Please connect to the Rain Classroom

Review, Homework, Preview

Review: 5.5-5.8, 6.1, 6.2
Preview: 6.3, 6.4, 7.1, 7.2
Homework: 6-2, 6-8, 3 extra exercises (on the Online Learning Platform)

Specific Topics:
Introduction to High Voltage Experiment

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Contents

I. Safety and Hygiene Regulations of HV Laboratory

1. Before the experiment, teachers should provide **safety education** to students
2. The high-voltage test must be carried out by **no less than 2 persons**. Before the test, the safety operating instructions of the equipment and instruments must be read well, and the wiring must be checked to be correct.
3. **Live wiring or disconnection is strictly prohibited**
4. Instruments and equipment not used in the experiment may **not be used** without the permission of the teacher or person in charge.
5. After the experiment, **turn off the power**, put the experimental supplies in order, put them back to their original places, and do a good job of hygiene and tidiness.

I. Safety and Hygiene Regulations of HV Laboratory

6. If an accident occurs, **stay calm, cut off the power quickly**, and report the situation to the teacher in charge. If the equipment is damaged, make a written inspection and wait for processing.
7. Smoking, eating, spitting, littering, loud noise, and disorderly behavior are strictly prohibited in the laboratory. Keep clean, obey the guidance of the person in charge, and conduct regular cleaning and tidying.
8. Before leaving the laboratory, conduct checks on water supply, electricity supply, doors and windows in the room. The laboratory should have designated duty personnel for overall inspections to ensure safety.
9. Must obtain permission to enter the laboratory outside of working hours, report to the on-duty personnel, and leave on time.

II. Student Experimental Regulations of HV Laboratory

1. Students must well prepare and complete assigned tasks, with each group consisting of no less than **2 persons**.
2. Before the experiment, a meticulous inspection is required, covering equipment, instruments, safe distances for wiring, grounding, grounding rods, interlocks, and other protective measures. Only after confirmation of the conducting teacher can the power be switched on, and **live wiring is strictly prohibited.**
3. High-voltage experiments must be conducted with seriousness, focus, and without joking. No one is allowed to deviate from their duties. Important operations must be communicated through **verbal commands to ensure safety**.

II. Student Experimental Regulations of HV Laboratory

4. During the experiment, carefully observe instruments, meters, and experimental phenomena, make accurate records, and dismantle the circuit only after the experiment results are signed by the teacher.
5. If an accident occurs, **stay calm, cut off the power quickly**, and report the situation to the teacher in charge. If someone is electrocuted, rescue immediately; if there is a fire, it should be extinguished immediately.
6. After completing the experiment, it is mandatory to **discharge the high-voltage areas using a grounding rod.** For capacitive equipment, it should be discharged through a resistor. Don't approach or touch the test equipment without discharging.

II. Student Experimental Regulations of HV Laboratory

7. Keep cleanliness and silence in the experimental area. After the experiment, promptly disconnect the power supply and organize relevant experimental articles.
8. Report the situation to the teacher in charge as an accident or damage to instruments and equipment occurs, and, make a written inspection and wait for processing.
9. Smoking and fire are strictly prohibited in the laboratory.
10. People with **fever, dizziness, insomnia, poor spirits or mental disorder** are not allowed to conduct experiments. No experiments are allowed after the laboratory is closed

III. Experimental Content and Instructors

- **Experiment 1. Gap discharge test**
  Instructors: Yangyang Fu, Yuanbiao Yang, Zheng Bai, Jiayu Cheng, Xiran Wang, Hangyue Mei
- **Experiment 2. Partial discharge test**
  Instructor: Shengyou Gao
- **Experiment 3. Measurement of dielectric material properties**
  Instructor: Chao Wu
- **Experiment 4. Corona discharge measurement**
  Instructor: Peng Wang

- **Experiment 1 is compulsory**
- **While experiments 2, 3 and 4 are optional, each person is limited to 1 choice, no more than 12 groups for each optional experiment (There are 30 groups in Chinese class and 7 groups in English class, the selection of the one more group may decided by teaching assistant together with the group members).**

IV. Schedule for Experiments (Example)

Time Group EXP	Week 12 (Mon. to Sun.)					Week 13					Week 14				
	Mon.	Tues.	Thur.	Fri.	Sat.	Mon.	Tues.	Thur.	Fri.	Sat.	Mon.	Tues.	Thur.	Fri.	Sat.
	14:20 16:55	14:20 16:55	14:20 16:55	19:00 21:35	14:20 16:55	14:20 16:55	14:20 16:55	14:20 16:55	19:00 21:35	14:20 16:55	14:20 16:55	14:20 16:55	14:20 16:55	19:00 21:35	14:20 16:55
EXP1 (209)															
EXP1 (209)															
EXP1 (209)															
EXP2 (102)															
EXP3 (103)															
EXP4 (102)															

Total is 33 groups: 25 in Chinese class, 18 in English class

清華大學
Tsinghua University

Be careful during experiments!

