Chapter

Application of an Asynchronous Synchronous Alternator for Wind Power Plant of Low, Medium and High Power

Sergey Gandzha and Anton Kotov

Abstract

The chapter shows the prospects for the development of alternative energy. The growth rate of wind energy is ahead of other types of alternative energy, but the development of wind energy is constrained by a number of technical contradictions that need to be solved. The main problem of wind power is that the power and direction of the wind flow are continuously changing. This leads to the fact that the frequency of rotation of the generator constantly varies and alternator produces energy with nonstandard parameters in amplitude, frequency and phase. Converting this energy into energy with standard parameters is a difficult technical task. A brief analysis of the different directions to solve this problem is shown. It is proved that the promising direction of solving this problem from the point of view of efficiency is the use of double-fed induction alternator (DFIA). The chapter describes the principle of operation of the DFIA, the theory of energy conversion based on equivalent circuits. Approaches to the optimal design of generators based on generalized variables are shown. Two variants of the generator design are described. One option is to contain an additional exciter generator to power the rotor. The design of this 10 kW generator is presented. In another version, the power supply function of the rotor is performed by the battery. In addition, the battery performs the function of accumulation of electricity. It is concluded that the development of wind power in the direction of the DFIA is promising. On the basis of the proposed concept, a number of wind power plants can be built with power from 10 kW to 6 MW. DFIA can operate in standalone mode and in conjunction with electrical grid. The design for the range of wind turbines will be the same type. The DFIA will differ only in size.

Keywords: windmill, double-fed induction alternator, asynchronous synchronous alternator, electronic control system, brushless electric machine, exiting alternator, standard energy, nonstandard energy

1. Introduction

The last 10 years in the world scientific community there are heated discussions about the ways of development of modern energy. The conservative part of scientists believes that hydrocarbon energy based on the use of coal, oil and gas will remain the main source of heat and electricity for economically developed countries for a long time. There are grounds for this view. Hydrocarbon reserves on earth are still quite large. The hydrocarbon industry has a well-established infrastructure. There are enterprises for the production of the necessary equipment, enterprises for the construction and maintenance of energy facilities, scientific results to improve the efficiency of electricity generation in this way.

The advantages of the traditional energy system based on hydrocarbons, is faced with many problems and contradictions. These contradictions are growing every year and, ultimately, can lead to a crisis of traditional energy, if you do not attempt to develop alternative energy.

One of the reasons is the rise in the cost of hydrocarbon production. Cheap oil, gas and coal have already have used. We have to penetrate to great depths under the earth's surface, to work at the bottom of the ocean, to explore the remote Northern areas for mining. It may not be economically feasible after all.

The second very important reason is environmental problems. Nature has been creating an ecological balance of carbon dioxide in the atmosphere for millions of years. Hydrocarbon power industry disturbs this balance. Humanity has not yet fully appreciated the consequences of this imbalance. The crisis can affect more than just climate change. The next step is a violation in nature. At the final stage, problems will arise in the social community. But, probably, it will be too late to solve these problems.

Very little is said about the low efficiency of traditional energy. The highest efficiency of thermal power plants is about 30%. According to various estimates, their share in the global energy balance ranges from 60 to 70%. These figures show that we heat our planet and clog it with emissions of production. Nature will inevitably take revenge on humanity for these actions.

The development of technical systems has its own laws with its stages of development [1]. Qualitatively, this process is shown in **Figure 1**.

At the first stage, the technical system is born. This is the stage of laboratory research and scientific analysis. This stage requires a lot of effort from scientists. As a rule, this stage requires large financial investments in scientific research and is not commercial.

At the second stage, the technical system is developing very quickly. Industrial production shows great interest in the system, because it gives a commercial result.

At the third stage, the technical system comes to the saturation phase. Staying at a high level, it has exhausted its resources. The pace of its development is very slow. Further investment of finances in its development does not give a commercial result.

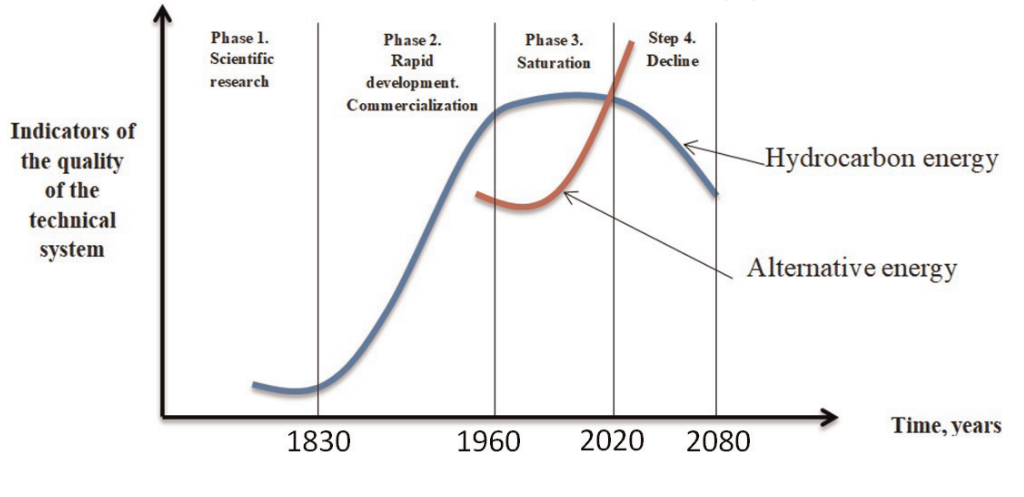

Figure 1.
Stages of development of technical systems.

