Welcome to High Voltage Engineering

Please enter the rain class

Department of Electrical Engineering, Tsinghua University

Spring 2024 High Voltage Engineering Lecture 13

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May 30, 2024

Preface, preface to the first edition, preface to the second edition, introduction

The development of high-voltage power transmission
Current situation and prospect of China’s electric power industry
Special problems under high voltage and high field strength
Special phenomena and their application at high voltage

1: Analysis of gas discharge process

collision ionization, self-sustained discharge, Townsend discharge, Paschen’s law, corona discharge, electron avalanche, steamer, lead, effect of polarity, long gap discharge

2: Insulation characteristics of air under different voltage waveforms

High field strength and high voltage, non-uniform electric field, adjustment of the electric field distribution, lightning and switching impulse voltage, 50% breakdown voltage, v-t characteristics, electrical strength of the air, high vacuum insulation, SF_6 insulation

3: High voltage outdoor insulation and surface discharge

Atmospheric conditions correction, high tension insulator, external insulation, surface discharge ,Sliding discharge, pollution discharge, hydrophobic migration, silicone rubber for organic external insulation

4: Electrical performance of liquid and solid dielectrics

dielectric, polarization, Conductor loss, bridge breakdown, electric breakdown, thermal breakdown, electrochemical breakdown, aging, cumulative effect, space charge, paper oil insulation, electric field in the dielectric

5: Insulation test and diagnosis

Insulation test and monitoring, insulation diagnosis, withstand voltage test, non-destructive test ,insulation resistance, leakage current, $\tan\delta$, Schering bridge, partial discharge(PD), gas chromatography

6: The generation of high voltage and high impulse current

Testing transformer, multistage impulse voltage generator, capacitive test article voltage increase, high voltage resonance test equipment, voltage DC and cascade DC, ripple factor, impulse voltage generator, parallel charge and series discharge, front resistor and discharge resistor, impulse current generator

7: High voltage measurement

Standard measuring system and approved measuring system, expanded uncertainty, sphere gap measurement, resistor divider, capacitor divider, resistor-capacitor divider, matched impedance, step response, return stroke, shield and anti-interference

8: Travelling Wave on Transmission Line

Surge impedance, refraction and reflection coefficient, full voltage reflection and full current reflection, travelling waves through parallel capacitor and series inductor, centralized parameters and distributed parameters

9: Lightning overvoltage and its protection

Lightning parameters, lightning location system, lightning rod and lightning conductor, arrester, grounding device, earth resistance, induced overvoltage, lightning withstand level, lightning outage rate

10: Switching overvoltage and insulation coordination

Multiples of the switching overvoltage, the off and closing of circuit breaker, reclosing, no-load line closing overvoltage, excise the no-load line overvoltage, extra-fast and transient overvoltage, closing resistor, Insulation coordination, basic impulse insulation level (BIL)

Appendix A: Withstand voltage of power equipment
Appendix B: Parameters of some high-voltage laboratories domestic and abroad

Chapter 8 Travelling Wave on Transmission Line

8.1 Travelling wave and surge impedance

8.2 Refraction and reflection, attenuation and deformation of travelling wave

8.3 Travelling wave through parallel capacitance and series inductance

The core concepts of this chapter:

Travelling wave, surge impedance, refraction and reflection coefficient, voltage full reflection and current full reflection, travelling wave through parallel capacitance and series inductance, Centralized parameter and distributed parameter

8.1 Travelling wave and surge impedance

High voltage engineering study and learn the travelling wave phenomenon of electromagnetic wave propagation along the conductor from the perspective of overvoltage protection of transmission lines and power equipment.

In the operation of the power system, in addition to the long-term operational voltage, there will also be various overvoltages with amplitudes much higher than the rated working voltage.

The overvoltage of power system can be divided into external overvoltage and internal overvoltage. The former mainly refers to the lightning overvoltage, while the latter can be divided into switching overvoltage and temporary overvoltage.

The duration of lightning overvoltage is extremely short, the duration of switching overvoltage is generally less than 0.1 seconds; the temporary overvoltage includes power frequency voltage increase and resonant overvoltage, the duration is longer than the switching overvoltage.

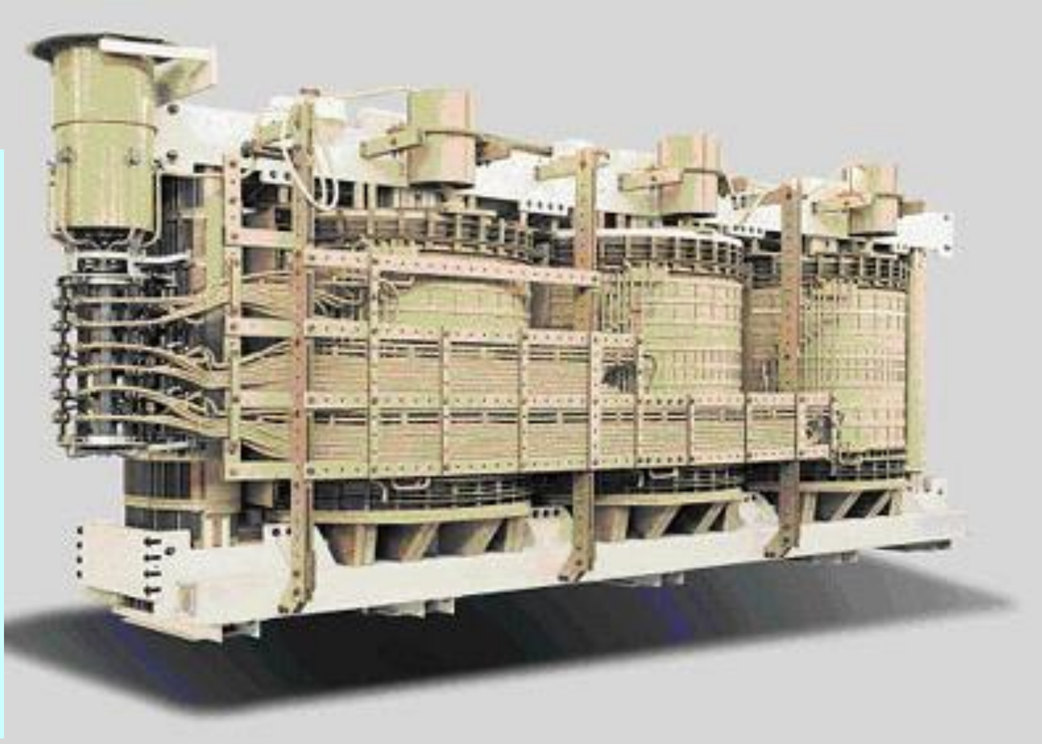
Lightning overvoltage and switching overvoltage are impulse voltage.

When lightning strikes the grid, how large is the influencing area?
When the rest of the grid will be subjected to an overvoltage?
How high is the overvoltage amplitude?

When lightning strikes the grid, how large is the influencing area?
When the rest of the grid will be subjected to an overvoltage?
How high is the overvoltage amplitude?

If an overvoltage appears in one place in substation, is there any overvoltage in other places of the substation? Is the overvoltage with the same amplitude?

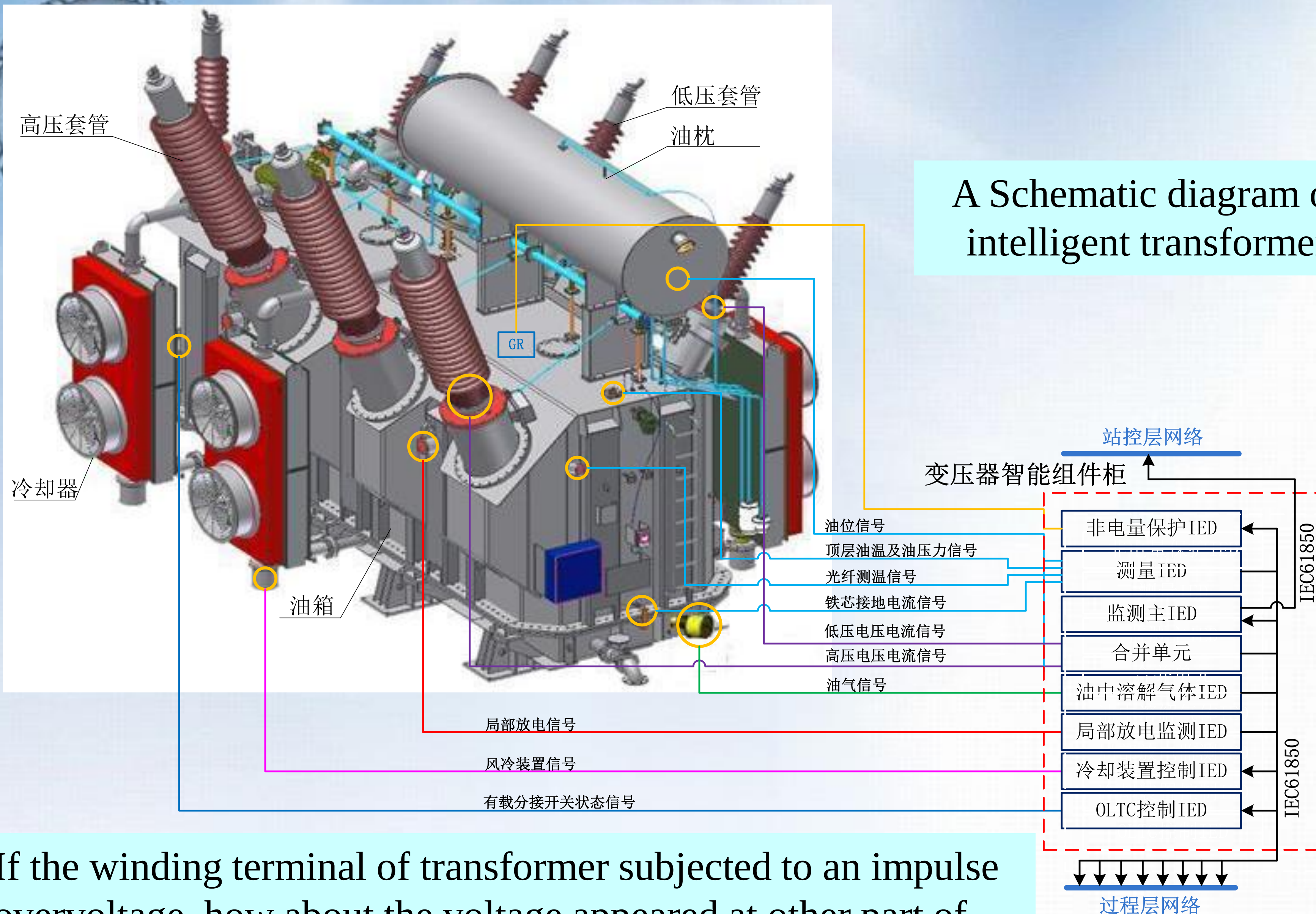
The power transformer with the shell opening



If the winding terminal of transformer subjected to an impulse overvoltage, how about the voltage appeared at other part of the transformer?

For different places of the winding, is the transient voltage the same?

A Schematic diagram of intelligent transformer



If the winding terminal of transformer subjected to an impulse overvoltage, how about the voltage appeared at other part of the transformer? For different places of the winding, is the transient voltage the same?

When the overhead line, cable, generator or transformer winding faces the impulse voltage, the wavelength corresponding to the wave front (rising edge) or the chopped wave tail (descending edge) of the impulse voltage is comparable to the length of line or winding (the wavelength can be compared with the size of the high voltage equipment or components).

In this case, the voltage (or current) at different places of the line or winding are no longer the same at the same moment; the voltage (or current) at each point also change with time.

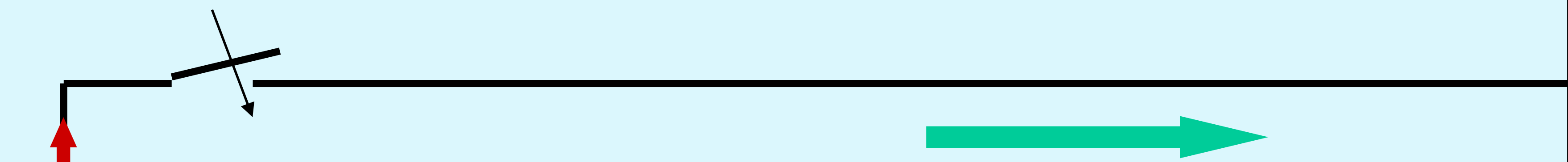
$$\begin{cases} u = u(x, t) \\ i = i(x, t) \end{cases}$$

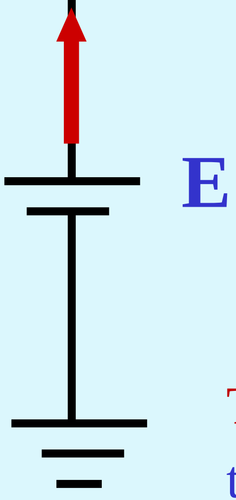
Therefore, the analysis of the voltage (or current) on the overhead line, cable, transformer winding and motor winding should be analyzed on the circuit with distributed parameters. The electromagnetic transient process in the circuit with distributed parameters belongs to the propagation process of the electromagnetic wave, referred to as the travelling wave process.