Teacher in charge of the experiments: Shengyou Gao

MB: 13691484232

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Tsinghua University

Mixed model: Online teaching live + offline
Network teaching: Rain Class

High Voltage Engineering

Insulation Test and Diagnosis (2)

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Chapter 5 Insulation test and diagnosis

投票 最多可选1项 设置

What gases may present in insulating oil in power transformer?

- A Air
- B Gases separated from insulating materials and metals
- C Gases released by decomposed of insulating materials
- D All of the above exist

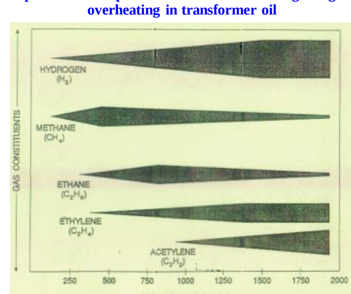
提交

5.5 Chromatographic analysis of dissolved gases in insulating oil

1. Sources of dissolved gases in insulating oil

- **Non-failure gases**
  - ✓ Air is the main gas in new insulation oil, which contains N_2 (78.1%), O_2 (20.9%) and a small amount of inert gases, carbon dioxide and water vapor;
  - ✓ Chemical reactions of water in the oil with solid insulating materials under the sunlight generate gas
  - ✓ The limited gas content generally does not affect the normal operation of the equipment.
- **Failure gases**
  - ✓ Due to electrical, thermal failure or aging, oil and insulating paper may be decomposed to generate gases

Relationship between temperature and characteristic gases generated by overheating in transformer oil

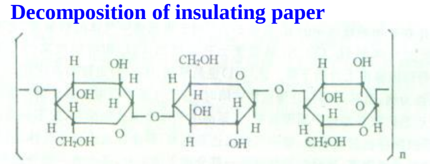


5.5 Chromatographic analysis of dissolved gases in insulating oil

Characteristic gases produced in the decomposition of transformer oil

- **Main components of transformer oil, hydrocarbons such as** alkanes (烷烃), cycloalkanes (环烷), aromatic hydrocarbons (芳香烃), and olefins(烯烃)
  - ✓ When temperature is less than 800 ℃, pyrolysis produces: low molecular alkanes (methane CH_4, ethane C_2H_6), low molecular olefins (ethylene C_2H_4, propylene C_3H_6), hydrogen (H_2)
  - ✓ Gases decomposed by arc discharge in transformer oil: mostly H_2, C_2H_2 (acetylene), and a certain amount of CH_4, C_2H_4
  - ✓ When partial discharge occurs: the main gas decomposed by the transformer oil is H_2 and a small amount of CH_4
  - ✓ When spark discharge occurs: there is more C_2H_2

Decomposition of insulating paper



In the molecular structure of cellulose(纤维素), the glucose(葡萄糖) groups are connected by **1-4** bonds. The general chemical formula is $(C_6H_{10}O_5)_n$. n is the **degree of polymerization**(聚合度). Generally, n**=1300** for new paper. After aging, the life ends, n is about **150~200**, producing **CO** and CO_2 etc.

Characteristic gas components produced by different failure types GB 7252

Fault Types	Major Gas Components	Minor Gas Components
Oil overheating	CH_4, C_2H_4	H_2, C_2H_6
Spark discharge in oil	H_2, C_2H_2	
Arcing in oil	H_2, C_2H_2	CH_4, C_2H_4, C_2H_6
Oil and paper overheating	CH_4, C_2H_4, CO, CO_2	H_2, C_2H_6
PD in oil-impregnated paper	H_2, CH_4, CO	C_2H_2, C_2H_6, CO_2
Arcing in oil and paper	H_2, C_2H_2, CO, CO_2	CH_4, C_2H_4, C_2H_6

Note: Damp or gas bubbles in the oil may increase the H_2 content in the oil.

