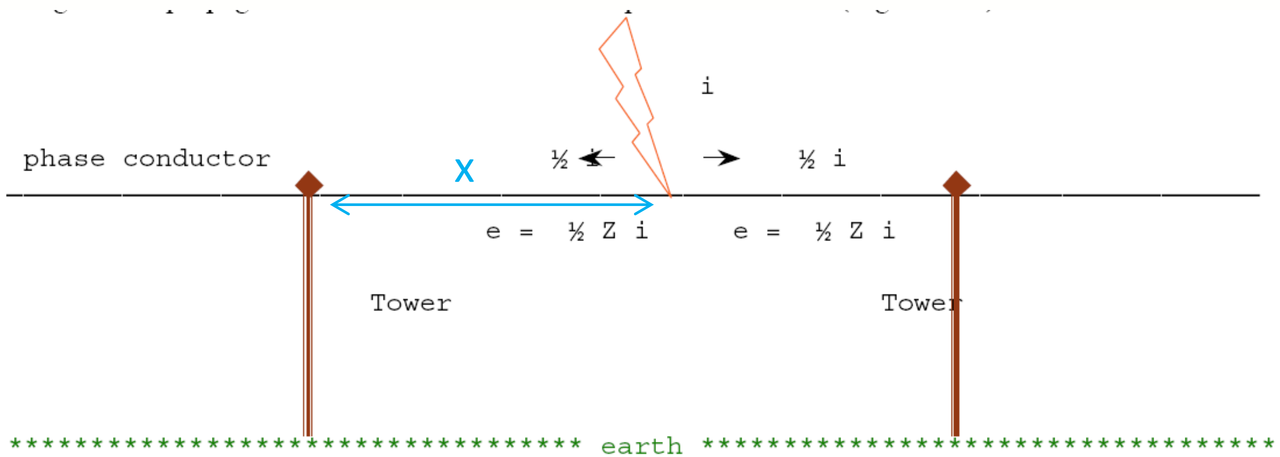
4. **A** 100m **coaxial transmission line** having a broken conductor at 50m.

3. Computation of tower voltage

Computation of prospected tower voltage

Lightning Surge

- A lightning strike on a conductor can cause current to flow in the conductor to discharge the charges in the cloud. This current surge produced a corresponding voltage surge at the point of strike, the shape of which is the same as the current shape.

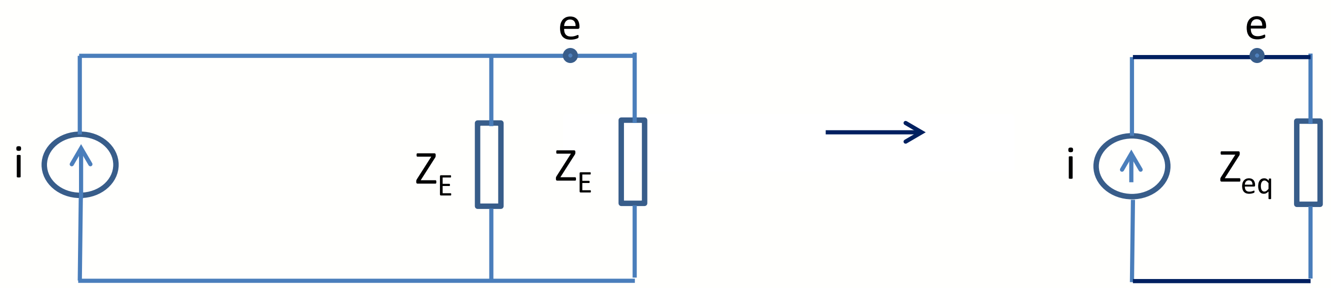


- Note, the lightning current will always split into **two** irrespective of the point on the earthing wire. That is, the current split does **not** depend on the **distance** (**x**) from the tower.

- The waveshape of these voltage surges is similar to that of the current in the lightning discharge. The discharge current splits itself equally on contact with the phase conductor, giving travelling waves of magnitude e.

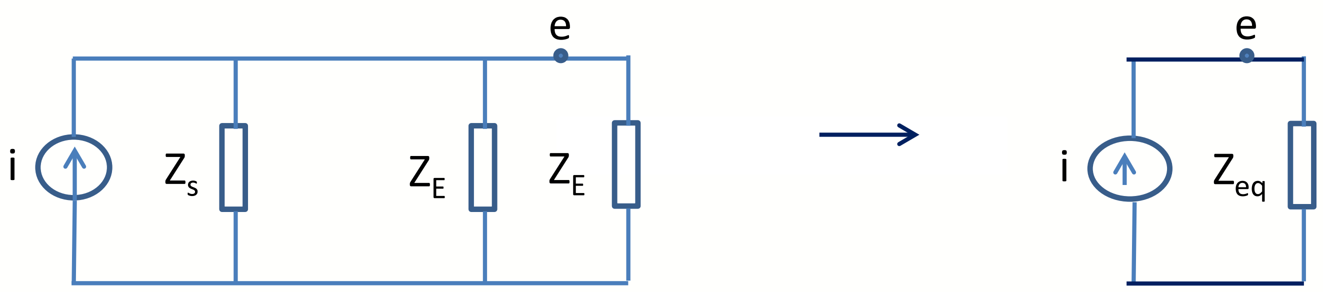
$$e = \tfrac{1}{2} Z i \left(e^{-\alpha t} - e^{-\beta t} \right) = E \left(e^{-\alpha t} - e^{-\beta t} \right)$$

where Z is the surge impedance of the phase conductor.



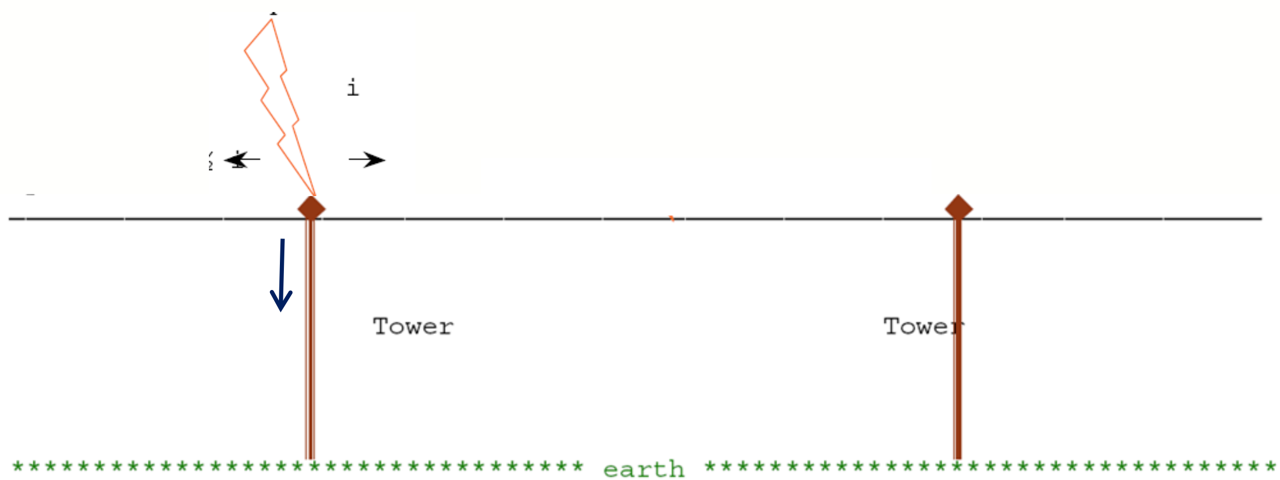
- Using a typical value for the line surge impedance (say 300 ohm) and an average lightning current (20 kA), the voltage waves on the line would have a prospected crest value of $E = \tfrac{1}{2} Z i = (300/2) \times 20 \times 10^3 = 3$ MV

- The above calculations assume that the lightning channel impedance or the source impedance is infinite. If the lightning channel impedance is not infinite, say Z_s where Z_s is the lightning channel (source) surge impedance, then an equivalent circuit of the current source can be

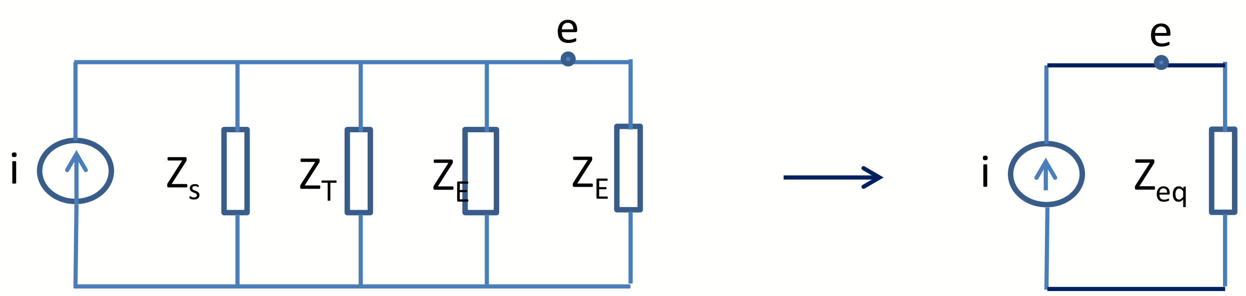


- Hence, the voltage waves on the line would have a prospected crest value of $E = Z_{eq}\, i = (Z_s)//(300/2) \times 20 \times 10^3$

- A lightning strike on a tower can cause current to flow in the conductor as well as the tower to discharge the charges in the cloud. The current now split into **three** separate paths. This current surge produced a corresponding voltage surge at the point of strike, the shape of which is the same as the current shape. The current splits into three parts. One part into the tower and the other two into the wire in both directions.



- Hence the equivalent circuit is



$E = i.Z_{eq}$

Z_{eq} is the equivalent surge impedances = $Z_s // Z_T // Z_E // Z_E$

Exercise

Determine the **prospected** crest value of the voltage wave that generated for the following cases (Assume Z_E = 600 ohm, Z_{tower} = 150 ohm):

1. A lightning strike of 20kA peak and waveshape $I_p(e^{-\alpha t} - e^{-\beta t})$ striking the top of a tower with a single earth wire connected at the top.
2. A lightning strike of 20kA peak and waveshape $I_p(e^{-\alpha t} - e^{-\beta t})$ striking the top of a tower with a single earth wire connected at the top. A lightning channel impedance of 2500 ohm is specified.
3. A lightning strike of 20kA peak and waveshape $I_p(e^{-\alpha t} - e^{-\beta t})$ striking the top of a tower without any earth wire connected.
4. A lightning strike of 20kA peak and waveshape $I_p(e^{-\alpha t} - e^{-\beta t})$ striking the top of a tower without any earth wire connected. A lightning channel impedance of 2500 ohm is specified.
5. A lightning strike of 20kA peak and waveshape $I_p(e^{-\alpha t} - e^{-\beta t})$ striking the top of a an end tower with a single earth wire connected at the top (earth wire on one side of the tower only). A lightning channel impedance of 2500 ohm is specified.

Lightning Surge and determination of tower voltage

- In previous slides, we describe the prospected peak voltage that can be reached at the striked point, given a current peak value.
- However, due to wave attenuation/magnification because of travelling wave effect such as at the discontinuity points where reflection, transmission, and attenuation occur, the resultant voltage wave may be modified. Hence the final shape of the voltage, taking consideration of all the travelling wave effects may be quite different than the original striked wave or incident wave.
- In the next few slides, we will consider the tower top voltage and try to determine its shape and peak magnitude with all the travelling wave effects taken into consideration.
- Of course, we will start with the original current wave as reference. **One thing that is constant is the duration to current peak. This wave signature, that is the duration to peak, will be kept throughout the determination of voltage wave process.**

- Illustrate what happen to the surge when it strikes an earth wire at midspan (consider only a single earth wire on top of transmission towers).
- Basically, the surge current splits into two. Voltage surges then travel in both directions towards the transmission towers. Once a surge ($\mathbf{v_{incident} = v_s}$) arrives at the tower top, it sees a discontinuity. Some of the incident wave will be reflected, and some other will be transmitted into the tower structure as well as the other side of the earthing wire. Since there are two forward transmission paths (the tower and earthing wire), an approximation of the reflection and transmission coefficients can be calculated by paralleling the earth wire and the tower as Z_2.

$$Z_2 = Z_{earth} // Z_{tower}$$

- Hence $\alpha_1 = (Z_2 - Z_1)/(Z_2 + Z_1)$; $Z_1 = Z_{earth}$ and $\beta_1 = \alpha_1 + 1$.

- The transmitted wave into the tower is given as

$$v_t = \beta_1 v_{incident} = \beta_1 v_s$$

- This transmitted wave ($\beta_1 v_s$) will now travels towards the bottom of the tower which is now regarded as a transmission line with an impedance Z_{tower}. The time taken to reach the bottom of the tower from the top is

$$T = h/c_s$$

where h is the height of the tower and c_s is the propagation speed (a fraction of the speed of light c or sometimes is assumed to be the same as the speed of light)

- As soon as the incident wave (β_1 v_s) arrives at the bottom of the tower, it sees another discontinuity.

- Hence $\alpha_2 = (Z_2 - Z_1)/(Z_2+Z_1)$; $Z_1 = Z_{tower}$, $Z_2 = R_{tower\ footing\ resistance}$
  and $\beta_2 = \alpha_2 + 1$

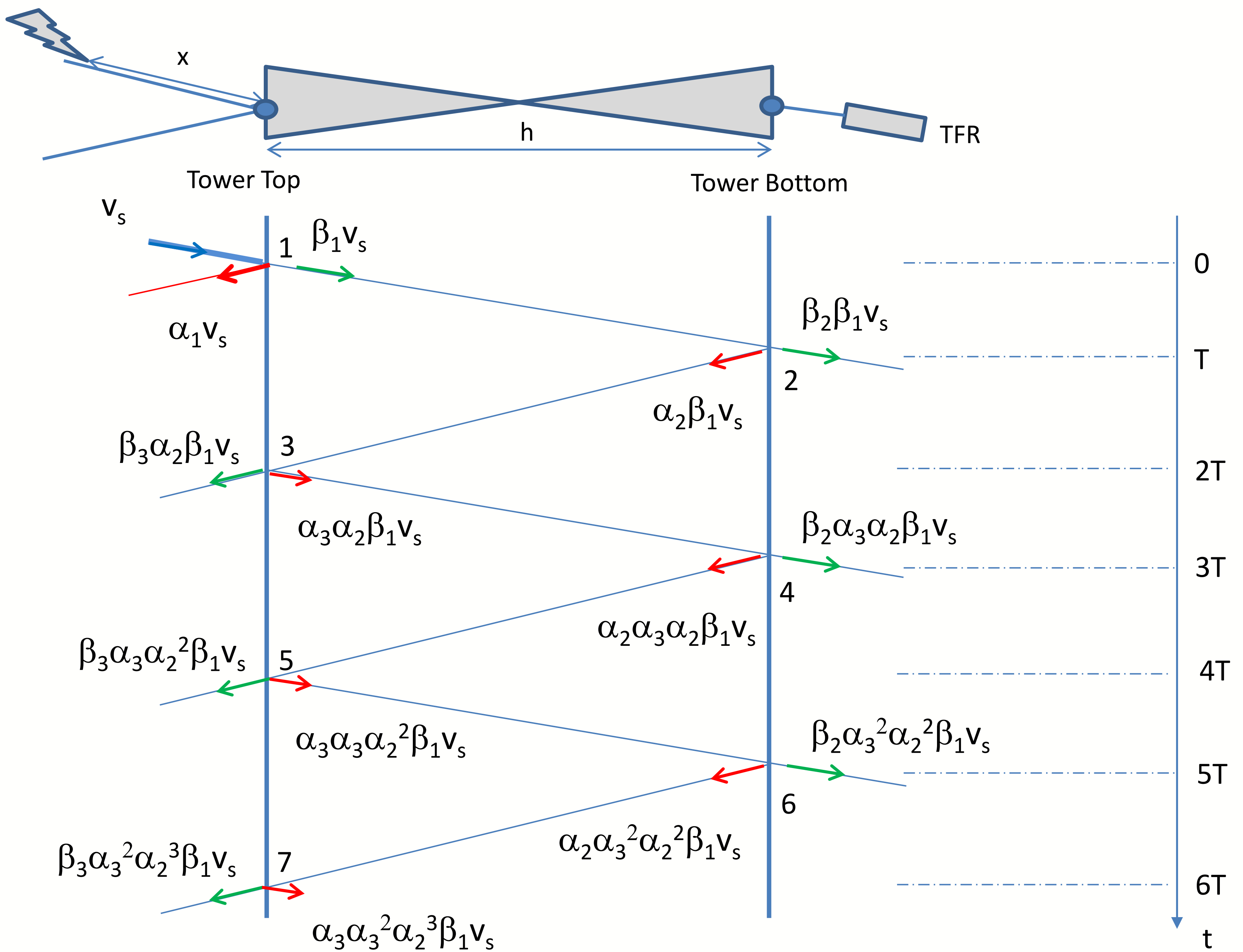
Some of the incident wave got reflected as $v_r = \alpha_2\, v_{incident}$ (= $\alpha_2\, \beta_1\, v_s$ and travels back towards the top of the tower.

- When it reaches the top of the tower, this wave sees another discontinuity. Since there are two forward transmission paths (the earthing wire on both directions), the reflection and transmission coefficients can be calculated by paralleling the earth wire as Z_2.

$$Z_2 = Z_{earth} // Z_{earth}$$

- Hence $\alpha_3 = (Z_2 - Z_1)/(Z_2+Z_1)$; $Z_1 = Z_{tower}$
  and $\beta_3 = \alpha_3 + 1$.

The complete Bewley Lattice diagram of the wave propagation within the tower can then be drawn:


x
h
TFR
Tower Top
Tower Bottom
v_s
1
$\beta_1 v_s$
$\alpha_1 v_s$
$\beta_2\beta_1 v_s$
2
$\alpha_2\beta_1 v_s$
$\beta_3\alpha_2\beta_1 v_s$
3
$\alpha_3\alpha_2\beta_1 v_s$
$\beta_2\alpha_3\alpha_2\beta_1 v_s$
4
$\alpha_2\alpha_3\alpha_2\beta_1 v_s$
$\beta_3\alpha_3\alpha_2^2\beta_1 v_s$
5
$\alpha_3\alpha_3\alpha_2^2\beta_1 v_s$
$\beta_2\alpha_3^2\alpha_2^2\beta_1 v_s$
6
$\alpha_2\alpha_3^2\alpha_2^2\beta_1 v_s$
$\beta_3\alpha_3^2\alpha_2^3\beta_1 v_s$
7
$\alpha_3\alpha_3^2\alpha_2^3\beta_1 v_s$
0
T
2T
3T
4T
5T
6T
t

- The surge voltage developed at the points in the tower and at different times, in terms of the original incident wave $v_s = Z_{eq} \times I_p(e^{-\alpha t} - e^{-\beta t})$, is given as

$$
\begin{aligned}
v_1 &= \beta_1 v_s && t > 0 \\
&= v_s + \alpha_1 v_s \\
v_2 &= \beta_2\beta_1 v_s && t > T \\
&= \beta_1 v_s + \alpha_2\beta_1 v_s \\
v_3 &= \beta_3\alpha_2\beta_1 v_s && t > 2T \\
&= \alpha_2\beta_1 v_s + \alpha_3\alpha_2\beta_1 v_s \\
v_4 &= \beta_2\alpha_3\alpha_2\beta_1 v_s && t > 3T \\
&= \alpha_3\alpha_2\beta_1 v_s + \alpha_2\alpha_3\alpha_2\beta_1 v_s \\
&= \alpha_3\alpha_2\beta_1 v_s + \alpha_3\alpha_2^2\beta_1 v_s
\end{aligned}
$$

etc.

- To determine the full surge voltage developed at the **top of the tow**er, we need to add all the arriving voltages at **the top of the tower** in terms of the original incident wave $v_s = Z_{eq} \times I_p(e^{-\alpha t} - e^{-\beta t})$

$$v_{Tower\ Top} = v_1 + v_3 + v_5 + v_7 + \ldots..$$

$$= \beta_1 v_s + \beta_3 \alpha_2 \beta_1 v_s(t - 2T) + \beta_3 \alpha_3 \alpha_2^2 \beta_1 v_s(t - 4T) + \ldots$$

- To determine the resultant wave, a graphical solution can be carried out (since this equation is time dependent)
- The resultant voltage wave is the actual voltage appearing at the top of the tower as the time increases.