The analysis and calculation of travelling wave are the theoretical basis of overvoltage protection and insulation coordination.

For the whole power system, study the propagation of the travelling wave in the system, and in the process of refraction and reflection, attenuation and deformation, etc., the purpose is to better understanding the overvoltage amplitude and its duration inside power equipment or in between different equipment, so as to better study the principle of insulation coordination and measures of power equipment overvoltage protection.

Travelling wave in the transmission line with distributed parameters





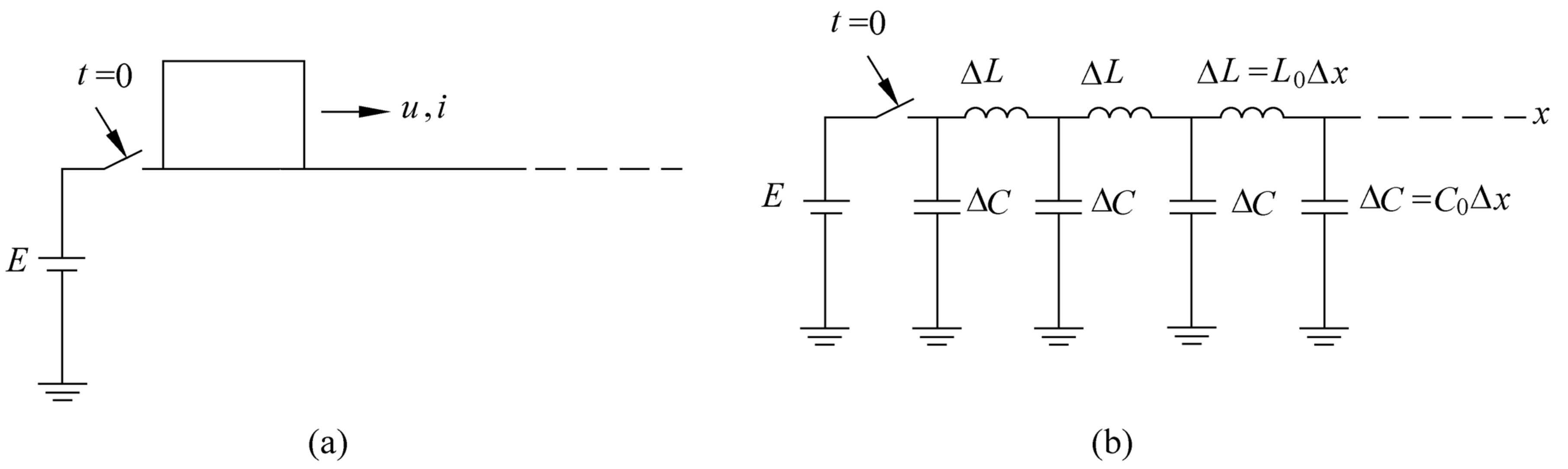
For a uniform, single, infinite long, lossless line, closing switch at $t = 0$, there is a voltage wave and current wave propagating along the line in x direction, and gradually establish its electric field and magnetic field around the line.

The voltage and current on the line are not only variable with time for the same place, but also variable with position for a given same time,

$$i=i\ (x,t),\ u=u\ (x,t)$$

The ratio of voltage and current at the same time, the same place, the same direction, the same wave

surge impedance $Z = \sqrt{L_0/C_0} = u_f/i_f = -u_b/i_b$



Travelling wave in single lossless conductor
(a) Head of single lossless conductor closing to E at t=0; (b) Equivalent circuit

L_0 and C_0 are the inductance and capacitance per unit length of line respectively. The wave arrives to the position x, the capacitance of the line is $C_0 x$. It was charged the voltage of $u=E$ and received the charge of $C_0 xu$. This charge was delivered from the line during time of t, then

$$C_0 x u = i t$$

During the time t, there is a current i in the line within the length of x, its inductance is $L_0 x$. The magnetic flux linkage is $L_0 xi$. This magnetic flux is built during time t, so the inductance potential u at the line is

$$u = L_0 x i / t$$

From $C_0 x \cdot u = i \cdot t$ and $u = L_0 x \cdot i / t$ cancelling t, get *the ratio of voltage to current* at the same time, the same place, the same direction, the same wave on the transmission line, called the **surge impedance** of the transmission line

$$Z = u/i = \sqrt{L_0/C_0} = u_f/i_f = -u_b/i_b$$

For overhead line

$$C_0 = \frac{2\pi\varepsilon_0}{\ln\frac{2h}{r}} \qquad L_0 = \frac{\mu_0}{2\pi}\ln\frac{2h}{r}$$

$$Z = \frac{1}{2\pi}\sqrt{\frac{\mu_0}{\varepsilon_0}}\ln\frac{2h}{r} = 60\ln\frac{2h}{r}\text{，单位为}\Omega$$

For a single transmission conductor, Z≈500Ω; under impulse voltage, corona will increase the C_0, Z≈400Ω; equivalent radius of split conductor is larger, then Z≈300Ω.

Although the surge impedance with the dimension of resistance, it is completely different from the centralized parameter of resistance (what is the difference?……)

What is the direction of travelling wave? (forward, backward)

For overhead line

$$C_0 = \frac{2\pi\varepsilon_0}{\ln\frac{2h}{r}}$$

$$L_0 = \frac{\mu_0}{2\pi}\ln\frac{2h}{r}$$

$$Z = \frac{1}{2\pi}\sqrt{\frac{\mu_0}{\varepsilon_0}}\ln\frac{2h}{r} = 60\ln\frac{2h}{r}，单位为\Omega$$

For cable, the magnetic flux linkage is concentrated between the core and external grounding sheath, and the distance between the core and the sheath is much shorter than that of overhead line. So the surge impedance of cable is much smaller than overhead line. Say tens of Ohms.

The electromagnetic wave travelling speed *v* can also be obtained from

$C_0 x u = i t$ and $u = L_0 x i / t$

This is the speed of light in vacuum.

$$v = \frac{x}{t} = \frac{1}{\sqrt{\mu_0\varepsilon_0}} = 3\times10^8\,(\mathrm{m/s})$$

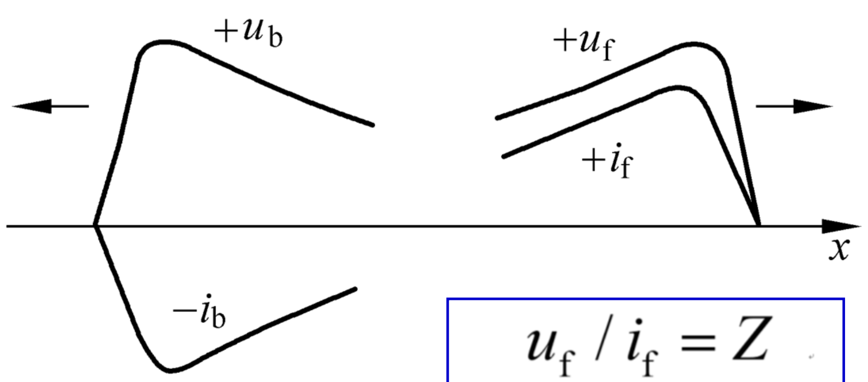
The dielectric material of cable $\varepsilon_r \approx 4$, and the wave speed of its electromagnetic wave propagation is only about the half of that of overhead line

There ae not only the forward travelling wave of u_f and i_f, but also the backward travelling wave u_b and i_b at the transmission line. For any point of the line, its potential (or current) is the combination of forward and backward travelling wave

$$\begin{cases} u(x,t) = u_\mathrm{f} + u_\mathrm{b} \\ i(x,t) = i_\mathrm{f} + i_\mathrm{b} \end{cases}$$

Define the potential of travelling wave u_f and u_b are related only on the electric charge at the capacitance of the line to the ground, no relation to the wave travelling direction, and define current of wave i_b is positive if positive charge moves to the positive direction (along the x to the right direction)

$$\boxed{\begin{aligned} u_\mathrm{f} / i_\mathrm{f} &= Z \\ u_b / i_b &= -Z \end{aligned}}$$



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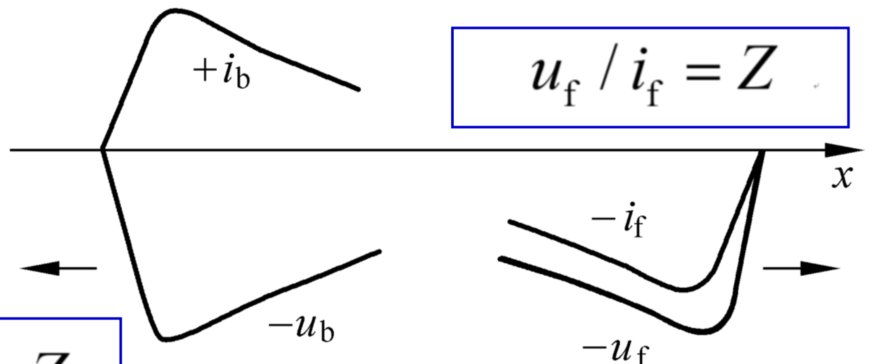


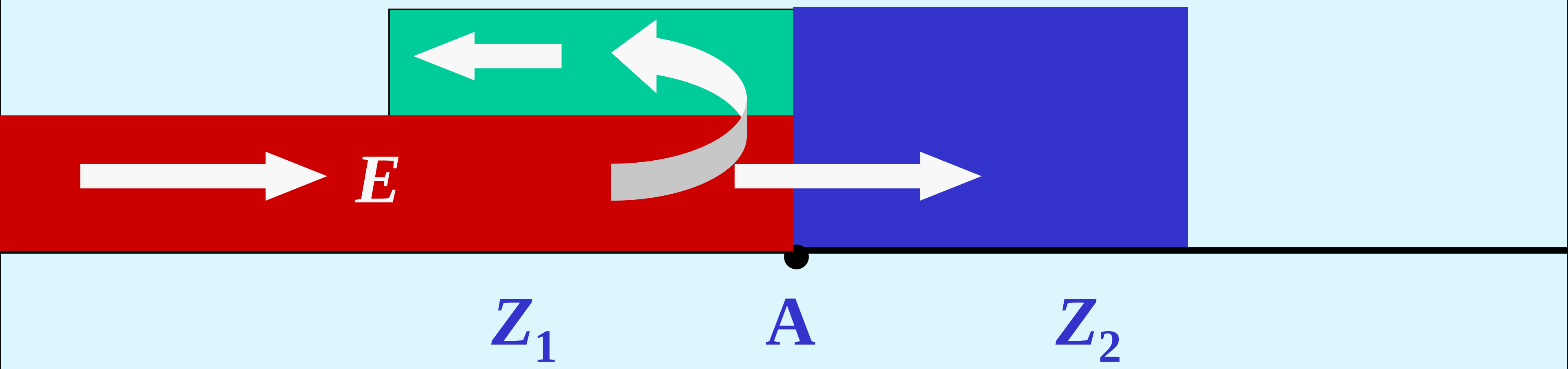
$$\boxed{u_\mathrm{f} / i_\mathrm{f} = Z}$$

$$\boxed{u_b / i_b = -Z}$$

8.2 Refraction and reflection, attenuation and deformation of travelling wave

The refraction and reflection will happen when travelling wave through different surge impedance lines

If $Z_1 < Z_2$ refraction and reflection lead to a higher voltage in both lines, and lower current in both lines



Both sides of the node have equal voltage and equal current!

