Improving The Reliability Of STD-12500-2-Type Electric Motor Of Turbocompressors By Predicting Its State By Means Of Spectrum Analysis

Oleg Krukov
Full Professor
of Department of Science and Research
LLC "TSN-Electro"
Nizhny Novgorod, Russia
o.v.kryukov@mail.ru

Igor Gulyaev
Full Professor of Department
of Electronics and Nanoelectronics
National Research
Ogarev Mordovia State University
Saransk, Russia
ivgulyaev@mail.ru

Dmitriy Teplukhov
PhD Student of Department
of Electronics and Nanoelectronics
National Research Ogarev Mordovia
State University
Saransk, Russia
dmitry-tepluhov-95@bk.ru

***Abstract* — The article considers operating conditions of electric drive motors used in electric gas pumping units. A technique for predicting the technical state of high-voltage synchronous machines rested on the analysis of the dynamics of spectrum components was proposed. In the research the said technique was compaired with fuzzy models and artificial neural networks methods.**

Keywords — high-voltage synchronous machine, prediction of technical state/condition, electric drive gas pumping unit, spectrum analysis.

I. Introduction

The most expensive part of the technological installations utilized in the Fuel & Energy Complex, in particular, in electric gas pumping units (EGPU) is a powerful high-voltage synchronous motor (SM) [1-3], the reliability of which determines the faultless operation of the whole technological process. The most severe failure of such motor is the failure of its stator winding, caused by the disrupture of the motor frame and slot insulation [4-7].

The reason for above in most cases is physical and chemical processes of insulation degradation, which occurs due to the temperature, electromagnetic and mechanical impacts. The most significant effect on the aging rate of insulation is produced by temperature and electromagnetic influences, as well as partial discharges [8-11].

Electric motors STD-12500-2 operate at an average daily insulation temperature of 70-80 °C. The maximum temperatures of iron and copper are observed in the middle part of the stator bore, which is attributed to design features of the motor cooling system. However, on various aggregates operating under similar loads and cooling air temperature, thermal modes may differ.

The change in the stator temperature of the electric motor is greatly influenced by the supply voltage. Input Nominal Voltage for STD-12500-2 type electric motors comprises 10 kV.

As earlier works have proved [12,13] its increase above 11 kV leads to an increase in magnetic induction and appearance of large parasitic currents in structural elements of motor frame, causing its excessive heating.

Considering the following works [14,15], it is possible to identify a number of basic technical parameters of SM's states while in operation. These include the temperatures of the three stator windings (T1, T2, T3), and the stator currents (I_A, I_B, I_C). This set of parameters is sufficient for preliminary diagnostics of STD-12500-2 and prevention of emergency situations related to insulation depriciation.

We will analyze the time series describing the real parameters of the processes during the operation of electric motors, namely, changes in temperature and stator current.

II. Multistep Prediction Of The Temperature Regime In STD-12500-2 Type Electric Motors Of Turbocompressors.

Predicting the temperature regime enables to work out timely and more effective solutions for its adjustments and thus extend the operation life of electric motor. On the other hand, studies have shown that an uncontrolled increase in the temperature of the stator's midpoint is a harbinger of an emergency situation, disabling the EGPU for a long time (from 1860 to 2500 hours). At the same time, being able to predict an uncontrolled increase in temperature will not only extend the service life of motors utilized in EGPU, but also remove emergency situations.

Let us consider the time series [16, 17], describing full-day fluctuations in stator's temperature (Fig. 1) and analyze the effectiveness of inertial predictive methods. To do so, we shall divide the known time series, describing the change of temperature, into two parts, the first of which will constitute the prediction source, and the second one will be used for verification of the posterior precision of prediction.

