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On Diagnostic Systems of Electrical Equipment in Cement Production

Kh.T. Tasheva, F.M. Makhammadiev

Senior Researcher, Department of "Operation of Electrical Technologies and Power Equipment, te of Energy Problems, Academy of Sciences of the Republic of Uzbekistan, Tashkent, Uzbekistan

Head of Department of "Operation of Electrical Technologies and Power Equipment, te of Energy Problems, Academy of Sciences of the Republic of Uzbekistan, Tashkent, Uzbekistan

ABSTRACT: This paper discusses modern approaches to diagnosing electrical equipment in cement production using intelligent technologies. A model incorporating artificial intelligence elements is presented for diagnosing the technical condition of power equipment in cement manufacturing. The model implements a digital twin of a laboratory installation, a neural network model, and an executive module that simulates various operating modes and automatically identifies faults. The diagnostic method is based on electromagnetic spectral analysis of phase currents and voltages using the discrete Fast Fourier Transform (FFT), which allows detecting a wide range of electrical and mechanical defects. To classify the technical states of the electric motor, an artificial neural network (ANN) trained by polynomial logistic regression is employed, ensuring high accuracy in recognizing early-stage defects. The results demonstrate that intelligent diagnostic systems enhance equipment reliability and energy efficiency, reduce the risk of emergency shutdowns, and support the implementation of intelligent power systems with active-adaptive networks within Uzbekistan's energy sector. The developed system can be used both for research and educational purposes in training specialists in intelligent control, protection, and diagnostic systems of power complexes.

KEYWORDS: Asynchronous Motor, Diagnostics, Cement Production, Artificial Intelligence, Neural Network, Digital Twin, Spectral Analysis, FFT, Logistic Regression, Monitoring, Intelligent System, Technical Condition, Electrical Equipment, Energy Efficiency, Digitalization.

I. INTRODUCTION

Currently, power engineering complexes in economically developed countries are undergoing profound modernization through the digitalization and intellectualization of control systems. Uzbekistan's energy sector is also part of this transformation, as innovative scientific and technical policies in electrical power engineering have become a state priority. Government decrees and resolutions are directed at introducing green energy solutions using artificial intelligence technologies. An intelligent energy system with an active-adaptive network represents an integrated energy-information complex featuring intelligent control and continuous monitoring of the technical condition and operating modes of all its components.

This concept helps to reduce electricity generation and transmission costs, minimize technical and commercial losses during energy transport, and significantly improve equipment reliability through remote intelligent diagnostic monitoring. A review of publications devoted to the development of intelligent diagnostic systems for electrical power complexes has shown the following trends [2-3].

Studies [6–7] propose the use of convolutional neural network (CNN) models and their advanced variant, the multi-channel one-dimensional CNN (1D-CNN), for fault diagnosis in electric motors under varying load levels. In [8], a multiclass dataset-based method is proposed for diagnosing rotor bar faults and classifying defect types. Authors in [9–10] describe fault detection methods for induction motors based on artificial neural network classifiers (ANN), where feedforward and backpropagation networks are applied for identifying various bearing conditions.

An analysis of domestic laboratory equipment manufacturers indicates the absence of laboratory installations designed for studying intelligent diagnostic tools for electrical complexes. To meet the educational requirements of the master's program 'Intelligent Tools and Systems of Control, Protection, and Diagnostics of Power Complexes,' a decision was made to develop an educational and research complex titled 'Diagnostic Systems of Power Complexes.'

II. SIGNIFICANCE OF THE SYSTEM

The proposed system integrates Fast Fourier Transform (FFT)–based spectral analysis, Artificial Neural Networks (ANN), and a digital twin model to diagnose electrical equipment in cement production. It enables real-time monitoring and early detection of electrical and mechanical faults in induction motors, improving operational reliability and energy efficiency.

By combining data-driven modeling with virtual simulation, the system minimizes downtime, reduces maintenance costs, and supports the digital transformation of industrial power systems. The structure of this paper is as follows: Section III reviews related studies, Section IV describes the methodology, Section V presents the results, and Section VI provides conclusions and future work.

III. MATERIALS AND METHODS

The object of diagnostics selected for this study was a three-phase squirrel-cage induction motor, which is part of the electrical machine load module. It is the most common type of electric machine used in industry, including cement production. Its popularity is due to its simple design, reliability, low cost, and relatively easy maintenance. In the technological lines of cement plants, induction motors are used to drive mills, fans, conveyors, pumps, compressors, and other equipment that ensures the continuity of the production process.