- To determine the full surge voltage developed at the **bottom of the tow**er, we need to add all the arriving voltages at **the bottom of the tower** in terms of the original incident wave $v_s = Z_{eq} \times I_p(e^{-\alpha t} - e^{-\beta t})$

$$v_{Tower\ Botttom} = v_2 + v_4 + v_6 + \ldots..$$

$$= \beta_2 \beta_1 v_s(t - T) + \beta_2 \alpha_3 \alpha_2 \beta_1 v_s(t - 3T) + \beta_2 \alpha_3^2 \alpha_2^2 \beta_1 v_s(t - 5T) + ..$$

- To determine the resultant wave, a graphical solution can be carried out (since this equation is time dependent)
- The resultant voltage wave is the actual voltage appearing at the bottom of the tower as the time increases.

Example

An EHV transmission line consists of towers with 45-m height, 300-m span between towers, and a single ground wire with 500-ohm surge impedance. The tower itself has a surge impedance of 150 ohm. A lightning flash, represented by a current surge shown in Fig. Q1, strikes the ground wire at a distance of 90 m from a tower. The source impedance of the lightning channel is 2500 ohm and the footing resistance of the tower is 10 ohm.

(i) If the surge travels on the ground wire and in the tower at the speed of light, determine the voltage at the top of the closest tower 0.8 us after the lightning flash contacts the ground wire.

Speed of light, $c = 3 \times 10^8$ m/s.

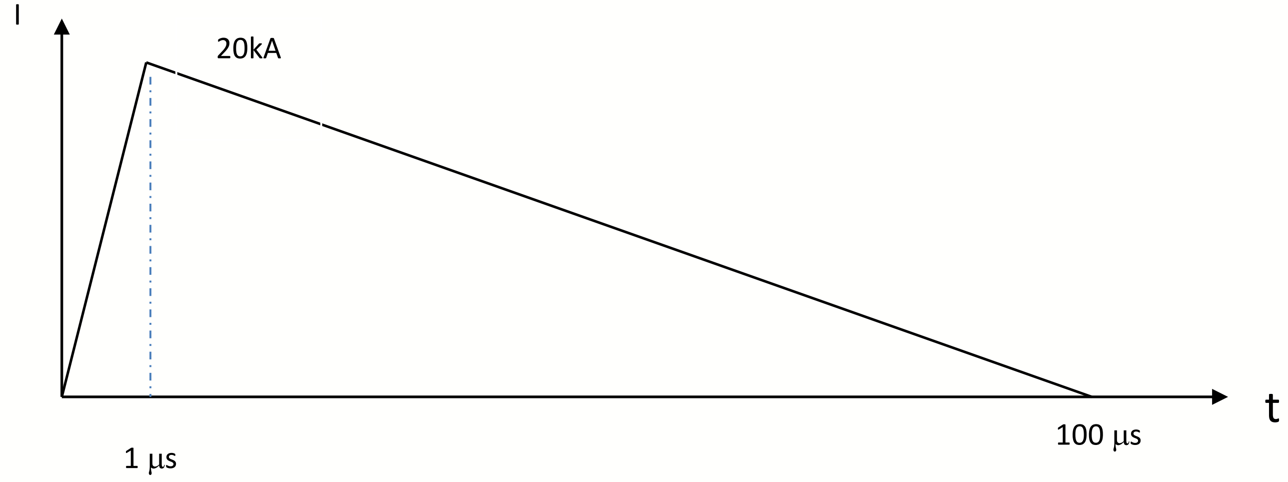


Fig. Q1 (drawn not to scale)

(ii) The volt-time curve data of the insulator string, for the surge waveform, are as follows:

t (us)	0.3	0.4	0.5	0.6	0.7	0.8	1.0
V (kV)	1454	1091	773	636	500	455	409

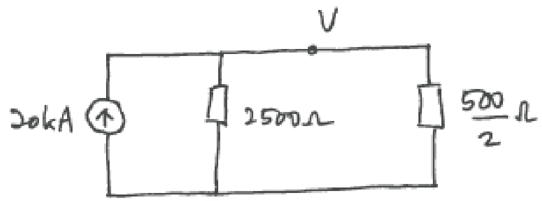
Assuming a coupling factor of (a) 1.0, (b) 0.8, and neglecting the power frequency voltage, will flashover occur? If so, when will it occur?

If yes, what happen to the network/power system?
What can be done to improve the flashover rate/to prevent fault?

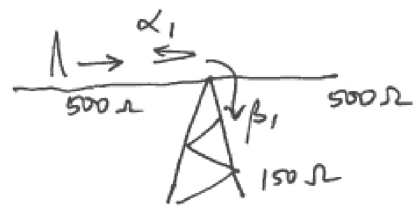
Solution:

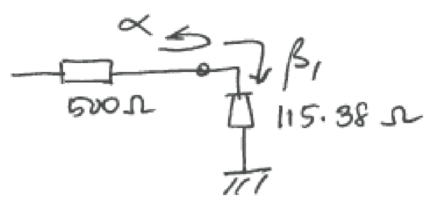
Q1. Tower height 45m, Tower span 300m, $Z_G = 500\ \Omega$, $Z_T = 150\ \Omega$
Distance to strike 90m, $Z_s = 2500\ \Omega$, $R_G = 10\ \Omega$

(i)

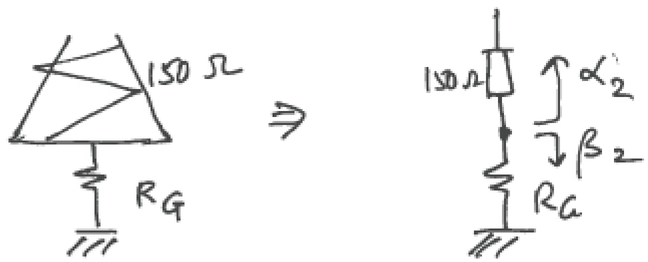


$$V = 20k \times \frac{2500 \times 250}{2500 + 250} = 4.545\ MV$$



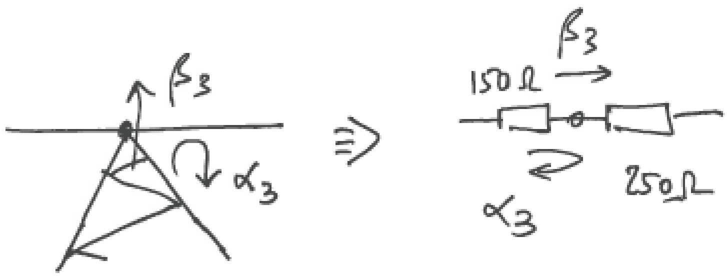


$$\beta_1 = \frac{2 \times 115.38}{500 + 115.38} = 0.375$$



$$\alpha_2 = \frac{10-150}{10+150} = -0.875$$

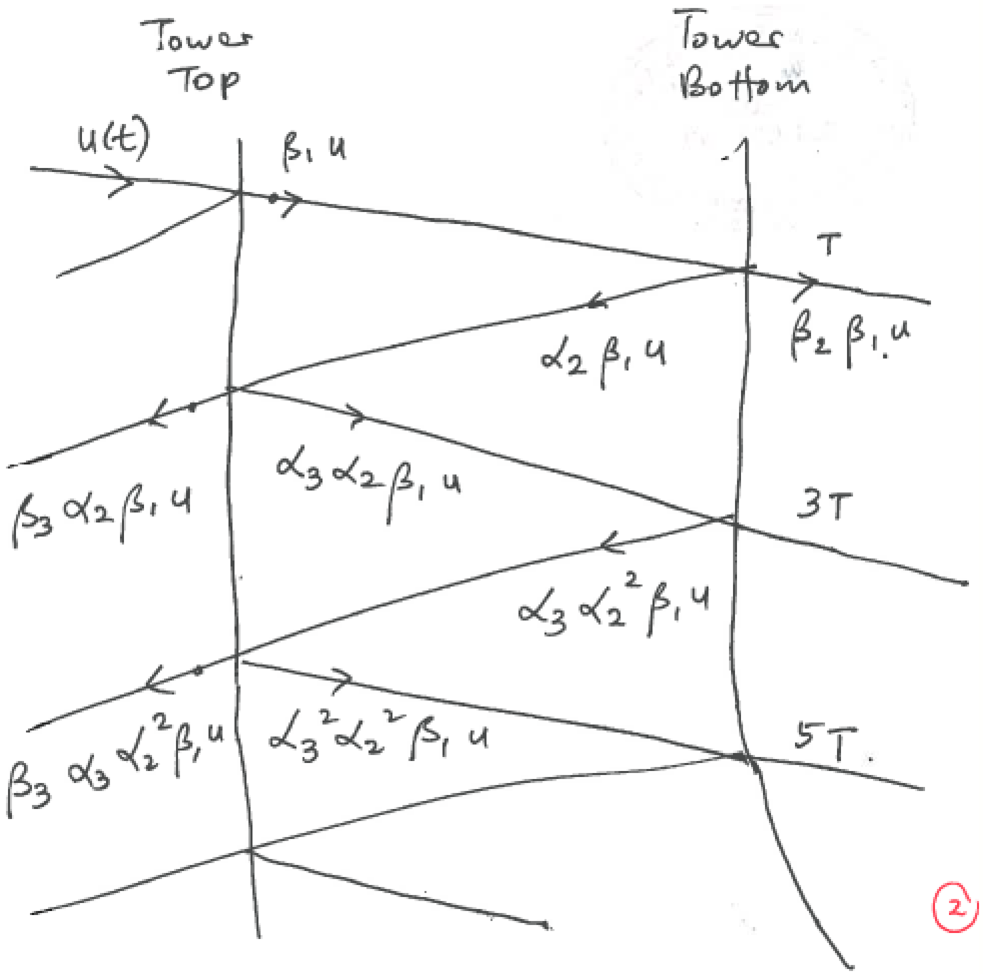
$$\beta_2 = \alpha + 1 = 0.125$$



$$\alpha_3 = \frac{250-150}{250+150} = 0.25$$

$$\beta_3 = 1 + \alpha = 1.25$$

4



Zulkurnain Abdul Malek Mar 2021

V_{TT}

$= \beta_1 u + \beta_3 \alpha_2 \beta_1 u(t-2T) + \beta_3 \alpha_3 \alpha_2^2 \beta_1 u(t-4T)$

$= 0.375 u + 1.25(-0.875)(0.375) u(t-2T) + 1.25 \times 0.25 \times 0.875^2 \times 0.375 u(t-4T)$

$= 0.375 u + (-0.410) u(t-2T) + 0.0897 u(t-4T)$

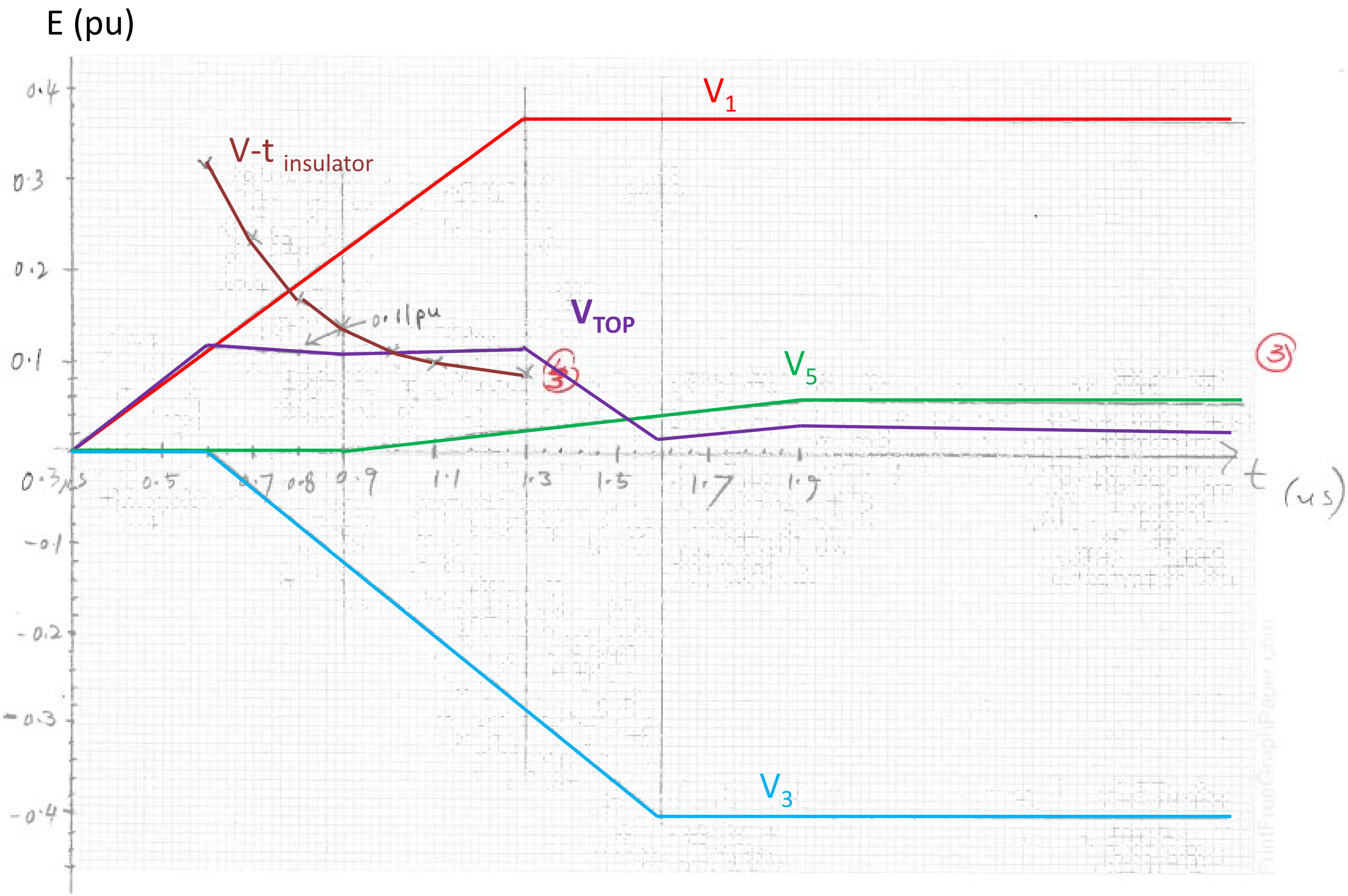
$T = 45/c = 45 / 3x10^8 = 0.15$ us

90 m -> $90/c = 0.3$ us

From the graph, at t = 0.8us

$V = 0.11 \times 4.545$

$= 0.4545$ MV


E (pu)
V1
V-t insulator
0.11pu
VTOP
V5
V3
0.4
0.3
0.2
0.1
-0.1
-0.2
-0.3
-0.4
0.3μs
0.5
0.7
0.8
0.9
1.1
1.3
1.5
1.7
1.9
t (μs)

ii) From the graph, the string insulator will flashover at t= 1.0 us.

t (us)	V (kV)	V (pu)
0.6	1454	0.32
0.7	1091	0.24
0.8	773	0.17
0.9	636	0.14
1.0	500	0.11
1.1	455	0.10
1.3	409	0.90

Exercise 1

An EHV transmission line consists of towers with 90-m height, 300-m span between towers, and a single ground wire with 600-ohm surge impedance. The tower itself has a surge impedance of 150 ohm. A lightning flash, represented by a current surge with a front time or time to peak of 0.4 μs, strikes a point on the ground wire located at 90 m from a tower. The peak current is 30 kA. The footing resistance of the tower is 10 ohm.

The volt-time curve data of two different insulator strings, for the surge waveform, are shown in Table Q.1.

Given the above case, will the insulator flashover? When will it flashover and at what voltage?

Neglect the coupling factor and the power frequency voltage. Assume all surges propagate at **one half** of the speed of light.

	t (us)	0.9	1.45	2.0	3.0	3.75
Insulator	V (kV)	3770	2900	2400	1970	1910

Exercise 2

An EHV transmission line consists of towers with 90-m height, 300-m span between towers, and a single ground wire with 600-ohm surge impedance. The tower itself has a surge impedance of 150 ohm. A lightning flash, represented by a current surge with a front time or time to peak of 0.4 µs, strikes a tower. The peak current is 30 kA. The footing resistance of the tower is 10 ohm.

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	t (us)	0.9	1.45	2.0	3.0	3.75
Insulator	V (kV)	3770	2900	2400	1970	1910

Schemes to reduce backflashover rate

- Better (lower) tower footing resistance
  - ✓ Lower tower footing resistance means lower tower voltage and hence the string insulators are less likely to flashover.

- Overvoltage protective devices (line arresters)
  - ✓ Putting an arrester in parallel with the string insulator means the string insulator is now protected against overvoltage which causes it to flashover. Instead, the surge is clamped to the protective level of the surge arrester, and hence no short circuit occurs (which means no operation of circuit breaker occurs).

Surge propagation into substation

- Please note that, once backflashover occurs, especially when the occurrence is close to a substation, the surge introduced into the phase conductor will propagate towards the substation.
- Substation equipment are now exposed to the surge.
- Another protection scheme is therefore required at the substation.
- In the next few slides, we will look into the surge propagation into high voltage stations and protected zones.
- The same travelling wave effects will be used.

4. Lightning surge arresters

- In this section , we will look into the following topics:

  - ✓ Insulation coordination principles
  - ✓ Overvoltage protective devices
  - ✓ Surge propagation into high voltage stations and protected zones

Insulation Coordination Principles

- Insulation has to withstand a variety of overvoltages with a large range of shapes, magnitudes and durations

- The problem before us is therefore:
  - To ascertain the magnitudes, shapes, frequency and duration of overvoltages, and changes they undergo when travelling from the point of origin to the equipment affected
  - To determine the voltage withstand characteristic, in respect to these overvoltages, of the various types of insulation in use;
  - To adapt the insulation strength to the stresses

- As the economic limit intervenes well before the technical limit, we deliberately accept certain probability of breakdown in the design of power system equipment
- When breakdowns are inevitable, they are confined to locations where they cause minimum damage and the least disturbance to operation

- The purpose of insulation coordination exercise in a high voltage substation is to either
  - ✓ prevent breakdown due to overvoltages

  or
  - ✓ where prevention is uneconomical or impractical, to confine breakdowns to locations where they cause minimum of damage and the least possible disturbance to system operation

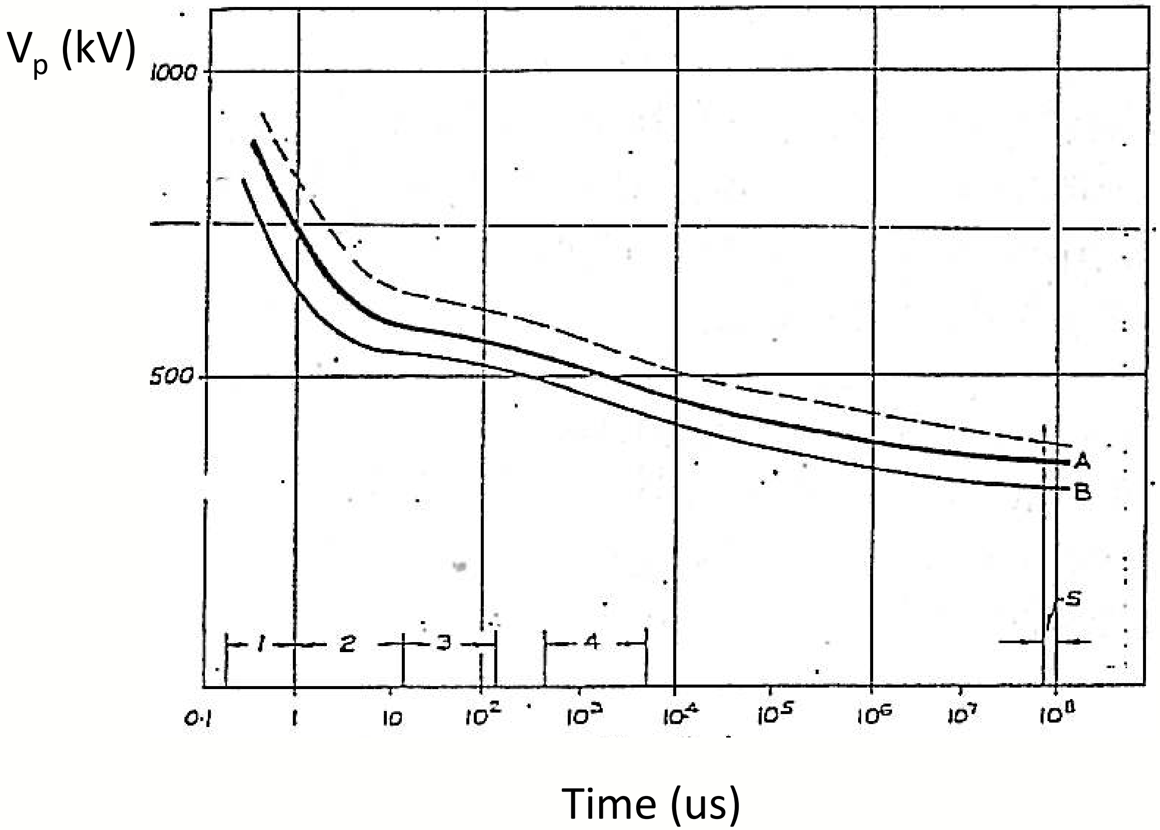
- All types of system overvoltages are to be considered
  - ➢ Power frequency & harmonic voltages; these are of limited and generally predictable magnitudes
  - ➢ Switching surges: below 300 kV system voltage, switching surges are as little a critical factor in stations as in transmission lines
  - ➢ Lightning overvoltages: necessary to take steps to withstand against them with use of protective devices and proper station design

- Whenever possible, the protection level of the protective device should be selected so that it will not operate on switching overvoltages which, because of their relatively long duration, may cause thermal overload and damage to the device. This condition may force up the BIL (basic insulation level) of the system equipment.

