Ministry of Science and Higher Education of the Russian Federation

ST. PETERSBURG
POLYTECHNICAL UNIVERSITY OF PETER THE GREAT

Yu.E. Adamyan, S.I. Krivosheev, S.G. Magazinov

High voltage technology. Laboratory course.

Textbook

Saint-Petersburg

2020

The text book corresponds to educational master program13.03.02_21 Electrical Engineering. Intended to implementation of the laboratory course "High voltage technology" К.М.06.01. The main goal of the course is obtaining practical skills in arrangement of experiments, measurements, processing and representation of the experimental data in the specific environment of high voltage technique . For all works the specialized laboratory installations are equipped, providing safe operating conditions and variety of experimental abilities.

Some data needed for calculations are presented in the works descriptions, some, that are commonly used, in the Appendix.

Contents

The list of laboratory works

The following laboratory works can be implemented on the basis of the educational high voltage laboratory of the Institute of Energy:

1. **Breakdown of air gaps at DC voltage**
2. **Breakdown of air gaps at AC voltage**
3. **Surface discharge in gas**
4. **Corona discharge at DC voltage**
5. **Corona discharge at AC voltage**
6. **String of insulators**
7. **High voltage pulse generator**
8. **High voltage AC measurements**

Work1. Breakdown of air gaps at DC voltage.

1.1. Work program

Obtain dependences of DC breakdown voltage on air gap length for the gap geometries: pin – plane (at positive and negative pin polarity) and pin-pin. Determine dependences of the average electric field strength on the gap length.

1.2. Work basics

The high voltage level at which the air gap loses its electrical strength is called breakdown voltage. Starting discharge voltage is the voltage at which self-discharge conditions are reached in the gap. At the uniform and weakly nonuniform field the breakdown and starting voltages are practically equal. In the uniform field at the standard atmospheric conditions the average air electric strength is about 30 kV/cm. In nonuniform fields, like pin-plane or pin-pin geometries, the starting voltage is always lower than breakdown voltage. The conditions at which the local field strength is higher than starting one are fulfilled firstly in the vicinity of the electrode with small curative radius (pin).

At the positive polarity of the pin electrode, the excess positive space charge is created near the electrode because of electrons drift in the electric field. The electrons mobility is approximately two orders of magnitude higher than ions mobility, so they are rapidly moving to the electrode where they are neutralized. Being prolonged inside the gap this positive spatial charge increases the field strength in outer zone of the developing discharge channel. Such field distribution eases conditions of the breakdown development.

At the negative electrode polarity the space charge consists of positive ions in narrow near-electrode zone being surrounded by electrons and negative ions. Such distribution of the field reduces field out of the near-electrode zone and toughens conditions of the breakdown development.

So, the breakdown voltages in nonuniform fields at negative polarity of the pin electrode are substantially higher than at the pin positive polarity.

1.3. Determination of breakdown voltage dependence on the gap length for the gaps: pin – plane, pin-pin at positive and negative pin polarity.

The DC experimental installation circuit diagram is displayed on fig. 1.1 The AC voltage 220V 50Hz from the power network feeds the regulating transformer T1 through automatic circuit braker QF and the magnetic switch KM1. Magnetic switch KM2 connects T1output to the primary winding of the high voltage transformer T2. The secondary (HV) winding of T2 is loaded by the rectifier VD, C, where C is the filtering capacitor. The high voltage resistor R protects the circuit at the gap (TO) breakdown. The gap voltage measurement is provided by resistive-capacitive voltage divider R1,C1,R2,C2. The divider output voltage is measured by low voltage voltmeter on the plant control panel.

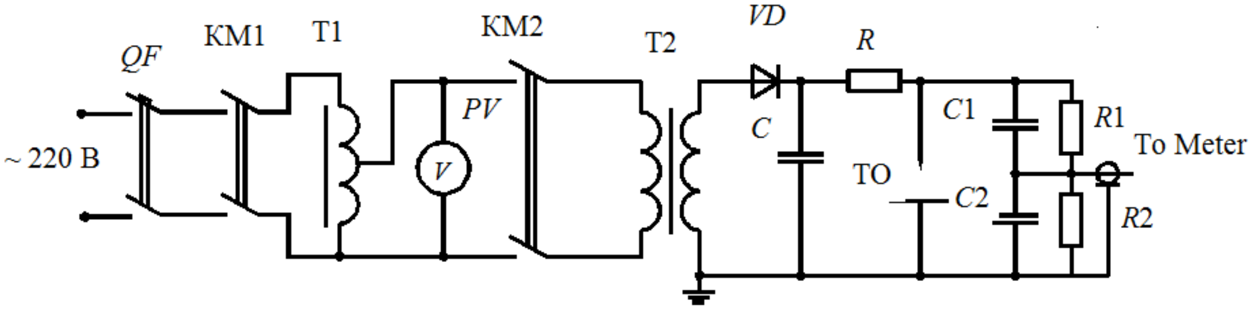

Fig. 1.1 Experimental plant circuit diagram

Before starting measurements it is necessary to register the atmospheric pressure and readings of the dry and wet thermometers of the laboratory psychrometer. The difference between these temperatures allows calculation of the air humidity.

1.4 The procedure of breakdown voltages measurements:

Fix the electrodes on the supporting bench (plane electrode must be grounded). Set the gap length 2cm.

Reconnect the circuit elements to get positive potential on the rectifier output.

Remove grounding rod from the high voltage supply output.

Switch on QF circuit breaker.

Push the button K1 on the control panel switching on the magnetic switch KM1. Check for zero voltage on the secondary side of the voltage regulator T1 using meter PV. If the voltage is not zero, set it by the counterclockwise rotation of the regulator handle.

Push the button K2 on the control panel switching on the magnetic switch KM2.

Gradually raise the transformer T2 input voltage up to air gap breakdown (rise the voltage approximately 30sec before breakdown).

Write down the readings of the meter on control panel (1μA corresponds to 1kV). To reduce statistical error repeat measurement at least 3 times.

Measurements have to be performed at 5-7 different gap distances for each gap geometry and polarity (For equipment safety keep maximal gap voltages not higher than 80-90kV). Gap distance step should be opted for current experimental conditions (the gap change step is approximately 1-2 cm).

Register atmospheric pressure and temperature before voltage measurements (it is important for matching of tabulated spark gap discharge voltage with atmospheric conditions).

Recalculate obtained breakdown voltages to the normal atmospheric conditions using correcting coefficients

$$U_0 = \frac{U_m K_\gamma}{K_p K_t}$$

Here Um – measured voltage, K_γ, K_p, K_t - correcting coefficients for the humidity, pressure and temperature

$$K_p = \frac{P}{P_0}, \qquad K_t = \frac{293}{273+t},$$

P – current pressure, P_0 – normal pressure, t – current temperature in centigrades.

Absolute humidity correcting coefficient K_γ have to be considered for DC positive polarity and can be determined by graph fig A.1 in Appendix using temperatures of the dry and wet thermometers (curve “a” on the left side of the figure).

For the negative polarity humidity correcting coefficient is not used.

Average values of breakdown field strength can be determined by division of breakdown voltages by the gap length.

1.5 The report content.

The report must contain:

a) Experimental plant circuit;
b) Tables of the results of measurements
c) Graphs representing dependences of breakdown voltages and average electric field strength on the gap length for all gap geometries;
d) Results summary. Focus on the impact of the voltage polarity on the breakdown voltages.

Work2. Breakdown of air gaps at AC voltage.

2.1Work program

Obtain dependence of AC breakdown voltage on air gap length for the following gap geometries:

pin – plane, pin-pin, spherical electrodes, Rogowski electrodes.

