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Modular wind generators for autonomous power supply to remote mining areas mineral resources

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Abstract

The use of renewable energy sources to supply power to energy-isolated areas is an urgent topic. The simplicity of the design and high reliability of inductor generators create good prospects for their use in wind power plants as an alternative to synchronous and asynchronous electric machines that are currently in use. An obstacle to such an application is the specifics of the design, construction, and execution of modular machines with magnetic switching, concentrated windings, and a distributed magnetic system integrated into the wind turbine design. The purpose of the study is to consider cause-effect relationships and establish relationships between magnetic flux, EMF, the geometry of electric and magnetic circuits, the structural arrangement of electric windings, and circuit solutions of an automatic electromagnetic excitation system for the design of a new type of generators.

The current issues of the effective use of an exciting magnetic flux for voltage regulation in power supply systems powered by power plants, the main generators of which contain a distributed magnetic system with concentrated electric windings, are considered. The optimal structural compositions and geometry of the ratios of electric and magnetic circuits are determined from the machine's basic calculation equation, which is obtained under the condition of maximum magnetic flux. The reasons for the induction of variable EMF in the DC excitation windings, which prevent the effective magnetization of the machine, have been established. The location of the electric windings is proposed, which makes it possible to weaken or completely compensate for the pulsations of the magnetic flux coupled with the exciting circuits. It is established that in order to eliminate parasitic EMF in the exciting windings, it is necessary to use two-circuit circuits for alternating switching of the magnetic flux in the circuits, with sequential activation of the sections of the windings of the exciting circuits. To completely eliminate these EMFs, performing two-circuit magnetic flux switching circuits with a common exciting winding is advisable. The methods and features of the circuit implementation of the conditions of electromagnetic excitation and maintenance of voltage constancy at the output of generators of a new type are considered.

Keywords

wind inductor generator; modular machine; distributed magnetic circuit; concentrated windings; magnetic flux switching; control.

Introduction

The use of renewable energy sources to supply power to energy-isolated areas is an urgent topic. Despite the development of technologies for wind power plants (wind turbines) with a vertical axis of rotation, the issue of choosing the optimal design parameters remains open, and each project is unique and has many features, while the least reliable elements of wind turbines are control and control systems (Shpenst & Ermolovich, 2023; Rakhimov, 2022; Samarskaya et al., 2021; Melekhin, 2020; Kovanič et al., 2023a; Kelentev et al., 2017; Kovanič et al., 2023b). Currently, developers are paying special attention to innovative autonomous power supply systems based on energy modules, new generator designs, and optimization of wind turbine parameters (Kostin & Kulichenko, 2020; Bychkov et al., 2020; Tatevosyan, 2021; Shtepa, 2021). Great importance is attached to the methods of creating, calculating, and controlling exciting magnetic fluxes in electric machines, which determine their main characteristics (Zubkov & Vladimirov, 2020; Tatevosyan, 2019; Voronin & Chernyshev, 2020; Miglierini et al., 2006; Krasovsky & Vostorgina, 2022). By themselves, generating plants are not able to maintain the regulatory values of voltage and frequency in the electrical network when power consumption changes; therefore, they must work in conjunction with automatic excitation control systems (AEC) of generators (Gorozhankin & Korzhov, 2022; Shevyreva et al., 2021; Zubkov et al., 2023; Sugakov et al., 2023). The wind turbine must provide for stabilization of the shaft rotation frequency at a given frequency of electrical generation; otherwise, the use of devices for dynamic stabilization of alternating voltage systems is required (Mytsyk & Maslov, 2020; Zolotov & Shevtsov, 2021; Biryukova et al., 2022).

Due to the simplicity of the design and high reliability, inductor generators have good prospects for use in aerodynamic power plants of renewable energy and can form an alternative to synchronous and asynchronous electric machines that are currently in use (Shaitor et al., 2020; Shaytor, 2021; Shaitor et al., 2021; Shaitor et al., 2022).

The purpose of the study is to consider cause-effect relationships and establish optimal relationships between magnetic flux, EMF, the geometry of electric and magnetic circuits, the structural arrangement of electric windings, and circuit solutions of an automatic electromagnetic excitation system for the design of a new type of generator. This goal can be achieved by designing an optimal exciting magnetic flux at the appropriate location of the electric windings, as well as using a high-speed AEC system to maintain the quality of generated electricity when the load changes.