At the fourth last stage of its development, the technical system is in decline. Industry is losing interest in its reproduction. It becomes unprofitable.

Hydrocarbon energy has more than 150 years of its development. According to various experts, it finishes the second phase of its development and moves into the third phase. The third phase can last for several decades and will inevitably come the phase of decline.

The theory of development of technical systems determines that in this process at a certain stage of development of the first system, the second alternative technical system is born. At first, it is difficult to compete with the dynamically developing first system, but it goes through all 4 phases of development and replaces the first technical system when it comes to decline.

This function is currently performed by alternative energy. **Figure 2** shows this tendency.

The question arises in what direction and how to develop alternative energy.

Alternative energy includes different types:

- Geo thermal energy;
- Water power energy;
- Bio gas energy;
- Solar energy;
- Wind energy.

The diagram shows that the share of wind energy in the total balance is the largest today.

Among others renewables the windmills are the most developing devices due to several advantages:

- Wind is the endless power source.
- It is an ecologically clean device.

Wind energy trends should be taken into account. It is shown in **Figure 3**.

It should be noted that the wind turbines are really environmentally friendly devices. They do not produce harmful emissions during their work and do not require dirty technology for their manufacture. In the production of solar panels are used a harmful production. Thus, the development of wind energy is an urgent task.

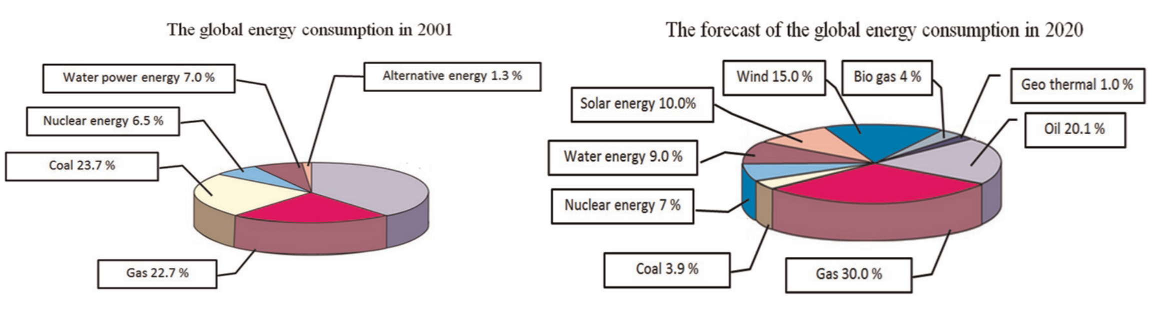

Figure 2.
Forecast of alternative energy development.

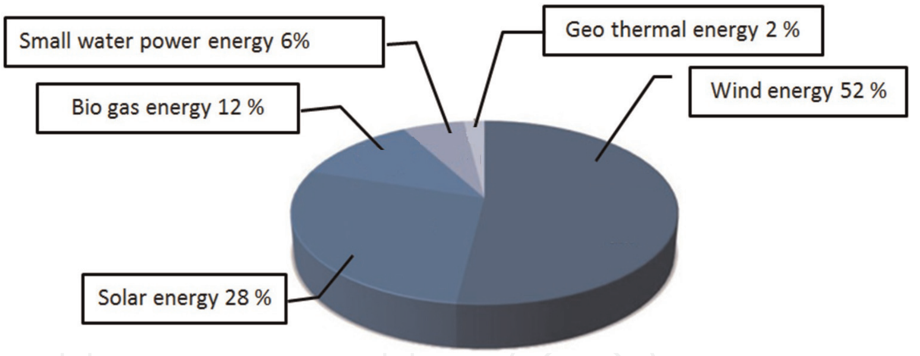

Figure 3.
Share of wind energy in the total balance of alternative energy.

2. Various of the designs of wind turbines

Wind turbines can be classified into the following types by output power

- wind turbines of low power (up to 10 kW);
- wind turbines of average power (from 10 to 100 kW);

