Evaluation of Fault Tolerance of Power Supply Systems of Industrial Enterprises

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Keywords: Power supply of industrial enterprise, Failure rate, Failure probability, Fault tolerance, Power transformer, Circuit breaker, Magnetic starter, Contactor, Switch.

Abstract: Industrial facilities of Kazan, as it is known, have in their composition technological cycles of varying degrees of complexity and the corresponding electrical equipment of the shop-floor power supply systems, to the reliability of operation of which, the requirements in modern conditions are significantly increasing. At present, new approaches are required to assess the fault tolerance of the entire power supply system as a whole, as well as individual elements of electrical equipment. The scientific and practical significance of this study is to assess and analyze the main characteristics of fault tolerance of low-voltage electrical equipment of the power supply system of industrial enterprises.

1 INTRODUCTION

In modern developed countries, the main source of energy is electrical energy supplied by thermal, hydro and nuclear power plants.

At industrial enterprises, electrical energy is supplied to the working apparatuses by a highly reliable uninterrupted power supply system. The larger and more powerful the electrical consumers, the more complex the power supply system of the enterprise in its structure and topology.

Increasing the reliability of the power supply system is currently an urgent problem. Below is the analysis of some scientific works of scientists conducting research in this area.

In their work Byk F.L., Kakosha Yu. (Byk, Kakosha, Myshkina, 2020) developed a methodology for calculating the forecast values of power supply continuity indicators used in 0.4-10 kV distribution networks. This methodology allows to compare the efficiency of implementation of various measures taking into account the changes in the structural and functional reliability of the distribution network.

Scientists Zatsepina V.I., Astanin S.S. (Zatsepina, Astanin, 2021) considered the development of power supply systems and analyzed the methods of calculating the expected failure rate. According to the results of the analysis, the general aspects for the most effective methods were highlighted and used in the development of the expression for determining the frequency of power supply failures.

In the studies conducted by scientists Petrova R.M., Gracheva E.I. et al. (Petrova, Abdullazyanov, Grachieva, Valtchev, Yousef, 2021; Gracheva, Petrova, Valtchev, Sinyukova, 2023) determined the laws of change of probabilistic characteristics of reliability of the main low-voltage electrical equipment - power transformers, circuit breakers, magnetic starters and contactors on the basis of statistical data of operation. The conformity of the probabilistic characteristics of electrical equipment to the normal distribution law using the Kolmogorov and Pearson criteria has been checked.

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The work of Rodzin S.I. (Rodzin, 2005) is devoted to the creation of fundamentally new devices on a modern microelectronic base with a high degree of fault tolerance and ensuring an acceptable level of safety of their operation.

The authors Shpiganovich A.N., Astanin S.S., Rychkov A.V. (Shpiganovich, Astanin, Rychkov, 2021) evaluated the frequency of electrical equipment failures, as well as the frequency of the time of repair and preventive maintenance. The proposed method makes it possible to estimate the failure-free electrical energy of the system of technological machines of an industrial enterprise.

In their studies A. N. Shpiganovich, E. P. Zatsepin (Shpiganovich, Zatsepin, 2018) investigated the estimation of fault tolerance of power supply systems of industrial enterprises by using probabilistic methods, namely on the basis of the theory of random pulse flows.

A. Younesi, Z. Wang, H. T. Nguyen and P. Mandal in their work (Younesi, Wang, Nguyen, Mandal, 2022) investigated the improvement of fault tolerance of modern distribution systems in terms of portable power distribution.

The authors C. Shao, M. Shahidehpour, X. Wang, X. Wang and B. Wang (Shao, Shahidehpour, Wang, Wang, Wang, 2017) proposed a scheduling algorithm for a complex power transportation system to improve the fault tolerance. Numerical results indicate that the proposed integrated scheduling is an effective approach to improve the fault tolerance of power transportation system.

Researchers L. Yi et al. (Yi, 2023) proposed to develop a fault tolerance model of power distribution system based on probability theory with a certain algorithm.

At present, new approaches are required to assess the fault tolerance of the entire power supply system as a whole, as well as individual elements of electrical equipment. The scientific and practical significance of this study is to assess and analyze the main characteristics of fault tolerance of low-voltage electrical equipment of the power supply system of industrial enterprises. Object of the study: systems of in-plant power supply.