Designing the optimal exciting magnetic flux of wind turbines

In most cases, the obstacles to the use of traditional inductor machines are large weight and size indicators compared to synchronous and asynchronous machines. However, this disadvantage is not found in promising designs of modular inductor machines with magnetic switching, concentrated windings, and a distributed magnetic system, which combine well with wind turbines with a vertical axis and a hollow rotor. Figure 1 shows one of these variants of wind turbines containing a rotating hollow rotor 1 with blades mounted in the housing of the wind turbine 2 on a shaft with a bearing 3. A confuser 4 is installed on the side of the inlet of the housing, and a weather vane 5 is installed on the side of the outlet. The wind turbine provides for mechanical stabilization of the shaft rotation frequency by changing the angles of attack of the rotor blades. (Patent 2671078 Russian Federation, IPC F03D 3/04, F03D 3/06, F03D 7/06 (2006.01). Wind turbine / Yu.I. Ryaskov, N.M. Shaitor, V.L. Sklyaruk. – No. 2016120467; application. 05/25/16; publ. 10/29/18. Byul. No. 31. – 9p.).

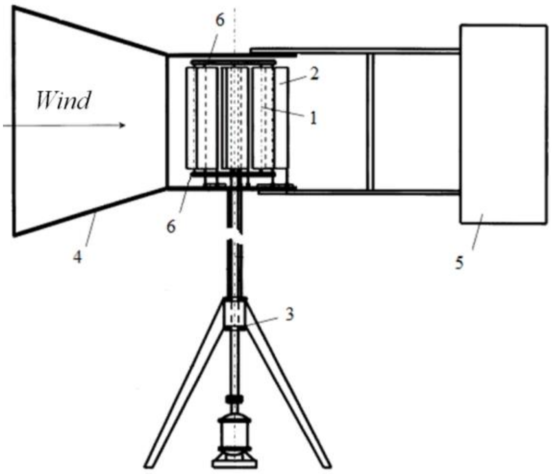


Fig. 1. Wind power plant with modular inductor generator

The modular inductor generator is represented by coaxial electric windings 6, which are covered along the entire outer perimeter of the rotor by U–shaped charged cores rigidly fixed to the housing (Sága et al., 2019). The reduction in the mass of the inductor generator is achieved by excluding its own rotor, the function of which is performed by the hollow rotor of the wind turbine.

The simplest electromagnetic module (Fig. 2) is a structure consisting of a pair of U-shaped charged cores of transformer type 1. Modules with windings 2 are fixed motionlessly on the housing along the outer circumference of the rotating rotor 3 in such a way that the ends of their teeth are located opposite each other, forming a gap in which magnetic flux switches are located, made on the rotor in the form of inserts 4 of ferromagnetic material. By appointment, the windings are working or exciting; according to the method of connection in electrical and magnetic terms - sequential or parallel, counter or consonant; according to the location relative to the axis of rotation - axial or radial.

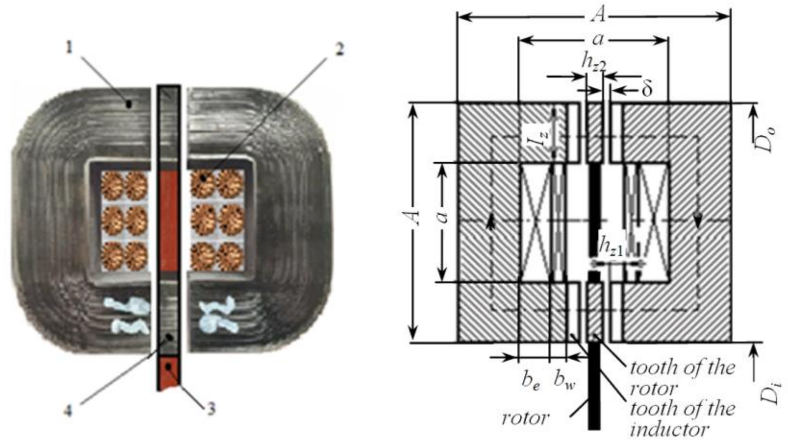


Fig. 2. Sectional view of the simplest electromagnetic generator module

The main dimensions of the machine are determined by the outer diameter of the rotor:

$$D_o = D_i + A \tag{1}$$

The inner diameter of the module location closest to the axis of rotation is determined based on the minimum allowable tooth width:

$$D_i = zb_z / \pi\alpha_z \,, \tag{2}$$

where: $b_z = b_{z\,min} = (3 \div 5) \cdot 10^{-3}$ m – minimum allowable tooth width, which can be increased for design reasons;