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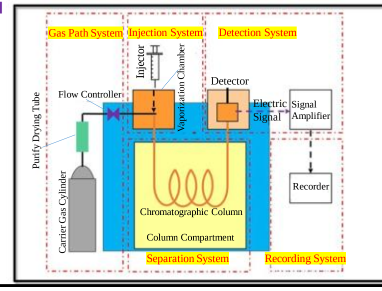
2. Gas chromatography method for measuring dissolved gases in transformer oil

H_2, CH_4, C_2H_4, C_2H_6
C_2H_2, CO, CO_2, ……



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3. Failure analysis by dissolved gases in oil

a) **Characteristic gas composition and failure types**
b) **Characteristic gas content and severity of failures**
c) **Growth rate of gas content with time and severity of failures**
d) **Comprehensive judgment of failures: three ratio method**

✓ The main method to determine the nature of failure in oil-filled electrical equipment such as transformers or reactors
✓ Take out the **five characteristic gas contents** of H_2, CH_4, C_2H_2, C_2H_4 and C_2H_6, calculate the **three ratios** of C_2H_2/C_2H_4, CH_4/H_2, C_2H_4/C_2H_6 respectively, then code these three ratios according to certain rules, and the nature of the failure is determined according to specific criteria.
✓ For example, when the ratio is **0:1:0**, means low energy density **PD** in oil caused by high humidity and high gas content occurs inside the equipment.

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Chapter 5 Insulation test and diagnosis

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5.6.1 AC voltage withstand test


Changzhi UHV substation PD on-site test

- **Two voltage application methods**

✓ External AC voltage withstand test
✓ Induction AC voltage withstand test

- **Duration** of power frequency voltage withstand test:

  1 min usually; 5 min for SF_6 circuit breakers

- **Test voltage required by standard**

✓ **DL/T 596** 《Preventive Test Procedures for Electric Power Equipment》: The test voltage for overhaul and all winding replacements as well is the ex-factory test voltage, and the rest is that of 85% (also refer to the national standard **GB 1094.3**)
✓ For graded insulation transformers, the external AC voltage withstand test shall be carried out according to the test voltage specified for the neutral terminal.
✓ **Frequency doubling (to avoid magnetic flux saturation) induction** voltage withstand test, duration $t=60\times100/f$

1000kV Transform: U_m=1100kV, $U_{withstand}$=1100kV, 5min

500kV Transform: U_m=550kV, $U_{withstand}$=680kV

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5.6.2 DC voltage withstand test

For AC equipment tested with DC voltage, the DC voltage should be carefully selected.

- For insulation leakage current tests of power transformers, where the voltage is not high, it can be considered a non-destructive test.
- For high-capacity equipment such as cables, attention should be given to composite insulation, such as oil-impregnated paper insulation, where the voltage distribution differs under AC and DC.
  - Under AC voltage, the voltage mainly acts on the oil layer, while oil has lower electric strength. Under DC voltage, the voltage mainly acts on the paper layer, and paper has higher electric strength. So oil-impregnated paper insulated cables can withstand higher DC voltages.
  - The voltage withstand test of oil-impregnated paper insulated cables is 5 min
- Under DC voltage, there is a risk of insulation breakdown due to the accumulation of space charges which induce distortion of the electric field distribution. This can be understood from the fact that after DC voltage withstand tests, there are increased PD levels observed during power frequency voltage withstand tests.

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投票 最多可选1项

设置

Do you agree that AC electrical equipment may use DC voltage withstand test instead of AC one?

A Agree

B Disagree

提交

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5.6.3 Lightning impulse voltage withstand test

- According to National standards:
  - ✓ It should be performed on ex-factory test of 110 kV and above transformers.
  - ✓ It should not be performed on the insulation preventive test and project handover tests.
- To prevent insulation damage from cumulative effects, only three impulses are applied at the specified test voltage.

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5.6.4 Switching impulse voltage withstand test

- **Ex-factory tests** should include this test, for
  - ✓ power transformers with a rated voltage of 330 kV (?) and above,
  - ✓ other power equipment with that of 330 kV and above
- **Two voltage application methods**
  - ➢ **Apply voltage directly**, usually in factories and laboratories
  - ➢ The other one is **inductive switching impulse voltage withstand test,** which is performed on-site and can also be conducted in factories, using the electromagnetic induction of the transformer itself to increase the test voltage.
- Switching impulse voltage withstand test do not cause residual damage to the insulation.

