Ministry of Education and Science of Ukraine

ZAPORIZHZHA NATIONAL TECHNICAL UNIVERSITY

STUDY OF SWITCHING PHENOMENA IN ELECTRIC APPARATUS

Methodical instructions for laboratory works on the subject:
“Fundamentals of the Theory of Electrical Apparatus”

for students of the specialty 141:
"Electrical Power, Electrical and Electromechanical Engineering"
(educational program **“Electric and Electronic Apparatus”**

2018

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CONTENTS

1. LABORATORY WORK №5.
STUDY OF CURRENT-VOLTAGE CHARACTERISTICS OF ELECTRIC ARC DISCHARGE

Duration of the laboratory study is 4 hours

1.1 Purpose of the work

The purpose of the work is to determine experimentally the static and dynamic volt-ampere characteristics of the electric arc discharge.

1.2 Subject of the study

Virtually every real electric circuit has a certain store of electromagnetic energy accumulated in its inductive elements. When switching the circuit with the switching device contacts, this store is dissipated in the form of initiating electric arc discharge, which is one of the varieties of gaseous discharge. Besides an arc discharge, there exist also the following gaseous discharge types:

- *dark discharge* that is so-called *non-self-sustaining discharge* because electric current carriers come into existence under action of external agents (cosmic and X-ray radiation etc.), therefore values of dark discharge current very small (10^{-11} A and lower);
- *Townsend discharge* (named after the scientist who developed the theory of this type of discharge) is the so-called *self-sustaining discharge*; electric current carriers in this case arise as a result of the so-called *shock* or *field ionization*, i.e. due to a strong electric field at high voltage of the power supply;
- *glow discharge* differs from the Townsend one with the high current density at the cathode;

An electric arc discharge or *electric arc* initiates in the case when the voltage and current more than corresponding critical values of the arc formation. An electric arc is a plasma channel in which the electric current flows from one electrode (contact) to another. The length of an arc discharge has a heterogeneous structure. It contains three characteristic zones (regions) that qualitatively differ: *cathode region, arc column and anode region*. It should be noted that the cathode and anode regions have a small length (10^{-4}…10^{-5} cm) and relatively constant values of the voltage drop (10...30 V in the cathode and up to 10 ... 12 V in the anode). That’s why it can be assumed that the processes occurring in arc column determine the properties of an arc discharge and its voltage-ampere characteristic.

The arc column is a highly ionized volume of gas. Because of this, it has a relatively high electrical conductivity (which is close to the electrical conductivity of metals). Moreover, an arc plasma offers the properties of *quasi-neutrality* (i.e., the concentrations of ionized positive and negative particles are the same) and *thermodynamic equilibrium* (i.e., the physical properties of an arc plasma are single-valued functions of its temperature).

The processes of ionization and deionization permanently occur in an arc column. *Ionization* is the process of formation of ionized particles (positive ions and free electrons), which is mainly carried out through the decay of neutral atoms in the gas. The ionization encountered in gaseous discharges is essentially of two types, shock ionization and thermal ionization.

Field or *shock ionization* results from the collision of a free electron, accelerated by an electric field, with a neutral atom. It should be noted that shock ionization plays a key role in the formation of ionized particles in the Townsend and glow discharges and plays a very small role in the electric arc discharge, where their formation is carried out almost exclusively by *thermal ionization*. With an increase in the gas temperature, the rms velocity of atoms increases, their kinetic energy increases and the probability of their collision with the formation of ionized particles increases. The process of thermal ionization precedes the process of *dissociation*, i.e., the decay of molecules to atoms resulted from their collision under the thermal motion.

In parallel with ionization, the inverse process occurs called *deionization*. This process is carried out in two ways: *recombination*, i.e., the bond of two oppositely charged ionized particles and *diffusion*, i.e., outgoing of ionized particles from the arc column to its surrounding.

When the electrodes (contacts) are separated, the electric arc becomes a component of the electric circuit being interrupted and substantially affects the process of its interruption. As an electric circuit component, an electric arc is characterized by a volt-ampere characteristic, which is the dependence of the voltage drop from the arc current $u_{д} = f\left(i_{д}\right)$. There are two varieties of electric arc characteristics: static and dynamic.

Static volt-ampere characteristics are the ones measured under unchanged (steady state) values of the current and voltage. A typical static characteristic of an arc freely burning in the atmospheric air (i.e., any measures that contribute to its quenching are not used) is given in Figure 1.1.

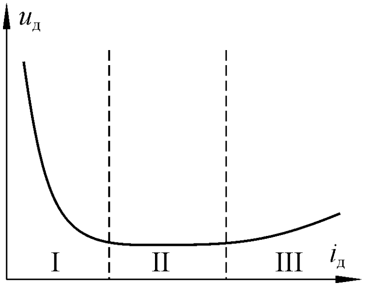

Figure 1.1 – Typical static characteristic of the electric arc burning in the atmospheric air

It has three typical zones: zone I – the falling characteristic is evident at sufficiently low currents (up to 10–15 A); zone II covers a very wide current range (up to 5-8 kA), where the voltage practically not depend upon the current that is explained by proportional increase in cross-sectional area of the arc column with increase of the current; zone III – at very high currents due to the pinch-effect the arc voltage increases slightly under increasing the current [10].

Dynamic volt-ampere characteristics are the characteristics measured during the process of changing the current. Their behavior significantly depends on the rate of change of the current.

