DOI: https://doi.org/10.15407/techned2024.06.056

COMPUTER MODELING OF TRANSIENT ELECTROMECHANICAL PROCESSES IN A WIND POWER PLANT WITH A MAGNETIC GEARBOX

V.V. Grebenikov[1*], **O.D. Podoltsev**[1**], **R.V. Gamaliia**[1***], **A.A. Tazhibaev**[2****], **N.N. Arynov**[2], **O.A. Sakhno**[3*****]
[1] Institute of Electrodynamics National Academy of Sciences of Ukraine,
Beresteyskyi Ave., 56, Kyiv, 03057, Ukraine, e-mail: podoltsev.alexander@gmail.com.
[2] "UMAY R&D" LLP,
Kabanbay Batyr Ave., 53/11, Astana, Z05H0P9, Republic of Kazakhstan.
[3] "ENERGY AUTOMATION" LLC,
60/31 Nemorovich-Danchenko Str., Zaporizhzhya, 69091, Ukraine.

In this work, a computer Simulink model of a wind power plant has been developed, which uses a magnetic gearbox instead of a mechanical gearbox and also contains a synchronous permanent magnet generator. A separate Simulink model of a magnetic gearbox built on the basis of a modulated magnetic field in the air gap was developed, which allows to study the stability of its operation both in steady-state and transient modes. Calculations of various dynamic modes of the wind power plant's operation were carried out, based on the developed model, such as the starting mode, an instantaneous increase in the wind speed acting on the wind turbine, and an increase in the load of the electric generator. According to the results of the calculations, it is shown that in transient modes, when short-term overloads occur, both rotors of the magnetic gearbox can fall out of synchronous motion for a certain period of time and then, depending on the parameters of the gearbox (as well as its other elements), the electromechanical system either reaches a certain operating steady-state mode or loses the ability to transfer mechanical power from the wind turbine to the generator. It has been shown that the use of a more powerful magnetic gearbox, with an increased value of the maximum magnetic torque, allows of a more overload-resistant operation of both: a gearbox and the wind plant as a whole. References 9, figures 10.

Keywords: wind power plant, magnetic gearbox, permanent magnet generator, computer modeling, plant operation modes, stability of magnetic gearbox.

1. Introduction. Nowadays, the use of renewable energy sources is becoming more widespread due to the increasing obstacles to the use of energy obtained from the combustion of natural substances. The use of wind energy is a solution that helps to generate electricity in a rational way [1]. Any wind power plant consists of two parts: mechanical and electrical; the mechanical part includes a wind turbine and a mechanical gearbox, and an electric generator with a semiconductor converter and a load make up the electrical part. As is known [2], the presence of a mechanical gearbox containing the contacting surfaces of two rotors rotating at different angular speeds significantly complicates the maintenance of such systems and prompts the search for other alternative circuit solutions for the structure of modern wind power plants.

Over the past decades, experts in the field of electrical machines have paid much attention to the creation and research of magnetic gearboxes (MG) [3, 4]. The peculiarity of their design is the absence of contacting surfaces, and the transmission of mechanical power between two rotors is carried out due to the contactless interaction between permanent magnets. At present, the best design is considered to be the MG design with a modulated magnetic field in the air gap, which was proposed in [5]. To determine the possibility of using such MG in wind power plants, it is necessary to conduct preliminary researches of the operation of such systems both in steady-state and transient modes. It should be noted that although electromechanical processes directly in the MG have been considered in many works, for example, [6, 7], the dynamic processes in the MG which is as an element of a complex electromechanical system - a wind power plants - have not been sufficiently researched.

ORCID: [*] https://orcid.org/0000-0002-1114-1218; [**] https://orcid.org/0000-0002-9029-9397;
[***] https://orcid.org/0000-0002-5729-7891; [****] https://orcid.org/0009-0004-4395-3722;
[*****] https://orcid.org/0000-0002-3283-3731

Considering the above,the purpose of this work is to develop a computer model and research the related mechanical and electrical dynamic processes in the main elements of a wind power plant, which uses a magnetic gearbox instead of a mechanical gearbox.

