Investigation of Reliability of Emergency Shutdown of Consumers in Electric Power Systems of Explosive Hazardous Zones

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Abstract—The dependence of reliability of emergency shutdown of consumers in electric power systems of explosive hazardous zones on such parameters of electric network as nominal currents of electromagnetic declutch of circuit breaker and fusible fuse insert, approximate calculated impedance of transformer, material, cross - section and length of cable. The obtained results will prevent the appearance of ignition sources of electrical origin during the operation of consumers in electric power systems of explosive hazardous zones

Keywords—power system, emergency mode, short circuit, explosive hazardous zone, circuit breaker, fuse, current multiplicity

I. INTRODUCTION

The data of world fire statistics, published annually by the Center for Fire Statistics of the International Association of Fire and Rescue Services (CTIF) [1], give reason to believe that quite often fires occur due to violations of fire safety rules during installation and operation of electrical installations. In particular, in Ukraine, according to [2], this cause is the second most common (up to 20% annually of their total number). Up to 60% of fires due to violation of fire safety rules during the installation and operation of electrical installations leads to a short circuit (SC) of the electrical network.

Consumers of electric power systems located in explosive hazardous zones (EHZ) are especially dangerous. In this case, the main components of the fire are usually located nearby – the source of ignition and combustible substance [3, 4]. Each fire causes a number of hazardous factors, such as heat, hazardous combustion products and the blast wave [5]. The consequences of fires in EHZ are extremely resonant compared to normal conditions. Hazard assessment of facilities is an integral part of the industrial safety system. Mistakes in this area can cause harm to the environment, increase complexity [6]. Such events can lead to large-scale emissions of hazardous chemicals [7]. Fires can trigger acid rain [8] and pollute aquifers [9]. The largest fire during the independence of Ukraine, which led to significant human and material losses, was a fire on June 8, 2015 on one of the fuel tanks in the oil depot of the group of companies "BRSM-Nafta" in the Kryachky village, Vasylkiv district, Kyiv region, killed five people, including three rescuers, and 16 were injured. The fire lasted for two weeks. The cause of the fire was a lack of construction and production of electrical installations, resulting in a SC in a mobile pumping unit located in the EHZ. The consequences of such fires are increasingly forcing us to focus on the development and improvement of fire extinguishing technologies [10, 11]. However, the most effective way to increase fire safety is to prevent fires and fires.

To ensure the safe operation of electrical equipment of power systems in EHZ, a number of enhanced engineering and technical measures are used [12]. In order to prevent the explosion of an external explosive environment, the shells of electrical equipment are made with explosion protection, which must correspond to the class of the EHZ. In order to prevent the spread of fire and to prevent external damage, cable productions (CP) are selected of special brands also depending on the class of the EHZ. In most EHZ, the use of CP with aluminum elements in the structure is prohibited. In order to ensure electrical strength, the cross-section of the cores of CP is chosen to be increased by 25% compared to the calculated values. Emergency shutdown of electrical consumers in the EHZ is arranged with special requirements compared to normal operating conditions.

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Therefore, in particular, the problem of ensuring the reliability of emergency shutdown of consumers of power systems located in EHZ is relevant.

II. ANALYSIS OF DANGER OF CONSUMER WORK IN ELECTRIC POWER SYSTEMS OF EXPLOSION HAZARDOUS ZONES

By power system we mean the electrical part of the power system and the receivers of electricity supplied from it, united by a common process of production, transmission, distribution and consumption of electricity. Electricity consumer – a receiver or group of receivers of electricity, combined with the technological process, which are located in a certain area [13]. Consumers of electric power systems located in EHZ are especially dangerous. The authors consider an experimental study of the fire process for different rooms and materials [14].

