清華大学 Tsinghua University

Please connecting to the Rain Classroom

Revision, preview and assignment

Revision: 6.3, 7.1, 7.2, 7.4, **Self-study:** 6.4, 7.3

Preview: 7.5, 7.6, 7.13, **Self-study:** 7.7-7.12

Homework: 6-9, 6-13, 6-15, 7-1

1

Special Topic: On-site Partial Discharge Test for Large Power Transformers

Yuanxiang Zhou
Department of Electrical Engineering
Tsinghua University
Email：zhou-yx@tsinghua.edu.cn
MB：13911097570

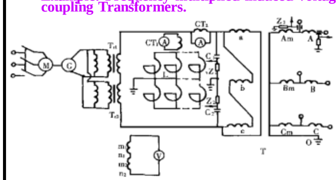
2

Contents

3

1. Multiple Frequency for Induced Voltage Withstand and Partial Discharge Tests

- GB/T 1094.3-2017 Power Transformers – Part 3: Insulation Levels, Dielectric Tests, and External Gaps in Air
- GB/T 7354-2018 High-voltage Test Techniques – Partial Discharge Measurements
- Example: Frequency-multiplied induced voltage partial discharge test for Self-coupling Transformers.



Test circuit for partial discharge testing of large power transformers.
(Full-voltage excitation for Phase A, while Phase B & C half-voltage)

M——Three-phase asynchronous motor, 280kW, 380V, 50Hz
G–Three-phase medium frequency brushless synchronous generator, 500kVA, 660V, 250Hz
T_{r1}, T_{r2}– Single-phase medium frequency step-up transformers, 400kVA, 35/ 0.66 - 0.66kV, 250Hz
m_1n_1, m_2n_2–Medium frequency transformer measuring winding 35/0.2kV
L–Compensation reactor group, including 8 reactors with a single capacity of 80kvar
CT_1, CT_2–Clamp-on ammeters
C_1, C_2–Coupling capacitors, 60kV, 1000pF
Z_1, Z_2–Partial discharge detection impedances
T–Tested transformer

4

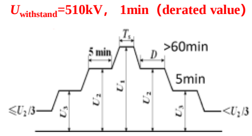
1. Multiple Frequency for Induced Voltage Withstand and Partial Discharge Tests

- Why increase frequency for induced voltage withstand tests?
- Multiple Frequency for Induced Voltage Withstand test (duration of withstand voltage in the case of multiple frequency t=60×100/f)

1000kVtransformer：U_m=1100kV，$U_{withstand}$=1100kV，5min（type test without derating)
500kV transformer：U_m=550kV，$U_{withstand}$=680kV，1min（derated value)
330kV transformer：U_m=363kV，$U_{withstand}$=510kV，1min（derated value)

- Partial discharge test voltages:

330 kV transformer：
U_1=1.7U_m/√3
U_2=1.5U_m/√3
U_3=1.1U_m/√3



5

2. Multi-terminal Calibration and Multi-terminal Measurement

Table 3 Multi-terminal calibration results in the case phase B is excited alone and three phases are measured simultaneously. Unit: pC

注入端 \ 测量端	A	B	C	Am	Bm	Cm
A —地	1 000	53	60	312	205	82
B —地	55	1 000	56	131	342	100
C —地	50	58	1 000	63	252	333
Am —地	255	90	60	1 000	250	378
Bm —地	47	210	38	244	1 000	270
Cm —地	51	86	231	323	288	1 000

Table 4 Multi-terminal measurement results in the case phase B is excited alone and three phases are measured simultaneously. Unit: pC

电压标么值 \ 测量端	A	B	C	Am	Bm	Cm
0.5	106	1 500	120	292	1 233	270
0.7	227	4 500	300	729	2 444	612
0.8	553	7 000	1 020	2 250	4 888	2 378
0.9	461	6 000	600	1 375	4 666	1 081

- The results strongly implies that there is defect in Phase B.

6

3. Partial Discharge Test as Phase B is Short circuited

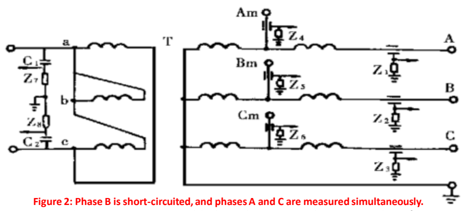


Figure 2: Phase B is short-circuited, and phases A and C are measured simultaneously.
C_1, C2 - coupling capacitor; Z_1~Z_8–Partial discharge detection impedance; T–Tested transformer

- Partial Discharge Test as Phase B is Short circuited to prove if there was partial discharge defect in Phase B.

7

3. Partial Discharge Test as Phase B is Short circuited

表 6　B 相短接 ,A、C 两相试验时的多端测量结果

施加电压标么值	测量端及放电水平/ pC					
	A	B	C	Am	Bm	Cm
0.8	96	88	135	313	70	592
0.9	149	125	260	417	228	833 *
1.3	461	276	650	1 250 *	340	1 944 *

注:表中带“ * ”的数据为电晕放电量。

- The Result of Partial Discharge Test as Phase B is Short circuited to provide another evidence of the existence of partial discharge defect in Phase B.

8

4. Electrical-Ultrasonic Combined Test

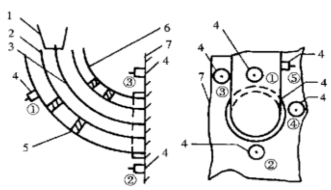


Figure 3. Probe placement diagram of ultrasonic partial discharge detection device
1. Casing 2. Aluminum shielding tube 3.330kV high voltage lead wire 4. Ultrasound probe 5. Insulating partitions 6.330kV lead box shell 7. Transformer box wall
①, ②, ③, ④, ⑤ -- Ultrasonic probe detection position
(a) Side view of the A-phase 330kV high-voltage lead-out line
(b) Front view of the B-phase 330kV high-voltage lead-out line

- Ultrasonic probe was used to determine the location of partial discharge in Phase B.

9

5. Electrical-Ultrasonic Combined Test

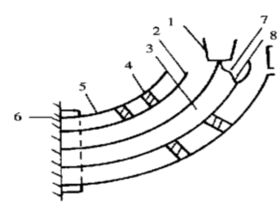


Figure 4: Inspection result after hanging cover for turret of Phase B.

- Disconnection of shielding wire with high-voltage lead inside turret of Phase B.

10

Thank you!