Determine dependences of the average electric field strength on the gap length.

2.2Work basics

The gap breakdown process development time is many times shorter than the power network AC voltage period. At the alternating voltage applied to the electrodes, the field distribution near the electrode with small curvative radius (pin) are slightly different from DC voltage case because of residual charges at the voltage oscillation.

So the gap breakdown takes place at positive voltage half-period on the electrode with small curvative radius because the gap electric strength is lower at this polarity.

In addition to the gap geometries used in the previous work the Rogowski electrodes and spherical electrodes are used where the electric field is close to uniform at gap length smaller than the electrode radius. For these geometries the breakdown field strength is close to maximal value for the air $E_{max} \approx 30$ kV/cm.

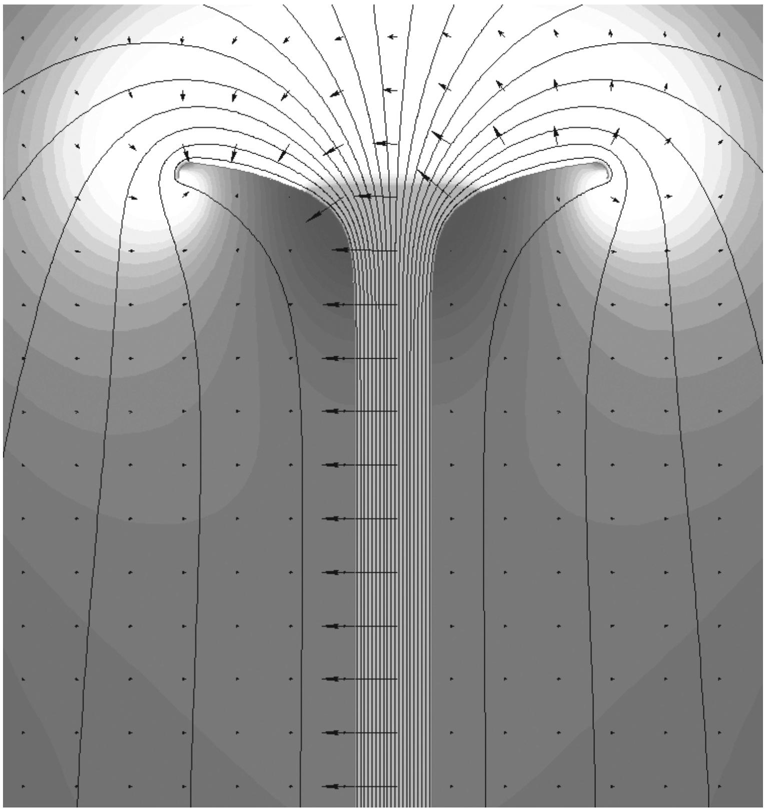

Fig. 2.1. Electric field of the Rogowski electrodes. If the electrodes are set precisely parallel, the field in the central space are close to uniform.

2.3 Determination of AC breakdown voltage dependence on the gap length for the gaps pin – plane, pin-pin, Rogowski electrodes and spherical electrodes.

For AC measurements exclude rectifier from the test circuit. Circuit diagram for these measurements is displayed on fig 2.2.

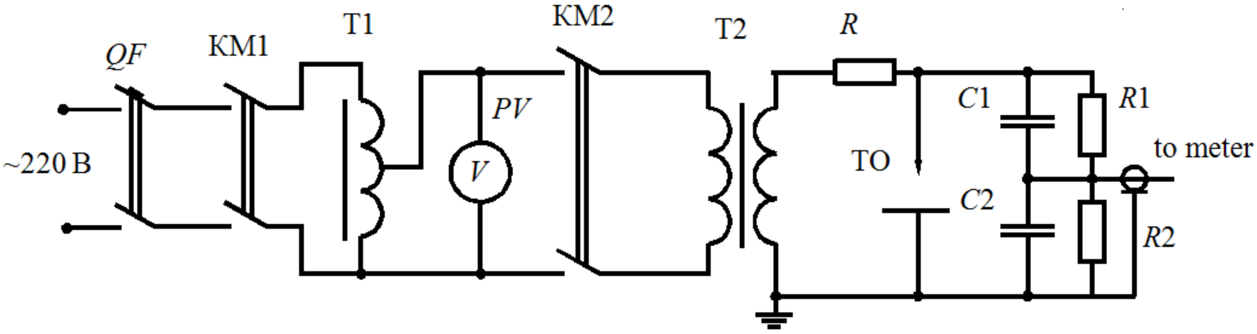

Fig. 2.2. Test circuit diagram for AC measurements.

Measurements procedure is the same as in p.1.3. *Note that the meter on the control panel shows the amplitude value of the gap voltage*.

Recalculate obtained breakdown voltages to the normal atmospheric conditions, determine average breakdown field strength.

2.4 The report content.

The report contains:

a) Experimental plant circuit;

b) Measurements results tables;

c) Graphs representing dependences of breakdown voltages and average electric field strengths on the gap length for all gap geometries;

d) Results summary. Focus on the impact of the electrodes shape on their breakdown voltages;

Work 3. Surface discharge in gas.

3.1. Work program

1. Obtain dependence of the discharge voltage on the air gap size for the electrodes laying on glass surface at following conditions:

a) without grounded conductive sheet under glass.

b) with grounded conductive sheet under glass at two different values of the glass thickness.

Present dependences of the discharge voltage and average electric field strength on the air gap size for all cases at tabular and graph form.

3.2.Work description

A combination of current leading and insulating parts is inevitable at high voltage equipment design. The stylized pictures of such compositions are presented on fig. 3.

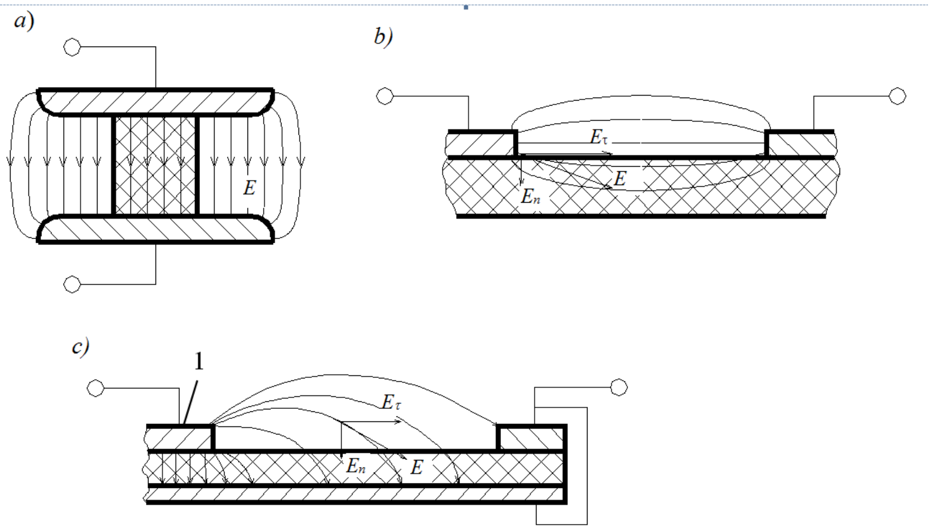

Fig. 3.1 Typical surface discharge geometries

In the first case (a), charged particles and ions of adsorbed water deform the field in the gap. Inevitable presence of small gaps between electrodes and insulator results in local field strength increasing. Thus, the discharge voltage decreases slightly in comparison with the case of insulator absence inside the gap.

In the second case (b), the field between the electrodes is nonuniform. The insulator on which the electrodes are placed does not actually influence on the discharge voltage and this voltage is practically similar to the same geometry of electrodes in air.