$z = 60f / n$ – number of pairs of teeth of the inductor (rotor);

f – current frequency;

n – rotor rotation speed, specified by the design specification;

α_z – tooth overlap (the ratio of the tooth width to the tooth division).

The EMF of the working windings for modular machines is determined by a well-known expression for inductor machines, which, with a winding coefficient of $k_w = 1$ for a concentrated winding, taking into account the reserve factor for regulating the generator, can be rewritten as follows:

$$\mathrm{E} = 2{,}22 k_{rr} w f \Phi (k_\lambda - 1)/k_\lambda, \tag{3}$$

where: $k_\lambda = \Phi_{max}/\Phi_{min}$ – flow modulation coefficient;

Φ_{max} – maximum magnetic flux;

Φ_{min} – minimum magnetic flux;

$\Phi = z\Phi_{max}$ – total magnetic flux of the machine;

z – number of pairs of modules.

The expression for the effective value of the magnetic flux, based on Ohm's law for a magnetic circuit, is written as:

$$\Phi = F\Lambda_c/(C_2 + 1), \tag{4}$$

where: $C_2 = \Lambda_c/\Lambda_\delta$ – constant ratio of the magnetic conductivity of steel to the conductivity of the gap;
$F = jk_{cf}\mathrm{a}^2$ – resulting MDS of the excitation winding;
j – current density;
k_{cf} – copper fill factor;
α – internal dimension of the module, which determines the copper cross-section.

Optimal excitation is achieved by single-parameter optimization of the magnetic flux along the internal dimension of the machine module. The study of the function (3) at the extremum by taking the derivative *dΦ(a)/da* = 0 leads to the equation:

$$\mathrm{a}^2 + \mathrm{Aa} - \mathrm{A}^2 = 0, \tag{5}$$

where *A* – the outer dimension of the module, which determines the total cross-section of steel and copper.

The physical meaning in this equation has a positive root a = 0,61*A*. Hence, the radial size of the module tooth is obtained:

$$b_{z1} = 0{,}5(A - a) = 0{,}32a. \tag{6}$$

Expressions (1-6) give optimal ratios of copper and steel, which lead to the maximum magnetic flux of excitation and EMF of the generator (3). With the cross-section shape of an electromagnetic module that differs from a square section, the optimal ratios (5-6) of dimensions a and A must satisfy the dimensions of its parallel sides.

The main calculation equation of the modular machine establishes the ratio of the geometry of the machine to the power, electrical, magnetic, and mechanical parameters specified in the design specifications (Rojek et al., 2021):

$$\mathrm{a}^3 - \mathrm{a}S_{\text{в}} - \mathrm{c} = 0 \tag{7}$$

In this expression, the copper section of the excitation winding:

$$S_{\text{в}} = k_{sc}k_{rr}k_F k_{sf} B_\delta \delta'/\mu_0 k_{cf} j, \tag{8}$$

where: k_{sc} = 1,5 ÷ 2.0 - scattering coefficient of the magnetic flux;
k_{rr} = 1,15 - reserve coefficient for regulating the voltage of the generator;
k_F = 1,25 ÷ 1,45 - ratio of the MDS of the magnetic circuit to the MDS of the gap;
$B_\delta = B_{z1} k_{sf}\, \alpha_z$ - induction in the gap;
k_{sf} = 0,81 ÷ 0,99 - steel filling coefficient;
B_{z1} - permissible the value of induction in the teeth of the inductor;
$\delta' = 4\,(i - 1)\,\delta$ - calculated value of the air gap (i is the number of axial layers or disks of the stator);
$\mu_0 = 4\pi \cdot 10^{-7}$ Hn/m - magnetic constant;
k_{cf} = 0,35 ÷ 0,65 - coefficient of filling the window with copper;
j - current density in the windings.