2. Computer model of the wind power plant. Fig. 1 shows the structure of a wind power plant containing a wind turbine with a shaft connected to a low-speed rotor (*LS*) of a magnetic gearbox, a permanent magnet synchronous generator connected to a high-speed rotor (*HS*) of a magnetic gearbox. The generator winding is connected to a rectifier with an active load. The developed Simulink model of such an installation corresponding to the above structure is shown in Fig. 2. Further, we present the mathematical models and show the internal structures of the main blocks of this model.

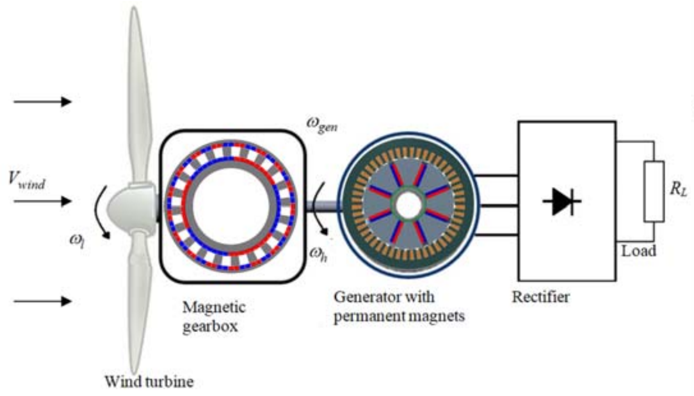


Fig. 1

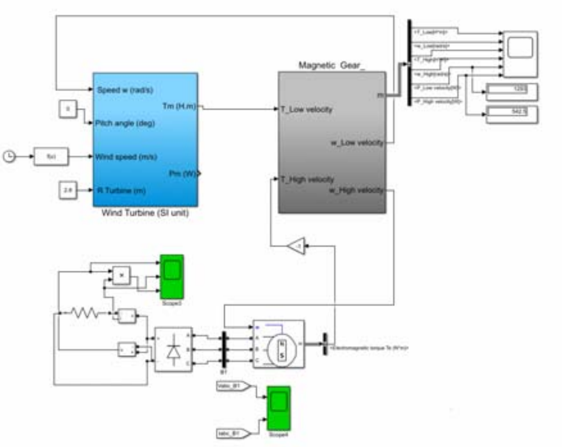


Fig. 2

2.1. Wind turbine. The mechanical power and mechanical torque of a wind turbine are calculated based on the following expressions [1]:

$$P_{turbina} = C_P(\lambda,\beta)0,5\rho A V_{wind}^3, \qquad T_{turbina} = P_{turbina} / \omega_{turbina}, \qquad (1), (2)$$

where ρ is an air density; $A = \pi R^2$ (R is a outer turbine radius); $\omega_{turbina}$ is angular speed of the turbine shaft, dimensionless coefficient C_P calculated as

$$C_P(\lambda,\beta) = C_1(C_2/\lambda_i - C_3\beta - C_4)e^{-C_5/\lambda_i} + C_6\lambda, \qquad \lambda_i = \left(\frac{1}{\lambda + 0,08\beta} \cdot \frac{0,035}{\beta^2 + 1}\right)^{-1},$$

where $\lambda = \omega_{\text{turbina}} R / V_{wind}$; β is an angle of the turbine blades, degrees.

The results of calculating the mechanical torque of the turbine according to expression (2) as a function of the angular speed of the turbine $\omega_{turbina}$ at different wind speeds V_{wind} and at β=0 $R = 2{,}8$ m, which corresponds to a nominal power of the turbine of -10 kW, are shown in Fig. 3. This figure shows that for each value V_{wind} there is an optimal value $\omega_{turbina}$, when the mechanical power of the turbine reaches the maximum value $P_{turbina}^{max}$.