Detail test and diagnosis process refer to:
Field Partial Discharge Defect Investigation and Cause Analysis for Power Transformers (Available on the online learning platform)


变压器 TRANSFORMER
Vol. 38 No. 9 September 2001

变压器现场局部放电缺陷查寻及原因分析

运行维护

周远翔[1],孙昌富[1],李光范[2],梁曦东[1],关志成[1]

(1. 清华大学,北京 100084;2. 中国电力科学研究院高压所,北京 100085)

关键词:变压器;局部放电;超声波定位

Yuanxiang Zhou
MB：13911097570

11

清华大学 Tsinghua University

Hybrid: offline
Network teaching: Rain Class

High Voltage Engineering

Generation of high Voltage and Large Current (2)

Yuanxiang ZHOU
zhou-yx@tsinghua.edu.cn, 13911097570
Department of Electrical Engineering, Tsinghua University

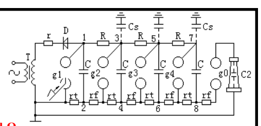
12

Chapter 6 Generation of high voltage and large impulse current

6.3.1 Basic principle of impulse voltage generator

- **Impulse voltage (two types)**
  - **Lightning impulse voltage:** caused by lightning strikes in nature
  - **Switching impulse voltage:** caused by the operation of power system equipment
- **Impulse voltage generator**
  - **Concept:**
    - ✓ A DC high-voltage source charges a set of parallel energy storage high-voltage capacitors for tens of seconds.
    - ✓ A sudden discharge occurs through copper spheres in series with a resistor, creating an impulse voltage waveform with steep-rising front on test specimen.
    - ✓ The duration of the impulse wave is measured in microseconds, and the voltage peak is generally tens of kV to several MV.
  - **Inventor:**
    - ✓ The multi-stage circuit of the impulse generator that produces higher voltage was first proposed by the German E. Marx.
    - ✓ For this purpose, he obtained a patent in 1923 and the device was called the Marx circuit.

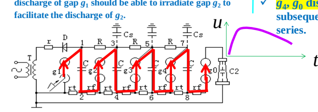
- **Lightning impulse voltage generator circuit (universal high-efficiency discharge circuit)**
  - r: Protection resistor, usually several hundreds of kΩ
  - R: Charging resistor, usually tens of kΩ
  - r_f: Front resistor of each stage, about dozens of Ω
  - r_t: Discharge resistor of each stage, about several hundred Ω
  - C: Main capacitor of each stage, usually a few tenths of μF



An impulse voltage generator of high-efficiency discharging circuit

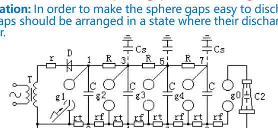
  - C_s: Stray capacitance to ground at each corresponding point, usually only a few pF
  - C_2: Load capacitance, its value depends not only on the test specimen but also on the wave modulation. Generally ranging from several hundreds of pF to a few nF
- **Switching impulse voltage generator circuit**
  - Circuit: the same as the lightning impulse voltage generator circuit
  - The difference from the lightning impulse voltage generator circuit: When generating switching impulse voltage, the resistance values in the circuit must be increased by at least two orders of magnitude.

- **Working principle**
  - C charged in parallel, then discharged in series
  - ✓ **Charge of main C:** The main capacitor C is charged in parallel to voltage U through the rectification source.The gap between various spheres are pre-adjusted to withstand the voltage U. If the applied voltage is slightly higher than U, the gap will breakdown.
  - ✓ **Discharge of spark gap:** When the generator is required to act, a pulse voltage of 5kV to 8kV amplitude can be applied to the needle electrode of the spark gap. A small spark is generated between the needle electrode and the grounded sphere surface. Due to the ultraviolet irradiation, the spark gap g_1 discharge.
    Note: The ultraviolet irradiation produced during the discharge of gap g_1 should be able to irradiate gap g_2 to facilitate the discharge of g_2.
  - ✓ **Elevation of Potential at Point 2:** Following the discharge of g_1, point 1 suddenly changes from the original $-U$ to zero potential, while point 2 changes from the original zero potential to $+U$.
  - ✓ **Gap g_2 discharge:** The potential difference across gap g_2 becomes $2U$ after the discharge of g_1, which is twice the withstandable voltage. Therefore, g_2 promptly discharges under the influence of ultraviolet irradiation caused by the discharge of g_1.
  - ✓ **Elevation of potential at point 4, g_3 discharge:** The potential at point 4 becomes $+2U$, and the instantaneous voltage difference across g_3 reaches $3U$, leading to an immediate discharge.
  - ✓ **g_4, g_0 discharge:** Gaps g_4 and g_0 discharge subsequently, connecting C and r_f of each stage in series.



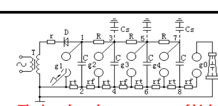
The impulse voltage generator of high-efficiency discharging circuit

- **Operating characteristics of impulse voltage generator**
  - **Charging and discharging process**
    - ✓ **4 main capacitor C converted from parallel to series:** by a set of sphere gaps operating in insulation or discharge state.
    - ✓ **Charge resistor R:** plays the role of connecting the circuit during charging, while plays the role of isolation during discharging
  - **The key to output waveform**
    - **The stray capacitance C_s:** maintain the potential of each point
    - **Potential holding time:** Because the stray capacitance C_s is very small, the duration of the overvoltage applied to each intermediate sphere gap before discharge is very short.
    - **Maintain synchronization:** In order to make the sphere gaps easy to discharge synchronously, simply used sphere gaps should be arranged in a state where their discharge (ultraviolet) can irradiate to each other.



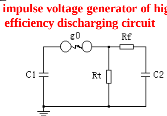
The impulse voltage generator of high-efficiency discharging circuit

- **Equivalent circuit during discharge**
  - C_1: Equivalent main capacitor, the series value of four capacitors C is $C/4$.
  - R_f: Front resistor $= 4r_f$
  - R_t: Tail resistor $= 4r_t$
  - Nominal voltage: $U_1 = 4U$
  - If the number of stages is n, 4 of the above is replaced by n

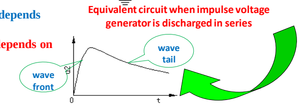


The impulse voltage generator of high-efficiency discharging circuit

- **Impulse voltage waveform**
  - Voltage waveform: After g_0 breakdown, as shown in the figure, the voltage u_2 acting on the sample C_2 deeply increases then slowly decreases.
  - Selection of C_1: In order to make the voltage applied to C_2 close to the original charging voltage of C_1 (i.e. nominal voltage), $C_1 >> C_2$ should be selected
  - Voltage rise rate: The rise duration of u_2 mainly depends on the time constant R_fC_2.
  - Voltage fall rate: The fall duration of u_2 mainly depends on the time constant $(C_1 + C_2)R_t$.