The operating principle of an induction motor is based on the interaction between the rotating magnetic field of the stator and the currents induced in the rotor windings (or short-circuited bars). The difference in speed between the rotating magnetic field and the rotor—known as slip—determines the nature of the electromechanical energy conversion. Structurally, motors can be distinguished as having either a squirrel-cage or wound rotor, which allows optimization of parameters according to specific operating conditions.

In cement production, induction motors operate under harsh conditions, including high dust levels, vibration, load fluctuations, and temperature variations. These factors significantly affect the lifespan of insulation, bearing assemblies, and windings, as well as the overall reliability of the equipment. Therefore, timely diagnostics of the technical condition of electric motors is crucial for preventing emergency shutdowns, optimizing maintenance schedules, and increasing energy efficiency in production.

Modern diagnostic systems for induction motors are based on the analysis of electrical, vibration, and thermal parameters. They allow early detection of faults, such as inter-turn short circuits, rotor imbalance, bearing wear, or supply deviations. The use of intelligent monitoring systems, integrated into the automated control systems of cement plant processes, improves the reliability and performance of the entire electrical infrastructure of the enterprise.

Induction motors bear the main industrial load and account for approximately 80% of the total electricity consumption in cement production. Their reliable operation is essential for the successful functioning of production; motor failures can lead to serious consequences, including emergencies, economic losses, and environmental damage. Therefore, monitoring the technical condition of motors driving technological units and detecting faults at early stages is highly relevant [14–15].

One of the promising methods for motor diagnostics is the electromagnetic spectral method, which is based on analyzing the spectral parameters of the harmonic components of phase currents and voltages of the motor. The essence of this diagnostic method lies in recording the phase currents and voltages of the motor, followed by spectral analysis using the Fast Fourier Transform (FFT) [16]. This method enables the identification of a wide

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range of faults in both the electrical and mechanical parts of the device with fairly high accuracy. When a fault occurs, the motor generates a characteristic spectrum of higher harmonic components of currents and voltages. The set of harmonic parameters allows the identification of a specific fault or characterization of the overall technical condition of the motor.

This diagnostic method is relatively inexpensive, does not require the installation of special measurement sensors in hard-to-reach locations, and allows for remote diagnostics—that is, current and voltage sensors can be connected not only directly to the motor terminals but also to distribution devices that supply power to the motors. This feature makes the electromagnetic spectral method attractive for use in an intelligent energy system with an actively adaptive network as part of a smart diagnostic system for the power complex.

Using the spectral method to analyze the frequency characteristics of a motor allows solving the inverse problem—simulating various technical conditions and operating modes of the motor [17]. The development of frequency models of the motor using parameters of harmonic components generated by its phase currents and voltages was carried out in MATLAB Simulink and Typhoon HIL software packages [16].

The model under study is based on the existing equipment of cement plants and is supplemented by its digital counterpart—a neural network, a database of frequency models, and an interface ensuring interaction between the individual elements of the educational and research complex [12–13, 18–19].

The structure of the software part of the model consists of the following components:

- Digital twin of the laboratory bench.
- Neural network.
- Database of motor frequency models.
- Visual interface.

To implement this structure, the Python programming language version 3.9 was chosen, with its extensive standard library. The integrated development environment for Python is PyCharm. The digital twin of the laboratory bench is implemented as a windowed application using the PyQt5 library, which contains the Qt graphical framework for Python, and the QtDesigner application, which provides a convenient graphical interface. Mathematical calculations are performed using the numpy library, which offers a rich set of built-in functions, is open-source, and supports array and matrix operations. The software part of the model contains a visual interface and applications that create the overall structure and organize interactions between software elements.

The identification of the technical condition of the motor is carried out by analyzing the parameters of harmonic components of the phase currents and voltages generated by the motor using an artificial neural network (ANN). An intelligent data classifier is used for this purpose, solving a multi-class classification problem with the support vector machine method. The data processing tool in the ANN classifier is polynomial logistic regression, a type of multiple regression aimed at analyzing the relationship between several independent variables and a dependent variable.

The structure of the ANN, based on the polynomial logistic regression model, is shown in Figure 1. It contains three layers:

- Input layer (the first layer of the neural network that receives input signals and passes them to subsequent layers).
- Hidden layer (computational layer).
- Output layer (the final layer of the network, representing the target function).