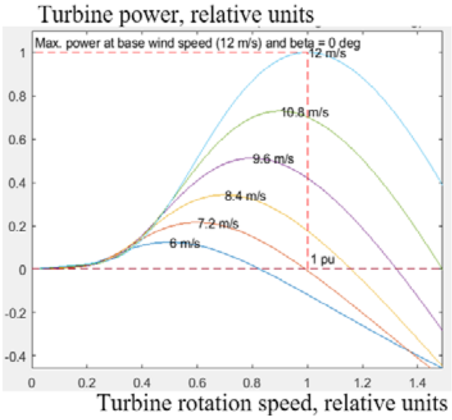


Fig. 3

On the basis of expressions (1), (2), a *Simulink block* was developed, shown in Fig. 2 in blue, which allows the input values located on the block on the left to calculate the output values – $T_{turbina}, P_{turbina}$, located on the right. This block is further used as an element of the integrated model of the entire wind turbine.

2.2. Magnetic gearbox. The schematic structure of the magnetic gearbox is shown in Fig. 4 and consists of a low-speed rotor *1* connected to the wind turbine shaft, a high-speed rotor *2* connected to the electric generator shaft, and a magnetic flux modulator *3*. The rotors of the magnetic gearbox are equipped with permanent magnets *4*. The mathematical model describing the dynamics of the rotational motion of the magnetic gearbox rotors is as follows [8]:

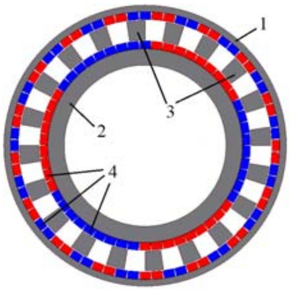


Fig. 4

$$
\begin{gathered}
J_l \frac{d\omega_l}{dt} + k_l \omega_l = T_{turbine} - T_{\max} \sin(p_l \theta_l - p_h \theta_h)\,, \\
J_h \frac{d\omega_h}{dt} + k_h \omega_h = \frac{T_{\max}}{G} \sin(p_l \theta_l - p_h \theta_h) - T_{gen}\,, \\
\frac{d\theta_l}{dt} = \omega_l\,, \quad \frac{d\theta_h}{dt} = \omega_h\,,
\end{gathered}
\tag{3}
$$

where $J_{l,h}$ is the moment of inertia of the *LR* (denoted by the index *l* is a low speed) and *HR* (denoted by the index *h* is a high speed); $\omega_{l,h}$, $\theta_{l,h}$ are the angular speed and angular position of both shafts; $p_{l,h}$ is a number of pairs of poles; $k_{l,h}$ is a coefficient of viscous friction; T_{max} is a maximum value of the magnetic torque acting on the *LR*; $G = p_l / p_h$ is a reduction ratio of the magnetic gearbox.

The developed *Simulink model* of the magnetic gearbox that implements the system of equations (3) is shown in Fig. 5. This model is constructed as an equivalent mechanical circuit consisting of a circle for the *R* and a mechanical circuit for the *HR*, which are interconnected by an information signal corresponding to the expression $\sin(p_l\theta_l - p_h\theta_h)$ in the mathematical model (3) and depends on the instantaneous position of both rotors. Two torques are used here as input values – $T_{turbine}$, T_{gen} and the angular rotation speeds $\omega_{l,h}$ of both rotors are used as output values.