In the third case (c), where the insulator thickness is substantially less than the gap length the electric field at the electrode edge is distinctly nonuniform due to closeness of the conductive backing. Here the corona discharge starts at relatively low applied voltage. At further voltage rise the diffused corona discharge transforms into streamer stage and at the next stage – to arc (compare with pin-plane discharge in the air).

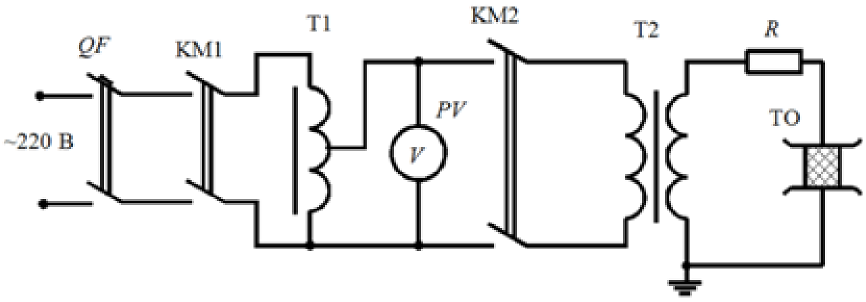

Fig. 3.2. Test circuit diagram

The presence of the conductive backing dramatically reduces the discharge voltage and this effect is more distinguished at thinner insulating layer.

3.3 The experimental setup

Operation of the experimental HV- installation is analogous to described in work 2. It is possible to measure discharge voltage by the meter PV on the primary side of the high-voltage transformer T2 with known transformation rate K=500. For obtaining the voltage amplitude multiply the meter readings by 500*√2.

There are two sheets of glass, metal sheet for backing electrode, and the set of length-measuring bars for assembling the discharge geometry. The copper plates, connected with ground and HV supply with flexible conductors are used as electrodes. Measurements have to be performed at 5-7 different gap distances for each gap geometry. Please, keep maximal gap voltages not higher than 80-

90kV.When measuring, try to distinguish corona, streamer, and arc stages of the discharge registering corresponding voltages.

3.4 The report content.

The report contains:

a) Experimental installation circuit diagram;

b) Measurements result tables;

c) Graphs representing starting voltages of corona, streamer and arc for all studied configurations;

d) Results summary. Focus on the impact of conductive backing on all stages of the discharge

Work 4. Characteristics of corona discharge on wires at DC voltage.

4.1. Work program

1. Determine starting voltage of the corona discharge and dependence of the discharge current on voltage at positive and negative wire voltage polarity.

2. Calculate starting voltage of corona discharge for wires used.

4.2. Work basics

Corona discharge is self-discharge appearing in strongly non-uniform electric field in the high field strength area. At avalanche corona discharge form thickness of ionized gas is about few millimeters. In the rest of the discharge gap having lower field strength, electron-ion impact ionization is absent but ions are moving in the electric field. In collisions with gas molecules ions are transferring to them a part of the kinetic energy obtained at the acceleration in the electric field. As the result the gas is heated by the energy lost by ions. Besides the ionization the molecules excitation process takes place. Molecules are retained in the excited state for a very short time and then get back to the stationary state with photons emission. That is why the corona discharge is accompanied with blue glow. Pulse currents presenting in corona discharge have very high frequency that cases electromagnetic influence for electronic devices.

4.3. Determination of the corona discharge starting voltage and discharge current dependence on voltage at positive and negative wire voltage polarity.

Determination of the voltage of the corona discharge beginning and discharge current dependence on voltage are carried out on the special high voltage plant. The circuit diagram is displayed on fig. 4.1.

Uninsulated wire is located coaxially in metallic cylinder 1 having 600mm diameter and active length 1.2 m. The cylinder edges are rounded to avoid edge effects. The cylinder is insulated from the ground and surrounded by the metallic screen for measuring circuits protection from electromagnetic influences. For measuring of the corona current the microammeter PA is connected between the cylinder and the ground. The PA scale has zero point in its middle that allows conducting measurements at positive either at negative wire voltage polarity.

The wire voltage measurement is provided by resistive-capacitive voltage divider R1,C1,R2,C2. The divider output voltage is measured by low voltage voltmeter on the plant control panel. Measuring devices and magnetic switches control buttons are mounted on the control panel.

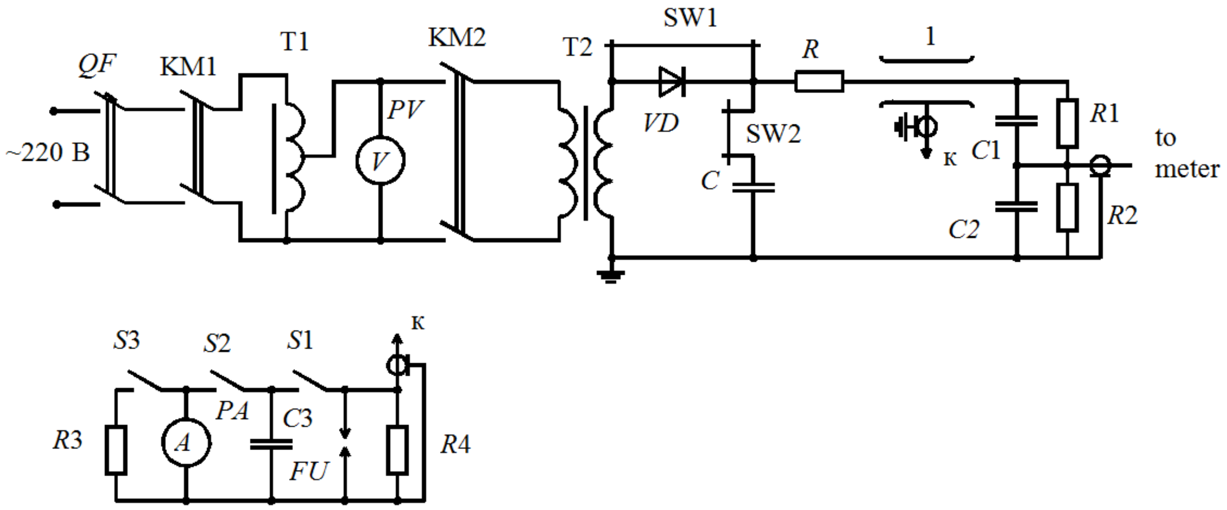

Fig.4.1. The schematic of the for corona discharge installation

Before starting measurements it is necessary to register the atmospheric pressure and reading of the dry thermometer.

Measurements procedure:

Fix the 1.2mm diameter wire in the cylinder 1.

Remove shorting connector SW1 from the HV diode VD, set VD anode to the transformer output, connect diode cathode with filtering capacitor C. Remove the grounding rod from the capacitor HV electrode and close the fence door.

Set position “x1” of the switch S3 on the control panel, switch on S1 and S2.

Switch on QF circuit breaker.

Push the button K1 on the control panel switching on the magnetic switch KM1. Check for zero voltage on the secondary side of the voltage regulator T1 using meter PV.

Push the button K2 on the control panel switching on the magnetic switch KM2.

Gradually raise the transformer T2 input voltage up to appearing of the corona current through the microammeter PA.

Write down the reading of the HV voltage meter (1µA corresponds to 1kV). Voltage obtained is the measured voltage of the corona discharge beginning.

To reduce statistical error repeat measurement at least 3 times.

Gradually raise the wire voltage to get corona voltage-current dependence. Measurements have to be performed at 8-10 voltage values. When the current reaches 80-100 µA set S3 to the position “x5”.