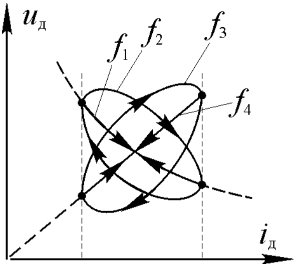

Figure 1.2 – Dynamic characteristics of the arc at different frequencies of the current sine component

An illustrative example of dynamic characteristics is the characteristics of an arc measured for a current having two components: dc and sine, changing with different frequencies, Figure 1.2, where f_1 is very low frequency resulting in the dynamic characteristic practically coincides with the static one; f_2 is low frequency; f_3 is high frequency, at which the dynamic characteristic essentially differs from static one; f_4 is very high frequency, when the dynamic characteristic practically coincides with the characteristic of pure resistance [10].

1.3 Description of the laboratory plant

An arc discharge is initiated with the help of special plant. Its appearance is shown in Figure 1.3. The circuit schematic for the study is represented in Figure 1.4.

The main component of the plant is the carbon electrodes 1 fastened by special holders 2 mounted on the basement 3 and connected to the electric circuit with the help of flexible conductors with terminals 4. When the knob 5 is rotated, the movable carbon electrode first opens the electric circuit, initiating an arc discharge, and then is driven along its axis, defining the arc length. The arc discharge can be visually examined and its length can be approximately determined through the dimming window 6. The installation is closed by a casing 7 with gaps in its upper part.

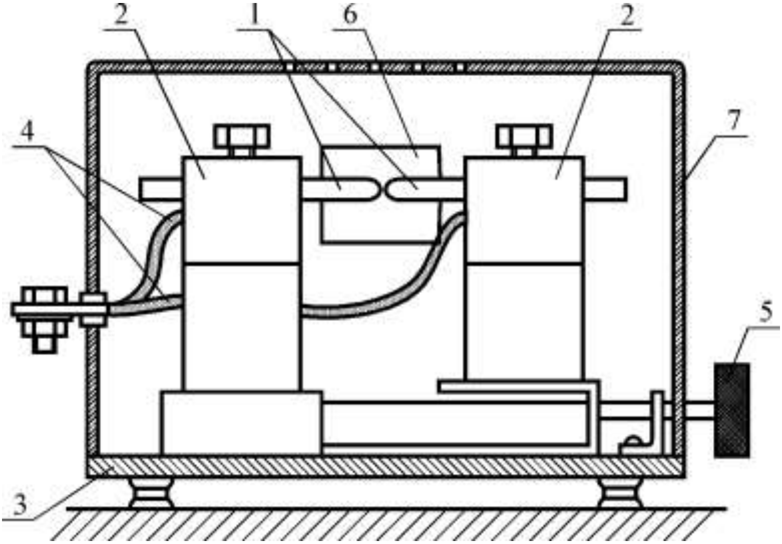

Figure 1.3 – Laboratory plant for the study of electric arc

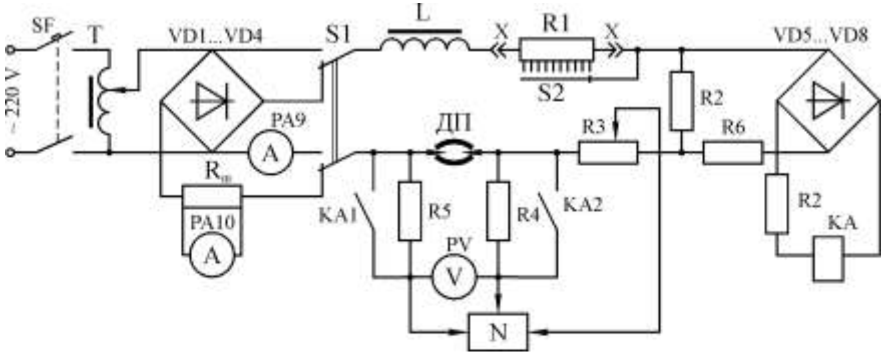

Figure 1.4 – Circuit diagram for measurement of static and dynamic characteristics of electric arc

Besides the coal electrodes forming the arc discharge (arc gap) ДП, the circuit also contains a reactor L to enhance the arc burning stability, a measuring shunt R_{sh} and resistors R1, R2, R3. The resistor R1, with the help of multi-position switch S2, carries out stepping regulation of the current value in the circuit. The switch S1 connects the circuit to a DC or AC voltage source. In the first case, the static characteristics of the arc are studied; in the second case, the dynamic characteristics of the sine-changing current are studied. In studying the static characteristics, the current and voltage measurements in the circuit are carried out by ammeter PA9 and voltmeter PV, respectively. In studying the dynamic characteristics, the current is measured by the device A10 by means of the shunt R_{sh} (the indications of the device A10 must be multiplied by 10). The voltage drop across the resistor R3 is applied to the oscilloscope input to measure the arc current waveform. The current relay KA protects the voltmeter and the oscilloscope from increased recovery voltage at the arc extinction.

1.4 Task

1.4.1. Measure the static volt-ampere characteristics of the arc with an arc length of 3 and 5 mm.

1.4.2. Measure the dynamic volt-ampere characteristic at the current and length of the arc specified by the instructor.

1.4.3. Make conclusions on the work.

1.5 Methodical instructions

1.5.1. Prepare the experimental installation to the work; for this purpose perform the following operations:

a) adjust the resistor R1 to state 3;

b) lift the cover of the installation casing and clean the coal electrodes from the coke;

c) install the carbon electrodes so that the arc burns in front of the window with the dimming element.

d) with the help of the turning handle bring together the carbon electrodes to close the circuit;

e) with the help of switch S1 transfer the circuit to the given operation.