The constant *c* in the main calculation equation represents the effective volume of the working winding:

$$\mathrm{c} = [\mathrm{P}\; k_\lambda/42{,}62(k_\lambda - 1)\; k_{rr}k_{cf}j\;\; b_z B_\delta] \times (n/f^2), \tag{9}$$

where *P* - electromagnetic power specified in the design specification.

The basic calculation equation (7) has a practical solution for two cases.
If $(c/2)^2 - (S_в/3)^3 \geq 0$, you should use Cardano's solution, in which the first real root has a physical meaning:

$$\mathrm{a} = \sqrt[3]{\mathrm{c}/2 + \sqrt{(\mathrm{c}/2)^2 - (S_{\text{в}}/3)^3}} + \sqrt[3]{\mathrm{c}/2 - \sqrt{(\mathrm{c}/2)^2 - (S_{\text{в}}/3)^3}}. \tag{10}$$

Otherwise, it is necessary to resort to a trigonometric solution:

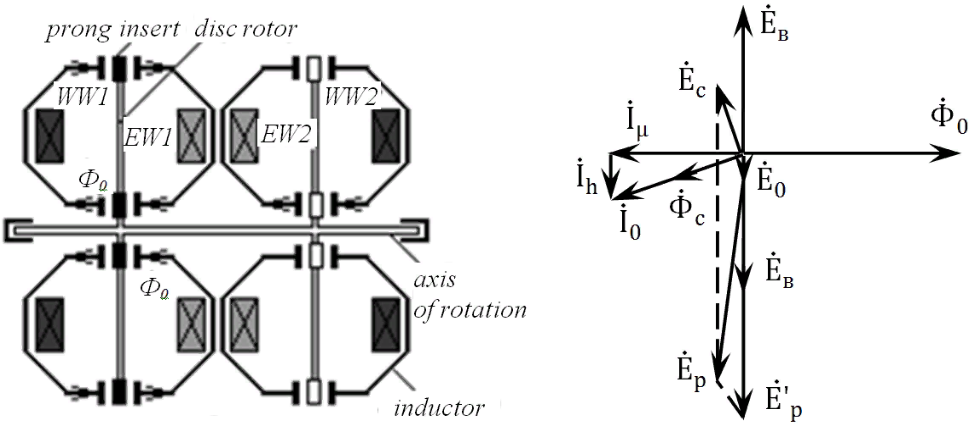
$$\mathrm{a} = 2\sqrt{(S_{\text{в}}/3)}\, cos(\alpha/3), \tag{11}$$

where $\alpha = arkcos\left[c/2\sqrt{(S_{\text{в}}/3)^3}\right]$ is a constant determined by the parameters of the machine's electrical windings.

The analysis shows that the Cardano solution (10) must be used to calculate small, medium, and high–power machines, and the trigonometric solution (11) for low-power machines and micromachines.

The optimal location of the exciting windings of the modular generator

Fig. *3a* shows a two-circuit circuit for switching magnetic fluxes with separate laying of the exciting and working windings (arrows indicate the directions of the switched magnetic fluxes in the circuits). Each magnetic circuit contains sections of working WW1, WW2, and exciting EW1 and EW2 windings and is switched individually by a common rotor, and the teeth of the first circuit are offset relative to the teeth of the second circuit in the direction of rotation by half a tooth pitch, with sequential activation of the sections of the excitation windings. A direct current is supplied to the field windings.