EHZ – hazardous area classification based on the frequency of the occurrence and duration of the explosive atmosphere. Hazardous area – area in which an explosive gas atmosphere (EGA) is present or can be expected to be present, in quantities such that special precautions for the construction, installation and use of equipment are required [12, 15, 16]. EGA can form EHZ of three classes: zone 0 (area in which an EGA is present continuously, or for long periods, or frequently), zone 1 (area in which an EGA is likely to occur occasionally in normal operation), zone 2 (area in which an EGA is not likely to occur in normal operation, but, if it does occur, will exist for a short period only) [12, 15]. Explosive dust atmospheres (EDA) similarly form EHZ of three classes: zone 20 (a place in which an EDA, in the form of a cloud of dust in air, is present continuously, or for long periods or frequently), zone 21 (a place in which an EDA, in the form of a cloud of dust in air, is likely to occur in normal operation occasionally), zone 22 (area in which an EDA, in the form of a cloud of combustible dust in air, is not likely to occur in normal operation but, if it does occur, will persist for a short period only) [12, 16]. It should be noted the difference between European and North American approaches to the establishment of classes and sizes of EHZ [17]. The gas environment of premises under conditions of danger is a complex system with a dissipative structure, non-linear dynamics, and self-organization [18].

A typical emergency mode of operation of the power system is the appearance of overcurrent – current, the value of which exceeds the largest operating (estimated) value of the electric circuit current. Most often, overcurrents are caused by SC – contact formed between several current-carrying parts, which is accompanied by a decrease in the potential difference between these parts to zero or a value close to zero [14, 19]. The study and modeling of the conditions of occurrence and development of SC in power systems is devoted, in particular, work [20-22]. If the time of action of the overcurrent in the electric network of the electric power system is not limited, the temperature of the current-carrying cores of the conductors increases and an ignition source of electric origin appears [23]. Automatic fire protection systems can be used for early detection of temperature rise [24], the most common sensitive elements of which are temperature control sensors [25]. Different methods of statistical data processing are used for early forecasting of emergency situations in electric power systems [26].

The appearance of an ignition source in EHZ instantly leads to an explosion [25].

Any electrical network in its entirety or its emergency part must be switched off within a certain period of time if it may pose a threat to property or the health of people and domestic animals. To protect the electrical network from overcurrents are used protection devices: circuit breakers, fuses, combinations of switching devices with thermal relays and fuses, specialized electronic devices.

III. INVESTIGATION OF RELIABILITY OF EMERGENCY DISCONNECTION OF CONSUMERS IN ELECTRIC POWER SYSTEMS OF EXPLOSION ZONES

A. Conditions for ensuring reliability

To ensure the reliability of disconnection of consumers in the power systems of EHZ from power sources in the event of a SC is normalized multiplicity (ratio) of SC currents to rated currents of sensitive elements of protection devices [12, 27]. Reliable disconnection of the damaged part of the network is provided if the ratio of the lowest rated SC current to the rated current $I_{\text{r.c.-net}}$ of the solenoid circuit breaker or the rated fuse current $I_{\text{r.c.-fuse}}$ of the fuse is not less than the following value:

- for circuit breakers with electromagnetic release:

$$\frac{I_{\text{SC}}}{I_{\text{r.c.-net.}}} \geq 1{,}25\,(1{,}4)\,, \tag{1}$$

where I_{SC} – SC current;

coefficient 1,25 – for circuit breakers for rated currents above 100 A;

coefficient 1,4 – for circuit breakers for rated currents up to 100 A;

– for fuses:

$$\frac{I_{\text{SC}}}{I_{\text{r.c.-fuse}}} \geq 4\,. \tag{2}$$

B. Derivation of mathematical relations

We believe that the electrical network of the power system located in the EHZ will be reliably disconnected in the event of an emergency mode in the form of a SC under conditions (1) and (2). Accordingly, if conditions (1) and (2) are not met, the electrical network will not be disconnected in the event of an emergency mode in the form of a SC.

We assume that the EHZ electrical network is made with the type of grounding TN-S [12, 19]. Consider the case of a single-phase SC. The calculation of SC current I_{SC} is performed according to Ohm's law:

$$I_{SC}=\frac{U_L}{Z_{SC}}, \tag{3}$$

where U_L – phase voltage in the network, B;

Z_{SC} – impedance of series-connected circuit elements of single-phase SC, Ohm.

