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ABSTRACT

of the dissertation for the degree of Doctor of Technical Sciences

MODELING AND RESEARCH OF TRANSIENT PROCESSES IN ELECTROMECHANICAL CONVERTERS OF SYSTEM WIND ELECTRIC INSTALLATIONS UNDER THEIR CONTROL

Specialty: 3340.01 – Electrical systems and complexes

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Dissertation council ED 2.04 of Supreme Attestation Commission under the President of the Republic of Azerbaijan operating at Azerbaijan Technical University

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GENERAL DESCRIPTION OF WORK

Relevance of the topic and the degree of development. The development of scientific methods for the analysis and study of the operating modes of modern wind turbines operating in the power system began almost simultaneously with the release and implementation of the first industrial wind turbines in the late 70s and early 80s of the last century. Although the first works on the principles of operation of wind power plants of low power appeared earlier in the 50-60s, however, there were no system studies.

A significant amount of work has been devoted to the study of the operating modes of wind power plants operating on an electric network, moreover, the geography of these works is extensive – these issues are intensively dealt with in Europe (Denmark, Germany, Spain, England), in America (mainly in the USA), in Asia (China, India). These studies are devoted to a wide range of issues: the study of the wind energy characteristics of the regions suitable for systemic wind energy[1]; study of the characteristics and performance of the wind turbines themselves[2]; research and optimization of the operating modes of electromechanical converters used in systemic wind energy[3], and finally research on the issues of joint operation of wind power plants in parallel with the power system[4].

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[1] Региональные аспекты ветроэнергетики / Иванова, И. Ю., Карамов, Д. Н., Постников, И. В. [и др.]; отв. редакторы В. А. Стенников, В. Г. Курбацкий; Рос. акад. наук, Сиб. отд-ние, Ин-т систем энергетики им. Л. А. Мелентьева СО РАН. – Новосибирск: СО РАН, – 2020. – 296 с.

[2] Дзензерского, В.А., Пивняка, Г.Г. Ветроэнергетика. Информационно-аналитический обзор по альтернативной энергетике: монография /С.В. Тарасов, Ф.П. Шкрабец, В.А. Задонцев, С.В. Отчич; под общ. ред. В.А. Дзензерского и Г.Г. Пивняка; М-во образования и науки Украины, Нац. горн. ун-т. – Д.: НГУ, – 2014.

[3] Bellarbi, S. Electromechanical study the wind energy conversion system based DFIG and SCIG generators // International journal of mechanics. – 2021; Vol. 15, – p. 102-106.

[4] Qazi, S. H., Mustafa, M. W. B. Technical issues on integration of wind farms with power grid-A review // International Journal of Renewable and Sustainable Energy. – 2014. Vol.3, No. 5, – p. 87-91.

Each of the above areas is a separate independent problem in the general problem of global issues of the development and operation of industrial system wind power plants of large capacities operating on an electric network.

In this dissertation, a circle of research has been outlined only by electromechanical converters (i.e. electric machines) of wind turbines. In our opinion, this wind power plants assembly is one of the most important and complex, but most importantly, it is the most easily managed (including by optimal laws) wind turbine assembly, which makes it possible to increase the stability and efficiency of the entire wind turbine.

Since the work deals with large wind turbines of a megawatt class operating on an electric network, it is natural that the network and consumers make high demands primarily on the quality of the generated electricity, while achieving economic and technological efficiency of the operation of the wind turbines themselves, which are provided by the corresponding automation and control systems.

Processing and analysis of numerous sources of technical literature[5] shows that to date, systems of electromechanical conversion of wind energy into electrical energy consisting of "classical" synchronous and asynchronous squirrel-cage generators containing frequency converters in stator chains of these machines. Moreover, the frequency converters used in wind energy are made on fully controlled gate turn-off thyristor (GTO), or on insulated gate bipolar transistors (IGBT) power transistors.

In addition to the above generators, generators based on double-fed asynchronous machines, controlled by frequency converters on the rotor side, as well as frequency-controlled synchronous generators with permanent magnets, are widely used in wind energy.

The application of the above schemes for generating electric energy is determined by the type and power of the wind power plants,

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[5] Касьянов, С. Е., Москаленко, В. В., Рывлин, И. А. и др. Принципы моделирования ветроэнергетических установок для расчета токов короткого замыкания // Известия НТЦ единой энергетической системы. – 2017. № (1) 76, – с.21-26.

the wind characteristics of the region where the wind turbine is installed, the conditions put forward by the electric networks in the places of their connection, the nature of the load, etc.

For all electromechanical converters used in wind energy, one circumstance is indisputable – the energy carrier in them is the wind flow, the speed of which determines the power that the wind power plants give out to the power system.

The wind speed is variable, the range of its changes can reach significant values, moreover, the rate of change of wind speed fluctuations (i.e. accelerations) can reach significant values.

All this dictates the need for knowledge, the ability to determine and control the dynamic modes of operation of frequency-controlled electromechanical converters used in modern wind power plants.

As noted, in addition to studying dynamic modes and ensuring the stability of the operation of frequency-controlled wind power plants generators, the problem of increasing the efficiency of the operation of wind power plants in quasi-stationary operating modes and ensuring the quality of electric energy delivered to the network is important.

Of course, there are many sources of technical literature where the above issues have been resolved to one degree or another. However, a literature review shows that today there are no universal and relatively simple engineering methods for modeling and studying the dynamic and static operating modes of megawatt-class system wind power plants, the electromechanical converters of which are equipped with frequency converters, the control and optimization issues are not fully addressed operating modes of these wind power plants.

All of the above clearly allows us to conclude that the topic of the dissertation is relevant.

Object and subject of the study. The object of the study is the alternating current machines used in wind turbines. The subject of the study is the development of a universal structure of the mathematical model of alternating current electric machines and the study on these models of various modes of operation of these machines.

Purpose and objectives of the research. The purpose of this dissertation is the development of universal, relatively simple methods of mathematical modeling of frequency-controlled synchronous and asynchronous generators of various types used in systemic wind energy, the study of these models of dynamic and quasi-established wind power plants operating modes together with their control and optimization.

Achieving this goal will significantly increase the sustainable and high-quality conversion of wind energy into electrical energy.

In turn, this goal can be achieved by solving the following **tasks** of the theme:

– development of a universal structure of a mathematical model of almost all types of electric machines used in wind power plants, based on equations written in axes that rotate with the speed of the machine rotor. The structure of the model makes it possible to take into account all possible types of control of AC machines: frequency regulation both from the side of their stator and from the rotor;

– development of a three-coordinate mathematical model of frequency-controlled three-phase asynchronous wind power plants machines with both a squirrel-cage rotor and a phase rotor (double-fed asynchronous machine);

– development of a mathematical model of a frequency-controlled synchronous wind power plants generator with permanent magnets and with electromagnetic excitation;

– study of dynamic and quasistatic modes of operation of all types of frequency-controlled wind power plants generators, on developed mathematical models with the issuance of recommendations for the management and optimization of these modes.

The combination of these tasks and their solution is sufficient to achieve the goal set in the thesis, and this will improve the design quality of large wind power plant, as well as the efficiency of their functioning.

Research methods. The methods used to study electric machines used in this work are based on the three laws of electromechanics:

– electromechanical energy conversion cannot be feasible with an efficiency of 100%, i.e. $\eta < 100\%$;

– all electric machines are reversible, i.e. the same electric machine can work both as a generator and as an engine;

– electromechanical energy conversion is carried out by electromagnetic fields motionless relative to each other. That is, the resulting field in the machine is created by the stator and rotor fields, while in the steady state these fields are stationary relative to each other.

The main research method in this thesis is the method of mathematical modeling of AC electric machines used in systemic wind energy. The originality of the proposed simulation methods for electromechanical transducers lies in the fact that they are firstly universal, i.e. in one structure they allow you to study different types and types of machines, and secondly they allow you to relatively easily reproduce all the control methods of these machines, naturally, for AC machines, the main control method is frequency for both synchronous and asynchronous machines, as well as excitation control synchronous machines and voltage amplitude for asynchronous machines.

In addition to this basic method, for solving particular problems, the Pontryagin optimal control method, methods of transformation using Fourier series, and also methods of the theory of automatic control and regulation found additional application in the work.

Thus, to solve the tasks and achieve the goal of the dissertation, the following mathematical apparatus:

- theory of linear and nonlinear differential equations;
- theory of automatic regulation and control;
- elements of optimal control theory.

Moreover, it should be noted that all modeling methods developed and applied for research should fully satisfy the three laws of electromechanics presented above.

The basic provisions giving to the defence:

1. The unified structure of the mathematical model of all the main frequency-controlled electric machines used in wind energy, which allows to significantly simplify the modeling and research procedure and easily compare and evaluate the results of studies of various types of wind power plants generators.

2. A three-coordinate model of a frequency-controlled asynchronous dual-power machine, which is especially important for studies of asymmetric and non-phase modes of operation.

3. The mathematical model of a synchronous generator with permanent magnets of wind power plants, the essence of which is to take into account the influence of a permanent magnet in the equations of the generator, as well as in the method of controlling the amplitude and frequency of the stator voltage of the generator.

4. The study of the static and dynamic characteristics of wind power plants containing synchronous generators with permanent magnets, ways to increase stability and damping the oscillations of the rotors of these generators.

5. The simulation model of the system, “wind – wind turbine – electromechanical converter – electric network”.

6. A method for taking into account the influence of higher harmonic voltages on the operating parameters of adjustable electric wind turbines.

7. Analysis of the performance of asynchronous machines with scalar control.

8. A comparative analysis of the frequency starting modes of asynchronous wind power plant generators.

9. The method of transferring double-fed asynchronous machines to the synchronous generator mode with technological necessity and its mathematical model.

10. The method of modeling the angle of rotation of the blades of wind turbines of wind power plant.

11. Methods of reactive power compensation for asynchronous generators of various designs.

12. Consideration of the influence of external network parameters and local load on the mode of operation of wind power plant with double-fed asynchronous machines.

13. Modeling and research of wind power plant operation modes with double-fed asynchronous machines in parallel with a limited power source.

The scientific novelty of the work lies in the further development of the scientific direction in wind energy, which includes the development of new provisions in the methodology of modeling, research, including with elements for optimizing transient and quasi-stationary processes in all types of electromechanical wind power plants operating on an electric network.

Scientific novelty includes:

– development of a unified structure of a mathematical model of wind-driven electric machines for alternating current wind power plants;

– development of a three-coordinate mathematical model of wind power plants asynchronous machines;

– development of a simulation method for a synchronous wind power plants generator with permanent magnets controlled by a frequency converter from the stator;

– research and analysis of various laws of regulation in quasistationary modes for synchronous wind power plants with permanent magnets and with electromagnetic excitation in frequency control;

– modeling and research of dynamic modes of wind power plants equipped with frequency-controlled synchronous generators with permanent magnets;

– vibration damping of rotors of frequency-controlled synchronous machines with permanent magnets using elements of Pontryagin's theory of optimal control;

– modeling and research of the influence of higher harmonic voltages of the frequency converter on the operating parameters of a synchronous generator with permanent magnets and the parameters of double-fed asynchronous machines wind power plants;

– the effect of changes in the mains voltage on the mode of operation of a wind power plants with a double-fed asynchronous machine and ways to increase the system dynamic stability;

– evaluation of the results of the calculation of wind power plants operation modes with double-fed asynchronous machines using the full and simplified equations of the mathematical model;

– analysis of the functioning efficiency of frequency-controlled asynchronous machines with a squirrel-cage rotor with scalar control and ensuring minimum power losses in the machine itself, as well as the constancy of the overload capacity and magnetic flux;

– comparative analysis of the frequency start-up modes of wind power plants with asynchronous squirrel-cage generators and wind power plants with double-fed asynchronous machines;

– technical solution for the use of double-fed asynchronous machines wind power plants in synchronous operation, its modeling and research;

– simulation method for adjusting the angle of rotation of the wind power plants blades;

– methods of reactive power compensation for asynchronous generators with squirrel-cage rotor and for double-fed asynchronous machine;

– modeling and research of the influence of external network parameters and local load on the wind power plants operating modes with a dual power machine operating on an infinite power network;

– study of wind power plants operating modes with double-fed asynchronous machines while working in parallel with a limited power source;

– simulation of wind power plants operating modes with various electromechanical converters.

The theoretical and the practical importance of the research. The proposed modeling methods, calculation algorithms, as well as numerous fluctuograms obtained on various models are brought to the engineering perception and can be used both at the design stage of a wind park consisting of several tens of wind power plant and at the stage of its operation.

The obtained research results and technical solutions can significantly increase the stability and efficiency, including economic, of the operation of wind power plant with various electromechanical converters, including in the wind conditions of Azerbaijan.

Over the years, the results in the form of practical recommendations have been systematically transmitted (implemented) to the relevant Azerenerji services. Some of the recommendations were also submitted for practical use at the State Agency for Alternative and Renewable Energy Sources of Azerbaijan.

Approbation and application of the research work. The main results and scientific provisions of the dissertation were reported at international conferences:

– "Energy Relations of Russia and East Asia: Development Strategy in the 21st Century. Joint Symposium. Irkutsk, Russia: August 30 – September 10, 2010;

– 6th International Conference on "Technical and Physical Problems of Electrical Engineering" (ICTPE-2010), Tabriz, Iran: September14–16, 2010;

– 3rd International Conference on Control and Optimization in Industry (COIA 2011), Ankara, Turkey: August 22–24, 2011";

– 8th International Conference on Technical and Physical Problems in Power Engineering (ICTE-2012), Ostfold University College, Fredrikstad, Norway: September 5–7, 2012;

– "Methodological issues of researching the reliability of large energy systems." International Scientific Seminar Yu. I. Rudenko "Reliability of liberalized energy systems." St. Petersburg, Russia: June 30 – July 4, 2015;

– International Conference Modern Electric Power Systems (MEPS'15), Wroclaw, Poland: July 6–9, 2015;

– 12th International Conference on "Technical and Physical Problems of Electrical Engineering" (ICTPE-2016), Bilbao, Spain: September 7–9, 2016;

– 18th IFAC Conference on Technology, Culture and International Stability (TECIS 2018), Baku, Azerbaijan: September 13–15, 2018;

– 1st International Conference on energy of Future: Challenges and Opportunities (ICEFCO– 2018), Baku, Azerbaijan: September 10–13, 2018;

– 14th International Conference on “Technical and Physical Problems of Electrical Engineering”. Nakhchivan State University (ICTPE-2018), Nakhchivan, Azerbaijan: October 15–17, 2018;

– 15th International Conference on “Technical and Physical Problems of Electrical Engineering” (ICTPE-2019), Istanbul, Turkey: October 13–15, 2019.

In addition, the results were reported at seminars of the Azerbaijan Scientific Research and Design and Survey Institute of Power Engineering and in the relevant services of Azerenergy OJSC.

The results in the form of practical recommendations have been systematically transferred (implemented) to the relevant services of Azerenergy OJSC over a number of years. Some of the recommendations have also been transferred for practical use to the State Agency for Alternative and Renewable Energy Sources of Azerbaijan.

The name of the institution where the dissertation work was performed. The dissertation work was carried out at the Azerbaijan Scientific-Research and Design-Prospecting Power Engineering Institute.

Publication level of the research. The main results of the dissertation work are presented in 60 scientific publications, including 46 scientific articles, 12 materials and abstracts of international scientific conferences, as well as 1 monograph and 1 patent. Of the total number of publications, 34 works were published abroad. Twelve articles are posted in periodicals indexed in international databases: Web of Science (3 articles) and Scopus (9 articles). Six scientific articles were written by the author independently, without co-authors.

The structure of the dissertation with a sign including a separate volume of the structural units of the dissertation. The total volume of the dissertation in characters with the indication of the volume of its structural sections separately. The content of the dissertation is presented on 354 pages together with 14 tables, 70 figures and a list of technical literature, numbering 267 titles, 22 of which are Internet resources. The total volume of the dissertation (excluding spaces, tables, graphs and the list of used literature) was 343808 characters: Introduction – 26 pages (41296 characters), four chapters (Chapter I – 51 pages, (51980 signs); Chapter II – 72 pages (78886 signs); Chapter III – 109 pages (111604 signs); Chapter IV – 44 pages (37987 signs)), Conclusions – 11 pages (18257 signs).

THE CONTENT OF THE WORK

The introduction analyzes the dynamics of growth of wind energy capacities throughout the world [6,7], as well as assesses the state and development of wind energy in Azerbaijan[8,9].

The substantiation and formulation of the tasks to be investigated. The relevance of the topic of the dissertation is determined, the objectives of the study are formed, research methods are given with their justification.

It also characterizes the scientific novelty of the tasks solved in the dissertation, the main provisions to be defended, the practical value of the work, as well as approbation of the work, the list of publications and the structure of the dissertation.