- For very high voltages, it is therefore economically desirable to use a protective device for the limitation of both switching and lightning overvoltages. Owing to the progress in surge arrester technology, this is indeed feasible.

- Notwithstanding the above, many engineers till prefer to assign to the equipment a switching impulse insulation level (SIL) with a small margin above the controlled switching surge level, so that surge arrester would operate on switching surges only rarely.

- The behaviour of insulation is described by a **volt-time curve**. It is a plot describing the behavior of the insulation for various voltage waves ('speed').
- For example, for a 132kV transformer, the insulation behaves differently under different types of applied voltage – higher breakdown voltage when the wave is faster and lower breakdown voltage for pf wave.
- For each wave, there is a voltage level known as withstand voltage, i.e. the voltage at which no breakdown will occur.
- There is also a voltage level known as the mean breakdown voltage, i.e. the average breakdown voltage or the voltage at which 50% probability of breakdown occurs



Volt-Time Curve for a 132 kV Transformer

Curves:

A = Mean b.d. voltage;

B = Withstand Voltage

Time regions:

1 = Steep fronted lightning surges;

2 = slower lightning surges;

3 = fast switching surges;

4 = slow switching surges;

5 = 1 minute 50 Hz test

- If we consider the lightning waveshape, that is an impulse breakdown, there is also volt-time (U-t) curve behavior of an insulation

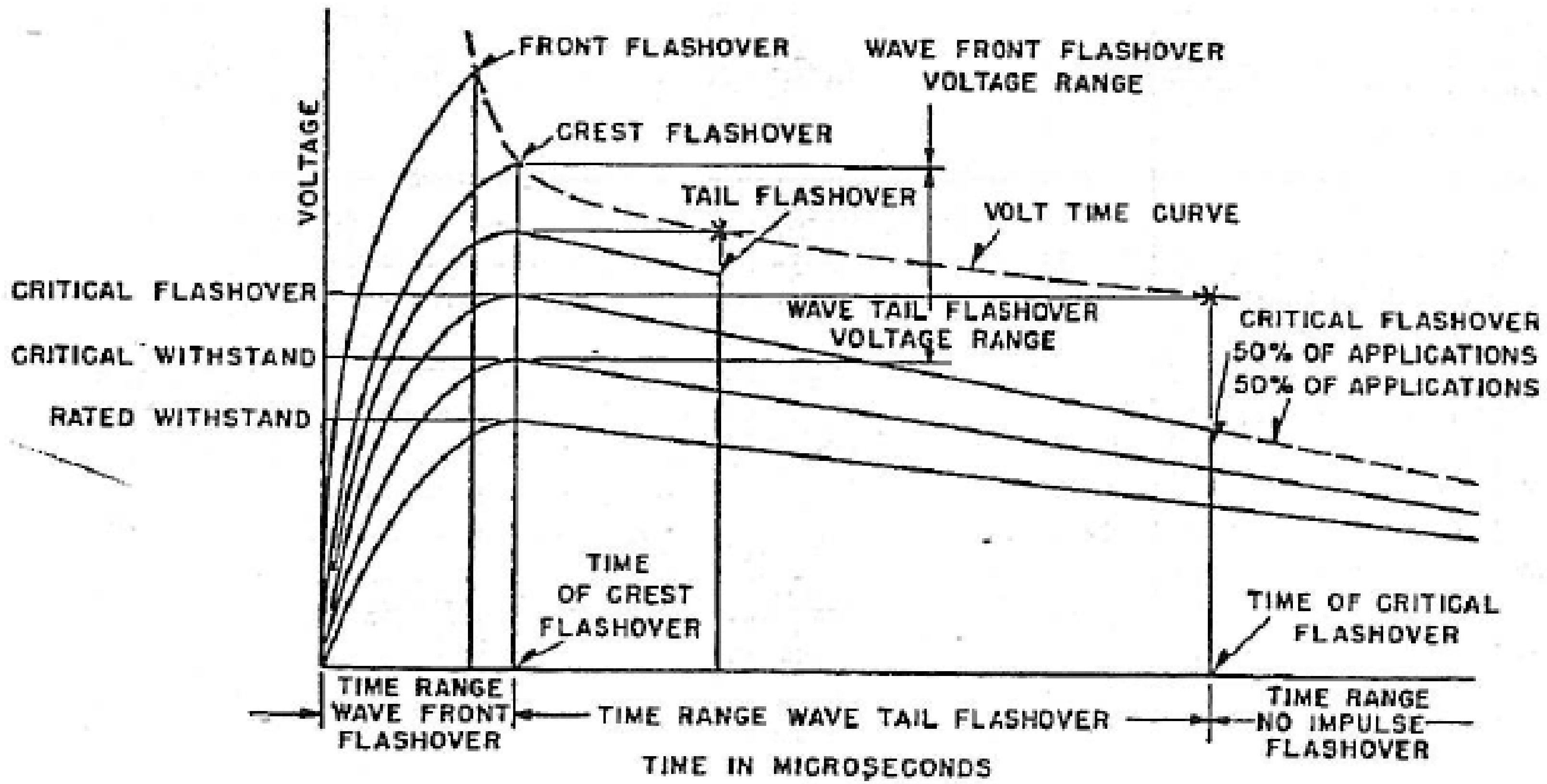
- In this case, the time to breakdown is dependent on the prospective peak of the lightning impulse.

- The bigger the peak voltage, the faster the time to breakdown.

- There is also a critical flashover voltage at which there is 50% probability breakdown occurs. Associated with this is the breakdown time for critical flashover voltage.

- There is also a critical withstand peak voltage at which no breakdown occur.

- The U-t curve is made by plotting the peak voltage against the corresponding time to breakdown.



Construction of a volt time curve for an insulation under impulse voltage stress

- In practice, there is considerable scatter of times to breakdown (t_B)
- Time to breakdown consists of at least 2 components, viz.,

$T_{statistical}$ = time for appearance of a free electron to initiate breakdown

$T_{formative}$ = time for formation of avalanche breakdown

- Generally, any insulation has a basic impulse insulation level or BIL. BIL is the impulse withstand of an insulation.

- The basis of insulation coordination is to ensure that all insulation in a substation is of the same value – then protective devices can protect all equipment

- The protective level is chosen to be below the BIL value
  eg select BIL = 1.25 -1.4 x protective level

- But considering only BIL value is not sufficient. The time factor also need to be considered. This requires us to look at the U-t curves (withstand) of the insulation as well as the U-t curves (operation) of the protective device.

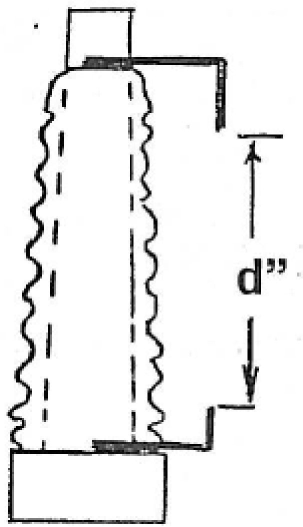
Behaviour of protective devices

- Requirements:
  - Should not operate in presence of abnormal voltages due to faults and loss of load
  - Volt-time curve must lie below the withstand level of the protected insulation in any time region where protection is required
  - Able to discharge high energy surges without changes in its protective level or damage to itself or adjacent equipment

- Another property is highly desirable:
  - after discharging a surge, it should reseal or become non conducting in the presence of system overvoltages due to faults and loss of load

Rod gaps

- Simple and cheap, but do not reseal after discharging a surge. Approximately 85% of rod gap flashovers are accompanied by power outage. Limited protection for surges having fast rise-times.

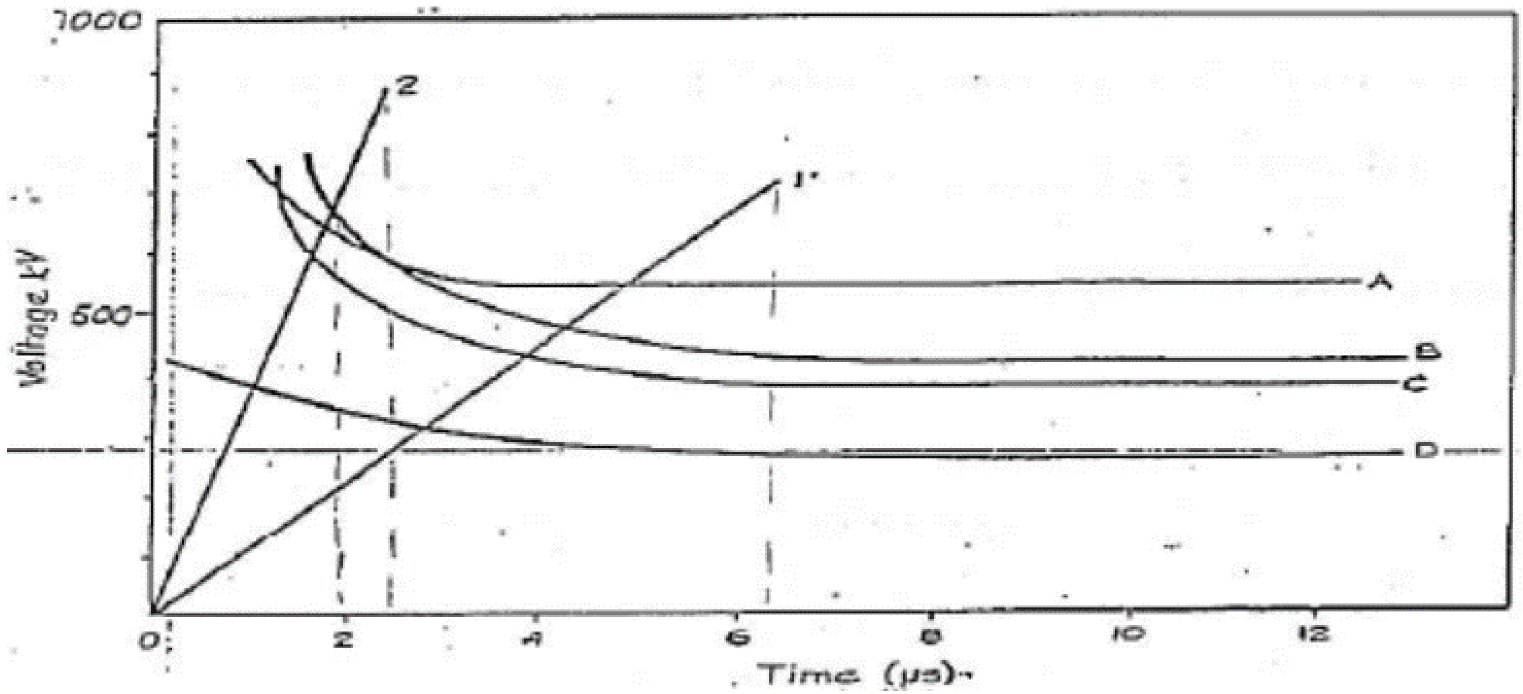


- An application of an impulse U-t curve is shown below.

  A is the withstand U-t curve for a 132 kV transformer insulation
  B is the flashover U-t curve for a 26” protective rod gap
  C is the flashover U-t curve for a 22” protective rod gap
  D is the operating U-t curve for a surge arrester (see later)

- Protection can be achieved in any time region where the volt-time (breakdown) curve of **the protective device lies below** the withstand volt-time curve of the protected insulation (transformer)

- However, the rod gaps will protect the transformer insulation against surges in certain time scale (front times) only (>2.5us for 26” and >1.5us for 22”).



A, 132 kV transformer (withstand)
B, 26" rod gap (flashover)
C, 22" rod gap (flashover)
D, 120 kV surge diverter s.o.v./discharge voltage

- If we analyse the transformer and rod gaps U-t characteristics for different wave shapes, we have the following peak values (kV):

	LI	SI	pf
132kV Transformer withstand:	550	440	325
26” rod gap breakdown:	420	380	362
22” rod gap breakdown:	380	340	310

Apparatus	50Hz F.O.V kVp	50% 1/50μs F.O.V. kVp	Switching surge F.O.V. kVp
Transformer	325	550	440
26” rod gap	362	420	380
22” rod gap	310	380	340

- Assuming a switching surge level of **360kVp** for this 132kV system:
  - No protection against switching surge is required
  - The 26” gap gives inadequate protection at short times (FOV=420 kV is too close to 550kV transformer BIL) and should not operate on switching surges (380kV > 360kV)
  - The 22” gap is preferable in the short time region (FOV=380kV), but will operate quite frequently on switching surges (FOV=340kV).
- 26” rod gaps have been used in British 132 kV grid.

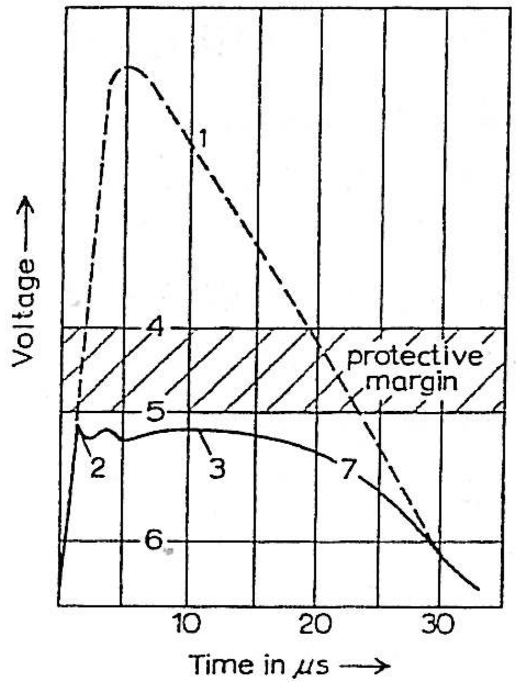
Other protection devices

Expulsion gaps

- The intermediate electrode is so proportioned that flashover takes place inside the vented tube
- The gases from the enclosed fibre tube are violently expelled through the vent and the effects of gas pressure, cooling, arc channel constriction and the rapid ejection of the ionised gases permit extinction of the power follow arc at its first current zero

Surge arresters

- New gapless (using zinc oxide non linear elements) as well old gapped type (using SiC non linear elements)
- Non-linear resistor (**$V = k.i^{\beta}$**, where β ~40 for gapless and ~0.2 for gapped)
- Protective level of surge arrester Ep is the maximum voltage which appears across the arrester
- Allowance must be made for the voltage drops in connecting leads



Response of a lightning arrester to an impulse voltage, showing its protective qualities:

1 impulse without arrester,
2 arrester sparkover voltage V_S,
3 arrester residual voltage V_r,
4 impulse withstand level of substation equipment,
5 protection level (see Section 1.7),
6 peak value of the system voltage,
7 impulse with arrester

Surge arrester selection

- Arresters are selected on the basis of voltage rating. To ensure safe resealing, the rated voltage of the surge arrester must equal or exceed the highest power frequency line to earth voltage which can appear at its point of installation

- Surge arrester operating characteristics may be found in manufacturers catalogues

- When the rating has been chosen, the operating conditions and protective level may be determined and the BIL of other equipment fixed with **a suitable margin** (usually about **25%**) above the protective level.

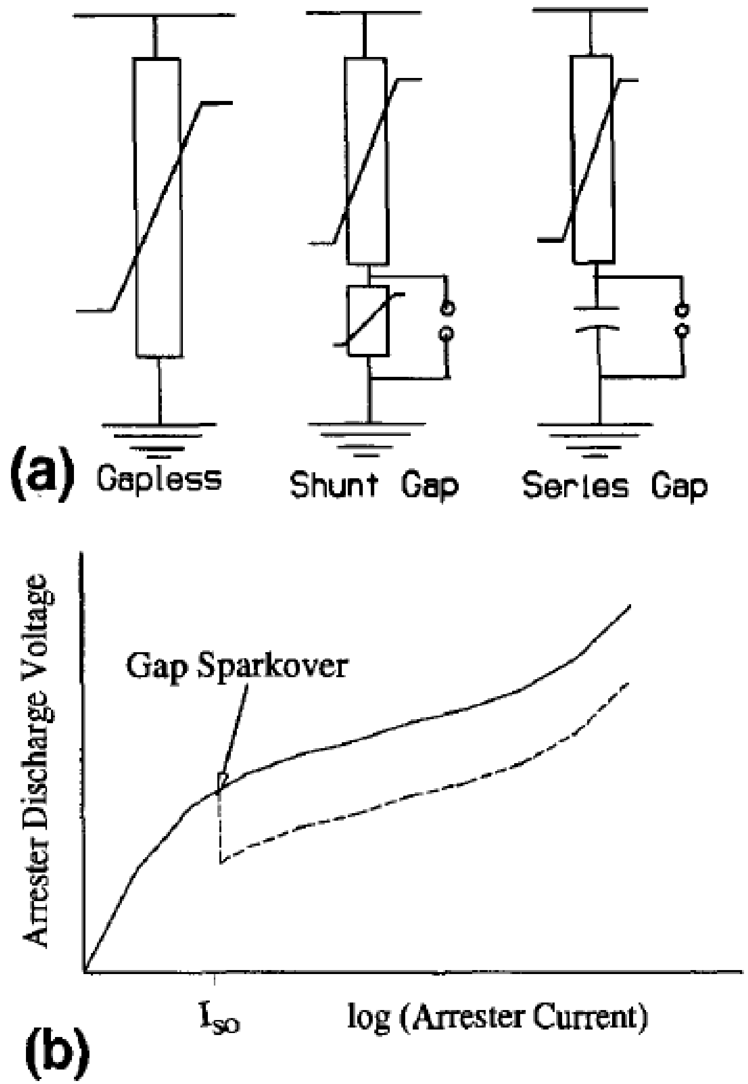


Figure 3 (a) Types of metal oxide arresters; (b) general characteristic of gapped MO arrester.