To establish the value Z_{SC}, we use the simplest calculation scheme of a single-phase SC (Fig. 1).

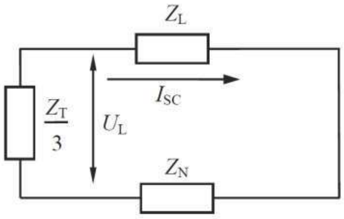

Fig. 1. Calculation scheme of a single-phase short circuit

Formula (3) will take the form:

$$\dot{I}_{SC}=\frac{U_L}{\dot{Z}_{SC}}=\frac{U_L}{\frac{Z_T}{3}+\dot{Z}_L+\dot{Z}_N}, \tag{4}$$

where Z_T – approximate calculated impedance of a three-phase transformer of the power system, Ohm, Z_T depends on the power of the transformer and the connection scheme of its windings;

$\dot{Z}_L = R_L + j \cdot X_L$ – impedance of a linear conductor, Ohm;

$\dot{Z}_N = R_N + j \cdot X_N$ – impedance of the neutral conductor, Ohm;

R_L – active resistance of a linear conductor, Ohm;

X_L – inductive resistance of a linear conductor, Ohm;

R_N – active resistance of the neutral conductor, Ohm;

X_N – inductive resistance of the neutral conductor, Ohm.

After the transformation we get:

$$Z_{SC}=Z+\frac{Z_T}{3}, \tag{5}$$

where

$$Z=\sqrt{R^2+X^2}, \tag{6}$$

– impedance of SC conductors connected to the transformer winding;

$$R=\sum R_L+\sum R_N+\sum R_{\text{K}}, \tag{7}$$

$$X=\sum X_L+\sum X_N, \tag{8}$$

$R_L=\rho_L\cdot\frac{\ell}{S_L}$; $X_L=a_L\cdot\ell$ – active and inductive resistance of the linear conductor, respectively, Ohm;

$R_N=\rho_N\cdot\frac{\ell}{S_N}$; $X_N=a_N\cdot\ell$ – active and inductive resistance of the neutral conductor, respectively, Ohm;

S_L and S_N – the cross section of the cores of linear and neutral conductors, respectively, mm^2;

ρ – resistance of the conductor material, Ohm·mm^2/km;

ℓ – the length of the section with the same cross-section of the cores and the same brand of conductor, km;

a_L, a_N – the average value of the inductive resistance of the conductor, Ohm·km;

R_{K} – transient resistance of contact connections, Ohm.

C. Analysis of the obtained relations

The fulfillment of conditions (1) and (2) is influenced by the following parameters: rated current $I_{\text{r.c.-net}}$ electromagnetic circuit breaker, rated current $I_{\text{r.c.-fuse}}$ fuse insert, approximate calculated impedance Z_T three-phase transformer, material, cross section and length of conductors of CP electrical network.

The value of $I_{\text{r.c.-net}}$ and $I_{\text{r.c.-fuse}}$ are standard values. Their recommended values are multiples of 10: 0.6; 0.8; 1; 1.25; 1.6; 2; 2.5; 3.2; 4; 5; 6.3; 8; 10 [28, 29]. For the standard value U_L = 220 V [30] the impedance of the series-connected elements of the SC Z_{SC} for circuit breakers with release $I_{\text{r.c.-net.}} \le 100$ A must not exceed the following values: $I_{\text{r.c.-net.}} = 6$ A – $Z_{SC} \le 26{,}190$ Ohm, 8 A – 19,643 Ohm, 10 A – 15,714 Ohm, 12,5 A – 12,571 Ohm, 16 A – 9,821 Ohm, 20 A – 7,827 Ohm, 25 A – 6,286 Ohm, 32 A – 4,911 Ohm, 40 A – 3,929 Ohm, 50 A – 3,143 Ohm, 63 A – 2,194 Ohm, 80 A – 1,964 Ohm, 100 A – 1,571 Ohm in accordance. For fusible inserts with $I_{\text{r.c.-fuse}} \le 100$ A fuses, the impedance of the series-connected circuit elements of the SC Z_{SC} should not exceed the following values: $I_{\text{r.c.-fuse}} = 6$ A – $Z_{SC} \le 9{,}167$ Ohm, 8 A – 6,875 Ohm, 10 A – 5,500 Ohm, 12,5 A – 4,400 Ohm, 16 A – 3,438 Ohm, 20 A – 2,750 Ohm, 25 A – 2,200 Ohm, 32 A – 1,719 Ohm, 40 A – 1,375 Ohm, 50 A – 1,100 Ohm, 63 A – 0,873 Ohm, 80 A – 0,688 Ohm, 100 A – 0,550 Ohm in accordance.

