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DIGITAL TECHNOLOGIES FOR IMPROVING THE RELIABILITY OF POWER SUPPLY FACILITIES

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Abstract
This article explores the role of digital technologies as a means of improving the reliability of railway traction power supply. The importance of digitalization in implementing the Central Asian Republic Development Strategy is emphasized. Current challenges and their solutions are identified. The organizational and practical aspects of digital technologies are considered. A classification system for devices, objects, failure modes, wear, and misalignment of measuring systems, devices, and automation, as well as contamination and aging, is proposed.

Keywords: Digital technologies, reliability, digital economy, economic efficiency, electric power industry, traction power supply.

Introduction

ЦИФРОВЫЕ ТЕХНОЛОГИИ ПОВЫШЕНИЯ НАДЕЖНОСТИ ОБЪЕКТОВ ЭЛЕКТРОСНАБЖЕНИЯ

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Аннотация:
В статье рассматривается роль цифровых технологий как инструмент повышения надежности тягового электроснабжения железных дорог. Подчеркнуто значение цифровизации в контексте реализации Стратегии развития республик Центральной Азии. Выявлены проблемы настоящего времени и их решения. Рассмотрены организационно-практические направления цифровых технологий. Предложено применение

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классификации устройств, объектов, видов отказов, износов, разрегулировок измерительных систем, устройств и автоматики, а также загрязнений и старения.

Ключевые слова: цифровые технологии, надежность, цифровая экономика, экономическая эффективность, электроэнергетика, тяговое электроснабжение.

INTRODUCTION

Currently, in the context of global economic development, the electric power industry is undergoing significant transformational changes driven by the need to improve the efficiency of the energy system, particularly in Central Asian countries. The relevance of introducing digital technologies in railway traction power supply is determined by a combination of financial, technical, innovative, and social factors that create the preconditions for large-scale modernization of railway traction power supply.

The development of digital technologies in the field of power supply management is the Automated Control System for Power Supply Facilities (hereinafter referred to as the System). First and foremost, this is a modern, multi-level System that effectively and cost-effectively combines the following key functions:

– control and management;
– monitoring and diagnostics of digital substations and overhead contact systems;
– organization and automation of power supply facility operation;
– interaction with external systems.

Main functions	
Control and management	Monitoring and diagnostics of digital substations and overhead lines
organization and automation of operations at the power supply facility	interaction with external systems

The System is being developed using modern software and hardware solutions. The System's structure, interfaces, and data exchange protocols enable efficient data transfer over existing communication channels, even in areas with limited bandwidth.

The key components of any modern digital technology, from sensors to automated workstations, are microcontrollers such as the MP-16 and MP-32, and processors. Today, the electronics industry in developed countries such as China, Germany, and Japan mass-produces products with characteristics sufficient for the development of a wide range of automation equipment, including automated workstations.

Furthermore, the industry in developed countries produces a limited range of auxiliary electronic components, such as various interface converters and Ethernet switches. These components have also found application within the System.

In terms of software, complex challenges remain: studying the system and application software (hereinafter referred to as software) of developed countries and applying them to Central Asian countries, taking into account the regional and climatic characteristics of these countries, which is a pressing and necessary issue of our time. One of the most important internal tasks of any

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modern digital system (and not just a control system) is ensuring a unified time. All data in the system is transmitted with time stamps indicating the value change. Unified time is important both for transmitting analog values over digital channels, including IEC 61850 SV, and for analyzing various events that occur during the operation of the controlled facility. Here, it is necessary to take into account government decisions regarding the opening of transport communications between southeastern and European countries.

Moreover, different levels of the system must ensure uniform synchronization accuracy, which necessitates the use of various time synchronization methods and protocols. A simple and optimal method is time synchronization from the GLONASS and GPS satellite systems [1]. The electronics industry produces the necessary components for this task (e.g., GLONASS NV modules).

This article cannot ignore the currently fashionable term "digital substation." This term primarily refers to the construction of a substation in accordance with the requirements of the IEC 61850 standard. This includes the use of a centralized relay protection and automation system, optical current transformers, digital voltage transformers, PAS and PDS devices, etc. These solutions, compared to traditional designs, are significantly more expensive and complex to implement (in terms of commissioning, operation, and qualification) in Central Asian countries.

These solutions cannot be fully implemented using equipment manufactured in developing countries. The industry in developing countries currently does not produce Ethernet switches (an important component of the system) with the required characteristics [2].

The concept of a "digital substation" implies increased reliability and operational safety, and reduced construction and operating costs.

First and foremost, a prudent choice of technologies used to create control systems is important. For example, it is not economically feasible to use expensive solutions; It is cheaper and easier to implement solutions using a classic digital interface and protocol with a wide range of functionality, achieving the necessary and sufficient functionality at a lower cost.