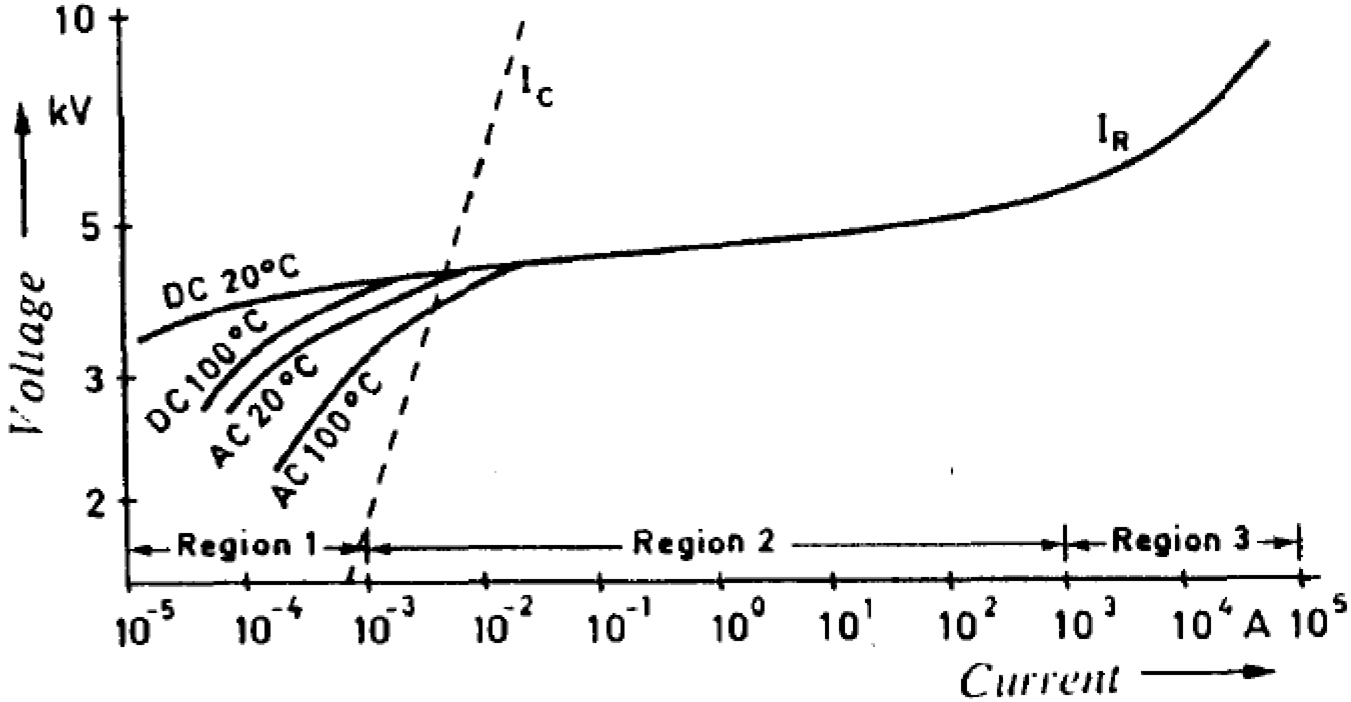
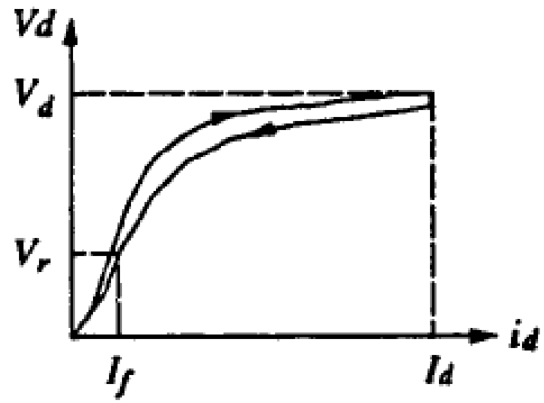


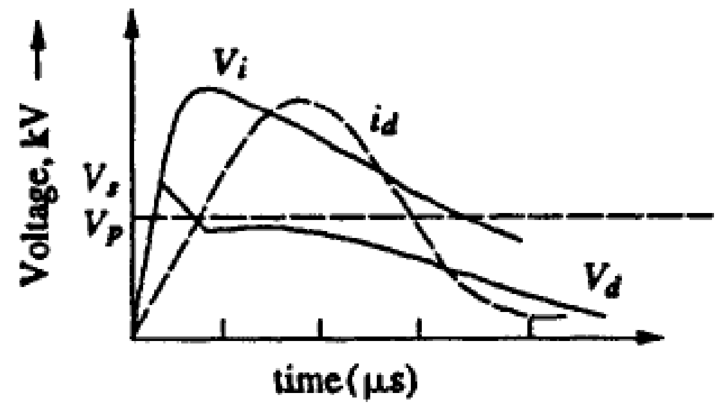
Figure 1 Typical characteristics of a metal oxide arrester disc: diameter = 80 mm, height = 20 mm. (From Ref. 7)

Table 1 IEEE Standard MCOV and Duty-Cycle Ratings of Arresters in kV, rms [1]

MCOV	Duty-cycle	MCOV	Duty-cycle	MCOV	Duty-cycle
2.55	3	42	54	209	258
5.1	6	48	60	212	264
7.65	9	57	72	220	276
8.4	10	70	90	230	288
10.2	12	76	96	235	294
12.7	15	84	108	245	312
15.3	18	98	120	318	396
17.0	21	106	132	335	420
19.5	24	115	144	353	444
22.0	27	131	168	372	468
24.4	30	140	172	392	492
29.0	36	144	180	428	540
31.5	39	152	192	448	564
36.5	45	180	228	462	576
39.0	48	190	240	470	588
				485	612



(a) Volt-ampere characteristic of a non-linear resistor block



(b) Surge diverter operation

I_f — Power frequency follow-on current at system voltage V_r

V_d — Max. voltage across the diverter during discharge of surge current with peak value I_d

V_s — Sparkover voltage

V_p — Protective level

V_i — Surge voltage

i_d — Discharge current

V_d — Voltage across the diverter when discharging the current i_d

Fig. 8.24 Characteristics of a surge diverter

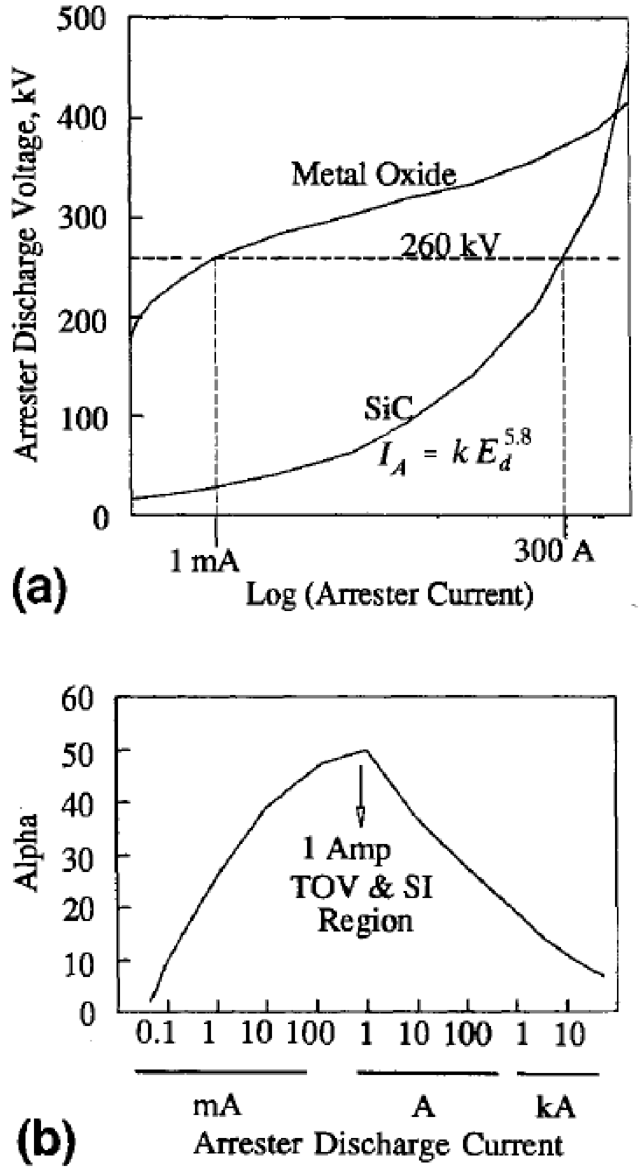


Figure 2 (a) Comparison of SiC and MO characteristics; (b) alpha characteristics of MO.

5. Surge arrester application in a substation and its protection performance

Step by step procedure for insulation coordination of substations with protected zone

It is assumed that a preliminary physical layout of the substation is available, including the location of all apparatus and possible locations for surge arresters.

1. shield the station against direct lightning strokes and estimate the incident surge voltage magnitude E_i and the slope K entering the station

2. select surge arrester rating and hence its protective level E_p

3. select transformer BIL (basic insulation level)

4. determine the protective zone of the surge arrester on the transformer side

5. select BIL of equipment on line-side of surge arrester

6. check switching surge performance

7. determine and check all minimum air clearances of substation equipment

8. refine calculation of all overvoltage based on the preliminary insulation coordination and repeat above procedures to modify and fine tune design wherever necessary (digital computer methods & programs for the calculations are available)

Example 1

A single transformer in a substation is supplied by a double circuit 132 kV overhead line. Using the **data** given below, select suitable lightning arresters for the protection of the transformer (for all cases below).

Transmission line

- Steel towers – **two** overhead **earthwires**
- Insulation level – **1100 kVp** (**50% flashover**)
- Surge impedance – **350 ohm for two parallel earthwires**
  - 350 ohm for phase conductor
- **Attenuation** – use $E_x = E_0 /(1 + KE_0X)$

  where K = 0.00016, E_0 is in kV and X is in miles
  Front prolongation – **2 us/mile**

Station equipment

- BIL – **650 kV**p
- **Earth resistance** – 0.5 ohms

Systems

- **Maximum** system voltage – 140 kV
- **Dynamic power frequency overvoltage** – 20%
- **Coefficient of earthing** – 80%

Determine the arrester current in each of the following cases:

(i) A lightning flashover at the first tower, 1200 feet from the substation, with one circuit already out of service

(ii) As for (i) but with both circuits connected to the substation bus

(iii) A lightning stroke at the first tower causes simultaneous back flashover to the same phase of both circuits (both connected to substation bus)

Solution

- **Coefficient of earthing** is defined for a three-phase system at a selected location as:

$$\frac{\text{highest rms line-to-earth power frequency voltage on a sound phase}}{\text{rated line-to-line voltage}}$$

- The coefficient is calculated from the phase sequence impedance components of the system as viewed from the selected location, using, for rotating equipment, the sub-transient reactances

- For: coefficient of earthing = 0.8

  Dynamic power frequency overvoltages = 20%

  Maximum system voltage = 140 kV (for 132 kV system)

  Then: max. line-to-earth voltage = **140 x 0.8 x 1.2 = 134** kV rms
- This value of max line-to-ground voltage is used to select the **rating** of the lightning arrester

- Selection of arrester – maximum 50 Hz voltage at point of installation
  = 140 x 1.2 x 0.8 = 134 kV rms.

  Referring to data sheets an arrester rated at 144 kV is selected

- Magnitude of surge entering substation after 1200’ of travel along line
  = E_i.1200’=0.227 miles.

  The initial surge voltage is taken as 1.2 x insulation level or 132 kV

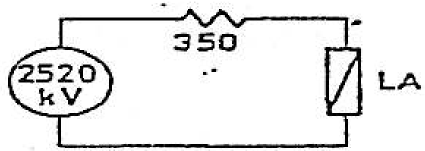
  $$E_i = 1320 / (1 + 1320 \times 0.00016 \times 0.227) = 1260 \text{ kV}$$

- Front time = 2 x 0.227 us = 0.454 us. Rate of rise 2770kV/us.

  Normally this front steepness would be unacceptably high – in this example the effect will be ignored

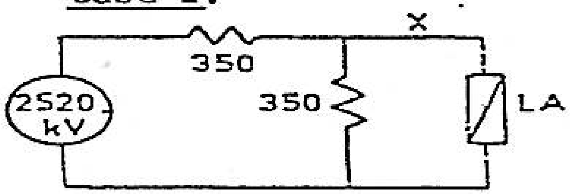
- The Thevenin equivalent circuits for the three cases are given below

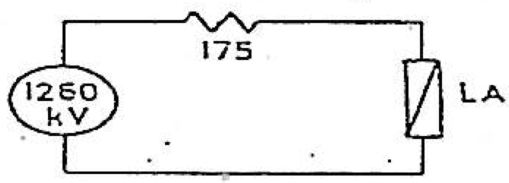
Case 1.



I = 6.4 kA

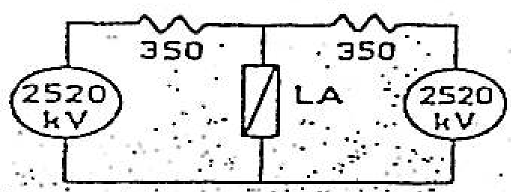
Case 2.



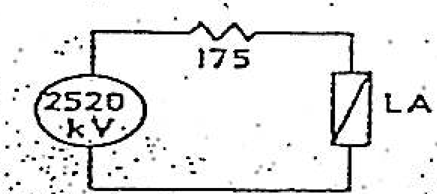


I = 5.6 kA

Case 3.

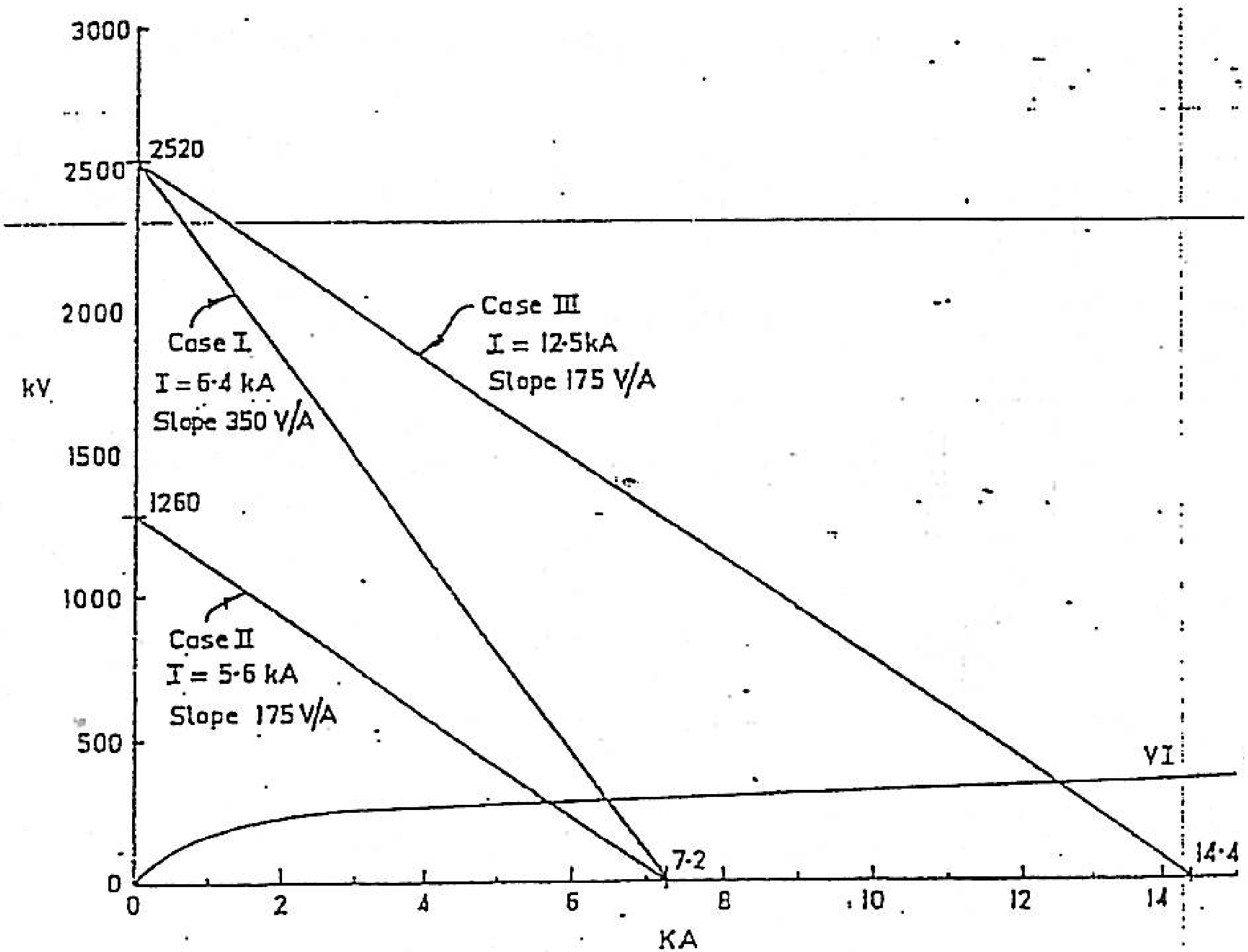


which is equivalent to



I = 12.5 kA.

- The graphical solutions for each of the three cases are shown below.



Appendix 1

PROTECTIVE CHARACTERISTICS

Arrester Rating KV RMS	Max. ASA Front-of-wave Sparkover KV Crest	Max. 1.½ x 40 Sparkover 1½ ± .2 μ sec. Range KV Crest	Max. Switching Surge Sparkover KV Crest	Max. 60 Cycle Sparkover KV RMS	Maximum Discharge Voltage (in Crest KV) at Indicated Impulse Current, 8 x 20 μ sec.					
					1.5 KA	3.0 KA	5.0 KA	10.0 KA	20.0 KA	40.0 KA
3	12	12	12	5.3	5.0	5.8	6.4	7.3	8.3	10.2
4.5	16	15	15	7.9	7.4	8.7	9.5	10.8	12.3	15.1
6	20	18	18	10.5	9.8	11.5	12.6	14.3	16.3	19.9
7.5	25	22	23	13.2	12.2	14.3	15.7	17.7	20.3	24.8
9	30	25	27	15.8	14.6	17.1	18.8	21.2	24.3	29.6
12	39	32	35	21.0	19.4	22.7	24.9	28.1	32.1	39.2
15	48	39	43	26.3	24.2	28.2	31.0	35.0	40.0	48.8
18	57	47	51	31.5	28.9	33.7	37.1	41.8	47.8	58.5
20	66	54	59	36.8	33.7	39.3	43.2	48.7	55.5	68.0
25	76	61	67	42.0	38.4	44.8	49.2	55.5	63.5	77.5
30	95	75	84	52.5	47.8	56.0	61.5	69.5	79.0	96.5
37	113	90	110	63.0	57.5	67.0	73.5	83.0	94.5	115
40	123	97	108	68.3	62.5	72.5	79.5	89.5	102	125
50	151	118	132	84.0	76	89.0	97.5	110	125	153
60	180	136	142	99	95	111	122	137	156	190
72	213	166	170	119	114	133	146	164	187	227
78	231	183	184	129	123	144	158	178	202	246
84	247	198	198	139	133	155	170	191	217	265
90	267	214	213	149	142	166	182	204	232	283
96	280	231	227	159	151	177	194	218	248	302
108	315	262	253	178	170	198	218	245	278	339
120	347	294	284	198	188	220	241	272	309	376
132	380	320	312	218	207	241	263	294	333	402
144	413	350	340	238	226	262	287	321	363	439
168	497	396	397	277	263	305	334	374	422	510
180	538	430	425	297	281	327	358	400	452	550
192	580	460	453	317	300	349	382	427	482	585
228	702	547	539	376	355	413	452	510	575	695
240	743	575	567	396	374	435	476	535	605	730
258	805	623	609	426	402	467	515	575	650	785
264	825	640	624	436	411	478	525	585	665	800
276	876	672	650	455	429	500	550	615	690	835
288	907	706	680	475	448	525	570	640	720	875
300	948	738	709	495	467	545	595	665	750	910
312	988	771	737	515	485	565	620	690	780	945

- The curve VI is the discharge voltage versus discharge current relationship for the arrester plotted from the data on arresters.

- Note that this curve relates peak current and peak voltage and that these values do not necessarily occur simultaneously – therefore, the solutions will be approximate only.

Example 2

A backflashover on the phase A of a transmission line insulator causes a surge of 1100-kV magnitude to travel to a surge arrester protected transformer in a substation. The surge impedance of the conductor is 350 Ω. The characteristics of the arrester is given below:

I (kA)	1.0	2.0	4.0	6.0	9.0	12.0
V (kV)	500	650	750	800	825	850

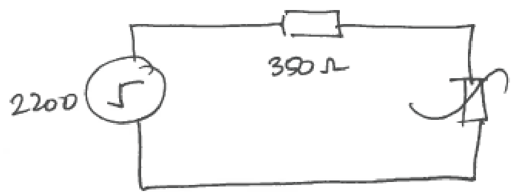
If no attenuation of the surge during travel is assumed, determine

- The discharge current and the residual voltage of the arrester if no other circuit conductors are connected to the transformer.
- The discharge current and the residual voltage of the arrester if two other circuit conductors are connected to the transformer.
- The discharge current and the residual voltage of the arrester if another circuit conductor is also connected to the transformer with exactly the same backflashover voltage traveling towards the transformer.
- The discharge current and the residual voltage of the arrester if two other circuit condcutors are also connected to the transformer with exactly the same backflashover voltage traveling towards the transformer.
- The discharge current and the residual voltage of the arrester if two other circuit condcutors are also connected to the transformer with exactly the same backflashover voltage traveling towards the transformer, AND two other circuit conductors are also connected to the transformer,

Note: Neglect the effects of surge attenuation and earthing factors.

