Effect of asymmetry of supply voltages on asynchronous motor operation modes

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Abstract. Effect of asymmetry of supply voltages on asynchronous motor operation modes was investigated using the computer-aided simulation experiments, the software complex Matlab and the package program Simulink. Publication relevance is determined by the necessity for performance of comparative analysis of the level of effect of asymmetry of supply voltages on asynchronous motors of different series and power capacities. Six motors of three different power capacities (5.5, 55, 160 kW) and of two different series (4A, AI) were modeled for investigation. The value of asymmetry of supply voltages was changed from 0 to 5%. The motor shaft load was changed from 0 to 120% of the motor rated load. Comparison of dependencies of the phase currents on the voltage unbalance ratio by reverse sequence (K_{2U}) of asynchronous motors with short-circuited rotor series 4A and AI was made. The analysis and discussion of obtained investigation results were performed, recommendations on operation of asynchronous motors series 4A and AI in conditions of asymmetry of supply voltages were given.

1 Introduction

At present the three-phase AC asynchronous motors (AM) is the most common type of the electrical machines. As a rule, AM are produced by large series, of which the most widely spread are the general purpose machines of series 4A, AI. Series 4A, AI are the mass series of asynchronous motors designed for using in different industry areas. In accordance with [1,2], the asynchronous motors are designed for a life time 15 – 20 years without overhaul provided that they are operated properly. Proper operation implies their running under rated parameters specified in AM passport certificate. However, under actual operating conditions of motors, depending on different factors, there is significant deviation from the rated modes of operation.

As the investigations [3-6] and many years' experience of operation demonstrate, one of the dominant causes for breakdown of motors is the asymmetry of supply voltage. AM operation under conditions of asymmetry of supply voltages results in change of the maximum rotation moment, sliding, currents in the motor windings. As a result, due to excess of the phase current rated values [7], heating of AM active parts occurs leading to winding insulation overheating and reduction of asynchronous motor lifetime. Thus, with asymmetry of voltages making 2%, the asynchronous motor lifetime, due to additional real power loss, reduces by 10 % [8].

Currently, in Russia a number of regulatory documents exists, which establish the set of the electric energy indicators and standards of quality [9], as well as requirements for reliability electrical machines [10,11,12].

The regulatory base for formation of recommendations aimed at ensuring AM operational reliability, includes:

- GOST 32144-2013 “Electrical power. Electromagnetic compatibility of technical equipment. Electrical power quality standards in the general purpose power supply systems”,
- GOST IEC 60034-26 – 2015. Part 26. Effect of unbalanced voltages on on operating characteristics of three-phase asynchronous motors,
- GOST P 52776-2007. Rotating electric machines. Rated data and features.

In accordance with GOST 32144 – 2013, the following standard values of the voltage unbalance ratio by reverse sequence K_{2U} are established: the values of the voltage unbalance ratio by reverse sequence K_{2U} in the electrical power delivery point, averaged at 10 minutes time intervals shall not exceed 2% during 95% and 4% during 100% of one-week time interval.

In accordance with GOST IEC 60034-26 – 2015. AM with K_{2U} above 1% (during continuous mode of operation) shall be unloaded “… to avoid its breakdown”. And AM operation “ with 5% of asymmetry excess is not recommended”.

The analysis of modern publications [4,5,13] showed that these values do not always correspond to GOSTs and, in practice, can significantly exceed them.

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Within the framework of this publication, it is necessary to perform investigation of synchronous motor with short-circuited rotor, their most common series 4A and AI, to make analysis of the effect of asymmetry of voltages on AM operation modes based on the motor series and power capacity. To get a more complete picture of the effect of asymmetry of voltages on AM, it is necessary to compare dependencies of AM phase currents on the voltage unbalance ratio by reverse sequence (K_{2U}), under different motor shaft load values. It is obvious, that such investigation will make it possible to solve the issue of determining the level of effect of the asymmetry of voltages different series and power capacity AM, and besides, to identify the permissible rate of K_{2U} (under AM standard mode of operation) depending on AM load.