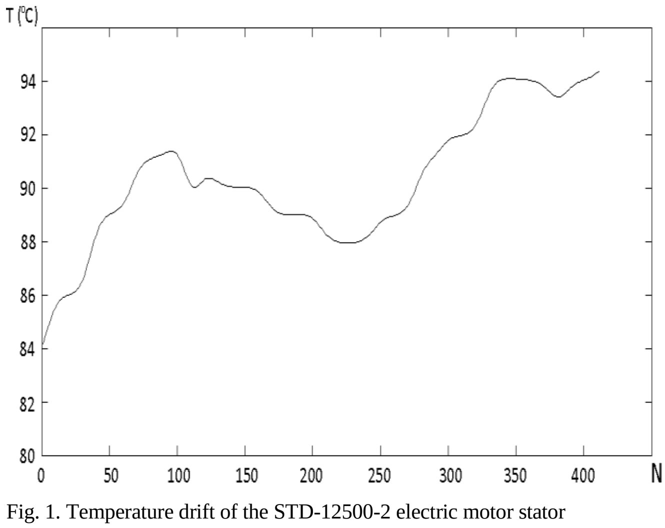

Fig. 1. Temperature drift of the STD-12500-2 electric motor stator

978-0-7381-2588-6/21/$31.00 ©2021 IEEE

Application of ARMA-models based methods [18-20] is possible, in particular, Box-Jenkins method was employed, as numerical series of first order differences of the temperature time series is stationary. The graph shows that methods based on Box-Jenkins models give a very pessimistic prediction with a rising trend (Figure 2b). Following the obtained data, it is impossible to reliably determine the moment when the temperature values go beyond the acceptable limits. The average relative error of the prediction was 23-58% ($\Lambda = 0.23 - 0.58$).

The method based on artificial neural networks (ANN) was also employed to test the effectiveness. For this purpose, a Ward's network was utilized, the inputs of which were fed with previous values of the time series. The choice of this type of ANN is explained by the fact that such neural networks are capable of making classification of the input values' significance.

The simulation showed that the constructed and trained artificial neural network at the border of indeterminateness of the temperature time series allows us to determine the general trend of temperature increase, but gives an optimistic prediction (Fig. 2 c). Following the above prediction, it is possible to determine the general trends in the development of the process, but it is impossible to reliably determine the moment when the stator temperature values go beyond the border of permissible values. The average relative error of the prediction was 16-46% ($\Lambda = 0.16$-0.46).

To predict the time series by the method based on the analysis of the dynamics of spectral components (SSA method), the prehistory of the temperature series with a size of $N = 400$ samples was employed. The resulting multi-step prediction allows us to identify the increasing trend of the time series and determine with high accuracy the moment when the temperature series values go beyond the permissible limits. The average relative error of the prediction was 8-34% ($\Lambda = 0.08$-0.34).

Therefore, the above research efforts affirm that the use of the SSA method makes it possible to make more accurate predictions about the drift of temperature parameters of STD-12500-2 electric motor stators in comparison with widely used methods based on ARMA models and artificial neural networks (ANN).

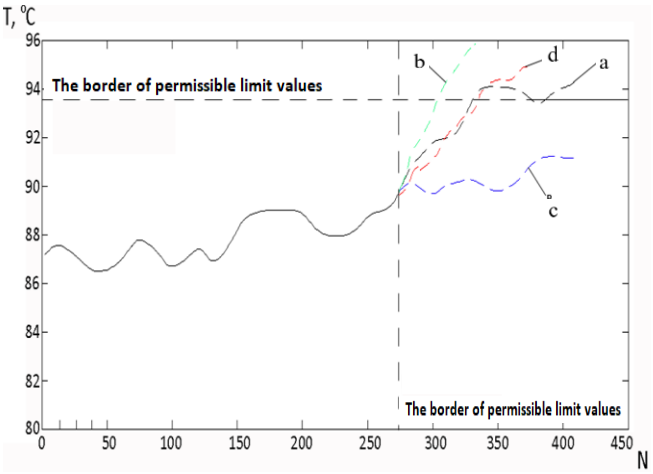

Fig. 2. The prediction of the stator temperature of the STD-12500-2 motor: *a* – the actual temperature time series, *b* – the ANN prediction, *c* – Box-Jenkins model prediction, *d* – Singular Spectrum Analysis prediction (SSA)

III. MULTISTEP PREDICTION OF STD-12500-2 TYPE ELECTRIC MOTOR STATOR'S CURRENTS.

One of the main parameters influencing the stator's heat output, as an electrical system, is currents of the stator windings. The currents flowing in the stator have a double effect on the stator's insulation survival in EGPU electric motor. On the one hand, they have a direct thermal effect when flowing through the windings, and an indirect one generating eddy currents in the metal elements of the motor frame. On the other hand, the stator currents create high-intensity electromagnetic fields, causing electrochemical degradation processes in the insulation.

Predicting trends in stator currents will enable us to develop more effective control units, the purpose of which is to stabilize the EGPU's operating mode.