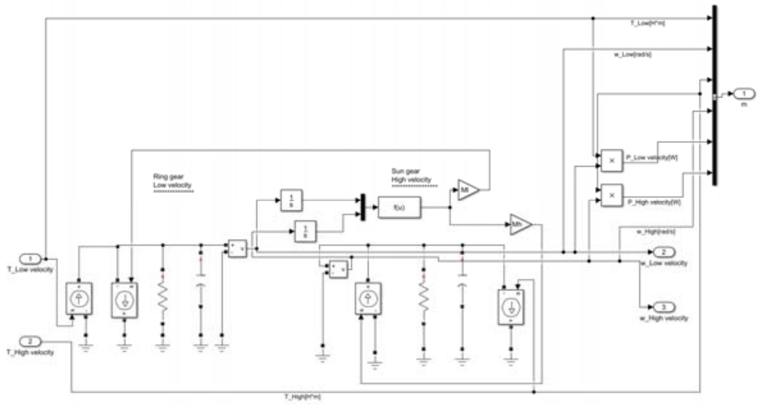


Fig. 5

2.3. Model of an electric generator and rectifier. The basic model from the *Simscape library* of a permanent magnet synchronous generator and a model of a rectifier, built on the basis of the *Universal bridge* block, were used in this work (Fig. 2). In the design and calculation of the permanent magnet electric generator (Fig. 6), the stator of a mass-produced AIR132MB8 induction motor was used, the main technical characteristics of which are as follows: rated power P_r = 5.5 kW, rated voltage when the stator windings are connected in a "star/delta" U_r = 380/220 V, rated current I_r = 8/14 A, rated speed n = 710 rpm, efficiency = 78.5%. The stator has the following dimensions: outer diameter D_a = 225 mm, inner stator diameter D_i = 158 mm, number of slots Z_p = 48; height of slots h_s = 17.6 mm, length of the active part of the core l_{Fe} = 160 mm. The air gap between the stator and rotor is equal to δ = 1.5 mm. The rotor with permanent magnets has an outer diameter equal to D_{ra} = 155 mm, in which 8 permanent magnets of size (160 × 40 × 10 mm) are placed. The magnets in the rotor have a tangential arrangement. Such an arrangement of magnets in the rotor makes it possible to obtain the best specific characteristics [9]. Fig. 6 shows the general view and pattern of the magnetic field at a current density of J = 8 A/mm^2.

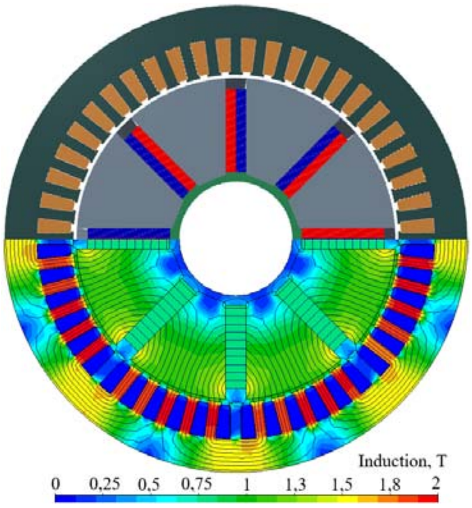


Fig. 6

3. Calculation of steady-state and transient modes of operation of a wind plant with a magnetic gearbox. The developed *Simulink model* of the plant as a whole, shown in Fig. 2, consists of a model of a wind turbine, a magnetic reducer, a permanent magnet synchronous generator, and a rectifier connected to the generator output and to a resistive load. The following initial data were used for the calculations.

– Wind turbine: rated power – 10 kW, rated speed – 400 rpm;

– Magnetic gearbox: $T_{\max} = 406$ N·m, $k_l = k_h = 0{,}008$ N·m·s, $p_l = 17, p_h = 3, J_l = J_h = 0{,}001$ kg·m^2, reduction ratio $G = p_l / p_h = 5{,}67$. To calculate these MG parameters, we used the finite element method of the field problem in the *Simcenter Magnet* package;

– Generator: active phase resistance – 0,022 Ω, phase inductance – 26.7 μH, number of pairs of poles – 4, flux cohesion from permanent magnets – 0.26 V·s. To calculate these generator parameters, we used the finite element method of the field problem in the *Simcenter MotorSolve* package. The active load impedance is 20 Ω. The following are the results of calculating the operation of the plant with the specified parameters in different modes.