It is clearly understood that experimental investigations play significant part in provision of AM reliability. In their turn, they enable formulating the proposals aimed at improvement of AM operating reliability and, in addition, prevention of occurrence of situations determined by overheating of winding insulation.

2 Investigation materials and methods

During investigation of AM operation modes, the computer-aided simulation is taken as the basis for virtual model implemented in the visual and efficient means for interactive environment simulation modeling Simulink and programming Matlab [14,15], using T-shaped scheme for asynchronous motor replacement.

Earlier, the publication author developed the computer model enabling to make analysis of AM operation modes in conditions of asymmetry of supply voltages [16]. Besides, in the obtained computer model, there is an option for investigation of transition processes in the asynchronous motor, for reading operational and imitation mechanical characteristics, of supply grid voltage, currents and frequency.

The scheme for investigation of operation modes for synchronous motor with short-circuited rotor created by means of simulation modeling in Matlab/Simulink environment is given in (Fig.1).

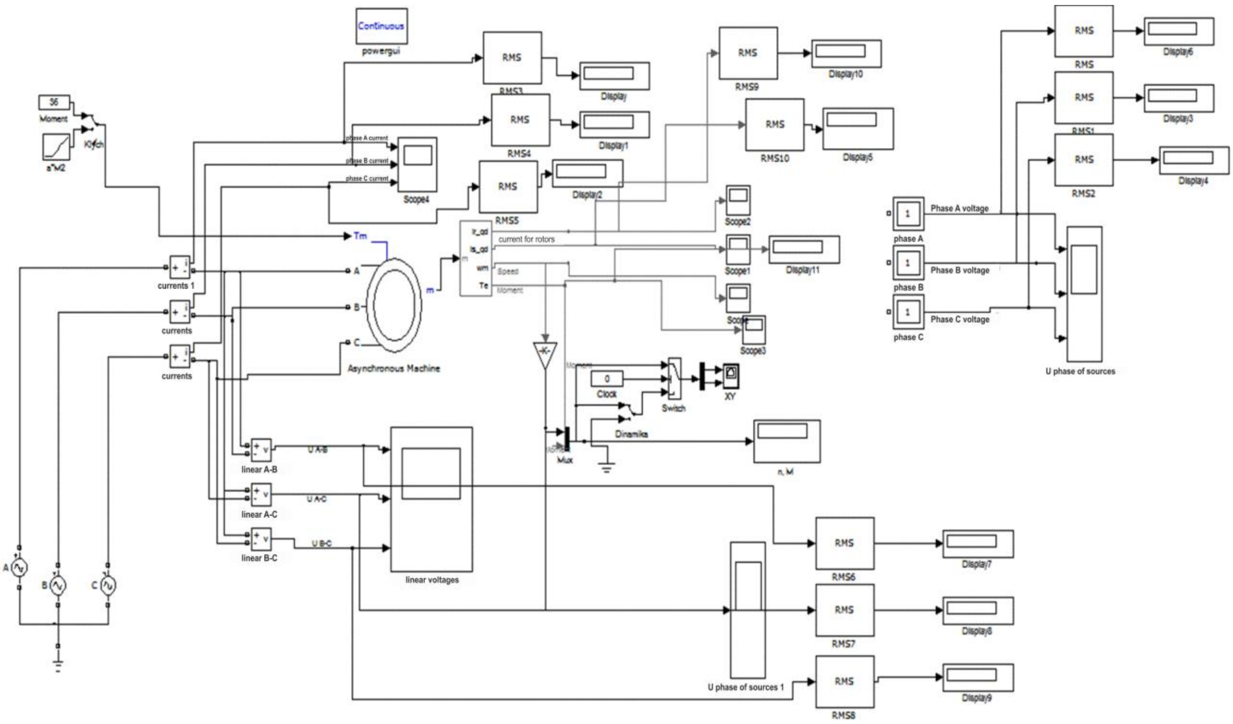

Fig.1. Simulation scheme implemented in Matlab/Simulink environment.