$u_{1f}+u_{1b}=u_{2f}$, $i_{1f}+i_{1b}=i_{2f}$, introduce $u_f/i_f=Z$, and $u_b/i_b = -Z$

It is easy to obtain: $u_{2f} = \alpha u_{1f}$, $u_{1b}= \beta u_{1f}$, here

refraction coefficient $\alpha = 2Z_2/(Z_1+Z_2)$

reflection coefficient $\beta = (Z_2-Z_1)/(Z_1+Z_2)$, $\alpha = 1+ \beta$

8.2 Refraction and reflection, attenuation and deformation of travelling wave

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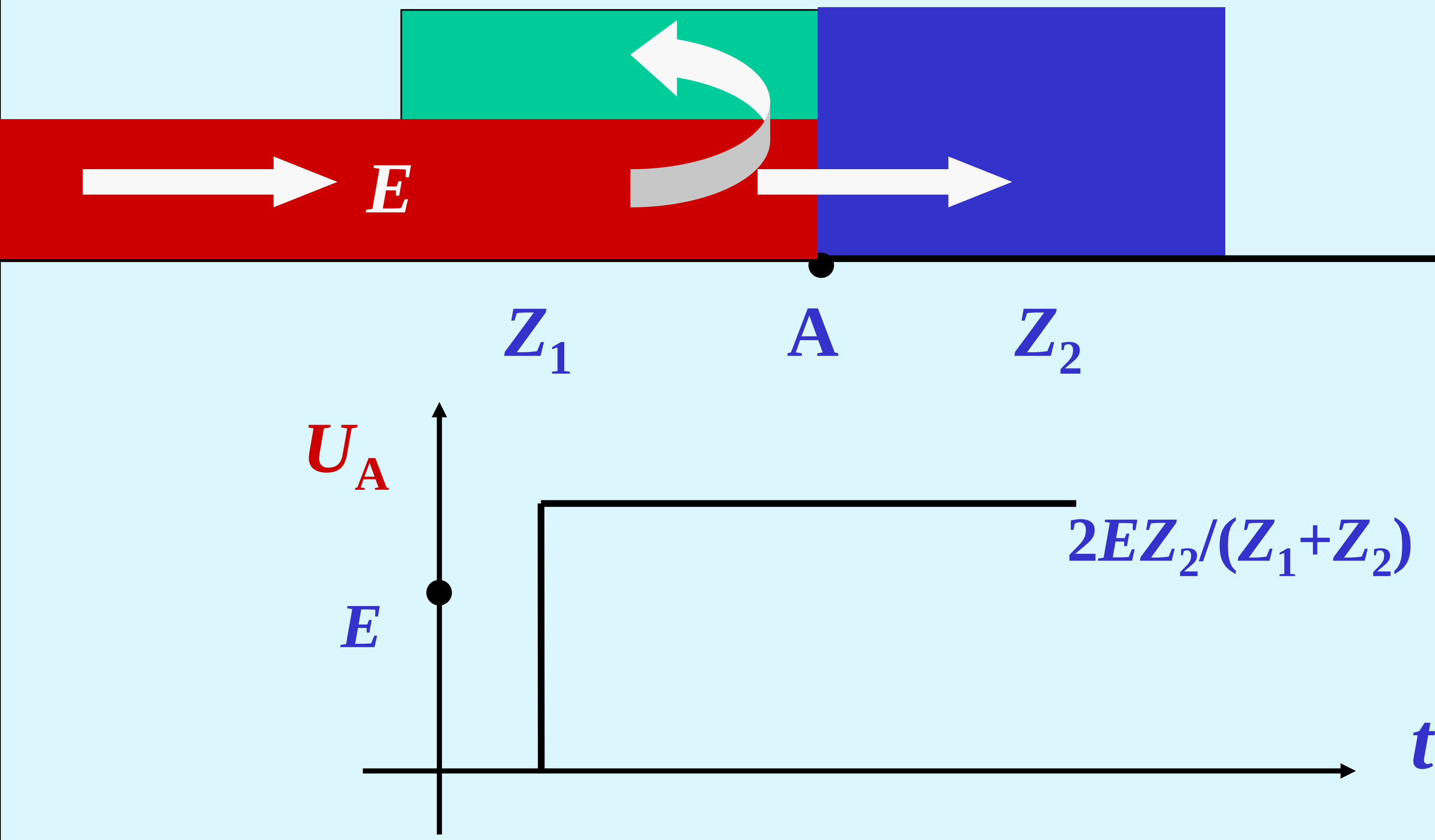

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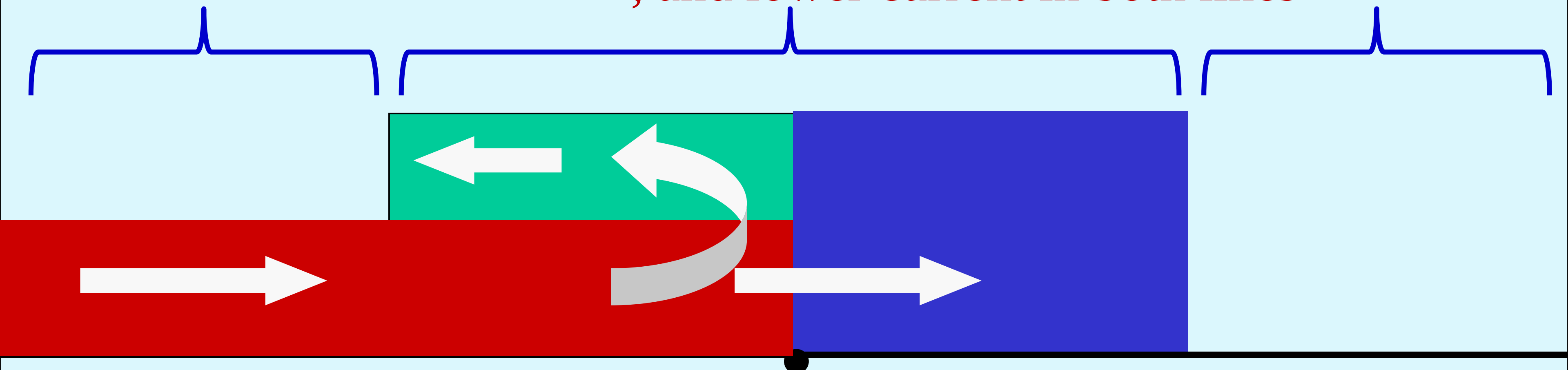

Z_1 A Z_2

$$u_{2f} = \alpha u_{1f} = u_{1f} + u_{1b} > u_{1f}$$

$$u_{1b} = \beta u_{1f}$$

Smaller current for positions with forward and backward wave arrival

$$i_{2f} = i_{1f} + i_{1b} < i_{1f}$$

8.2 Refraction and reflection, attenuation and deformation of travelling wave

If $Z_1 > Z_2$ refraction and reflection lead to
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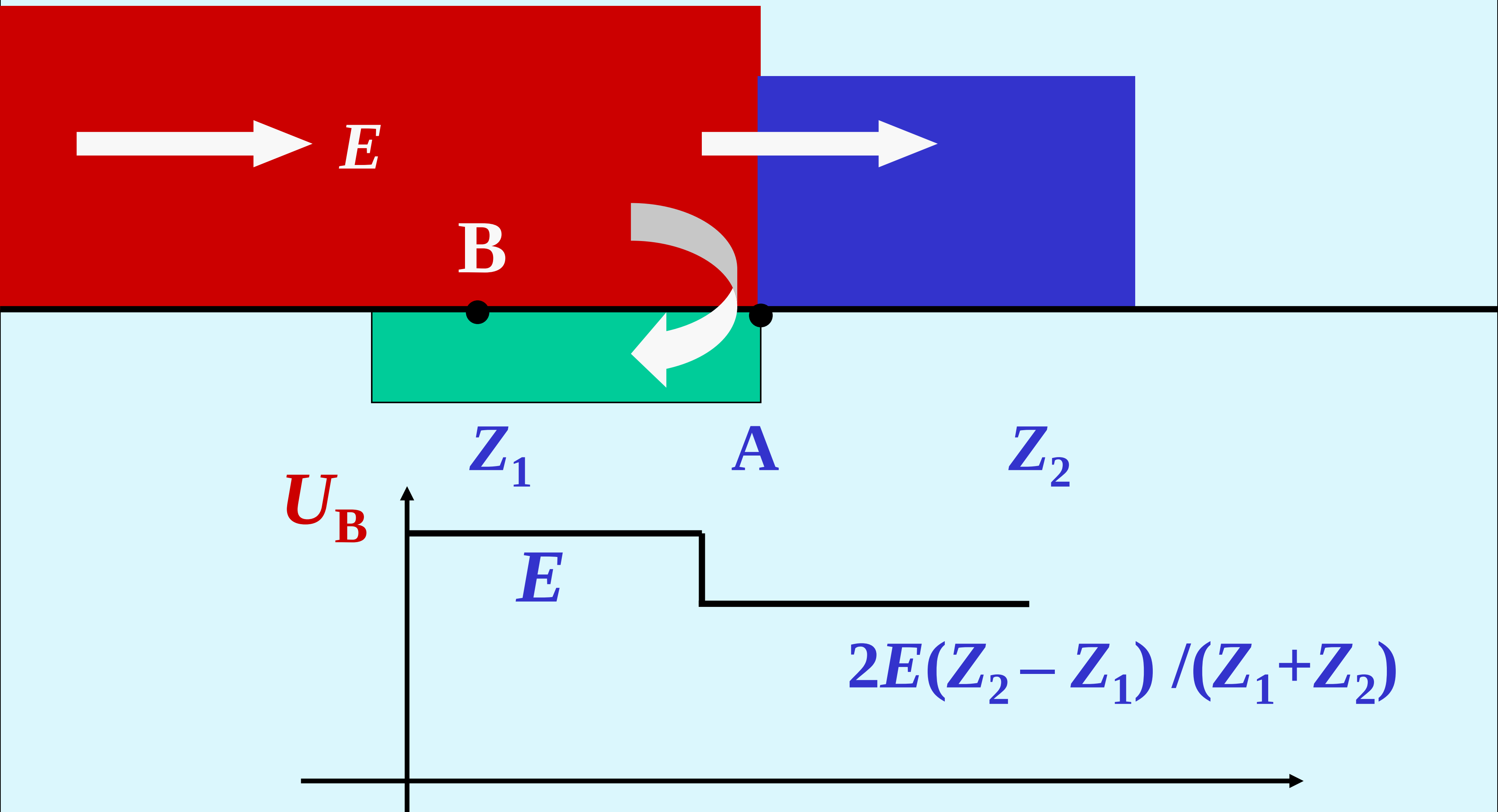

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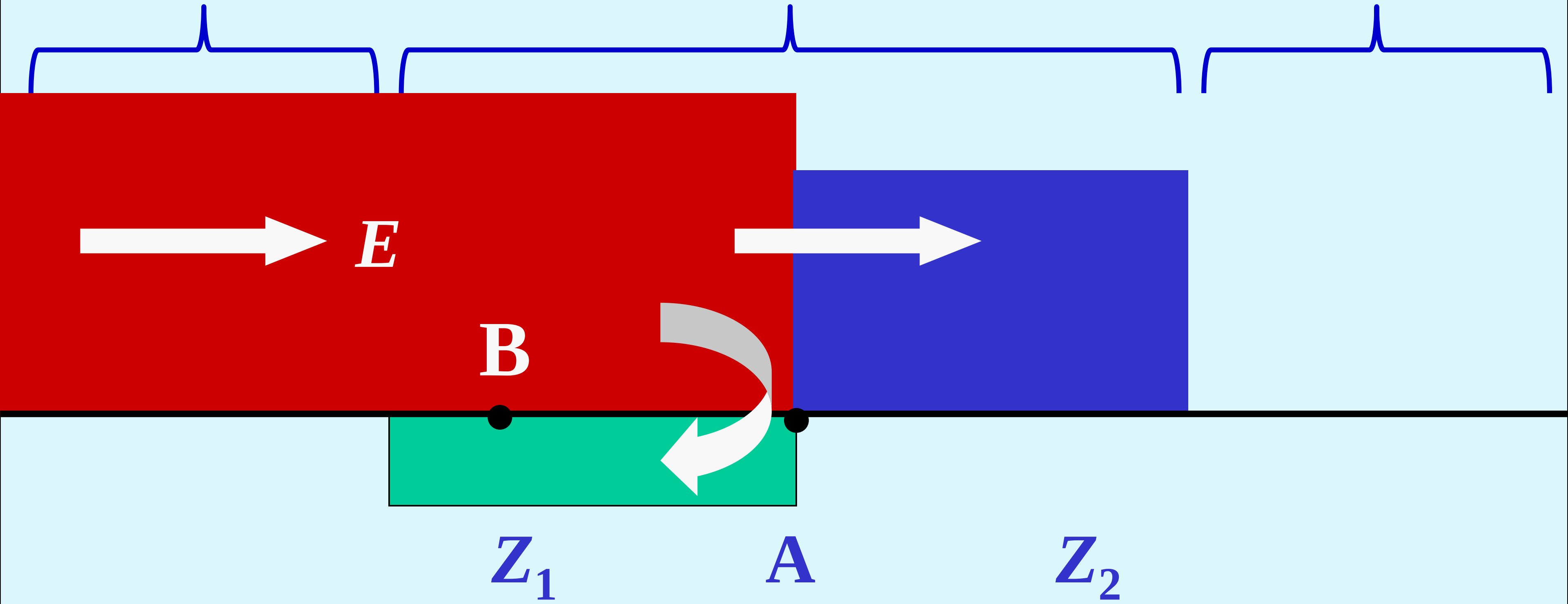


$$u_{2f} = u_{1f} + u_{1b} < u_{1f}$$

Higher current for positions with forward and backward wave arrival

$$i_{2f} = i_{1f} + i_{1b} > i_{1f}$$

- When the wavelength of the electromagnetic wave is comparable to the size of the line or the equipment, there is a travelling electromagnetic wave propagation process in the line or the equipment
- At this situation, the voltage and current in the line or equipment is not only a function of time, but also a function of position. It must be analyzed using the circuit with distributed parameters

- The voltage (or current) at the same moment but at different places are no longer equal (a function of position)
- The voltage (or current) at the same point but at different moment is not equal (a function of time)