1.5.2. Connect the laboratory panel to the power supply and measuring devices with short jumpers.

1.5.3. Close the switch SF and, using the resistor R3, adjust the current equal to 5 A in the circuit.

1.5.4. Separate the electrodes at a distance of approximately 1.5–2 mm and warm up them during 3–5 minutes, and then separate the electrodes at a given distance (i.e., 3 or 5 mm, according to the task).

1.5.5. In the event that the arc burns stably, measure its volt-ampere characteristic, using the switch S2 for step-by-step regulation of the current in the circuit. The measured findings are to be entered into Table 1.1.

Table 1.1 – Static characteristics of the arc.

$l_{\text{arc}} = 3\,\text{mm}$	I_{arc}, A	
	U_{arc}, V	
$l_{\text{arc}} = 5\,\text{mm}$	I_{arc}, A	
	U_{arc}, V	

1.5.6. According to measured findings, construct graphs of static volt-ampere characteristics $U_{\text{arc}} = f\left(I_{\text{arc}}\right)$

1.5.7. Connect the oscilloscope to the network and warm up it during 3–5 minutes. Connect the oscilloscope input to the object of the study using a high-frequency cable in accordance with the circuit diagram given in Figure 1.4. Adjust the oscilloscope so that to obtain a stable image of the time diagram on the screen.

1.5.8. Copy the arc dynamic characteristic from the oscilloscope's screen (the value of the current and the length of the arc is predetermined by the instructor).

1.5.9 **WARNING!** After experiments, turn off the oscilloscope from the network and open the circuit breaker SF.

1.5.10. The laboratory work report should include:

a) research tasks;
b) the principal scheme;
c) list of electrical equipment and devices;
d) the table and static current-voltage characteristics of the arc;
e) dynamic volt-ampere characteristics of the electric arc;
e) conclusions on the work.

1.6 Self-examining questions

1.6.1 Variations of gas discharge and their brief characteristics.

1.6.2 What is an electric arc discharge?

1.6.3 The voltage components across an arc gap.

1.6.4 Processes of ionization and deionization in an arc gap.

1.6.5 Thermal ionization and its role in the formation of the arc column.

1.6.6 Static and dynamic characteristics of the electric arc.

1.6.7 The condition of the DC electric arc extinction. The notion of the arc critical length.

1.6.8 Factors that influence on the character of the arc dynamic volt-ampere characteristics.

2. LABORATORY WORK № 6.

STUDY OF VOLTAGE RECOVERY PROCESSES IN CLEARING SHORT CIRCUIT FAULTS

The duration of the laboratory study is 4 hours.

2.1 Purpose of the work.

The purpose of the laboratory work is to experimentally determine the parameters of the transient recovery voltage across the switching device contacts in the process of clearing the terminal fault and the short-line fault.

2.2 Subject of the study.

Extinction of the electric arc, initiated whenever the AC circuit is interrupted, normally occurs at the current-zero crossing. Consequently, processes occurring in the current-zero region are very important, because they play a key role in the circuit interruption process. Just after current-zero moment for a very short time the contact gap resistance rises from a very small (the arc discharge resistance) to a very large (resistance of almost completely deionized gap) value. At this short time, the electric arc plasma is very intensively deionized and rapidly disintegrated. As a result, the arc column acquires qualitatively new properties of the *residual arc space*. This phenomenon is usually named the recovery of dielectric strength (*dielectric recovery process*).

At the same time during this period, the voltage recovery process occurs. Before the arc extinction, the voltage between the switching device contacts is dependent on the arc volt-ampere characteristic and at the current-zero moment it corresponds to its extinction peak. After the current-zero the power frequency voltage is restored across the switching device contacts called the *power frequency recovery voltage* (PFRV).

Of course, the restoring the power frequency voltage cannot occur instantaneously, because the real electric circuits always contain capacitive components, and thus a transient stage of the voltage recovery process is initiated. The instantaneous voltage during this stage is the *transient recovery voltage* (TRV).

The most important case for practice is TRV in clearing the short circuit, which occurred directly behind the switching device (circuit breaker) called *terminal fault*. The equivalent circuit for determining the TRV for this case is an active-inductive circuit shown in Figure 2.1.

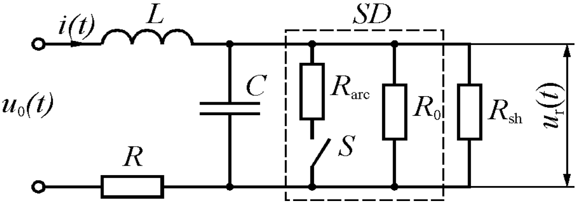

Figure 2.1 – Equivalent circuit for determining the TRV in clearing the terminal fault

There following designations are accepted in the circuit. *L*, *R*, and *C* are the parameters of the circuit that is formed in the event of the terminal fault. It should be pointed out that capacitance *C* plays significant role in the voltage recovery process, but not at all effect on the value of the fault current to be interrupted. R_{arc} R_{o} are the parameters of the switching device *SD* that clears the fault: the resistance, respectively, of the arc at its extinction moment and of the residual arc space after the arc is extinguished. *S* is the so-called *ideal switch* that interrupts a circuit with no arcing at the current-zero moment; it has zero resistance, when is in closed position, and infinite resistance, when it is in open position. R_{sh} is the shunting resistance connected across the switching device *SD*. $u_0(t)$ is the time-varying PFRV. It should be noted that transient stage of recovery voltage occurs sufficiently rapidly and the PFRV has no time to change significantly, that's why it is accepted time-invariable and is equal to its instantaneous value at the arc current-zero moment:

$$U_0 = \sqrt{2}U_{\text{ph}}K_{\text{c}}\sin\varphi, \qquad (2.1)$$

where U_{ph} is the phase voltage;

φ is the phase shift between the current and voltage;

K_{c} is the circuital coefficient.