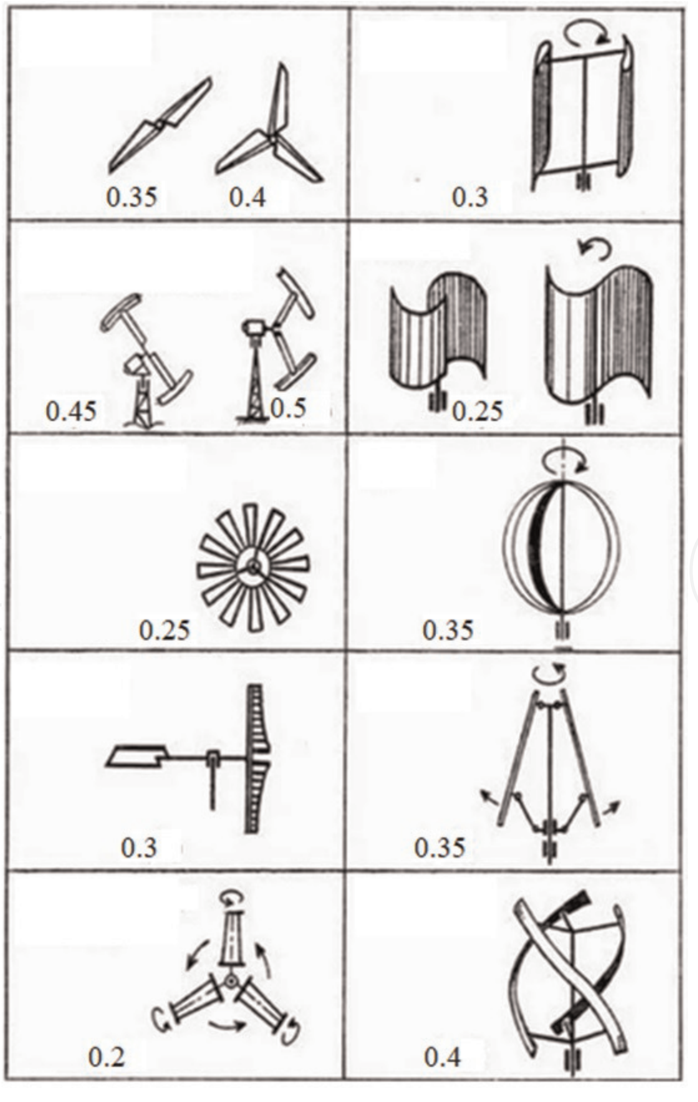

Figure 4.
Different designs of wind wheels and their efficiency.

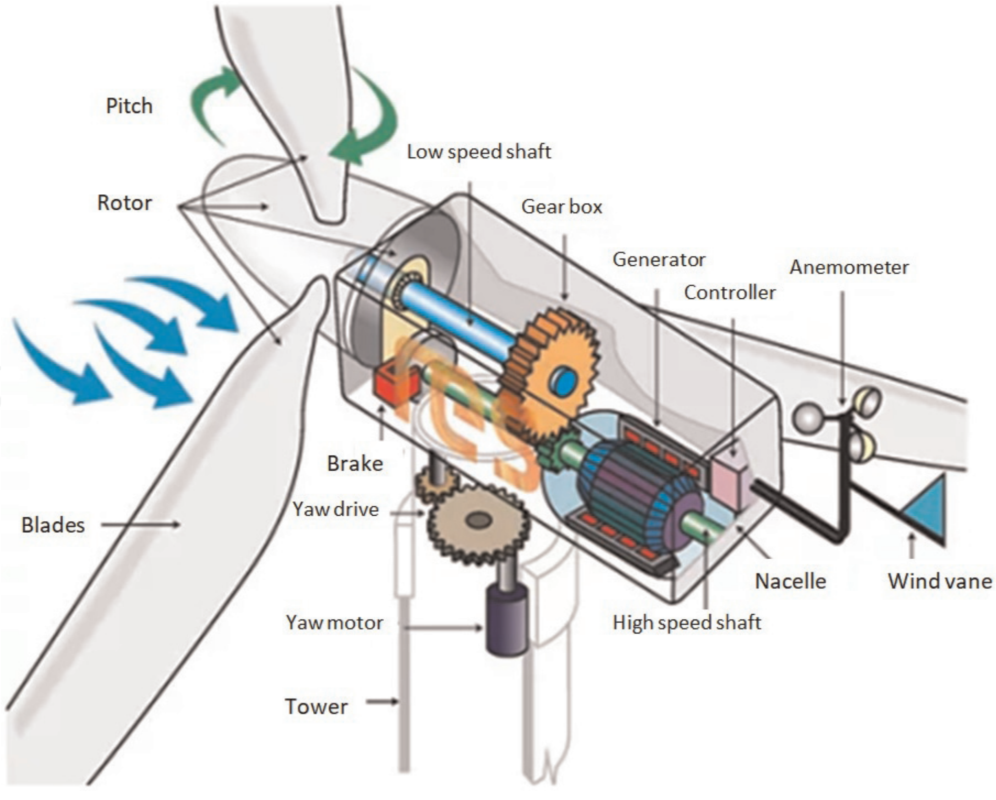

Figure 5.
The main elements of the wind turbine with a horizontal axis of rotation.

- high power wind turbines (more than 100 kW).

Wind power plants have many versions, but they can be divided into two main types

- Wind turbines with horizontal axis of rotation;
- Wind turbines in the vertical axis of rotation;

The efficiency of the wind wheel of a wind turbine is defined as the ratio of the mechanical power on the shaft to the power of the wind flow. It depends on the wind speed and the design of the wind wheel. The maximum efficiency for different wind turbines is shown in **Figure 4**.

Wind turbine is a complex technical device. It consists of many components and parts [2–4]. The design of the wind turbine with a horizontal axis of rotation is shown in **Figure 5**.

The most important elements of the wind turbine are an electric alternator and an electronic control system. The efficiency of the entire wind turbine depends on the correct choice of the alternator type.

3. The main problem of wind power

It is necessary to solve very serious problem for using windmills effectively [5–7].

The main problem of windmill's energy is the changing of the speed and the direction of wind flow. Thus, the windmill rotor rotates with a different speed and alternator gives the voltage with variable parameters of amplitude, frequency and phase (**Figure 6**). It is impossible to use this nonstandard energy. It is

