Development and research of an intelligent diagnostic system for equipment of electric power complexes

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Abstract. Intelligent systems represent a new direction in the electrical power industry, and training students in this area requires appropriate updating of curricula and laboratory equipment. In this regard, it is necessary to create educational and research complexes in special disciplines to train specialists in intelligent electric power systems. This article presents an educational and research laboratory complex with elements of artificial intelligence for diagnosing the technical condition of equipment in electric power complexes. A free version of the IDE was used as an integrated development environment, which provides the basic functions and tools necessary for developing and debugging Python projects. The software part of the complex has been developed, including a digital twin of the laboratory installation, an executive part and a neural network model.

1 Introduction

Currently, the electric power complexes of all economically developed countries are undergoing deep modernization due to the intellectualization of their control systems. The energy complex of Russia is also involved in this process, innovative scientific and technical policy in the electric power industry has become the basis of the state energy policy, orders and resolutions of the Government of the Russian Federation have been issued aimed at implementing the country’s electric grid complex using the technology of “smart” electric grids. In 2012, JSC Scientific and Technical Center for Electric Power Engineering and specialized institutes of the Russian Academy of Sciences developed the basic document “Concept for building an intelligent energy system with an active-adaptive network” (IES AAN), and in 2015, the “Concept for the implementation of the national project “Intelligent Energy System of Russia” was developed " Further intellectualization of the country's energy sector is developing in accordance with the National Strategy for the Development of Artificial Intelligence until 2030. An intelligent energy system with an active-adaptive network is a unified energy information complex with intelligent control and continuous monitoring of the technical condition and operating mode of all its elements [1].

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The new concept makes it possible to reduce the cost of production and transmission of electrical energy, reduce technical and commercial losses during the transportation of electricity, and significantly increase the reliability of electrical equipment through remote intelligent diagnostic monitoring [2-3]. The development, operation and maintenance of smart electric power systems requires specialists with competencies not only in the field of power engineering and electrical engineering, but also in the field of digital technologies and artificial intelligence. The training of such specialists requires the presence of educational laboratories equipped with educational and research complexes with intelligent control systems [4-5].

Before starting work on the project, a review of publications on the research and development of intelligent tools and diagnostic systems for electric power complexes was carried out.

Articles [6 - 7] propose to use a convolutional neural network (CNN) model, as well as its more updated version - a multi-channel 1D convolution neural network (1D CNN), for diagnosing faults in electric motors. The neural network recognizes various faults at different load levels. [8] presents a method for using multi-class data sets to diagnose the condition of a rotor bar and classify the fault based on these data.

The authors of [9 - 10] describe a method for diagnosing faults in asynchronous motors, based on the use of an ANN classifier. A forward and back propagation neural network is used to classify different bearing conditions.

Analysis of the range of laboratory installations produced by domestic manufacturers of educational equipment, intended for the study of intelligent tools and diagnostic systems of electrical complexes, showed that today there are no such laboratory installations.

To provide conditions for the implementation of the educational program for master's training "Intelligent means and systems for control, protection and diagnostics of electric power complexes", it was decided to create an educational and research complex "Intelligent diagnostic systems for electric power complexes".

2 Materials and methods

During the implementation of the project, technical and methodological documentation of the laboratory stands "Active-adaptive electrical networks" and "Automation of electrical power systems", a virtual simulator for active-adaptive electrical networks of LabSys LLC and a set of virtual laboratory works "Active-adaptive electrical networks" were used. GalSen company.

The laboratory stand “Model of an electrical system with a complex load unit” of the Scientific and Production Enterprise “Uchtech-Profi” was chosen as the basis for creating an educational and research complex. When developing the complex, the technical documentation of the stand, methodological instructions for performing laboratory work and the experience accumulated by the department of “Electrical equipment and automation of industrial enterprises” in the development of educational laboratory installations with elements of artificial intelligence were used [11-13]. To expand the functionality of the laboratory complex, the physical model of the electrical system was supplemented with its digital twin and an intelligent diagnostic system based on an artificial neural network. The complex is complemented by certain types of real electrical equipment and virtual control, protection and diagnostic tools.

The laboratory stand contains a set of modules that allow you to create variable configurations and operating modes of power supply systems for consumers. A three-phase asynchronous electric motor with a squirrel-cage rotor, which is part of the electric machine load module, was chosen as the object of diagnosis. Asynchronous electric motors make up the bulk of the industrial load and account for about 80% of all electrical energy consumed.
in oil and gas production. The successful functioning of production depends on their reliable operation; failures of electric motors can lead to serious consequences - the creation of emergency situations, economic and environmental damage. Therefore, the task of monitoring the technical condition of electric motors that drive technological units and identifying faults in the early stages of development is very relevant [14-15].