For the necessary level of reliability assessment of both electrical and technological equipment, important parameters are the time characteristics of the duration of failures elimination, as well as the analysis of failures in the percentage ratio.

Fig. 1 shows the types of protection and failure ratio, % for electric motors, cable lines, power transformers and 0.4 kV busbar section.

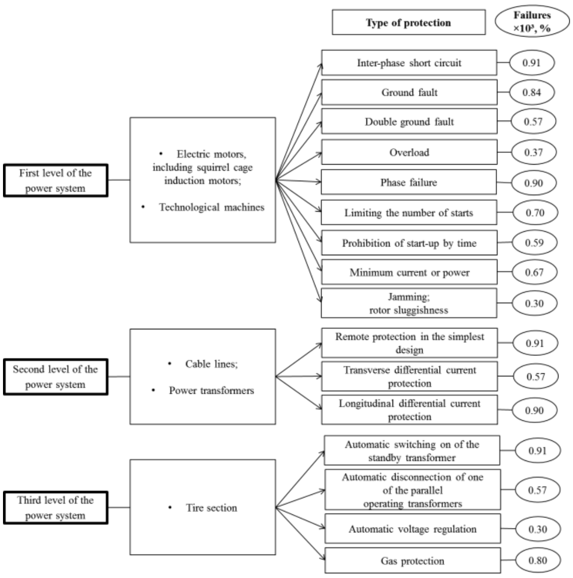

Figure 1: Percentage value of failures of electrical equipment protections.

The data in Fig. 1 are derived from the analysis of failure data of large manufacturing enterprises.

Figures 2-5 show the percentage of failures of single-phase and three-phase electric motors; circuit breakers, magnetic starters and contactors; switches and power transformers.

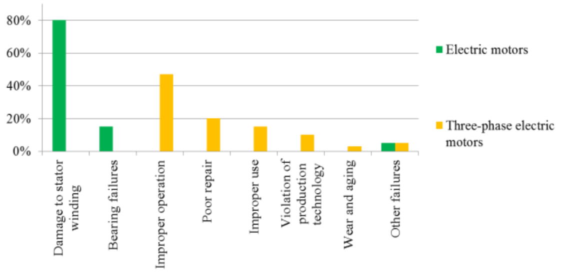

Figure 2: Percentage value of electric motor failures.

About 70-80% of the total number of failures for electric motors are caused by stator windings. Failures of motor bearings are equal to 15-20%, other failures – 4%.

The causes of failure of three-phase electric motors are: improper operation – 47%, poor quality repair – 20%, misuse – 15%, violation of production technology – 10%, wear and aging – 3%, other – 5%.

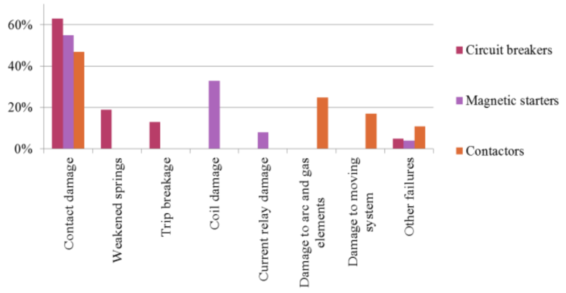

Figure 3: Failure percentages for circuit breakers, magnetic starters and contactors.

For circuit breakers, the main failures are contact damage – 63%, which includes burned and worn contacts (45%), damage to the mechanism of free release and contact adjustment (18%). The remaining failures are related to the weakening of springs – 19% and breakage of the release – 13%, other failures – 5%.

The majority of magnetic starters failures are related to damage of contacts (57%) and coil (33%). Damage to the thermal relay takes 8% of the total and 4% of failures are not detected. For contactors – damage of contacts (47%), arc suppression elements (25%) and moving system (17%). Other failures – 11%.