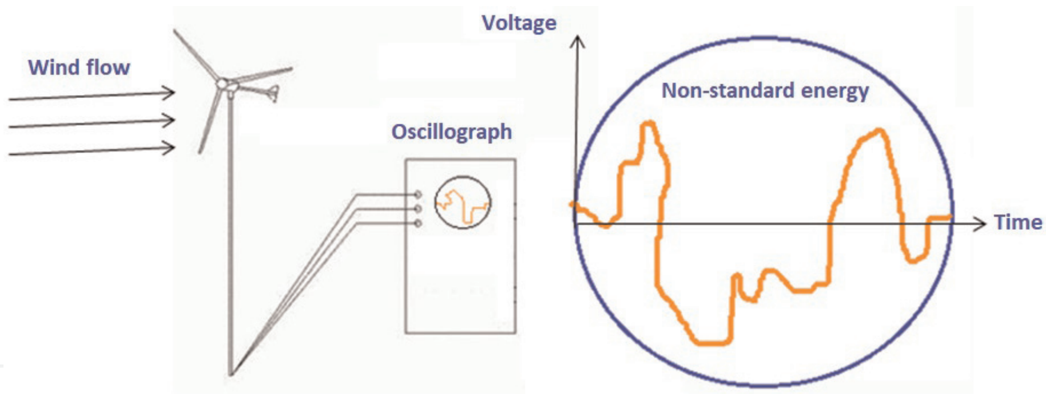

Figure 6.
Illustration of wind turbine operation.

necessary to transform the nonstandard energy to the energy with standard parameters [4, 8–18].

In practice some methods to solve this problem are known.

1. Application of asynchronous (induction) alternator.

Figure 7 shows the design of the inductor alternator.

The disadvantages of this method are:

- It is necessary to supply the reactive energy for working of the induction alternator. Such windmills can work only with electric grid or with battery of capacitors;
- When induction alternator works with electric grid it uses the reactive power and makes parameters worse.

2. Application of permanent magnet synchronous alternator with rectifier and invertor.

Figure 8 shows the design of synchronous alternator.

The disadvantages of this method are:

- They are many stages for transforming the nonstandard energy to standard energy (the rectification, the stabilization, the inversion). Every stage has his own loses and efficiency. So, the total efficiency is very low.
- The equipment for this method is very expensive.

3. Application of an asynchronous synchronous alternator (double fed inductor alternator) (DFIA)

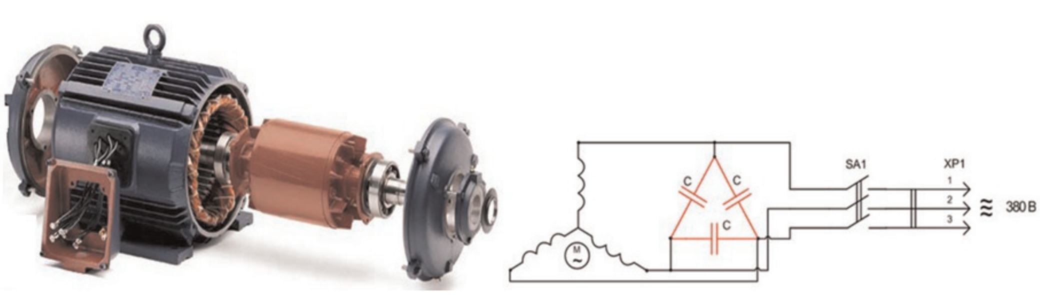

Figure 7.
Design of the inductor alternator.

DOI: http://dx.doi.org/10.5772/intechopen.89255

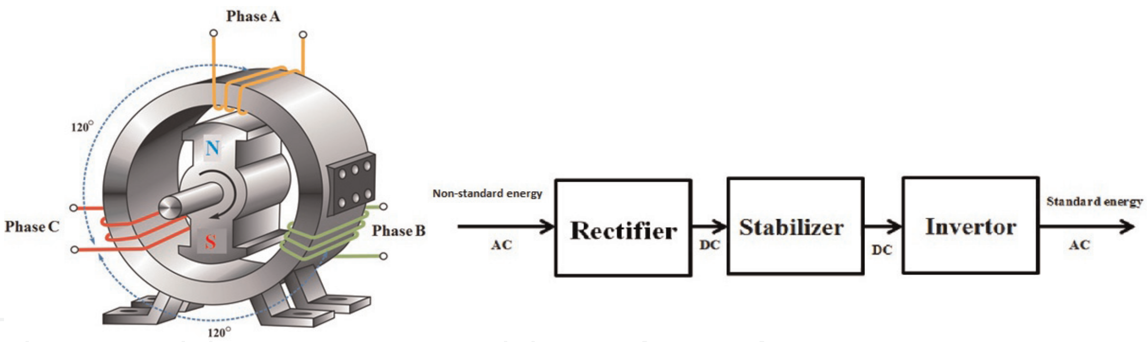

Figure 8.
Design of the synchronous alternator.

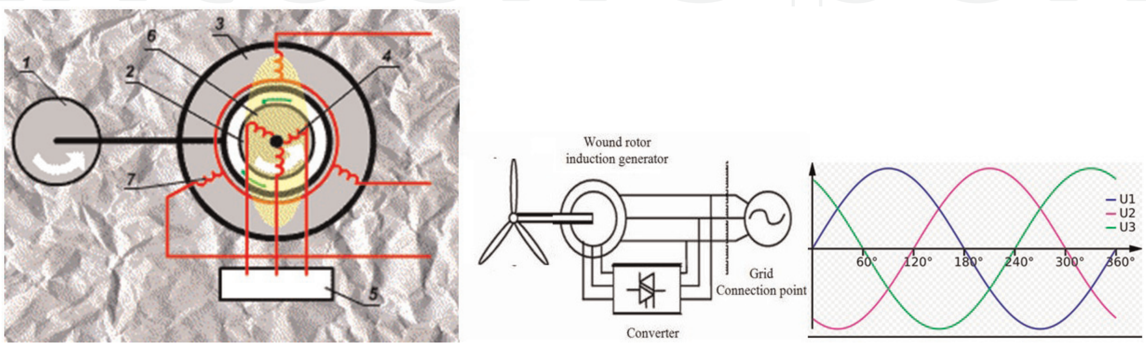

Figure 9.
Design of the asynchronous synchronous alternator (1, wind turbine; 2, rotor; 3, Stator; 4, rotor; 3 phases winding; 5, electronic control system; 6, rotating magnetic field; 7, Stator 3 phases winding).