AM operation modes with account of below listed parameters were investigated using the developed model:

– the value of the motor shaft load was changed from 0 to 120 % with the pitch of 20 under different values of K_{2U},

– the value of the voltage unbalance ratio by reverse sequence – from 0 to 5 % with the pitch of 1 %.

The asynchronous motors series 4A, AI with the motor rated rotation frequency n=1500 rpm, with significant
scatter by power capacities from 5.5 kW to 160 kW were subjected to investigation.

The asynchronous motors with short-circuited rotor series 4A (4A112M4Y3 with Pn = 5.5 kW; 4A225M4Y3 with Pn = 55 kW; 4A315S4Y3 with Pn = 160 kW) and series AI (AIR112M4 with Pn = 5,5 kW; AIR225M4 with Pn = 55 kW; AIR315S4 with Pn = 160 kW) with the rated parameters [17,18] given in (Table1) were selected as examples.

Table 1. Cataloged data of investigated three-phase motors.

Motor power capacity, Pn, kW	Motor model	Rated rotation frequency, n, rpm	η	cosφ	Starting torque-to-nominal torque ratio, Kst	Starting current-to-rated current ratio, Ksc
5.5	4A112M4Y3	1500	85.5	0.85	2.2	7
55	4A225M4Y3	1500	92.5	0.9	2.5	7
160	4A315S4Y3	1500	93.5	0.91	2.2	6
5.5	AIR112M4	1500	85.5	0.86	2.5	7
55	AIR225M4	1500	93	0.89	2.6	7
160	AIR315S4	1500	93.5	0.91	2	5.5

Characteristic curves of phase currents from K_{2U} for AM series 4A, AI were obtained during computer-aided simulation. Current curves in the function from K_{2U}, under different values of motor shaft load were plotted for each phase of considered AM.

The main type of current change in the most loaded phase (phase "A") of AM series 4A, AI with Pn = 5.5; 55; 160 kW, under different values of K_{2U} and different values of motor shaft load is given in (Fig.2 - 4).