The first chapter discusses the analysis of the types and types of electromechanical converters[10] used in modern wind power installations of the megawatt class, operating on an electrical

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[6] Renewable Energy Statistics 2022: [Electronic resource] / International Renewable Energy Agency (IRENA). – July 18, 2022. URL: https://www.irena.org/Statistics

[7] IEA Wind TCP Annual Report – 2020, – p. 56.

[8] Насибов В.Х. Развитие ВИЭ и энергоэффективности в Азербайджане за последние годы: [Elektron resurs] / UNECE – October 11, 2021. URL: https://unece.org/sites/default/files/2021-11/10-Valeh-Nasibov-Azerbaijan.pdf

[9] Отчет GWEC: [Elektron resurs] / – 2021. URL: https://www.gwec.net/

[10] Котов, А. А. Применение генератора двойного питания для ветроэнергетических установок малой, средней и большой мощности / А. А. Котов, Н. И. Неустроев // Вестник ЮУрГУ. Серия «Энергетика». – 2017; – Т. 17, № 4. – с. 80-89.

network[11]. It is noted that the method of mathematical modeling is the most effective and promising method for studying transient and quasi-steady-state modes of operation of electric machines in wind power plants[12,13].

In this regard, a new structure has been developed for a universal mathematical model of frequency-controlled electric machines of wind-driven installations. It allows in one structure of equations to describe and explore all types of electrical machines used in wind energy. Below is the structure of a universal mathematical model of frequency-controlled electric wind turbines.

The well-known Park-Gorev[14] equations, which are written in the axes rotating at the speed of rotor ω_r, are taken as the basis for the mathematical model of frequency-controlled electric AC machines, and the machine is equipped with two stator and four rotor windings. In contrast to the Park-Gorev equations in the presented equations, the main parameter is not the angle of power θ between the axis of the rotor rotating with the speed of the rotor ω_r and the synchronous axis rotating with the synchronous speed ω_s, but the angle between the axis of the rotor and the fixed axis, which is denoted by the angle α. Thus, the rotor speed is $\omega_r = p\alpha = \dfrac{d\alpha}{d\tau}$, where p – differentiation symbol, τ – synchronous time equal $\tau = \omega_s \cdot t = 314 \cdot t$, t – time in second[1].

In this case, the equations of controlled electric AC machines can be written in the cell-matrix form:

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[11] Yaramasu, V. High-power wind energy conversion systems: State-of-the-art and emerging technologies / V. Yaramasu, B. Wu, P.C. Sen [et al.] // Proc. IEEE – 2015.103, – p. 740-788.

[12] Копылов, И.П. Математическое моделирование электрических машин: учебник для ВУЗов / под ред. И.П.Копылова. – 3-е изд., перераб. и доп. – Москва: Высшая школа, – 2001. – 327 с.

[13] Соколова, Н.И. Применение аналоговых вычислительных машин в энергетических системах / Н.И.Соколова, И.А.Груздев, К.П.Кадомская, [и др.] – Москва-Ленинград: Энергия, – 1964. – 408 с.

[14] Воропай, Н.И. Электромеханические переходные процессы: учеб. пособие / Н.И. Воропай. – Благовещенск: АмГУ, – 2013. – с. 151.

$$\begin{bmatrix} p\boldsymbol{\Psi}_s \\ p\boldsymbol{\Psi}_f \\ p\boldsymbol{\Psi}_r \end{bmatrix} = \begin{bmatrix} \boldsymbol{A}_{s1} & \boldsymbol{A}_{s2} & \boldsymbol{A}_{s3} \\ \boldsymbol{B}_{f1} & \boldsymbol{B}_{f2} & \boldsymbol{B}_{f3} \\ \boldsymbol{C}_{r1} & \boldsymbol{C}_{r2} & \boldsymbol{C}_{r3} \end{bmatrix} \cdot \begin{bmatrix} \boldsymbol{\Psi}_s \\ \boldsymbol{\Psi}_f \\ \boldsymbol{\Psi}_r \end{bmatrix} + \begin{bmatrix} \boldsymbol{U}_s \\ \boldsymbol{U}_f \\ \boldsymbol{U}_r \end{bmatrix} \tag{1}$$

Column matrices are the essence of a vector with projections on the *d*, *q* axis: –differential flux linkages of the stator, excitation and rotor windings:

$$p\boldsymbol{\Psi}_s = \begin{bmatrix} p\boldsymbol{\Psi}_{ds} \\ p\boldsymbol{\Psi}_{qs} \end{bmatrix};\ p\boldsymbol{\Psi}_f = \begin{bmatrix} p\boldsymbol{\Psi}_{df} \\ p\boldsymbol{\Psi}_{qf} \end{bmatrix};\ p\boldsymbol{\Psi}_r = \begin{bmatrix} p\boldsymbol{\Psi}_{dr} \\ p\boldsymbol{\Psi}_{qr} \end{bmatrix};\ \boldsymbol{\Psi}_s = \begin{bmatrix} \Psi_{ds} \\ \Psi_{qs} \end{bmatrix};$$

$$\boldsymbol{\Psi}_f = \begin{bmatrix} \Psi_{df} \\ \Psi_{qf} \end{bmatrix};\ \boldsymbol{\Psi}_r = \begin{bmatrix} \Psi_{dr} \\ \Psi_{qr} \end{bmatrix}\ \text{и}\ \boldsymbol{U}_s = \begin{bmatrix} U_{ds} \\ U_{qs} \end{bmatrix}; \boldsymbol{U}_f = \begin{bmatrix} U_{df} \\ U_{qf} \end{bmatrix};\ \boldsymbol{U}_r = \begin{bmatrix} U_{dr} \\ U_{qr} \end{bmatrix}.$$

The remaining matrices are equal:

$$\left.\begin{aligned}
&\boldsymbol{A}_{s1} = \begin{bmatrix} -r_s \cdot k_{ds} & -\omega_r \\ \omega_r & -r_s \cdot k_{qs} \end{bmatrix}; \quad \boldsymbol{A}_{s2} = \begin{bmatrix} -r_s \cdot k_{dsf} & 0 \\ 0 & -r_s \cdot k_{qsf} \end{bmatrix}; \\
&\boldsymbol{A}_{s3} = \begin{bmatrix} -r_s \cdot k_{dsr} & 0 \\ 0 & -r_s \cdot k_{qsr} \end{bmatrix}; \quad \boldsymbol{B}_{f1} = \begin{bmatrix} -r_{df} \cdot k_{dsf} & 0 \\ 0 & -r_{qf} \cdot k_{qsf} \end{bmatrix}; \\
&\boldsymbol{B}_{f2} = \begin{bmatrix} -r_{df} \cdot k_{df} & 0 \\ 0 & -r_{qf} \cdot k_{qf} \end{bmatrix}; \quad \boldsymbol{B}_{f3} = \begin{bmatrix} -r_{df} \cdot k_{dfr} & 0 \\ 0 & -r_{qf} \cdot k_{qfr} \end{bmatrix}; \\
&\boldsymbol{C}_{r1} = \begin{bmatrix} -r_{dr} \cdot k_{dsr} & 0 \\ 0 & -r_{qr} \cdot k_{qsr} \end{bmatrix}; \quad \boldsymbol{C}_{r2} = \begin{bmatrix} -r_{dr} \cdot k_{dfr} & 0 \\ 0 & -r_{qr} \cdot k_{qfr} \end{bmatrix}; \\
&\boldsymbol{C}_{r3} = \begin{bmatrix} -r_{dr} \cdot k_{dr} & 0 \\ 0 & -r_{qr} \cdot k_{qr} \end{bmatrix}.
\end{aligned}\right\}$$

where r_s, r_{df}, r_{qf}, r_{dr}, r_{qr} – respectively, the active resistance of the stator, field windings and rotor windings along the axes *d*, *q*; the coefficients k_{ds}, k_{dsf}, k_{qs}, k_{qsf}, k_{qsr}, k_{df}, k_{dfr}, k_{qf}, k_{qfr}, k_{dr} and k_{qr} connect the stator currents i_{ds}, i_{qs} of the i_{df}, i_{qf} field windings and i_{dr}, i_{qr} rotor windings with the corresponding flux linkages.

They are easily determined from the equality of the following matrices:

$$\begin{bmatrix} k_{ds} & 0 & k_{dsf} & 0 & k_{dsr} & 0 \\ 0 & k_{qs} & 0 & k_{qsf} & 0 & k_{qsr} \\ k_{dsf} & 0 & k_{df} & 0 & k_{dfr} & 0 \\ 0 & k_{qsf} & 0 & k_{qf} & 0 & k_{qfr} \\ k_{dsr} & 0 & k_{dfr} & 0 & k_{dr} & 0 \\ 0 & k_{qsr} & 0 & k_{qfr} & 0 & k_{qr} \end{bmatrix} = \begin{bmatrix} x_{ds} & 0 & x_{ad} & 0 & x_{ad} & 0 \\ 0 & x_{qs} & 0 & x_{aq} & 0 & x_{aq} \\ x_{ad} & 0 & x_{df} & 0 & x_{ad} & 0 \\ 0 & x_{aq} & 0 & x_{qf} & 0 & x_{aq} \\ x_{ad} & 0 & x_{ad} & 0 & x_{dr} & 0 \\ 0 & x_{aq} & 0 & x_{aq} & 0 & x_{qr} \end{bmatrix}^{-1} \quad (2)$$

where x_{ds}, x_{qs}, x_{df}, x_{qf}, x_{dr}, x_{qr} – are the total inductive resistances of the AC machines, respectively, of the stator windings, field windings and rotor circuits along the d, q axes; x_{ad}, x_{aq} – mutual induction resistance along the d, q axes. In addition to equations (1) and (2), it is necessary to keep in mind the equations of motion of an electric machine with a moving (braking) moment m_t and electromagnetic moment m_{em}:

$$\left.\begin{array}{l} T_j \cdot p\omega_r = m_T - m_{em} \\ m_{em} = (k_{qs} - k_{ds}) \cdot \Psi_{ds} \cdot \Psi_{qs} + k_{qsf} \cdot \Psi_{ds} \cdot \Psi_{qf} + k_{qsr} \cdot \Psi_{ds} \cdot \Psi_{qr} - k_{dsf} \cdot \Psi_{qs} \cdot \Psi_{df} - k_{dsr} \cdot \Psi_{qs} \cdot \Psi_{dr} \end{array}\right\} \quad (3)$$

where T_j – inertial constant of the moving parts of the "electric machine" system drive (brake) mechanism in [radian].

With such a record of equations, as control parameters in the universal structure, models of AC machines can be used: U_{ds} and U_{qs} – are the components of the stator winding voltage, the amplitude and frequency of which can be regulated; U_{df} and U_{qf} – are the dc voltage values supplied to the field windings along the longitudinal and transverse axes d, q; U_{dr}, U_{qr} – components of the voltage supplying the rotor winding of the machine, which can also be regulated in amplitude and frequency.

Since the structure of the universal mathematical model of alternating current machines is based on the form of writing equations in the d, q axes rotating at the rotor speed of machine ω_r, it is not difficult to model the voltages U_{df} and U_{qf}, since they are supplied from the output of the excitation regulators, the components are also easily simulated voltage of the rotor winding U_{dr} and U_{qr} in the same form as they are obtained at the output of the frequency converter, supplying the rotor winding of electrical machines.

For the stator winding, it is necessary that the stator voltage components U_{ds} and U_{qs} be presented in such a way that they reflect the change (regulation) of the amplitude and frequency of the voltage supplying the stator winding of the machines.

From the diagram of the coordinate axes of AC machines, by means of appropriate geometric transformations, the expressions for the components of the stator voltage are obtained, which include the control parameters k_{us} and k_{fs}:

$$\begin{aligned} U_{ds} &= 0{,}707 \cdot k_{us} \cdot \left[cos\left(k_{fs} \cdot \tau\right) \cdot \left(cos\,\alpha - sin\,\alpha\right) - sin\left(k_{fs} \cdot \tau\right) \cdot \left(cos\,\alpha + sin\,\alpha\right)\right] \\ U_{qs} &= 0{,}707 \cdot k_{us} \cdot \left[cos\left(k_{fs} \cdot \tau\right) \cdot \left(cos\,\alpha + sin\,\alpha\right) + sin\left(k_{fs} \cdot \tau\right) \cdot \left(cos\,\alpha - sin\,\alpha\right)\right] \end{aligned} \tag{4}$$

where $k_{us} = U_s / U_{s0}$; $k_{fs} = f_s / f_{s0}$, moreover U_s и f_s – current values of the module and frequency of the stator voltage, U_{s0} and f_{s0} – their base values $U_{s0} = f_{s0} = 1$.

For rotor winding:

$$\left.\begin{aligned} U_{dr} &= k_{ur} \cdot \sin(k_{fr} \cdot \tau) \\ U_{qr} &= k_{ur} \cdot \cos(k_{fr} \cdot \tau) \end{aligned}\right\} \tag{5}$$

where $k_{ur}=U_r / U_{r0}$, $k_{fr}=f_r / f_{r0}$, $U_{r0} = f_{r0} = U_{s0} = f_{s0} = 1$.

Thus, the universal structure of the matmodel of AC electric machines allows one to take into account all possible types of control of these machines – frequency control from both the rotor and stator sides, as well as excitation regulation (for synchronous machines) for both longitudinal and transverse windings.

On the developed structure, almost all types of AC machines can be investigated, including those found in wind power plant – frequency-controlled synchronous and asynchronous machines, a synchronous machine with excitation from permanent magnets, an asynchronous machine with longitudinally transverse excitation, asynchronous machines with frequency control, as with stator side and rotor side.

The examples of calculations of some wind turbine AC machines using the developed universal structure of a mathematical model with frequency control from both the stator and the rotor, as well as comparing the calculation results with the experimental data presented in the technical literature, confirmed the adequacy, reliability and effectiveness of the universal structure matmodels.

Figure 1 shows the fluctuograms of the change in the operational parameters of a double-fed asynchronous machine with frequency control, both from the stator and from the rotor. On the stator side, the amplitude and frequency of the voltage supplied to the stator winding were set at $k_{us}=k_{fs}=0.7$. After start-up, the rotor speed is set at $\omega_r=0.709$ (the value of ω_r greater than the synchronous ω_{r0} = 0,7 (indicates the generator mode) figure 1, *a*. In this case, the rotor winding is shorted in the range from 0 to 1000 radian. The electromagnetic moment is equal to the moving moment $m_{em}=–0.3$ (figure 1, *b*). Accordingly, the magnitude of the active and reactive powers at the terminals of the machines is $p_{ov}=–0.21$ (a minus sign indicates the output of active power to the network) (figure 1, *c*) and $p_{ov}=–0.17$ (reactive power is consumed from the network) (figure 1, *d*).

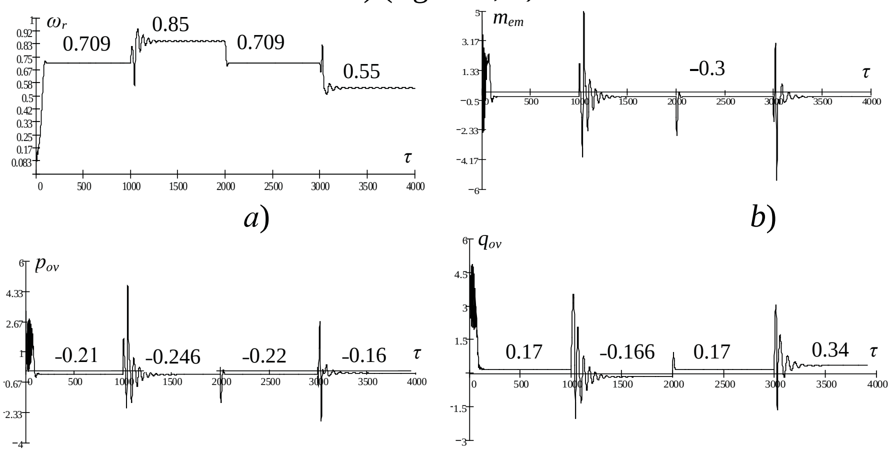


Figure 1. Fluctograms of change of operational parameters of a double-fed asynchronous machine when regulating voltage and frequency both from the side of the stator and from the side of the rotor $k_{us}=k_{fs}$= 0.7 and $k_{us}=k_{fs}$= ±0.15

A technique is proposed for modeling a frequency-controlled asynchronous machine with a squirrel-cage rotor in the three-coordinate system α_s, β_s, γ_s motionless in space, which makes it possible to relatively easily reproduce on the model the change (regulation) of controlled parameters – the amplitude and frequency of the phase voltage of the stator of electric machines, which is difficult or impossible to reproduce on two-axis models.

For the first time, equations are proposed and on their basis a three-dimensional mathematical model of a frequency-controlled asynchronous machine with a phase rotor and a frequency converter in the rotor circuit is compiled, the equations of which are written in the axes α_r, β_r, γ_r, rotating with rotor speed ω_r.