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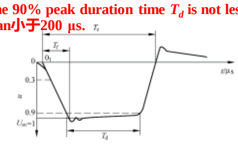
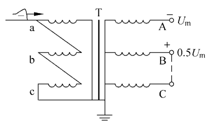
- **IEC 60076-3** and the national standard **GB 1094.3** specify the waveform for the switching impulse test of power transformers.
  - ➢ **The first half-wave is negative, with a apparent front time T_f not less than 100 µs, typically less than 250 µs.**
  - ➢ **apparent wavelength time T_z is not less than 500 µs, preferably reaching 1000 µs.**
  - ➢ **The 90% peak duration time T_d is not less than小于200 µs.**



- **Test** (apply voltage, inductive voltage)
  - ➢ GB specify the test circuits for transformers.
  - ➢ GB 1094.3 and JB/T 10780 specify the switching impulse withstand voltage for the line terminals of transformers with rated voltages from 220 kV to 500 kV.



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5.7 Characteristics of preventive test methods

S/N	Test method	Detectable defects
1	Insulation resistance and leakage current measurement	Penetrating moisture, dirt and conductive paths
2	Absorption ratio measurement	Large areas affected by moisture and penetrating concentrated defects.
3	tanδ measurement	Insulation is generally affected by moisture and deteriorates.
4	PD measurement	Partial defects with gas discharge
5	Gas chromatography analysis of oil	Overheating and Partial Discharge
6	AC or DC voltage withstand test	Partial defects in the main insulation that reduce electric strength to a certain extent
7	Switching impulse and double-frequency induction voltage withstand test (transformers)	Partial defects both in the main or longitudinal insulation that reduce electric strength to a certain extent

Items 6 and 7 are destructive tests, while the rest are non-destructive tests.

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Hybrid: Online teaching live + offline
Network teaching: Rain Class

High Voltage Engineering

Generation of high Voltage and Large Current (1)

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Chapter 6 Generation of high voltage and large impulse current

6.1.1 Overview of test transformer

1. Application of test Transformers

- **AC High Voltage Test Equipment:** Mainly refers to high-voltage test transformers, and high-voltage series resonance test equipment.

- **Application:**
1. Generate power frequency voltage for testing.
2. Serve as a power source for DC and impulse voltage generators.
3. Generate switching impulse voltages.

- Generating long-front-time switching impulse waves.
- Generate power frequency high voltage applied to the insulation of the tested electrical equipment to assess the insulation level of the electrical equipment.
- Study characteristics of high-voltage power generation and transmission systems.
  - ✓ Gas insulation gap, corona loss, flashover voltage of long string insulators
  - ✓ PD, electrostatic induction, live-line work, etc.

- **Equipment Capability:**
- There are 2250 kV test transformers in China and most developed countries.
- Some countries have already achieved 3000 kV.

2. Differences & relationship between test and power transformers

Different operating conditions

Operating conditions	Test transformer	Power transformer
Place of use	Indoor	Outdoor
Load properties	Capacitive	Inductive
Equipment Capacity	Small	Large
Operating Time	Short	Long (all one's life)
Operating Temperature	Low	High (up to 90℃)
Safety Factor	Small (1.1)	Large (Chapter 5)




Different working duration

- ✓ The test transformer can only operate for a short time, only work continuously for 30 minutes at rated power.
- ✓ Some ultra-high voltage test transformers can only operate for 5 minutes at rated voltage and capacity.
- ✓ Power transformers can operate continuously under rated conditions.

3. Safety Factor of Test Transformers

The margin of safety for test transformers is smaller than that of power transformers.

✓ **Withstand voltage and margin of safety for test transformer**

- For voltages between 50 kV and 250 kV, the withstand voltage is only 25 kV higher than the rated voltage (1.5 times to 1.1 times of the rated voltage).
- For higher voltages (≥300 kV), only 10% higher than the rated voltage (1.1 times of the rated voltage).
- For a 500 kV test transformer, the 5 min 100 Hz self-induced withstand voltage is 550 kV, 10% higher than the rated voltage (1.1 times of the rated voltage).
- For domestically produced YDC - 1500/1500 two-stage series test transformer, the self-induced withstand voltage for a single 750 kV transformer is only at 110% of the rated voltage (1.1 times). When two transformers are in series, only 105% of the rated voltage (1.05 times).

多选题 1分 设置

Which of the following voltages are line voltages?