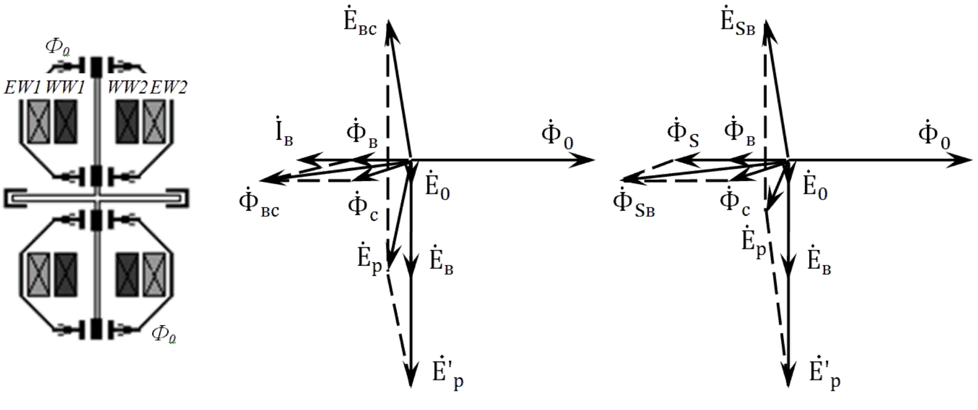


a *b*

Fig. 3. Double-circuit switching of a modular generator

Figure *3b* shows a vector diagram of the first harmonic EMF induced in the working windings during two-circuit switching. The harmonic component of the main flow induces an EMF in sections WW1 and WW2, in sections EW1 and EW2, and a vortex EMF in the inductor steel, lagging behind the flow by an angle. Since the sections of the excitation winding in the circuits are connected in series, and the magnetic fluxes of the circuits are in antiphase, the EMF of the sections induced into the excitation windings are mutually compensated and do not create a harmonic component of the current and a demagnetizing MDS.

A consequence of the eddy EMF E_0 is the current I_0 and the additional scattering flux in the steel Φ_c. This current contains a demagnetizing reactive I_μ and active component I_h, taking into account the phenomena of hysteresis and eddy currents. The scattering flux Φ_c coupled to the working windings induces an EMF E_c in them, as a result of which the phase is shifted, and the effective EMF E_p value of the working winding is slightly reduced due to eddy current losses and hysteresis.



a *b* *c*

Fig. 4. Single-circuit switching of a modular generator

Fig. *4a* shows a single-circuit switching circuit. The case of the separate arrangement of the sections of the exciting and working windings corresponds to the experiment with sections of the windings EW1 – WW2 (or EW2 – WW1), vector diagrams of which are shown in Fig. *4b*. The case of the joint arrangement of sections of the exciting and working windings corresponds to the experiment with sections of the windings EW1 – WW1 (or EW2 – WW2), vector diagrams of which are shown in fig. *4c*.

If the magnetic flux is created by only one section of EW1, the EMF $E_{\text{в}}$ of this section turns out to be uncompensated; therefore, a harmonic current $I_{\text{в}}$ component appears in the section, which lags behind the EMF by an angle $\pi/2$, Fig. *4b*.

This current creates a demagnetizing magnetic flux $\Phi_{\text{в}}$, which, combining with the scattering flux Φ_c and forming a common flux $\Phi_{\text{в}c}$, inducts in a separately located section of the working winding WW2 EDS $E_{\text{в}c}$. As a result of the demagnetizing action of the excitation winding section, the effective value decreases twofold with a phase shift of the EMF E_p section of the working winding WW2.

In the section of the working winding WW1, laid in common slots with section EW1, the energy conversion loses even more efficiency due to the magnetic scattering flux Φ_S coupled to the working winding, Fig. *4c*. In this case, the vector diagram constructed in Fig. *4c* for section WW1 is supplemented by a scattering flux Φ_S, which is in antiphase with the main one flow Φ_0 and has a demagnetizing effect on it.

As a result of the addition of the flows Φ_c , $\Phi_{\text{в}}$ and Φ_S, a flow $\Phi_{S\text{в}}$ is formed, and an EMF $E_{S\text{в}}$ is induced in the WW1 section, which is practically in antiphase with the initial EMF E'_p. The effect of these factors reduces the effective value by an order of magnitude and significantly shifts the phase of the resulting EMF E_p section of the working winding WW1.

Excitation control system of a modular wind turbine generator

Most AEC generator systems are built on the principle of deviation of the effective voltage value at the generator output when the load changes, while the self-excitation of the generators is provided by supplying and converting the rectified voltage from the generator output to the input of the excitation winding. The use of an active, rather than an instantaneous voltage value, reduces the performance of the AEC system, and the similarity of frequencies in the generator and excitation circuits does not ensure the quality of the generated sine wave. The method of voltage regulation of a modular wind turbine generator is based on the task of increasing the speed of regulation and reducing the distortion of the output sine wave of the phase voltage, which is realized by converting the time interval into the inverse of the delay angle relative to the beginning of each half-cycle of the rectified excitation voltage. In this case, the frequency of the excitation voltage is many times higher than the frequency of the generator voltage, which reduces the intermittency of the excitation current and reduces the distortion of the sine wave of the EMF and the phase voltage of the generator.