Unfolded equation of state for a double-fed machine:

$$\left.\begin{aligned}
&p\Psi_{s\alpha} = U_{s\alpha}\cdot sin\theta + \frac{1}{\sqrt{3}}\omega_r\left(\Psi_{s\beta} - \Psi_{s\gamma}\right) - r_s\cdot i_{s\alpha}\\
&p\Psi_{s\beta} = U_{s\beta}\cdot sin\left(\theta - \frac{2\pi}{3}\right) + \frac{1}{\sqrt{3}}\cdot\omega_r\left(\Psi_{s\gamma} - \Psi_{s\alpha}\right) - r_s\cdot i_{s\beta}\\
&p\Psi_{d\gamma} = U_{s\gamma}\cdot sin\left(\theta + \frac{2\pi}{3}\right) + \frac{1}{\sqrt{3}}\cdot\omega_r\left(\Psi_{s\alpha} - \Psi_{s\beta}\right) - r_s\cdot i_{s\gamma}\\
&p\Psi_{r\alpha} = k_{us}\cdot sin\left(k_{fr}\cdot\tau\right) - r_r\cdot i_{r\alpha}\\
&p\Psi_{r\beta} = k_{us}\cdot sin\left(k_{fr}\cdot\tau - \frac{2\pi}{3}\right) - r_r\cdot i_{r\beta}\\
&p\Psi_{r\gamma} = k_{us}\cdot sin\left(k_{fr}\cdot\tau + \frac{2\pi}{3}\right) - r_r\cdot i_{r\gamma}\\
&p\theta = 1 - \omega_r\\
&p\omega_r = \frac{p_m}{J}\cdot\left(m_{em} - m_v\right)\\
&m_{em} = \frac{\sqrt{3}}{2}\cdot p_m\cdot x_m\left[\left(i_{s\alpha}\cdot i_{r\gamma} + i_{s\beta}\cdot i_{r\alpha} + i_{s\gamma}\cdot i_{r\beta}\right) - \left(i_{s\alpha}\cdot i_{r\beta} + i_{s\beta}\cdot i_{r\gamma} + i_{s\gamma}\cdot i_{r\alpha}\right)\right]
\end{aligned}\right\}\quad(6)$$

The relationship between currents and flux linkages is represented as:

$$\begin{bmatrix} i_{s\alpha} \\ i_{s\beta} \\ i_{s\gamma} \\ i_{r\alpha} \\ i_{r\beta} \\ i_{r\gamma} \end{bmatrix} = \left. \begin{bmatrix} x_{s\alpha} & -0{,}5x_m & -0{,}5x_m & x_m & -0{,}5x_m & -0{,}5x_m \\ -0{,}5x_m & x_{s\beta} & -0{,}5x_m & -0{,}5x_m & x_m & -0{,}5x_m \\ -0{,}5x_m & -0{,}5x_m & x_{s\gamma} & -0{,}5x_m & -0{,}5x_m & x_m \\ x_m & -0{,}5x_m & -0{,}5x_m & x_{r\alpha} & -0{,}5x_m & -0{,}5x_m \\ -0{,}5x_m & x_m & -0{,}5x_m & -0{,}5x_m & x_{r\beta} & -0{,}5x_m \\ -0{,}5x_m & -0{,}5x_m & x_m & -0{,}5x_m & -0{,}5x_m & x_{r\gamma} \end{bmatrix}^{-1} \cdot \begin{bmatrix} \psi_{s\alpha} \\ \psi_{s\beta} \\ \psi_{s\gamma} \\ \psi_{r\alpha} \\ \psi_{r\beta} \\ \psi_{r\gamma} \end{bmatrix} \right\} \quad (7)$$

In expanded form:

$$\left. \begin{aligned} i_{s\alpha} &= k_{s\alpha_1} \cdot \psi_{s\alpha} + k_{s\alpha_2} \cdot \psi_{s\beta} + k_{s\alpha_3} \cdot \psi_{s\gamma} + k_{s\alpha_4} \cdot \psi_{r\alpha} + k_{s\alpha_5} \cdot \psi_{r\beta} + k_{s\alpha_6} \cdot \psi_{r\gamma} \\ i_{s\beta} &= k_{s\beta_1} \cdot \psi_{s\alpha} + k_{s\beta_2} \cdot \psi_{s\beta} + k_{s\beta_3} \cdot \psi_{s\gamma} + k_{s\beta_4} \cdot \psi_{r\alpha} + k_{s\beta_5} \cdot \psi_{r\beta} + k_{s\beta_6} \cdot \psi_{r\gamma} \\ i_{s\gamma} &= k_{s\gamma_1} \cdot \psi_{s\alpha} + k_{s\gamma_2} \cdot \psi_{s\beta} + k_{s\gamma_3} \cdot \psi_{s\gamma} + k_{s\gamma_4} \cdot \psi_{r\alpha} + k_{s\gamma_5} \cdot \psi_{r\beta} + k_{s\gamma_6} \cdot \psi_{r\gamma} \\ i_{r\alpha} &= k_{r\alpha_1} \cdot \psi_{s\alpha} + k_{r\alpha_2} \cdot \psi_{s\beta} + k_{r\alpha_3} \cdot \psi_{s\gamma} + k_{r\alpha_4} \cdot \psi_{r\alpha} + k_{r\alpha_5} \cdot \psi_{r\beta} + k_{r\alpha_6} \cdot \psi_{r\gamma} \\ i_{r\beta} &= k_{r\beta_1} \cdot \psi_{s\alpha} + k_{r\beta_2} \cdot \psi_{s\beta} + k_{r\beta_3} \cdot \psi_{s\gamma} + k_{r\beta_4} \cdot \psi_{r\alpha} + k_{r\beta_5} \cdot \psi_{r\beta} + k_{r\beta_6} \cdot \psi_{r\gamma} \\ i_{r\gamma} &= k_{r\gamma_1} \cdot \psi_{s\alpha} + k_{r\gamma_2} \cdot \psi_{s\beta} + k_{r\gamma_3} \cdot \psi_{s\gamma} + k_{r\gamma_4} \cdot \psi_{r\alpha} + k_{r\gamma_5} \cdot \psi_{r\beta} + k_{r\gamma_6} \cdot \psi_{r\gamma} \end{aligned} \right\} \quad (8)$$

Naturally, the coefficients $k_{s\alpha_1} \div k_{r\gamma_6}$ are determined from the inverse matrix (7), composed of the parameters of the machine.

Thus, the system of equations (6) and (8) constitute a three-coordinate mathematical model of a frequency-controlled double-fed asynchronous machine, written in the axes α_r, β_r, γ_r, rotating with the speed of the machine rotor.

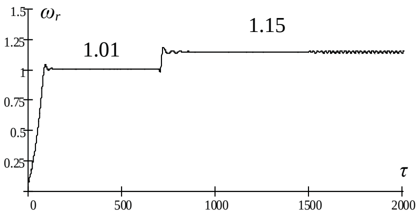
Using the calculation example, we demonstrate the efficiency and reliability of the results. The chosen research mode is an open in one of the phase windings of the rotor (or lack of power). Figure 2 shows the fluctuograms of the change in the operational parameters of the double-fed machine, a mathematical model that is based on the three-coordinate system α_r, β_r, γ_r, rotating with the rotor speed of the machine ω_r.

Figure 2 (*a*, *b*, *c*, *d*, *e*, *f*, *g*, *h*) respectively shows the frequency of rotation of the machine ω_r (figure 2, *a*), machine electromagnetic moment m_{em} (figure 2,*b*), stator phase currents $I_{s\alpha}$, $I_{s\beta}$, $I_{s\gamma}$ (figure 2, *c*, *d*, *e*) and rotor currents $I_{r\alpha}$, $I_{r\beta}$, $I_{r\gamma}$ (figure 2, *f*, *g*, *h*).

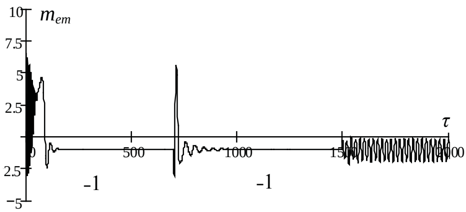
In the time range from 0 to 700 radian, a direct connection is made to an electric machine with a torque on the shaft equal to m_T=–1 when the rotor windings are short-circuited.

At the 700th radian, voltage is supplied to the three-phase rotor winding from the frequency converter with equal values of the amplitude and frequency for all three phases: $k_{ur}=k_{fr}=-0.15$.

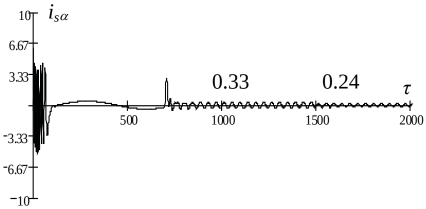
In this case, the rotor rotational speed rises to the value ω_r=1.15, the stator and rotor currents are symmetric and equal to $I_{s\alpha}=I_{s\beta}=I_{s\gamma}$=0.33 and $I_{r\alpha}=I_{r\beta}=I_{r\gamma}$=0.45, the electromagnetic moment value is $m_{em}=m_T$= –1 (the machine is operating in generator mode).



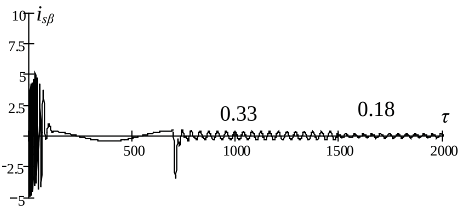
a)



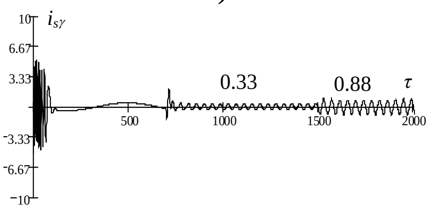
b)



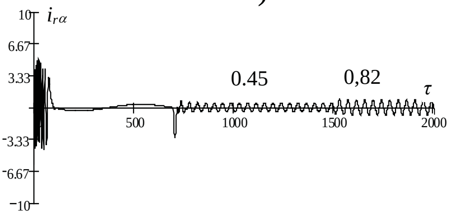
c)



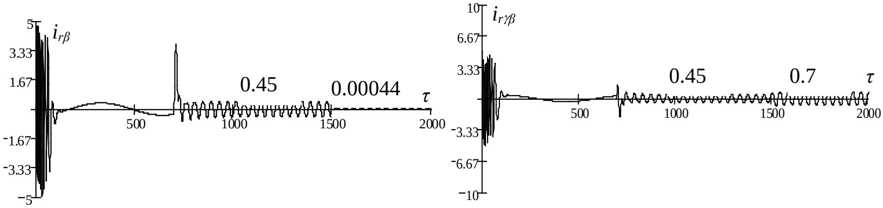
d)



e)



f)



g) *h*)

Figure.2. Fluctograms of change of operational parameters of an dual-fed asynchronous machine, obtained on a three-coordinate matmodel when controlled by the $k_{ur}=k_{fr}=0.15$ rotor

At 1500 radian, the phase break mode β of the generator rotor is simulated. In this case, the machine is set to an asymmetric mode of operation with high-frequency oscillations in the curves of the rotor speed ω_r and the moment m_{em}.

The stator currents become asymmetric $I_{s\alpha}$=0.24, $I_{s\beta}$=0.18, $I_{s\gamma}$=0.88. Asymmetric rotor currents are also $I_{r\alpha}$=0.82, $I_{r\beta}\approx 0$ (open circuit is imitated precisely in this phase), $I_{r\gamma}$=0.7.

The second chapter presents the developed method for modeling frequency-controlled synchronous machines with both electromagnetic excitation and permanent magnets, the latter being increasingly used in wind energy[15].

When deriving the equations of a frequency-controlled synchronous machine with permanent magnets, the well-known and tested Park-Gorev equations are taken as the basis. In this case, the equations are written with respect to the derivatives of flux linkages and controlled currents as functions of the flux links themselves and these currents. To transform these equations into equations of synchronous machines with permanent magnets it is necessary and, of course, to equate to zero the derivative of the flux linkage of the field winding $p\Psi_{df} = 0$, then from the equation of voltage balance the current in the field of excitation will appear in the form:

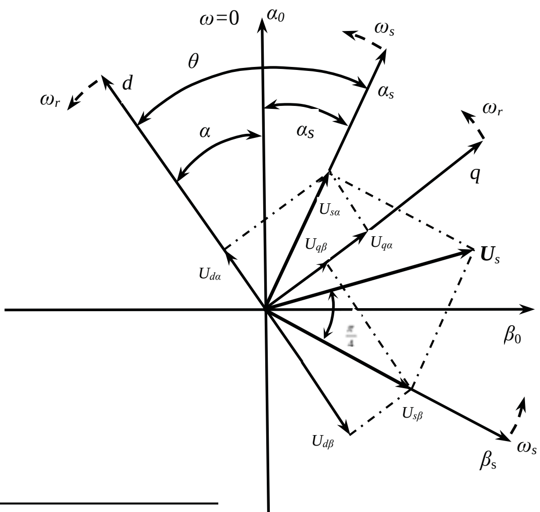
[15] Heng, T. Y., Ding, T. J., Chang, C. C. W., et al. Permanent Magnet Synchronous generator design optimization for wind energy conversion system: A review // Energy Reports. – 2022. Vol. 8, Sup. 16, – p. 277-282.

$$i_{df} = \frac{U^{*}_{df}}{x_{ad}} \tag{9}$$

Substituting the values of this current into the remaining equations of the machine and excluding the equation for i_{df} connecting its values with flux linkages, we obtain the equations of a synchronous machine with permanent magnets. But in the new equations, the voltage U^{*}_{df} must be interpreted not as the excitation voltage, but as the energy of the magnet, referred to a unit of its volume, or for small values of residual induction as the coercive force of the magnet (it is further denoted by the symbol M_f). For example, it is necessary to take such a value of the magnet energy, which is capable of providing an e.m.f. value when the generator is idling on its clamps equal $e_{\text{no-load}}=1$[16,17].

In addition, since we are talking about frequency-controlled synchronous machines, it is necessary to adapt the Park-Gorev equations so that they reflect the change in both the amplitude and frequency at the terminals of the synchronous wind turbine generator.

We turn to the diagram in figure 3.



[16] Иванов, П. А., Смирнов, В. Л. Исследование характеристик синхронных машин с постоянными магнитами в ветроэнергетике. – Москва: Энергия, – 2015. – 220 с.

[17] Gajewski, P., Pienkowski, K. Analysis of sliding mode control of variable speed wind turbine system with PMSG // In 2017 International Symposium on Electrical Machines (SME), – 2017, – p. 1-6.

Figure 3. The location diagram of the coordinate axes of AC machines

Here α_0, β_0 – are the coordinate axes fixed in space; α_s, β_s – synchronously rotating axes with an angular frequency corresponding to the frequency of the current at the output of the frequency converter; d, q – coordinate axes rotating with rotor speed ω_r; $\alpha_s = \omega_s \cdot \tau$ – is the angle between the axes α_s, β_s and α_0, β_0; the angle between the axes d, q and the fixed axes α_0, β_0 is $\alpha = \omega_r \cdot \tau$ and, finally, θ – is the angle between the axes d, q and the axes α_s, β_s.

From the diagram we have:

$$\theta = \alpha + \alpha_s = \omega_r \cdot \tau + \omega_s \cdot \tau \qquad (10)$$

where $\tau = \omega_{baz} \cdot t = 314 \cdot t$ – synchronous time in [radian], t – time in [second].

If you place the voltage vector U_s in the initial (initial) mode at an angle of 45^0 to the axes α_s, β_s, then its projections on these axes will be identical and equal to $U_{s\alpha_0} = U_{s\beta_0} = 0{,}707 \cdot U_s$ (for U_s=1).