It is much more important to invest in the development of monitoring and diagnostic systems for digital substations and overhead lines. However, the diagnostic approach must be:

- reasonable – the cost of diagnostic devices should be no more than 15-20% of the cost of the equipment being diagnosed, especially in developing countries in Central Asia. The physical operating principles of sensors and devices should ensure their simple design and reliable operation (e.g., voltage, current, and temperature sensors). The service life of diagnostic devices and their main expensive components should be no less than the service life of the equipment being diagnosed;
- not redundant – the operation of the diagnostic system should not lead to the shutdown of the equipment being diagnosed due to incorrectly identifying pre-failure or equipment failure conditions.

It is important to consider the following factors:

– Many of the sensors, instruments, and systems are measuring instruments operating in the harsh natural conditions of developing countries in Central Asia, which results in additional costs associated with their periodic verification. Therefore, when selecting sensors and instruments

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(and developing design documentation), it is important to evaluate the verification interval for each specific device;
– requirements for the availability of consumables.
The design documentation must include a forecast estimate of these costs and their frequency.
Most sensors at power facilities are installed in areas exposed to hazardous electromagnetic voltage, which increases the operating costs of the monitoring and diagnostics system. In the event of a malfunction, the primary equipment will need to be taken out of service to identify the cause of the malfunction and replace the sensor to ensure electromagnetic compatibility [3].
The next question regarding monitoring and diagnostics is: what to do with the vast volumes of information received from sensors, devices, and subsystems? The simplest way to process the collected information is to identify whether the values and their derivatives exceed the pre-failure/current failure setpoints. Equipment lifespan is obtained from relay protection and automation terminals and local diagnostic subsystems (if technically feasible). The next method is to process interconnected analog and discrete parameters to identify pre-failure/current failures and determine the equipment lifespan. The most comprehensive status information is obtained using predictive analytics algorithms, enabling forecasting of the future state of power supply facilities for optimal decision-making.
Solutions involving the use of digital instrument transformers with data transmission in accordance with IEC 61850-9-2.
Currently, there are two main options for this modern and promising technology:
– analog signal converters (ASCs) coming from traditional electromagnetic instrument transformers to a digital stream in accordance with IEC 61850-9-2;
– digital current and voltage transformers with an optical interface in accordance with IEC 61850-9-2.
The cost of digital instrument transformers is currently an order of magnitude higher than that of traditional electromagnetic ones. Moreover, due to the lack of necessary demand, serial production is minimal (according to information from the transformer manufacturer). These parameters are interconnected: if there is the required economics, there will be demand; if there is demand, there will be economics [4].
Currently, there are stereotypes, doubts about operational reliability, and a lack of standard solutions. Among the many functions implemented by a modern digital System, the following key functions should be highlighted:
– control and management of power supply equipment at the controlled point and power supply distance levels;
– monitoring and diagnostics of the power supply equipment condition at the controlled point, power supply distance, and road levels, with the transmission of incident information to the Unified Design Automatic Information Management System;
– efficient and safe organization and automation of power supply facility operation;
– interaction with external systems, including the transmission of information to the Regional Dispatch Center of the Unified Energy System Operator for 110/220 kV facilities.
In terms of hierarchical levels, the following levels should be distinguished in the System:
– controlled point;

– power supply distance;
– Energy Supply Directorate.

At the controlled point level, in terms of collecting status information, several sublevels can be distinguished.

First, information sources. These devices primarily include relay protection and automation terminals, which provide status monitoring, protection, measurement, and control of switching devices. Important sources of information include measuring transducers for electrical network parameters.

For collecting diagnostic information on the primary equipment's condition, various sensors and monitoring and diagnostic subsystems serve as sources of information. Monitoring and diagnostic subsystems, unlike sensors, provide algorithmic processing of the collected data and provide information on the current and predicted condition of the primary equipment.

It is important to note that a single device can be a source of information for multiple tasks. For example, a 110/220 kV Relay Protection and Automation terminal is a source of information for both the power control center dispatcher and the grid operator's Regional Dispatch Center dispatcher. The terminal provides critical diagnostic information for operating personnel (warning and emergency events, equipment lifespan, oscillograms).

This example demonstrates that, given the objectives, it is impractical and even impossible to artificially divide a single integrated system into separate, isolated systems, such as a telemetry system, a data collection and transmission system for the Relay Dispatch Center, or a monitoring and diagnostic system. This separation leads to a significant increase in project implementation costs due to the increased amount of equipment.

Another simple and effective source of diagnostic information is a process video surveillance subsystem, including one equipped with television cameras. Modern hardware and software provide a relatively inexpensive way to collect diagnostic information. To prevent network overload with video information, access from higher levels is provided only upon request and only in the required volume [5].

Secondly, there are devices for collecting and processing information. These devices include various controllers at the controlled point level, generally integrated into a single information network (for example, a substation bus in the terminology of the World Economic Forum standard 61850).