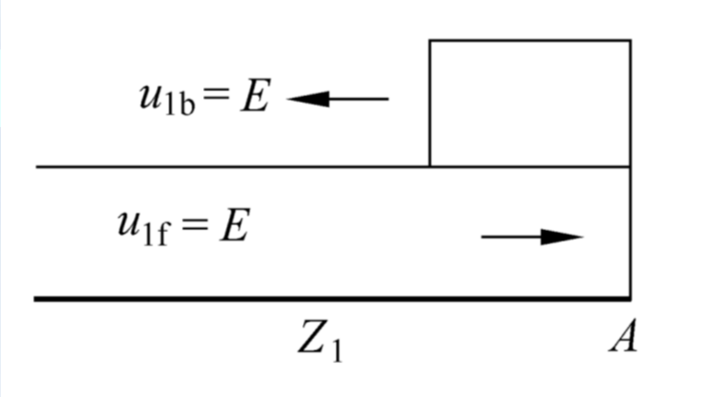
- When the electromagnetic wave travels in the conductor, the ratio of voltage and current is the surge impedance of the conductor
- When the electromagnetic wave passes through lines with different surge impedance, the refraction and reflection process will occur at the connection node

- refraction coefficient $\alpha = 2Z_2/(Z_1+Z_2)$
- reflection coefficient $\beta = (Z_2-Z_1)/(Z_1+Z_2)$
- The refraction and reflection coefficient at the node is related to the propagation direction of the electromagnetic wave

- When the electromagnetic wave travelling through a circuit with both distributed and concentrated parameter, the voltage and current at the connection node can still be calculated by the refraction and reflection coefficient
- If there is more than one transmission line or a centralized element at the connection node, then Z_2 could be treated in parallel. It is well understood from the perspective of wave transmission
- If electromagnetic wave passes through a capacitor and inductance from a distributed parameter line, the refraction and reflection will also happen at the connection node
- When the electromagnetic wave passes through the line with resistance (with losses), the attenuation and deformation of the wave will occur

refraction coefficient $\alpha = 2Z_2/(Z_1+Z_2)$, reflection coefficient $\beta = (Z_2-Z_1)/(Z_1+Z_2)$

Refraction and reflection at the open end line



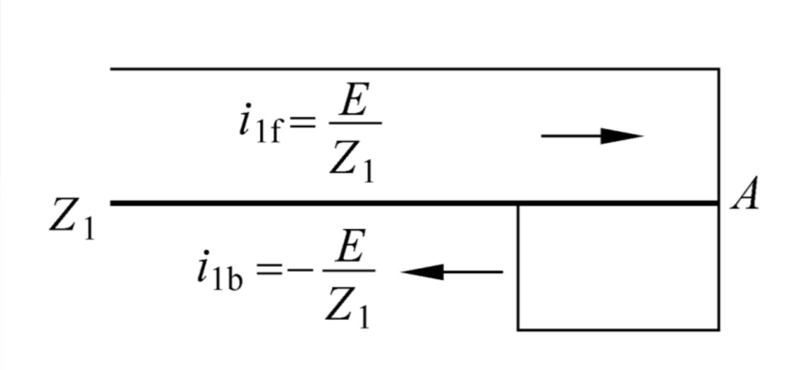
$Z_2 = \infty$, now $\alpha = 2$, $\beta = 1$

"Full reflection of voltage"

The reflected wave of voltage equals to the incident voltage wave, so the voltage amplitude doubles where the reflected wave arrives

The incident wave of current and reflected wave of current can be calculated according to the formula of $u_f/i_f = Z$, and $u_b/i_b = -Z$. Reflective current: $i_{1b} = -i_{1f}$

The reflected current equals to the negative incident current, so the current is zero wherever the reflected wave arrives

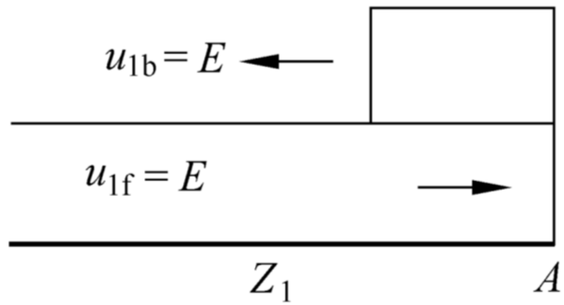


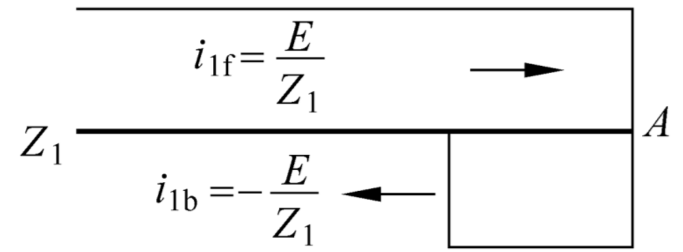
refraction coefficient $\alpha = 2Z_2/(Z_1+Z_2)$, reflection coefficient $\beta = (Z_2-Z_1)/(Z_1+Z_2)$

Refraction and reflection at the open end line

$Z_2=\infty$, $\alpha = 2Z_2$, $\beta=1$

$u_{1b} = u_{1f}$ "Full reflection of voltage"



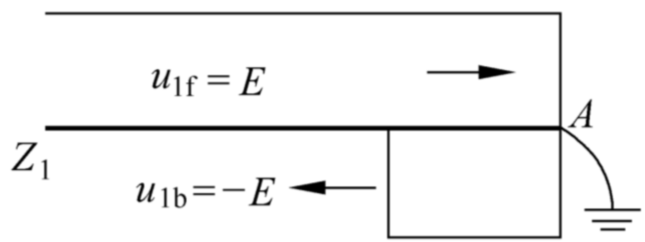


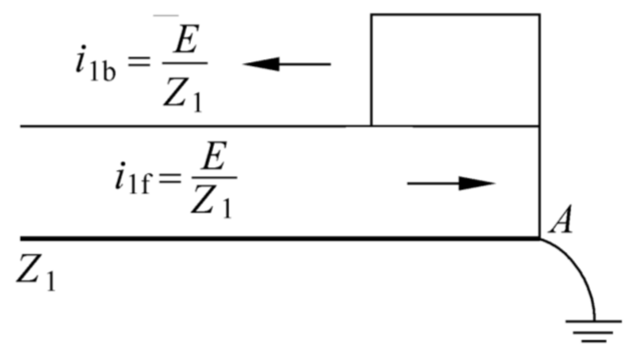
The voltage is doubled and current is zero wherever the reflected wave arrives

Refraction and reflection at the short circuit line

$Z_2=0$, $\alpha = 0$, $\beta = -1$

$i_{1b} = i_{1f}$ "Full reflection of current"



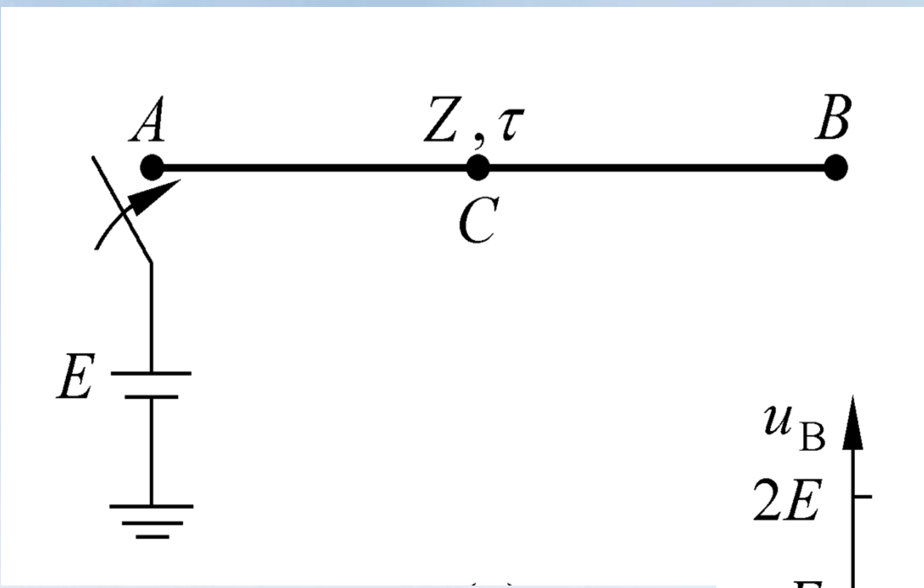


The voltage is zero and current is doubled wherever the reflected wave arrives

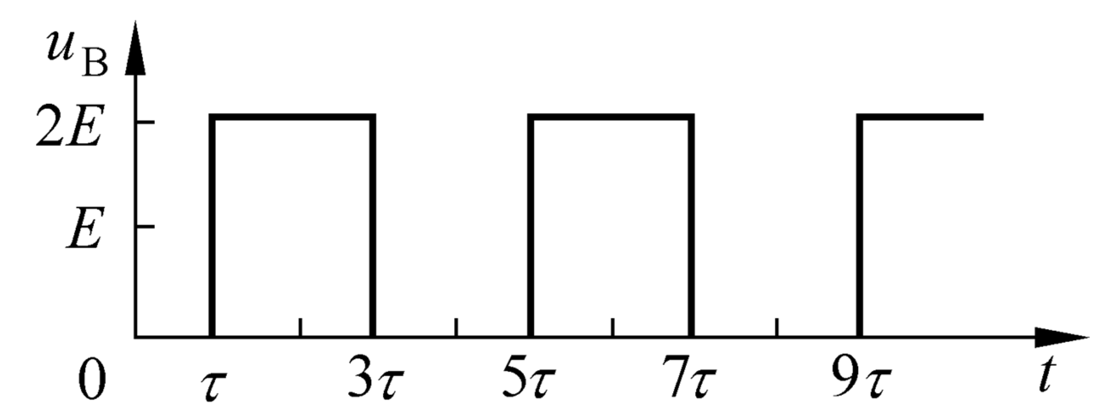
Refraction and reflection examples:

Example: DC power supply E switches on a open-end line with length of l at t=0.
What is the potential waveform of point B at the end of the line?

Solution: Set τ is the time of travelling wave go through the length of l in the line



What is the voltage and current waveform of the point C which is in the middle of the line?



Refraction and reflection examples:

例题：波阻抗 Z_1=300 Ω，波速 v_1=300m/μs 的无损长线连接到波阻抗 Z_2=75 Ω，波速 v_2=150m/μs，长度 300m 的电缆首端 *A* 点，电缆末端 *B* 点连接到波阻抗 Z_3=425 Ω，波速 v_3=300m/μs 的无损长线，如图 1 所示。幅值 *E*=1000 kV 的无穷长直角波在 t= 0 时刻到达 *A* 点。

请画出 $t \le 8\mu s$ 内 *A*、*B* 两点电压随时间变化的波形 $u_A(t)$、$u_B(t)$，以及 $t = 8\mu s$ 时刻沿无损线及电缆段电压的空间分布示意图。

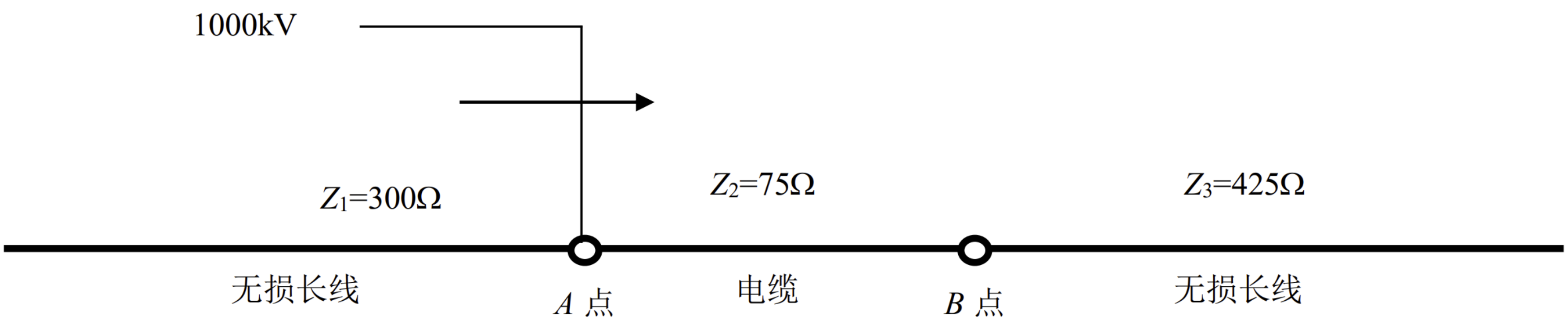


图 1

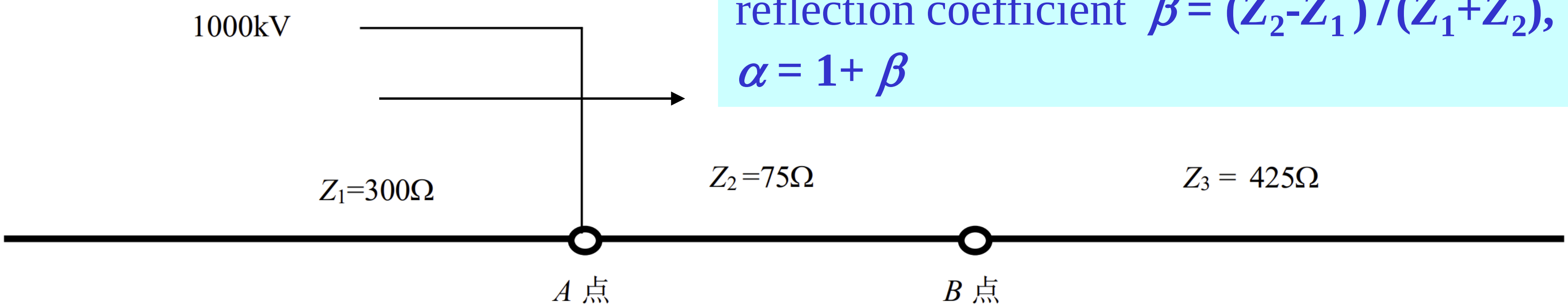
Refraction and reflection examples:

解:

refraction coefficient $\alpha = 2Z_2/(Z_1+Z_2)$

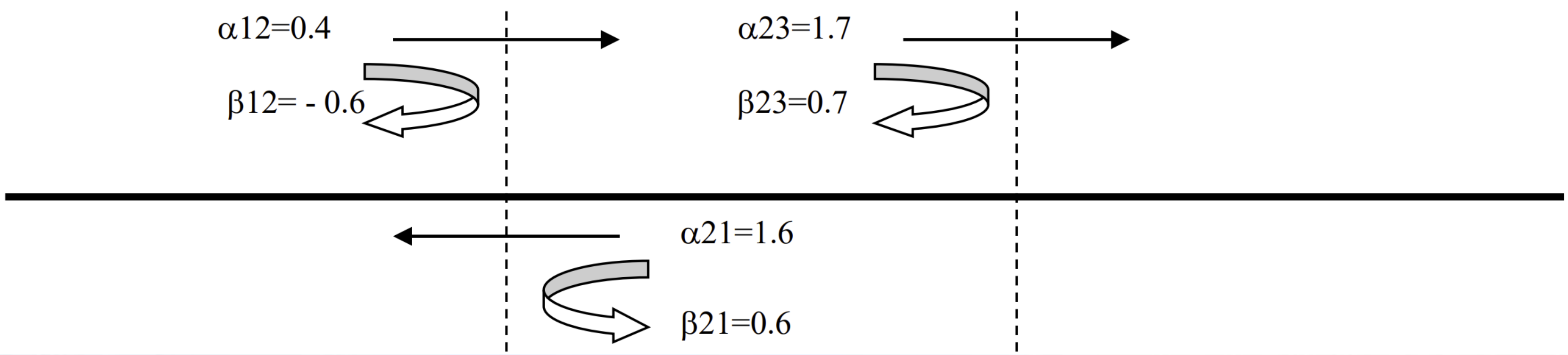
reflection coefficient $\beta = (Z_2-Z_1)/(Z_1+Z_2)$,

$\alpha = 1+\beta$



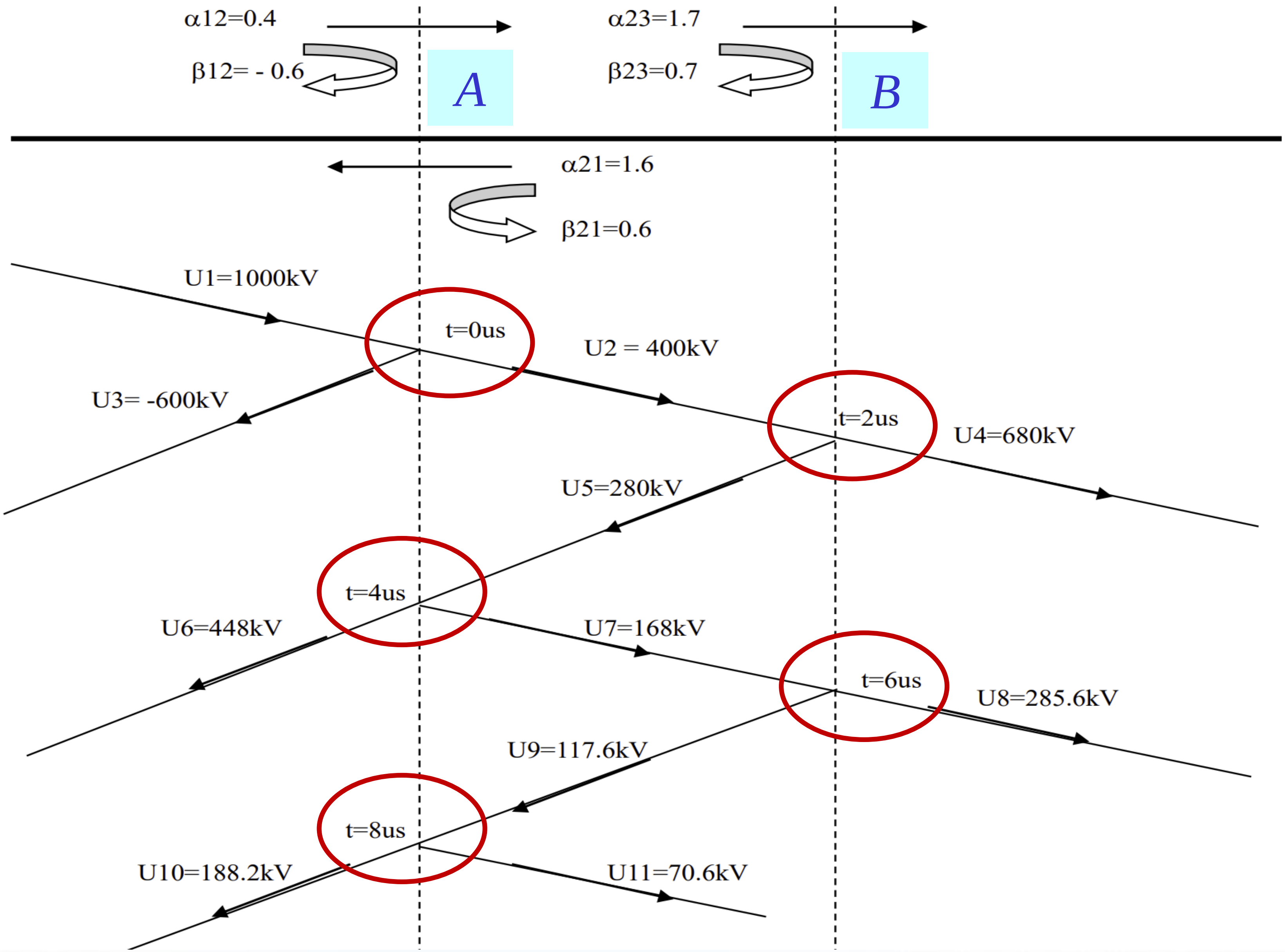
t = 0 μs

t = 2 μs

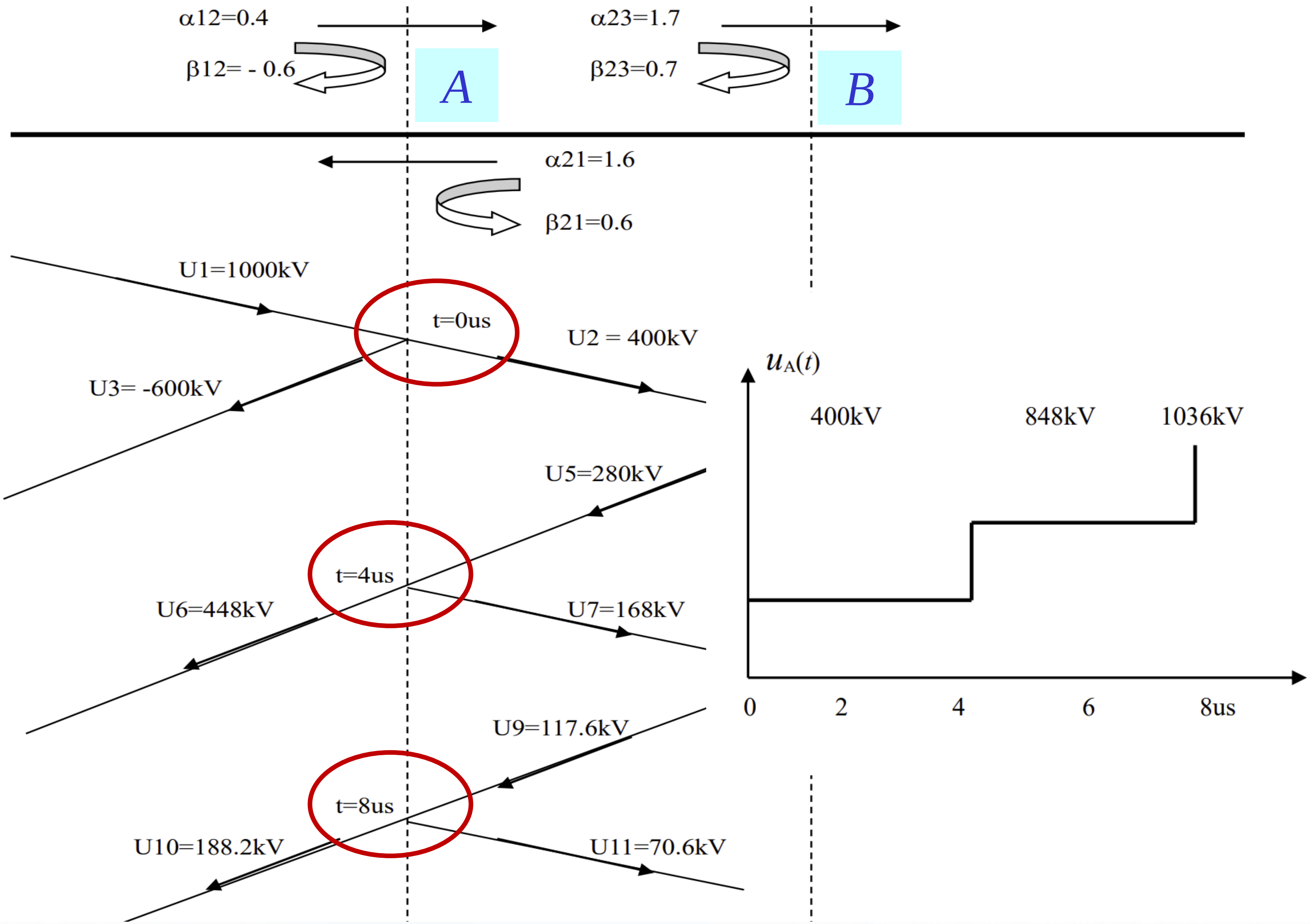


t = 4 μs

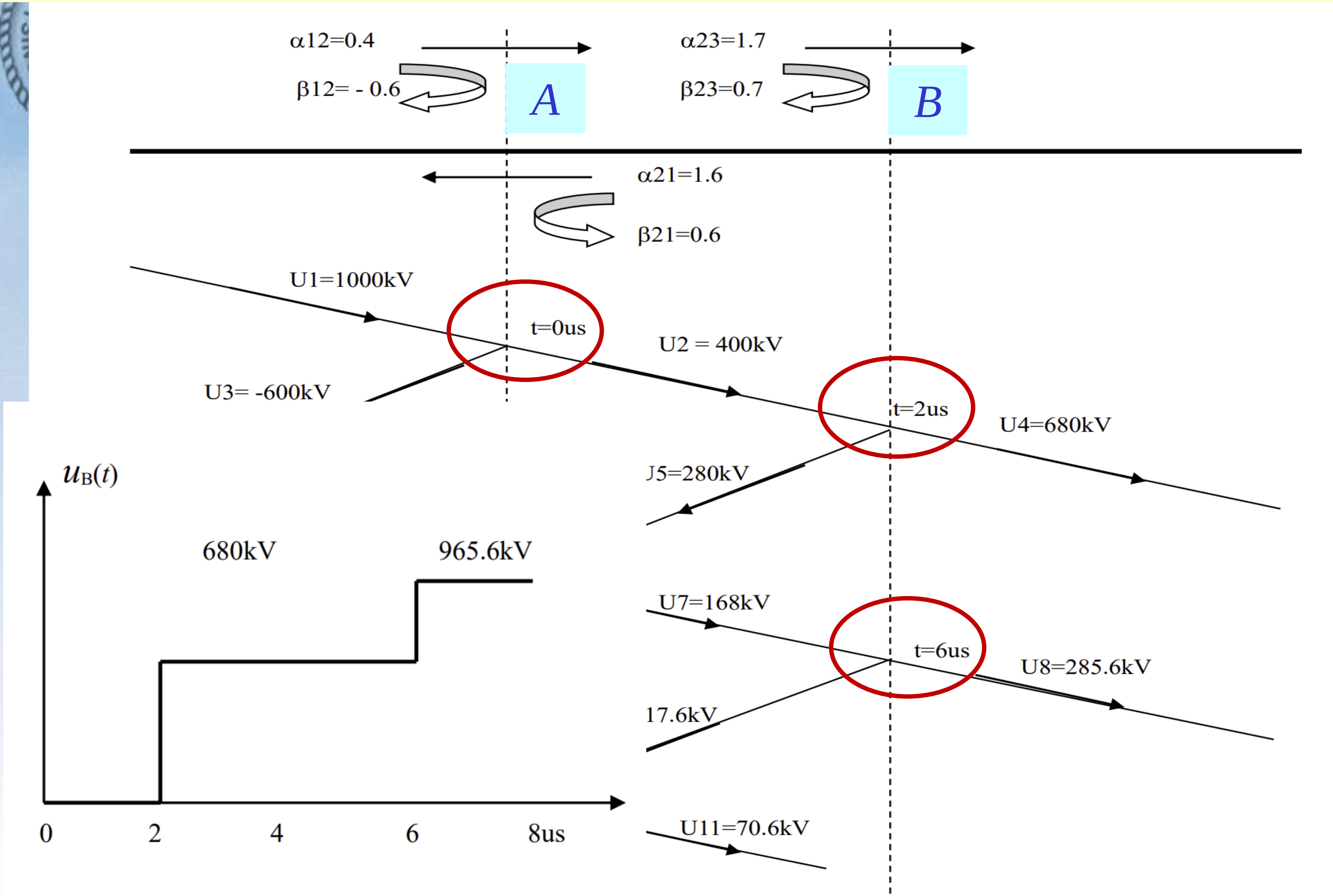
Refraction and reflection examples:



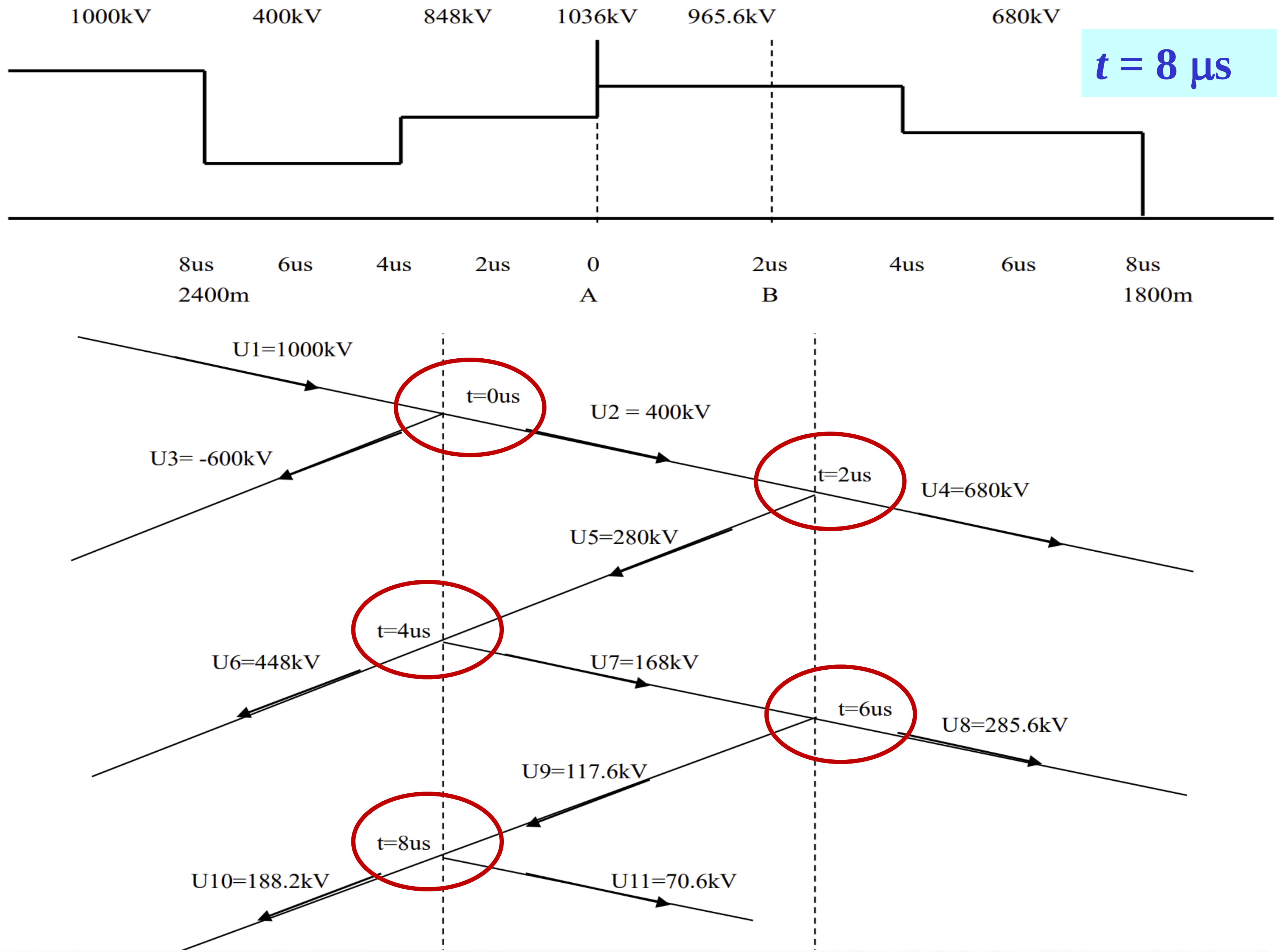
Refraction and reflection examples:



Refraction and reflection examples:



$t = 8\ \mu s$



1000kV
400kV
848kV
1036kV
965.6kV
680kV
8us
6us
4us
2us
0
2us
4us
6us
8us
2400m
A
B
1800m
U1=1000kV
t=0us
U2 = 400kV
U3= -600kV
t=2us
U4=680kV
U5=280kV
t=4us
U6=448kV
U7=168kV
t=6us
U8=285.6kV
U9=117.6kV
t=8us
U10=188.2kV
U11=70.6kV

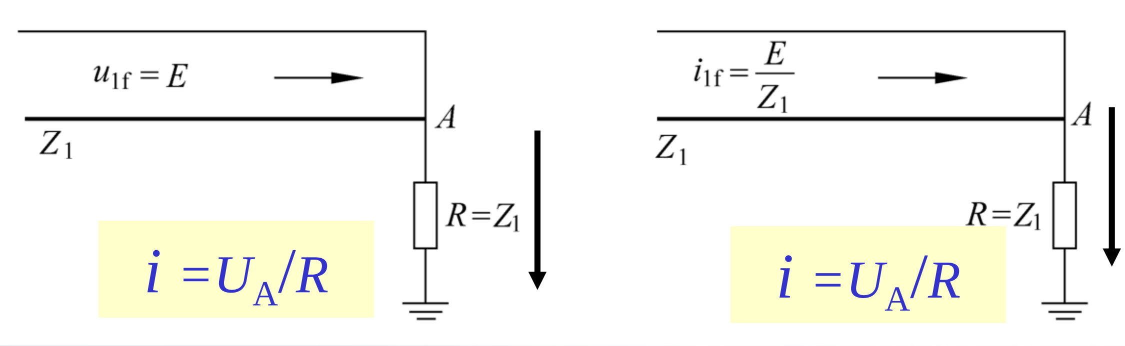
refraction coefficient $\alpha = 2Z_2/(Z_1+Z_2)$, reflection coefficient $\beta = (Z_2-Z_1)/(Z_1+Z_2)$

Refraction and reflection at the line terminated through a resistance R (lumped parameter)

When the ends are matched,

$Z_2=R=Z_1$, $\alpha = 1$, $\beta = 0$

The R will be heated for the current $i = U_A/R$.



When the end of line is connected to the centralized parameter load, but $R \neq Z_1$, the refraction and reflection will occur at the node A, it can be analyzed as above.

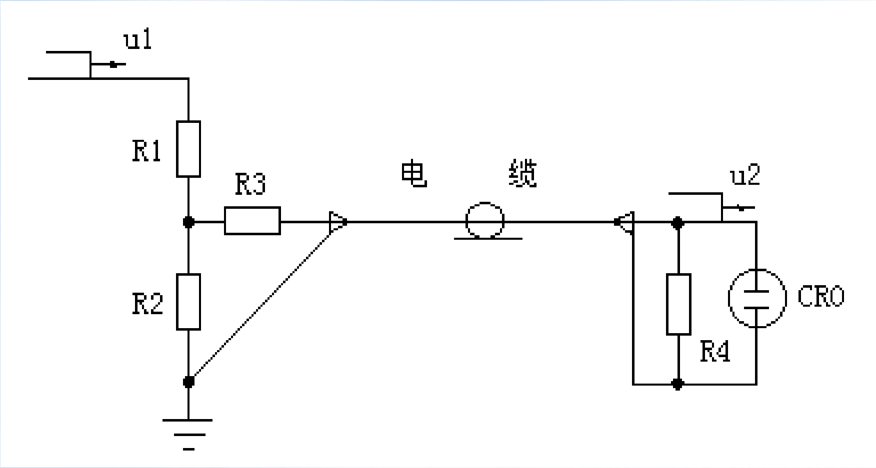
The resistance will be heated for the current $i = U_A/R$.

In Chapter 7, the measurement of impulse HV. The "match" of measurement cable is highly emphasized!

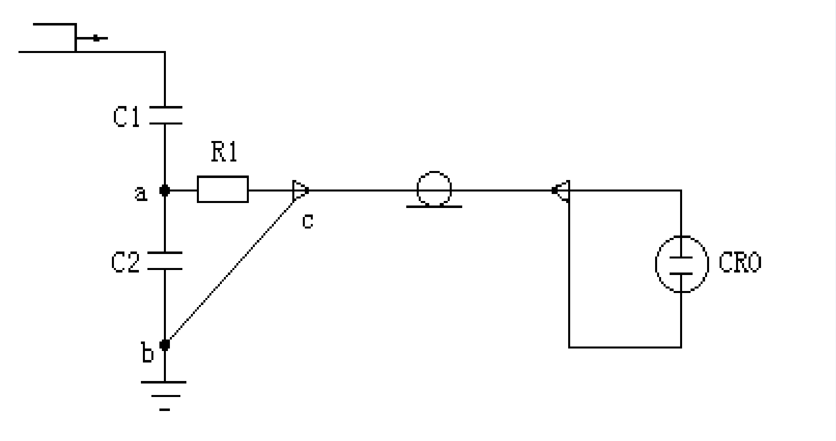
Basic concept of travelling wave is the most important content in Chapter 8

The impedance matching of the low voltage arm from the perspective of travelling wave

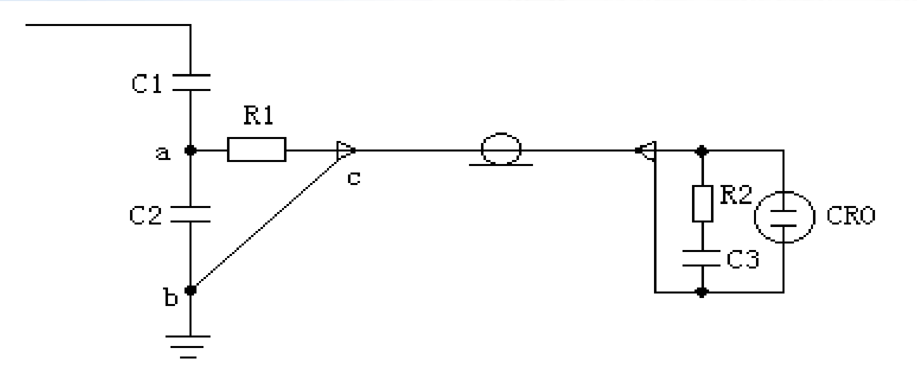
- Resistance and capacitance divider
- Head match, head and end match



(1) resistance divider for impulse voltage measurement, match at head and end of cable