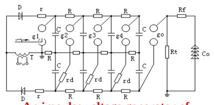


Equivalent circuit when impulse voltage generator is discharged in series



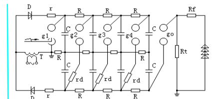
The waveform of voltage u_2 on C_2

- **Impulse voltage generator of bilateral charging circuit**
- The figure shows two half-wave DC charging circuits.
- The front resistor and tail resistor are Centralized parameters.
- **Damping resistor r_d**
  - To prevents high-frequency oscillations caused by stray inductance and stray capacitance distributed to ground, or to ensures a smooth front of the impulse waveform.
  - Generally, each stage is 5Ω～25Ω, and the actual value can be determined through experiments.
  - If the number of stages is n, the total series value of damping resistors, nr_d, is referred to as R_d.
  - R_d also plays a role in adjusting the front time.
  - During discharge, R_d which in series with R_t will cause a voltage division, leading to a reduction in the output voltage.



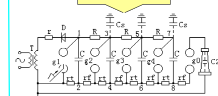
An impulse voltage generator of bilateral charging circuit

- **Impulse voltage generator of bilateral charging circuit**
- **Bilateral charging circuit:** The generator adopts a configuration where the front resistor and discharge resistor are centrally placed. The figure shows two half-wave DC charging circuits.
- **Damping resistor r_d**
  - Prevents high-frequency oscillations caused by stray inductance and stray capacitance distributed to ground or ensures a smooth front of the impulse waveform.
  - Generally, each stage is 5Ω～25Ω, and the actual value can be determined through experiments.
  - If the number of stages is n, the total series value of damping resistors, nr_d, is referred to as R_d.
  - R_d also plays a role in adjusting the front time.
  - During discharge, it and R_t will cause a partial voltage division, leading to a reduction in the output voltage.
- **The difference between impulse voltage generator circuits for bilateral charging and efficient charging**



An impulse voltage generator of bilateral charging circuit

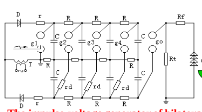
r_f and r_d voltage efficiency



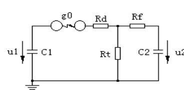
Impulse voltage generator of high-efficiency circuit

6.3.2 Approximate calculation of discharge circuit of the bilateral generator

1. Computation circuit of the basic circuit

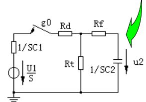


The impulse voltage generator of bilateral charging circut



Equivalent circuit of the basic circuit during discharge

- **Computation circuit during discharge**
- **Initial charging voltage:** U_1 **on the main capacitor** C_1
- **Laplace transform computation circuit**
- **Output voltage:** $U_2(s) = U_1 \cdot d/(s^2+as+b)$



Computation circuit during discharge

2. Approximate calculation of discharge circuit

- **Approximate expression of discharge output voltage:** In practical applications, approximation methods are often used to calculate loop parameters for lightning impulse waves. For the bilateral discharge equivalent circuit, the expression of the output voltage u_2 of the discharge circuit is:

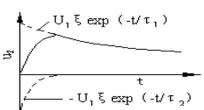
  $u_2(t)=U_1\varepsilon[\exp(s_1t)-\exp(s_2t)]$
- **Time constant:** Use τ_1 and τ_2 to express s_1 and s_2 respectively, then

  $\tau_1= -1/s_1$, $\tau_2= -1/s_2$
- **Approximate expression:**

  $u_2(t)= U_1\varepsilon[\exp(-t/\tau_1)-\exp(-t/\tau_2)]$

  $u_2(t)\approx U_{2m}[\exp(-t/\tau_1)-\exp(-t/\tau_2)]$
- **1.2/50μs lightning impulse wave**

  $|s_2|>>|s_1|$, $\tau_1>>\tau_2$



The two exponential components are superimposed to form u_2

- **Mathematical-physical explanation:** $u_2(t)$ is composed of the superposition of two exponential components. The wave front time is much shorter than the wave tail half-peak time
- **Wavefront time:** determined by the smaller time constant τ_2
- **Half-Peak Time:** determined by the significantly larger time constant τ_1

- **Wave front time and wave tail time defined by standard wave**
- At t_1 voltage: $u_2=0.3U_{2m}$
- At t_2 voltage: $u_2=0.9U_{2m}$
- At T_t voltage: $u_2=0.5U_{2m}$
- **Front time calculation**
- For the calculation of the wavefront time T_f and its relation to circuit parameters, it can be approximated that $\exp(-t/\tau_1)$ remains nearly constant with time t, and its value is considered constant at 1. Thus,

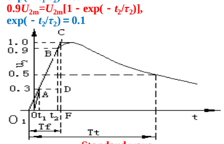
  $u_2(t)\approx U_{2m}[1-\exp(-t/\tau_2)]$

∴ $0.3U_{2m}=U_{2m}[1-\exp(-t_1/\tau_2)]$,

$\exp(-t_1/\tau_2)=0.7$

$0.9U_{2m}=U_{2m}[1-\exp(-t_2/\tau_2)]$,

$\exp(-t_2/\tau_2)=0.1$



Standard wave

- Then $t_2-t_1=\tau_2 \ln 7$
- Front time: As the triangles ΔO_1CF and ΔABD are similar in the diagram, T_f can be expressed as:

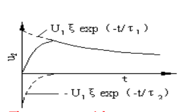
  $T_f=(t_2-t_1)/(0.9-0.3)$

  $=\tau_2 \ln 7/0.6$

  $=3.24\tau_2$
- After the gap g_0 discharge, the voltage u_2 rises. τ_2 represents the charging time constant. Thus,

  $\tau_2=(R_d+R_f)C_1C_2/(C_1+C_2)$
- Therefore, $T_f=3.24(R_d+R_f)C_1C_2/(C_1+C_2)$

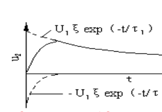
  Considering $C_1>>C_2$, therefore $T_f\approx 3.24(R_d+R_f)C_2$



The two exponential components are superimposed to form u_2

- **Half-peak time (wave tail time) calculation**
- For the calculation of the half-peak time and its relation to circuit parameters, it is considered that $\tau_1>>\tau_2$
- The exponential term $\exp(-t/\tau_2)$ in the half-peak time expression has decayed to near-zero value.
- When determining the half-peak time T_t, considering $T_t>>T_f$ and neglecting the influence of T_f :
- $u_2(t)\approx U_{2m}\exp(-t/\tau_1)$
- According to the waveform definition,