Thus, the behavior of the TRV is determined by the parameters of the electric circuit to be interrupted, namely *L*, *R*, *C*, R_{arc}, U_{o}, as well as the properties of the switching device being characterized by R_{arc}(t), R_{o}(t). TRV, determined with consideration of the switching device properties, is an *actual TRV*, which has a purely scientific significance, but has no practical application.

Practical significance is the so-called *system TRV*, which is determined without consideration of the switching device properties and allows unambiguously and objectively to determine the switching conditions generated by the electrical network, in which the device makes the interrupting operations. Currently, it is likely that system TRV plays a significant role in the electric circuit interrupting process and, to a large degree, determines the ability of the switching device (circuit breaker) to clearing the short circuit faults.

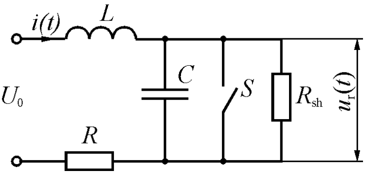

Figure 2.2 – Single-frequency circuit to determine system TRV

Consequently, in determining system TRV it should be proceeded from the fact that an ideal switch interrupts the electric circuit, and the equivalent circuit becomes simpler as shown in Figure 2.2. This is the simplest case for determining a system TRV called a *single-frequency circuit.*

When the parameters of the circuit being interrupted is predetermined, the behavior of the TRV is significantly dependent upon the value of the shunting resistance R_{sh} that, in turn, depends on the network place where the switching device is arranged. If the shunting resistance is sufficiently great (100 kOhms and above) or is not available, the voltage recovery process will have clearly defined slightly damping oscillating behavior as shown in Figure 2.3a.

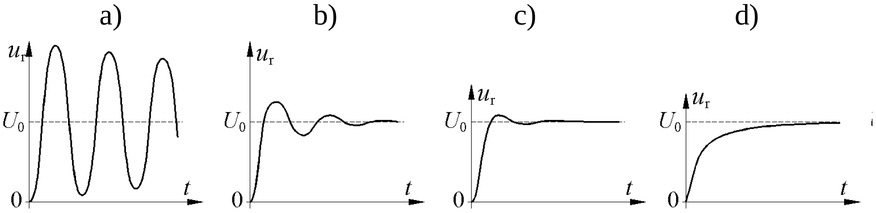

Figure 2.3 – Transient recovery voltage at different values of shunting resistance

If the shunting resistance value is in the range of a few ones to several tens kilo-ohms, the oscillating behavior of TRV is still retained, however the oscillations damp much faster as shown in Figures 2.3b and 2.3c. When the shunting resistance is further reduced, the behavior of the TRV becomes aperiodic as shown in Figure 2.3d.

There following parameters characterizing TRV are:

a) the *fundamental frequency* (for oscillating behavior of TRV);

b) *peak factor of TRV*, i.e. the ratio between the TRV maximal value the and the instantaneous value of the PFRV;

c) the *rate of rise of TRV.*

In operational practice of electric equipment, there is frequently needed interruption of electric circuits containing a section of power transmission line. It is, as a rule, the cases of interrupting the faults occurring in a transmission line somewhat removed from the circuit breaker called *line fault*. In this case, the TRV behavior depends not only on the components arranged at the supply side, but also on the properties of the transmission line.

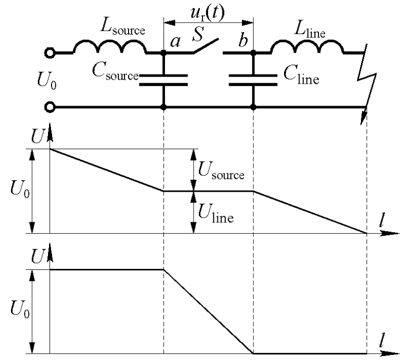

Figure 2.4 – Equivalent circuit to determine TRV with available transmission line

Simplest equivalent circuit to determine TRV for this case is represented in Figure 2.4, where L_{source}, C_{source} are the parameters of the circuit on the supply side; L_{line}, C_{line} are the parameters of the transmission line section. Under short-circuit conditions (when the ideal switch S is in closed position) the PFRV U_0 is distributed to two components, namely, supply side voltage U_{source} and line side voltage U_{line} as shown in Figure 2.4. After the circuit is interrupted (when the ideal switch S is in opened position), the potential of point A increases by the value U_{source} (from U_{line} to U_0), and the potential of point B decreases from U_{line} to zero.

The TRV from the supply side has usually of an aperiodic behavior. The TRV from the line side will be determined by the wave processes in the transmission line, that is, the running and reflection of the voltage wave with amplitude U_{line}. The line side TRV curve, taking into account the reflection of the wave from the fault location, will have the waveform of triangular (saw-tooth) oscillations with slight damping.

If the line section has a sufficiently large length (in the range of 50 to 100 km), then the reflected voltage wave comes after the completion of the recovery voltage process and practically does not affect the behavior of the TRV. When the line section has a small length (less than 1 km), the amplitude of the saw-tooth oscillations is very small and does not play a role in the recovery voltage process. When the line section has a length in the range from 2 to 5 km, the so-called *short-line fault* takes place. In this case, the switching device (circuit breaker) clearing the fault operates in especially heavy duty, because a sufficiently large current being interrupted combines with a high rate of rise of TRV. In this situation, the probability of thermal re-ignition after current-zero moment is sharply increased that is the failure of the switching device.