3.1 Startup mode of the wind turbine and steady-state operation. In this work, the starting mode of the wind turbine under the condition that the wind speed slowly increases from zero to 12 m/s and then the turbine operates in steady-state mode was calculated. The active load of the generator is 20 Ohms. The results of calculation the time characteristics of the MG – angular velocity, mechanical torque, and mechanical power for the *LR* and for the *HR* are shown in Fig. 7. It can be seen that at the beginning of the process (time interval 2.3÷3 s), all characteristics on the *LR* shaft connected to the wind turbine have oscillations that reflect the process of entering the synchronism of the *HR*. After reaching the steady-state mode, the mechanical power on the turbine shaft and the *LR* shaft is 10 kW, and on the *HR* shaft and the generator shaft is 9.5 kW (average value). Hence, the calculated value of the gearbox efficiency is 95%. This figure also shows that the ratio of speeds and mechanical powers of the *LR* and *HR* is equal to a reduction ratio of 5.67. The electrical characteristics of the generator in this mode of operation are shown in Fig. 8. It can be seen that when the *HR* is drawn into synchronism, the three-phase voltages and currents at the generator output increase to the steady-state value (Fig. 8, *a*). The shape of these curves on an increased time scale is shown in Fig. 8, *b*, and Fig. 8, *c* shows the electrical characteristics of the resistive load.

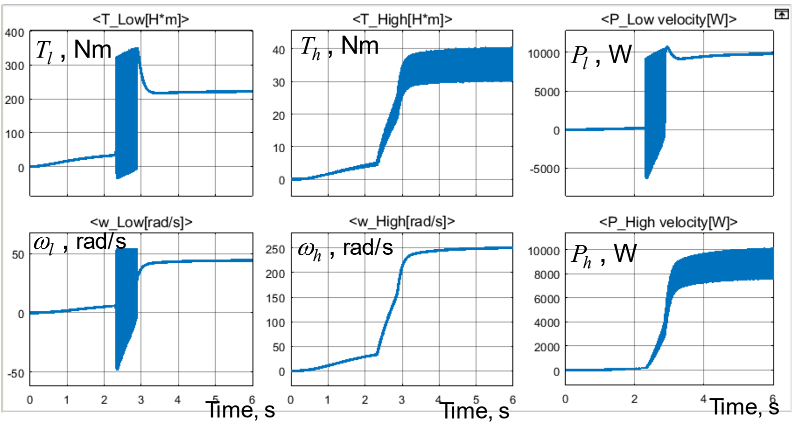


Fig. 7

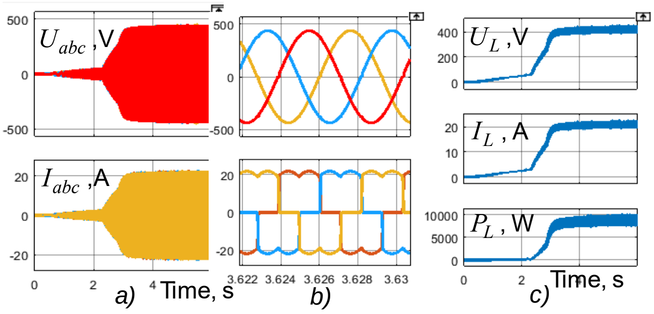
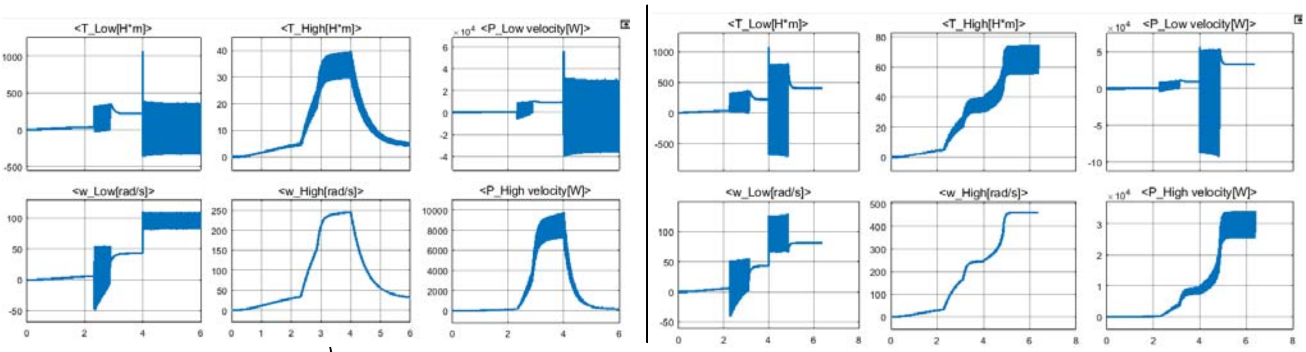