Switch off the installation, set regulating transformer to zero, open the door and put the grounding on the HV transformer output.

Rotate the HV diode VD at 180 degrees to change the wire voltage polarity.

Repeat measurements at negative wire voltage.

To study the influence of the wire diameter conduct measurements at 2mm and 3mm wire.

Match measured voltage values to the normal atmospheric conditions.

There is no need to insert the humidity correcting coefficient in the corona measurements. Determine the atmospheric conditions correcting coefficient

$$\delta = \frac{P * 293}{P_0(273 + t)}$$

Voltage matched value U_0=Um/δ, here Um is the measured voltage, P and P_0 – current and normal atmospheric conditions.

4.4. Calculation of the corona discharge starting voltage.

For coaxial wire system the corona discharge starting voltage can be calculated by formula $Uv=Ev \cdot r1 \cdot ln(r2/r1)$. Here *r1* and *r2* – radii of the wire and the cylinder ;

Ev – field strength of the corona discharge start, which can be calculated for the wire radius less than 1cm as $E_v = A \cdot \delta \cdot (1 + \frac{0.298}{\sqrt{\delta \cdot r1/r}})$ (Peek's law, index "v" means "visual critical corona voltage"). A=3.03·10^6 V/m, δ - relative air density, r1 – wire radius, r=0.01m. Calculate this value for all wire diameters used.

4.5. The report content.

The report must contain:

e) Experimental plant circuit;
f) Measurements result tables
g) Graphs representing corona voltage-current characteristics ;
h) Experimental and calculated values of the voltages of the corona discharge beginning.
i) Results summary.

Work 5. Characteristics of corona discharge on wires at AC voltage.

5.1. Work program

1. Determine critical voltage of the AC corona discharge and obtain power loss dependence on voltage for coaxial wire system.

2. Calculate critical voltage of AC corona discharge.

5.2. Work basics

In the electric field two types of ions (positive and negative) can appear in air media. If the ion polarity is coincided with wire voltage polarity it moves outside from the wire. Ions of the opposite polarity are in the majority neutralized on the wire surface. Therefore, the spatial discharge near the wire consists mostly of ions with polarity corresponding to the wire polarity. At AC voltage interaction between charged particles generated in the gas at previous half period leads to partial neutralization of the spatial discharge. It eases the corona triggering and intensifies corona discharge. At AC corona minimal voltage and field strength at that the corona discharge exists are called “critical”. Corona discharge is accompanied with energy losses. At AC voltage losses during one voltage period can be measured as square of Volt-Coulomb characteristics of the discharge gap. For obtaining of the transferred charge signal, the corona current signal is integrated by capacitor.

5.3. Measuring of the corona discharge critical voltage and obtaining dependence of energy loss on voltage for coaxial wire system.

Measuring of the corona discharge critical voltage and obtaining dependence of energy loss on voltage is performed on the same plant as for DC corona (fig.4.1). The plant circuit should be modified as follows:

Switch off S2 on the control panel. After grounding of the installation:

HV diode VD must be shorted by connector SW1.

Filtering capacitor C must be disconnected.

Fix the 1.2mm diameter wire in the cylinder 1.

Volt-Coulomb characteristics are measured by the oscilloscope in XY-mode.

Connect the voltage signal output from the measuring divider with oscilloscope Y channel.

Connect the charge signal from the capacitor C3 with oscilloscope X channel.

Switch the equipment on in the same way as in 4.3.

If the corona discharge is absent, figure on the oscilloscope screen looks like straight sloping line. As corona discharge appears the line transforms to loop. Register this moment for determination of the critical voltage.

Voltage increase leads to increase of the loop area. Make 5-7 oscillograms of Volt-Coulomb characteristics at different voltage amplitudes from the critical voltage to 80-90kV.

Determine power loss as $P=S\cdot Ku\cdot Kq\cdot f$

Here S – square of a Volt-Coulomb characteristic (div^2), Ku and Kq – voltage and charge scales, f – power net frequency (50Hz).

$Ku=U/hy$. Here U – voltage amplitude on the wire, hy – maximal vertical oscilloscope beam displacement.

Respectively $Kq=hx\cdot C3$. Here hx – oscilloscope horizontal sensitivity 0.2 or 1.0 V/div depending on the oscilloscope settings; C3 – $0.47\cdot 10^{-6}$F.

Repeat measurements at wires diameters 2 and 3 mm.

Match the results obtained to normal atmospheric conditions as it described at 4.3

5.4 Calculation of the critical voltage for industrial frequency corona discharge.

For coaxial wire system the critical voltage of the corona discharge can be calculated by formula $Uc=Ec\cdot r1\cdot \ln(r2/r1)$. Here r1 and r2 – radii of the wire and the cylinder ;Ec –critical field strength of the corona discharge which can be calculated for the industrial frequency as

$$E_c = 24.5 \cdot \delta \cdot \left(1 + \frac{0.613}{(\delta \cdot r1)^{0.4}}\right) \qquad \text{kV/cm}$$

Here, δ - relative air density, r1 – wire radius. Calculate this value for all wire diameters used.

5.5. The report content.

The report must contain:

a) Experimental plant circuit;
b) Measurements result tables
c) Oscillograms of Volt- Coulomb characteristics;
d) Graphs representing dependences of corona loss on wire voltage
e) Experimental and calculated values of the voltages of the corona critical voltages.
f) Results summary.

Work 6. Voltage distribution on a string of insulators

6.1 Work program

Determine: a) Voltage distribution on a string of insulators;

b) Break-down voltage of a “cap and pin” insulator .

6.2. Brief description of the work

Cap and pin insulators are widely used on power lines 35 kV or higher. Porcelain, glass or plastic are typical materials for this class of insulators.

For AC voltage a string of insulators can be represented by circuit, consisting of capacitors (see the fig. 6.1), that equivalents constructive capacitances of insulators and between insulator pins, wire and grounded elements of power line.

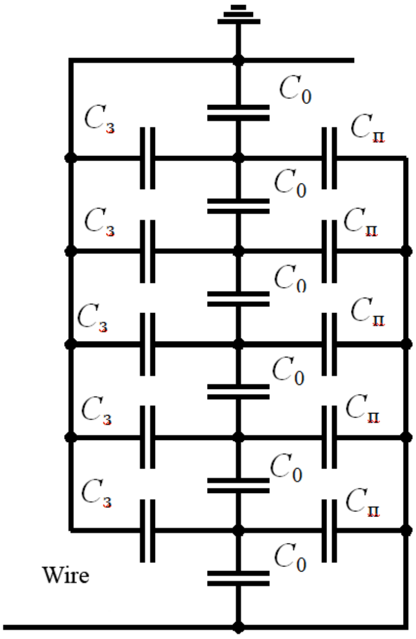

Fig. 6.1. Equivalent circuit of the string of insulators
Here: C0 = 50–70 pF – the capacity between pins of insulators, Cп = 0.5–1 pF – capacity of separate insulators to HV-wire, and Cз = 4–5 pF capacity to grounded parts of a transmission line tower. Currents, flowing through the capacities of Cз and Cп, substantially disturb the linear distribution of the voltage along the string, formed by capacities of C0 that are connected in series. As Cз>Cп, the highest voltage is applied to the first insulator which is closest to the HV wire.

In accordance with technical regulations, the string must be designed so that the highest voltage level on this insulator does not exceed the allowed value, corresponding to the acceptable level of electromagnetic influences (noises). For lowering of the voltage value on the first insulator, electric shields (e.g. of toroidal shape) can be used.

6.3. Measuring of voltage distribution on a string of insulators

Measuring of voltage distribution on a string of insulators can be implemented on the high voltage installation as it is displayed on fig. 6.2.