When designing these projections on the d, q axis will have:

$$\left.\begin{aligned}
U_{d\alpha} &= U_{s\alpha} \cdot \cos\theta = U_{s\alpha} \cdot \cos(\alpha + \omega_s \cdot \tau) \\
U_{q\alpha} &= U_{s\alpha} \cdot \sin\theta = U_{s\alpha} \cdot \sin(\alpha + \omega_s \cdot \tau) \\
U_{d\beta} &= U_{s\beta} \cdot \sin\theta = U_{s\beta} \cdot \sin(\alpha + \omega_s \cdot \tau) \\
U_{q\beta} &= U_{s\beta} \cdot \cos\theta = U_{s\beta} \cdot \cos(\alpha + \omega_s \cdot \tau)
\end{aligned}\right\} \qquad (11)$$

The common projections of these vectors on the d, q axis are equal:

$$\left.\begin{aligned}
U_{ds} &= U_{d\alpha} - U_{d\beta} \\
U_{qs} &= U_{q\alpha} + U_{q\beta}
\end{aligned}\right\} \qquad (12)$$

Bearing in mind that, what $k_{us} = \dfrac{U_s}{U_{s0}}$ and $k_{fs} = \dfrac{\omega_s}{\omega_{s0}}$, where in rel. un. $U_{s0} = 1$ we get:

$$\left.\begin{aligned}
U_{ds} &= 0{,}707 \cdot k_{us}\left[\cos(\alpha + k_{fs} \cdot \tau) - \sin(\alpha + k_{fs} \cdot \tau)\right] \\
U_{qs} &= 0{,}707 \cdot k_{us}\left[\sin(\alpha + k_{fs} \cdot \tau) + \cos(\alpha + k_{fs} \cdot \tau)\right]
\end{aligned}\right\} \qquad (13)$$

Finally, through trivial transformations, we can obtain:

$$\left.\begin{aligned}U_{ds} &= 0{,}707 \cdot k_{us}\left[\cos(k_{fs}\cdot\tau)\cdot(\cos\alpha-\sin\alpha)-\sin(k_{fs}\cdot\tau)\cdot(\cos\alpha+\sin\alpha)\right]\\ U_{qs} &= 0{,}707 \cdot k_{us}\left[\cos(k_{fs}\cdot\tau)\cdot(\cos\alpha+\sin\alpha)+\sin(k_{fs}\cdot\tau)\cdot(\cos\alpha-\sin\alpha)\right]\end{aligned}\right\} \tag{14}$$

Thus, a digital model of a synchronous generator of wind turbines with permanent magnets will appear in the form:

$$\left.\begin{aligned}
&p\Psi_{ds} = U_{sd} - \omega_r \cdot \Psi_{qs} - r_s \cdot i_{ds}\\
&p\Psi_{qs} = U_{sq} + \omega_r \cdot \Psi_{ds} - r_s \cdot i_{qs}\\
&p\Psi_{dr} = -\frac{r_{dr}}{x_{dr}} \cdot \Psi_{dr} + \frac{r_{dr} \cdot x_{ad}}{x_{dr}} \cdot i_{ds} + \frac{r_{dr}}{x_{dr}} \cdot M_f^*\\
&p\Psi_{qr} = -\frac{r_{qr}}{x_{qr}} \cdot \Psi_{qr} + \frac{r_{qr} \cdot x_{aq}}{x_{qr}} \cdot i_{qs}\\
&p\omega_r = \frac{1}{T_j} \cdot m_{wt} - \frac{1}{T_j} \cdot m_{em}\\
&p\alpha = \omega_r\\
&m_{em} = \psi_{ds} \cdot i_{qs} - \Psi_{qs} \cdot i_{ds}\\
&i_{ds} = \frac{x_{dr}}{\Delta d} \cdot \Psi_{ds} - \frac{x_{dr} - x_{ad}}{\Delta d} \cdot M_f^* - \frac{x_{ad}}{\Delta d} \cdot \Psi_{dr}\\
&i_{qs} = \frac{x_{qr}}{\Delta q} \cdot \Psi_{qs} - \frac{x_{aq}}{\Delta q} \cdot \Psi_{qr}
\end{aligned}\right\} \tag{15}$$

where M_f – magnet energy referred to a unit of its volume (for small values of residual induction, the coercive force of magnets); $\Delta d = x_{ds} \cdot x_{dr} - x^2_{ad}$, $\Delta q = x_{qs} \cdot x_{qr} - x^2_{aq}$.

To equation (15), it is necessary to add equations for the active and reactive powers of wind turbines, which are presented in the form:

$$\left.\begin{aligned}p &= U_{ds} \cdot i_{ds} + U_{qs} \cdot i_{qs}\\ q &= U_{qs} \cdot i_{ds} - U_{ds} \cdot i_{qs}\end{aligned}\right\} \tag{16}$$

Using this model, the modes of operation of the permanent magnet generator P_n =1500 kW of a “Vensys 77”[18] type wind turbine were investigated. Moreover, the estimated wind speed is 13 m/s, the initial

[18] Windenergie 2006. BWE – Service GmbH. – 2006.

wind speed is 3 m/s and the maximum allowable speed is 22 m/s. The range of regulation of the rotational speed of the wind wheel is 9–17.3 rpm., i.e. almost 1:2. The studies were carried out under the assumption that M_{df} =1.2= *const*, the torque of the wind turbine is determined by the expression:

$$m_{wt} = k_m \cdot \omega_r^2 \qquad (17)$$

It should be noted that this expression "works" only in the speed control range.

In the steady state in this range, a study was conducted with three control methods:

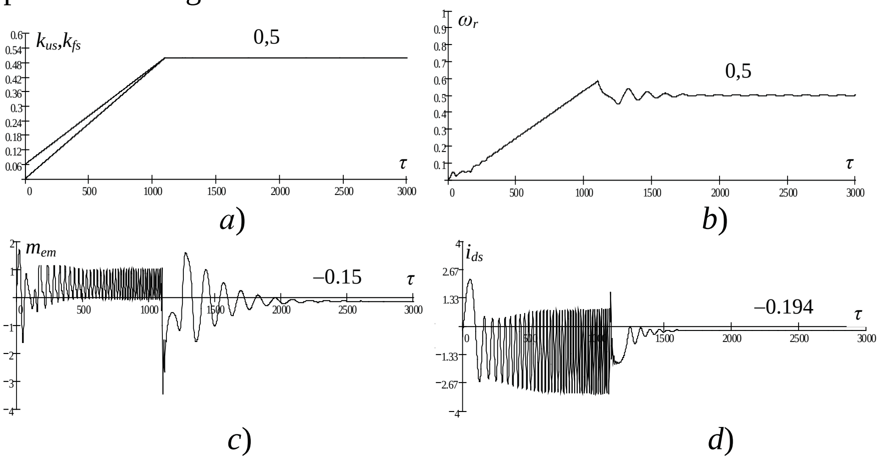
a) control with equal coefficients of change in the amplitude and frequency of the voltage supplied to the stator winding of the generator, i.e. $k_{us}=k_{fs}$; b) management of the constancy of the issuance of reactive power; c) control for the constancy of the power factor $\cos\varphi \approx 1$. Results are shown below:

a) Control at $k_u= k_f$						
$k_u= k_f$	0.5	0.6	0.7	0.8	0.9	1.0
m	–0.150	–0.215	–0.296	–0.389	–0.486	–0.598
p	–0.074	–0.128	–0.205	–0.304	–0.435	–0.596
q	–0.137	–0.158	–0.175	–0.180	–0.177	–0.155
i_{ds}	–0.200	–0.200	–0.210	–0.220	–0.234	–0.257
i_{qs}	–0.136	–0.197	–0.265	–0.346	–0.441	–0.543
b) Regulation on the constancy of the issuance of reactive power q = *const*						
k_f	0.5	0.6	0.7	0.8	0.9	1.0
k_u	0.484	0,592	0.698	0.799	0.899	0.991
q	–0.179	–0.180	–0.180	–0.181	–0.180	–0.179
i_{ds}	–0.270	–0.232	–0.216	–0.217	–0.237	–0.257
c) Power factor constancy control $\cos\varphi \approx 1$						
k_f	0.5	0.6	0.7	0.8	0.9	1.0
k_u	0.545	0.650	0.758	0.860	0.960	1.055
q	–0.0017	–0.0017	–0.00173	–0.0017	–0.0018	–0.0017
i_{ds}	–0.01	–0.0187	–0.033	–0.055	–0.089	–0.137

An analysis of these data shows that the moment, which is proportional to the square of the rotation frequency ω_r, for all control cases is determined by the network current frequency and when the frequency k_{fs} changes from 0.5 to 1, it changes from –0.15 to –0.6. This moment corresponds to the active power p, which also varies from –0.074 to –0.6 and the active current i_{qs}, whose variation range is from –0.136 to –0.543. These values are the same for all modes.

It is interesting to note that in the frequency range from 0.65 to 0.9 when regulated according to the law $k_{us} = k_{fs}$ and to the constancy of the output of reactive power q= const, the parameter values slightly differ from each other.

It is of interest to study the frequency start mode wind power plant of a synchronous generator with permanent magnets, the fluctuation of which is shown in figure 4. Start-up is carried out in the presence of a driving moment on the generator shaft equal to m_{wt}=–0.15, which corresponds to the initial wind speed $V_{st.}$=4.5 m/s. The voltage amplitude and frequency of the stator current vary linearly, with $k_{us}=f(\tau)$ at the start of acceleration slightly ahead of $k_{fs}=f(\tau)$ in order to select the "dead zone" for $\omega_r=f(\tau)$. The process of retraction into synchronism ends at the 2000th radian. The exit time of the amplitude and frequency to the steady state ($k_{us}=k_{fs}$=1) is 1100 radian (3.5 second). The magnitude of the electromagnetic moment m_{em} does not exceed 2 times the value, although its average value during acceleration is $m_{em\ md}$ = 0.5. The amplitudes of the currents i_{ds} and i_{qs}, as well as the values of reactive and active powers q and p, do not exceed 2-fold values. All this confirms the high efficiency of the application of a synchronous generator of wind turbines with permanent magnets.



–0.194

–0.133 τ

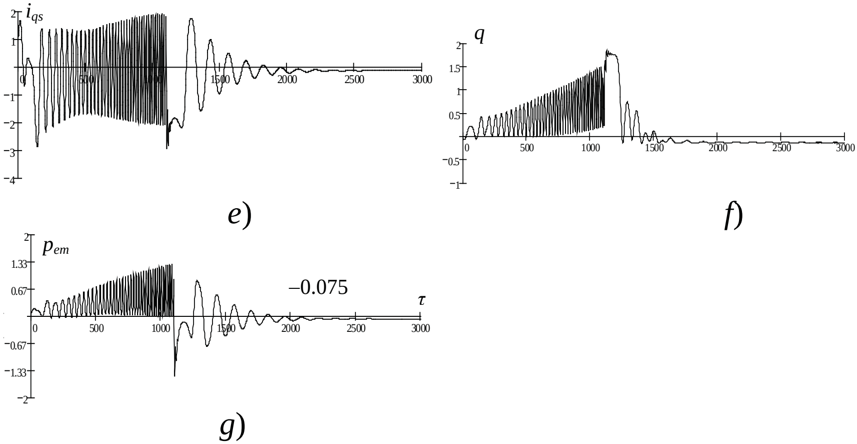


Figure 4. Fluctograms of change of operational parameters of a synchronous generator with permanent magnets of a wind power plant at a frequency start

A comparative analysis of the adjustment properties of wind power plant a synchronous generator with electromagnetic excitation and wind power plant synchronous generators with permanent magnets is also carried out.

Comparing the laws of regulation on the constancy of the output of reactive power q=const and on the constancy of the power factor $cos\varphi\approx1$ of wind power plant synchronous generators with electromagnetic excitation and with permanent magnets, we can state the following:

– for a synchronous generator with electromagnetic excitation, and in the range of variation of the frequency of the stator current from 0.5 to 1 ($k_{us}=k_{fs}$) to ensure $cos\varphi\approx1$, it is necessary to almost linearly change the excitation voltage as a function of the change in the frequency of the stator current. When implementing another law – maintaining constant reactive power output q=const, the adjustable function $q=f\ (k_{fs})$ is essentially non-linear;

– for wind power plant of a synchronous generator with permanent magnets in the same range of variation of the frequency of the stator current, to ensure $cos\varphi\approx1$, it is necessary with insignificant slope in the low frequency range to almost linearly regulate the voltage amplitude of the frequency converter supplying the stator winding of the generator, as a function of the frequency change. When implementing the regulation law at q=const, the form of the curve remains the same as when regulating at $cos\varphi \approx 1$, only the curve is located higher. That is, both curves retain congruence.

When studying the dynamics wind power plant of a synchronous generator with permanent magnets, it is of interest to determine the influence of the flywheel masses (inertial constant T_j) of the system on the nature of the process, since gear and gearless (the so-called Ringgenerator) wind power plant with the indicated electromechanical converters are used. In addition, an opportunity is created to study the effect of the magnitude of the magnetic energy of a magnet on transients. This is especially important for the design wind power plant of synchronous permanent magnet generators for operation in various regions characterized by wind power potential with significant gusts of wind speed.

In the study of dynamics, studies were conducted with an idealized model of abrupt change in wind speeds[19] (in automatic control theory, the indicated disturbance changes are typical), which we also proposed earlier in the trapezoidal form of changes in wind speed in dynamics, synthesized on the basis of real fluctuation patterns of changes in wind speed in the Absheron region republics[20].

The fluctuograms in figure 5, *a* show the changes in the operating parameters of the generator, with permanent magnets, simulating the operation of a wind turbine of the "GE Energy" type[21] with the initial

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[19] Андрианов, В.Н. Ветроэлектрические станции / В.Н. Андрианов, Д.Н.Быстрицкий, К.П.Вашкевич и др. – Москва-Ленинград: Госэнергоиздат, – – 1960. – 319 с.

[20] Гасанова, Л.Г. Моделирание и исследование режимов работы системных ветроэлектрических установок с асинхронными генераторами при частотном управлении: / Диссертация на соискания ученой степени кандидата технических наук. / – Баку, – 2008. – 159 с.

[21] GE Renewable Energy. [Electronic resource] / A challenge–and an opportunity. Ready for tomorrow. – 2020. / URL: www.ge.com/renewableenergy/wind-energy

data T_f ≈1 second (333.3 radian) And magnet energy M_f =1.8, which corresponds to the leading value cosφ=0.8 (tgφ=0.75). The mode of a draft of approximately twice the value of the driving moment of the wind turbine is simulated, that is, 10000 radian the driving moment from m_{wt}= –0.8 (nominal value) jumps up to m_{wt}=–1.75. This corresponds to a gust of wind, the speed of which with $V_{cal.}$=13 m/s sharply changes to V_{max}=19 m/s, while the duration of the gust is 1 second (314 radian). From the analysis of the fluctuogram, we can conclude that the system is dynamically stable, although the fluctuations in frequency and amplitude reach significant values (q_{max}=3.5). It should also be noted that with a momentum value >1.75 the generator goes out of synchronism.

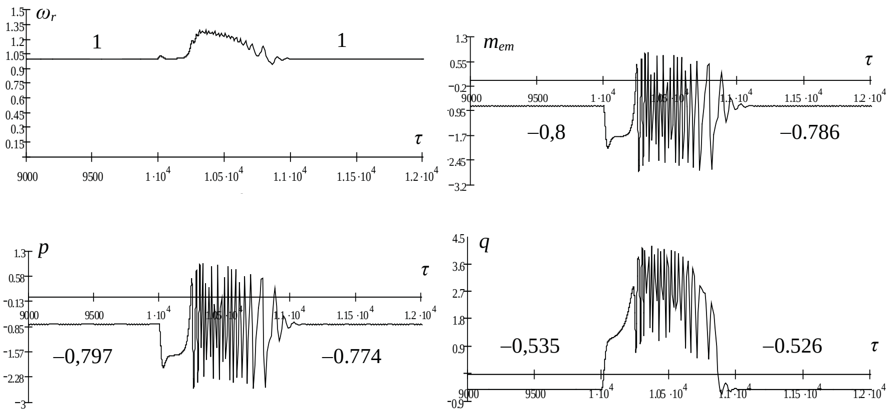

Figure 5, *a*. Fluctograms of transient parameters of a model wind power plant synchronous generator simulating a system of type "GE Energu"

Figure 5, *b* shows the fluctuograms of the change in operating parameters when the inertial constant of the rotating parts of the wind power plant is significantly increased, which is equal to T_j=5 second, which to some extent imitates the operation of a gearless wind power plant with the corresponding generators with permanent magnets.

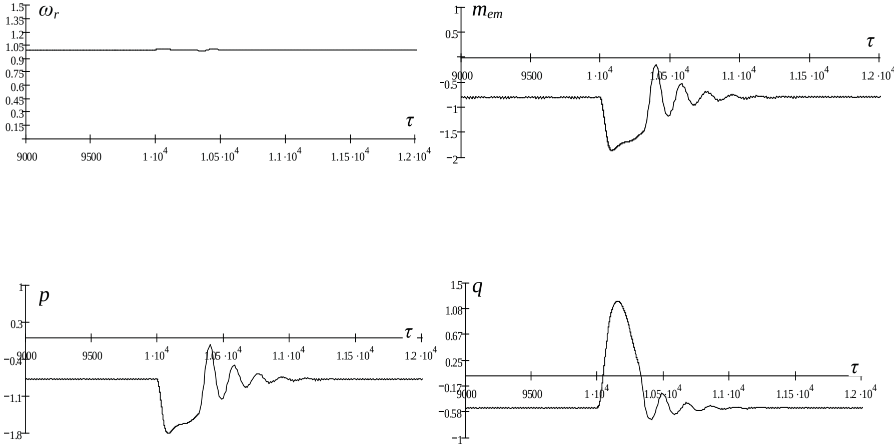

Figure 5, *b*. Fluctograms of change of operational parameters of a synchronous generator with permanent magnets of wind power plant

Fluctograms show that in this case the maximum values of the operating parameters are significantly reduced, for example, $q_{\max}\approx 1$ and their oscillation frequencies. There is practically no fluctuation in the curve of the rotational speed ω_r.