Figure 9 shows the design of the double fed alternator.

This type of alternator can transform the nonstandard energy into standard energy without complex units and without additional stages of energy conversion. This is a new approach to solving the problems of wind energy. This Chapter will be devoted to the description of this promising wind turbine.

4. The application of the DFIA

It is well-known the principle of operation of the double-fed alternator [12, 14–16]. Electric machine of this type has been studied by scientists around the world since 1960. It has different applications, but in wind power it is used only for the last 10 years. The authors offer a unique design that they have developed for a row of wind power plants. The design has a Russian patent. It is described below.

The alternator consists of two electric machines. The main electric machine is a power alternator. It is the induction machine with a phase rotor. So, the stator and the rotor have three phase windings. The alternator has the inverse design. It means that the rotor is settled outside of stator. It is very comfortable for the windmill because it is possible to attach the blades to the rotor. The three phase rotor winding is supplied by an adjustable voltage source. The rotor creates the rotating magnet field. This magnet field generates the voltage in the stator winding. If the rotor is fixed the speed of rotation of magnet field depends only from frequency of voltage source. But if the rotor begins to rotate, the speed of magnet field is added to the speed of rotor rotation. So, the total speed of magnet field is combined with two parts. We can change the frequency of the adjustable three phase voltage sources. When the speed of rotor is variable we can choose the necessary frequency of voltage source and we will have the stable frequency in the stator winding. In this way, we solve the problem of voltage frequency stabilization with different speed of rotor rotation. The amplitude of stator voltage is regulated by amplitude of rotor winding voltage.

But it is necessary to solve one serious problem to provide the reliability to windmill. It is impossible to use the sliding contact for windmill because it is very difficult to serve this device at height and in a difficult environment. The system has the second alternator (exciter) for brushless current supply. The brushless electric machine with combine excitation is used for the exciter. This type of electric machine has the stable external voltage with different speed of rotation. It is very comfortable in this case. In details, this type of electric machine is described in [1, 4, 19].

The sketch of alternator with exciter, 3D model and diagram of electronic control system is present in **Figures 10–12**. They allow understanding the principle of operation more carefully.

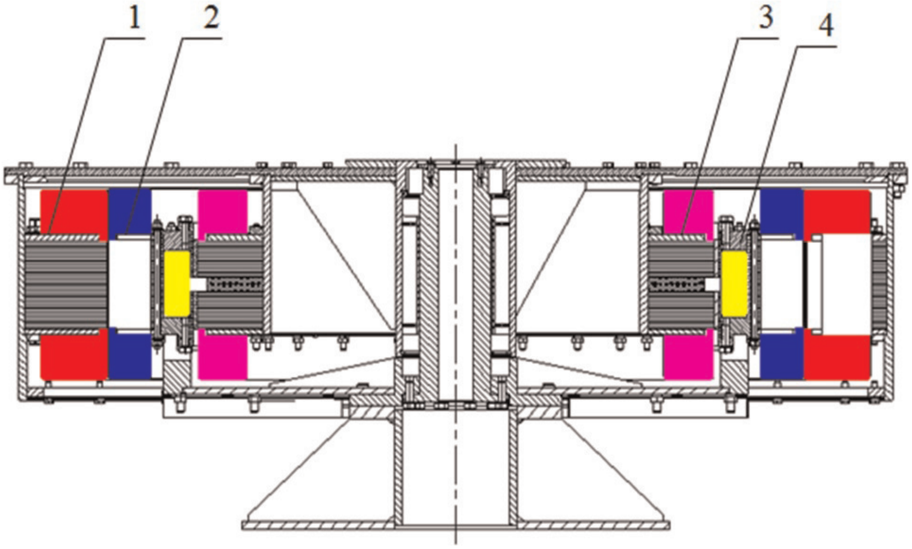

Figure 10.
Sketch of double-fed alternator with exciter. (1, rotor of power alternator; 2, stator of power alternator; 3, rotor of excitation alternator; 4, stator of exciter alternator).

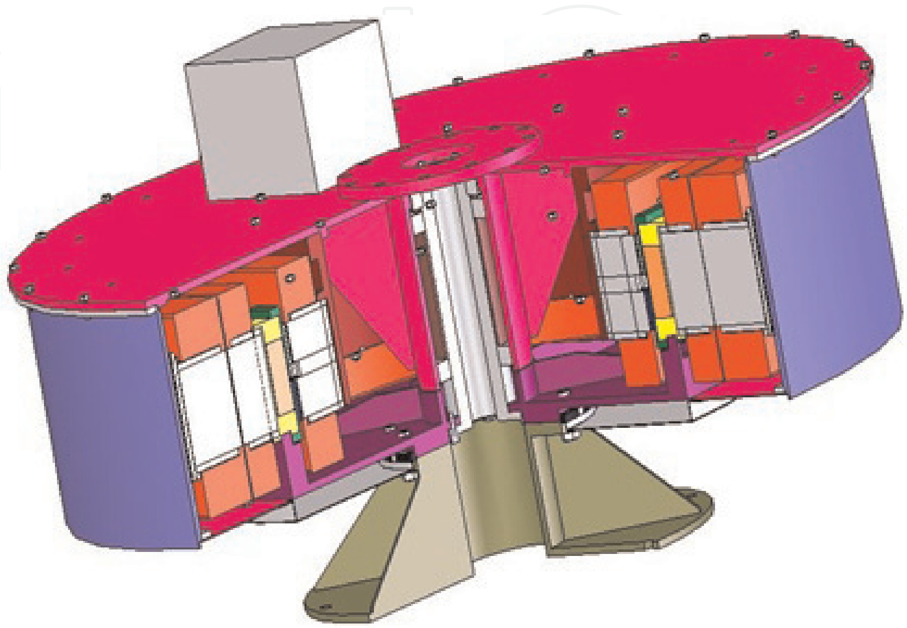

Figure 11.
3D model of the windmill alternator.