The first component of the impedance Z_{SC} of the series-connected circuit elements of a single-phase SC is the approximate calculated impedance Z_T of a three-phase oil SC current transformer. Z_T values are fixed in the range from 0,020 to 3,110 Ohm [31]. The approximate calculated impedance Z_T has a significant effect on the value of the impedance Z_{SC} series-connected circuit elements of a single-phase SC, if their values are comparable. This is the case if a circuit breaker with an electromagnetic release from 40 A to 100 A is used for SC protection and if a fuse with fusible inserts from 10 A to 100 A is used for SC protection. For example, if a circuit breaker is used with $I_{\text{r.c.-net.}} = 6\ \text{A}$, then the value is the maximum allowable $Z_{\text{SC}} = 26{,}190\ \text{Ohm}$. The maximum value of the estimated impedance Z_T=3,110Ohm. Then $\frac{Z_T}{3} = \frac{3{,}110}{3} \approx 1{,}037\ \text{Ohm}$ and therefore this impedance will not have a significant effect on the final value Z_{SC}. If a circuit breaker is used with $I_{\text{r.c.-net.}} = 100\ \text{A}$, then the maximum allowable value is already $Z_{\text{SC}} = 1{,}572\ \text{Ohm}$. The maximum possible value $\frac{Z_T}{3} = \frac{3{,}110}{3} \approx 1{,}037\ \text{Ohm}$ will affect the final value Z_{SC}.

The second component of Z_{SC} is the impedance Z of the conductors of the SC connected to the transformer winding, which is determined by the active and inductive resistances of the linear and neutral conductors of the selected CP and the number and quality of contact connections. Active resistance depends on the material, cross section and length of the conductor, inductive resistance – on the length of the conductor and the type of CP (cable or wire).

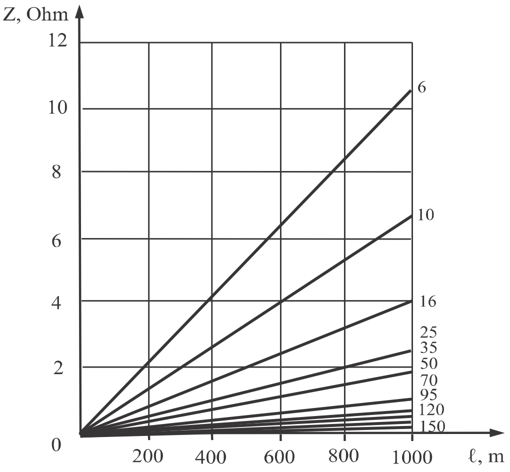

Fig. 2. Dependences of the impedance Z of two cores of a segment of a cable with aluminum cores of various sections on cable length ℓ