When studying the influence of the magnetic energy of the permanent magnets of the generator on its dynamic characteristics, it was found that the larger the value of M_f, the more stable the machine is to change perturbing influences. So, for M_f =1.62, which corresponds to cosφ=0.9 (lead.). Then for the magnitude of the flywheel masses corresponding to T_j =1 second the generator goes out of synchronism already at m_{wt}= –1.65, and with significant flywheel masses (T_j =5 second) the machine goes into asynchronous mode with m_{wt}= –1,6. This becomes even more noticeable if the machine is designed for cosφ=1 (which corresponds to M_f =1.3). Here, at m_{wt}= –1.3 and T_j =5 second the generator goes into asynchronous mode, and at T_j =1 second it goes out of synchronism with m_{wt}= –1.45, which corresponds to a wind speed of $V_{\text{мах}}$=17.5 m/s. This circumstance indicates the fact that the strengthening of the electromagnetic coupling between the stator and rotor circuits wind power plants of a synchronous generator favorably (i.e. increases) its dynamic stability.

It is known that air has a mass density that cannot change abruptly, so the trapezoidal representation of gusts of wind is the most adequate representation of the dynamics of changes in wind speed. With this representation of gusts of wind, studies have shown that stability is affected by both the rate of rise of the wind on both the rising and falling branches of the trapezoid. One feature was identified in these studies. So, for example, if before a gust of wind, the synchronous wind power plant engine worked at a rotation frequency of ω_r=0,7 (with m_{wt}=–0.5), and then for t=0.5 second the wind speed increased (which corresponds to an increase in the driving moment of the wind turbine from m_{wt}= –0.5 to m_{wt}=–1.7), and then during Δt=1 second remains unchanged, then for 0.5 second decreases linearly to m_{end}=–0.5 (i.e., it returns to its original value), then the wind turbine generator with T_j=5 second remains in sync. However, when trying to increase the moment after the falling branch of the trapezoid to m_{end}=–0.8, the machine goes out of synchronism. Thus, stability depends not only on the rates of rise and fall of wind speeds and its maximum value, but also on the value of the steady-state wind speed after a gust of wind.

To increase the dynamic stability wind power plant of a synchronous generator with permanent magnets, there are two control channels that can to some extent affect the nature of transients. This is the regulation of the angle of rotation of the blades of the wind turbine and the regulation of the current frequency of the stator of the generator using a frequency converter connected to its stator winding. When gusts of wind last 1–2 seconds power control by changing the angle of rotation of the blades of the wind turbine leads to a negligible effect, since the time constant of the specified control channel for the vast majority of system wind power plant is quite significant. Therefore, the only control channel in the dynamics remains the regulation of the frequency of the stator current of the generator using the frequency converter of synchronous wind turbine generators with permanent magnets, the coercive force of which is equal to M_f =1.8 (which corresponds to cosφ=0.8 lead.) and $T_j \approx 5$ second, when working at rated load, it was subjected to a gust of wind equal to V_{gust}=21 m/s (which corresponds to m_{wt}=–2.1), the gust time is Δt_{gust}=1 sec. (314 radian). Half a second after the start of the rush, the process of regulating the frequency of the stator current began, which decreased from k_{fs} =1 to k_{fs}=0.8 (accordingly, the generator rotor speed also decreased from ω_r=1 to ω_r=0.8). After a certain time, the frequency of the stator current was restored to the initial value k_{fs}=1. Such regulation (reduction) of the stator current frequency allowed the synchronous machine to remain in synchronism. Numerous fluctograms of this mode revealed that there is a limit to the decrease in the frequency of the stator current at which the machine remains stable (or resynchronizes). For example, if the frequency k_{fs} is reduced to the value k_{fs}=0.95 or k_{fs}=0.9, the machine does not resynchronize, only with k_{fs}=0.8 and lower, the synchronous mode is restored. In addition, a certain time is necessary after the end of the gust of wind and its return to its original state, so that the control parameter (stator current frequency k_{fs}) is restored to the value of the initial mode (i.e., to k_{fs}=1).

The next important question is the damping of oscillations of the rotors of frequency-controlled synchronous machines of windmills with permanent magnets. For damping oscillations in the thesis, control based on the Pontryagin maximum principle is used[22,23]. The amplitude k_{us} and frequency k_{fs} of the voltage supplied to the stator winding were chosen as the control parameters of the system under study. Recall that in order to transfer the phase coordinates of a system from one arbitrary state to another, an admissible control must first “accelerate” (or “slow down”) the system’s movement, and then “slow down” (or “accelerate”) it in the next period of time. Thus, when choosing k_{us}=k_{fs} as the control coordinates and, for technical reasons, limiting their variation range to 10 percent, we find that during the control they can change by Δk_{us}=Δk_{fs}= ±0.1 (at nominal values of k_{us}=k_{us}=1). Figure 6 shows the fluctuograms of the change in the electromagnetic moment m_{em} (Figure 6, *a*) during its discharge and surge..

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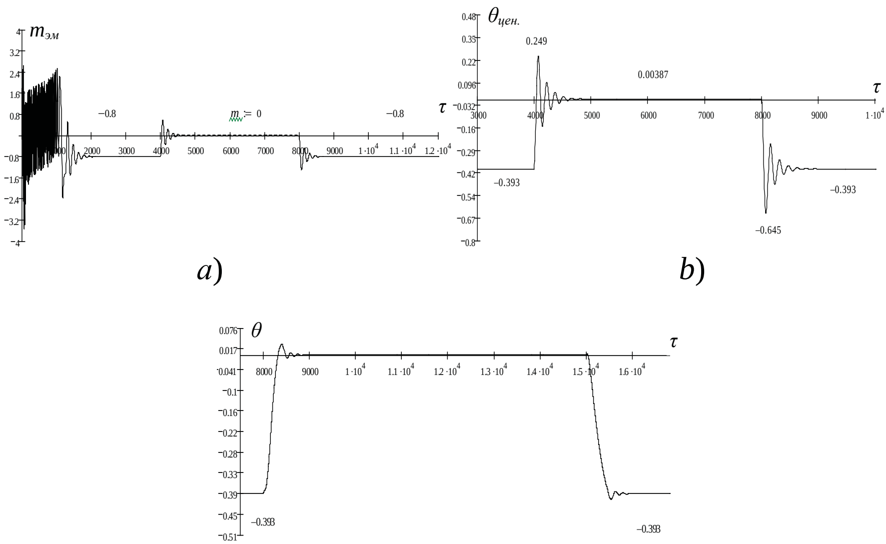
[22] Соколов, М.М. Электромагнитные переходные процессы в асинхронном электроприводе / М.М. Соколов, Л.П. Петров, Л.В. Масандилов [и др.] – Москва: Энергия, – 1967. – 201 с.

[23] Петров, Ю.П. Использование «принципа максимума» для нахождения оптимального закона регулирования синхронных машин // – Москва: Электричество, – 1964. №10, – с. 45-48.



a) *b*)

c)

Figure 6. Damping of oscillations during the dumping and surge of a wind turbine driving moment with control based on the Pontryagin principle

Figure 6, *b* shows the fluctogram of the change in the internal angle of a synchronous machine without control, i.e. at constant values $k_{us}= k_{fs}= 1$. At 8000 radian, the moment is reset from $m_{wt}= –0.8$ to $m_{wt}= 0$. In this case, the angle after oscillations is set to $\theta \approx 0$, and the maximum angle overhang is 65%; the same pattern is observed with repeated overload

Figure 6, *c* shows the fluctogram of the change in the angle θ under control in accordance with the Pontryagin maximum principle. When reset to 8000 radian at the same time, they are controlled by a jump $k_{us}=k_{fs}$ to the value $k_{us}=k_{fs}= 0.9$ (i.e., $\Delta k_{us}=\Delta k_{fs}= –0.1$ is added to the initial value $k_{us}=k_{fs}=1$) the action $k_{us}=k_{fs}= 0.9$ continues from 8000 up to 8150 radian (i.e., $\Delta\tau=150$ radian).

Further, in accordance with the Pontryagin principle, $\Delta k_{us}=\Delta k_{fs}$ change their signs and become equal to $\Delta k_{us}=\Delta k_{fs}=+0.1$ (i.e., $k_{us}=k_{fs}$ becomes equal to $k_{us}=k_{fs}=1.1$). The action $k_{us}=k_{fs}=1.1$ lasts from 8150 rad. up to 8450 radian after which the initial mode $k_{us}=k_{fs}=1$ is restored. With 8450 up to 15000 radian the generator runs without load

m_{em}=0. At 15000 radian, the mode of load surge is simulated from zero to m_{wt}=–0.8.

In this case, the regulator takes effect and the value is reproduced; the duration of which is 150 radian, i.e. with 15,000 glad. up to 15150 radian, and with τ=15150 radian up to τ=15450 radian $k_{us}=k_{fs}$ is set abruptly to the values $k_{us}=k_{fs}$=0.9 (i.e., $\Delta k_{us}=\Delta k_{fs}$=–0.1). Further from 15450 radian the value $k_{us}=k_{fs}$=1 is restored.

As can be seen from figure 6, *c* in the case of optimal control based on the Pontryagin maximum principle, the oscillatory transition process is practically reduced to aperiodic with a maximum overhang of the angle equal to only 5% of the established.

A technique has been developed for modeling higher harmonic voltages in the stator circuit of the synchronous circuit wind power plant of a synchronous generator, powered by a frequency converter[24]. The essence of the technique is to represent the components of the stator voltage, taking into account the higher harmonic components in the form:

$$\left.\begin{aligned}
&U_{ds} = A_{11}\cdot(\cos\alpha - \sin\alpha) - A_{12}\cdot(\cos\alpha + \sin\alpha)\\
&U_{qs} = A_{11}\cdot(\cos\alpha + \sin\alpha) + A_{12}\cdot(\cos\alpha - \sin\alpha)\\
&\\
&A_{11} = 0{,}707\cdot k_{us}\,(0{,}9\cdot\cos(k_{fs}\cdot\tau) - 0{,}035\cdot\cos(8\cdot k_{fs}\cdot\tau) + 0{,}15\cdot\cos(10\cdot k_{fs}\cdot\tau) -\\
&- 0{,}125\cdot\cos(11\cdot k_{fs}\cdot\tau) + 0{,}125\cdot\cos(13\cdot k_{fs}\cdot\tau) - 0{,}15\cdot\cos(14\cdot k_{fs}\cdot\tau) +\\
&+ 0{,}035\cdot\cos(16\cdot k_{fs}\cdot\tau))\\
&\\
&A_{12} = 0{,}707\cdot k_{us}\,(0{,}9\cdot\sin(k_{fs}\cdot\tau) - 0{,}035\cdot\sin(8\cdot k_{fs}\cdot\tau) + 0{,}15\cdot\sin(10\cdot k_{fs}\cdot\tau) -\\
&- 0{,}125\cdot\sin(11\cdot k_{fs}\cdot\tau) + 0{,}125\cdot\sin(13\cdot k_{fs}\cdot\tau) - 0{,}15\cdot\sin(14\cdot k_{fs}\cdot\tau) +\\
&+ 0{,}035\cdot\sin(16\cdot k_{fs}\cdot\tau))
\end{aligned}\right\} \quad (18)$$

Thus, in the expressions (18) of the voltage curve, the 8th, 10th, 11th, 13th, 14th and 16th harmonic components are taken into account. This technique allows you to analyze the effect of each of the harmonics on

[24] Vargas, U., Ramirez, A. Extended harmonic domain model of a wind turbine generator for harmonic transient analysis // IEEE Trans. Power Del., – 2016. Vol. 31, No. 3, – p. 1360-1368.

the operating parameters of the generator and, if necessary, adjust the filter parameters.

In conclusion of the chapter, a simulation mathematical model of the system "wind – wind turbine – electromechanical converter (synchronous generator) wind power plant – electric network" is proposed. It allows you to reproduce specific modes of operation of wind turbines depending on the actual values of wind speeds characteristic of the studied region; wind power plant torque characteristics for each of the range of wind speeds; and a mathematical model of the state of electromechanical converters of wind power plant (in this case, a synchronous generator with permanent magnets).

The third chapter discusses the issues of modeling and regulating the operational parameters of double-fed asynchronous machines[25,26] of a wind power plant operating on an electric network. Equations of frequency-controlled double-fed machines are given, taking into account the developed universal structure of frequency-controlled electric machines of alternating current. It should be noted that these equations allow, if necessary, the frequency control of these machines, both from the side of the rotor and from the side of the stator. Moreover, the presented equations are written in the axes d, q, rotating with the rotor speed ω_r, i.e. they are written in the form of Park – Gorev equations for synchronous machines. Therefore, it is advisable, by analogy with synchronous machines, to simplify the equations of double-fed asynchronous machines by neglecting the e.m.f. in the stator circuits slip and transformer emf, as well as the active resistance of the stator winding of the double-fed asynchronous machine and, naturally, evaluate the accepted assumptions. After trivial

[25] Amine, B. B. M. E., Ahmed, A., Houari, M.B., Mouloud, D. Modeling, simulation and control of a doubly fed induction generator for wind energy conversion systems // International Journal of Power Electronics and Drive System (IJPEDS), – 2020, Vol.11, No.3, – p. 1197–1210.

[26] Соколов, А. И., Климов, Ю. П. Алгоритмы управления асинхронными машинами двойного питания в ветроустановках // – Москва: Научный центр "Энергия и технологии", – 2021. – 205 с.

transformations, the simplified double-fed asynchronous machine equations appear in the form:

$$\left.\begin{aligned} p\Psi_{dr} &= U_{dr} - r_r\left(k_r \cdot \Psi_{dr} + k_m \cdot U_s \cdot cos\theta\right) \\ p\Psi_{qr} &= U_{qr} - r_r\left(k_r \cdot \Psi_{qr} + k_m \cdot U_s \cdot sin\theta\right) \\ p_s &= \frac{1}{T_j} \cdot m_{wt} - \frac{1}{T_j} k_m \cdot U_s\left(\Psi_{dr} \cdot sin\theta - \Psi_{qr} \cdot cos\theta\right) \\ p\theta &= s \end{aligned}\right\} \qquad (19)$$

where $k_r = \dfrac{x_s}{x_s \cdot x_r - x_m^2}$; $k_m = \dfrac{x_m}{x_s \cdot x_r - x_m^2}$; $U_{dr} = -U_s \cdot k_{ur} \cdot sin\left(k_{fr} \cdot \tau\right)$; $U_{qr} = U_s \cdot k_{ur} \cdot cos\left(k_{fr} \cdot \tau\right)$.

Thus, a complete system of equations having a 6th order as a result of simplifications and transformations is reduced to 4th order equations.

When evaluating the errors from these simplifications, it was revealed that the steady-state values of the operating parameters vary in the range of 0–7%, which is quite acceptable for engineering calculations. The dynamic components of the operating parameters during an abrupt change in the control coordinates of the machines (k_{us} and k_{fs}) in the first swing can vary significantly in amplitude from each other, but the transition process time and the number of swings practically coincide. The same components with an abrupt change in external disturbances in amplitude and number of swings slightly differ from each other.

When studying the influence of the mains voltage at the place of connecting the wind power plant with double-fed asynchronous machine to the electric network[27], it was revealed that when the mains voltage decreases to $U_s \leq 0.85$ at the nominal wind turbine load, in order to maintain stability, it is necessary to reduce the torque of the

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[27] Ибрагим, А. и др. Влияние резкого снижения напряжения на асинхронную машину двойного питания в системе генерации ветроэнергетической установки // Известия НТЦ Единой Энергетической Системы. –2019. 1(80), – с. 122-131.

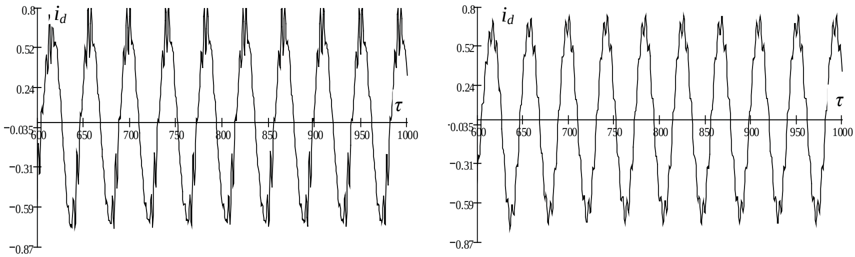
wind power plant by adjusting the angle of rotation of the wind turbine blades. With a small load of a wind power plant, stability can be maintained by separately regulating in the direction of increasing the amplitude of the voltage supplying the double-fed asynchronous machine rotor winding by only 5% (for example, from k_{ur}=0.22 to k_{ur}=0.23).