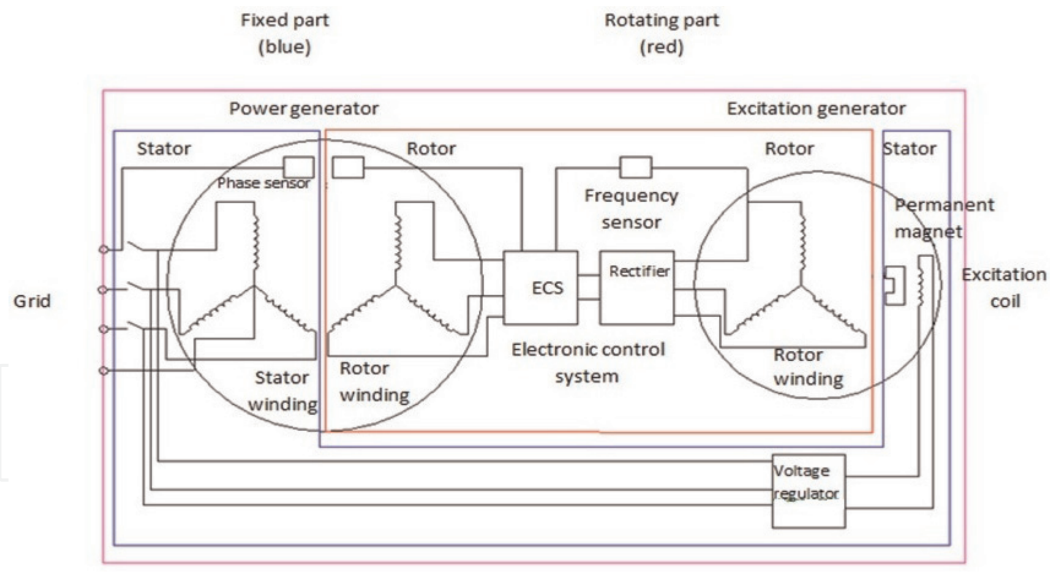

Figure 12.
Diagram of electronic control system.

The electronic control system is built in to the alternators. This concept allows having very high efficiency and very low cost.

This idea was realized for the windmill 10 kW but the concept can be scaled to megawatts sizes.

5. Theory of double-feed induction machine

The beginning of the work in the field of the theory of DFIA was initiated by the research in the late 1960s — early 1970s by the laboratory of double feeding machines under the guidance of doctors of technical sciences M. Botvinnik and Yu. G. Shakaryan [20].

The results of these works were the development of the foundations of the theory, structural schemes, principles of construction, as well as the creation of a number of experimental and industrial installations.

In a double-feed machine, energy is supplied (or withdrawn) to both the stator and rotor windings. This allows you to control the flow of active and reactive power of the dual-feed machine. The expediency of using DFIA is observed in the construction of alternator sets with a variable speed of rotation of the shaft, which is very important for wind power plants.

The stator windings of the machine are connected to the power supply network (U_1 = const, f_1 = const), and the rotor windings are connected to a separate controlled power source (active semiconductor converter ASC).

There are various options for implementing a controlled power supply in the rotor circuit. A scheme of independent rotor power supply is interested in wind power plants (**Figure 13**).

The active Converter is a three-phase bridge circuit of the inverter, made on transistors. The main property of the active Converter is the ability to two-way transmission of active power. When transmitting power from an AC source, ASC acts as an active controlled rectifier (ACR). When transmitting power from the DC link, ASC acts as an Autonomous Inverter (AI). Such structures allow you to control the flow of active and reactive power between the supply network and the machine.

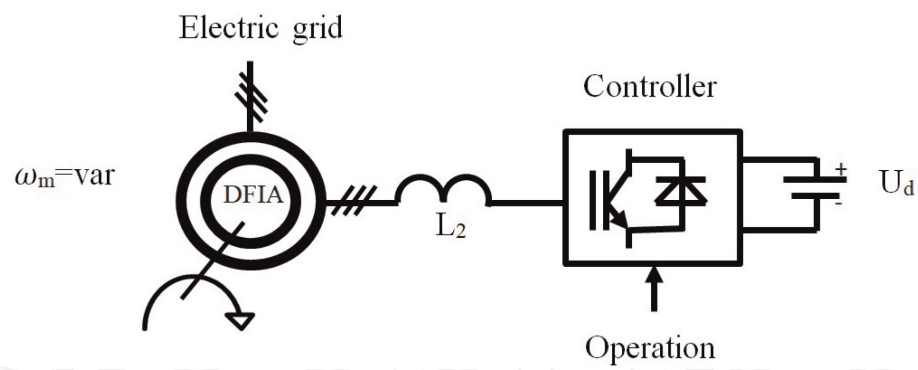

Figure 13.
Controlling of rotor power.