Q3 (a) BIL insulator 1100-kV
$Z_L = 350\Omega$.

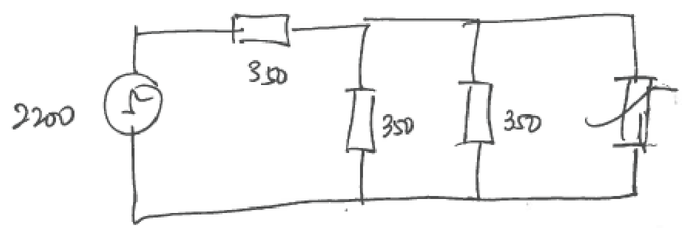
(i) Equivalent circuit :



From the graph, the discharge current is 4.15 kA ; V_{res} = 750 kV

(4)

(ii)



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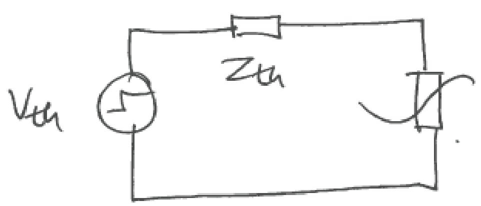


(6)

$$V_{th} = \frac{175}{175+350} \times 2200 = 733.3\ kV.$$

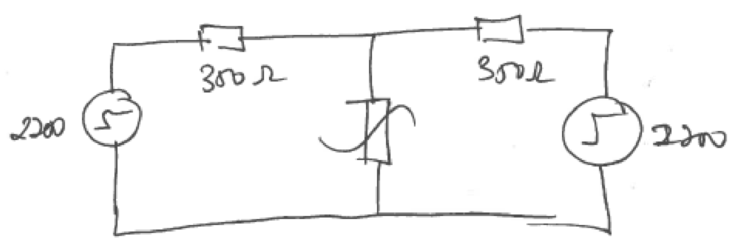
$$Z_{th} = \frac{350}{3} = 116.7\ \Omega$$

From the graph, the discharge current

$= 1.4\ kA.$

$V_{res} \simeq 575\ kV$

(iii) Equivalent circuit:



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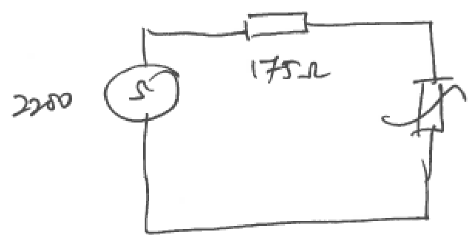


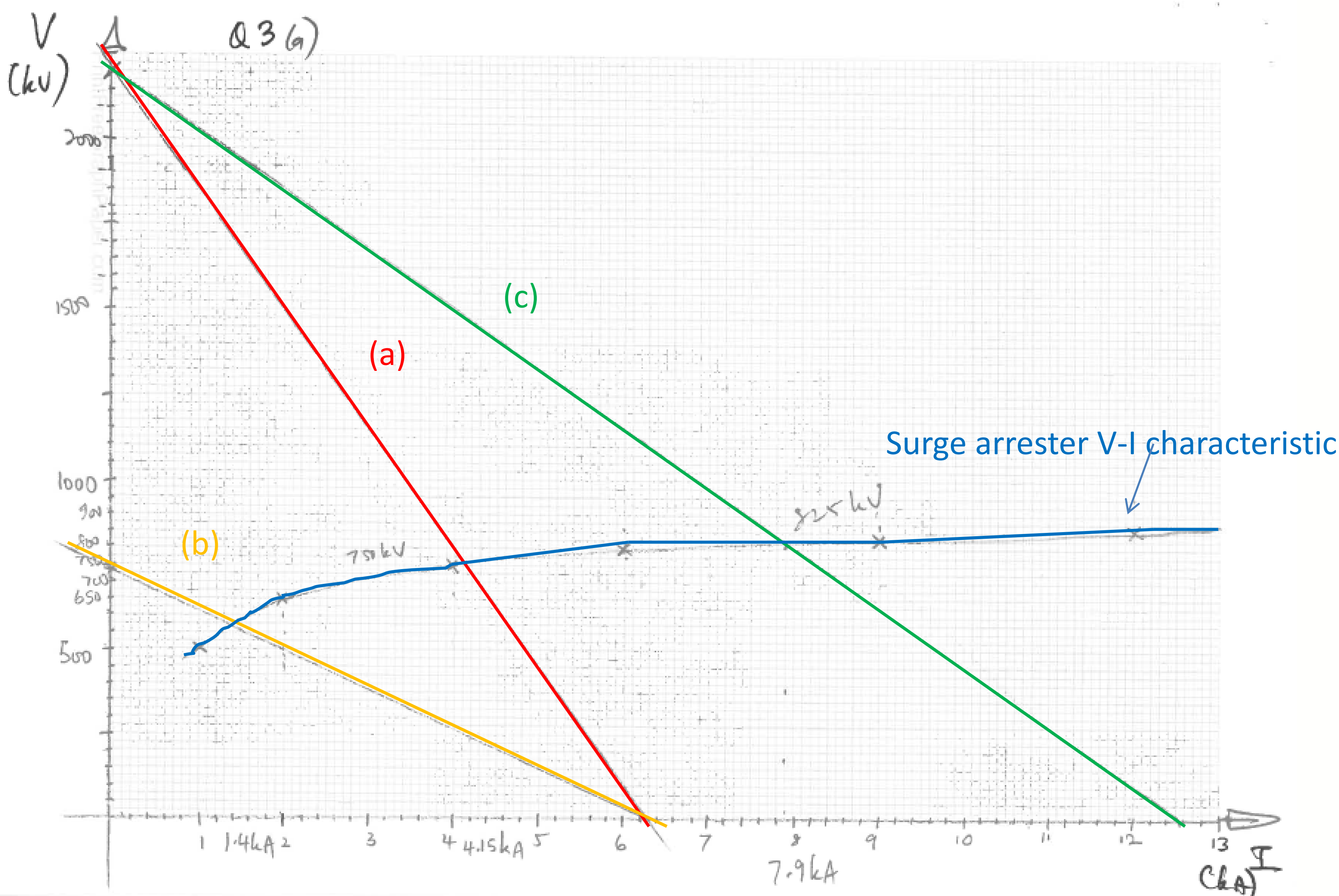
From the graph

$I = 7.9\ kA$

$V_{res} = 825\ kV$ #

5

Zulkurnain Abdul Malek Mar 2021

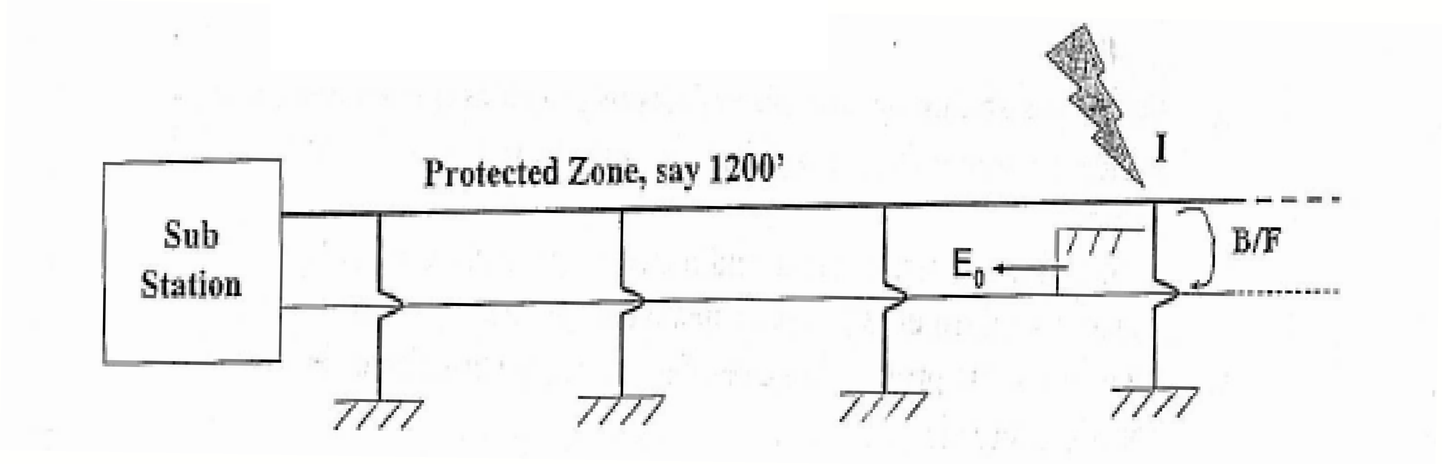


Q 3 (a)
V (kV)
I (kA)
2000
1500
1000
900
800
750
700
650
500
1
1.4kA
2
3
4
4.15kA
5
6
7
7.9kA
8
9
10
11
12
13
750kV
825kV
(a)
(b)
(c)
Surge arrester V-I characteristic

- A very good protected zone with low probability of shielding failure and backflashover is provided some distance from the substation

- Surges can then only enter the substation via a backflashover

- After backflashover we have a stepped wave, of magnitude = BIL of the insulator string, being propagated into the substation along the phase conductors



- Because of variation of test voltages in different conditions and test plant impedances, etc as well as differences between 50% flashover voltage and the **worst case** of flashover voltage (FOV), we take

$$E_0 = 1.2 \times BIL^* \text{ of insulator string}$$

* BIL value for negative test wave

(This originating surge of magnitude E_0 undergoes attenuation and distortion before reaching the substation)

- For steep front travelling waves, the voltages at different points in the substation will exceed the protective level by amounts depending on the distance from the arrester location, the steepness of the wavefront and the electrical parameters of the station.

- The BIL (basic lightning insulation level) is often determined by simply adding a MARGIN of, say 25% to 30% to the protective level of the surge arrester and then selecting the next higher BIL from the list of standard values.

Distance Effect

- For large and important stations, it is necessary to allow for the 'DISTANCE EFFECT' more accurately
- It is seen that the maximum voltage at an object at a distance D from the surge arrester either upline or downline is

$$V(D) = V_p + 2ST$$

where

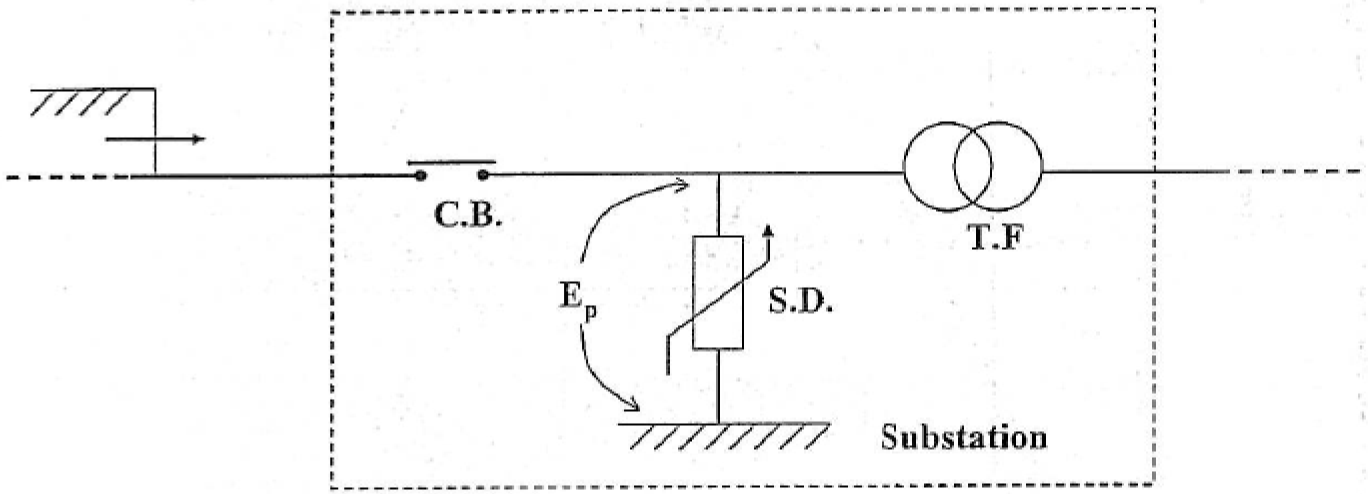
T = D/v = travel time between SA and object

S =K = slope of wave in kV/us

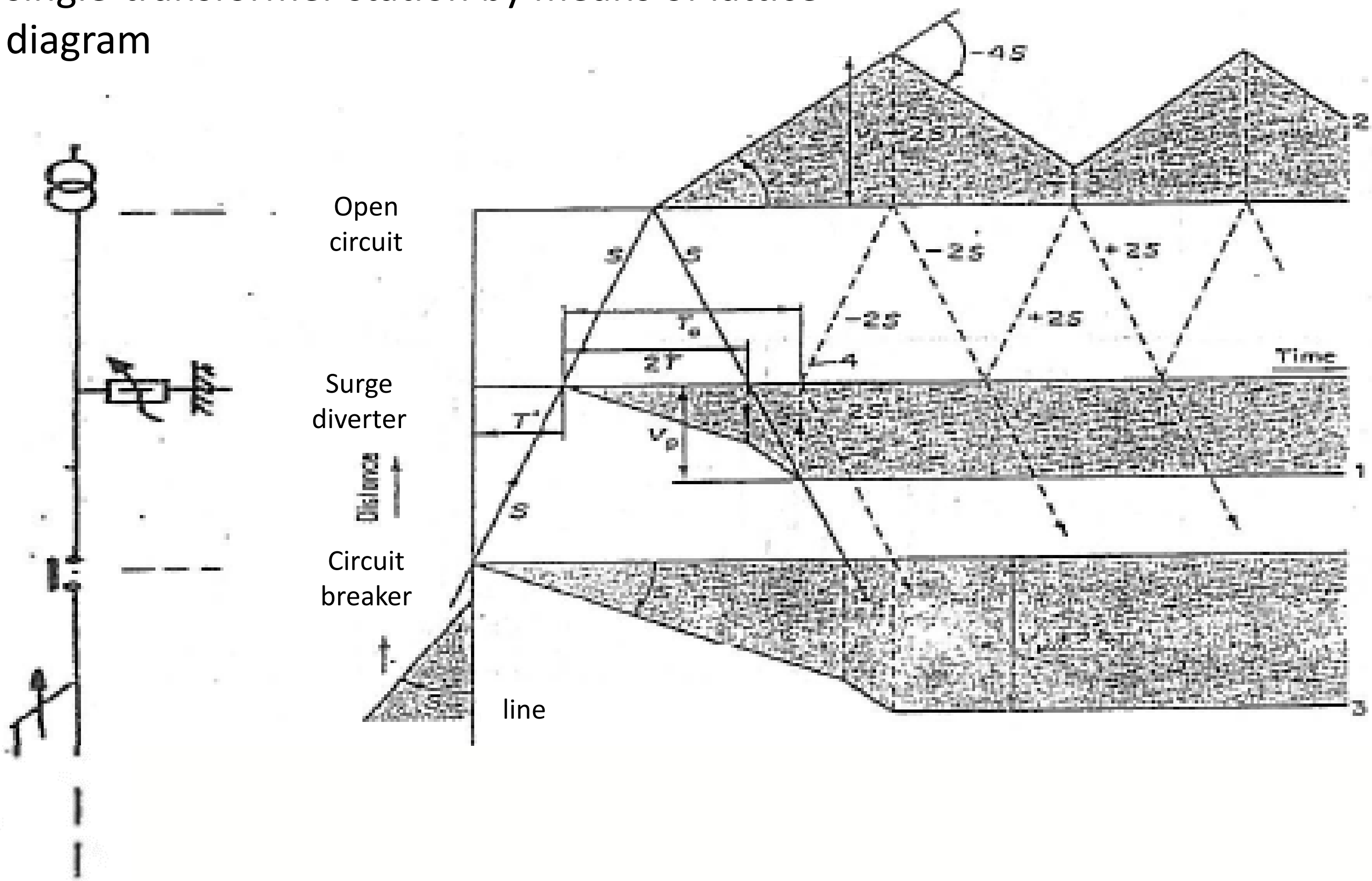
v= = velocity of surge propagation

- Irrespective of the slope of the incoming surge, V(D) cannot exceed $2V_p$; this maximum value is attained for 2T > $_{T0}$, where T_0 = time to SA operation

Distance Effect



Determination of surge voltages in single-line, single-transformer station by means of lattice diagram



Example 1

For the configuration shown in Fig. Q3(b), the time taken for the wave with a slope of K kV/μs to travel the distance D is T. Plot the travelling waves observed at the arrester and at the transformer for up to t = 6T. The arrester operates at $t_o = 2.5T$.