The following is a methodology for studying the effect of higher harmonic voltage on a frequency converter double-fed asynchronous machine wind power plant. Frequency converters for wind power plant are based on power IGBT transistors or on fully controlled GTO thyristors with pulse-width modulation control. The harmonic composition of the output voltage of an inverter with a sinusoidal pulse-width modulation when it is operated on an active-inductive load is the dependence of the amplitudes of the harmonic components of the output voltage on the magnitude of the modulation coefficient for various harmonics at certain values of the ratio of the carrier frequency to the modulation frequency[28]. With bipolar modulation and the ratio of the carrier frequency to the modulation frequency equal to ε=12, the 8th, 10th, 11th, 13th, 14th and 16th harmonics will be present in the output voltage curve With bipolar modulation and the ratio of the carrier frequency to the modulation frequency equal to ε=12, the 8th, 10th, 11th, 13th, 14th and 16th harmonics will be present in the output voltage curve. That is, the voltage on the rotor circuits will look as follows:

$$\left.\begin{aligned} U'_{dr} &= -U_s \cdot k_{ur}\,(0{,}9 \cdot sin(k_{fr} \cdot \tau) - 0{,}035 \cdot sin(8 \cdot k_{fr} \cdot \tau) + 0{,}15 \cdot sin(10 \cdot k_{fr} \cdot \tau) - \\ &\quad - 0{,}125 \cdot sin(11 \cdot k_{fr} \cdot \tau) + 0{,}125 \cdot sin(13 \cdot k_{fr} \cdot \tau) - 0{,}15 \cdot sin(14 \cdot k_{fr} \cdot \tau) + \\ &\quad + 0{,}035 \cdot sin(16 \cdot k_{fr} \cdot \tau)) \\ U'_{qr} &= U_s \cdot k_{ur}\,(0{,}9 \cdot cos(k_{fr} \cdot \tau) - 0{,}035 \cdot cos(8 \cdot k_{fr} \cdot \tau) + 0{,}15 \cdot cos(10 \cdot k_{fr} \cdot \tau) - \\ &\quad - 0{,}125 \cdot cos(11 \cdot k_{fr} \cdot \tau) + 0{,}125 \cdot cos(13 \cdot k_{fr} \cdot \tau) - 0{,}15 \cdot cos(14 \cdot k_{fr} \cdot \tau) + \\ &\quad + 0{,}035 \cdot cos(16 \cdot k_{fr} \cdot \tau)) \end{aligned}\right\} \tag{20}$$

[28] Garcia, H., Segundo, J., Rodriguez-Hernandez, et al. Harmonic modelling of the wind turbine induction generator for dynamic analysis of power quality // Energies, – 2018, Vol. 11, No. 1, – p. 104.

Figure 7 shows the fluctuograms of the change in the corresponding stator current id double-fed asynchronous machine of the wind power plant, taking into account the modeling of all harmonic components (figure 7, *a*), and when filtering higher harmonics starting from the 11th (figure 7, *b*). As can be seen from a comparison of the curves, after filtering, the current shape somewhat approaches the sinusoidal.



a) *b*)

Figure 7. Fluctograms of changes in the stator current id double-fed asynchronous machine taking into account all harmonic components (*a*), after filtering the higher harmonics, starting from the 11th (*b*)

In the next section, a comparative analysis of the various laws of voltage variation at the terminals of an asynchronous squirrel-cage machine as a function of the frequency of the stator current is provided, at which the minimum active power loss in the machine itself is ensured; maintaining the constancy of its overload capacity (the law of M.P. Kostenko)[29,30,31] and maintaining the value of the magnetic flux in the machine unchanged.

$$k_{us} = k_{fs} \cdot \sqrt{m_{\text{дв}}} \cdot \sqrt[4]{\frac{k_{\Delta}}{(0{,}61 + 0{,}39 \cdot k_{fs}) \cdot k_{fs}}}$$

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[29] Костенко, М.П. Электрические машины, специальная часть // – Москва-Ленениград: Госэнергоиздат, – 1949. – 712 с.

[30] Булгаков, А.А. Частотное управление асинхронными электродвигателями / А.А.Булгаков. – Москва: Наука, – 1966. – с. 216.

[31] Усольцев А.А. Частотное управление асинхронными двигателями/Учебное пособие. СПб: СПбГУ ИТМО, – 2006, – 94 с.

$$k_{us} = k_{fs} \cdot \sqrt{m_{дв}}$$

$$k_{us} = k_{fs}$$

To analyze the efficiency of the operating modes of frequency-controlled asynchronous machines with squirrel-cage rotors for scalar control, it is advisable to use the calculation data obtained on the proposed mathematical model, together with the data of analytical calculations of other types of power losses not taken into account in the model.

$$\begin{aligned}
&p\Psi_{ds} = U_{ds} - \omega_r \cdot \Psi_{qs} - r_s \cdot i_{ds} \\
&p\Psi_{qs} = U_{qs} + \omega_r \cdot \Psi_{ds} - r_s \cdot i_{qs} \\
&p\Psi_{dr} = -r_r \cdot i_{dr} \\
&p\Psi_{qr} = -r_r \cdot i_{qr} \\
&Tp\omega_r = m_{wt} - m_{em} \\
&m_{em} = \Psi_{ds} \cdot i_{qs} - \Psi_{qs} \cdot i_{ds} \\
&U_{ds} = 0{,}707 \cdot k_{us}\left[\cos(k_{fs} \cdot \tau) \cdot (\cos\alpha - \sin\alpha) - \sin(k_{fs} \cdot \tau) \cdot (\cos\alpha + \sin\alpha)\right] \\
&U_{qs} = 0{,}707 \cdot k_{us}\left[\cos(k_{fs} \cdot \tau) \cdot (\cos\alpha + \sin\alpha) + \sin(k_{fs} \cdot \tau) \cdot (\cos\alpha - \sin\alpha)\right]
\end{aligned} \tag{21}$$

When choosing the law of controlling the amplitude of the stator voltage of a machine, it is necessary to take into account not only the minimum power loss in the asynchronous machine itself, but also the minimum consumed reactive power, since this power determines the additional energy loss in the networks to which these machines are connected.

According to the above criteria, it is most advisable to apply two control laws - regulation on the constancy of the overload capacity and regulation on the constancy of the magnetic flux. The simplicity of execution is preferable to the last control law, but with the fan-like nature of the change in moment, the control law is more effective at a constant overload capacity $k_{us} = k_n^{'} \cdot k_{fs} \cdot \omega_r$.

Based on the developed three-coordinate mathematical models of squirrel-cage asynchronous generators and double-fed asynchronous machines, studies and a comparative analysis of their frequency start modes were carried out. This issue is especially relevant in those cases when wind power plants and wind parks containing several tens of wind power plants are connected to networks quite remote from power centers and poorly compensated by reactive capacities. In these cases, the modes of connecting wind power plants with asynchronous generators can lead to a significant voltage drop during the start-up period. Studies have shown that from the point of view of the impact on electrical networks during the start-up period, the most preferable are frequency-controlled asynchronous wind power plants generators with a squirrel-cage rotor. With a frequency start, their starting current is 2 times less than the starting current of the double-fed asynchronous machines wind power plants, and, importantly, the energy spent on the start-up process is also 55% lower, since the total starting time for a wind power plants with an asynchronous generator is about 400 radian for the example under study, and for wind turbines with double-fed asynchronous machines – about 600 radian.

When used in wind power plants, double-fed asynchronous machines is proposed in the case when the range of changes in wind speeds is very small (almost constant), i.e. when there is no need to adjust the speed of the wind power plants, put it in synchronous operation[32]. To do this, connect the double-fed asynchronous machines rotor winding after appropriate reconnections to a DC source, for this it is enough to disconnect it from the output of the frequency converter (inverter) and connect it to the output of the rectifier, as this image in figure 8.

[32] Ferre, A. J., Bellmuntriol, G., Sumper, A. Modeling and control of the doubly fed induction generator wind turbine // Simulation Modelling Practice and Theory. – 2010. Vol. 18, Issue 9, – p. 1365-1381.

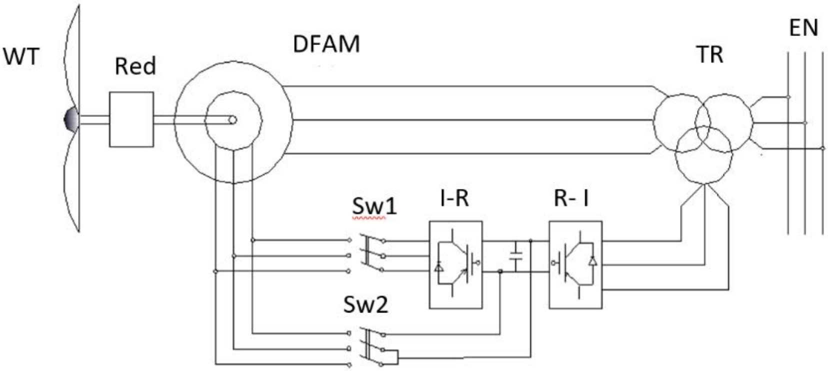
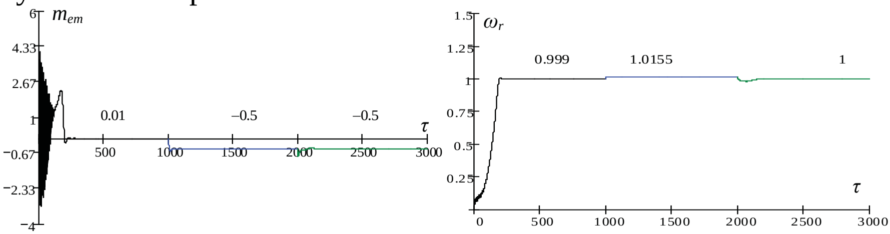


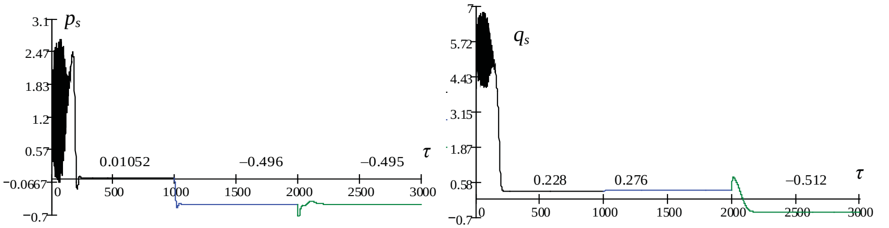
Figure 8. The electric circuit transfer double-fed asynchronous machines, with a frequency converter in the rotor circuit, in synchronous operation

The originality of this circuit lies in the fact that the rotor winding receives power from the DC link of the frequency converter. In this case, the two phases of the rotor winding are connected in parallel with each other and in series with the third phase.

Figure 9 shows the fluctuograms of the change in the parameters of the double-fed asynchronous machines during its transfer to the synchronous operation mode.



a) *b*)



c) *d*)

Figure 9. Fluctograms of the change of operational parameters of double-fed asynchronous machine wind power plants when transferring it to asynchronous operation mode

In the time range from 0 to 1000 radian, double-fed asynchronous machines was directly launched with shorted rotor windings, while the torque is zero (figure 9, *a*), the rotor speed is ω_r=0.999 (figure 9, *b*), the active stator power is also practically is zero p_s=0.01 (figure 9, *c*), and reactive power is q_s=0.228 (a plus sign indicates that it is consumed by their electric network (figure 9, *d*). In the time range from 1000 to 2000 radian, a wind appears, creating a driving moment on the wind power plant shaft equal to m_{wt}=–0.5, the machine goes into generator mode, the rotation frequency becomes equal to ω_r=1.015 (figure 9, *b*), the values of active and reactive power become equal, respectively, p_s=–0.496 (active power is supplied to the network) and q_s=0.276 (reactive power is consumed from the network (figure 9, *d*) with 2000 radian. Double-fed asynchronous machines is switched to synchronous operation mode, in this mode the reactive power changes from q_s=0.276 to q_s=–0.512 (is supplied to the network). In this case, the direct current in the winding of the double-fed asynchronous machines rotor becomes i_f=–0.889, and rotor voltage U_f=–0.04. Thus, the simulation results confirmed the efficiency and effectiveness of the proposed method for transferring the wind power plants in synchronous operation.

In the conclusion of this section, a mathematical model of the system for controlling the angle of rotation of the blades of a wind turbine is presented during the operation of a wind power plants with a double-fed asynchronous generator[33]. It is known that the angle of rotation of the blades of the wind power plants is carried out in the zone of change of wind speeds from the calculated value of V_{cal}, at

[33] Smida, B. M., Sakly, A. Pitch Angle Control for Variable Speed Wind Turbines. - Journal of Renewable Energy and Sustainable Development (RESD), – 2015. Vol. 1, No. 1, – p. 81-88.

which the rated power of the wind power plants is issued, to the maximum operating wind speed V_{max}, after which the wind turbine is transferred to the vane position and stops[34].

The essence of the proposed method lies in the fact that using the catalog data of specific types of wind power plants, namely, the change (decrease) in the utilization of wind energy C_p as a function of wind speed in the above range of wind speeds, it is possible to synthesize the dependence of the torque of the wind turbine as a function of angle turning his blades. On the example of a specific wind power plants of the Nordex N80 type[35], with a power of P_{nom}= 2500 kW, the expression for the torque of the wind turbine, reduced to the generator shaft in the form:

$$m_{WPP} = V^3\left[A\cdot\beta^2 + B\cdot\beta + C\right] \tag{22}$$

где $A = \dfrac{a_2\cdot k_\beta^2}{C_{pn}\cdot V_{cal}^3}$; $B = \dfrac{a_1\cdot k_\beta}{C_{pn}\cdot V_{cal.}^3} + \dfrac{2\cdot a_2\cdot k_\beta}{C_{pn}\cdot V_{cal.}^2}$;

$C = \dfrac{a_0}{C_{pn}\cdot V_{cal.}^3} + \dfrac{a_1}{C_{pn}\cdot V_{cal.}^2} + \dfrac{a_2}{C_{pn}\cdot V_{cal.}}$; V – current wind speed; a_0, a_1, a_2 – coefficients of approximation of the expression C_p by a polynomial of the second degree; C_{pn} –value of the coefficient of utilization of wind energy at which the rated power is issued; $V_{cal.}$–calculated wind speed [m/s], at which the wind power plants produces rated power; k_β – coefficient of proportionality between the angle of rotation of the blades β and the wind speed. For WEI of the Nordex N80 type, these coefficients are equal A= $2.58\cdot10^{-8}$; B= $-0.44\cdot10^{-5}$; C= $-0.265\cdot10^{-4}$.
The algorithm of the "operation" of equation (22) is as follows: when a wind speed of any value V_1 is reached, which is in the range $V_{cal.} \div V_{max}$ with the corresponding time constant of the entire path for controlling the angle of rotation of the wind turbine blades, a value for

[34] Цгоев, Р. С. Повышение эффективности ветроэнергетического агрегата регулированием угла установки лопастей ветроколеса/ Р.С. Цгоев, Г.А. Яковенко// Электричество. – 2014. – № 3. – с. 25-30.
[35] Nordex Company. Products & Servic. [Electronic resource] / URL: https://www.nordex-online.com/en/product/product-main-page

β_1 is established that converts equation (22) to unity $m_{wt}=1$, i.e. after the action of the regulator, the steady-state value of the driving moment of the wind turbine remains constant equal to the nominal value. The rotational angle control system of the Nordex N80 wind power plants blades with a double-fed asynchronous machine was investigated on a mathematical model with an automatic control system based on two control principles – perturbation control and deviation control. The wind speed was adopted as a disturbing effect, and the second control is based on regulation of the deviation of the active power of the double-fed asynchronous machines from the nominal value. A comparative analysis of the calculation results revealed that, ceteris paribus, the duration of the transition process when reproducing the principle of control "by deviation" (with a statism of 3–4%) is more than an order of magnitude less than the duration of the transition process when implementing the principle of control "perturbation".

In addition, the issues of reactive power compensation in the installations of the applied wind power plants have been studied[36]. It was revealed that the maximum amount of reactive power is consumed in asynchronous generators when they are connected to the power system. The ways of reducing the consumption of reactive power in asynchronous generators of these installations are shown.

Numerous studies of reactive power during the start-up and operation of asynchronous generators of wind power plants allow, depending on the requirements of the electrical network, to calculate the required values of reactive power compensation, i.e. select the type and parameters of the compensated capacitors.