  $U_{2m}/2= U_{2m}\exp(-T_t/\tau_1)$
- $T_t=\tau_1 \ln 2\approx 0.69\tau_1$

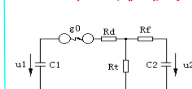


The two exponential components are superimposed to form u_2

- After the voltage u_2 reaches the peak value U_{2m}, as shown in the equivalent circuit diagram, the capacitors C_1 and C_2 discharge through the resistor R_t.
- Since $C_1>>C_2$, the discharge rate is primarily determined by C_1. Therefore,

∴ $\tau_1\approx(R_d+R_t)(C_1+C_2)\approx (R_d+R_t) C_1$

- The half-peak time $T_t=0.69(R_d+R_t)(C_1+C_2)$
- or $T_t\approx 0.69 (R_d+R_t) C_1$



Equivalent circuit of the basic circuit during discharge

3. Voltage efficiency of the generator

$\eta = [C_1/(C_1+C_2)][R_t/(R_d+R_t)]$

- This implies that the peak value U_{2m} of the output voltage is lower than the initial charging voltage U_1 on capacitor C_1.
- This is due to the voltage division between C_1 and C_2 as well as the voltage division between R_t and R_d.

By the way, for the high-efficiency circuit, the output voltage u_2 is only deceased by the voltage division between C_1 and C_2, while there is no other voltage division. Thus the generator is called high-efficiency circuit one.

4. Nominal value of the generator

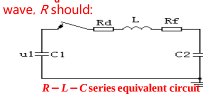
- **Nominal voltage:** the nominal voltage of the impulse voltage generator U_{1n}, $U_{1n} \geq U_1$
- **Nominal energy:** $W_n = C_1 U_{1n}^2/2$

25

6.3.3 Approximate calculation considering circuit inductance

- When calculating the rise time (wavefront time), a simplified condition is still used: $R_t \to \infty$
- Taking the loop inductance L into consideration, the discharge loop will become an R-L-C series loop.
- Where R is the sum of damping resistor R_d and wavefront resistor R_f. To obtain a non-oscillatory impulse wave, R should:

$$R \geq 2\sqrt{\frac{L}{C_1C_2/(C_1+C_2)}}$$



$R-L-C$ series equivalent circuit

- Assuming critical damping, after simplification, the expression for the wavefront time is obtained:

$T_f = 2.33\tau_2 = 2.33RC_1C_2/(C_1+C_2)$

Inductance makes the waveform steeper and the wavefront time shortened (?)

26

投票 最多可选1项 设置

Does the loop inductance affect the wave tail time T_t?

A Yes

B No

提交

27

6.3.4 Examples calculation of discharge circuit of impulse voltage generator

Set up an impulse voltage generator, which is required to meet the lightning impulse discharge and withstand voltage test of 110 kV electric porcelain products.Please select its rated voltage U_N, impulse capacitance C_1, initially determine the load capacitance C_2, calculate the wavefront resistance R_f, discharge resistance R_t, voltage efficiency η and rated capacity W_N, etc.

E.g.

Solution:

- **GB standards specify the lightning impulse withstand voltage of a 110 kV porcelain product as 450 kV.**
  - ✓ **Discharge voltage is generally less than 850 kV, but practically taken as 900 kV.**
  - ✓ **Preliminary voltage efficiency is considered as 85%, so the nominal voltage is calculated as 1060 kV.**
  - ✓ **Considering frequent discharges affecting the lifetime and possible special product tests, a nominal voltage of 1200 kV is chosen.**
  - ✓ **Also considering meeting the 1000 kV/μs steep wave test for composite insulators.**

28

Set up an impulse voltage generator, which is required to meet the lightning impulse discharge and withstand voltage test of 110 kV electric porcelain products.Please select its rated voltage U_N, impulse capacitance C_1, initially determine the load capacitance C_2, calculate the wavefront resistance R_f, discharge resistance R_t, voltage efficiency η and rated capacity W_N, etc.

E.g.

Solution: (Continued)

- **Porcelain products have small capacitance, and the load capacitance mainly consists of the divider and the stray capacitance of the generator itself.**
  - ✓ **The capacitance of the low-damping resistor-capacitor divider is 300 pF.**
  - ✓ **stray capacitance and sample capacitance, is taken as 200 pF.**
  - ✓ **Total load capacitance is 500 pF.**
- **Considering only the voltage efficiency, C_1 can reach 5 nF~10 nF, and 20 nF is selected for the enhancement effect.**
- **Using a high-efficiency circuit, assuming the voltage of each stage is 200 kV, a total of 6 stages are required, and the capacitance of the capacitor C of each stage is 0.12 μF.**
- **Calculation method: second-order resistor-capacitor loop calculation, approximate calculation of discharge loop**

29

Chapter 6 Generation of high voltage and large impulse current

30

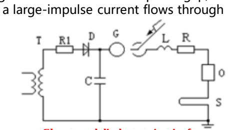
6.4.1 Function of impulse current generator & regulations of current waveform

● **Function of impulse current generater:**
Simulating lightning current and generating pulse power.
● **Impulse current waveforms:**
In electrical engineering, two classes of waveforms are specified:
- **Type 1 (T_1/T_2) Waves:** 1 μs/20 μs, 4 μs/10 μs, 8 μs/20 μs, 30 μs/80 μs
- **Type 2 (Approximate Square Wave):**
  - ✓ **Peak Duration (Td):** 500 μs, 1000 μs, 2000 μs, or 2000 μs and 3200 μs
  - ✓ The specified allowable deviation and definitions of T_d and T_t are shown in Chinese national standard **GB/T 16927.1**

31

6.4.2 Basic principle of impulse current generator

● **Large capacitor stores energy to generate impulse current**
- ✓ The working principle is essentially similar to that of an impulse voltage generator.
- ✓ A set of high-voltage and large-capacity capacitors are first **charged in parallel** through DC high-voltage supply.
- ✓ The charging time is tens of seconds to several minutes.
- ✓ Next, by triggering the breakdown of the sphere gap, **discharge in parallel** to the test specimen, so that a large-impulse current flows through the specimen.



Charge and discharge circuit of impulse current generator

32

6.4.3 Structure of impulse current generator

● **The total loop inductance**

It is composed of residual inductance of capacitors, connecting line inductance, sphere gap inductance, and specimen inductance.

To achieve the maximum impulse current, it is essential to minimize circuit inductance. **Strategies for minimizing circuit inductance:**
- Low inductance pulse capacitors are preferred
- **Make the connecting wires as short as possible**, use **a large aluminum plate** as connecting wires, and the two aluminum plates connecting the electrodes are almost close to each other; or **use coaxial cables**
- **Reduce the length of the discharge spark to reduce the inductance during sphere gap discharge**

● To avoid capacitor explosion caused by single capacitor failure

● **To avoid current flowing through the grounding system causing the ground potential to rise**, the current from the impulse current generator should flow back to the lower electrode of the capacitor through a good metal circuit.