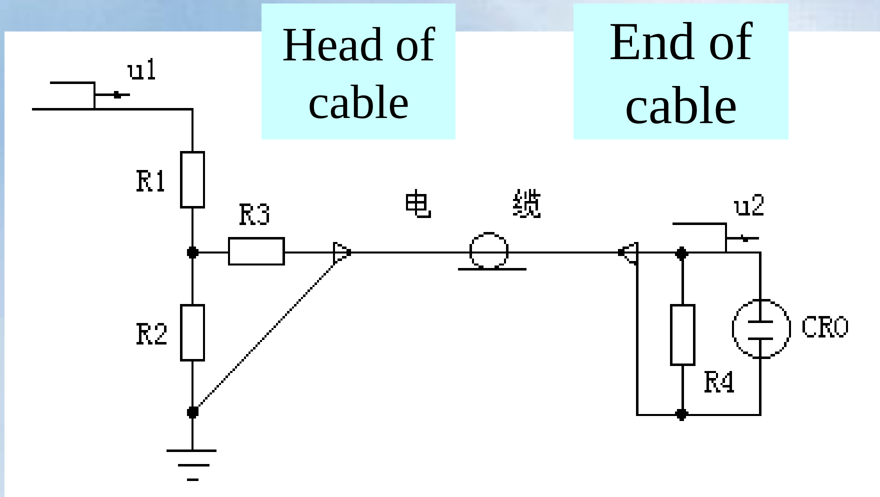


(2) Capacitance divider for impulse voltage measurement, head match only



(3) Capacitance divider for impulse voltage measurement, head and end match

Impedance match of the measuring cable for resistance potential divider



measurement circuit of resistance divider for impulse voltage

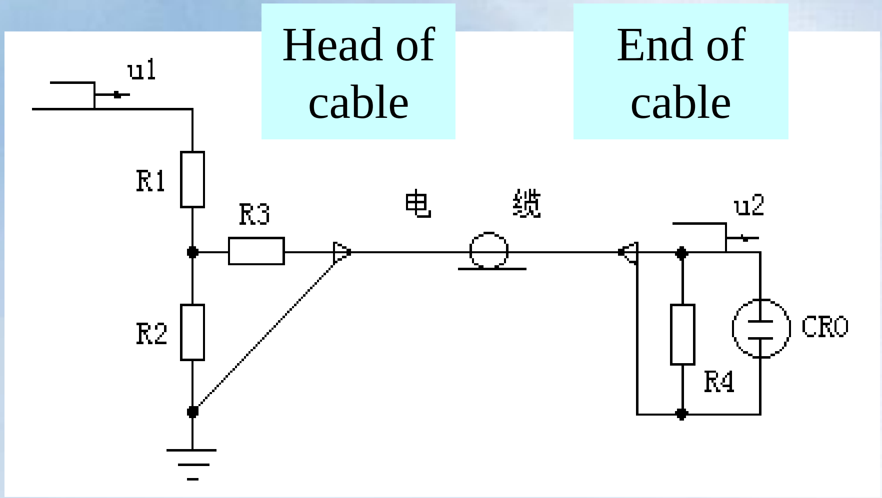
- Impedance matching at the head and end of the measuring cable

✓ The surge impedance Z of measuring cable is mostly 50 Ω, 75 Ω

✓ Impedance matching: no refraction and no reflection

- R_1 and R_2 are the resistance of high voltage and low voltage arm respectively
- R_4 is the end matching resistance, R_4 is normally = Z
- R_3 is the matching resistance at the head of cable, $R_2+R_3=Z$, *Why?*

Impedance match of the measuring cable for resistance potential divider

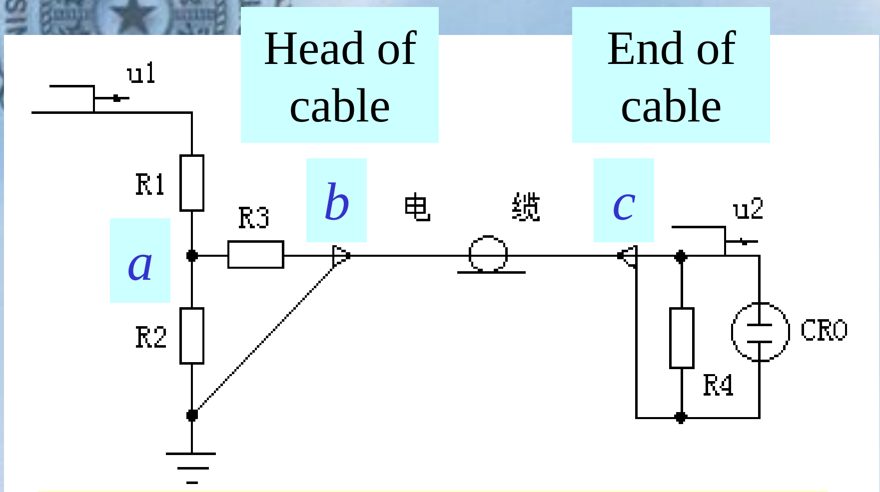


measurement circuit of resistance voltage divider for impulse voltage

- End matching: the impulse voltage wave enters the cable from the voltage divider, no reflection is required when it reaches the end of the cable. The impedance "looks" to the right from the end of the cable equals to the impedance of the cable, then $R_4 = Z$

- Head matching: the impulse voltage wave returns from the end of cable, no reflection is required when it reaches the head of the cable. The impedance "looks" to the left from the head of the cable equals to the impedance of the cable, then $R_2 + R_3 = Z$

Impedance match of the measuring cable for resistance potential divider



Measuring circuit of resistance voltage divider for impulse voltage

- voltage ratio (scale factor)
- ✓ The voltage ratio at t=0 is called the initial voltage ratio
- ✓ The voltage ratio at $t\to\infty$ is called the steady-state voltage ratio

When measuring the step wave, the initial voltage ratio and the steady voltage ratio of this circuit are equal

✓ Total voltage ratio K: the ratio of the input high voltage u_1 of divider to the voltage u_2 measured by the oscilloscope

$$K=[(R_1+R_2)(R_3+R_4)+R_1R_2]\,/\,R_2R_4$$

✓ Head match or end match: if the K value is too large, only the head match or end match are used by the selection of matching resistance

✓ Resistance of cable core: when cable is very long, the dividing voltage of the cable core resistance should be considered

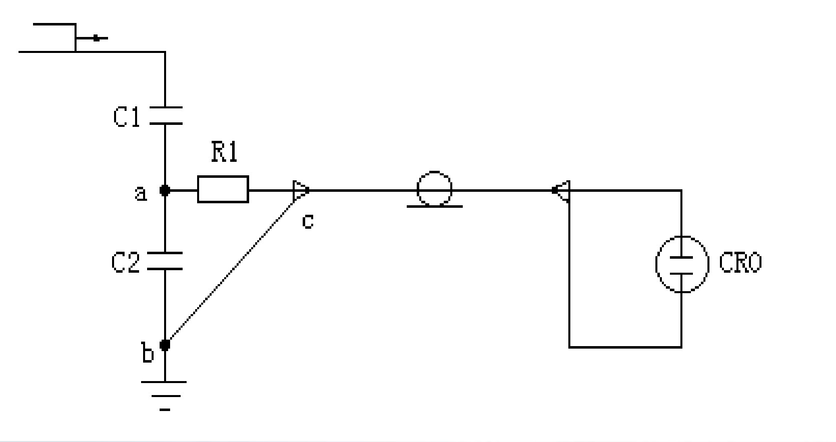
Impedance match of the measuring cable for capacitance potential divider

- The measurement circuit of the coaxial cable with head matching only

➢ Amplitude of incident wave to the cable: At the initial moment of the coming of step voltage, the amplitude into the cable is

$U_1[C_1/(C_1+C_2)][Z/(Z+R_1)]$

$=C_1U_1/[2\cdot(C_1+C_2)]$ (matching, R_1=Z)



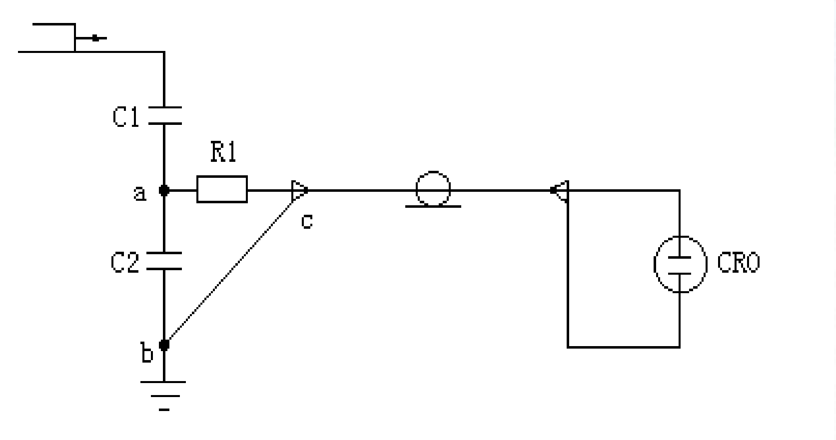
measuring circuit of capacitance divider for impulse voltage with head matching coaxial cable, $R_1=Z$

✓ When the reflected wave runs to the head of cable (wave direction from right to the left), because C_2 is large and R_1 has matched the impedance of cable, there is no reflected wave at the first end

➢ Initial voltage ratio: $\boldsymbol{K_1=(C_1+C_2)/C_1}$

Impedance match of the measuring cable for capacitance potential divider

- The initial wave process:
  - ✓ The incoming wave amplitude to the cable: $C_1U_1/[2\cdot(C_1+C_2)]$
  - ✓ The end of the cable connects to the oscilloscope input, its input impedance is very high because its input capacitor is very small, so it can be seen as an open circuit
  - ✓ Therefore, the wave subjected to a positive reflection at the end of cable. The reflected wave is added to the incident wave, and the voltage obtained by the oscilloscope is $C_1U_1/(C_1+C_2)$



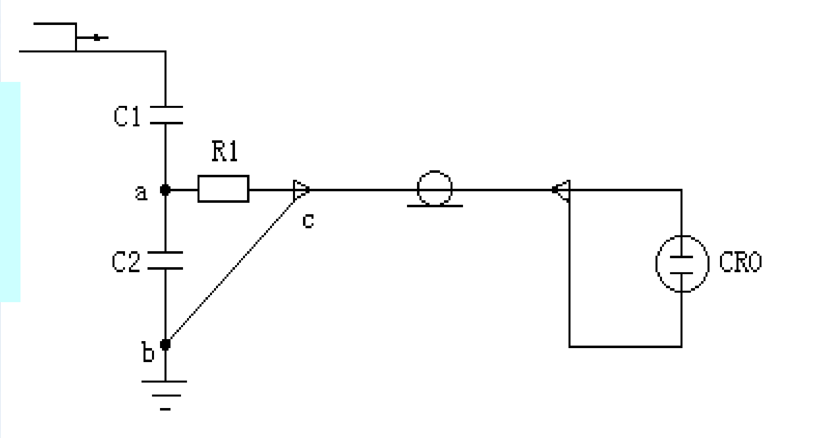
measuring circuit of capacitance divider for impulse voltage with head matching coaxial cable, $R_1=Z$

- The seemingly steady state
  - ✓ After wave runs twice in the cable for a travel time of 2τ, it can be considered to reach a seemingly steady state
  - ✓ At this point, the cable is seen as a capacitor C_0, so when $t \geq 2\tau$,

$$K_2=(C_1+C_2+C_0)/C_1$$

Impedance match of the measuring cable for capacitance potential divider

- Initial voltage ratio: $K_1 = (C_1+C_2)/C_1$
- Steady state voltage ratio: $K_2 = (C_1+C_2+C_0)/C_1$



measuring circuit of capacitance divider for impulse voltage with head matching coaxial cable, $R_1=Z$

- **Voltage overshoot problem**

✓ There is some difference between K_1 and K_2, and the coaxial cable will cause the voltage error, which is related to $C_0/(C_1+C_2) \approx C_0/C_2$

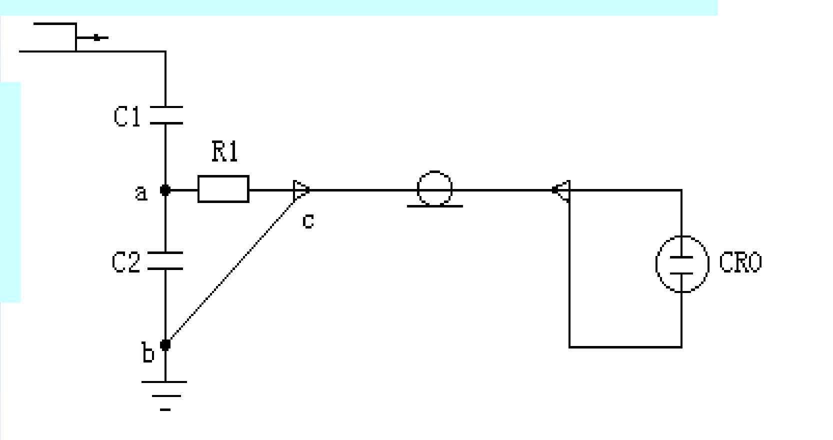
✓ For short or medium-length cables, and for high C_2 values, or a high voltage ratio, this overshoot has little effect and can be ignored

Higher voltage ratio will result the lower measured voltage

$K_2 > K_1$ result the problem of overshoot in the measurement of impulse voltage

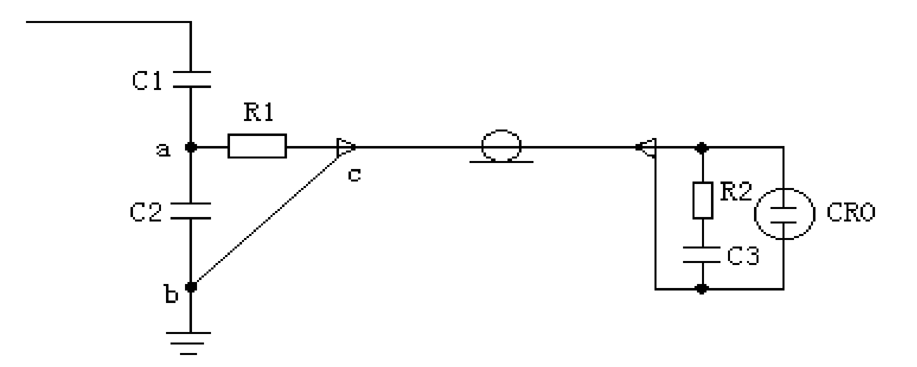
Impedance match of the measuring cable for capacitance potential divider

- Initial voltage ratio: $K_1=(C_1+C_2)/C_1$
- Steady state voltage ratio: $K_2=(C_1+C_2+C_0)/C_1$



measuring circuit of capacitance divider for impulse voltage with head matching coaxial cable, $R_1=Z$

- ✓ **Solution of the error:** a long cable is often necessary when capacitance voltage divider is used in the measurement of transient voltage field test. At this time, the circuit proposed by F.G. Burch many years ago is helpful to eliminate the voltage error problem of overshoot.