One of the promising methods for diagnosing electric motors is the electromagnetic spectral method, based on the analysis of the parameters of the spectrum of the harmonic components of the phase currents and voltages of the electric motor. The essence of this diagnostic method is to register the phase currents and voltages of the electric motor with subsequent spectral analysis using a discrete fast Fourier transform FFT (Fast Fourier Transform) [16]. This method allows you to identify with fairly high accuracy a wide range of faults in both the electrical and mechanical parts of the unit. When damage occurs, the electric motor generates a characteristic spectrum of higher harmonic components of currents and voltages. The set of harmonic parameters makes it possible to identify a specific malfunction or characterize the general technical condition of the engine. This diagnostic method is relatively inexpensive, does not require the installation of special measuring sensors in hard-to-reach places and allows for remote diagnostics, i.e. connect current and voltage sensors not only directly to the motor terminals, but also in switchgears to the connections from which the motors are powered. The latter circumstance makes the electromagnetic spectral method attractive from the point of view of use in an intelligent energy system with an active-adaptive network as part of an intelligent diagnostic system for the electric power complex.

To create a physical model of a power supply system with a motor load, the following modules of the laboratory stand were used: stand power supply, three-phase network, single-phase transformers, switch, power line, power meter and electrical machine load.

The use of the spectral method for analyzing the frequency characteristics of an electric motor makes it possible to solve the inverse problem - to simulate various technical states and operating modes of the engine [17]. The development of frequency models of an electric motor using the parameters of the harmonic components of phase currents and voltages generated by it was carried out in the MATLAB Simulink and Typhoon HIL software packages [16].

The physical model of the laboratory bench is complemented by its digital twin, a neural network, a base of frequency models and an interface that communicates between the individual elements of the educational and research complex [12-13, 18-19].

The structure of the software part of the laboratory complex consists of the following parts:

- Digital twin of the laboratory stand.
- Neural network.
- Base of electric motor frequency models.
- Visual interface.

To implement this structure, the Python programming language version 3.9, which is accessible and has an extensive standard library, was chosen. The integrated development environment for the Python language is PyCharm. The digital twin of the laboratory bench is implemented as a window application using the PyQt5 library, which contains a set of the Qt graphical framework for the Python language, and the QtDesigner application, which has a convenient graphical interface. Mathematical calculations are performed using the numpy library, which has a rich set of built-in functions, is open source, and supports array and matrix operations. The software part of the laboratory complex contains a visual interface and applications that create a general structure and organize the relationship between program elements.
Identification of the technical condition of the electric motor is carried out by analyzing the parameters of the harmonic components of phase currents and voltages generated by the electric motor, an artificial neural network (ANN). For this purpose, an intelligent data classifier is used, which solves the problem of multi-class classification using support vector machines. The data processing tool in the ANN classifier is polynomial logistic regression - a type of multiple regression, the purpose of which is to analyze the relationship between several independent variables and the dependent variable. The structure of the ANN based on the polynomial logistic regression model is shown in Fig. 1. It contains 3 layers:

- Input layer (input layer, the first layer in the neural network, which receives incoming signals and transmits them to subsequent levels).
- Hidden layer, computational layer.
- Output layer (output layer, last layer in the network, target function).

![Neural network structure](image)

Fig. 1. Neural network structure.

It has been experimentally established that to ensure the required level of signal-to-noise ratio and acceptable accuracy in identifying the technical condition of the electric motor, it is sufficient to use the first 9 harmonics (from 2 to 10) of the current and voltage of phase A. The first harmonics of current and voltage - the main harmonics - are excluded from the analysis due to incomparability in magnitude with the amplitudes of other harmonics and low information content. As informative parameters of the harmonic components of phase currents and voltages, their amplitudes are taken, which are the input data for the ANN. A data sample is generated in MS Excel format in a database for further loading into the ANN. One line corresponds to one measurement, consists of 9 values of current harmonic amplitudes, 9 values of voltage harmonic amplitudes and a class mark (one of 5 technical states of the electric motor is preset). The neural network is trained on the principle of supervised learning using the logistic regression method, which involves identifying the influence of input independent variables on some output.

Data from the input layer enters the hidden layer, where the values of the elements of the weight matrix and the bias vector are calculated. Logits are vectors of the original predictions generated by the classification model. When solving a classification problem, logits become input data for the activation function - softmax. The softmax function generates a vector of normalized probabilities with one value for each possible class. The states of the softmax activation function correspond to 5 specified states of output neurons, which determine the highest probability of belonging to one of the 5 technical states of the electric motor. After loading the training sample, the automatic ML.NET model builder selects an ANN model with the best accuracy acceptable for practical use.
The result of ANN training is an intelligent model. When loading the measurement results of new values of the parameters of the harmonic components of phase currents and voltages, they are sent to the input of the intelligent model, which determines which of the 5 technical states of the electric motor its current technical state belongs to [11, 13-14, 19 - 22].