● **Single-point grounding for discharge circuit**

33

清華大學 Tsinghua University

Hybrid: offline
Network teaching: Rain Class

High Voltage Engineering

Measurement of High Voltage (1)

Yuanxiang ZHOU
zhou-yx@tsinghua.edu.cn, 13911097570
Department of Electrical Engineering, Tsinghua University

34

Chapter 7 Measurement of high voltage

*Note: self-study

35

Chapter 7 Measurement of high voltage

7.1 Basic concepts of HV measurement

36

7.1.1 Introduction to high voltage measurement

- **Challenges in High Voltage Measurement:**

✓ **Safety and reliability**
✓ **The influences of leakage current and corona**
✓ **The Influences of stray parameters under AC and impulse voltages**
✓ **Good step response characteristics under impulse voltage**
✓ **There is enhanced difficulties in measurements at voltage levels high up to the MV Range**

投票 最多可选1项 设置

Can the sphere-sphere gap be used to measure the AC / DC and impulse high voltage?

A Yes

B No

C Not sure

提交

Object \ Method		Direct measure		Indirect measure				
				Voltage dividers			Standard capacitors	
		Sphere Gap	Electro-static volt-meter	resistor	capacitor	resistor-capacitor	Centralized capacitor divider	Differential integration
Steady-state HV	AC voltage	○	○	○	○	○	○	△
	High frequency voltage	△	○	○	○	○	○	△
	DC voltage	△	○	○	×	×	×	×
	DC voltage with large pulsating component	△	△	○	×	×	×	×
Impulse HV	Lightning	○	×	○	△	○	○	○
	Switching	△	×	×	○	○	○	△
	Steep-front	△	×	○	△	○	○	○
	Very fast transient voltage	△	×	○	△	○	○	○
	Oscillatory voltage	△	×	×	○	○	○	△

7.1.2 High voltage measurement systems

- **High-voltage measurement system**

➢ **Definition:** In international standards such as **IEC 60060-2** and national standard **GB/T 16927.2** related to high-voltage testing techniques, **the entire set of devices used for high-voltage or impulse current measurements** is referred to as a measurement system.

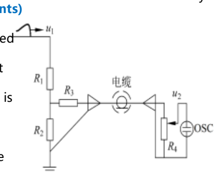
➢ **Measurement system composition (4 components)**

✓ **Transducer (converter):** Device that converts the measured quantity into a value that can be indicated or recorded by instruments.

✓ **Leads:** Wires connecting the transducer to the test object or current circuit.

✓ **Connection system:** The output of the transducer is connected to the indicator or recorder through a connection system, which includes attenuators, terminals, matching impedance or networks, indicators or recorders, and wires connected to the power supply.

✓ **Grounding Wire:** must be appropriate arranged



- **Classification of measurement systems and measurement uncertainty**

➢ **Classification of Measurement Systems**

IEC 60060-2 and the national standard **GB/T 16927.2** both classify measurement systems into two categories:

✓ **Standard Measurement System (Reference Measuring System):** A standard measurement system with higher measurement accuracy.

✓ **Approved Measurement System:** Measurement systems commonly used in laboratories are approved measurement systems that can be compared and calibrated using the standard measurement systems.

➢ **Measurement Uncertainty**

✓ In high-voltage testing, measurement uncertainty is described using **expanded uncertainty**.

✓ Expanded Uncertainty: is a quantity that determines the interval of measurement results, with the expectation that the measured value is most likely to fall within this interval. The coverage probability is less than 100%.

7.1.3 Measurement of AC and DC high voltage

- **Standard Measurement System:**

When measuring the peak or effective value of AC voltage or the arithmetic mean of DC voltage, the expanded uncertainty should not exceed the range of ±1%.

- **Approved AC Measurement System:**

The expanded uncertainty for measuring the peak or effective value of test voltage at the rated frequency should be within the range of ±3%.

- **Approved DC Measurement System:**

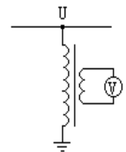
➢ The measurement expanded uncertainty for the arithmetic mean of test voltage should generally not exceed ±3%.

➢ When measuring the ripple amplitude of DC voltage, the expanded uncertainty should not exceed ±10% of the ripple amplitude or ±1% of the DC voltage average value.

- **High voltage measurements in power systems and laboratories**

➢ **Power systems**

The power operation department measures AC high voltage through **voltage transformers and voltmeters**.



Measuring AC voltage with voltage transformer

43

➢ **High voltage measurements in the laboratory**

✓ **Voltage transformers are not used much, because......**

- The voltage values in HV laboratories often exceed rated voltage of existing transformers, and customizing a transformer for such a high voltage is relatively expensive.
- High-voltage transformers are bulky and cumbersome.

✓ **Laboratory AC and DC high voltage measurement methods**

- Gas discharge methods, such as sphere gaps,to measure AC and DC HV
- Electrostatic force methods, such as electrostatic voltmeters, for AC and DC HV measurement

(The first two are direct measurement methods)

- Rectified capacitor current methods, such as peak voltmeter, for AC HV
- Rectified charging voltage methods, such as peak voltmeter, for AC HV
- Using a high-ohm resistor connected in series with a DC milliamp meter can measure the average value of the DC voltage. It is a convenient and commonly used measurement system.

44

投票 最多可选1项 设置

Can an electrostatic voltmeter be used to measure the impulse high voltage?

A Yes

B No

C Not sure

提交

45

➢ **Methods to expand the range:**

The range of various measuring instruments is limited, and a **voltage divider** is often used to expand the range of the instrument. That is:

- make most of the measured voltage fall on the HV arm of the voltage divider,
- the instrument only measures the voltage drop on the low-voltage arm.
- multiplied by the voltage dividing ratio, the measured voltage can be obtained.

➢ **Optoelectronic measurement technology:**

Optical fiber technology is increasingly used in the electrical field.

- The optical fiber itself is an insulating material. Therefore, when it is used in high-voltage measurements, it has no spray and electromagnetic interference, and therefore has great advantages.
- When measuring steady-state voltage, there are no requirements for frequency characteristics. As long as you pay attention to selecting photoelectric components with good temperature characteristics, it is easier to meet the measurement accuracy requirements.
- Photoelectric measurements of high voltages require calibration using other measurement methods

46

多选题 1分 设置

Which of the following statements is correct?