- A Power grid voltage level
- B Phase A to ground voltage
- C Phase A to phase B voltage
- D Maximum operating voltage of the equipment
- E Power frequency withstand voltage

提交

✓ **Withstand voltage of the power transformer**

- The preventive test procedure stipulate that the withstand voltage of the replacement winding for overhaul is the factory withstand voltage, and the rest is 85% of the factory test
- 1 min power frequency withstand voltage of power transformer

35 kV	(40.5 kV)	: 85 kV	(3.64 times)
110 kV	(126 kV)	: 200 kV	(2.75 times)
220 kV	(252 kV)	: 395 kV	(2.71 times)
330 kV	(363 kV)	: 510 kV	(2.43 times)
500 kV	(550 kV)	: 680 kV	(2.14 times)
750 kV	(800kV)	: 900 kV	(1.95 times)
1000kV	(1100kV)	: 1100 kV	(1.73 times, 5min)

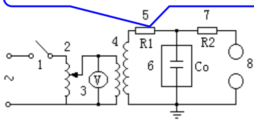
- Calculation of withstand voltage multiples:

$$\text{multiple of withstand voltage} = \frac{\text{withstand voltage}}{\text{maximum operating voltage}/\sqrt{3}}$$

- The magnetic flux density of the test transformer core is small (to avoid distortion of waveform)
- Corona-free test transformer can meet the requirements of partial discharge test

4. Circuit of test transformers

The resistance value of transformer protection resistor is provided by the manufacturer. If there is no manufacturer data, select it as 0.1 Ω/V.



Basic circuit of power frequency high voltage test

1-Power switch; 2-Voltage regulator; 3-Voltmeter;
4-Test transformer; 5-Transformer protection resistor; 6-Test sample;
7-Protection resistor of copper ball gap; 8-Copper ball measure gap

4. Frequency and waveform of test voltage

- During AC voltage withstand test
  - ✓ Breakdown is related to peak values.
  - ✓ For some materials, breakdown is also related to frequency.
  - ✓ When the third harmonic component of the voltage waveform is big, the peak-to-RMS ratio is between 1.45 and 1.55, not $\sqrt{2}$
- Standards
  - ✓ GB/T 16927.1
  - ✓ IEC 60060-1
- Specify the test voltage waveform
  - ✓ Frequency: 45 ~ 65 Hz, special tests follow equipment standards.
  - ✓ Peak-to-RMS (effective) value ratio: Both GB and IEC specify: $\sqrt{2} \pm 0.05$
- Supplemently: If the root mean square value of the harmonic is not greater than 5% of the root mean square value of the fundamental wave, it is OK.

6.1.2 Voltage and capacity of test transformer

1. Regular test transformer (custom-made fee=design, trail manufacture, type setting test)

Rated voltage kV	5	10	25	35	50	100	150	250
Rated capacity kVA	3	3	3	3	5	10	25	250
	5	5	5	5	10	25	50	500
	10	10	10	10	25	50	100	1000
		25	25	25	50	100	150	
			50	50	100	200	300	
				100	250	250		
				150	500	400		
				200	750			
Rated voltage kV	300	500	750	1000	1500	2250		
Rated capacity kVA	300	300	750	1000	750	2250		
	1200	500	1500	2000	1500	9000		
		1000	3000					
		1500						

2. Selection of Test Transformers

(1) Voltage of test transformer: U_n should not be lower than test voltage U.
(2) Current of test transformer: $I_n > I_s = \omega C U \times 10^{-9}$ A (effective value)
(3) Capacity of test transformer: $P_n > P_s = \omega C U^2 \times 10^{-9}$ kVA
✓ ω: angular frequency of the applied voltage
✓ C: capacitance of the test sample (pF)

●Capacitance of common tested products

Sample	Capacitance value (pF)
Line insulator	<50
High voltage bushing	50 ~ 600
High voltage circuit breaker, current transformer, electromagnetic voltage transformer	100 ~ 1000
Capacitive voltage transformer	3000 ~ 5000
Power transformer	1000 ~ 15000
Power cable (per meter)	150 ~ 400
SF_6 insulated GIS	1000 ~ 10000

E.g. Selecting rated voltage and capacity of test transformer

To perform power frequency withstand tests on the high-voltage winding to low-voltage winding, as well as on the iron core and iron casing (both grounded) of a 35 kV/10 kV/3200 kVA power transformer after a major overhaul, a suitable high-voltage test transformer needs to be selected. The measured capacitance between the high-voltage winding to low-voltage winding and ground is 5870 pF, by using a bridge (generally is Schering Bridge).

- Determination of Parameters
  - ✓ The test voltage: According to relevant regulations (refer to Chapter 5 on AC voltage withstand tests), the test voltage for the transformer should be 85kV×85%=72kV.
  - ✓ Calculate the test current: During the test, the effective current flowing through the high-voltage winding of the test transformer is given by,
    $I_s = \omega C U \times 10^{-9}$ A $= 2\pi f C U \times 10^{-9} = 314 \times 5870 \times 72 \times 10^{-9} = 0.133$ A
  - ✓ Required test capacity:
    $P_s = I_s U$ kVA $= 0.133\text{A} \times 72\text{kV} = 9.58$ kVA

E.g. Example of selecting rated voltage and capacity of test transformer

To perform power frequency withstand tests on the high-voltage winding to low-voltage winding, as well as on the iron core and iron casing (both grounded) of a 35 kV/10 kV/3200 kVA power transformer after a major overhaul, a suitable high-voltage test transformer needs to be selected. The measured capacitance between the high-voltage winding to low-voltage winding and ground is 5870 pF, by using a bridge (generally is Schering Bridge).