In the stator windings of STD-12500-2 type electric motors, there is a current in the range of 600-630A. However, as practice shows, at certain points of time, the current strength may increase. There are many reasons for such changes, the main of which are related to changes in the parameters of the power grid. The main role in this process is played by the number of power grid consumers, which include external consumers and other EGPUs being part of the Compressor Station (CS). The research findings allow us to say that the process of changing the currents of the stator windings is a non-stationary process, subject to random surges lasting from several seconds to several hours.

Let us consider a time series describing the change in the current of one of the EGPA stator windings (Fig. 3). For prediction, as in the case with the temperature parameter, we shall use Box-Jenkins method, Ward's method of ANN and Singular Spectrum Analysis (SSA) [8-12].

The Box-Jenkins method prediction (Fig. 4) is not reliable and does not allow us to identify trends in the stator current values and determine the moment when they go beyond the permissible limits (the error is 34-127%). This is explained by the fact that the autocorrelation lag, to which the method was set at the time of the change in the series trend development, loses its validity, which prevents the construction of an accurate prediction. In this case, the Box-Jenkins method reveals its low flexibility in predicting short time series in conditions of rapid change of trends.

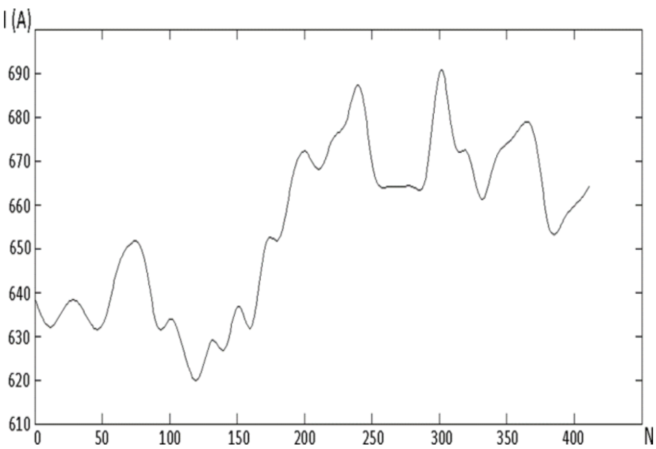

Fig. 3. Stator current drift during operation of the STD-12500-2 electric motor

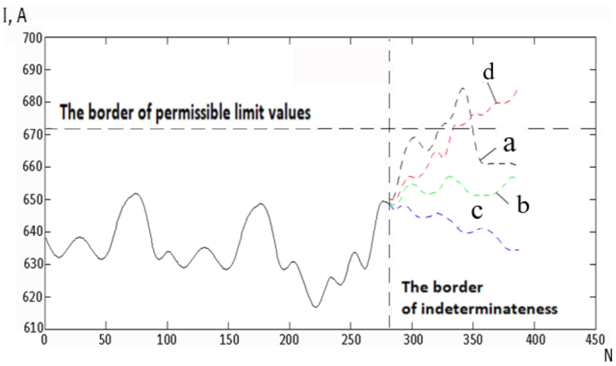

Fig 4. – Stator current prediction of the STD-12500-2 electric motor: *a* – actual time series, *b* – ANN-based prediction, *c* – Box-Jenkins model-based prediction, *d* – Singular Spectrum Analysis (SSA) based prediction

The results of Ward's ANN-based method (Fig. 4b) do not allow to determine reliably the point of exit of the technical parameter beyond the permissible limits (the error is 27-84%).

The explanation for this lies in the rapid changes in the development trend of the time series, in which the neural network does not have time to be retrained. As a result, the resulting multistep prediction can not be used to predict changes in stator currents. The use of Singular Spectrum Analysis (SSA) (Fig. 4g) for predicting changes in the stator current makes it possible to determine the moment when the parameter value goes beyond the permissible values with an error of 11-58%, depending on the degree of complexity and inhomogeneity of the time series describing it.

IV. The Results Of The Practical Implementation.

The results of experiments completed at the CS "Pochinkovskaya" and CS "Sechenovskaya" under Gazprom Trans-Gaz Nizhny Novgorod LLC with the application of above methodology [13-20], confirmed the necessity and reliability of monitoring the technical condition of the STD-12500 synchronous motor using the built-in system for diagnostics and prediction (BSDP) of the remaining life of the motor (Fig. 5).

The results of experimental measurements derived from the application of automated system for diagnostics and prediction of the technical state of EGPU's SM confirm the increased intensity of partial discharge (PD) in the slotted area and in the internal cavities of the insulation. However, the greatest impact on insulation wear is caused by thermomechanical loads and vibrations due to insufficient rigidity and loosening of stator winding slot-section support system during operation.