A The equivalent frequency of the standard switching impulse voltage waveform is lower than the power frequency

B The equivalent frequency of the standard lightning impulse voltage waveform is higher than the power frequency

C Measuring systems capable of measuring power frequency voltage can be used to measure switching impulse voltage

D Measuring systems capable of measuring lightning impulse voltage can be used to measure switching impulse voltage

提交

47

7.1.4 Measurement of impulse high voltage

- **Characteristics of impulse voltage**

➢ Whether it is lightning impulse voltage or switching impulse voltage, it is a voltage that **changes rapidly or relatively quickly**.

- **Features of impulse voltage measurement systems**

➢ The entire measurement system for measuring impulse voltage, including the voltage conversion device and indicating, recording and measuring instruments, must have **good transient response characteristics**.

➢ Some measurement systems that are suitable for measuring voltage of steady-state or slow processes (such as DC and AC voltages) are not suitable or impossible to measure impulse voltages.

➢ The measurement of impulse voltage includes two aspects: **peak measurement and waveform recording.**

48

● **Expanded uncertainty of measurement system**

➢ **for approved measurement systems**

✓ The expanded uncertainty for measuring the peak value of impulse full wave is within the range of ±3%.

✓ The uncertainty for measuring the chopped wave depends on the chopped time T_c

- When $0.5\ \mu s \le T_c < 2\ \mu s$, the total uncertainty is within the range of ±5%
- When $T_c \ge 2\ \mu s$, the total uncertainty is within the range of ±3%

✓ The total uncertainty in measuring time parameters of the impulse waveform (such as front time, half-value time, time to chopp, etc.) is within the range of ±10%

49

● **Measurement of impulse high voltage in laboratories**

✓ **Sphere Gap Method:** A direct method for measuring the peak value of high voltage.

✓ **Voltage divider - peak voltmeter:**

- only measures the peak value, not the waveform.
- Verify that the waveform complies with the standard in advance, or observe the waveform with an oscilloscope at the same time.

✓ **Voltage divider - oscilloscope (or digital recorder):**

- can measure the peak value and waveform at the same time.
- When using a digital oscilloscope or digital recorder, peak and time parameters can be obtained immediately and printed

✓ **Photoelectric measurement method:**

- A measurement method using fiber optic technology.
- Some still need to cooperate with a voltage divider, while others do not need.
- The measurement system has a special sensor or capacitive probe.

50

Chapter 7 Measurement of high voltage

7.2 Sphere gap discharge method to measure HV

7.2.1 Structure of measurement sphere gap

7.2.2 Sphere gap method measuring AC / DC high voltage

7.2.3 Sphere gap method measuring impulse high voltage

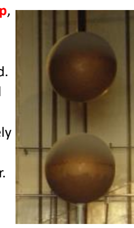
7.2.4 Advantages and disadvantages of the sphere gap method

51

7.2.1 Structure of measurement sphere gap

1. Sphere gap methods

There are two types, **vertical sphere gap** and **horizontal sphere gap**, as specified in **IEC 60052** publication or national standard **GB 311.6**



● **Measurement principle:**

➢ Air undergoes collision ionization only under a certain electric field.

➢ The discharge voltage of the air gap under an uniform electric field has a certain relationship with the gap distance.

➢ The gap discharge is used to measure voltage. There is no absolutely uniform electric field but it can be close to an uniform electric field.

➢ Sphere gap: consists of a pair of metal spheres with same diameter.

- When a voltage is applied, a slightly non-uniform electric field is formed between the sphere gaps.
- When other conditions are the same, the breakdown voltage of the sphere gap in the atmosphere depends on the distance of sphere gap

52

7.2.1 Structure of measurement sphere gap

1. Sphere gap method

● **Determination of sphere gap breakdown voltage**

➢ Due to the influence of **proximity effect**, it is difficult to calculate the electric field and breakdown voltage between spheres. The discharge voltage of the sphere gap is mainly determined by experiments.

➢ In 1938, IEC developed a **standard table*** for measuring sphere gap discharge voltage based on test data from laboratories in various countries.

➢ By 1960, IEC revised the standard table promulgated in 1938.

*Reference: "High Voltage Test Techniques" by Zhang Renyu et al., Tsinghua University Press, Beijing: 1982, p. 249."

53

投票 最多可选1项 设置

How are the sphere-sphere electrode for high voltage measurements mainly made in early years?

A Handmade

B Machine-made

提交

54

2. Sphere gap structure and measurement conditions

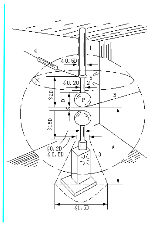
- **Determination of sphere diameter and gap**

➢ For a certain sphere diameter, the electric field in the gap becomes increasingly non-uniform with increasing distance.

➢ The higher the measured voltage, the larger the gap spacing, and the larger the sphere diameter is required to maintain a slightly non-uniform electric field.

➢ When **the ratio of S to D is greater than 0.5**, the accuracy of discharge values is relatively poor.

➢ To achieve the measurement accuracy achievable by the sphere gap, its structure and usage conditions must comply with **IEC or national standards**.



Vertical sphere gap

➢ **Sphere gap spacing:** S should not exceed **$0.4D$**.

➢ **Standard sphere diameter D** is: **2, 5, 6.25, 10, 12.5, 15, 25, 50, 75, 100, 150, 200 cm**

➢ **Measurable voltage peaks:** from a few **kV** to nearly **2000kV**

3. Pre-discharge and irradiation

- **Factors affecting discharge dispersion:**

➢ **Surface contamination:** Dust or dirt on the sphere surfaces can reduce the discharge voltage, affecting AC, DC and impulse voltage measurements similarly.

➢ **Insufficient ionization of air in the gap:** can lead to higher discharge voltages, especially is evident under impulse voltage.

- **Pre-Discharge**
  - If there is dust or fibrous in the air, abnormal and destructive discharges will occur.
  - Multiple pre-discharges must be performed before obtaining consistent data. Only after the discharge voltage value is stable can it be officially counted.
  - The final measurement should be the average of three consecutive numbers, with a deviation not exceeding **3%**.
- **Radiation exposure**

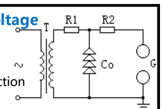
IEC recommends using **gamma rays** or **ultraviolet irradiation** when measuring voltages below **50 kV** peak and when using a sphere with a diameter of **12.5 cm** or smaller.

7.2.2 Sphere gap method measuring AC / DC high voltage

- **Serial protection resistors**

➢ R_1: Transformer protection resistor

➢ R_2: Damping protection resistor - When using a sphere gap to measure AC and DC voltages, it is often needed to connect a protection resistor in series with the gap.