- Select the test transformer:
  - ✓ Select the voltage: Choose the rated voltage of a test transformer as 100 kV.
  - ✓ Select the capacity: A 10 kVA transformer cannot be selected because the maximum current through the high-voltage winding of such a transformer is only 0.1A.
  - ✓ Determine the test transformer: In this case, an available test transformer with a rating of 100 kV/25 kVA should be chosen,
    as it satisfies the selection principle: 25 kVA > 13.3 kVA

3. Test transformer for high capacitive load

● Transformer capacity selection for corona loss test

➢ **Selection Basis:** In high-voltage laboratories with test line segments, it is necessary to consider supplying larger capacitive currents and corona currents.

➢ **Test line length:**

- One purposes of setting up test line segments is to study corona loss. For accurate measurement, a longer circuit is advantageous.
- However, due to economic considerations, extra-high-voltage test circuits are sometimes selected to be around **500 m**. Based on operational experience,
  - ✓ For the **330 kV** test line, select an **1 A** test transformer.
  - ✓ For test circuits of **500 kV** and above, an 1 A test transformer is insufficient.
  - ✓ For the corona loss test on a **750 kV** test line requires a transformer to supply a current abou **3 A**.
  - UHV: In China, UHV AC **1000 kV**,**1000 m** three-phase test line segments; In the Soviet Union, **1150 kV**, **1170 m** three-phase test line segments, select transformer 1150/500/10 kV, 3×417 MVA

3. Test transformer for high capacitive load

● Various methods to solve insufficient test capacity

➢ **Extra large capacitance of test samples (power equipment):**

✓ Coiled of high-voltage cables from cable plants

✓ Extra large capacity generator

➢ **Methods to solve the insufficient test capacity during voltage withstand tests:**

- Specially made test transformer to meet test requirements of high capacitive equipment
- Use of series resonant devices to meet test requirements
- Using low frequency (**2 Hz**) and ultra-low frequency (**0.1 Hz**) voltage withstand test
- Inductive compensation: Connect inductance coils **in parallel with** capacitive test samples to reduce the capacitive current in the high-voltage winding of the transformer.

The waveform is not good after compensation
Not applicable when measuring dielectric loss and corona loss

投票 最多可选1项 设置

For the voltage withstand test of extra-large capacity equipment, what kind of power supply do you think is the best?

- A Special manufacture large-capacity test transformer
- B Series resonance device
- C Low-frequency or ultra-low-frequency devices
- D Inductive compensation device

提交

4. Test transformer for high conductive load

➢ **Conductive load:** During the insulation wet flashover test and pollution flashover test, the conductive current is relatively large

✓ **Wet flashover test:** Generally, the conductivity current of wet flashover test can reach tens mA, so an 1 A test transformer can meet the requirements.

➢ **Short-circuit capacity or short-circuit current** requirements:

In order to ensure a more accurate breakdown voltage value, national standards stipulate the short-circuit capacity and short-circuit current:

(1) For **dry tests** on solid and liquid insulation samples, or a combination of the both, and for dry tests on self-recovering insulation (insulators, isolating switches, etc.), the short-circuit current should be **not less than 0.1 A** (rms).

(2) For **wet tests** on self-recovering insulation (insulators, isolating switches, etc.), the short-circuit current should be **not less than 0.5 A** (rms).

4. Test transformer for high conductive load

(3) For wet tests on large-sized specimens that may generate large leakage currents, the short-circuit current may reach up to 1 A.

(4) For artificial contamination flashover/withstand test

- The short-circuit current requirement is generally **15 A (rms)** or higher.
- The ratio of resistance to reactance **(R/X)** should be **≥ 0.1**.
- The ratio of capacitive current to short-circuit current should be within the range of 0.001 to 0.1.