When the fault is located at a short distance, saw-tooth oscillations of the TRV have high frequency at its small amplitude. In this case, the dielectric recovery curve lies higher than the TRV curve, which results in a successful clearing the fault that is shown in Figure 2.5a.

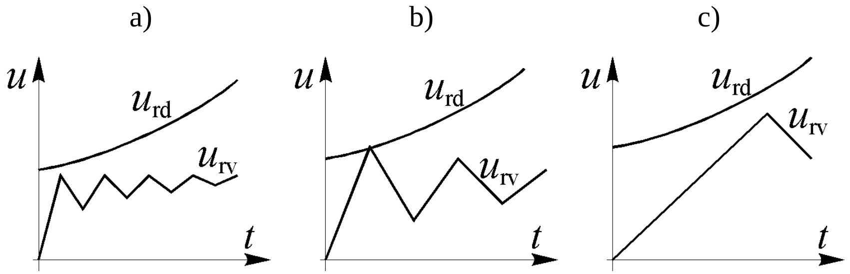

Figure 2.5 – Behavior of TRV and dielectric recovery at
(a) small, (б) middle and (c) great distance of the fault location

Under a certain increasing the fault location distance, the frequency of saw-tooth oscillations of the TRV, and hence its rate of rise somewhat decreases, but its amplitude (and hence first peak) increases. In this case, when the dielectric recovery strength has not yet sufficiently increased, a thermal re-ignition can occur that violates the design operation of the switching device, i.e. the unsuccessful clearing the fault take place, that is shown in Figure 2.5b. Further increasing the fault location distance leads to an even greater reduction of the fault current and, correspondingly, to increase in the dielectric strength of the contact gap. At the same time, the frequency and rate of rise the saw-tooth TRV decreases, so its first peak reaches a maximum at the instant, when the dielectric recovery strength has already increased sufficiently that is shown in Figure 2.5c.

2.3. Description of the laboratory plant

All elements of the laboratory plant are located inside the laboratory stand. Figure 2.6 shows a simplified test circuit imaged on the outer side of the laboratory panel where the oscilloscope nodes (points A and B), as well as the control equipment for the test are arranged. The electrical circuit diagram of the laboratory plant is shown in Figure 2.7.

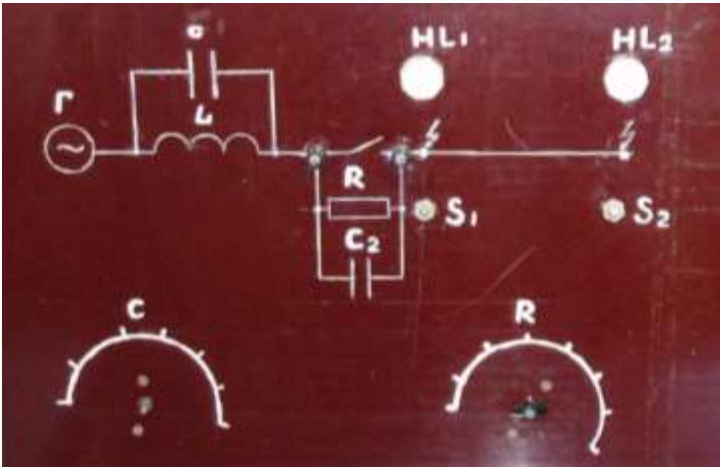

Figure 2.6 – Appearance of the outer side of the laboratory plant

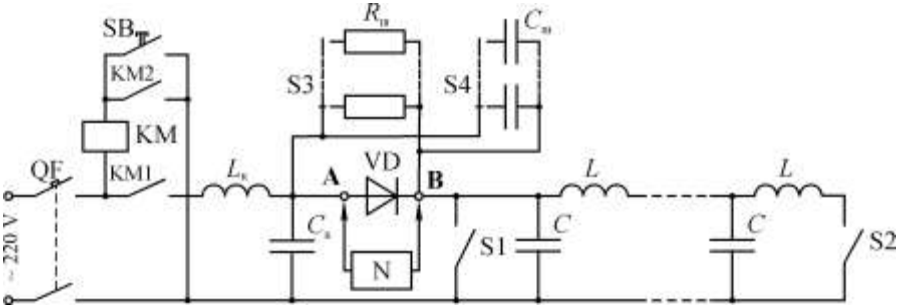

Figure 2.7 – Circuit diagram of the laboratory plant

Automatic circuit breaker energizes the laboratory plant. The circuit to be investigated is closed with magnetic starter KM by means of pressing the push-button SB. $L_{\text{к}}$ and $C_{\text{к}}$ are the parameters of the supply side of the faulty circuit. The fault current interrupting process is simulated with the help of the diode VD. At the end of each half-cycle, when the current reaches its zero value, the diode locks and the reverse voltage (supply voltage G) restores across it. Consequently, a conventional electronic oscilloscope displays a stable time diagram of TRV. The transmission line is simulated using inductive-capacitive LC-elements (in this case, L-elements). Toggle switches S1 and S2 are used to form one or another type of fault. When studying the terminal fault, the toggle switch S1 must be in closed position. In studying the short-line fault, the switch S1 must be opened, and the switch S2 –closed. The switch S3 is intended to change the resistance of the shunt resistor R_{sh}. Switch S4 changes the capacitance of the shunt capacitor C_{sh}.

2.4. Task.

2.4.1 Get to know the laboratory plant and the principle of its operation.

2.4.2 Experimentally determine the behavior of the TRV $u_r(t)$ under the terminal fault and its parameters:

- maximum value of the TRV;
- average rate of rise of the TRV at various values of the resistance of the shunting resistor R_{sh} and the shunting capacitance C_{sh}; determine the resistance of R_{sh} at which the TRV behavior alters from the oscillating to aperiodic;

2.4.3 Experimentally determine the behavior of the TRV $u_r(t)$ under the short-line fault and its parameters at invariable values of the resistance and capacitance. The teacher predetermines its values.