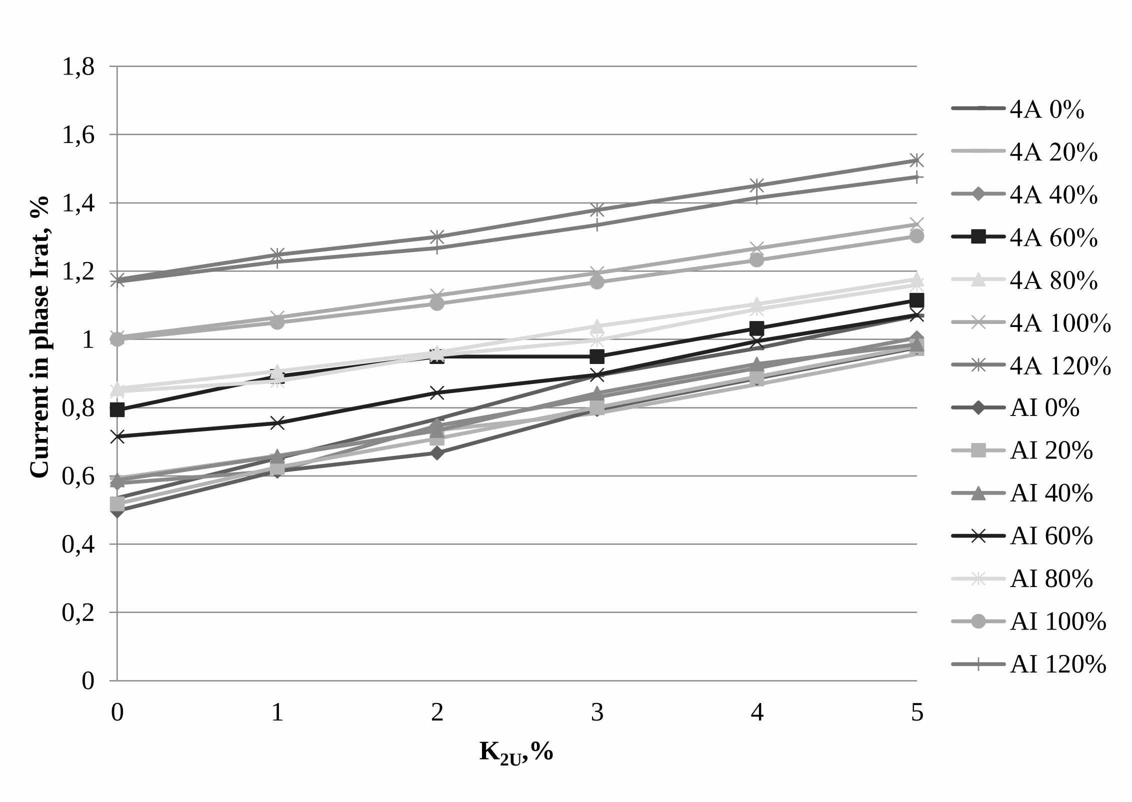

Fig.2. Curve of current in phase "A" AM series 4A, AI with Pn = 5.5 kW from K_{2U} under different permanent load factors.

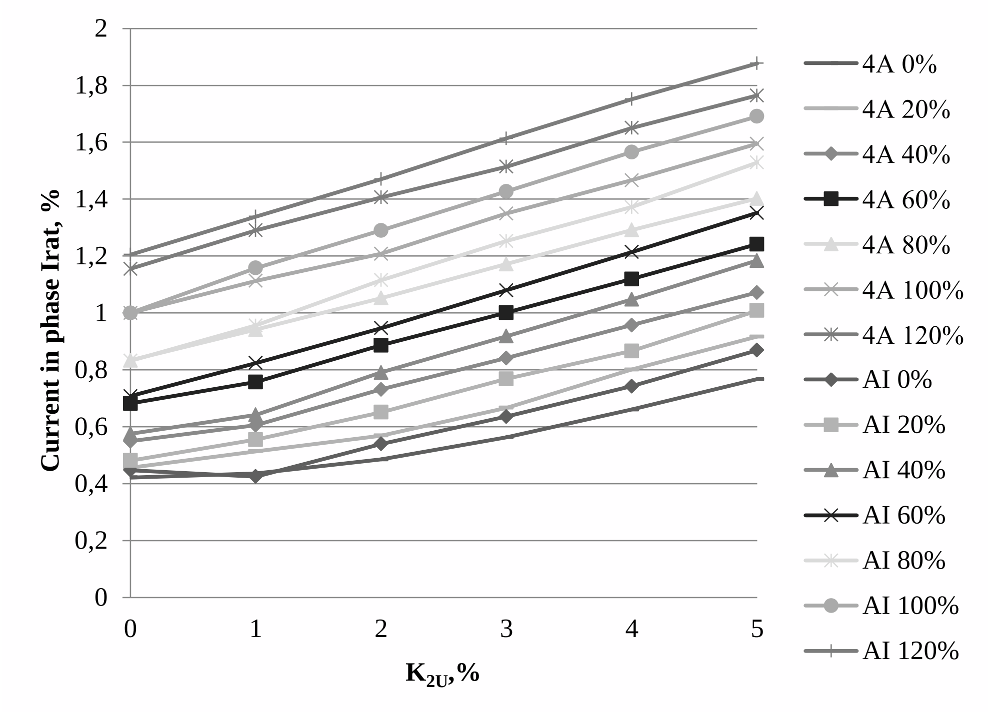

Fig.3. Curve of current in phase "A" AM series 4A, AI with Pn = 55 kW from K_{2U} under different permanent load factors.