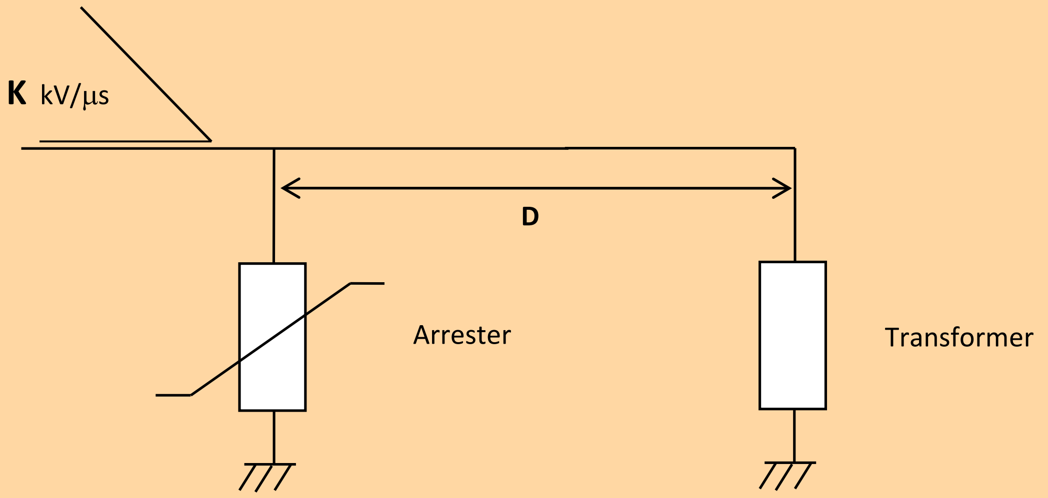
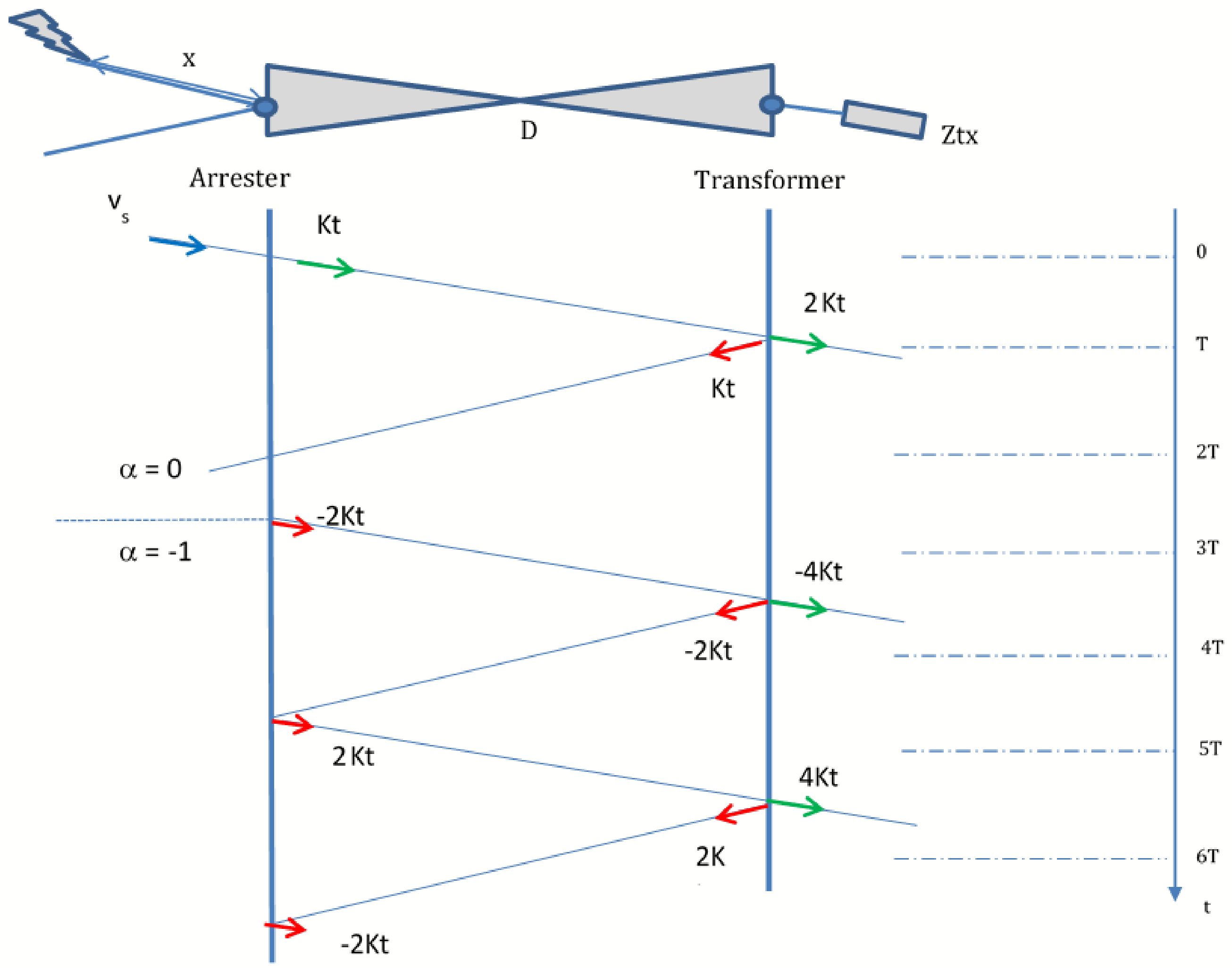
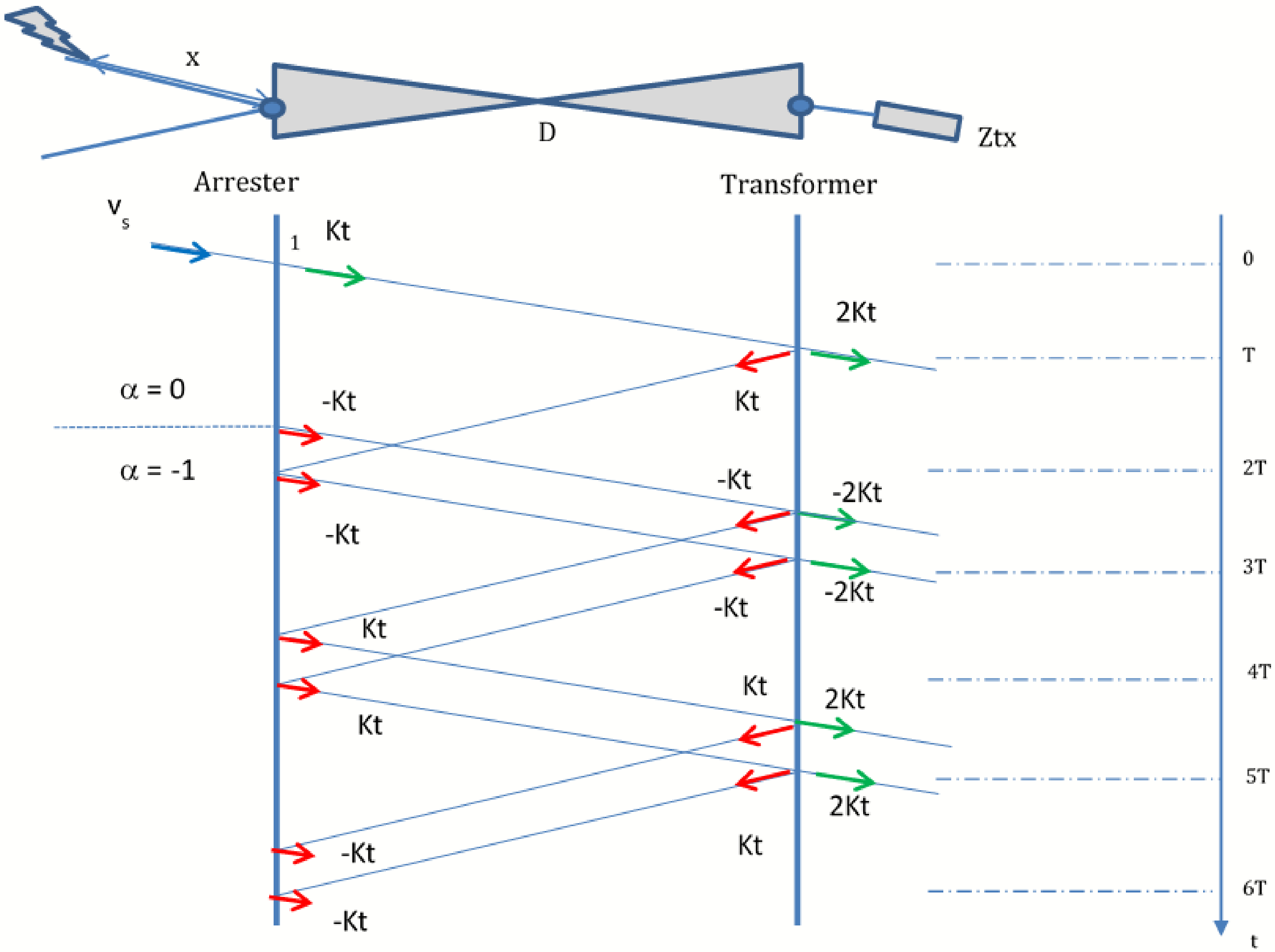
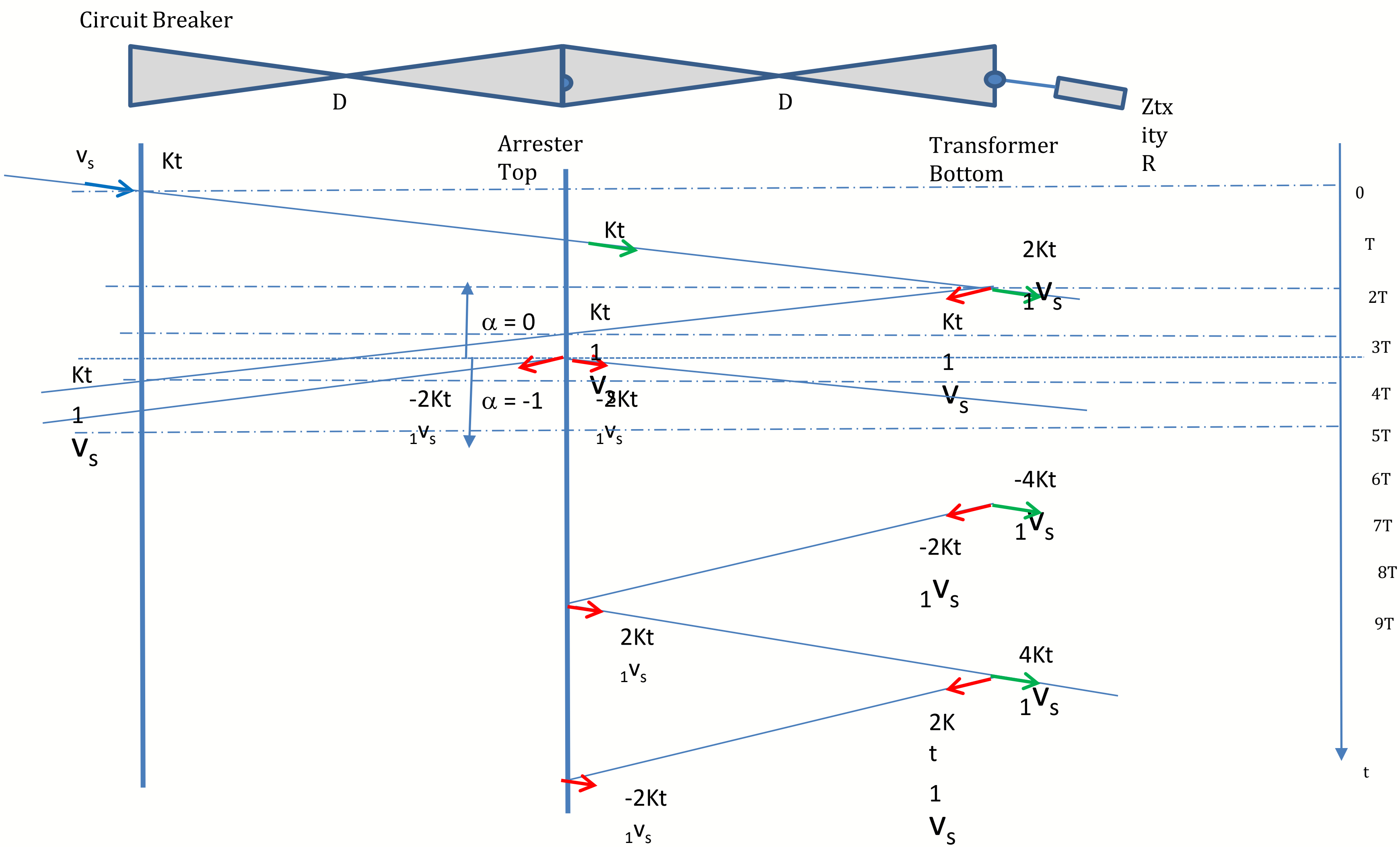


Fig. Q3(b)

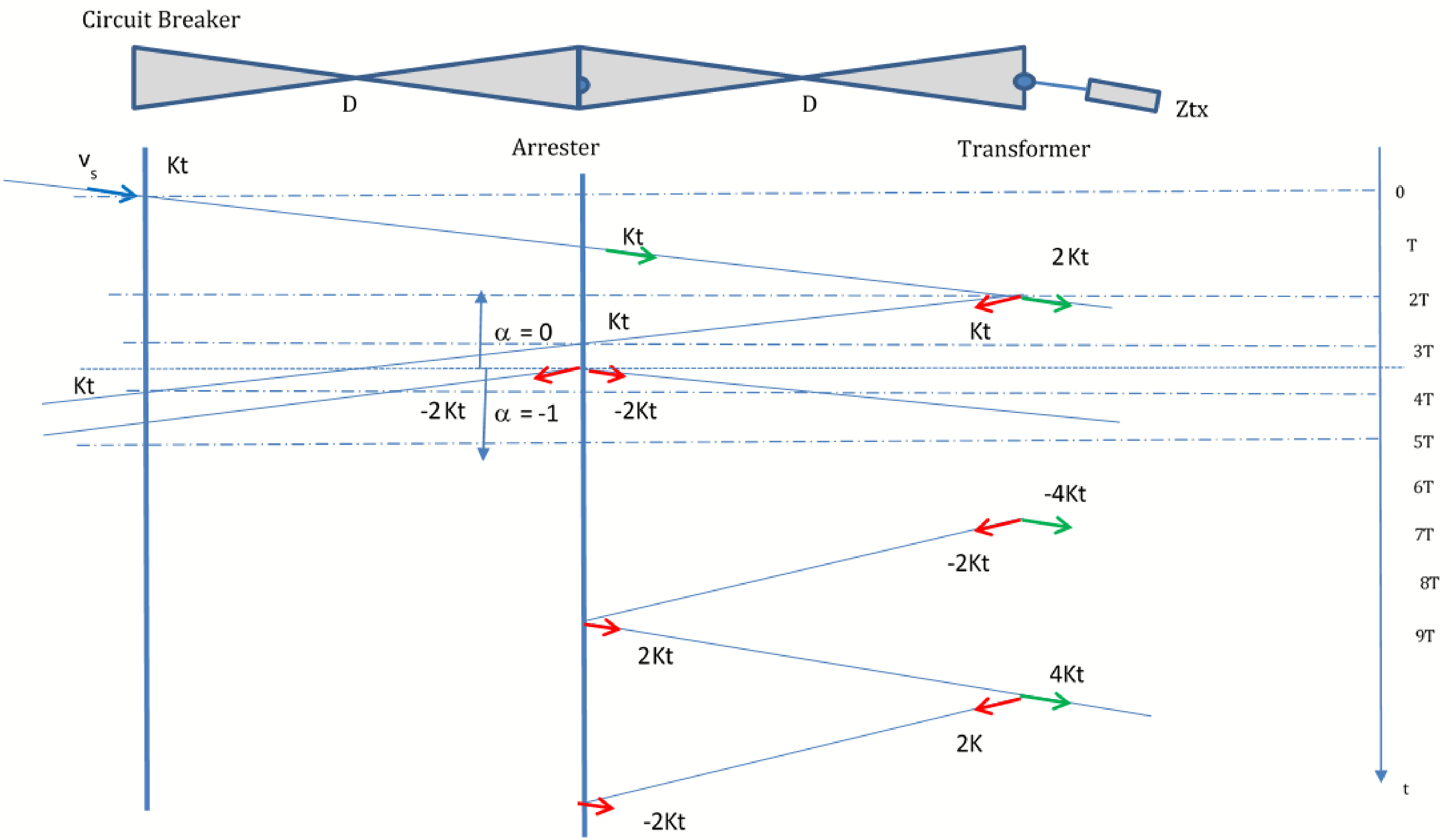

x
D
Ztx
Arrester
Transformer
Vs
Kt
2 Kt
Kt
α = 0
-2Kt
α = -1
-4Kt
-2Kt
2 Kt
4Kt
2K
-2Kt
0
T
2T
3T
4T
5T
6T
t



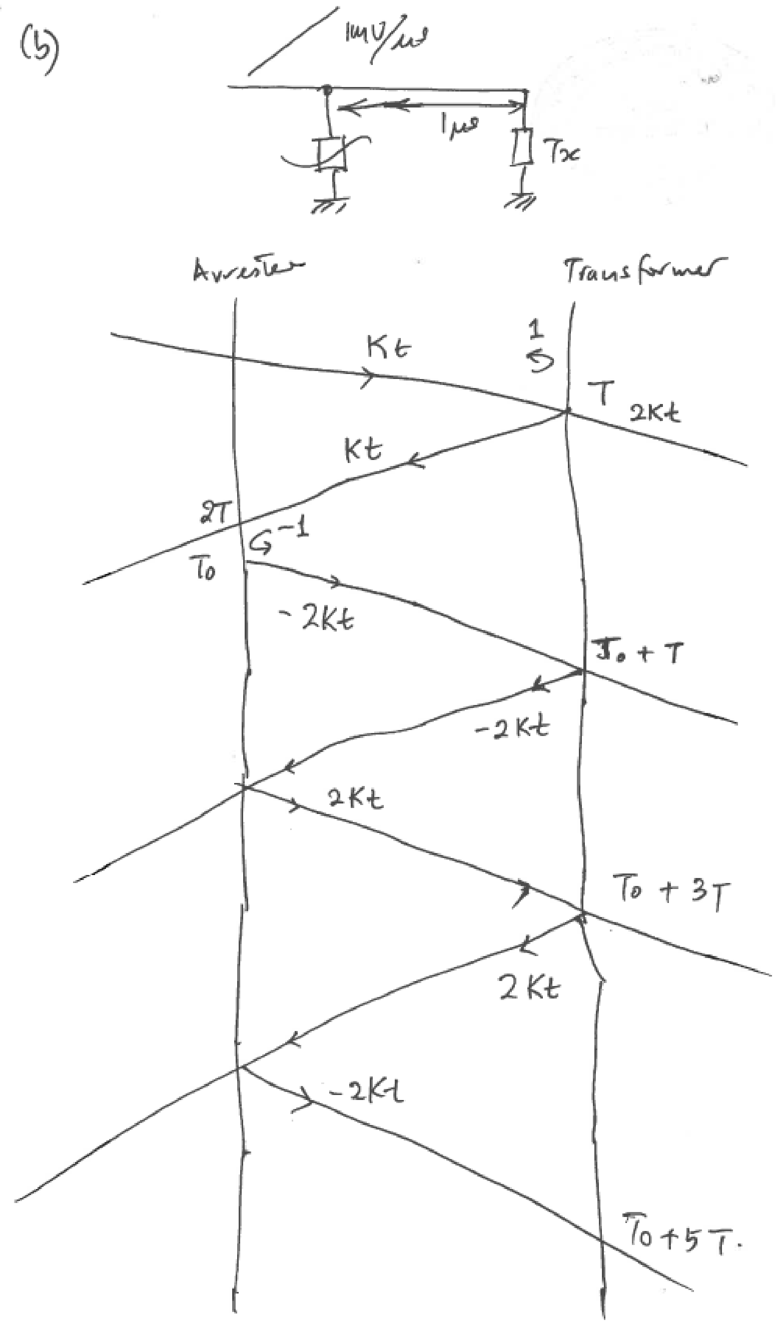
x
D
Ztx
Arrester
Transformer
V_s
1
Kt
2Kt
Kt
α = 0
α = -1
-Kt
-Kt
-2Kt
-Kt
-2Kt
-Kt
Kt
Kt
2Kt
Kt
2Kt
-Kt
Kt
-Kt
0
T
2T
3T
4T
5T
6T
t