Wring diagram of sphere gap for measuring AC and DC HV

- **Selection of resistance value for R_2**

➢ Selection principle:

- For current limiting and damping, a larger value for R_2 is desired.
- However, to avoid measurement errors caused by voltage drops across R_2, a smaller value for R_2 is preferred.

➢ **Protection resistor for AC/DC:** IEC recommends **100 kΩ** for DC and **50 Hz** AC

➢ **High-frequency protection resistor:** The charging current caused by the capacitance in the air gap under high-frequency can significantly impact the voltage drop, so the resistance value should be appropriately reduced.

➢ **Impact of Sphere Diameter:** As the sphere diameter increases, the permissible resistance value per volt decreases.

- the larger the sphere diameter, the larger the area, the greater the heat capacity and the better heat dissipation
- the sphere diameter Large, the capacitance between the balls is large, and the capacitor current is also large, leads to more impact on the voltage drop.

7.2.3 Sphere gap method measuring impulse high voltage

- **Differences and relationships between measuring impulse and steady-state HV**

➢ **Pre-discharge:** Both impulse and steady-state measurements require pre-discharge.

➢ **Free electron triggering:** Discharge must be initiated by **effective free electrons.**

✓ **AC/DC voltages:** Slow variations and long durations in AC and DC voltages make it relatively easy for effective free electrons to appear in the gap.

✓ **Impulse voltage:** Rapid changes and momentary durations in impulse voltages make it comparatively challenging for effective free electrons to appear in such brief instants.

- When measuring higher voltages with larger sphere diameters and larger gap spaces, the appearance of effective free electrons is relatively easy.
- When measuring lower voltages with smaller sphere diameters and smaller gap spaces, the appearance of effective free electrons is relatively challenging.

➢ **Methods for exciting free electrons:** According to international standards, when the sphere diameter is less than **12.5 cm** or the measuring voltage is below **50 kV**, artificial methods, such as irradiation, must be employed to ionize the air in the gap

- **Protection resistor**

✓ **When Measuring AC/DC Voltages:**

- The sphere gap must be connected in series with a protection resistor of high resistance to safeguard the sphere surface and prevent oscillations.

✓ **When Measuring Impulse Voltages:**

- The impulse discharge duration is short, eliminating the need to protect the sphere surface. Moreover, the capacitive current passing through the sphere gap before discharge is significant. If the series resistor is too large, it may affect the measurement results.
- However, completely omitting the series resistor is not advisable due to the risk of overvoltage. Generally, it is recommended to use a series resistor not exceeding **500 Ω**.

- **Impulse ratio**

✓ **General Gap:**

- The impulse discharge voltage is higher than the discharge voltage in AC and DC, resulting in an impulse ratio greater than 1.

✓ **Sphere Gap:**

- The sphere gap, being a slightly non-uniform electric field, exhibits a voltage-time characteristic that is generally a horizontal line, resulting in an impulse ratio equal to 1.

✓ **Discharge Voltage:**

- Because the impulse ratio is 1 for the sphere gap, the impulse discharge voltage and AC/DC discharge voltages can be listed together in the table of IEC Standard.
- The values in the table represent 50% breakdown voltage, which is the average value of the impulse discharge voltage.

● **Measurement of 50% breakdown voltage**

➢ **Concept of 50% breakdown voltage**

- the voltage at which the probability of discharge at the corresponding sphere gap distance is 50%, symbolled as U_{50}.

➢ **Explanation of the U_{50} concept based on measurement**

- A simple approach involves applying a specific impulse voltage to a certain sphere gap distance.
- If, in ten trials, there are five instances of discharge and five instances of no discharge, then the impulse voltage is considered as the 50% breakdown voltage for that sphere gap distance.
- However, it is difficult in practice to release exactly five times and not release five times out of ten times.
- Therefore, standards often allow considering cases where there are four discharges and six non-discharges or vice versa.

● **Measurement of 50% breakdown voltage (continue)**

➢ **Discharge probability:**

- represents the frequency of occurrence in multiple events, and may not be accurate if the number is small.
- It is very likely that even if the voltage and distance remain unchanged, the discharge probability in the first ten times is very different from that in the last ten times.
- However, if the number of times is large, it is still possible to obtain an accurate value.

➢ **The basis for using 50% breakdown voltage:**

- not only 50% breakdown voltage is used for ball gap measurement, but also all self-restoring insulation, as long as its discharge dispersion conforms to the normal distribution law, 50% breakdown voltage is used

➢ **Method to determine 50% breakdown voltage:**

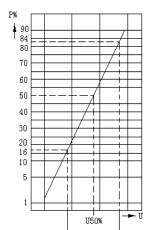
- Various methods, including multi-level method and up-down method.

● **Measurement of 50% breakdown voltage (continue)**

1. Multi-level method

✓ Concept:

- In the method for determining the **50% breakdown voltage** of the gap, the voltages (***U***) are applied to the gap step by step.
- For each voltage step, the experiment is repeated 10 times to calculate the approximate breakdown probability (***P*%**) at that voltage.
- These points are then plotted on normal probability paper.
- By fitting 4 to 5 points, a curve or line is obtained.
- From this curve, the voltage (***U***) corresponding to ***P*** = **50%** is determined, representing the 50% breakdown voltage (U_{50}).



Voltage and break-down probability

● **Measurement of 50% breakdown voltage (continue)**

1. Multi-level method

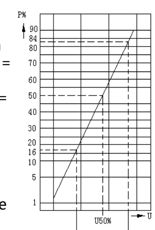
✓ General Approach

- It is generally assumed that the relationship between ***P*** and ***U*** is approximately linear within the range of ***P*** = **20%** to **80%**.
- By plotting one point at ***P*** = **50-80%** and another at ***P*** = **20-50%**, a line is formed, allowing the determination of U_{50}.

✓ Standard deviation

- From the normal probability paper, find the ***U*** value corresponding to the point ***P*** of **15.85%** and **84.15%**. The differences between the two point and U_{50} can be obtained.

2. Up-down method



Voltage and break-down probability

7.2.4 Advantages and disadvantages of sphere gap method for HV

● **Advantages of sphere gap method**

➢ **The only device that directly measures extra-high voltage:** It can measure the amplitude of steady-state high voltage and impulse voltage. It is almost the only device that directly measures extra-high voltage.

➢ **Structure:** simple, easy to make or buy, not easy to damage

➢ **It has a certain level of accuracy** and is generally considered to be within ±3% when measuring AC and impulse voltages.