The fourth chapter explores the modeling of wind power plants operation modes from double-fed asynchronous machine to an infinite power network, taking into account the parameters of the external

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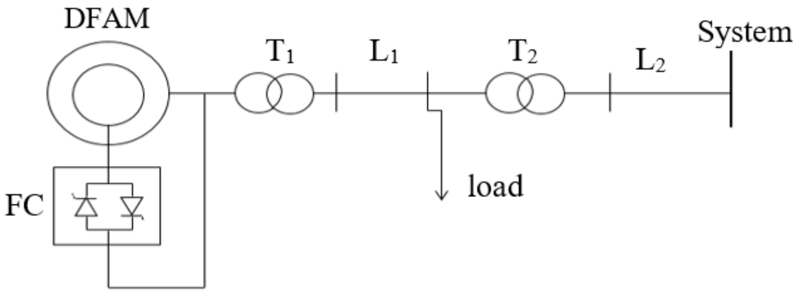
[36] Apata, O., Oyedokun, D. Novel reactive power compensation technique for fixed speed wind turbine generators // Proc. of the IEEE PES/IAS Power Africa, – 2018, – p. 628-633.

network[37,38]. The simulation method is based on the fact that the equations of the external network from the terminals of the generator $\dot{U}_g$ to the buses of infinite power $\dot{U}_s$ are written under the assumption that the axes of the complex plane are aligned with the axes d_0, q_0 rotating with a constant angular synchronous speed ω_s, with the condition that the axis q_0 coincides with an axis of real numbers. Further, these equations of the external network, expanded along the axes d_0, q_0, are jointly solved. Then, the transition of the voltage components and currents recorded in the axes d_0 and q_0, to the components recorded in the axes d, q double-fed asynchronous machine. Thus, the components of the voltage U_d, U_q and currents i_d, i_q double-fed asynchronous machine are synthesized. Figure 10 (*a*, *b*) shows the electrical circuit of the system and its equivalent circuit. $\dot{U}_g$ $\dot{U}_s$, $\dot{U}_n$ – are the voltages in complex form, respectively, at the generator output (double-fed asynchronous machine), at the load node, and at the buses of the receiving system.



a)

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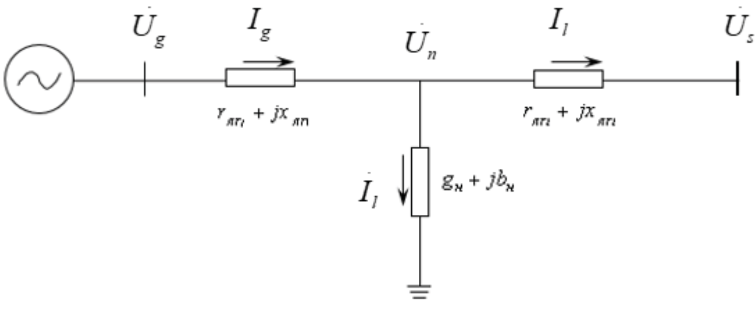
[37] Сидоров, Л. П., Орлов, В. С. Анализ электромеханических процессов в АМДП при подключении к энергосетям // Энергия будущего, – 2022. 4(23), – с. 28-36.

[38] Jiao, J., Yu, Y., Zou, J. Coordinated Frequency Control of Doubly-fed Induction Generator Based on Interconnected Grid // In Proceedings of the 2020 4th International Conference on Power and Energy Engineering (ICPEE), – Xiamen, China, – 2020, – p. 124-129.



b)

Figure 10. A wind farm power transmission circuit containing a generator based on double-fed asynchronous machine, transformers T_1 and T_2, power lines L_1 and L_2, a load, and a receiving bus system of infinite power: *a*) – electrical circuit; *b*) – equivalent circuit

After appropriate substitutions and transformations, we obtain the expressions for the voltage components of the generator, presented in the axes of the machine rotating at the rotor speed ω_r, U_{rd}, U_{rq} which will appear in the form:

$$\left.\begin{aligned} U_{rq} &= \left(k_1\cdot U_{cd_0} - k_2\cdot U_{cq_0}\right)\cdot\sin\theta + \left(k_1\cdot U_{cq_0} + k_2\cdot U_{cd_0}\right)\cdot\cos\theta + k_3\cdot i_{гq} - k_4\cdot i_{rd} \\ U_{rd} &= \left(k_1\cdot U_{cd_0} - k_2\cdot U_{cq_0}\right)\cdot\cos\theta + \left(k_1\cdot U_{cq_0} + k_2\cdot U_{cd_0}\right)\cdot\sin\theta + k_4\cdot i_{гq} - k_3\cdot i_{rd} \end{aligned}\right\} \quad (23)$$

where U_{cd_0} U_{cd_0} – voltage components of the receiving system $\dot{U}_s$, in synchronously rotating axes d_0, q_0; i_{rd}, i_{rq} – components of the generator currents (double-fed asynchronous machine) in the axes d, q at the output of the generator, taking into account the expressions $i_{rd} = i_{ds} + k_{ur}\cdot i_{dr}$ and $i_{rq} = i_{qs} + k_{ur}\cdot i_{qr}$; k_1, k_2, k_3, k_4 – coefficients depending on the active and inductive resistances of transformers T_1 and T_2, lines L_1 and L_2, as well as load; θ – double-fed asynchronous machine loading angle.

With this equation in mind, the voltage balance of double-fed asynchronous machine is written as:

$$\left.\begin{aligned} p\Psi_{sd} &= U_{rd} - \omega_r \cdot \psi_{qs} - r_s \cdot i_{sd} \\ p\Psi_{sq} &= U_{rq} + \omega_r \cdot \psi_{ds} - r_s \cdot i_{sq} \\ p\psi_{rd} &= -U_r \cdot k_{ur} \cdot sin\left(k_{fr} \cdot \tau\right) - r_r \cdot i_{rd} \\ p\psi_{rq} &= \pm U_r \cdot k_{ur} \cdot cos\left(k_{fr} \cdot \tau\right) - r_r \cdot i_{rq} \end{aligned}\right\} \quad (24)$$

where $U_r = \sqrt{U_{rd}^2 + U_{rq}^2}$.

Based on the simulation results of the above-described system, the operating modes of a wind power plants generator, made on the basis of double-fed asynchronous machine, were revealed, at which the values and directions of active and reactive powers (currents) flowing to the local load both from the double-fed asynchronous machine of a wind power plants and from the power system are changed. This position is especially necessary to know when calculating the consumption, delivery and control flows of active and reactive capacities in the studied node of the system, since the power generated by wind power plants is a variable value, depending on the values of wind speeds.

Of interest is the operation of a wind farm in a local alternating current system of limited power, for example, in conjunction with a diesel-electric or gas turbine installations in regions where there is no electrical connection to the power system[39]. The modes of operation of such systems can be investigated on the basis of the electrical circuit shown in figure 11.

Here, the synchronous generator SG of the diesel-electric installation is connected to the node *m* from which the load $r_{n1}+jx_{n1}$ is fed, a power line (power transmission line) with inductive resistance x_{mn} (active resistance is not taken into account for simplicity of analysis), which connects the two nodes *m* and *n*. The node *n* is connected to an asynchronous generator (DFAM) of a wind turbine and a load $r_{n2}+jx_{n2}$. The node voltages are respectively U_m and U_n.

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[39] Arnaltes, S., Rodriguez-Amenedo, J.L., Montilla-DJesus, M.E. Control of variable speed wind turbines with doubly fed asynchronous generators for stand-alone applications // Energies, – 2018, Vol. 11, – p. 26-32.

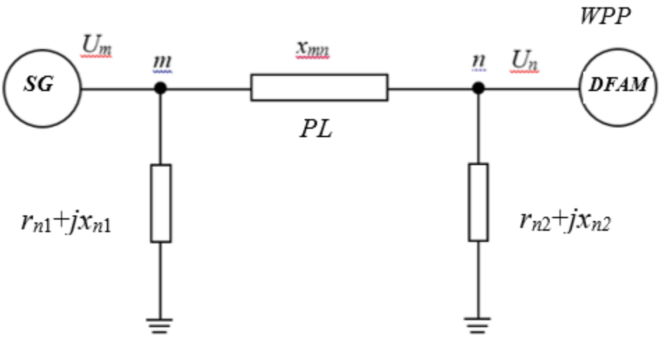

Figure 11. Connection diagram double-fed asynchronous machine wind power plants to a limited power system

To solve, the method of balancing active and reactive powers at nodal points is used. With this method, each electric machine, the equations of which can be described in any coordinate system, since only the values of their active and reactive powers, which are scalar quantities, are used. In this case, for each of the machines, the power is determined using the voltage of the node to which it is connected.

The solution of the power line equation between nodes *m* and *n* are determined from the relations:

$$\left.\begin{aligned} P_m &= \frac{U_m \cdot U_n}{x_{mn}} \sin\theta_{mn} \\ Q_m &= \frac{U_m^2}{x_{mn}} - \frac{U_m \cdot U_n}{x_{mn}} \cos\theta_{mn} \end{aligned}\right\} \tag{25}$$

Moreover, for nodes *m* and *n*, the conditions must be satisfied

$$\begin{aligned} P_m &= P_{СГ} - P_{н1} \\ Q_m &= Q_{СГ} - Q_{н1} \end{aligned} \quad \text{and} \quad \left.\begin{aligned} P_n &= P_{АГ} - P_{н2} \\ Q_n &= Q_{АГ} - Q_{н2} \end{aligned}\right\} \tag{26}$$

Thus, the active and reactive powers P_m and Q_m coming to the beginning of the section are considered to be known, as well as the voltage at the beginning of the section U_m, and the unknowns that need to be determined are the voltage, active and reactive powers, and the angle angle of the voltage vectors θ_{mn} at the end of the section.

After trivial transformations, are determined:

$$\left.\begin{aligned} \theta_{mn} &= arctg\frac{P_m \cdot x_{mn}}{U_m^2 - Q_m \cdot x_{mn}} \\ U_n &= \sqrt{\frac{P_m^2 \cdot x_m^2 + (U_m^2 - Q_m \cdot x_{mn})^2}{U_m^2}} \end{aligned}\right\} \quad (27)$$

It can be seen from equation (27) that, given the values of U_m, P_m, and Q_m, we can unambiguously obtain the expressions for θ_{mn} and U_n, which should be used at the end of the line section – they are input parameters for the double-fed asynchronous machine of a wind power plants.

Mathematical models of synchronous generator and double-fed asynchronous machine wind turbines are compiled; their powers are determined taking into account expressions (27). During the study, the parameters of the loads, the power of the wind turbine wind turbine, which depend on the wind regime, were varied, while the values of power flows and voltages at the load nodes were determined. The dynamic modes of the system were also studied with sharp changes in the values of the load resistances and torque on the shaft of the wind power plants dual-fed asynchronous machine.

MAIN CONCLUSIONS AND RESULTS OF THE WORK

1. The universal structure of the mathematical model of the main electric wind power plants has been developed; this structure makes it possible to implement all possible types of control of these machines – frequency on the stator side for both asynchronous machines with a squirrel-cage rotor and synchronous machines with excitation from permanent magnets and with electromagnetic excitation, frequency on the rotor side for asynchronous machines with a phase rotor (double-fed asynchronous machine).
2. A methodology for modeling a frequency-controlled asynchronous wind power plant with a squirrel-cage rotor in a three-coordinate system α_s, β_s, γ_s, which are motionless in space, is proposed. The introduced adjustments to the components of the stator voltage allow you to simply and effectively take into account the change in the

regulatory parameters – the amplitude and frequency of the phase voltage of the machine.

3. A mathematical model of a frequency-controlled synchronous machine with permanent magnets is proposed on the basis of a universal mathematical model of electric wind power plants. In the equations of this machine, a parameter is introduced that displays the magnetic energy of a permanent magnet, referred to a unit of its volume (if the residual induction is small, then we can assume that it simulates the coercive force of a permanent magnet).

4. When studying the dynamic stability of wind power plants with a synchronous generator with permanent magnets on a mathematical model, it was found that in addition to the magnitude of the gust of wind and its duration, the dynamic stability is also affected by the value of the set value of the wind speed after the gust of wind speed – the lower the wind speed, the higher the dynamic stability. It was revealed that with an increase in the magnitude of magnetic energy per unit volume, the dynamic stability increases. As a recommendation to increase dynamic stability, a short-term decrease in the current frequency in the stator winding of the generator during a gust of wind to a certain limit value is proposed.

5. It is proposed to effectively damp the oscillations of the rotors of synchronous wind turbine generators with permanent magnets, using the Pontryagin maximum principle, in case of sharp disturbances either from the side of the generator shaft or from the power system side, first increase the amplitude and frequency of the stator voltage of the generator at the same time and after a certain time, reduce them by 10% with a load surge. When loading the load, this procedure must be performed in the reverse order (i.e., first reduce by 10%, and then increase by the same amount).

6. The presented form for writing the equations of a synchronous wind turbine generator with permanent magnets allows you to simply and efficiently reproduce all the harmonic components in the voltage curve supplying the stator winding of the generator. This makes it possible to evaluate the effect of each of the harmonics on the

operating parameters of the generator, and, if necessary, implement and adjust the filter parameters.

7. An improvement of the previously developed mathematical model of a double-fed asynchronous machine of a wind power plants is proposed. The refinement consists in deriving formulas for the separate determination of the active and reactive powers of the stator and double-fed asynchronous machine rotor windings with its frequency control, and the total active and reactive powers of the machine are determined by their algebraic addition. The questions of the acceptability of simplification of the double-fed asynchronous machine equations are considered. When simplified by simultaneous neglect in the stator circuit of the machine, transformer EMF, EMF the slip and active resistances of the stator windings, the parameters of the steady state in comparison with the parameters calculated by the complete equations differ by 0–7%, which allows us to recommend such a simplification for the study of quasi-steady and static modes.

8. It was found that a decrease in the mains voltage at the point of connection of a wind power plants with double-fed asynchronous machine to the electric network to a value of U_s=0.85 and lower in the mode of operation of a wind power plants with a rated load, in order to maintain stability, it is necessary to reduce the magnitude of the wind turbine torque by adjusting the angle of rotation of the wind turbine blades. With a small load of wind power plants (50% and below), the stability of the system can be achieved by increasing, within 5–7%, the amplitude of the voltage supplying the rotor winding of the machine, i.e. at the output of the frequency converter.

9. A technique is given for analyzing the efficiency of the operation of a frequency-controlled asynchronous machine with squirrel-cage rotors with scalar control and ensuring a minimum of power losses in the machine itself, as well as the constancy of the overload capacity and magnetic flux. It was revealed that, taking into account the values of the total power losses and the consumed reactive power, the most appropriate is the regulation of the constancy of the overload capacity and magnetic flux at a constant value of the moment on the machine shaft. With the fan-like nature of the change in moment

on the machine shaft in terms of the combination of power losses and consumed reactive power, it is more effective to apply the law on the constancy of the overload capacity of the machine.

10. Based on the developed full three-coordinate mathematical models of a frequency-controlled asynchronous generator with a phase rotor (double-fed asynchronous machine) and a frequency-controlled asynchronous generator of a wind power plants with a squirrel-cage rotor, a comparative analysis of the frequency start modes is carried out. It has been found that the most appropriate from the point of view of minimal impact on electric networks in the areas where wind turbines are connected to them is the use of frequency-controlled asynchronous generators with a squirrel-cage rotor, because they have an inrush current of almost 2 times lower than the inrush current of the wind turbine motor, and the energy spent on start-up process is also 55% lower.

11. A new method is proposed for transferring double-fed asynchronous machine wind power plants to synchronous operation. This mode of operation, for example, can be carried out in wind turbines, when in a certain long period of time there is no need to control their rotation frequency. The originality of the method and the correspondingly developed matmodel consists in the fact that only the rectifier part of the double-fed asynchronous machine frequency converter is used to transfer the double-fed asynchronous machine into synchronous mode. The simulation results confirmed the efficiency and effectiveness of the proposed method.

12. A methodology has been developed for modeling the control of the angle of rotation of the blades of a wind turbine of modern wind power plants. The equations are synthesized and the automation system is simulated, working in conjunction with a system for controlling the angle of rotation of the wind turbine blades in a wind turbine equipped with a frequency-controlled double-fed asynchronous machine, as a result of which it was found that, ceteris paribus, if the control system incorporates the “deviation” control principle, the transition process duration (with a statism of 3–4%), it

is more than an order of magnitude less than the duration of the transient process when the principle of control according to “outrage”.

13. A technique is proposed for modeling and studying wind power plants with double-fed asynchronous machine when working on a network of "infinite power", taking into account the local load of the wind power plants and the parameters of the external network to the "infinite power" system. The essence of the proposed method lies in the “coordination” of the double-fed asynchronous machine equations written in the axes of the machine rotating at the rotor speed with the equations of the external network and load recorded in a synchronously rotating coordinate system. Based on the simulation results, operating modes were identified under which the values and directions of the active and reactive currents (capacities) flowing into the local load from the asynchronous wind power plants generator and from the power system (buses of infinite power) change. This is especially important to know when calculating the consumption, delivery and management of capacity flows in the studied node of the system.

14. A mathematical model of the system "double-fed asynchronous machine wind power plants – synchronous generator of limited power", i.e. double-fed asynchronous machine wind power plants operation for a limited power network. Moreover, each of the generators has a local load. This model is based on the principle of “power balance” and therefore does not require bringing the equations of generators and loads to a single coordinate system. All possible modes of operation of both a synchronous generator and an asynchronous wind turbine generator were studied at various power take-offs both at the terminals of the synchronous generator and at the terminals of the double-fed asynchronous machine wind power plants.

MAIN PROVISIONS OF THE THESIS ARE REFLECTED IN THE FOLLOWING PAPERS

Papers published in peer-reviewed scientific journals on the list of SAC

1. Мустафаев, Р.И., Гасанова, Л.Г. Моделирование и исследование квазистационарных режимов работы ветроэлектрических установок с асинхронными генераторами при частотном управлении // – Москва: Электричество, – 2009, №6, – с. 36-42.