The main advantages of DFIA are as follows:

1. Control is carried out on the rotor circuit; this makes the high energy efficiency of the system.

2. DFIA can operate at speeds above and below synchronous, both in motor mode and in alternator mode. Therefore, when using DFIA as a alternator, there are no difficulties with stabilizing the parameters of the generated voltage when changing the speed of the shaft rotation, which is important for wind turbines.

Modes of operation, vector and energy diagrams.

Theoretically, the following operating modes of DFIA are possible:

- motor mode at a speed below synchronous;
- motor mode at a speed above synchronous;
- alternator mode at a speed higher than synchronous;
- alternator mode at a speed below synchronous.

In all these modes, the system of equations describing the electromagnetic processes of the machine in a steady state using the method of the resulting vector [21], has the form:

$$\overline{U}_1 = R_s\overline{I}_1 + jX_{ls}\overline{I}_1 + \overline{E}_1 \qquad \frac{\overline{U}_2^{|}}{s} = \frac{R_r}{s}\overline{I}_2^{|} + jX_{lr}\overline{I}_2^{|} + \overline{E}_2 \qquad \overline{I}_m = \overline{I}_1 + \overline{I}_2^{|}, \tag{1}$$

where $\overline{U}_1$ is the line voltage; $\overline{I}_1, \overline{E}_1 = j\omega_1\overline{\Psi}_m = jX_m\overline{I}_m$ is the current and EMF in anchor winding; $\overline{U}_2^{|}, \overline{I}_2^{|}, \overline{E}_2^{|} = j\omega_1\overline{\Psi}_m = jX_m\overline{I}_m$ is the led voltage, current and EMF in rotor winding; $\overline{I}_m$ magnetizing current; $R_s, X_{ls} = \omega_1 L_{ls}$ is the active and inductive resistance of the stator; $R_r, X_{lr} = \omega_1 L_{lr}$ is the led active and inductive resistance of the rotor; $X_m = \omega_1 L_m$ is the inductive reactance of magnetization circuit; s is the slide. The T-shaped equivalent circuit based on Eq. (1) is shown in **Figure 14a**.

Let us transform the T-shaped equivalent circuit into a G-shaped equivalent circuit.

Conversion factor is:

$$C = 1 + \frac{X_{ls}}{X_m}. \tag{2}$$

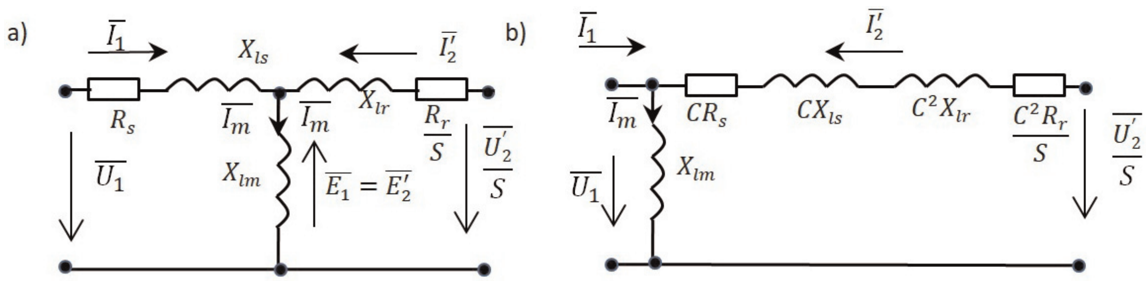

Figure 14.
Equivalent circuit of the DFIA: a) T-shaped equivalent circuit; b) G-shaped equivalent circuit.

We write down the equations for the G-shaped equivalent circuit (3)

$$\overline{U}_2^{|} = \overline{U}_1 + R_2\overline{I}_2^{|} + jX_2\overline{I}_2^{|};\ \overline{U}_1 = jX_{1m}\overline{I}_m, \overline{I}_m = \overline{I}_1 + \overline{I}_2^{|};\ R_2 = R_sC + \frac{R_r}{s}C^2 \approx R_s + \frac{R_r}{s};$$
$$X_2 = X_{ls}C + X_{lr}C^2 \approx X_{ls} + X_{lr};\ X_{1m} = X_{ls} + X_m \quad (3)$$

The following should be taken into account when assessing energy flows

1. The active power in the source is positive when the source gives energy and negative when the source consumes energy.

2. The reactive power in the source is positive (inductive) when the voltage is ahead of the current, and negative (capacitive) when the voltage is behind the current.

3. The mechanical power on the shaft is positive in the motor mode of your operation and negative in the generator mode of your operation. Active and reactive power sources $\overline{U}_1$ and $\overline{U}_2^{|}$ are determined from the expressions.

$$P_1 = \frac{3}{2}U_1I_1 \cos\varphi_1;\ P_2 = \frac{3}{2}\overline{U}_2^{|}\overline{I}_2^{|} \cos\varphi_2;\ Q_1 = \frac{3}{2}U_1I_1 \sin\varphi_1;\ Q = \frac{3}{2}\overline{U}_2^{|}\overline{I}_2^{|} \sin\varphi_2 \quad (4)$$

In the direction of the mechanical power acting on the shaft, the modes can be divided into motor mode and generator mode.

We consider only all generator modes for a wind turbine.

The mechanical power reported to the shaft of the machine at n < n0 (**Figure 15**) and the electrical power obtained by the rotor through a semiconductor converter, are transmitted to the stator and after deduction of losses are recovered to the grid.