Special device is used which consists of insulating handle MR and small spark gap (1-2mm). Thin metal wires (antennae) are intended for connection of the gap with electrodes. For the safety, the handle has grounding wire which is connected with the grounding circuit.

Switch on the QF and KM1. Set regulating transformer T1 to zero output voltage. Switch on KM2.

After connecting of the measuring gap with electrodes, gradually rise the voltage applied to the HV wire. Write down the voltage *Ui*, corresponding to the break-down of the gap at insulator #i.

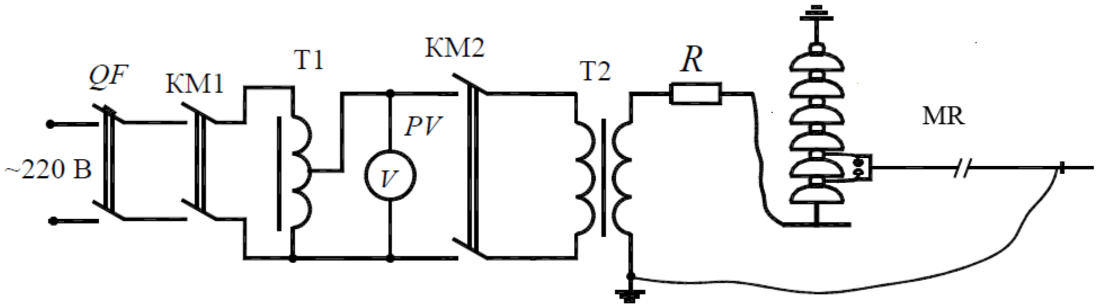

Fig. 6.2. Measuring circuit

Set regulating transformer T1 to zero output voltage. Repeat measurement on the next insulator.

After having all voltages measured, α_i – quote of each insulator, can be calculated as

$$\alpha_i = \frac{1/U_i}{\sum_{i=1}^{n} 1/U_i},$$

here$n$ – number of insulators in the string; i –index number of the insulator, counted from HV-wire site.

Install electric shields on top and bottom of the string. Repeat measurements in the shielded geometry.

6.4. Determining of the “cap and pin” insulator breakdown voltage

For determining of the break-down voltage of the “cap and pin” insulator, remove electric shields, short with the special wire all insulators of the string except one which is closest to HV wire.

Switch on the installation as it is described in 6.3. Gradually rise applied voltage until break-down is observed. Immediately after breakdown switch the HV off pushing red button on the control panel.

To get actual RMS value of the break-down voltage multiply the reading of meter PV by 500. That number is the transformation rate of the HV transformer T2.

6.5. The report content

a) Experimental plant circuit;

b) Measurements result tables;

c) Graphs representing the voltage distributions along the string of “cap and pin” insulators for geometries with and without shields

d) Conclusion, containing information about voltage distribution nonuniformity and effect of shields.

Work 7. High voltage pulse generator (Marx Generator).

7.1. Work basics

Marx generator is intended for generation of single HV pulses with amplitudes higher than 100 kV (typically 200-1000kV). Mostly the pulse shape is bi-exponential and can be characterized by two time constants – rise time (τ_r) and fall time (τ_f). Standard values of time constants for lightning modeling are 1.2 μs and 50μs respectively.

The generator operating principle is based on storing energy in set of capacitors at relatively low voltage level (up to 100kV) and discharging them through spark gaps in combination, providing series connection of the capacitors for the discharge time.

7.2 Experimental setup.

The generator schematic is presented on fig.7.1.

The HV transformer is supplied by AC voltage from regulating low voltage transformer (not shown on the schematic diagram). The transformer output is connected with two voltage doubling rectifiers producing DC high voltages of different polarities (fig.7.1. "+" and "-"). The rectifiers output voltages (indicated on the control panel) can be connected with capacitors by two ways, changing pulse polarity.

For the presented kind of schematic the generator output pulse amplitude roughly can be determined as capacitor charging voltage multiplied by doubled sections number. There are 4 sections in the laboratory generator, so the voltage multiplication rate is 8.

The generator main technical characteristics claimed by manufacturer are:

1	Output voltage amplitude kV	80-600
2	Voltage pulse shape (rise time/fall time) μs	1.2/50
3	Maximal energy stored kJ	9
4	Maximal value of short circuit current A	>1000
5	Maximal charging voltage kV	±80

The pulse front time is determined by front capacitor C_f and by discharge and section connecting resistors R_d,R_{cs}. The fall time is determined by the equivalent capacity of the stage $C_s/2$ and section connecting resistors R_{cs}.

Before pulse generation the capacitors C_s must be charged with certain level of uniformity. It requires long enough time because of their different charging time (being charged through bigger resistance capacitors of higher stages have longer charging time). To provide reliable operation, the spark-gap switches S1-S4 have the electrically driven gap adjustment system. Switch S1 is trigatron - type, so it can be triggered by high voltage pulse from control panel. After breakdown of the S1, transient process in the discharge circuit leads to breakdown of the resting switches.

For each level of output voltage the proper gap distance for spark gaps S1-S4 must be set according to fig.2. If the gap value is set inside working interval for the given charging voltage, the triggering pulse being applied to S1 after charging results in breakdown of all the spark gaps and forming of the output pulse. In automatic mode the gap length is adjusted automatically in accordance with charging voltage setting.

Increasing of the spark gap length needs to be accompanied with corresponding rise of the HV supply voltage. The criterion of normal operation is charging time before breakdown abut 20s.

The capacitive voltage divider C_f is used for a pulse shape registration by oscilloscope. Its transfer coefficient is 1:10000. Simultaneously it operates as a pulse front correcting capacitor. It does not fit well with the measurement functions because of resonant properties of the circuit branch formed by C_f and inductance of its connection to the generator output. So, it is preferable to use additional resistive-capacitive divider HVD for more precise pulse shape registration. In this case it needs special calibration (see below).