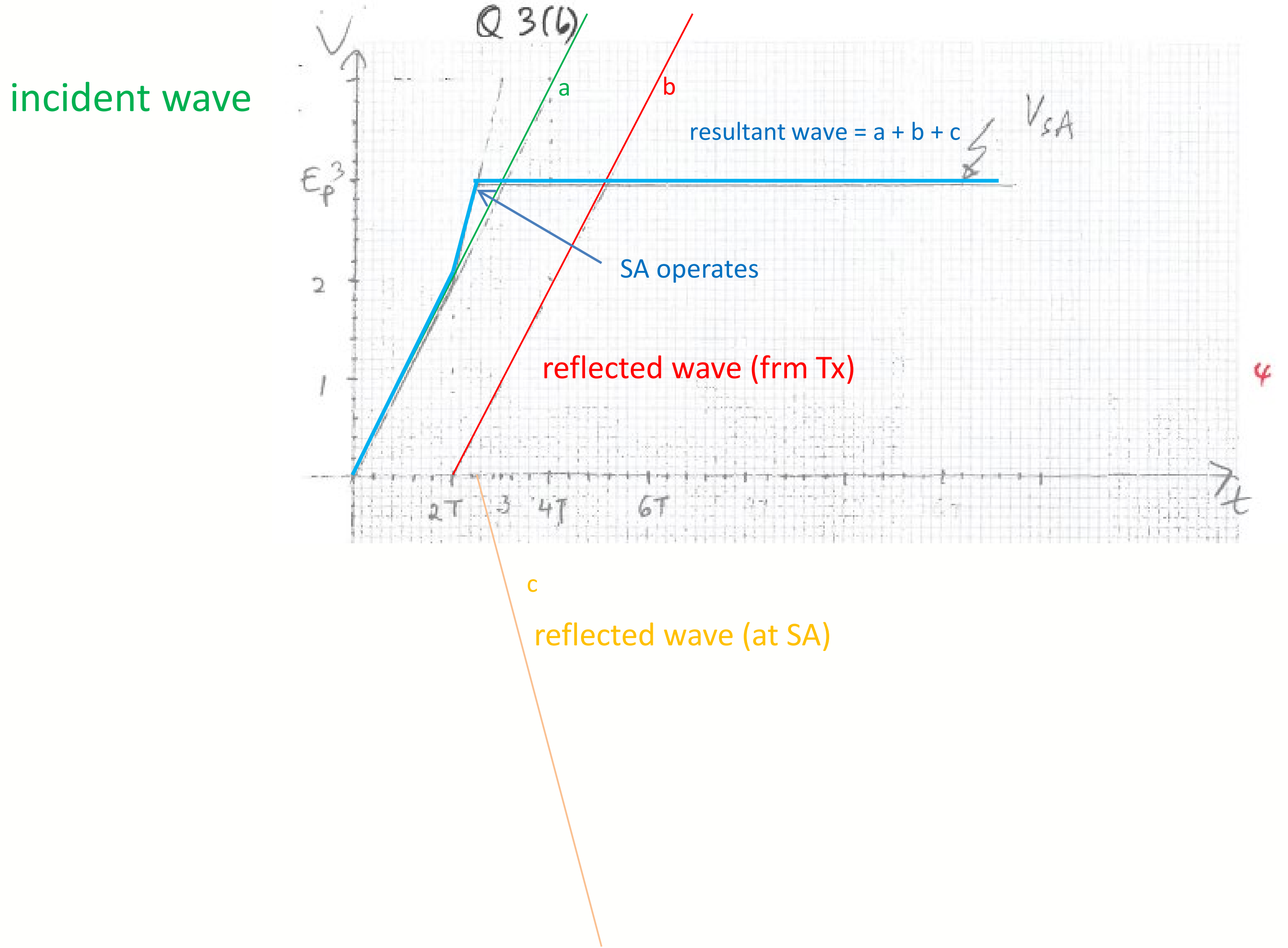


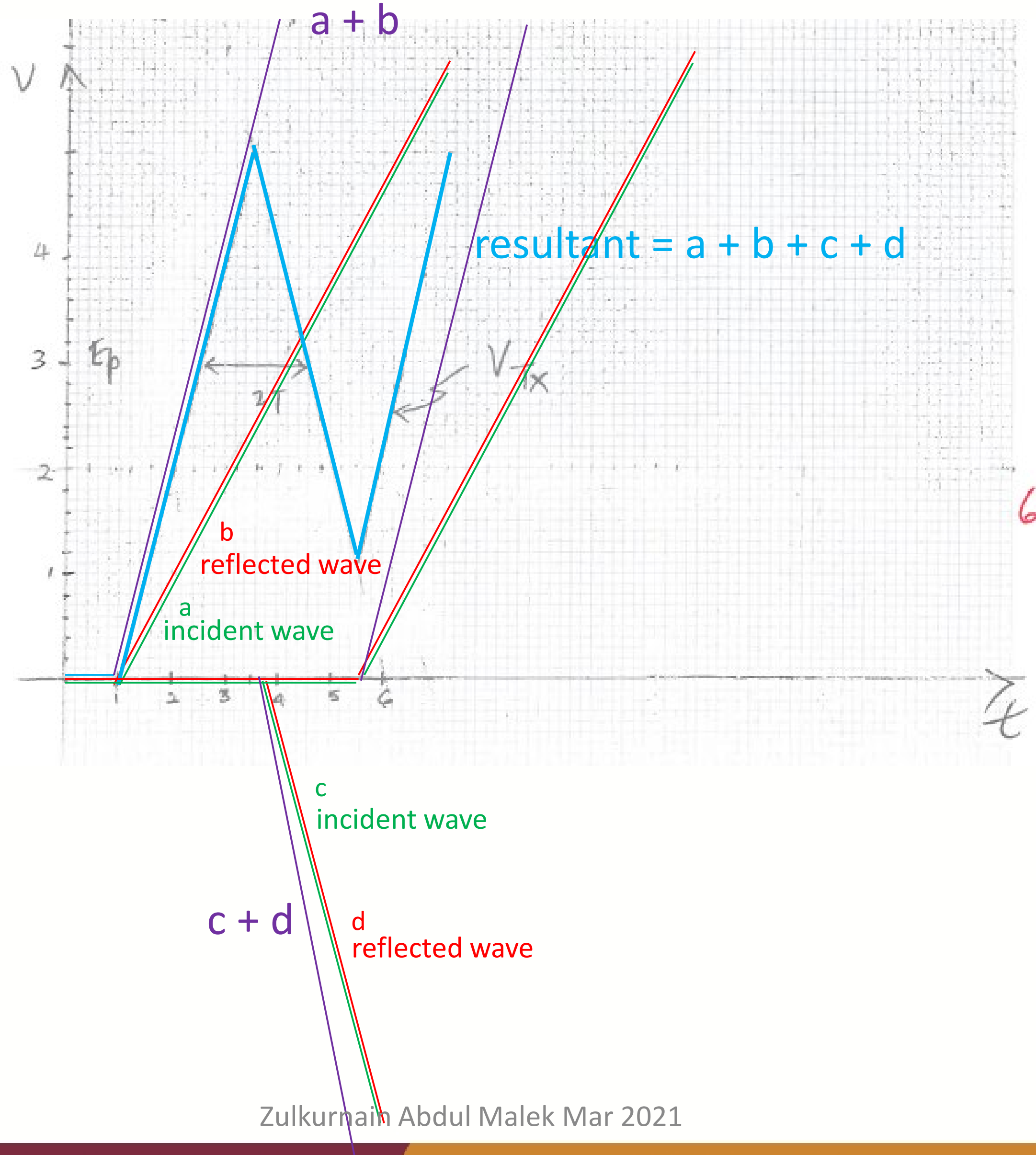
Circuit Breaker
D
D
Ztx
ity
R
Arrester
Top
Transformer
Bottom
vs
Kt
0
T
2T
3T
4T
5T
6T
7T
8T
9T
t
Kt
2Kt
1Vs
Kt
α = 0
Kt
1
Vs
α = -1
-2Kt
1Vs
-2Kt
1Vs
Kt
1
Vs
-4Kt
1Vs
-2Kt
1Vs
2Kt
1Vs
4Kt
1Vs
2K
t
1
Vs
-2Kt
1Vs

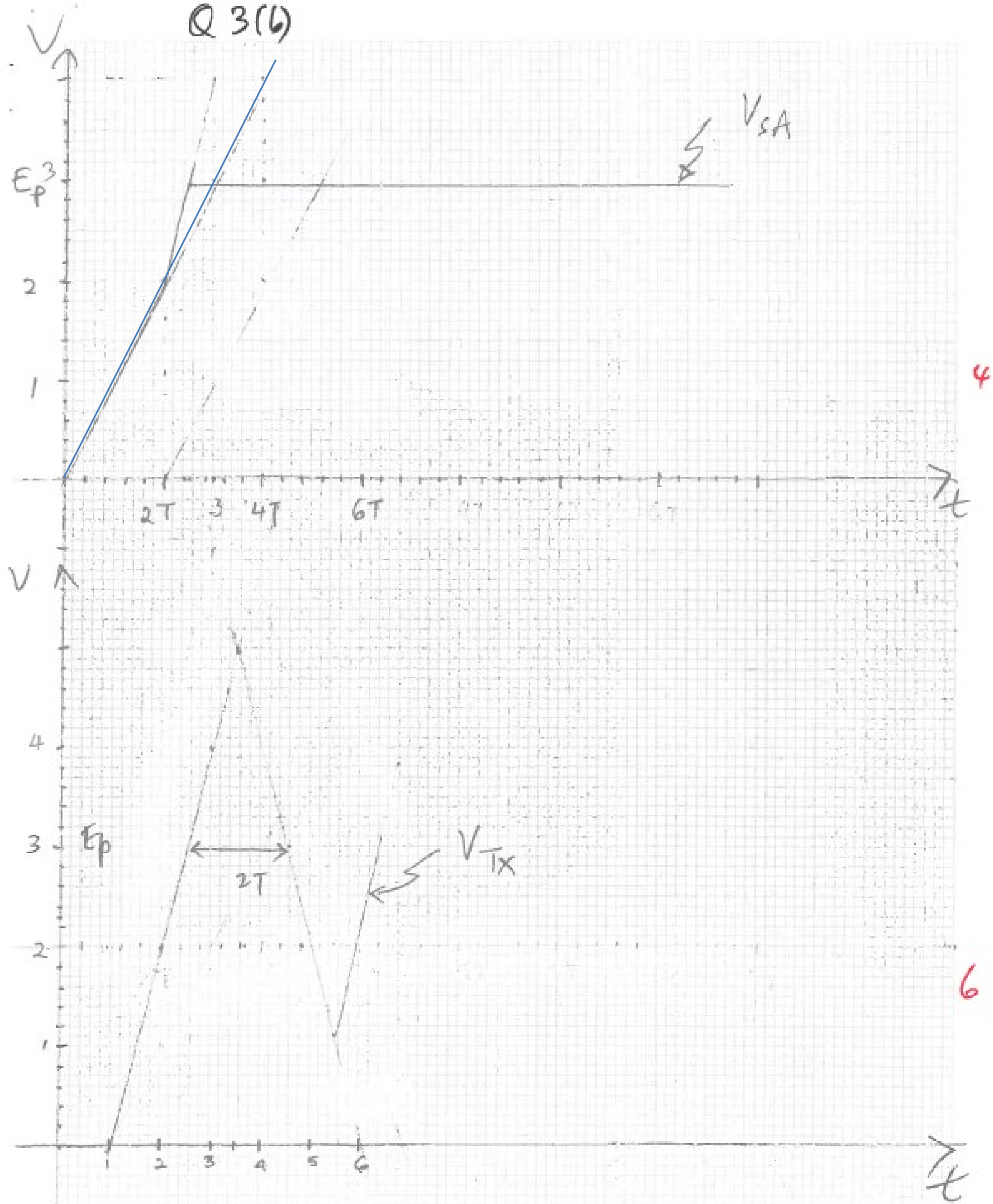

Circuit Breaker
D
D
Ztx
Arrester
Transformer
v_s
Kt
Kt
2 Kt
Kt
Kt
α = 0
Kt
-2 Kt
α = -1
-2Kt
-4Kt
-2Kt
2Kt
4Kt
2K
-2Kt
0
T
2T
3T
4T
5T
6T
7T
8T
9T
t

(b)


1MV/μs
1μs
Tx
Arrester
Transformer
Kt
1
T
2Kt
Kt
2T
-1
To
-2Kt
To + T
-2Kt
2Kt
To + 3T
2Kt
-2Kt
To+5T.


incident wave
Q 3(b)
V
a
b
resultant wave = a + b + c
V_{SA}
E_p 3
SA operates
2
1
reflected wave (frm Tx)
4
2T
3
4T
6T
t
c
reflected wave (at SA)


a + b
V
4
3
2
1
Ep
2T
V Tx
resultant = a + b + c + d
b
reflected wave
a
incident wave
1
2
3
4
5
6
t
c
incident wave
c + d
d
reflected wave
6


Q 3(6)
V
V_{SA}
E_p 3
2
1
2T
3
4T
6T
t
4
V
4
3
E_p
2T
V_{TX}
2
1
1
2
3
4
5
6
t
6

Example 2

For the configuration shown in Fig. Q3(b), the time taken for the wave with a slope of K kV/μs to travel the distance D is T. Plot the travelling waves observed at the arrester and at the transformer for up to t = 6T. The arrester operates at $t_o = 1.5T$.

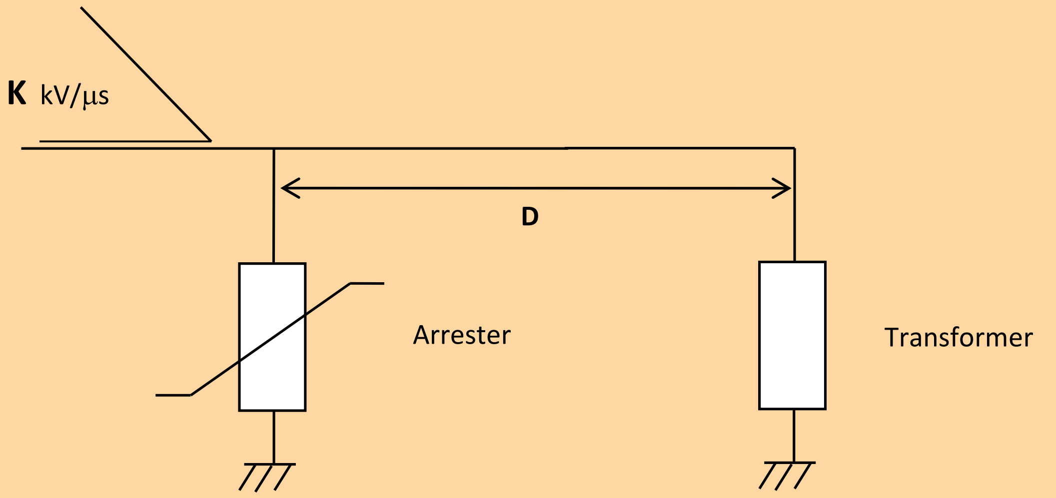


Fig. Q3(b)

Example 3

For the configuration shown in Fig. Q3(b), the time taken for the wave with a slope of K kV/μs to travel the distance D is T. Plot the travelling waves observed at the arrester and at the transformer for up to t = 6T. The arrester operates at $t_o = 1T$.

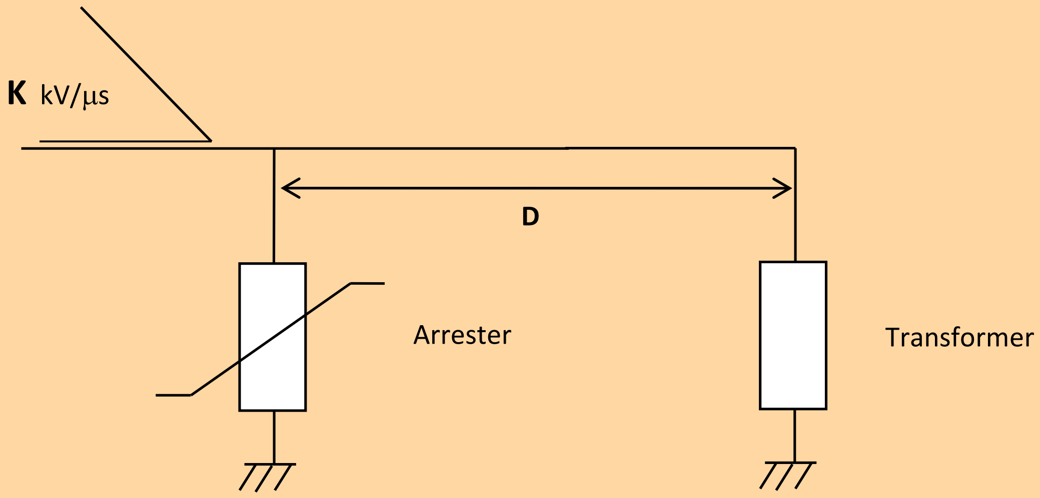


Fig. Q3(b)

Example 4

For the configuration shown in Fig. Q3(b), the time taken for the wave with a slope of K kV/μs to travel the distance D is T. Plot the travelling waves observed at the arrester and at the transformer for up to t = 6T. The arrester operates at $t_o = 2T$.

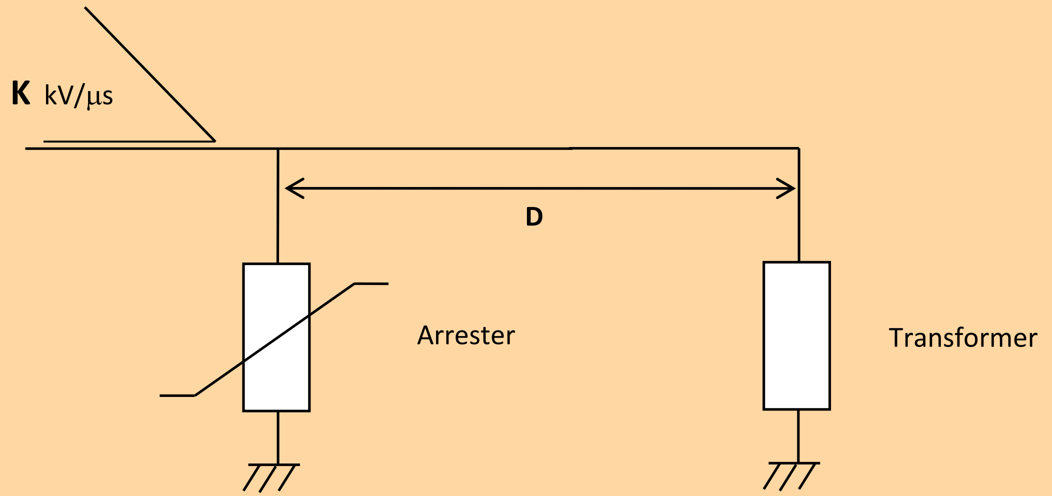


Fig. Q3(b)

Example 5

For the configuration shown in Fig. Q3(b), the time taken for the wave with a slope of K kV/μs to travel the distance D is T. Plot the travelling waves observed at the arrester and at the transformer for up to $t = 6T$. The arrester operates at $t_o = 3T$.

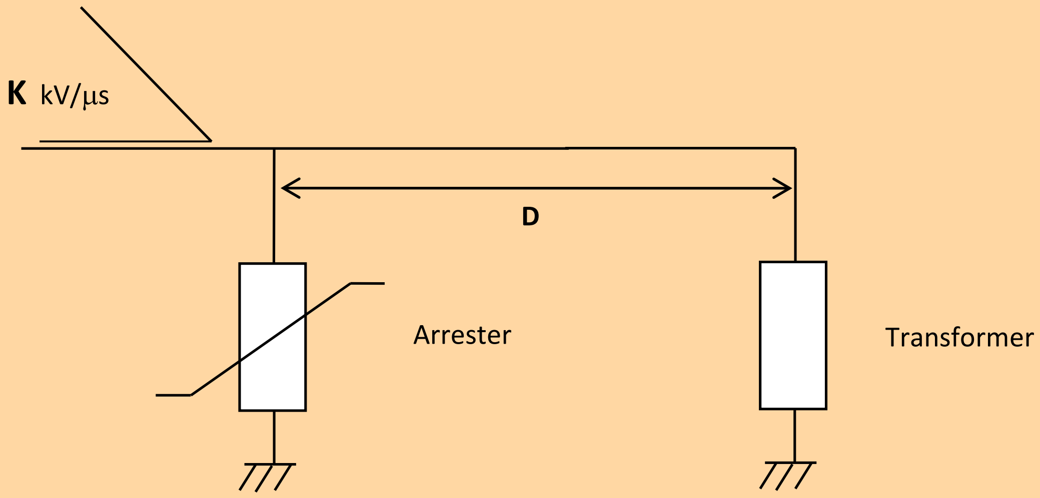
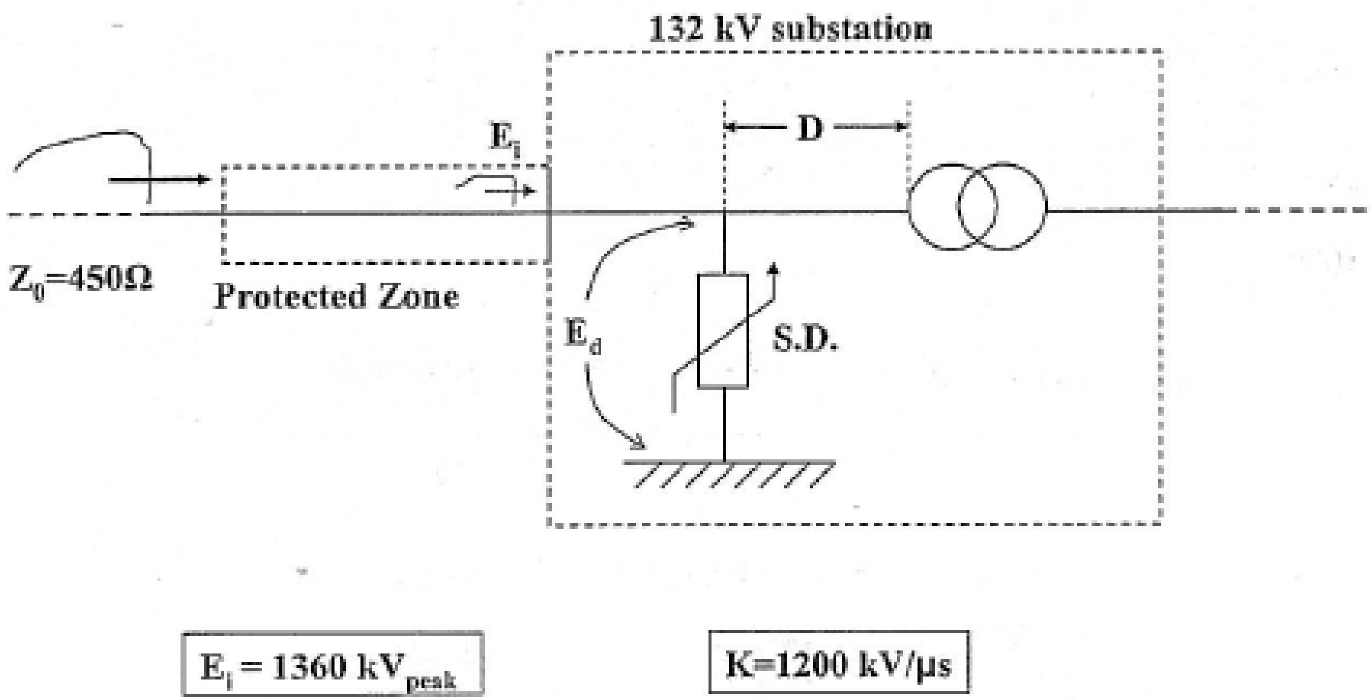


Fig. Q3(b)

Example

A 132 kV substation has a maximum 50 Hz line-earth voltage of 110kV rms. The incoming 132 kV line has overhead earthwires and the protected zone is designed to limit incoming surges to 1360 kV peak with a maximum rate of rise of 1200 kV/us. Z_0 for the line is 450 ohms. Design the protective system.