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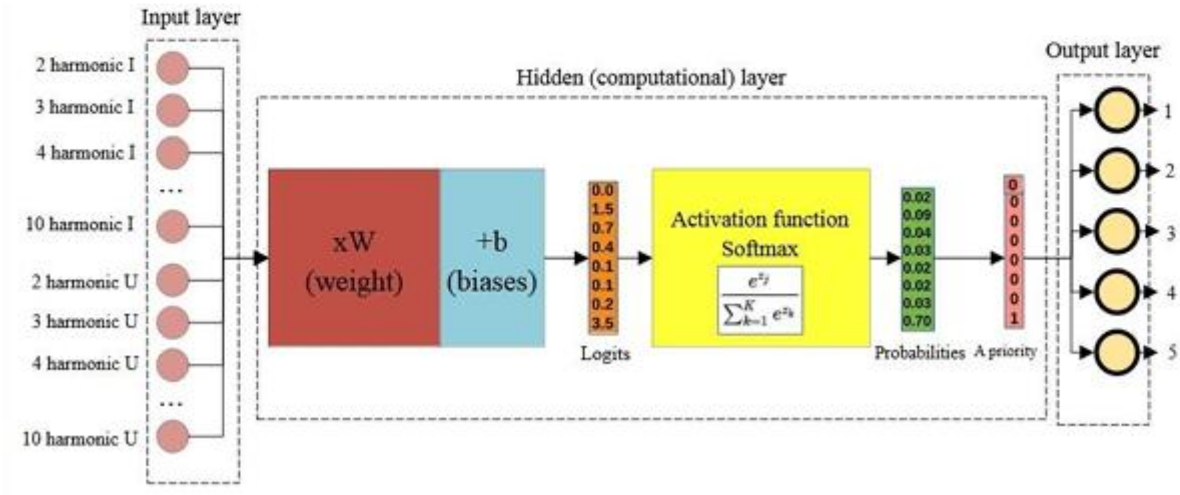

Fig. 1. Structure of the neural network.

It was established that, to ensure the required signal-to-noise ratio and acceptable accuracy in determining the technical condition of the electric motor, it is sufficient to use the first nine harmonics (from the 2nd to the 10th) of the phase A current and voltage. The first (fundamental) harmonics of current and voltage were excluded from the analysis because their amplitudes are incomparable with those of the higher harmonics and provide limited diagnostic information.

As informative parameters, the amplitudes of the phase current and voltage harmonics are used — these serve as the input data for the Artificial Neural Network (ANN). A dataset in MS Excel format is created for further uploading into the ANN. Each row of the dataset corresponds to one measurement and consists of nine current harmonic amplitudes, nine voltage harmonic amplitudes, and a class label indicating one of the five technical states of the electric motor.

The neural network is trained using supervised learning based on the logistic regression method, which determines the influence of input independent variables on specific output variables. The data from the input layer are passed to the hidden layer, where the weight matrix elements and bias vectors are calculated. The logits — vectors of initial predictions generated by the classification model — serve as input data for the *softmax* activation function. The *softmax* function produces a vector of normalized probabilities with one value for each possible class. The output of the *softmax* function corresponds to the five predefined output neurons, each representing the probability of the motor belonging to one of the five technical states.

After the training dataset is loaded, the automatic ML.NET model builder selects the ANN architecture with the highest accuracy suitable for practical implementation. The result of ANN training is an intelligent diagnostic model. When new measurements of harmonic parameters of phase currents and voltages are uploaded, they are fed into the intelligent model, which determines to which of the five technical states the current condition of the electric motor corresponds [11, 13–14, 19–22].

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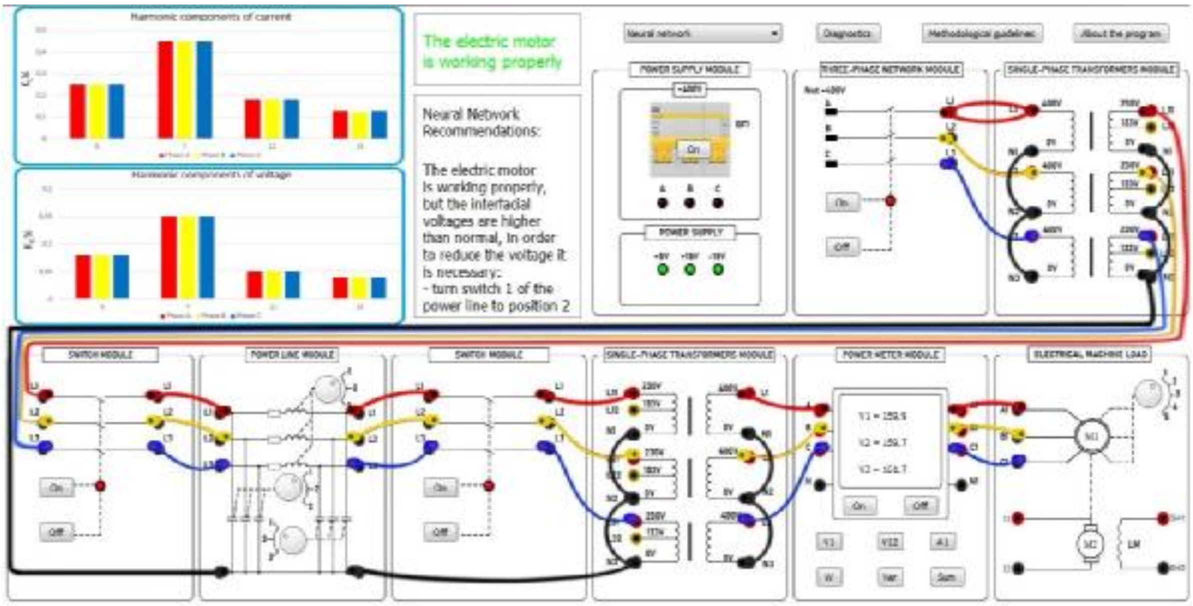