They were obtained by using experimental setup described using modern technical means of measuring equipment and standard panel-type electrical equipment of CS-25 "Pochinkovskaya" CC MG "Yamburg-Yelets-2" EGPU № 4.

- Rack frame of mounting electrical equipment A 705-15-05;

- digital thyristor exciter VTC-SD-SHCH 320/230;

- vibration measuring complex VVK EGPA-12,5;

- DRTD-3 measuring converters;

- R-500 type measuring device;

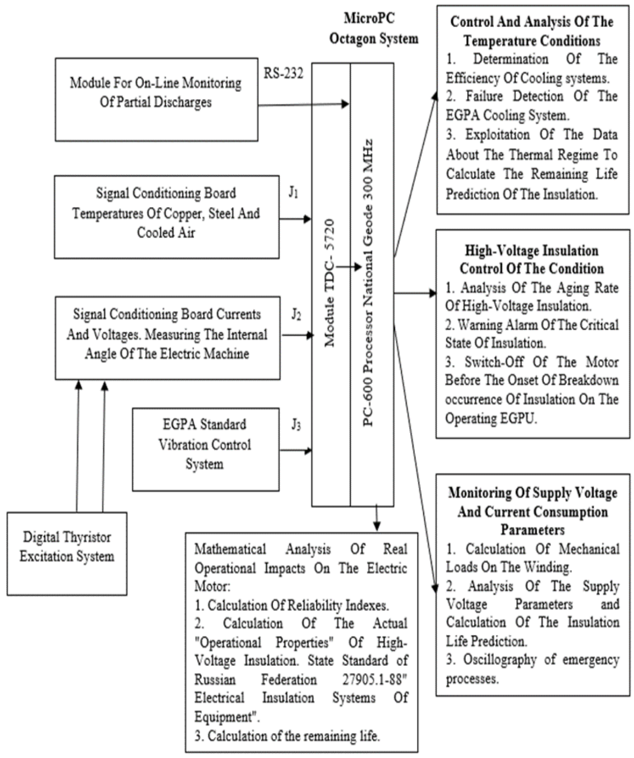

Fig 5. – Main part of the built-in system for diagnostics and prediction (BSDP) of the remaining life of the STD-12500 synchronous motor

- "Copper" temperature sensors of TSM-50 type;

- CPU Card 5070-5;

- ADC Board 5710-1S;

V. Conclusions.

1. It is shown that the method of Singular Spectrum Analysis (SSA) is applicable for short-term predictions of both stationary and non-stationary processes during various operating modes of electric machines, despite the limitations due to the inability to account for process correlations.

2. The research into the effectiveness of the Singular Spectrum Analysis (SSA) method in predicting the technical parameters of the STD-12500 in case of occurrence of gradual failures has shown that the said method gives more accurate results compared to traditional extrapolation methods and allows to make more adequate and timely decisions

3. It is shown that in a multi-step prediction of non-stationary processes when there is no additional information about the nature of the analysed process at the stage of model identification, the use of the Singular Spectrum Analysis (SSA) prediction method gives a more accurate result compared to extrapolation methods employing specific mathematical models or artificial neural networks (ANN).

References

[1] IEEE Guide to the Measurement of Partial Discharges in Rotating Machinery, in IEEE Std 1434-2000 , pp.1-64, 15 Aug. 2000. DOI: 10.1109/IEEESTD.2000.91905.

[2] O. V. Kryukov, D. A. Blagodarov, N. N. Dulnev Intelligent Control of Electric Machine Drive Systems. Proceedings of the 2018 X

International Conference on Electrical Power Drive Systems (ICEPDS). DOI: 10.1109/ICEPDS.2018.8571670.

[3] B. D. Vakser, O. P. Pishchulina. Prevention of Marginal Corona Discharges in the Insulation of High-Voltage Electric Machines. Russian Electrical Engineering, 2009, Vol. 80, № 3, pp. 136-138. DOI:10.3103/S1068371209030043.

[4] O. V. Kryukov. Monitoring of operating conditions of electric motors of gas-compressor units. Testing. Diagnostics, 2016, №12, pp. 50-58. (In Russian). DOI: 10.14489/td.2016.12.pp.050-058.