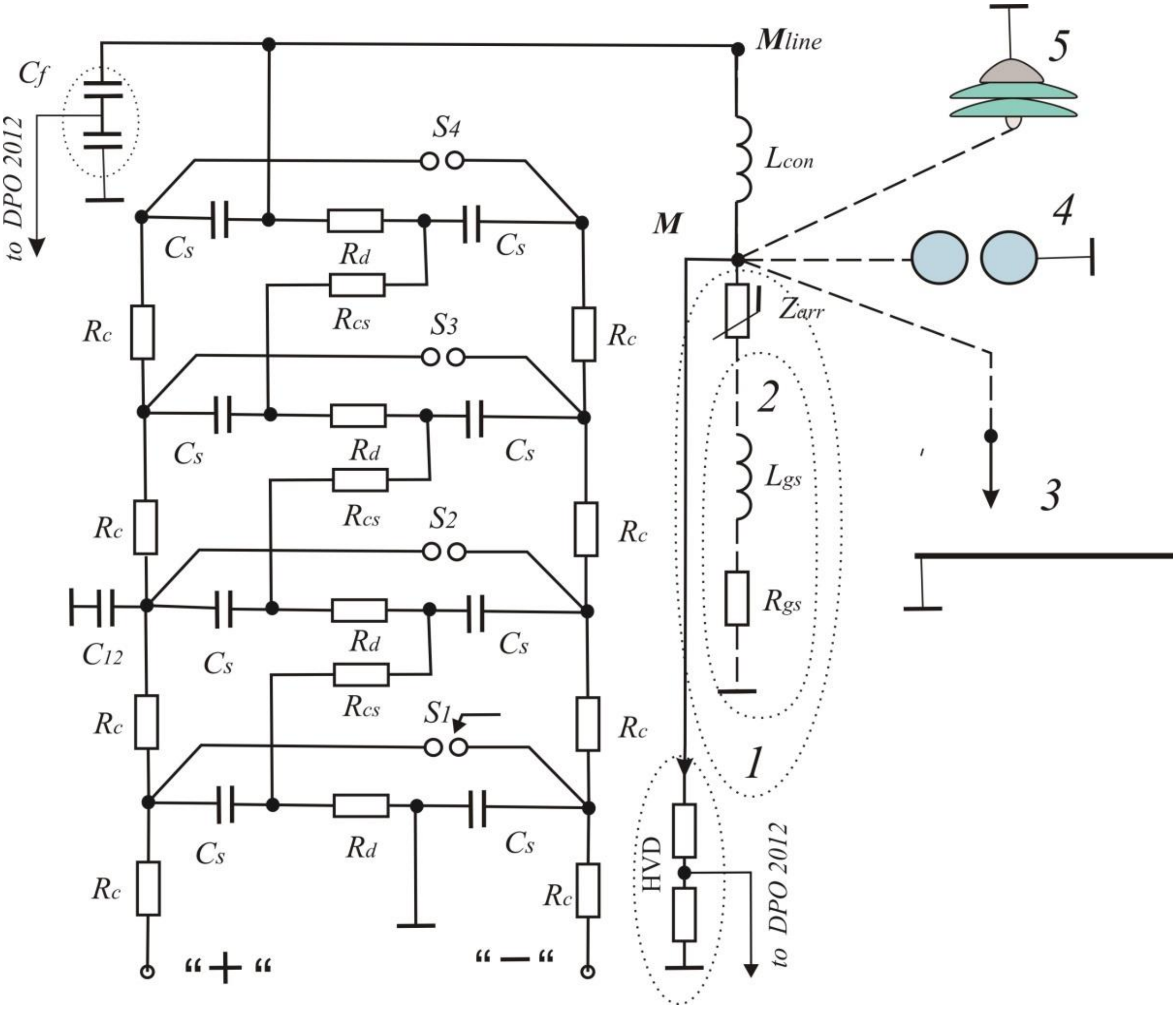

Fig . 7.1. The generator schematic

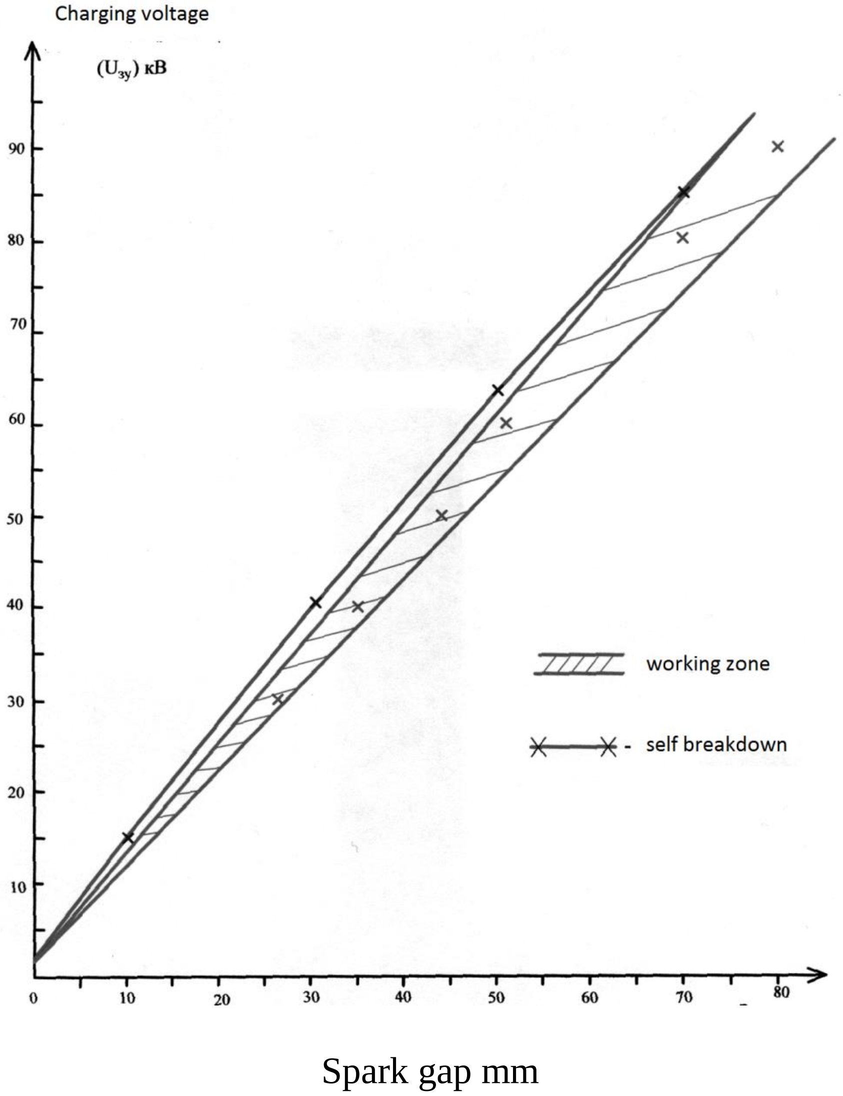

Fig.7.2. To the spark gap determination

The installation load part is presented on the right part of fig.7.1. Voltage pulse is formed in the point $\mathbf{M}_{line}$ and transferred to the point $\mathbf{M}$by connecting wire L_{con}. Objects of measurements can be connected with this point. E.g. it can be nonlinear overvoltage arrester (1) with the equivalent circuit of grounding (2), pin-plane spark gap (3), ball spark gap(4) or string of insulators (5).

Ball spark gap is a standard device for HV measurements (see Table A.1).

7.3. Measurements program.

1. Voltage divider calibration

These measurements need the pulse registration by oscilloscope.

Set the ball spark gap distance 50mm.

Gradually rise pulse amplitude, registering pulses shape by the oscilloscope. Determine oscilloscope voltage amplitude corresponding to 50% probability of the ball spark gap breakdown. From 50% breakdown oscilloscope voltage determine transfer coefficient of the HV divider using Table A. 1.

2. Obtaining voltage-time characteristics of ball spark gaps

Rising pulse amplitude above 50% breakdown level, obtain dependence of breakdown voltage on breakdown time interval from the pulse start. On fig. 7.3 two typical oscillograms of pulse voltages on air gap are presented. Here, U_1, U_2 - breakdown voltages, t_1, t_2 - breakdown times. Make at least 3 measurements on each level of charging voltage. With respect to the statistical deviations, collect 10-15 points, changing gap distance of the generator switches, and, correspondingly, HV supply output voltage.

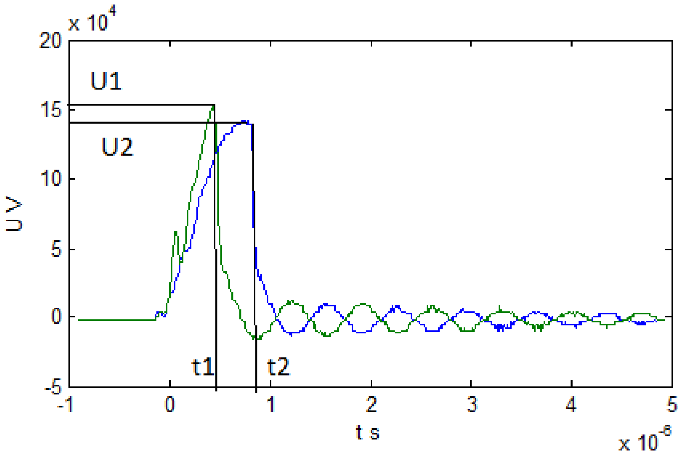

Fig. 7.3. Typical oscillograms of pulse voltages on air gap.