Fig. 8

3.2 Operation of the system in the event of a wind gust. The preliminary mode of operation of the wind plant is calculated with the difference that at a time point of 4 s, when the system has reached the steady-state mode of operation, the wind speed increases from 12 m/s to 20 m/s. The results of calculating the time characteristics of the MG are shown in Fig. 9, *a*. Here, all graphs show the same values as in Fig. 5. It can be seen that when a wind gust occurs (at a time point of 4 s), both MG rotors fall out of synchronization and the gearbox loses the ability to transfer mechanical power from the turbine to the generator. At the same time, in the steady-state mode, the *HR* starts to rotate at a relatively high speed as a reaction to a strong wind, and the *LR* rotates at a low speed, which is not the normal mode of operation of the MG.

To analyze the effect of the maximum torque of the MG on the stability of its operation, Fig. 9, *b* shows the results of similar calculations at a doubled value of the maximum MG torque, equal to 812 N·m. As can be seen from this figure, when a wind gust occurs, the MG falls out of synchronism for a certain period of time after the startup, but then the gearbox returns to normal operation. Thus, according to these calculations, it can be noted that in transient modes, when an overload occurs, both rotors of the MG can fall out of synchronous motion for a certain period of time and then, depending on the MG parameters, the system either reaches a certain operating mode or loses the ability to transfer mechanical power from the turbine to the generator. It should be noted that the process of falling out of synchronism is also affected by magnetic losses in the MG, but this issue is not sufficiently researched and presented in the scientific literature and will be investigated by the authors in the future.



a) b)

Fig. 9

In order to establish the general conditions for the stable operation of the MG in dynamic modes, let us consider the system of equations (3). From the analysis of the first and second equations, which reflect the balance of moments on the shaft, respectively, of the *LR* and *HR*, it can be assumed that for stable operation, two conditions must be met simultaneously:

$$T_{turbine} - J_l \frac{d\omega_l}{dt} - k_l\omega_l < T_{\max}, \qquad J_h \frac{d\omega_h}{dt} + k_h\omega_h + T_{gen} < \frac{T_{\max}}{G}. \tag{4}$$

From these two expressions, in the absence of the first components corresponding to the moments of inertia, the following conditions for the operation of the MG power plant in steady-state mode can be obtained: $T_{turbine} - k_l\omega_l < T_{\max}$, $k_h\omega_h + T_{gen} < \frac{T_{\max}}{G}$.

As noted in [3, 4], the use of a more powerful MG with an increased value of the maximum magnetic torque to $T_{\max} \geq (1.2 \div 1.5) T_{\text{turbine}}$ allows for a more stable operation of both the MG and the wind power plant as a whole.