[5] N. V. Kiyanov, O. V. Kryukov, D. N. Pribytkov, A. V. Gorbatushkov. A Concept for the development of invariant automated electric drives for the water recycling systems with fan cooling towers. Russian Electrical Engineering, 2007, Vol. 78, № 11, pp. 621-627. DOI: 10.3103/S1068371207110120.

[6] M. S. Ershov, V. A. Maksyutov. Monitoring of the operating mode and insulation resource of electrical equipment windings during operation. Industrial Power Engineering, 2009, № 4. pp. 20-22. (In Russian).

[7] O. V. Kryukov. Electric Drive Systems in Compressor Stations with Stochastic Perturbations. Russian Electrical Engineering, Vol. 84, № 3, 2013, pp. 141-145. DOI: 10.3103/S1068371213030085.

[8] V. Ya Bespalov, Yu. A Moshchinskij, V. I. Tsukanov. A Simplified Mathematical Model of Nonstationary Heating and Cooling of an Induction Motor Stator Winding. Electricity. 2003. №4, pp. 20-26. (In Russian).

[9] O. V. Kryukov, I. V. Gulyaev, D. Y.Teplukhov. Method for stabilizing the operation of synchronous machines using a virtual load sensor. Russian Electrical Engineering, 2019, Vol. 90, № 7, pp. 473-479. DOI: 10.3103/S1068371219070083.

[10] A. S. Belousov, V. N. Meshcheryakov, S. Valtchev. Development of a control algorithm for three-phase inverter in two-phase electric drives reducing the number of commutations Proceedings of the 1st International Conference on Control Systems, Mathematical Modelling, Automation and Energy Efficiency (SUMMA) Control Systems, Mathematical Modelling, Automation and Energy Efficiency (SUMMA), 2019, pp. 444-449. DOI: 10.1109/SUMMA48161.2019.8947487.

[11] M. A. Gashimov, N. K. Ramazanov Fault Diagnostics of Power Equipment for Express Evaluation of its State. Russian Electrical Engineering, 2006, Vol. 77, № 3, pp. 7-15.

[12] G. C. Stone, E. A. Boulter, I. Culbert, H. Dhirani. Electrical Insulation for Rotating Machines: Design, Evaluation, Aging, Testing, and Repair: Second Edition. IEEE Press, Piscataway, NY, USA. 2004. Pp. 371.DOI: 10.1109/MEI.2004.1307097

[13] Electric rotating machines. General test methods. State Standard of Russian Federation 11826-86. Publishing House of Standards, Moscow, 1987. (In Russian).

[14] E. S. Okhotnikov. Monitoring Systems of Technological Processes of Oil and Gas Producing Enterprises: Classification and Mathematical Modeling. Electronic Scientific Journal Oil and Gas Business. 2006, №2, pp. 1-13. Available at: http://ogbus.ru/files/ogbus/authors/Okhotnikov/Okhotnikov_1.pdf (In Russian).

[15] Association standard. Monitoring systems for aggregates of hazardous production facilities. General technical requirements. The standard of the Association "Rosexpertiza" SA 03-002-05 of 15.12.2004.(In Russian).

[16] O. V. Kryukov. Methodology and Tools for Neuro-Fuzzy Prediction of the Status of Electric Drives of Gas-Compressor Units. Russian Electrical Engineering, 2012, Vol. 83, №9, pp. 516-521. DOI: 10.3103/S1068371212090064.

[17] V. A. Chernyshev, Yu. A. Safronenkov, A. A. Gordilovskii, and V. A. Chernov. Modern Approaches to Evaluate the State of Insulation of High Voltage Machines. Russian Electrical Engineering, Vol. 79, № 4, 2008, pp. 186-189. DOI:10.3103/S1068371208040056

[18] A. Krings, G. Paulsson, F. Sahlén, B. Holmgren. Experimental Investigation of The Voltage Distribution in Form Wound Windings of Large AC Machines due to Fast Transients. Proceedings of the IEEE XXII International Conference on Electrical Machines (ICEM-2016). Lausanne, Switzerland. DOI: 10.1109/ICELMACH.2016.7732753

[19] O. V. Kryukov. Walsh algorithms of high-speed conversion in microprocessor electric drive control systems. University News. Russian Electromechanics, 2005, № 4, pp. 39-44. (In Russian).

[20] M. S. BallaL, D. M. BallaL, H. M. Suryawanshi. Fuzzy System for the Detection of Power Quality Performance on Induction Motor. Electrical Power Quality and Utilisation Journal, Vol. XIV, №1, 2008, pp.61-65.