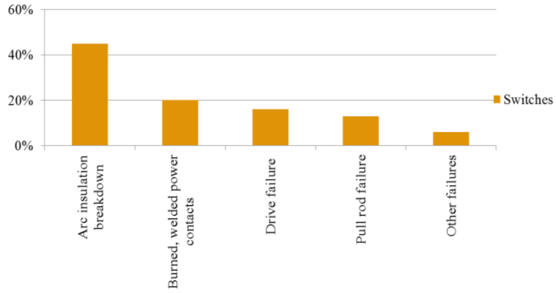

Figure 4: Percentage value of switches.

According to Fig. 4 shows that the largest number of failures is due to arc insulation breakdown – 45%. Other failures are related to burning and welding of power contacts – 20%, actuator failure – 16% and breakage of rods – 13%. Unidentified failures – 6%.

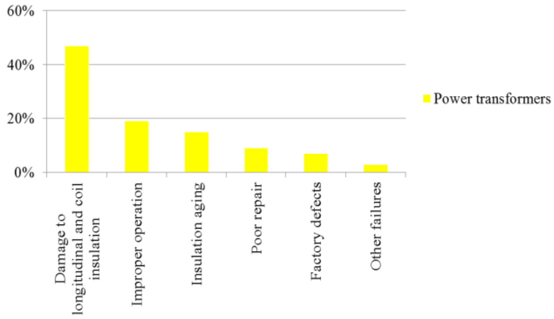

Figure 5: Percentage value of power transformer failures.

For power transformers (Fig. 5), failures occur due to damage to longitudinal and coil insulation – 47%, improper operation – 19%, insulation aging – 15%, poor quality repairs – 9%, factory defects – 7% and in other cases – 3%.

Figure 6 shows the power supply scheme of an industrial plant for which the probability of failure Q(t) is calculated. The system consists of highly reliable elements, when the time of failure-free operation exceeds the recovery time of the electrical installation, and the failure of more than two independent elements is an unlikely event. For clarity, let us divide the power supply scheme into I, II and III levels of the power system.

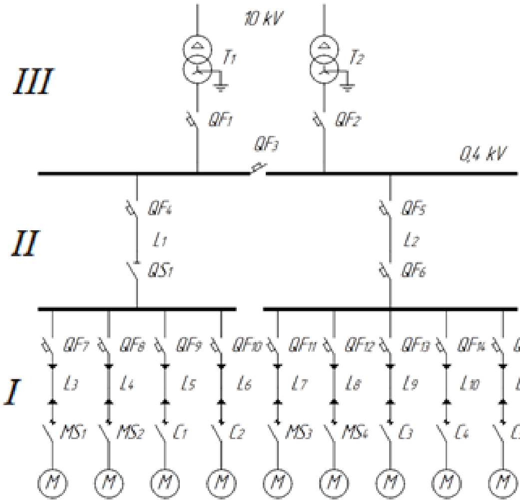

Figure 6: Electricity supply scheme of an industrial enterprise.

The electrical equipment of the first level (I) includes technological machines and electric motors, in this case squirrel cage induction motors M. Depending on the output of the production enterprise, technological machines and other electrical equipment causing the technological process may differ in type, brand and power consumption.

The second level (II) is different for production enterprises according to the output of products, the capacity of technological machines, equipped with magnetic starters MS and contactors C, circuit breakers QF and connecting cables L. Level at different technological and electrical systems are equipped with the same electrical apparatus, different in type and brand of apparatus depending on the consumed power.

The third level of the power system (III), includes a larger number of apparatuses: switches QS, connecting cable L, circuit breakers QF, 0.4 kV busbar section, sectionalizer and power transformers T. This level can also include fuses.

2 MATERIALS AND METHODS

Description of the scheme (Fig. 6) and initial data:

- cable lines: L_1=10 m, L_2=10 m, L_3=5 m, L_4=5 m, L_5=5 m, L_6=5 m, L_7=5 m, L_8=5 m, L_9=5 m, L_{10}=5 m, L_{11}=5 m;
- transformers: T1 – 10/0,4 kV; T2 – 10/0,4 kV;
- circuit breakers: QF_1, QF_2, QF_3 – sectional, QF_4, QF_5, QF_6, QF_7, QF_8, QF_9, QF_{10}, QF_{11}, QF_{12}, QF_{13}, QF_{14}, QF_{15};
- switch QS_1;
- power distribution cabinet: SHRs;
- power distribution point: PRs;
- magnetic starters: MS_1, MS_2, MS_3, MS_4;
- contactors: C_1, C_2, C_3, C_4, C_5;
- load: M_1, M_2, M_3, M_4, M_5, M_6, M_7, M_8, M_9;
- minimum permissible level of reliability for the scheme using switching low-voltage devices according to GOST 12434-83: P = 0.85, therefore, the permissible probability of failure Q = 0.15;