An important consideration is the technical and economic feasibility of choosing a particular type of information network for different facilities. For a traction substation, a redundant Ethernet network is a common option, but only for a small facility.

Thirdly, there are human-machine interface devices. These devices include stationary automated workstations, operator panels, and mobile devices. It should be noted that modern 4K display systems provide high image quality and comfortable display of the required volume of information at a relatively low cost. Solutions should be used that ensure comfortable conditions for personnel in terms of noise from computing equipment.

At the power supply level, the System supports the following tasks:
– control and management of power supply facilities;
– monitoring and diagnostics of equipment condition;

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– organization and automation of power supply facility operation;
– data exchange with controlled points;
– data exchange with the Energy Supply Directorate.
At the Energy Supply Directorate level, the System supports the following tasks:
– control of power supply facilities;
– monitoring and diagnostics of equipment condition;
– organization and automation of power supply facility operation;
– data exchange with the power supply level;
– interaction with external systems and databases, including the EKASUI, EKASUTR, and NSI databases.

In terms of data exchange with external systems, attention must be paid to information security at all levels of the System. This is primarily due to the fact that the System manages power supply facilities. This is especially critical at the points where information is transmitted to the Regional Dispatch Center of the UPS system operator for 110/220 kV facilities. In this case, the System provides the Regional Dispatch Center with all necessary information, blocking access to control functions and changes to relay protection settings (separating the flow of control and monitoring information).

The main indicators of reliability are the failure rate, mathematically determined by the following expression:

$$\lambda(t) = \frac{q(t)}{F(t)} = -\frac{dF(t)/dt}{F(t)}. \quad (1)$$

where

$$q(t) = \frac{dQ(t)}{dt} = -\frac{dF(t)}{dt}, \quad (2)$$

$$F(t) = \exp\left[-\int_0^t \lambda(x)dx\right]. \quad (3)$$

It should be noted that in a traction network, load and strength, which are random variables, are of particular importance.

The mean time to failure of an object is the mathematical expectation of the object's time to failure:

$$\mu_T = \int_0^\infty t \cdot q(t)dt = \int_0^\infty t \cdot \frac{dQ(t)}{dt} \cdot dt. \quad (4)$$

In a railway traction power supply system, the load distribution density and the strength distribution density are of great importance. A graphical representation of these two parameters is shown below (Fig. 1).

Let $f_П(x)$ be the strength distribution density, and $f_Н(x)$ be the load distribution density (Fig. 1). Failure occurs when the random strength value is less than the random load value. The shaded area indicates the overlap region of the load and strength distributions, which is characterized by a certain failure probability. This region is zoomed in for a more detailed examination:

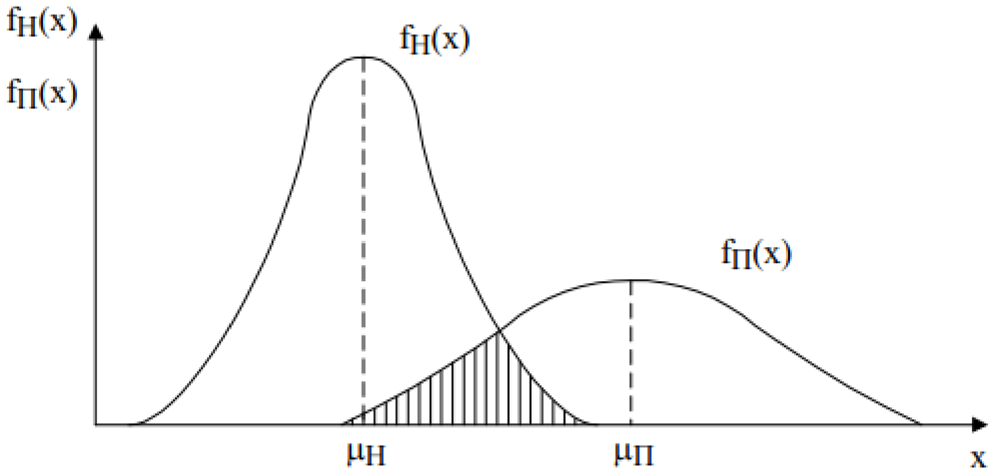

Fig. 1. Traction network load distribution and strength density.

Depending on the types of load distribution and strength, the probability of failure of the traction power supply system can be expressed using various formulas [ ].

CONCLUSIONS

A distinctive feature of reliability improvement methods and their digital calculations for AC railway facilities using digital technologies is the large number of design solutions, operating and functioning modes, and the presence of complex electromagnetic circuits, electronic components, automatic control devices, and relay protection. These can be grouped into three subsystems with specific characteristics.

The feasibility of using digital technologies allows for a universal classification of devices, objects, failure modes, wear, misalignment of measuring systems, automation devices, contamination, and aging.

The above-mentioned characteristics influence the choice of reliability calculation methods for power supply devices.

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