3.3 Operation of the wind power plant with increasing electrical load. This mode was calculated for the variant described in Section 3.1, provided that at a time of 4 s the active resistance of the generator's load decreases from 20 Ohm to 10 Ohm. The results of calculating the time characteristics of the MG are shown in Fig. 10, where all graphs show the same values as in Fig. 7. It can be seen that the MG does not lose its stability under such an increased load, while the rotational speeds of the *LR* and *HR* decrease monotonically, and the mechanical moments of both rotors increase. This leads to an increase in the mechanical power consumed from the turbine and transmitted to the electric generator in normal operation. Such a stable operation of the MG in this mode is associated with the fulfillment of conditions (4) in the dynamic mode.

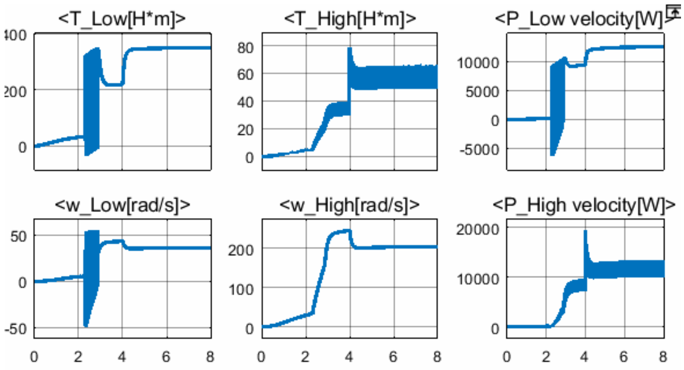


Fig. 10

Conclusions. In this work, the computer *Simulink model* of the 10 kW wind power plant has been developed, in which the magnetic gearbox instead of a mechanical gearbox, was used in pair with a synchronous generator with permanent magnets. The *Simulink model* of the magnetic gearbox was developed, which allows to research the stability of its operation in dynamic modes. On the basis of the developed model of the wind power plant, researches of the related mechanical and electrical processes in its main elements, in dif-

ferent operating modes, were carried out - starting mode, instantaneous increase of wind speed acting on the wind turbine and increase of the load of the electric generator.

According to the results of the calculations, it is shown that in transient modes, when short-term overloads occur, both rotors of the MG can fall out of synchronous motion for a certain period of time and then, depending on the parameters of the MG, the system can either reach a certain operating steady-state mode or lose the ability to transfer mechanical power from the turbine to the generator. It has been noted that using a more powerful MG with an increased value of the maximum magnetic torque to $T_{\max} \geq 1.2 \div 1.5)T_{\text{turbine}}$ allows for a more stable operation of both the MG and the wind power plant as a whole.

1. Siegfried Heier. Grid integration of wind energy onshore and offshore conversion systems. JonhWiley&Sons, 2014. 513 p. DOI: https://doi.org/10.1002/9781118703274.
2. Rashid M.H. Electric Renewable Energy Systems. Elsevier, 2016. 587 p.
3. Ruiz-Ponce G., Arjona M.A., Hernandez C., Escarela-Perez R. A Review of Magnetic Gear Technologies Used in Mechanical Power Transmission. *Energies*. 2023. Vol. 16(4). 1721. DOI: https://doi.org/10.3390/en16041721.
4. Bo Yan, Xianglin Li, Xiuhe Wang, Yubo Yang. A review on the field-modulated magnetic gears: Development status, potential applications, and existent challenges. *IET Electrical Power Application*. 2024. Vol. 18. Pp.1-17. DOI: https://doi.org/10.1049/elp2.12365.
5. Atallah K., Howe D. A novel high-performance magnetic gear. *IEEE Transactions on Magnetics*. 2001. Vol. 37. Issue 4. Pp. 2844-3846. DOI: https://doi.org/10.1109/20.951324.
6. M Sh Saleh, Ahmed EL-Betar, Ahmed EL-Assal. Review of Modeling and Simulation Technologies Application to Wind Turbines Drive Train. *Journal on Today's Ideas – Tomorrow's Technologies*. Vol. 2. No 2. 2014. Pp. 117-131. DOI: https://doi.org10.15415/jotitt.2014.22009.
7. Penzkofer A., Atallah K. Analytical Modelling and Optimisation of Pseudo Direct Drive Permanent Magnet Machines for Large Wind Turbines. *IEEE Transactions on Magnetics*. 2015. Vol. 51. No 12. Pp. 31-37. DOI: https://doi.org/10.1109/TMAG.2015.2461175.
8. Badr-El-Boudour Bidonche. Transient Performance of a Magnetic Geared Induction Machine. *COMPEL*. 2020. Vol. 39. Pp. 1113-1130. DOI: https://doi.org/10.1108/COMPEL-12-2019-0485.
9. Dobzhanskyi O., Grebenikov V., Gouws R., Gamaliia R., Hossain E. Comparative Thermal and Demagnetization Analysis of the PM Machines with Neodymium and Ferrite Magnets. *Energies*. 2022. Vol. 15. Issue 12. 4484. Pp. 1-15. DOI: https://doi.org/10.3390/en15124484.