3. Voltage-time characteristics of HV line insulator

Determine 50% breakdown voltage of the insulator for standard pulse as above.

Gradually rising pulse amplitude obtain dependence of breakdown voltage on breakdown time. Make at least 3 measurements on each level of charging voltage

Change pulse polarity and repeat measurements.

7.4. The lab report contents

Present results of measurements as tables and graphs.

Compare curves V vs t for ball spark gap and line insulator.

Typical voltage –time characteristics are presented on fig.7.4.

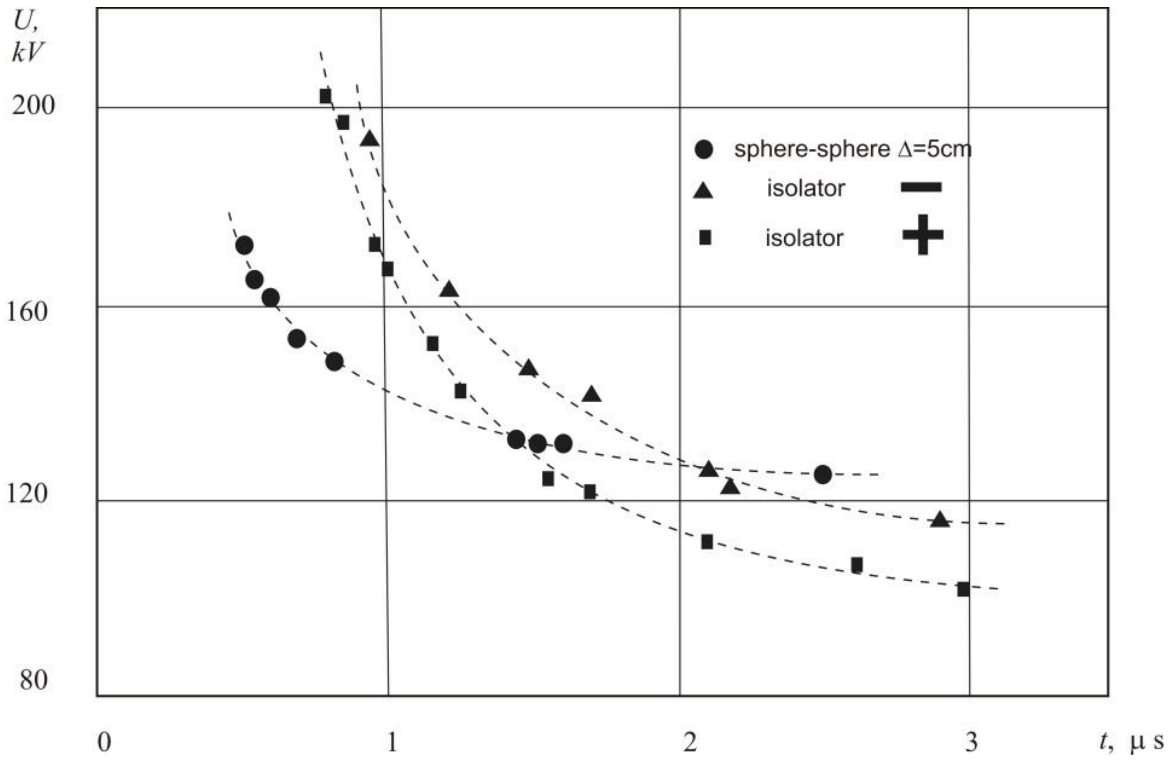

Fig.7.4.

Work 8. High voltage AC measurements.

8.1. Work program

1.Taking graduating curve of a HV transformer using standard air gap.

2. Making HV measurements using capacitive divider

    a) by static voltage meter

    b) by microammeter

3. Evaluating voltage sinusoid quality.

8.2. Work basics

The simplest way of AC measurements on a transformer's high voltage side is to measure voltage on low voltage side and recalculate it to HV using the transformer rate. But it is necessary to take into account that the relation between voltages on high and low sides will differ depending on voltage level and the transformer load.

It is caused by the transformer impedance, magnetic core nonlinearity and corona discharge losses on the HV side. That is why for precise recalculation of the measured low voltage to HV side it is necessary to have the transformer graduating curve specific for its actual load.

The another way, based on a capacitive divider application, requires additional equipment. Low voltage measuring devices have to be connected in parallel with the divider lower part. Measured high voltage is determined as low voltage meter count multiplied by divider rate. Measurement accuracy can be satisfactory if the meter impedance is much higher than the capacitive resistance of the divider lower part. DC voltage cannot be measured by this method.

8.3. Obtaining of the HV transformer graduation curve using test spark gap.

The circuit diagram is displayed on fig. 8.1

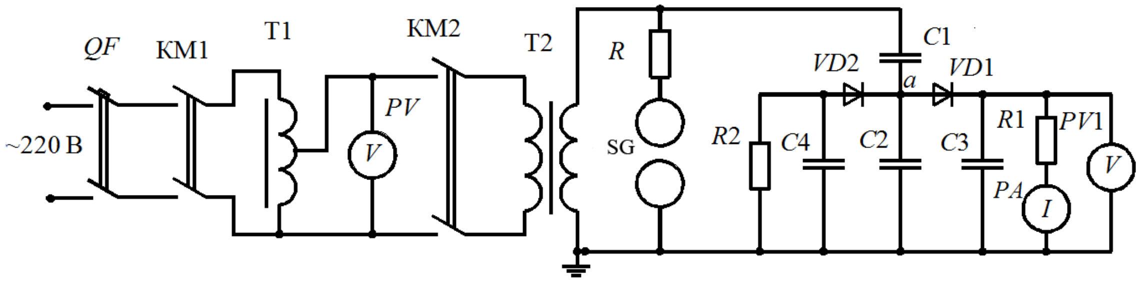

Fig. 8.1 Experimental plant circuit diagram

Before starting measurements register atmospheric pressure and temperature . It is important for matching of tabulated spark gap discharge voltage with atmospheric conditions.

To get one point of the graduation curve:

set the 0.5 cm distance between 12.5cm measuring spherical electrodes;

read from Table A.1 breakdown voltage for this gap length and voltage type;

remove grounding bar from HV electrode of the spark gap;

switch on QF circuit breaker.

Push the button K1 on the control panel switching on the magnetic switch KM1. Check for zero voltage on the secondary side of the voltage regulator T1 using meter PV. If the voltage is not zero, set it by the counterclockwise rotation of the regulator handle.

Push the button K2 on the control panel switching on the magnetic switch KM2.

Gradually raise the transformer T2 input voltage up to air gap breakdown (rise the voltage approximately 30sec before breakdown). Register the voltage value on PV just before breakdown (Ub). Write down the value obtained in result table. Measured value is RMS (repetitive medium square).Repeat the measurement two more times to get average value of the primary breakdown voltage.

Determine the atmospheric conditions correcting coefficient

$$\delta = \frac{P \cdot 293}{P_0(273 + t)}$$

Get the amplitude value of the spark gap breakdown voltage for current conditions $Um=\delta U_0$. It is recommended to set X-axis as PV voltage, Y-axis as Ub.

For the graduating curve forming repeat measurements at distances between measuring electrodes consequently 1.0, 1,5 and 2.0 cm.