2.4.4 Calculate the parameters of the TRV for both fault types under the conditions specified in items 2.4.2 and 2.4.3 and compare them with experimental values.

2.5. Methodical instructions

2.5.1 All measurements in this laboratory work are carried out using an oscilloscope that primarily should be adjusted so that the amplitude and sweep scales correspond to those indicated on the front panel. This is done using a calibrated voltage that is applied to the oscilloscope's working input. Set the scale of the oscilloscope according to its parameters.

2.5.2 To execute item 2.4.2 of the task, toggle switch S3 is to be adjusted in closed position, and S4 in opened position. Connect the oscilloscope input to the terminals A and B. Achieve a stable time diagram of the TRV and copy it at different magnitudes of $R_{Ш}$ and $C_{Ш}$. Taking into account the amplitude and sweep scales, determine the parameters of the TRV according to the task.

2.5.3 To execute item 2.4.3 of the task, toggle switch S3 is to be adjusted in opened position, and S4 in closed position. Achieve a stable time diagram of the recovery voltage taking into account the triangular shape of the voltage from the transmission line and with the help of a tracing tape to remove the curve of the voltage renewal process. Taking into account the scale of the oscilloscope, determine the parameters of the recovery voltage according to the task.

2.5.4 Using handbooks, as well as lecture materials, calculate the parameters of the recovery voltage in accordance with the task.

2.5.5 The report to the laboratory work should contain:

- name and purpose of the work;
- time diagrams of the recovery voltage under the terminal and short-line faults;
- parameters of the TRV found experimentally and by the way of calculations;
- conclusions on work.

2.6 Self-examining questions.

2.6.1 What is a recovery voltage?

2.6.2 What is power frequency recovery voltage and what does it depend on?

2.6.3 What is the reason for the appearance of the recovery voltage?

2.6.4 What are the main parameters of the transient recovery voltage?

2.6.5 What factors influence the nature and parameters of the transient recovery voltage?

2.6.6 Give the definition of an actual and system transient recovery voltage.

2.6.7 What are the features of the transient recovery voltage under the line fault?

2.6.8 What is short-line fault and why is it the heaviest duty for clearing a fault?

3. LABORATORY WORK №7.

STUDY OF OVERVOLTAGE IN INTERRUPTING SMALL INDUCTIVE CURRENTS

The duration of the laboratory study is 4 hours.

3.1 Purpose of the work.

The purpose of the laboratory work is to study the distinctive features of small inductive currents interruption, as well as to observe the phenomena of current chopping, overvoltage and to determine its parameters.

3.2 Subject of the study.

If the high-voltage circuit-breaker interrupts relatively high current (e.g., clears the fault), extinction of the electric arc occurs at the instant when the current reaches its natural zero value and electromagnetic energy stored by the circuit being interrupted is zero. In such cases, the amplitude of the TRV, as a rule, does not exceed the double magnitude of the PFRV.

When the circuit-breaker, having high breaking capacity, interrupts small inductive current (e.g., no-load current of a power transformer that usually in the range of 50 to 100 A), it frequently sharply decreases down to zero before its natural zero. This phenomenon is usually named *current chopping*. It can occur at any moment, including the current peak. At the current chopping moment the inductive circuit has a significant store of electromagnetic energy, which, in the interrupting process, must completely dissipate in its capacitive elements. Therefore, the interruption of small inductive currents is often occurred with significant overvoltage.

The phenomenon of the current chopping has not yet been adequately studied. Nevertheless, to date it has been reliably established that it results from the power frequency sine current is imposed by high frequency component resulted from the circuit capacitive elements located on both sides of the switching device and the inductance connecting them. As the investigations show, the high-frequency current peaks can reach values that significantly exceed the instantaneous values of the power frequency currents. Thus, when the currents are in opposite directions, the current zeros and arc extinction before the power frequency current-zero are possible. It is suggested that the high frequency arc current component is caused by the sharp change in the arc voltage under active deionization of the arc space, which is especially evident at low currents and, accordingly, the arc small diameter.

If the switching device properties are neglected and the worst case that the current chopping occurred at the maximum current is assumed, then the maximum possible value of the TRV can be determined from the law of conservation of energy:

$$\eta^2 L \frac{i_{\mathrm{ch}}^2}{2} = C \frac{u_{\mathrm{r\,max}}^2}{2} \tag{3.1}$$

where i_{ch} is the current chopping value; under the assumption accepted that the current chopping occurred at the current peak this value is equal to the amplitude value of the transformer idle current being interrupted $\sqrt{2}\, I_{\mathrm{o}}$;

L is the inductance of the unloaded transformer;

C is the transformer phase capacitance;

η is the coefficient taking into account copper and iron losses of the transformer (it is usually in the range of 0.3 to 0.45).

Thus, maximal possible peak of the TRV will be expressed as follows:

$$u_{\mathrm{r\,max}} = \eta \cdot I_{\mathrm{o}} \sqrt{\frac{L}{C}} \, . \tag{3.2}$$

The amplitude value of the transformer no-load current is evaluated according to the following expression:

$$I_{\mathrm{om}} = \frac{U_{\mathrm{m}}}{2\pi f L} \, . \tag{3.3}$$

Substituting this expression into (3.2) we obtain:

$$u_{\mathrm{r\,max}} = \eta \frac{U_{\mathrm{m}}}{2\pi f \sqrt{LC}} \, , \tag{3.4}$$

where $\frac{1}{2\pi\sqrt{LC}}$ is the expression that determines the fundamental frequency of the unloaded transformer f_0.