Fig. 2. Interface of the digital twin model for diagnostics of electrical equipment.

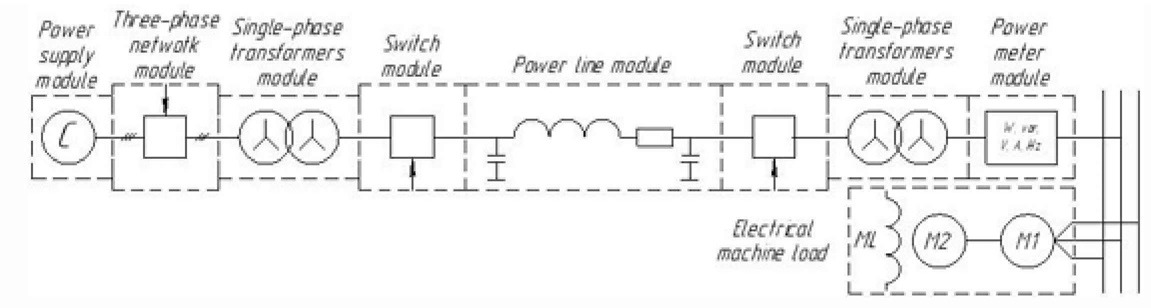

Fig. 3. Connection scheme of modules in the diagnostic model.

IV. RESULTS AND DISCUSSION

As a result of evaluating the applicability of various neural network architectures, the Artificial Neural Network (ANN) classifier based on logistic regression was identified as the most effective for diagnosing the technical condition of electric motors in cement production. The model utilizes a dataset of harmonic components of phase currents and voltages obtained through spectral analysis. Comparative testing of several ANN configurations demonstrated that feedforward neural networks with two hidden layers achieved the lowest error rates and the most stable performance.

The model's adequacy was verified through testing and cross-validation procedures to prevent overfitting. Statistical evaluation confirmed the objectivity, consistency, and efficiency of the model. As the sample size increased, the estimated values converged toward the true parameters, indicating the reliability and robustness of the developed diagnostic approach.

The implementation of the ANN-based diagnostic system improves the operational efficiency and reliability of cement plant electrical equipment while reducing the likelihood of emergency or critical failures. Furthermore, as intelligent power systems continue to evolve, the proposed model facilitates the integration of predictive maintenance and remote diagnostic tools into industrial automation frameworks, contributing to the broader adoption of smart energy technologies.

V. CONCLUSION

As a result of the conducted research, a diagnostic model for assessing the technical condition of electrical equipment in cement production has been developed using artificial intelligence methods. The proposed system integrates a digital twin of a laboratory installation, a neural network model, and a frequency database of induction motors, enabling the simulation of various operating modes and accurate identification of equipment conditions.

The application of electromagnetic spectral analysis using the Fast Fourier Transform (FFT), combined with an Artificial Neural Network (ANN) based on polynomial logistic regression, provides high diagnostic accuracy and enables early detection of electrical and mechanical faults. This approach enhances the reliability, operational stability, and energy efficiency of cement industry equipment while reducing the likelihood of unexpected failures and downtime.

The results confirm the feasibility and effectiveness of implementing intelligent diagnostic systems within Uzbekistan's power and industrial sectors. The developed system can be effectively applied both for research purposes and in educational environments to train specialists in intelligent control, protection, and diagnostic technologies for modern power systems.

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