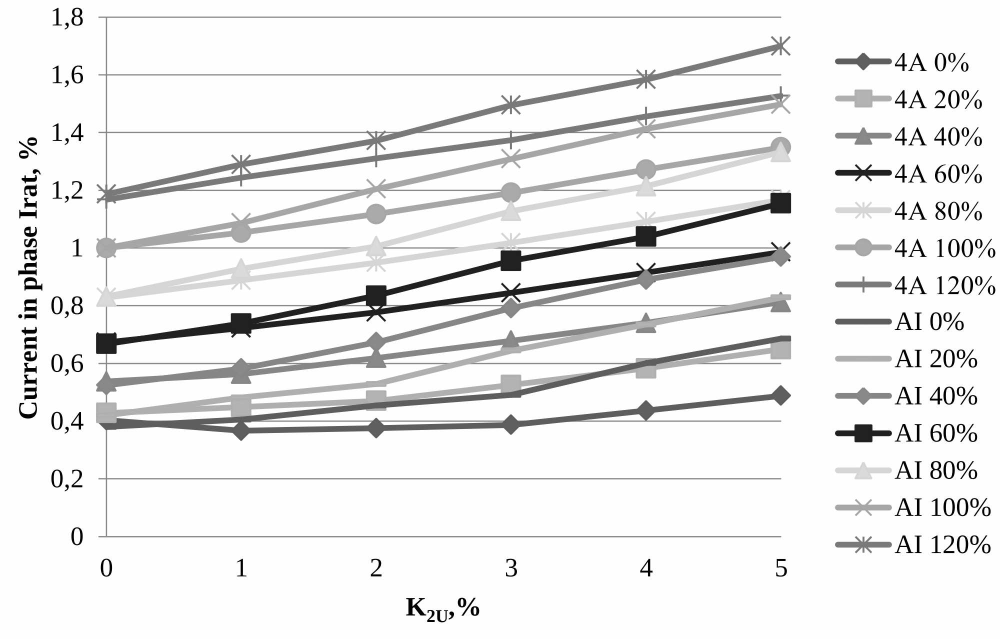

Fig.4. Curve of current in phase "A" AM series 4A, AI with Pn = 160 kW from K_{2U} under different permanent load factors.

3 Investigation results and their discussion

Analisys of computer-aided simulation (Fig.2-4) allowed revealing the following trends:

1) asynchronous motors with rated power capacity 5.5 kW:

- AM series 4A Pn = 5.5 kW, i.e. the specified series motors with small rated power, are subjected to greater effect of asymmetry of supply voltage and may breakdown even under standard GOST 32144–2013 values of K_{2U}. Thus, with the load value equal to 100%, the current in phase "A" exceeds the allowable over current accepted as equal to 1.1 of the rated current (this is the permissible excess value in accordance with relay protection requirement [19,20]), with K_{2U} = 1.3%, and for AM series AI Pn = 5.5 kW it occurs with the value K_{2U} = 2%. The motors series 4A overload under 80% load already working within the permissible range of K_{2U}, series AI under 100% load,

- overcurrent of motors series 4A Pn = 5.5 kW is observed with the value K_{2U} above 4% with K_z = 60%, and for series AI with K_z = 80%, under load factor increase up to 100%, the start of winding insulation heating is observed under K_{2U} from 1,3% to 2%,

2) asynchronous motors with rated power capacity 55 kW:

- the start of winding insulation heating is observed in the specified AM under K_{2U} = 0-4%, whereas this shall be outside that range limits. At that, this is observed with K_z = 60-100%,

- with the load of the motor series AI up to 40%, and the motor series 4A up to 60 %, AM standard operation mode will be observed with the standard value K_{2U} from 0 to 4%,

3) asynchronous motors with the rated power capacity 160 kW:

- for the motor series AI Pn = 160 kW under K_z up to 60% and the motor series 4A Pn = 160 kW under K_z up to 80% the standard operation mode with K_{2U} from 0 to 4% will be observed, which corresponds to GOST 32144–2013.