3 Results

The laboratory work consists of two stages. The first stage is performed using a physical model of the power supply system with a motor load. Students assemble an electrical circuit of the power supply system by connecting the stand modules according to Figures 2 and 3. Using the Metrel MI 2885 power quality indicator, the parameters of phase currents and voltages of a working electric motor are measured and decomposed into spectra of harmonic components. The harmonic amplitudes are sent to the input of the neural network and it is trained to recognize the serviceable state of the electric motor. By changing the positions of the switches of the power line module, they change the values of the active and reactive resistance of the line, thereby changing the operating modes of the power supply system model, which also affects the parameters of the harmonics of phase currents and voltages generated by the electric motor. By performing this operation in a cyclic mode for all possible switch positions, the minimum required database for training the neural network is formed.

The second stage of laboratory work will be performed using a digital twin of the physical stand. In addition to the frequency model of the good state of the engine, four more models corresponding to its four faulty states are loaded into the database of the laboratory complex. These models are created according to the methodology outlined in [15-17] and can be periodically updated. Each model of the technical condition of the electric motor corresponds to a certain position of the switch of the electric machine load module. By changing the values of the active and reactive resistance of the power line in a cyclic mode, the neural network is trained to recognize these faults. After completing the training of the neural network, the laboratory complex is ready to recognize the technical condition of the electric motor. The second stage of laboratory work can be performed entirely remotely.

Fig. 2. Interface of the digital twin of the laboratory educational and research complex.
Fig. 3. Connection diagram for modules of the educational and research complex.

4 Discussion

As a result of analyzing the possibility of using different types of neural networks, an ANN classifier was selected that uses a sample of parameters of the harmonic components of phase currents and voltages based on a logistic regression model to recognize the technical condition of the electric motor. Based on the results of comparing logistic regression models implemented by different neural networks, it was found that feedforward neural networks with two hidden layers have a lower error rate. The accuracy was assessed using a test sample with an additional check to ensure that the algorithm was not overtrained. An analysis of model adequacy was carried out, including assessments of unbiasedness, consistency and efficiency. As the sample size increases, the estimates become closer to the true values, which indicates the validity of the model.

The use of the educational and research complex makes it possible to increase the efficiency of training specialists in the field of smart electric power complexes, to minimize the risks of disruption of classes in the event of extreme situations similar to a pandemic or natural disasters, and provides the opportunity to remotely and virtually perform laboratory work for part-time students and people with limited mobility.

As smart electric power systems develop, so do smart tools and systems for remote diagnostic monitoring of the technical condition of electrical equipment. The results of research in this area have been published in the works of foreign and domestic researchers.

The paper [6] by M. Abdelmaksoud, M. Torki, M. El-Habrouk and M. Elgeneidy proposes a convolutional neural network (CNN) model for diagnosing faults of an induction motor at an early stage of development. The model is capable of detecting various faults (locked rotor, overload, voltage imbalance, overvoltage and undervoltage) at three load levels (light, normal and heavy load). The model uses several signals characterizing the state of the motor (phase voltages and currents, torque and rotation speed). R. Ribeiro, I. Areias, M. Campos, C. Teixeira, L. Silva and G. Gomes in [7] propose to use a multichannel 1D convolution neural network (1D CNN) to diagnose six different types of electric motor faults using two accelerometers. The use of convolutional neural networks requires significant computational resources, and training on real data can be difficult due to the variety of operating conditions. Effective learning requires a large amount of labeled input data. When using an intelligent diagnostic system for educational purposes, using a simpler ANN classifier is the optimal solution.

W. Abu Elhaija and Q. Abu Al-Haija in [8] use multi-class data sets based on the mapping of two induction motors to detect rotor bar faults. To solve the problem, the authors chose an ANN classifier and use an optimized self-tuning neural network model. The disadvantage of this solution is that it is aimed at identifying faults only in the rotor rods, while the complex presented in this article allows an integrated assessment of five levels of technical condition of the electric motor.

By A. Sharma, R. Jigyasu, L. Mathew and Sh. Chatterji published a paper [9] that describes a method for diagnosing bearings of asynchronous motors. In this paper, the
frequency characteristics of a three-phase induction motor are calculated based on experimentally collected data and used to classify bearing conditions. A forward and back propagation neural network is used to classify different bearing conditions. The disadvantage of this method is that it is aimed exclusively at diagnosing the condition of bearings.

The article [10] by R. Jigyasu, L. Mathew and A. Sharma presents a system for vibration diagnostics of multiple faults of asynchronous electric motors using a feed-forward neural network. The analysis is carried out only in the time domain using vibration and current signatures, and does not use the effective method of spectral analysis of the parameters of the harmonic components of phase currents and voltages.

5 Conclusion

An educational and research complex has been developed that contains an intelligent system for diagnosing the technical condition of electrical system elements. The complex consists of a physical model of the power supply system for a consumer with a motor load, its digital twin, a neural network, a base of frequency models and an interface that communicates between the elements of the complex. A three-phase asynchronous electric motor with a squirrel-cage rotor was selected as the object of diagnosis. In the future, other objects of electric power systems can be selected as diagnostic objects.

The complex is intended for use in the educational process of training specialists in the field of development, operation and maintenance of intelligent electric power complexes.

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