Selection of surge arrester

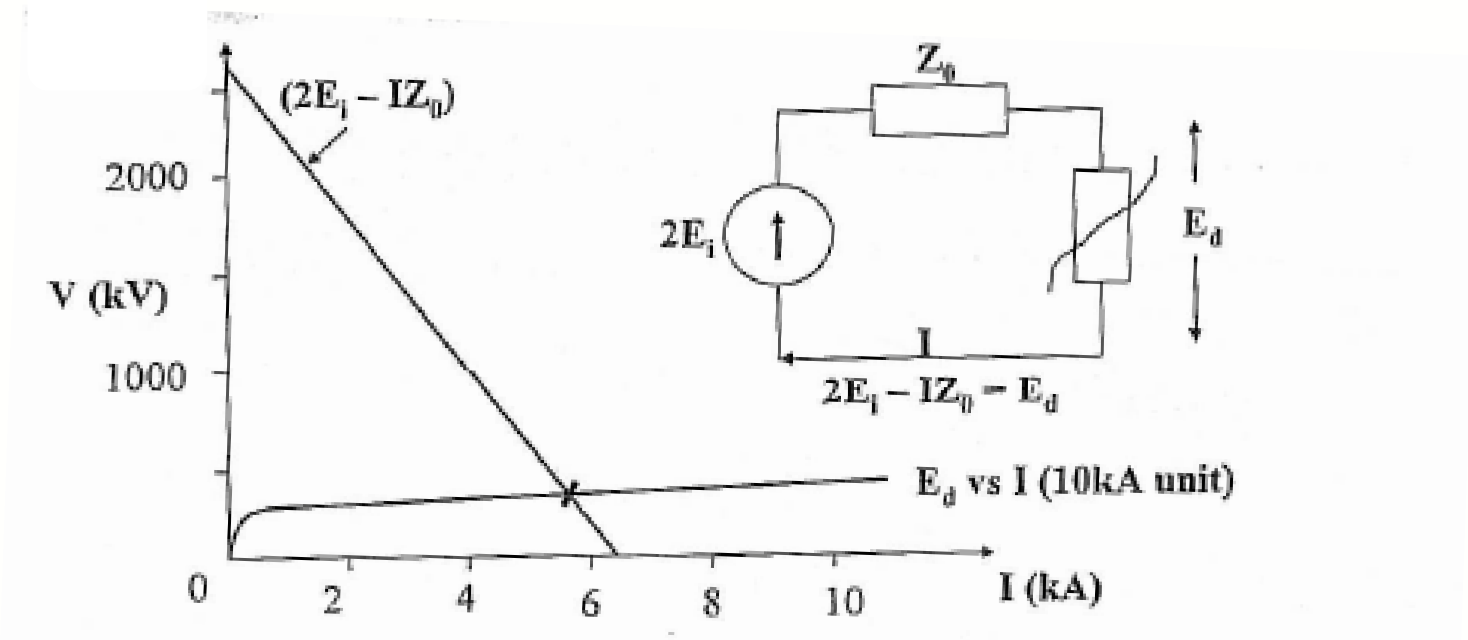
- From surge arrester characteristics, the lowest applicable rating is 120 kV

Determination of maximum discharge current

- Using the equivalent circuit as shown

$$2E_i = E_d + IZ_0$$

where E_0 = surge arrester terminal voltage for a discharge current I



- The graphical construction above is used to find E_d and I

  $\therefore E_d = 255$ kV, I = 6 kA

- Normally a 10kA arrester would be used although the risk of installing a 5kA unit might be acceptable.

The protective level E_p

E_p includes the IZ drops in connecting leads

$$E_p = E_d + IR + L\,di/dt$$

Now, at current peak

$I = I_{max}$, slope $di/dt = 0$; and di/dt is greatest at $t = 0$ for which $I = 0$.

In practice, $E_p = E_d + L\,di/dt$ at $t=0$

Assume 7m connections and L = 1.14 uH per m

∴ L = 8 uH

For 8/20 us current wave of 6 kA peak,

$dI/dt = 6\ kA/8\ us = 7.5 \times 10^{8}\ A/s$

∴ $E_p = 255 + 8 \times 10^{-6} \times 7.5 \times 10^{8} = 261\ kV$

This figure is an estimate of E_p based on discharge performance.

The possibility of a protection voltage in excess of 261kV must be considered.

The rate of rise of incoming surges will determine gap SOV (spark over voltage – for gapped arresters).

For an incident surge of 1360 kV peak at 1200 kV/us, the front time is ~1.2us.

The maximum gap SOV is, therefore approximately the 1.2/50 us SOV, ie 294 kV.

Thus, E_p is taken as 294 kV, and an appropriate transformer BIL can now be considered. BIL’s for 132 kV transformers: 550, 450, 380 kV.

- Assume 8m connections and L = 1uH per m

  ∴ L = 8 uH. For 8/20 us current wave of 6 kA peak,

  $dI/dt = 6\ kA/8us = 7.5 \times 10^{8}\ A/s$

  ∴ $Ep = 255 + 8 \times 10^{-6} \times 7.5 \times 10^{8} = 261\ kV$

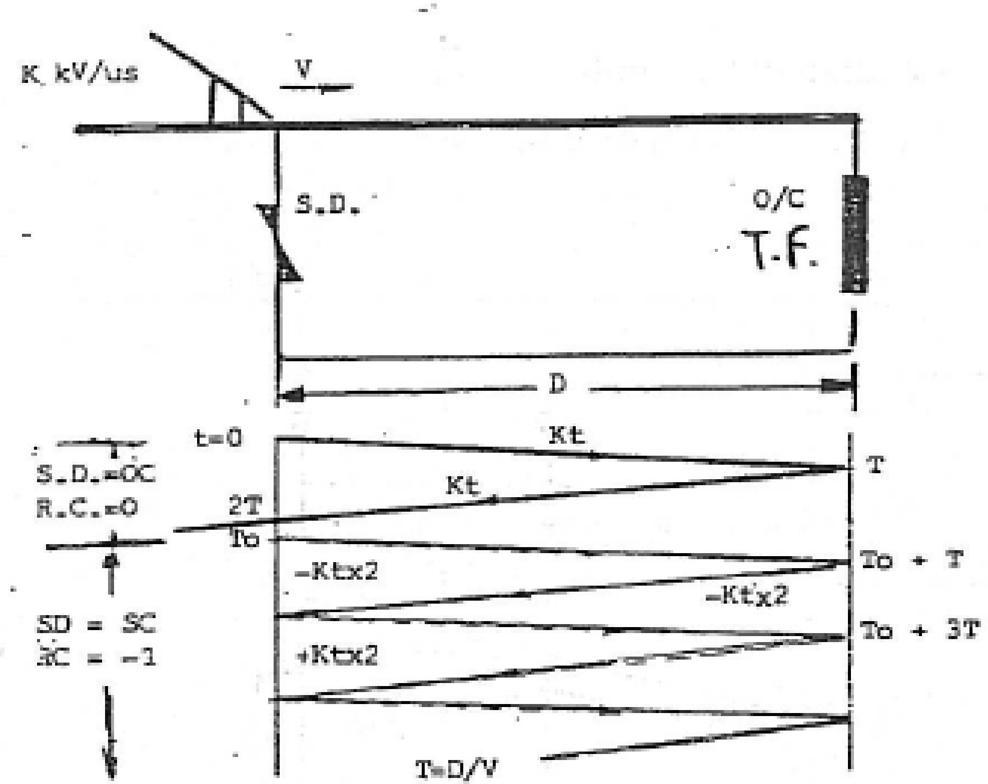
- This figure is an estimate of E_p based on discharge performance. The possibility of a protection voltage in excess of 261kV must be considered.

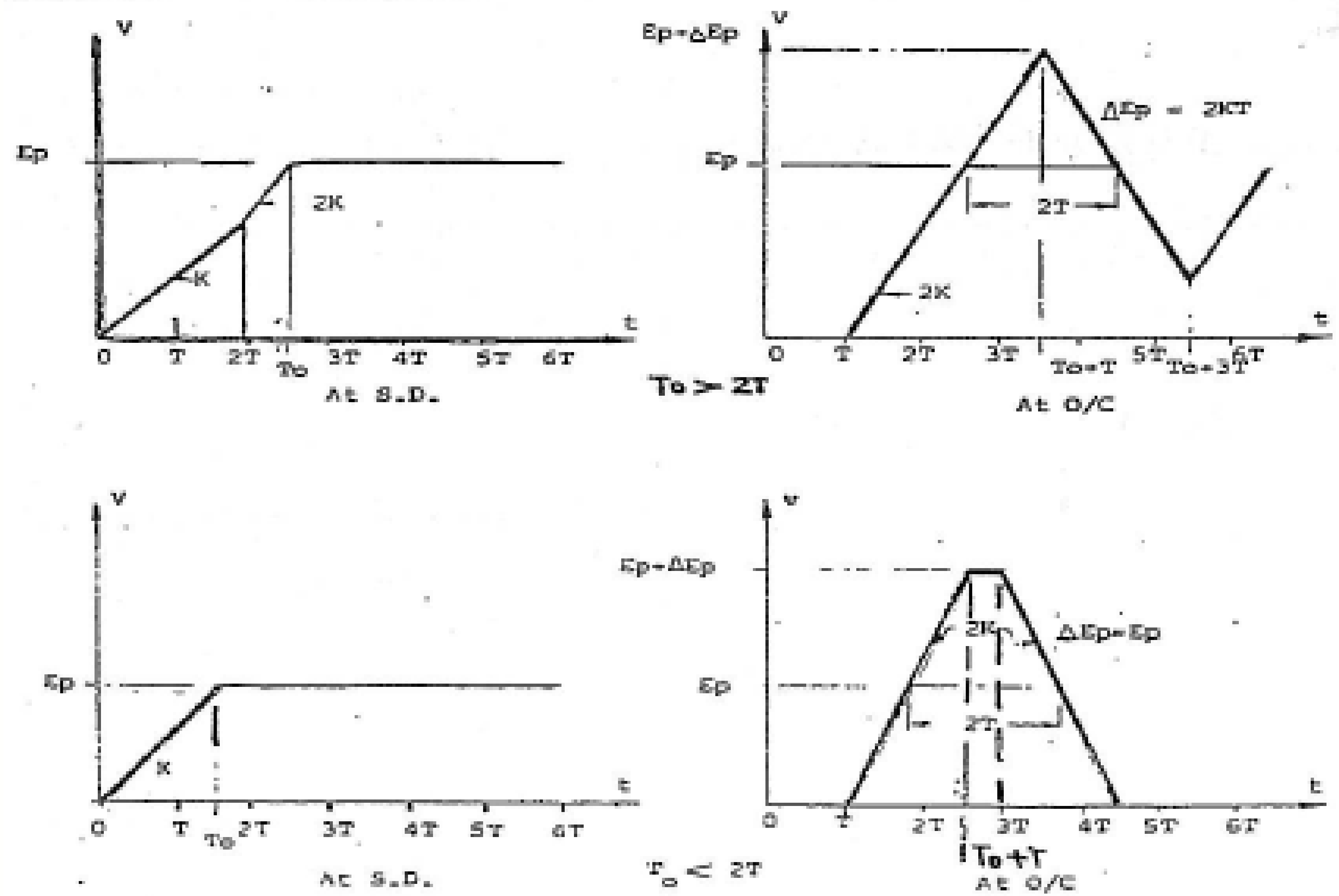
- The rate of rise of incoming surges will determine gap SOV. For an incident surge of 1360kV peak at 1200 kV/us, the front time is ~1.2us. The maximum gap SOV is, therefore approximately the 1.2/50 us SOV, ie 294 kV.

- Thus, E_p is taken as 294 kV, and an appropriate transformer BIL can now be considered. BIL's for 132 kV transformers: 550, 450, 380 kV.

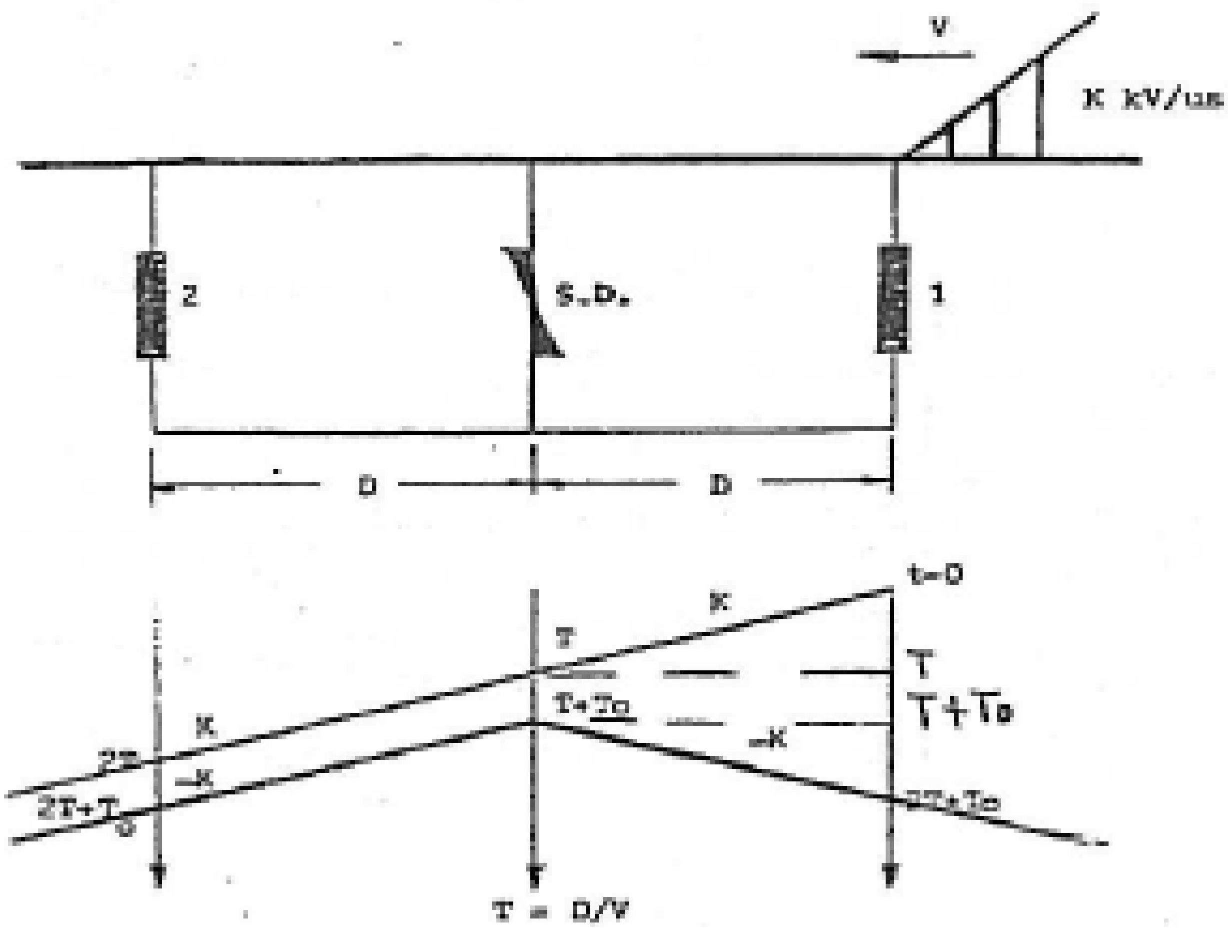
Travelling wave effects cause voltages remote from surge arrester to exceed its protective level Ep.

- **Case 1:** transformer connected at end of line d m from the arrester

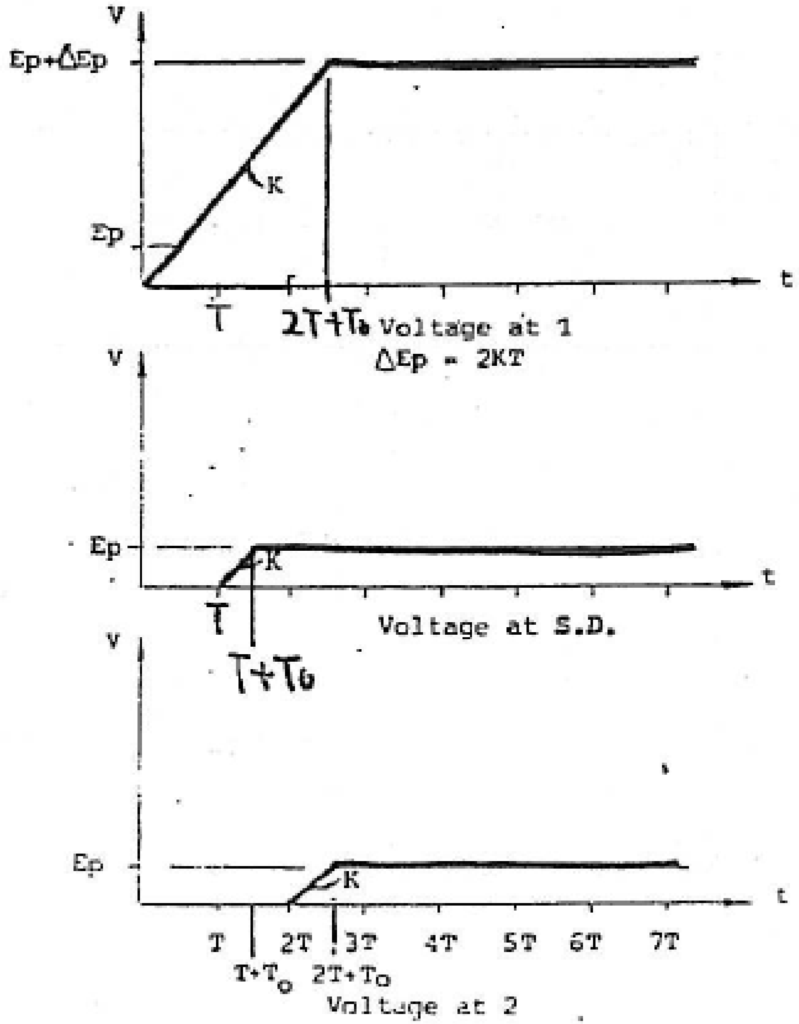



v
Ep
2K
K
t
0
T
2T
To
3T
4T
5T
6T
At S.D.
Ep+ΔEp
ΔEp = 2KT
2T
To=T
To+3T
To ≥ 2T
At O/C
To+T
ΔEp=Ep
To < 2T

- **Case 2:** surge arrester connected at centre of long line with apparatus connected to the line at a distance d m on either side



- Maximum voltage occurs UP LINE of arrester and $= E_p + 2KT$



- Since the voltage in excess of E_p is 2KT = 2K. d/v in either case- d should be made small to ensure adequate protection from steep fronted waves

- If the apparatus withstand level is (E_p+M) kV where M is the margin allowed, all apparatus within a distance M.v/2K feet of the arrester will be protected.

- If a BIL of 380 kV was selected, then margin M = 380 - 294 = 86 kV and the maximum permissible separation between surge arrester and transformer would be 100 x 86 / (2 x1200) = 36 feet