For smooth operation of the power supply system it is necessary to have a general approach to both the power supply system as a whole and to the automation and relay protection systems. When studying this issue it is necessary to proceed from the initial definition of reliability indicators of electrical equipment, namely from the failure rate f(t) and failure probability Q(t) (Table 1).

Table 1: Frequency of failures of individual elements of the power supply scheme of industrial enterprises.

Power system level	Electrical equipment, apparatus	Failure rate $\times 10^{-7}$, f(t), eql/year	The probability of failure $\times 10^{-7}$, Q(t)
First	Short-circuited asynchronous motor M	1500	0.35
Second	Magnetic starter MS_1, MS_2, MS_3, MS_4	1800	0.11
	Contactor C_1, C_2, C_3, C_4, C_5	700	0.03
	Connecting cable L_3 – L_{11}	200	0.03
	Circuit breaker QF_7 – QF_{15}	2100	0.23
Third	Switch QS_1	2400	0.10
	Connecting cable L_1, L_2	200	0.03
	Circuit breaker QF_4, QF_5, QF_6	2100	0.23
	0,4 kV busbar section	2800	0.14
	Sectional circuit breaker QF_3	2600	0.09
	Circuit breaker QF_1, QF_2	2100	0.23
	Power transformer T_1, T_2 10/0,4 kV	2900	0.07

According to the data of Table 1, let's calculate the probability of failures for the scheme of power supply of the industrial enterprise (Fig. 6) by the method concerning the distribution cabinet (SHRs) and distribution point (PRs). To do this, let's make a structural reliability diagram (Fig. 7).

Figure 7: Reliability structural diagram.

3 RESULTS AND DISCUSSIONS

The probability of failure for the power supply scheme of an industrial enterprise Q(t) is determined by the sum of failure probabilities of each element (Konyukhova, Kireeva, 2001):

$$Q(t) = q_1 + q_2 + q_3 + ... + q_n \quad (1)$$

where Q(t) – is the probability of system failure;
q_1, q_2, q_3, q_n – probabilities of failures of elements included in the power system.

Then the probability of failure $Q_1(t)$ with respect to SHRs:

$$Q_1(t) = q_{T1}+q_{QF1}+q_{L1}+q_{QF4}+q_{QS1}+q_{SHRs}+ +q_{L3}+q_{QF7}+q_{MS1}+q_M+q_{L4}+q_{QF8}+q_{MS2}+q_M+ +q_{L5}+q_{QF9}+q_{C1}+q_M+q_{L6}+q_{QF10}+q_{C2}+q_M = = q_T+6\cdot q_{QF}+5\cdot q_L+q_{QS}+q_{SHRs}+2\cdot q_{MS}+2\cdot q_C+2\cdot q_M = = 0.07+6\cdot 0.23+5\cdot 0.03+0.10+0.14+2\cdot 0.11+ +2\cdot 0.03+4\cdot 0.35 = 3.52\cdot 10^{-7}.$$

Failure probability $Q_2(t)$ with respect to PRs is calculated similarly by expression (1):

$$Q_2(t) = 4.29\cdot 10^{-7}.$$

Failure probabilities with respect to SHRs: $Q_1(t)$ and PRs: $Q_2(t)$ meet the requirements of GOST 12434-83 and do not exceed 0.15.

4 CONCLUSIONS

The calculated probabilities of failure with respect to SHRs: $Q_1(t) = 3{,}52\cdot 10^{-7}$ and PRs: $Q_2(t) = 4{,}29\cdot 10^{-7}$ meet the requirements of GOST 12434-83 and do not exceed Q = 0,15.

For the necessary level of reliability estimation of both electrical and technological equipment, the time characteristics of duration of failures elimination are important parameters. The main types of protections and the ratio of failures, % for electric motors, cable lines, power transformers and 0,4 kV busbar section are analyzed and given.

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