This method of regulating the voltage of the generator according to the principle of deviation of the instantaneous value of the voltage at the output of the generator when the load changes in time t is explained in Fig.*5*.

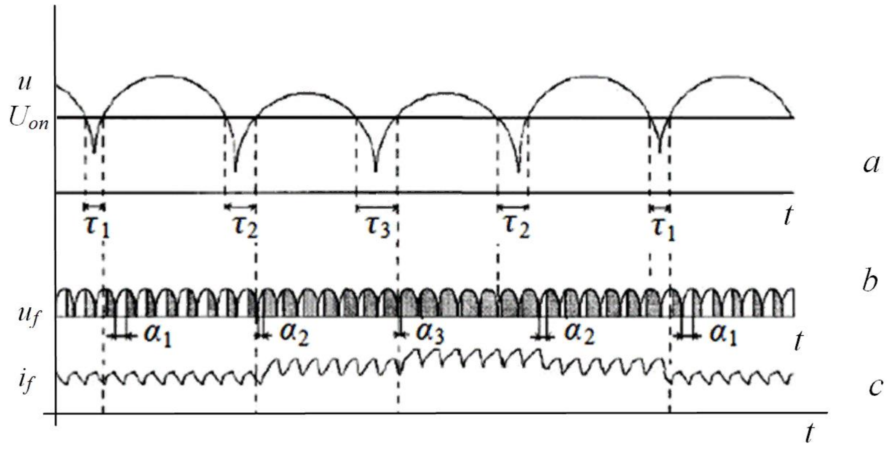


Fig. 5. Voltage regulation at the output of the modular generator

The measurement of the time interval τ of each cycle of pulsations of the instantaneous rectified voltage u of the generator along the comparison line with the specified reference voltage U_{on} is carried out at each half-cycle of the voltage, Fig. *5a*. With a decrease in voltage during an increase in the load by consumers, the width of the time interval increases. It is converted into the inverse of the delay angle α with respect to the beginning of each half-cycle of the rectified excitation voltage u_f, Fig. *5b*.

In this case, the angle α decreases, and the excitation voltage u_f and the excitation current i_f increase, Fig. *5b,c*. As a result, the voltage of the generator $\underline{u}$ is restored, and at the same time, the time interval τ, the voltage u_f, and the excitation current i_f are restored. The process proceeds in reverse order when the SG voltage increases during load reduction.

The implementation of the proposed method of regulating the voltage of the generator is carried out in three consecutive operations with instantaneous values of electrical quantities:

- measurement of the time interval of each clock cycle of the ripple of the rectified voltage at the output of the generator;
- conversion of the time interval to the inverse of the delay angle with respect to the beginning of each half-period of the rectified excitation voltage;
- a change in the delay angle relative to the beginning of each half-cycle of the rectified excitation voltage.

The implementation of the proposed method for regulating the voltage u of the GM main generator is explained in Fig.*6*.

The first operation is performed by measuring the time interval τ of each cycle of pulsations of the instantaneous rectified voltage u along the line of comparison with the specified reference voltage U_{on} on the measuring device MD.

The second operation consists of the use of a converter C, which transforms the time interval τ into a value inverse to the value of the delay angle α with respect to the beginning of each half-cycle of the rectified excitation voltage u_f.

The third operation is implemented using a controlled rectifier CR, the input of which receives control pulses with a delay angle α and a frequency f_2 of the exciter G, which is many times higher than the frequency f_1 of the main generator GM. The regulated voltage u_f and the excitation current i_f are supplied from the exciter G through a controlled rectifier CR to the excitation winding L of the main generator GM.