- for both series, with K_z above 80 % the start of winding insulation heating within the standard ranges of K_{2U} occurs,

4) the currents under motor full load are of ultimate interest. With the load value equal to 100%, the current in phase "A" for AM series 4A Pn = 5.5 kW exceeds the allowable overcurrent accepted as equal to 1.1 of the rated current under K_{2U} = 2% [19,20]. For the motor series 4A Pn = 55 kW, excess of the allowable overcurrent occurs upon reaching K_{2U} = 0.9 %. This attests to the fact that the motors have not only contrasting ranges of permissible values by K_{2U}, but also the values, which do not always correspond to the ones standardized by the GOST. Correspondingly, during operation of motors in locations with poor quality electric power, it is necessary to adjust the supply voltage guided not by the GOST for electric power quality, but by the motor operation mode.

Based on the objective set forth in the research study, the main conclusions can be represented:

1) the following indicators affect AM allowable operation mode under asymmetry of supply mode:

motor series, power capacity, load factor (K_z) and voltage unbalance ratio by reverse sequence (K_{2U}).

Thus, under K_z within the range from 60% to 80% the start of majority of AM is observed under K_{2U} value below 4%. The range of AM series 4A operation modes is under K_z from 0 % to 60%, the range of AM series AI is under K_z from 0 % to 80% with K_{2U} from 0% to 4%.

The medium power capacity AM series 4A and AI are most susceptible to asymmetry of voltages. Under motor full load, they have the allowable K_{2U} value:

- AM series 4A Pn = 5.5 kW allowable value K_{2U} = 1.3%, AM series AI Pn = 5.5 kW K_{2U} = 2%,
- AM series 4A Pn = 55 kW allowable value K_{2U} = 0.9%, AM series AI Pn = 55 kW K_{2U} = 0.7%,
- AM series 4A Pn = 160 kW allowable value K_{2U} = 1.8%, AM series AI Pn = 160 kW K_{2U} = 1.4%.

Consequently, the allowable value K_{2U} differs not by AM series only, but also due to motor series, because of the motor power capacity immediately,

2) the allowable range of K_{2U} (under AM standard operation mode) with permanent asymmetry of voltages, full motor load:

- for the motor series 4A Pn = 5.5 kW, the allowable range K_{2U} from 0 to 1.3%, for the motor series AI Pn = 5.5 kW K_{2U} from 0 to 2%,
- for the motor series 4A Pn = 55 kW the allowable range K_{2U} from 0 to 0.9%, for the motor series AI Pn = 55 kW K_{2U} from 0 to 0.7%,
- for the motor series 4A Pn = 160 kW the allowable range K_{2U} from 0 to 1.8%, for the motor series AI Pn = 160 kW K_{2U} from 0 to 1.4%.

Consequently, under excess of ultimate permissible value K_{2U}, overheating of AM winding insulation will be observed,

3) AM reliability significant reduction occurs under K_{2U} exceeding 4%. To exclude overheating of both AM series 4A, and AI breakdown, it is necessary to reduce the load.

AM full load is possible only under K_{2U} maximum 1 % [11].

Thus, after performing the complex of investigations on effect of asymmetry of voltages on asynchronous motor operation modes, the recommendations on AM series 4A and AI operation under asymmetry of supply voltages were stated:

1) AM series 4A are subjected to the largest effect of asymmetry of voltages, therefore, at the stage of AM power supply system designing and modernization, this condition should be taken into account. Consequently, AM series AI are less exposed to effect of asymmetry of voltages, and have increased operation reliability,

2) to avoid the motor overheating and premature breakdown, it is necessary to reduce its load,

3) rate setting of the voltage unbalance ratio by reverse sequence should be carried out based on the motor permissible operation modes and their models produced in lots,

4) to make responsive control during UPQI (unified power quality index) deviations, for stable operation of AM, it is necessary to control the electric power parameters at the enterprise input or at the respective motors,

5) it is proposed to use the investigation results for correction of current standards in the area of electric power quality standards, as well as in specifications for particular motor series,

6) the investigation results will be necessary for development and designing of PSP (power supply system) containing AM. Particularly, it will be relevant

for regions with large amount of one-phase non-linear load,
7) the obtained values of allowable values K_{2U} for AM play the key role during symmetry facilities selection and implementation in the power supply system with the motor drive load,
8) it seems feasible to use the approach based on the method of computer-aided simulation in Matlab/Simulink environment for assessment of affect of voltage supply asymmetry on AM operation.