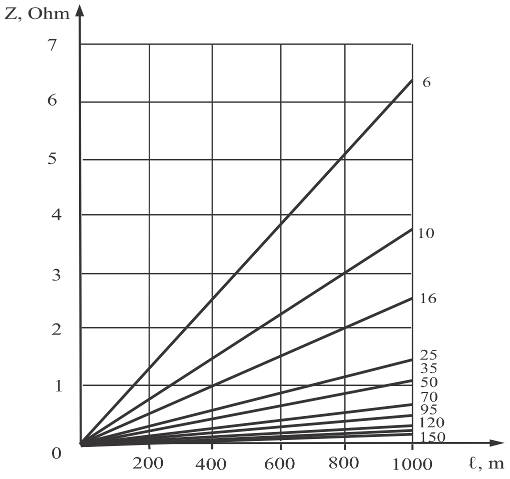

Fig. 3. Dependences of the impedance Z of two cores of a cable segment with copper cores of different cross sections on the cable length ℓ

In the general case, the SC current flows through the mains, distribution network and group network. Aluminum conductors are prohibited for use in zone 0, 1, 2, 20, 21 [12, 27]. Therefore, distribution and group networks are made of CP copper cores. The use of CP with both aluminum and copper cores is allowed in the power supply network. Fig. 2 shows the dependence of the impedance *Z* of the segment of the cable with aluminum cores of standard cross-sections on its length, and Fig. 3 – for the cable with copper cores, respectively (cross-section of the cores taken from tables [32]).

IV. DISCUSSIONS

Studies have shown that the reliability of disconnection of consumers in the power systems of EHZ from power sources in the event of a SC is influenced by the following parameters: rated current of the solenoid circuit breaker $I_{\text{r.c.-net}}$, rated current of the fuse insert $I_{\text{r.c.-fuse}}$, approximate calculated impedance Z_T of a three-phase transformer, material, cross-section and length of conductors of CP of the electrical network.

Analysis of formulas (1) - (2) shows that the lower the rated current $I_{\text{r.c.-net}}$ of the electromagnetic release of the circuit breaker or the rated current $I_{\text{r.c.-fuse}}$ of the fuse insert, the greater the allowable value of the impedance Z_{SC} series-connected circuit elements single-phase SC. When choosing a circuit breaker as a SC protection device, the value of the impedance of the Z_{SC} series-connected circuit elements of a single-phase SC is assumed to be much higher in comparison with the use of a fuse.

From formulas (1) - (5) it follows that for fuses the approximate rated impedance of a three-phase oil transformer Z_T affects the value of the impedance of the SC between the linear and neutral conductors Z_{SC} starting with a fuse current of 10 A, and for circuit breakers with electromagnetic release – from the current of the release 40 A.

From formulas (1) - (8) and the dependences shown in Fig.2 and Fig.3 it is seen that the greatest contribution to the impedance Z of the conductors of the SC connected to the transformer winding is the resistance of the power supply made of aluminum conductors.

The disadvantage of this algorithm is that the criterion of reliability of disconnection of consumers in the power systems of EHZ from power sources in the event of a SC is the multiplicity (ratio) of SC currents to rated currents of sensitive elements of protection devices [16, 27]. It is advisable to consider the time of disconnection of SC currents as sensitive elements of protection devices, which should not exceed the safest time of the ignition source of electrical origin "thermal action of SC currents" [23].

V. CONCLUSIONS

The reliability of emergency shutdown of consumers in the power systems of EHZ is ensured if the multiplicity (ratio) of the lowest rated SC current to the rated current of the circuit breaker or fuse-link will be not less than a certain value.

Studies have shown that the lower the rated current of the solenoid circuit breaker or the rated current of the fuse link, the greater the assumed value of the impedance of the series-connected circuit elements of a single-phase SC. When choosing a circuit breaker protection device, the value of this impedance is assumed to be much higher compared to the use of a fuse. The approximate calculated impedance of the oil transformer significantly affects the value of the impedance of the single-phase SC starting from the current of the electromagnetic release 40 A or the current of the fusible insert 10 A. The impedance of the SC conductors connected to the transformer winding and the number and quality of contact connections. Active resistance depends on the material, cross section and length of the linear conductor, inductive resistance – on the length of the conductor and the type of selected CP. The greatest contribution to the impedance is made by the resistance of aluminum conductors of the power supply network.

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