6.1.3 Cascade high voltage test transformer

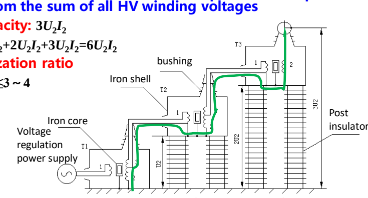
● **Basic Principles of Cascade Transformers: high voltage windings of several transformers in series with each other to produce multiple output voltage from the sum of all HV winding voltages**

✓ **Rated output capacity:** $3U_2I_2$

✓ **Total capacity:** $U_2I_2+2U_2I_2+3U_2I_2=6U_2I_2$

✓ **Low capacity utilization ratio**

✓ **Cascade stages:** $n \leq 3 \sim 4$



Schematic diagram of a cascade transformer composed of three transformers

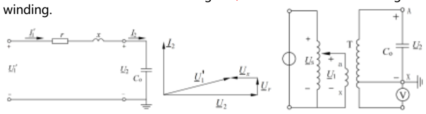
6.1.4 Voltage rise on capacitive test specimen of test transformer

- **Voltage rise on capacitive specimen of test transformer**
  - Steady-state voltage rise (capacity rise effect)
  - Transient voltage rise (voltage regulation resonance and flashover polarity effect)

1. Steady-State voltage rise

The issue arising from this is that the voltage on the test specimen cannot be obtained based on the turns ratio of the test transformer.

➢ **Measuring winding of test transformer**
- Generally, test transformers with a rating of ≥100 kV are equipped with a third winding specifically for measuring voltage.
- The number of turns in this winding is 1/1000 of the turns in the high-voltage winding.



Measurement winding diagram often found in test transformers above ≥100kV

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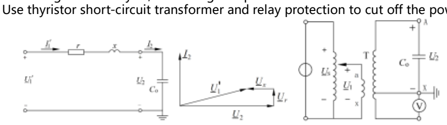
6.1.4 Voltage rise on capacitive test specimen of test transformer

2. Transient voltage rise

➢ **Case 1: resonance voltage rise**
- The short-circuit reactance of the voltage regulator is related to the position, and series resonance may occur during the voltage regulation process.
- Ball gaps can be used for protection.

➢ **Case 2: polarity effect voltage rise**
- In the positive half-cycle, capacitive specimens experience insulation flashover in air, followed by zero crossing recovery.
- In the negative half-cycle, the voltage amplitude rises due to resonance.
- Use thyristor short-circuit transformer and relay protection to cut off the power supply.



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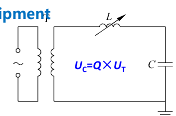
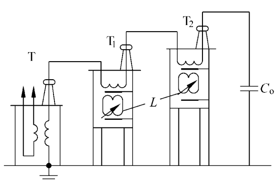
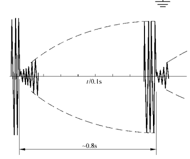
6.1.5 High-voltage series resonant test equipment

Working principle: R, L, C resonant circuit







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Chapter 6 Generation of high voltage and large impulse current

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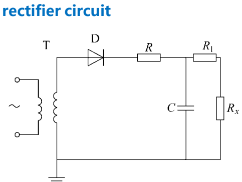
6.2.1 Half-wave rectifier circuit



T: Test transformer; **D**: High voltage silicon stack;
R: Protection resistor **C**: Filter capacitor
R_1: Current limiting resistor R_x: Test sample;

Half-wave rectifier circuit

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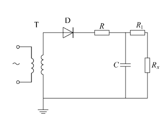
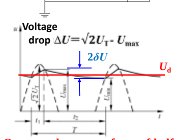
6.2.2 DC output and ripple factor





Output voltage waveform of half wave rectification circuit

- **Charge and discharge process and voltage stability**
  - ➢ t_1: Conduction time of the stack D
  - ➢ t_2: Cutoff time of the stack D
- **Half-wave rectifier circuit output voltage waveform**
  - ➢ U_T: Transformer voltage (RMS)
  - ➢ U_{max}: Maximum DC voltage
  - ➢ U_{min}: Minimum DC voltage
  - ➢ U_d: DC voltage arithmetic average
  - ➢ δU: Ripple amplitude

$$\delta U = (U_{max} - U_{min})/2$$

  - ➢ Ripple factor $S=\delta U/U_d$
- **Charge compensation:** The charge delivered by C to R_x during the time intervals t_1 and t_2 should be compensated by the charge $Q_1 = I_d T$ delivered by T to C during the time t_1 .

$$\delta U \approx Q_1 / 2C = I_d / (2fC);$$
$$S = \delta U / U_d \approx I_d / (2fC U_d)$$

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投票 最多可选1项 设置

Do you agree with the view: the higher the DC voltage, the easier it is to control the ripple factor in a smaller range

- (A) Agree
- (B) Disagree

提交

E.g. The national standard specifies $S \le 3\%$, using half-wave rectification equipment to generate a 50 kV DC voltage for a DC withstand test. Considering that the current I_d flowing through the test sample and the resistor divider will not exceed 5 mA, calculate the required capacitance of the filter capacitor C.