The measuring circuit of the capacitance divider with head and end matching $C_1+C_2=C_3+C_0$, $R_1=R_2=Z$

- Measurement circuit of coaxial cable matched at both ends

➢ Parameter selection: $C_1+C_2=C_3+C_0$, $R_1=R_2=Z$

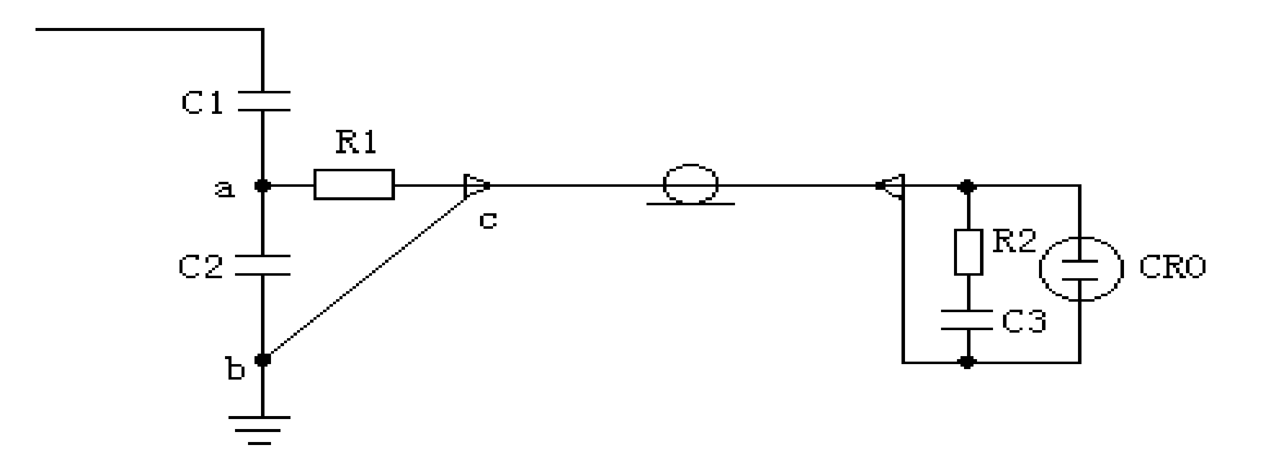
➢ Initial voltage ratio here: when $t=0^+$

$$K_1=\frac{U_1}{\left[C_1U_1/(C_1+C_2)\right]\left[Z/(R_1+Z)\right]}=2(C_1+C_2)/C_1$$

➢ Steady state voltage ratio here: when $t\geq 2\tau$

$K_2=(C_1+C_2+C_3+C_0)/C_1=2(C_1+C_2)/C_1$ **C_2, C_3 and C_0 is parallel**

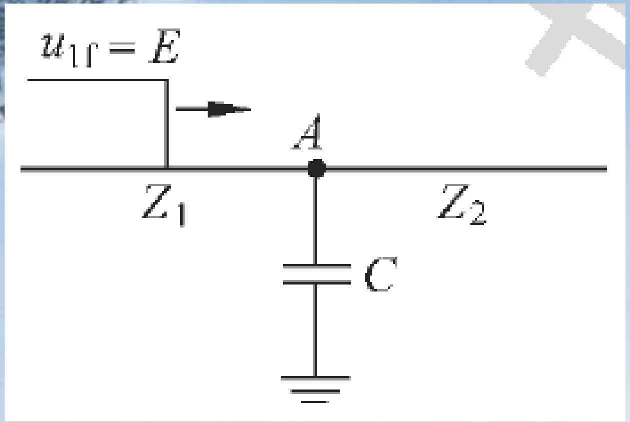
Then, initial voltage ratio and steady state voltage ratio are equal now

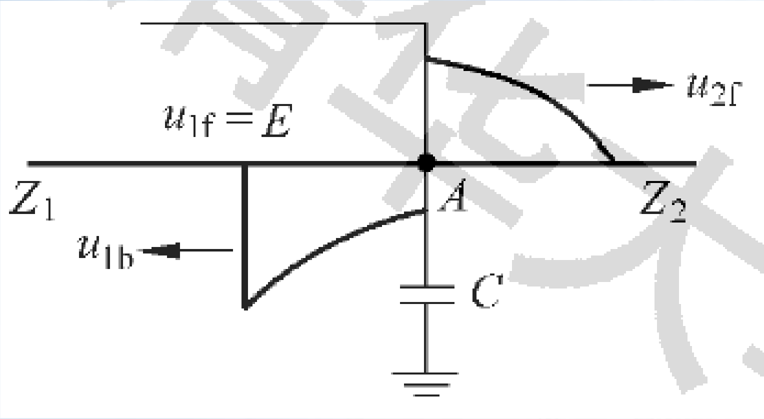


The measuring circuit of the capacitance divider with head and end matching

$C_1+C_2=C_3+C_0$, $R_1=R_2=Z$

8.3 Travelling wave through parallel capacitance and series inductance

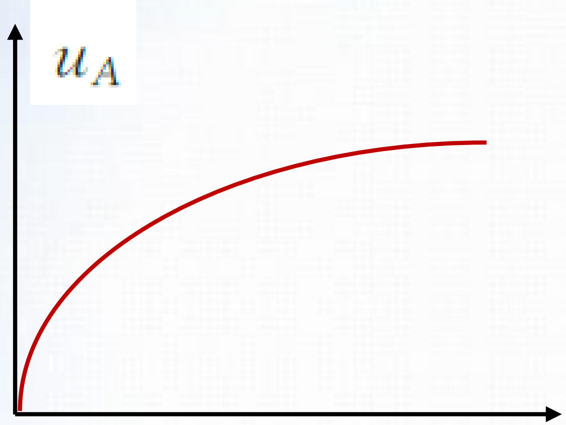




$$u_A(t) = \alpha E(1 - e^{-\frac{t}{T}}) = u_{2f}(t)$$

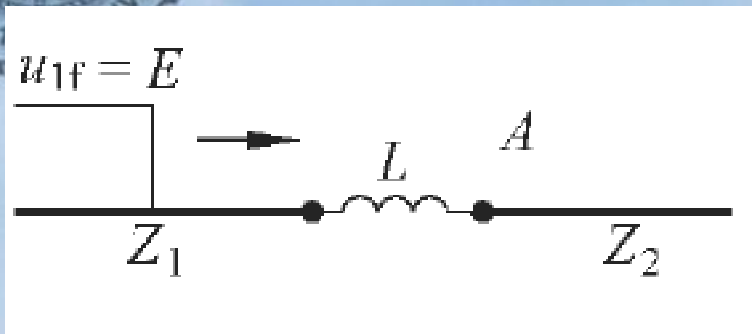
其中，$\alpha = \dfrac{2Z_2}{Z_1 + Z_2}$；$T = C\dfrac{Z_1 Z_2}{Z_1 + Z_2}$

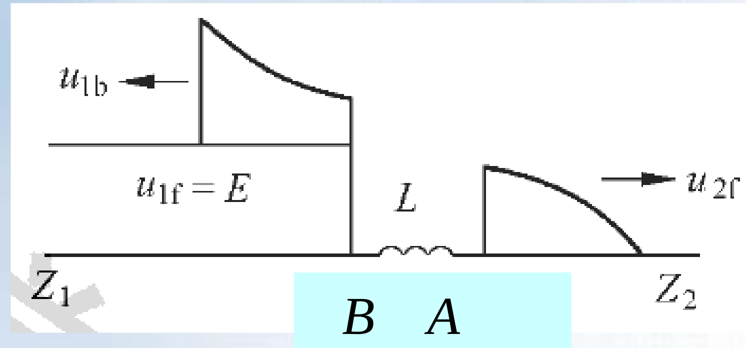
$$\left(\frac{du_A}{dt}\right)_{max} = \left.\frac{du_A(t)}{dt}\right|_{t=0} = \frac{\alpha E}{T} = \frac{2E}{Z_1 C}$$



Due to the existence of parallel capacitor *C*, the steepness of the forward voltage wave on Z_2 decreases greatly, and the voltage amplitude is not affected

8.3 Travelling wave through parallel capacitance and series inductance

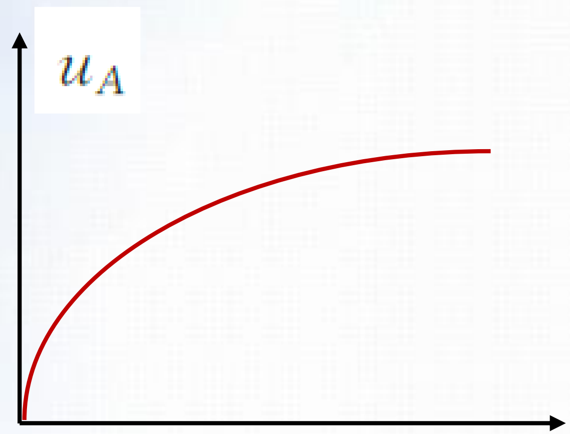




$$u_A(t) = \alpha E(1 - e^{-\frac{t}{T}}) = u_{2f}(t)$$

$$\text{其中}, \alpha = \frac{2Z_2}{Z_1 + Z_2}; \quad T = \frac{L}{Z_1 + Z_2}$$

$$\left(\frac{du_A(t)}{dt}\right)_{max} = \frac{du_A(t)}{dt}\bigg|_{t=0} = \frac{\alpha E}{T} = \frac{2EZ_2}{L}$$



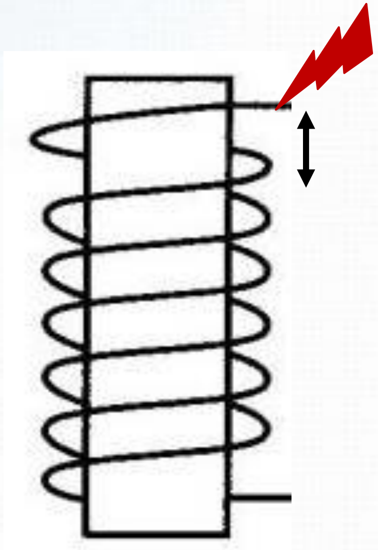
Due to the existence of series inductance *L*, the steepness of the forward voltage wave on Z_2 decreases greatly, and the voltage amplitude is not affected

Example: The incident step wave with an amplitude of 100kV, through the cable with surge impedance of $Z = 50\Omega$, comes to the generator winding. The winding length per turn is $l = 3$m, the speed of travelling wave along the winding $v = 6\times10^7$ m/s. The allowable voltage for turn-turn insulation is 600V. In order to protect the turn-turn insulation, what is the capacitance value C for the generator?

Analysis: The turn-turn capacitance of the generator winding is very small, and it can be regarded as a line with surge impedance under the impulse wave.

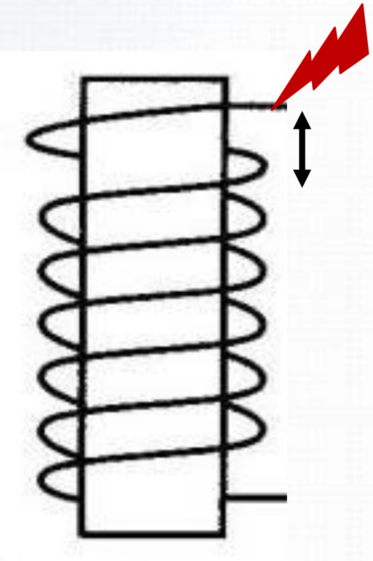
When the wave travels one turn along the winding, the turn-turn voltage $u = al / v$, where l is the length of one turn, v is the wave velocity (m/s), and a is the steepness of indecent wave (kV/μs).

After generator is manufactured, l and v will not change, so the steepness of the wave a must be limited.



Example: The incident step wave with an amplitude of 100kV, through the cable with surge impedance of Z = 50Ω, comes to the generator winding. The winding length per turn is l = 3m, the speed of travelling wave along the winding $v = 6\times10^7$ m/s. The allowable voltage for turn-turn insulation is 600V. In order to protect the turn-turn insulation, what is the capacitance value C for the generator?

Solution: Maximum allowable incident wave steepness $(du/dt)_{max}$ can be divided into $(du/dx)_{max}\times(dx/dt)$,



$$(du/dt)_{max} = (du/dx)_{max}\times(dx/dt) = (600V/3m)\times(6\times10^7 m/s) = 12kV/\mu s$$

So the required electrical capacity is

$$C = 2E / [Z^*(du/dt)_{max}] = 2\times100kV/(50\ \Omega\times12kV/\ \mu s) = 0.33\ \mu F$$