УДК 621.313.8

КОМП'ЮТЕРНЕ МОДЕЛЮВАННЯ ПЕРЕХІДНИХ ЕЛЕКТРОМЕХАНІЧНИХ ПРОЦЕСІВ У ВІТРОЕНЕРГЕТИЧНІЙ УСТАНОВЦІ ІЗ МАГНІТНИМ РЕДУКТОРОМ

В.В. Гребеніков[1], докт. техн. наук, **О.Д. Подольцев**[1], докт. техн. наук, **Р.В. Гамалія**[1], кан. фіз.-мат. наук,
А.А. Тажибаев[2], **Н.Н. Аринов**[2], **О.А. Сахно**[3], канд. тех. наук
[1] Інститут електродинаміки НАН України,
пр. Берестейський, 56, Київ, 03057, Україна, **e-mail:** **podoltsev.alexander@gmail.com.**
[2] ТОВ "UMAY R&D",
пр. Кабанбай Батир, буд. 53/11, Астана, Z05H0P9, Республіка Казахстан.
[3] ТОВ "Енергоавтоматизація",
вул. Немировича-Данченка, 60/31, Запоріжжя, 69091, Україна.

У роботі розроблено комп'ютерну Simulink-модель вітроенергетичної установки, в який замість механічного редуктора використовується магнітний, а також міститься синхронний генератор із постійними магнітами. При цьому окремо розроблено Simulink-модель магнітного редуктора, побудованого на основі модульованого магнітного поля в повітряному проміжку, яка дає можливість дослідити стійкість його роботи як в усталеному, так і в перехідних режимах. На основі моделі установки проведено розрахунки різних динамічних режимів її роботи – пускового, миттєвого збільшення швидкості вітру, що діє на вітрову турбіну, та збільшення навантаження електричного генератора. За результатами проведених розрахунків показано, що в перехідних режимах у разі виникнення короткочасних перевантажень обидва ротори магнітного редуктора на певний проміжок часу можуть випадати з синхронного руху і далі, в залежності від параметрів редуктора (а також інших її елементів), електромеханічна система або досягає певного робочого усталеного режиму, або втрачає можливість передавання механічної потужності від вітрової турбіни до генератора. Показано, що використання більш потужного магнітного редуктора із збільшеним значенням максимального магнітного моменту дає змогу отримати більш стійку до перенавантажень роботу як цього редуктора, так і вітроенергетичної установки в цілому. Бібл. 9, рис. 10.

Ключові слова: вітрова електростанція, магнітний редуктор, генератор з постійними магнітами, комп'ютерне моделювання, режими роботи установки, стійкість магнітного редуктора.

Надійшла 27.05.2024
Остаточний варіант 13.06.2024