The measurement error by graduating curve can be estimated as

$\frac{\Delta Um}{U_m} = \sqrt{(\frac{\Delta S}{S})^2 + (\frac{\Delta P}{P})^2 + (\frac{\Delta Upv}{Upv})^2 + (\frac{\Delta t}{273+t})^2 + 0.03^2}$, where estimated errors of the gap length, pressure, temperature and primary voltage measurements are considered as well as the error of spark gap standard measurements (0.03 are considered.)

8.4. High voltage measurement using the capacitive divider with electrostatic voltmeter.

For implementation of voltage measurement using the capacitive divider with electrostatic voltmeter it is necessary to turn on the installation as it is described in 8.3, set the voltage on the PV voltmeter to 60-70 V and write down the readings of the electrostatic voltmeter PV1. The amplitude of the transformer output voltage U=K·Upv1. K –division rate of the capacitive divider C1,C2 .

$K = \frac{C1+C2}{C1}$, C1=350 nF,C2=0.325μF. Note: due to action of rectifier VD1 and filter capacitor C3, Upv1 is the amplitude of the divider output.

The voltage measurement error can be estimated as

$$\frac{\Delta Um}{U_m} = \sqrt{(\frac{\Delta K}{K})^2 + (\frac{\Delta Upv1}{Upv1})^2 + 0.02^2}$$

Here $\frac{\Delta K}{K} = 0.02$ - relative error of the division rate measurement $\Delta Upv1$ – absolute error of the electrostatic voltmeter, 0.02 – relative error of the measurement circuit, determined by capacitors C3=C4=1μF and resistors R1=R2=910 kOhm;

8.5. High voltage measurement using the capacitive divider with microammeter.

Another option is measuring of the divider secondary voltage using resistor R1 and microammeter PA. The high voltage amplitude is U=K·R1·I, here I is the microammeter reading.

The voltage measurement error can be estimated as

$$\frac{\Delta Um}{U_m} = \sqrt{(\frac{\Delta K}{K})^2 + (\frac{\Delta I}{I})^2 + (\frac{\Delta R1}{R1})^2 + 0.02^2}$$

Here ΔI – absolute error of the current measurement by PA, $\frac{\Delta R1}{R1} = 0.01$ relative error of the R1 value.

8.6. Estimation of the high voltage sinusoid quality.

For the estimation of the sinusoid quality set the transformer primary voltage as it described in 8.4 and register the voltage amplitude Um by the electrostatic voltmeter PV1. Then disconnect PV1 with no switching off the plant and no changing voltage and switch it to the point “a”. Now PV1 will measure effective(RMS) voltage on the transformer output U.

If the voltage is practically sinusoidal $\frac{Um}{U} = \sqrt{2 \pm 0.07}$

8.7. The lab report content.

The report must contain:

a) Experimental plant circuit;

b)Measurements result tables

c)The transformer graduation curve;

d)Results summary.

Appendix.

Nomogram for humidity correction coefficient

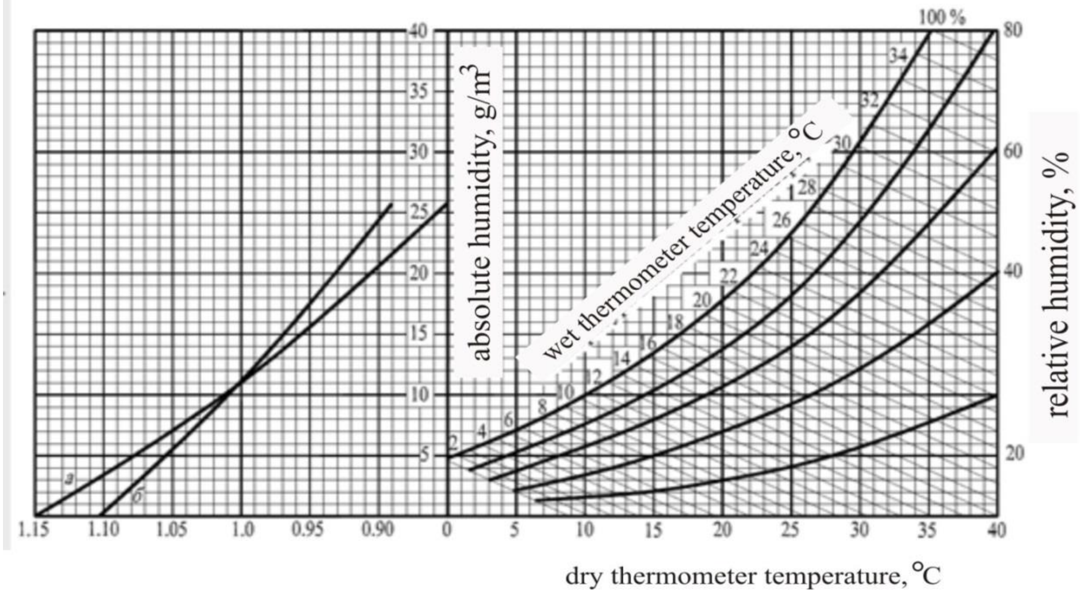

Fig. A.1. To determination of the humidity correcting coefficient
Curve a –DC and AC voltages, b – pulse voltages

Table A.1

Breakdown voltages for alternating sinusoidal voltages, DC voltages of both polarities, full standard and longer pulsed voltages of negative polarity (50% discharge) - a) and full standard and longer pulsed voltages of positive polarity (50% discharge) - b), kV

Distance between spheres, cm	Spheresdiameter , cm							
	6.25		12.5		25		50	
	a	b	a	b	a	b	a	b
0.4	14.2	14.2						
0.5	17.2	17.2	16.8	16.8				
0.6	20.2	20.2	19.9	19.9				
0.7	23.2	23.2	23.0	23.0				
0.8	26.2	26.2	26.0	26.0				
0.9	29.1	29.1	28.9	28.9				
1.0	31.9	31.9	31.7	31.7	31.7	31.7		
1.2	37.5	37.6	37.4	37.4	37.4	37.4		
1.4	42.9	43.2	42.9	42.9	42.9	42.9		
1.5	45.5	45.9	45.5	45.5	45.5	45.5		
1.6	48.1	48.6	48.1	48.1	48.1	48.1		
1.8	53.5	54.0	53.5	53.5	53.5	53.5		
2.0	58.5	59.0	59.0	59.0	59.0	59.0	59.0	59.0
2.2	63.0	64.0	64.5	64.5	64.5	64.5	64.5	64.5
2.4	67.5	69.0	70.0	70.0	70.0	70.0	70.0	70.0

2.6	72.0	73.5	75.5	75.5	75.5	75.5	75.5	75.5
2.8	76.0	78.0	80.0	80.5	81.0	81.0	81.0	81.0
3.0	79.5	82.0	85.0	85.5	86.0	86.0	86.0	86.0
3.5	(87.5)	(91.5)	97.0	98.0	99.0	99.0	99.0	99.0
4.0	(95.0)	(101)	108	110	112	112	112	112
4.5	(101)	(108)	119	122	125	125	125	125
5.0	(107)	(115)	129	134	137	138	138	138
5.5			138	145	149	151	151	151
6.0			146	155	161	163	164	164
6.5			(154)	(164)	173	175	177	177
7.0			(161)	(173)	184	187	189	189
7.5			(168)	(181)	195	199	202	202
8.0			(174)	(189)	206	211	214	214
9.0			(185)	(203)	226	233	239	239
10.0			(195)	(215)	244	254	263	263
11.0					261	273	286	287
12.0					275	291	309	311
13.0					(289)	(308)	331	334
14.0					(302)	(323)	353	357
15.0					(314)	(337)	373	380
16.0					(325)	(350)	392	402
17.0					(336)	(362)	411	422
18.0					(347)	(374)	429	442