2. Мустафаев, Р.И., Гасанова, Л.Г. Моментно-мощностные характеристики современных ветроэлектрических установок // – Москва: Электротехника, – 2009. №7, – с. 53-58.

3. Мустафаев, Р.И., Гасанова, Л.Г., Бабаев, М.А., Исламов, Ф.Х., Аббасов, Р.М. Моделирование и исследование режимов работы авиационных синхронных генераторов с постоянными магнитами // Milli Aviasiya Akademiyasının elmi əsərləri, Баку: –2010, №3, – с. 170-178.

4. Mustafayev, R.I., Saidov, R.A., Hasanova, L.H. The comparative analysis of wind power plants (WPP) using efficiency in Absheron peninsula conditions of the republic of Azerbaijan // TPE-Journal International Journal on Technical and Physical Problems of Engineering IJTPE, 2010 Issue 3, No. 2, Vol.2, p. 18-21.

5. Мустафаев, Р.И., Гасанова, Л.Г. Моделирование и исследование режимов работы синхронных генераторов ветроэлектрических установок при частотном управлении // – Москва: Электричество, – 2010. №7, – с.34-40.

6. Мустафаев, Р.И., Гасанова, Л.Г., Зейналов Р.Б. Частотный пуск и управление ветроэлектрических установок с синхронным генератором с постоянными магнитами // – Bakı: Azərbaycan Elmi-Tədqiqat və Layihə-Axtarış Energetika İnstitutunun elmi əsərlər toplusu, – 2010. – s. 89-98.

7. Mustafayev, R.I., Hasanova, L.H. Development of world wind-power engineering preliminary feasibility study of 50 MW wind power farm in Azerbaijan // ELECTROScientific – Industrial Journal, Baku: – 2010. v.1, No. 1, – p.25-36.

8. Mustafayev, R.I., Hasanova, L.H. Development and research mathematical models, modes of wind power plants’ electromechanical converters // – San Diego: Reliability: theory & applications. Journal is registered in the library of the U.S. congress, – 2011. Vol.2, No.2

(21), – p. 52-66.
9. Мустафаев, Р.И., Гасанова, Л.Г. Моделирование угла поворота лопастей ветродвигателя ветроэлектрической установки, работающей на электрическую сеть // – Москва: Электротехника, – 2011. №12, – с.22-27.
10. Мустафаев, Р.И., Гасанова, Л.Г., Зейналов, Р.Б. Исследование статических и динамических режимов в ветроэлектрических установках, содержащих асинхронные машины двойного питания // – Bakı: Azərbaycan Elmi-Tədqiqat və Layihə-Axtarış Energetika İnstitutunun elmi əsərlər toplusu, – 2011. – s.44-59.
11. Mustafayev, R.I., Hasanova, L.H. Parallel Operation of Wind Power Farm with Double Fed Induction Generators with Electric Power System // ELECTRO Scientific – Industrial Journal, – Baku: – 2011. Vol.2, No. 1, – p.13-22.
12. Мустафаев, Р.И., Гасанова, Л.Г. Модель для исследования режимов работы ветроэлектрических установок с асинхронными машинами двойного питания в энергосистеме // – Минск: Энергетика. Известия высших учебных заведений и энергетических объединений СНГ, – 2012, №3, – с.27-39.
13. Мустафаев, Р.И., Гасанова, Л.Г., Зейналов, Р.Б. Исследование влияния сетевого напряжения на режимы работы ветроэлектрических установок с асинхронной машиной двойного питания // – Bakı: Azərbaycan Elmi-Tədqiqat və Layihə-Axtarış Energetika İnstitutunun elmi əsərlər toplusu, Azərbaycan, –2012, – s.27-41.
14. Mustafayev, R.I., Hasanova, L.H., Musayev, M.M. Modelling starting regim work of the induction generators of wind turbine and small hydroplaning // International Journal of Recent Development in Engineering, – 2013. Vol.1, No. 3, – p. 16-23.
15. Mustafayev, R.I., Hasanova, L.H., Musayev, M.M. Some subjects of compensation of the induction generators reactive power in wind-power and small hydroelectric power plants // – San Diego: Reliability: theory & applications. Journal is registered in the library of the U.S. congress, – 2013. Vol.8, No.4 (31), – p. 2-13.

16. Мустафаев, Р.И., Гасанова, Л.Г. Влияние значения сетевого напряжения на режим работы ветроэлектрической установки с асинхронной машиной двойного питания // – Москва: Электротехника, – 2013. №4, – с. 43-49.
17. Мустафаев, Р.И., Гасанова, Л.Г. Режимы работы ветроэлектрических установок с АМДП в автономной электрической системе // – Bakı: Azərbaycan Elmi-Tədqiqat və Layihə-Axtarış Energetika İnstitutunun elmi əsərlər toplusu, – 2013. – s.36-56.
18. Мустафаев, Р.И., Саидов, Р.А., Гасанова, Л.Г. Исследование установившихся режимов работы частотно-управляемого асинхронного генератора ветроэлектрических установок // Энергетика. Известия высших учебных заведений и энергетических обединений СНГ, Минск: – 2014. №3, – с. 43-48.
19. Мустафаев, Р.И., Гасанова, Л.Г. Некоторые вопросы регулирования возбуждения синхронных генераторов малых ГЭС // – Баку: Проблемы Энергетики, – 2014. №2, – с. 3-7.
20. Mustafayev, R.I., Hasanova, L.H., Musayev, M.M., Aliyev Q.M. The excitation control and stability of small hydroelectric power stations synchronous generators when operation in power system // – San Diego: Reliability: theory & applications. Journal is registered in the library of the U.S. congress, – 2014. Vol.9, No.4 (35), – p. 29-36.
21. Мустафаев, Р.И., Гасанова, Л.Г. Универсальная структура математической модели управляемых электрических машин переменного тока // – Москва: Электричество, – 2015. №2, – с. 40-48.
22. Мустафаев, Р.И., Гасанова, Л.Г. Исследование динамики ветроэлектрических установок, оснащенных синхронными генераторами с постоянными магнитами // – Москва: Электротехника, – 2015. №4, – с. 23-29.
23. Мустафаев, Р.И. Гасанова, Л.Г., Мусаев, М.М, Мамедов Э.М., Набиев Х.И. Некоторые аспекты применения асинхронных машин двойного питания в качестве генератора малых ГЭС // – Баку: Проблемы Энергетики, – 2015. №1, – с. 3-13.
24. Мустафаев, Р.И., Гасанова, Л.Г. Математическое

моделирование управляемых трехфазных асинхронных машин // – Москва: Электричество, – 2016. №5, – с. 59-65.

25. Mustafayev, R.I., Hasanova, L.H. Study of Starting Duty of Wind Power Plant with Asynchronous Generators // – San Diego: Reliability: theory & applications. Journal is registered in the library of the U.S. congress, – 2016. Vol. 11, No. 4 (43), – p. 38-48.

26. Мустафаев, Р.И., Гасанова, Л.Г., Мусаев, М.М. Исследование статических и динамических характеристик гидроагрегатов малых ГЕС // – Москва: Электро. Электротехника, электроэнергетика, электротехническая промышленность, – 2016. №4, – с. 17-21.

27. Мустафаев, Р.И., Гасанова, Л.Г., Мусаев, М.М. Моделирование и исследование гидроагрегатов малых ГЭС с частотно-управляемыми синхронными генераторами с постоянными магнитами // – Минск: Энергетика. Известия ВУЗ и энергетических объединений СНГ, – 2016. Т. 59, №2, – с. 106-121.

28. Мустафаев, Р.И., Гасанова, Л.Г. Использование регулируемой асинхронной машины двойного питания в синхронном режиме // – Москва: Электричество, – 2017. №10, – с. 60-68.

29. Mustafayev, R.I., Hasanova, L.H. Simplification of Mathematical Model of Double Fed Asynchronous Machine // European Journal of Electrical and Computer Engineering, – 2017. Vol. 1, No. 3, – p. 16-22.

30. Мустафаев, Р.И., Гасанова, Л.Г. Методика исследования влияния высших гармонических напряжения на режимные параметры синхронного генератора с постоянными магнитами // – Мурманск: Вестник МГТУ, – 2017. Т. 20, № 4, – с. 705-713.

31. Мустафаев, Р.И., Гасанова, Л.Г., Мусаев, М.М. Применение регулируемых электрических машин в гидроагрегатах малых ГЭС, работающих на энергосистему // – Москва: Электротехника, – 2018. №5, – с.38-44.

32. Гасанова, Л.Г. Вопросы пуска синхронных машин с постоянными магнитами // – Баку: Проблемы Энергетики, – 2019. №3, – с. 31-38.

33. Гасанова, Л.Г., Мустафаев, Р.И. Анализ эффективности работы асинхронной машины с короткозамкнутым ротором при скалярном частотном управлении // – Москва: Электричество, – 2019. №3, – с. 46-54.

34. Гасанова, Л.Г. Фильтрация гармоник частотно-управляемых асинхронных машин двойного питания // – Мурманск: Вестник Мурманского государственного технического университета, – 2019. Т. 22, № 4, – с. 508-512.

35. Гасанова, Л.Г. Обоснование методов исследования режимов работы электрических машин в ветроэлектрических установках // – Баку: Проблемы Энергетики, – 2020. №1, с. 78-83.

Papers published in foreign publications included in Web of Science, Springer and Scopus

36. Mustafaev, R.I., Gasanova, L.G. Torque-power characteristics of modern wind-power facilities // Russian Electrical Engineering. – 2009. Vol. 80, № 7, – p. 406-411.

37. Mustafaev, R.I., Gasanova, L.G. Modeling of turning angle of the windmill blades of a working on the power network // Russian Electrical Engineering, – 2011. T. 82, № 12, – p. 659-664.

38. Mustafaev, R.I., Gasanova, L.G. The influence of supply voltage on the operating regime of a wind-power station working on the power network // Russian Electrical Engineering, – 2013. Vol. 84, № 4, – p. 216-220.

39. Мустафаев, Р.И. Гасанова, Л.Г., Мусаев, М.М, Мамедов, Э.М., Набиев, Х.И. Моделирование и исследование режимов работы гидроагрегатов малых ГЭС с машинами двойного питания // – Новочеркасск: Изв. ВУЗов Электромеханика, – 2015. №6, – с. 59-66.

40. Mustafaev, R.I., Gasanova, L.G. An investigation of the dynamics of a wind power unit equipped with synchronous generators with permanent magnets // Russian Electrical Engineering. – 2015. T.86, № 5, – p. 258-263.

41. Hasanova, L.H. Compensation of Reactive Power of Squirrel-Cage Asynchronous Generators, Used in Wind Power Plants and Small Hydroelectric Power Stations // IFAC (International Federation

of Automatic Control) Hosting by Elsevier Ltd. All rights reserved. Peer review under responsibility of International Federation of Automatic Control. – 2018. – p. 462-467.

42. Mustafayev, R.I., Hasanova, L.H., Musayev, M.M. Using regulated electrical machines in small hydropower plants operating in a power network // Russian Electrical Engineering. – 2018. T. 89, № 5, p. 322-327.

43. Мустафаев, Р.И., Гасанова, Л.Г. Моделирование и исследование асинхронного генератора с короткозамкнутым ротором при скалярном методе частотного управления // – Новочеркасск: Изв. ВУЗов Электромеханика, – 2019. Т. 62, № 5, – с. 37-43.

44. Hasanova, L.H. Method of conversion of double fed machine into synchronous operation mode and its simulation // – San Diego: Reliability: theory & applications. Journal is Registered in The Library of The U.S. Congress USA, – 2019, Vol.14 No.3 (54), – p. 18-24.

45. Mustafayev, R.I., Hasanova, L.H. Using control double fed machine into synchronous operation mode // International Jornal on Technical and Physical Problems of Engineering. – 2019. T. 86. № 5. – p. 258-263.

46. Mustafayev, R., Yusifbayli, N., Hasanova, L. Matrix structure of unified mathematical model of electric AC machines at control // E3S Web of Conferences, ENERGY-21 – Sustainable Development & Smart Managemen, – 2020. Vol. 209, No. 02023, – p. 1-6.

47. Mustafayev, R.I., Hasanova, L.H. Simulation of wind power plant with double-fed machine when operating in autonomous system in parallel with synchronous commensurable power generator // E3S Web of Conferences, High Speed Turbomachines and Electrical Drives Conference 2020 (HSTED-2020), – 2020. Vol. 178, No. 01034, – p. 1-5.

In other publications

48. Mustafayev, R.I., Saidov, R.A., Hasanova, L.H. Modeling and Study of Wind Power Plant’s Asynchronous Generator with Saturation Accounting / ICTPE Conference 6th International Conference on “Technical and Physical Problems of Electrical Engineering” – Tebriz:

–2010, September 14-16, p. 97-99.

49. Мустафаев, Р.И., Гасанова, Л.Г. Развитие мировой ветроэнергетики и предварительное технико-экономическое обоснование ВЭС мощностью 50 МВт в Азербайджане // Энергетические связи между России и Восточной Азией: стратегии развития в XXI веке. Объединенный симпозиум, – Иркутск: – 2010. Выпуск 60, – с. 343-349.

50. Mustafayev, R.I., Hasanova, L.H. Mathematical Models of Wind Power Plants' Electromechanical Converters // COIA 2011 Registration form 3rd international conference on control and optimization with industrial. Bilkent University, – Ankara: – 2011. – p. 111-112.

51. Yusifbəyli, N.A., Mustafayev, R.İ., Həsənova, L.H., Zeynalov, R.B. Azərbaycanda küləklərin izodinamik xəritəsi. Əsərin Qeydiyyatı Haqqında Şəhadətnamə, – Bakı: 2011, № 6956.

52. Yusifbayli, N.A., Mustafayev, R.İ., Hasanova, L.H., The modeling mode of operation of wind power farm with double fed asynchronous generators consideration the parameters of the electrical network / ICTPE Conference 8th International Conference on "Technical and Physical Problems of Power Engineering". Ostfold University College, – Fredrikstad: –2012, 5-7 September.

53. Мустафаев, Р.И., Гасанова, Л.Г. Имитационное моделирование режимов работы ветроэлектрической установки, оснащенной синхронным генератором с постоянными магнитами / Методические вопросы исследования надежности больших систем энергетики. Международный научный семинар им. Ю.Н.Руденко. Баку, Азербайджан. Проблемы надежности систем энергетики в рыночных условиях, – Баку: – 2013. – с. 486-496.

54. Мустафаев, Р.И., Гасанова, Л.Г. Сопоставление результатов расчета режимов работы частотно управляемого асинхронного генератора ветроэлектрических установок // Методические вопросы исследования надежности больших систем энергетики. Международный научный семинар им. Ю.Н.Руденко. Надежность либерализованных систем энергетики, – Иркутск: – 2015. – с. 343-349.

55. Mustafayev, R.I., Hasanova, L.H., Musayev, M.M., Mamadov, E.M., Nabiyev, Kh.I. Modeling and Study of Operating Modes of Small Hydro Power Plants with Double Fed Induction Generators // International Conference MEPS'15 Modern Electric Power Systems. – Wroclaw: – 2015. July 6-9, – p.206-211.

56. Mustafayev, R.I., Saidov, R.A., Hasanova, L.H., Musayev, M.M. Study of operating modes of small HPSS' hydroelectric units equipped with synchronous generator / 12th International Conference on "Technical and Physical Problems of Electrical Engineering" University of the Basque Country, – Bilbao: 2016. September, 7-9, – p.78-83.

57. Мустафаев, Р.И., Гасанова, Л.Г. Трехфазная математическая модель асинхронной машины двойного питания / – Baku: 1st International Conference on energy of Future: Challenges and Opportunities (ICEFCO), – Baku. – 2018. – c. 28-29.

58. Mustafayev, R.I., Hasanova, L.H. Method of conversion of double fed machine into synchronous operation mode and its simulation // 14th International Conference on "Technical and Physical Problems of Electrical Engineering" Nakhichivan State University, – Nakhichivan: – 2018. October 15-17, No. 14, – p. 1-6.

59. Hasanova, L.H. Three-coordinated mathematical model of double fed asynchronous machine with frequency control // 15th International Conference on "Technical and Physical Problems of Electrical Engineering" Istanbul Rumeli University – Istanbul, Turkey: –2019. October 14-15, – p. 27-32.

60. Гасанова, Л.Г. Мусаев, М.М. Моделирование и исследование электрических машин в гидроагрегатах малых гидроэлектростанций: Монография, – Баку: Элм, –2024, – с.170.

Author's personal contribution

Papers [32, 34, 35, 41, 44, 59], listed in the list of scientific works on the doctoral dissertation, are written by the author personally. In the papers [1-31, 33, 36-40, 42-43, 45-58, 60], co-authored, the formulation of the scientific problem, the ways and methods of its solution belong to the author.

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