7.2.4 Advantages and disadvantages of sphere gap method for HV

● **Disadvantages of sphere gap method**

➢ **Overvoltage produced by discharge:** Discharging during measurement disrupts the stable state and can cause overvoltage.

➢ **Statistical nature of discharge, time-consuming measurement:**

- Gas discharge is **statistical** and the data is **scattered**. The average of multiple discharge data must be taken.
- To prevent the influence of **free ions**, each **discharge** should have an **interval** of no less than one minute.
- The voltage rise rate during the final 25% of the breakdown voltage should not exceed 2% of the breakdown voltage per second.

➢ **Atmospheric conditions need to be calibrated.**

- **Disadvantages of sphere gap method (continue)**
  - **Curve calibration and 50% breakdown voltage:**
    - In practical use, multiple discharges are required for measuring steady voltage
    - The **50% breakdown voltage** method is used for impulse voltage measurement, making the procedures cumbersome.
  - **Impact on Building Dimensions:**
    - As the measured voltage increases, the sphere diameter also increase, and device increased bulkiness and impact the dimensions of the surrounding structure.
    - Currently, copper spheres with a diameter of up to 3 meters are used
    - From a developmental perspective, the future of using it raises concerns.
  - **Unsuitable for outdoor use:**
    - Generally, the spherical gap is not suitable for outdoor use.
    - Practice has proven that due to the influence of strong airflow, dust, sand, fiber and high humidity, sphere gaps often produce abnormal discharges when used outdoors.

- **Summary of measuring high voltage using sphere gap method**
  - ✓ **Standard measurement device**
    - Despite the mentioned drawbacks of the spherical gap method, both IEC and national standards specify it as a standard measurement device capable of measuring high voltage with defined accuracy.
  - ✓ **DC calibration**
    - Standards also specify the use of **rod-rod gap** for measuring high DC voltages and allow it to serve as a standard measurement device for calibrating unapproved measurement devices.
    - Under certain conditions, the estimated uncertainty of its measurements is less than ±3%.

Chapter 7 Measurement of high voltage

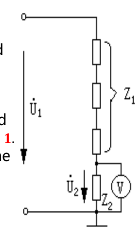
7.4 Voltage Divider

7.4.1 Function and requirements of voltage divider

7.4.2 Principle and classification of voltage divider

7.4.1 Function and requirements of voltage divider

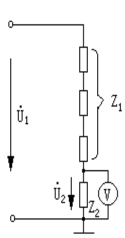
- **Function:**
  - Expanding the voltage range of some instruments and devices through voltage dividers.
- **Principles:**
  - The measured voltage and the voltage across z_2 should only differ in **amplitude** by a factor of K, typically $K >> 1$.
  - The **phase angle** should be completely identical, or the phase angle difference should be extremely small.



AC voltage divider wiring diagram

7.4.1 Function and requirements of voltage divider

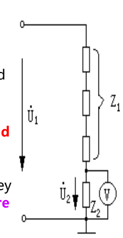
- **Basic Requirements:** It serves as an intermediate link.
  - The voltage waveform measured across the low-voltage arm should **be identical to the waveform** of the measured voltage.
  - The voltage divider should **not affect** the peak value and waveform of the original measured voltage.
  - The voltage dividing ratio should be independent of **the frequency and peak value** of the measured voltage.
  - The voltage dividing ratio should be independent or minimally affected by **atmospheric conditions** (air pressure, temperature, and general humidity under normal conditions).
  - The voltage dividing ratio should **be relatively stable**.
  - National standards specify that **the absolute value of the measurement uncertainty** of the voltage divider should be **within ±1%**.



AC voltage divider wiring diagram

7.4.1 Function and requirements of voltage divider

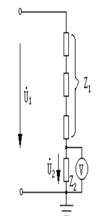
- **Basic Requirements (continue)**
- The **power consumed** by the voltage divider should be small and will not cause a large load effect on the power supply.
- Under certain cooling conditions, the **temperature rise** caused by the power consumption of the voltage divider should not result in a change in the voltage dividing ratio.
- The voltage divider should **be free from corona discharge and significant insulation leakage current**. There should be **no corona and large leakage current** in the voltage divider, or even if there is a very small amount of corona and leakage, they should have little impact on the voltage dividing ratio **(how are they affecting?)**
- Voltage dividers used for measuring AC or impulse high voltages should be **non-inductive**.



AC voltage divider wiring diagram

7.4.2 Principle and classification of voltage divider

- **The principle of voltage divider**
  - **Wiring diagram:** Take AC voltage divider as an example
  - **High-voltage arm:** Z_1 represents the impedance of the high-voltage arm of the voltage divider
  - **Low-voltage arm:** Z_2 represents the impedance of the low-voltage arm of the voltage divider
  - **Voltage dividing result:**
    - ✓ The majority of the measured voltage drops across Z_1
    - ✓ Only a small portion of the voltage drops across Z_2
  - **Voltage dividing ratio:**
    - ✓ Measuring the voltage across Z_2 with a low-range voltmeter, multiplied by a constant, yields the measured voltage
    - ✓ This constant is referred to as the voltage dividing ratio, denoted as K,



AC voltage divider wiring diagram

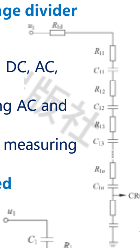
$$K = \dot{U}_1/\dot{U}_2 = (Z_1 + Z_2)/Z_2 \approx Z_1/Z_2$$

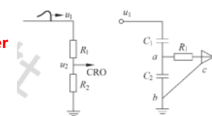
73

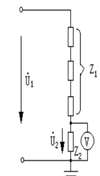
7.4.2 Principle and classification of voltage divider

Classification of voltage dividers

- **Based on Structural Composition**
  - **Resistor divider:** Suitable for measuring DC, AC, and impulse high voltages.
  - **Capacitor divider:** Suitable for measuring AC and impulse high voltages.
  - **Resistor-Capacitor divider:** Suitable for measuring AC and impulse high voltages.
- **Based on the Type of Voltage Measured**
  - **AC voltage divider**
  - **DC voltage divider**
  - **Impulse voltage divider**







AC voltage divider wiring diagram

74

多选题 1分 设置

Which of the following actions are correct?

- A Using a capacitive divider to measure DC high voltage
- B Using a resistor divider to measure switching impulse voltage
- C Using a resistor divider to measure lightning impulse voltage
- D Using resistor-capacitor divider to measure AC high voltage

提交

75

清華大學 Tsinghua University

High Voltage Engineering

Generation of high Voltage and Large Current (2) & Measurement of High Voltage (1)

THE END! THAKS!

76