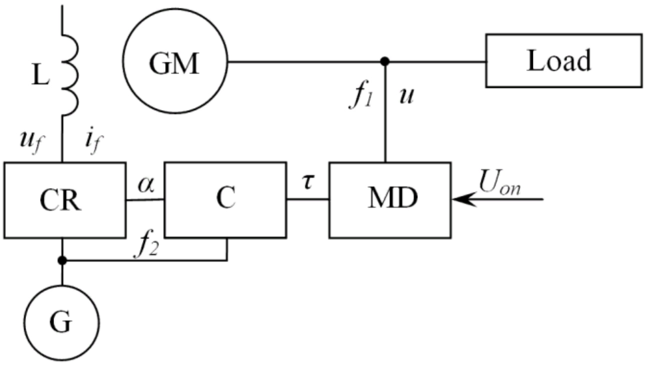


Fig. 6. Block diagram of AEC of a modular wind turbine generator

Exciter G is a modular inductor generator of low power and high frequency. The electric windings of this generator are located coaxially to the windings of the main GM generator, and the magnetic flux switches are made on the rotor in the form of permanent magnets.

The advantages of the method are high speed and low intermittency of the supply voltage of the excitation winding, which leads to a decrease in the distortion of the sine wave of the EMF and effective maintenance of the phase voltage of the generator.

Analysis of the results

The basic calculation equation is derived, and its solutions are obtained, representing mathematical relations and relationships between magnetic flux, EMF, the geometry of electric and magnetic circuits, and other components of modular inductor generators of wind turbines. When designing a modular generator, you should use the basic calculation equation and its solutions, as well as expressions, in order to provide the necessary geometry and arrangement of wind turbine components to obtain the maximum possible magnetic flux and generated electromagnetic power with an optimal ratio of copper and steel of the generator. There are also economic problems associated with copper mining (Wiecek et al., 2019).

It should be borne in mind that in single-circuit magnetic flux switching circuits, a harmful electromotive force is induced in the excitation windings of modular machines, which prevents the magnetization of the machine. When laying the working and exciting windings together, the EMF of the working winding decreases by an order of magnitude, and when laying separately, it is doubled. For mutual compensation of the EMF induced in the field windings, it is necessary to use two-circuit circuits with alternating switching of the flow in the circuits, with sequential switching of the sections of the windings of the exciting circuits. In this case, the method of laying the working and exciting windings is of no fundamental importance. Two-circuit flow switching circuits must be performed with a common exciting winding to avoid the EMF induced in the field windings completely. Due to this, the value of the total flux coupled to the excitation winding does not change during alternating switching of the flow, and the EMF is not induced by the excitation winding. Such a switching scheme makes it possible to increase energy conversion efficiency while reducing the copper's mass of the exciting winding (Kosinar and Kuric, 2011).

Regulation of the excitation of a modular wind turbine generator using a high-frequency exciter generator, according to the principle of deviation of the instantaneous voltage value at the output of the wind turbine generator with a change in power consumption, ensures high performance of the AEC system and leads to a decrease in the distortion of the EMF sine wave and maintaining the constancy of the phase voltage of the generator in transient load changes. The electric windings of the exciting modular generator can be made coaxially inside the windings of the main generator, and the magnetic flux switches are located on the rotor in the form of permanent magnets.

Conclusions

For the power supply of the development of isolated fields, modular wind turbines with their specific design is recommended. To excite the maximum magnetic flux with an optimal ratio of copper and steel of a modular wind turbine generator with a vertical axis of rotation, use the basic calculation equation and its solutions, linking the design assignment with the location and geometry of the electromagnetic modules of the generator.

An increase in energy conversion efficiency is achieved by the correct location of electromagnetic modules and electric windings, which exclude parasitic EMFs induced in the windings during magnetic flux switching. Preferred options are two-circuit flow switching circuits with a common exciting winding or individually exciting windings of switched circuits when connected in series. The option of single-circuit switching of the magnetic flux is less preferable when the working and exciting windings are located separately; the joint arrangement of the windings should not be used.

To maintain the quality of the generated sinusoid EMF, AEC systems should be used that work by deviation of the instantaneous value from the reference voltage, with indirect control of the excitation current coming from an exciting generator of increased frequency (Dodok et al., 2017). A modular exciting generator with permanent magnets on the rotor can be represented as part of the overall design of a modular wind turbine generator.

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