4 Conclusion

The effect of asymmetry of voltages on asynchronous motor operation modes was investigated using the computer-aided simulation experiments, the software complex Matlab and the package program Simulink. Following the investigation results, the significant effect of the asymmetry system of supply voltages on different series and power capacity AM operation modes was detected. Based on specific examples, change of characteristic curves, on the quantitative side, was demonstrated. Recommendations on operation of asynchronous motor series 4A and AI in conditions of asymmetry of supply voltages were presented.

During solution of issues for ensuring asynchronous motor operation reliability, the experimental investigations form the basis. Their practical implementation will allow for improving reliability of motors operated in conditions with available permanent asymmetry of voltages.

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References

1. GOST P 51137-98. Adjustable asynchronous electric drives for power generation facilities. General Specifications. – M.: IPC (Publishing and Printing Complex) Publishing House of Standards, **12** (1998).
2. M. Katsman, Electrical machines. – M.: Higher School, **463** (2000).
3. A. Gusarov, Electrical and Power Engineering. Scientific publications, Donetsk National Technical University. Issue 8 (140), 95 – 97 (2008).
4. I. Zhezhelenko, Yu. Sayenko, A. Gorpinich, I. Shvetsova, Priazovsk National Technical University Reporter: Collection of scientific articles / PNTU. – Mariupol Issue 15, P.2., 25 – 29 (2005).
5. M. Sorkind, Electric Engineering News. Information and Reference Publishing House No. 2 (32), (2005).
6. M. Fedorov, N. Ivchenko, A. Tkachenko, DNMBA (Donbass National Machine-Building Academy) Scientific Research Reporter. Collection of scientific papers No. 1 (11E) – DNMBA, Kramatorsk, 164–170 (2013).
7. O. Pipchuk, Electrical and Power Engineering. Scientific publications, Donetsk National Technical University. Issue 8 (140), 201 – 205 (2008).
8. I. Zhezhelenko, Electric power quality at industrial enterprises – M.: Energoatomizdat, – **261** (2005).
9. GOST 32144 – 2013. Electrical power. Electromagnetic compatibility of technical equipment. Electrical power quality standards in the general purpose power supply systems. – M.: Standartinform, **19** (2014).
10. GOST IEC 61000-4-27-2016 Electromagnetic compatibility (EMC). Part 4-27. Test and measurement methods. Test forimmunity to asymmetry of voltages for equipment with current consumption maximum 16 A per phase. – M.: Standartinform, **17** (2016).
11. GOST IEC 60034-26 – 2015. Part 26. Effect of unbalanced voltages on operating characteristics of three-phase asynchronous motors (IEC 60034-26:2006, IDT). – M.: Standartinform, **11** (2016).
12. GOST P 52776–2007 (IEC 60034–1–2004). Rotating electric machines. Rated data and features – M.:Standartinform, **68** (2008).
13. I. Suvorov, A. Sidorov, S. Khromov, Electrical safety. Quarterly Journal of Theory, Research and Practice – Chelyabinsk:SUSU (South Ural State University), No. 3, 17 – 30 (2014).
14. S. German-Galkin, G. Kardonov, Electrical machines: Laboratory works with PC. – SBR: Korona-print, **256** (2003).
15. I. Chernykh, Simulation of electrical devices using MATLAB, SimPowerSystems and Simulink. – SBR: Piter M.: DMK Press, **288** (2008).
16. V. Romanova, S. Khromov, Collection of scientific papers. – Voronezh: ITSRON (Russian Association Research Center), 35 – 41 (2015).
17. http:// principact.ru/content/view/166/72/
18. www.elektrikii.ru/publ/6-1-0-55
19. http://www.bmrzzakharov.narod.ru/raschet/overload.html
20. V. Kogorodsky, S. Kuzhekov, L. Paperno, Relay protection of motors with voltage above 1 kV. – M.: Energoatomizdat, **248** (1987).