Hence, the expression determining maximal possible overvoltage ratio will be as follows:

$$\kappa_{\mathrm{most}} = \frac{u_{\mathrm{r\,max}}}{U_{\mathrm{m}}} = \eta \cdot \frac{f_0}{f} \tag{3.5}$$

In other words, the maximum possible overvoltage multiplicity of the unloaded transformer to be interrupted will be determined by the ratio of its fundamental frequency in relation to the power frequency, as well as the copper and iron relative losses of the transformer.

Losses in the transformer significantly reduce overvoltage when the no-load current is interrupted, but they are sufficiently large and represent a serious danger for the electrical equipment isolation. The main methods to limit overvoltage are the use of valve arresters, oxide-zinc varistors, as well as the shunting of switching devices by resistors.

If an active resistance shunts the switching device contacts, then the TRV (having the oscillating behavior) after the chopping at the current peak will be determined by the following expression [6]:

$$u_{\mathrm{r}} = e^{-at} i_{\mathrm{ch}} \sqrt{L/C} \sin \omega_0 t \, . \tag{3.6}$$

Consequently, the overvoltage multiplicity in this case, taking into account formula (3.3), will be determined by the following expression:

$$\kappa = \frac{f_0}{f} e^{-a/(4 f_0)}, \tag{3.7}$$

where a is the damping factor of the TRV curve expressed as follows:

$$a = \frac{1}{2R_{\text{sh}}C} \tag{3.8}$$

Thus, the magnitude of the shunt resistance can be evaluated from the permissible overvoltage multiplicity κ_{perm}:

$$R_{\text{sh}} = \frac{1}{8Cf_0 \ln \frac{f_0}{\kappa_{\text{perm}} f}} \tag{3.9}$$

It should be noted that equation (3.6) and, therefore, formula (3.9) do not take into account iron and copper losses in the transformer.

3.3. Description of the laboratory plant.

The laboratory plant consists of a front panel and circuit elements for the study. Figure 3.1 shows the photo of the front panel where the power circuit is shown, as well as the buttons S1 (On) and S2 (Off), switch S3 to control the study, and jacks for oscilloscope are mounted.

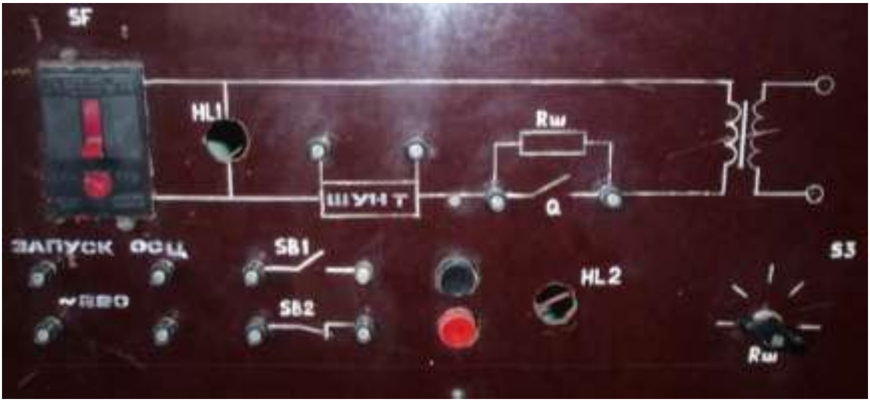

Figure 3.1 – Appearance of the facing side of the laboratory plant panel

The circuit diagram of the laboratory plant is shown in Figure 3.2. It includes a power unit, a control circuit and a measuring part. The power unit consists of 220 V supply voltage applied to the circuit by a circuit breaker QF, a transformer T, a shunt to measure the current time diagram and switching device Q, which interrupts a small inductive current (in this case, the vacuum contactor КВМ-10-5/400 is used). The control circuit includes the contactor electromagnetic actuator YA with buttons SB1 (On) and SB2 (Off), the switch S3 to change the resistance of the shunt resistor R_{sh}. The measuring part contains a measuring shunt and a memorizing oscilloscope N.

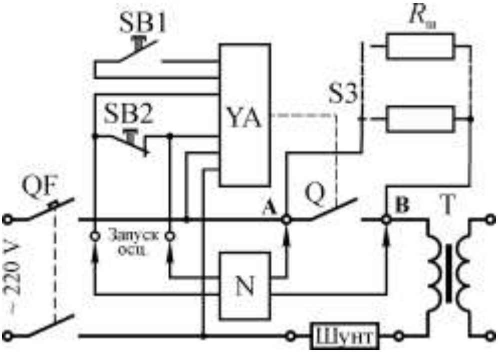

Figure 3.2 – Electric circuit diagram of the laboratory plant

The circuit is interrupted by de-energizing the actuator YA of the contactor Q. Simultaneously with this, the voltage is applied to the synchronizing input of the oscilloscope that is started and saves on its display the resulting time diagrams of the current chopping and recovery voltage.

3.4. Task.

3.4.1 Get acquainted with the laboratory stand and methods of measurements with the help of a memorizing oscilloscope.

3.4.2 In the absence of shunting resistance, experimentally determine the frequency of the TRV and the dependency the overvoltage value vs the switching phase.

3.4.3 Experimentally determine the dependency the overvoltage vs shunting resistance value.

3.4.4 Calculate the dependency the overvoltage vs the shunting resistance value and compare it with that found experimentally.