[Solution]

To save equipment investment, T adopts a power frequency test transformer with f=50 Hz.

Substitute the given values into the formula,

$S = I_d / (2f\, C\, U_d)$, then

$C = 5\ \text{mA} / (0.03 \times 2 \times 50 \times 50\ \text{kV}\cdot\text{s}^{-1})$

$= 0.033\ \mu\text{F}$

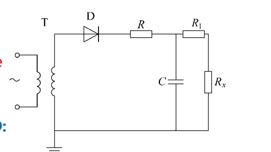
The capacitance of filter capacitor C should be no less than 0.033 μF.

6.2.3 Protection resistor and silicon stack selection

- **Protection resistor:** suppress the current flowing through the diode

$$R \ge \sqrt{2}U_T / I_s$$

- **Rated reverse voltage of stack D:** The highest reverse working voltage value allowed across the terminals of a diode or a high-voltage silicon stack when them are in the off state. Its value $U_r \ge 2.1U_{max}$



T: Test transformer; D: High voltage silicon stack; R_x: Test sample; C: Filter capacitor; R: Protection resistor; R_1: Current limiting resistor

Half-wave rectifier circuit

6.2.4 Voltage doubling rectifing circuit and cascade DC generator

- **Working Principle**
  - Output Peak Voltage $\sqrt{2}U_T$

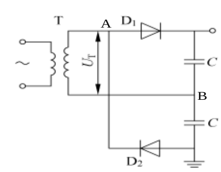
DC High Voltage $2\sqrt{2}U_T$

$U_{C1} = U_{C2} = \sqrt{2}U_T$

$U_B = \sqrt{2}U_T$

U_A can reach $2\sqrt{2}U_T$

- Requires high insulation level of transformer



DC voltage doubling circuit with ungrounded high-voltage transformer

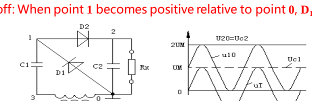
●DC voltage doubling circuit with one end of the transformer grounded

- **Transformer one end grounded**
  - ✓ Reducing the insulation level of the transformer.
  - ✓ A common transformer can be used as the transformer for the DC power supply.
- **Doubling voltage process**

1. Charge capacitor C_1:

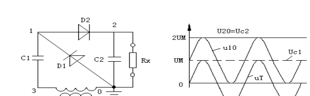
- When the voltage at terminal 3 of the high-voltage winding of transformer T is negative relative to point 0, D_1 conducts forward, allowing capacitor C_1 to charge.
- Once the charging stabilizes, a voltage of U_M is established between points 1 and 3.

2. D_1 cutoff: When point 1 becomes positive relative to point 0, D_1 starts to cutoff.



DC voltage doubler circuit with one end of the transformer grounded

The potential of each point when the circuit is unloaded



DC voltage doubler circuit with one end of the transformer grounded

The potential of each point when the circuit is unloaded

3. Charge capacitor C_2:

- When point 1 becomes positive relative to point 2, D_2 conducts, and capacitor C_2 charges.
- When the charging stabilizes, since the highest voltage at point 3 relative to 0 is +UM, and point 1 has already been charged with $+U_M$ voltage relative to point 3,
- the voltage at point 1 relative to ground can reach up to $+2U_M$. At this point, D_2 conducts, ultimately allowing C_2 to charge up to a voltage of $2U_M$.

- **Ripple factor:** Similar to half-wave rectification

?

● **Cascade DC device**

➢ **Concept:** Modular stacking of voltage doubling circuits

➢ **Voltage ripple amplitude:**

$\delta U \approx [n(n+1) I_d]/(4fC)$

➢ **Voltage drop:**

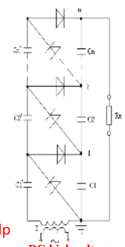
$\Delta U = [(8n^3+3n^2+n) I_d]/(12fC)$

✓ δU rises with the square multiple of the series (n).

✓ ΔU rises with the cubic multiple of n.

✓ Need to consider in design

- When n exceeds a certain value, increasing n will not help increase the output voltage
- but the number of components and the height of the entire structure will increase



DC high voltage cascade generator

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Tsinghua University

High Voltage Engineering

Insulation Test and Diagnosis (2) & Generation of high Voltage and Large Current (1)

THE END! THAKS!

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