3.4.5 Measure the time diagrams of the current under interrupting inductive circuit at different phases of the current chopping.

3.5. Methodical instructions.

3.5.1 Energize the oscilloscope and let it warm up for 10 minutes.

3.5.2 Get acquainted with the operating principle of a memorizing oscilloscope and measuring technologies for the one-time processes.

3.5.3 Adjust the oscilloscope’s switch "Режим работы" in position "Автомат".

3.5.4 Adjust the time and voltage sweep scales of the oscilloscope with the help of the source of calibration rectangular voltage.

3.5.5 Connect the oscilloscope input to the investigated points (jacks) of the circuit, and the synchronizing input to jacks "Запуск осцилографа" arranged on the face panel of the plant. Adjust the oscilloscope’s switch "Режим работы" in position "Ждущий".

3.5.6 Close the circuit-breaker QF.

3.5.7 Close the contactor Q by pressing the button SB1 (On).

3.5.8 Bring the oscilloscope to the ready state by pressing the button "Готов". This operation should result in the ignition of the neon light bulb.

3.5.9 Open the contactor O by pressing the button SB2 (Off).

3.5.10 Copy measured time diagram. The overvoltage magnitude is found from its first peak.

3.5.11 In performing item 3.4.2, measure as many time diagrams (at least 15–20) in order to find the maximal range of the current chopping moment in relation to the sine current waveform. All measurement findings should be shown in the experimental dependency.

3.5.12 In performing item 3.4.3, each point should be found as an arithmetic mean of three to four measurements.

3.5.13 Calculated dependencies should be shown in the same graphical diagram as the experimental one.

3.5.14 Laboratory work report should contain:

a) the name of the subject and purpose of the work;

b) the circuit diagram of the laboratory plant;

c) the TRV time diagrams measured at different phases of the current chopping and the values of shunting resistance;

d) the current time diagrams at different phases of the chopping;

e) experimental and calculated dependencies according to the task;

e) conclusions on the work, where it should be explained the behavior of the measured time diagrams and experimental dependencies.

3.6 Self-examining questions.

3.6.1 Why the interruption of unloaded transformers (small inductive currents) is a heavy duty of electric circuit switching?

3.6.2 What is a current chopping?

3.6.3 What explains the phenomenon of current chopping when a small inductive current is interrupted?

3.6.4 How the overvoltage is determined in the case of interrupting small inductive currents?

3.6.5 What the main technologies exist to limit overvoltage under interrupting small inductive currents?

Reference List

1. Таев И.С. Электрические аппараты: Общая теория / И.С. Таев. – М.: Энергия, 1977. – 272 с.

2. Основы теории электрических аппаратов: Учеб. для вузов/ [И.С. Таев, Б.К. Буль, А.Г. Годжелло и др.]; под ред. И.С. Таева. – М.: Высшая школа, 1987. – 352 с.

3. Теория электрических аппаратов/ [Г.Н Александров, В.В. Борисов, Г.С. Каплан и др.]; под ред. Г.Н. Александрова. – [2–е изд., перераб и доп.] – СПб.: Изд-во СПбГТУ, 2000. – 540 с.

4. Справочник по электрическим аппаратам высокого напряжения / [Н.М. Адоньев, В.В Афанасьев, И.М. Бортник и др.]; под ред. В.В. Афанасьева. – Л.: Энергоатомиздат, 1987. – 544 с.

5. Белкин Г. С. Коммутационные процессы в электрических аппаратах/ Г. С. Белкин. – М. : Знак, 2003. – 244 с.

6. Буткевич Г.В. Дуговые процессы при коммутации электрических цепей / Г.В. Буткевич. – М.: Высшая школа, 1967. – 195 с.

7. Самервилл Дж. М. Электрическая дуга/ Самервилл Дж. М. Пер. с англ. – М.-Л. Госэнергоиздат, 1962. – 120 с.

8. Брон О.Б. Электрическая дуга в аппаратах управления / О.Б. Брон. – М.: Госэнергоиздат, 1954. – 532 с.

9. Акодис М.М. Определение восстанавливающегося напряжения на контактах выключателя / М.М. Акодис, П.А. Корзун. – М.: Энергия, 1968. – 192 с.

10. Тиховод С. М. Метод ускоренного численного расчета переходных процессов в электрических цепях на основе аппроксимации решения алгебраическими полиномами / С. М. Тиховод, Т. М. Корнус, Д. Г. Паталах // Електротехніка та електроенергетика. – 2015. – № 2. – С. 48–54.

11. Яримбаш Д. С. Особливості розподілення магнітних потоків у режимі неробочого ходу силових трансформаторів / Д. С. Яримбаш, С. Т. Яримбаш, Т. Є. Дівчук, І. М. Килимник // Електротехніка та електроенергетика. – 2016. – № 2. С. 5–12.

12. Дивчук Т. Е. Подход к определению токов холостого хода силовых трехфазных трансформаторов с плоскими стержневыми магнитными системами / Т. Е. Дивчук, Д. С. Ярымбаш, С. Т. Ярымбаш, И. М. Килимник, М. И. Коцур, Ю. С. Безверхняя // Електротехніка та електроенергетика. – 2017. – № 2. – С. 56–66.

13. Circuit interruption: Theory and Techniques/ Edited by Jr. Thomas E. Browne, Taylor & Francis, New York, 1984. – 701 p.

14. Switching Phenomena in High-Voltage Circuit Breakers/ Edited by Kunio Nakanishi, Marcel Dekker, New York, 1991. – 292 p.

15. Van der Sluis L. Transients in power systems/ by Lou van der Sluis, John Wiley & Sons Ltd, New York, 2001. – 217 p.