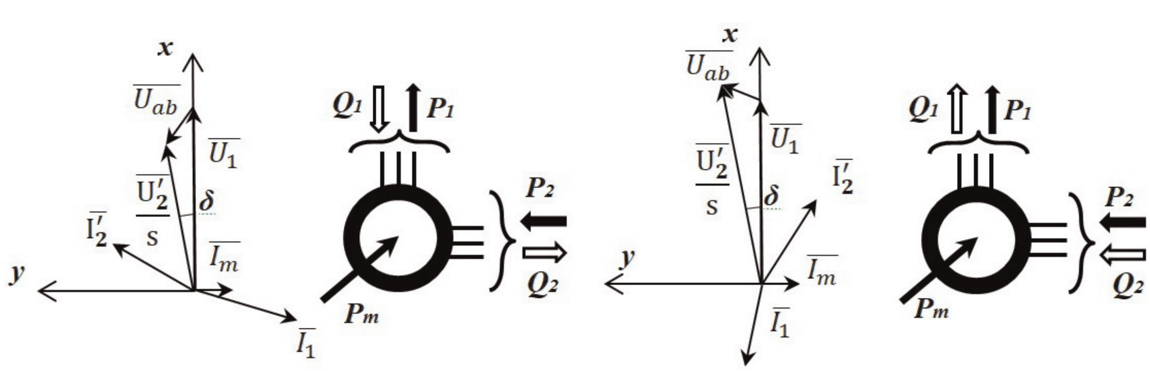

Figure 15.
Vector diagram and energy diagram of DFD in generator mode at $n < n_o$.

Energy diagrams of the generator mode DFIA at n > n0 are shown in **Figure 16**. In this mode, the mechanical power supplied to the shaft from the rotor side is converted into electrical power. Part of this power is given to the network from the rotor side. The other part is given to the stator circuit in the form of electromagnetic power and after deduction of losses is recovered in the network.

The balances of power in the various modes are summarized in **Table 1**.

A system of equations should be solved to quantify the properties of DFIA. This solution is carried out in a rotating coordinate system x (real axis) and y (imaginary axis). In this case, the voltage U1 is combined with the real axis x, and for the secondary voltage the ratio $U_{2m}= \frac{\omega 1U2}{\omega 2}$ and the phase σ are given. It is important to emphasize that when the real axis is combined with the voltage vector, the real component of the current is the active current of the stator, and the imaginary component is the reactive current of the stator.

$$I1 = \frac{\overline{(U1|)}\left(\frac{Rr}{s}+jXs\right) - j\frac{\overline{U2|}}{s}Xm}{(Rs+jXs)\left(\frac{Rr}{s}+jXs\right)-X_m^2}; \quad \overline{I2} = \frac{\frac{\overline{U2|}}{s}(Rs+jX) - j\overline{U1|}\,Xm}{(Rs+jXs)\left(\frac{Rr}{s}+jXs\right)-X_m^2}. \tag{5}$$

The total current of the rotor and stator are calculated by the formula:

$$I1 = \sqrt{I_{1x}^2 + I_{1y}^2}; \quad I2| = \sqrt{I|_{2x}^2 + I|_{2y}^2} \tag{6}$$

The electromagnetic moment is determined from the equation:

$$T_e = \frac{3}{2}pL_m\left(\overline{I_2}\cdot\overline{I_1}\right) = 1.5pL_m\left(I_{2x}I_{1y} - I_{2y}I_{1x}\right) \tag{7}$$

The energy properties of the MIS are determined after the calculation of the currents from the equations according to the following expressions.

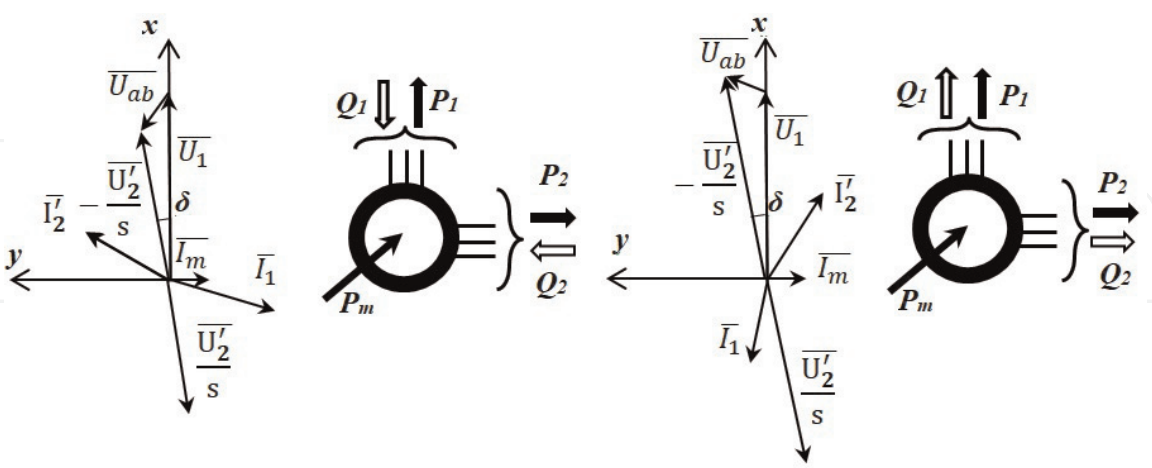

Figure 16.
Vector diagram and energy diagram of DFD in generator mode at $n > n_o$.

Slide	Generator mode
s > 0	$P_1 + P_m = -P_1 + \Delta P$
s < 0	$P_m = -P_1 + \Delta P - P_2$

Table 1.
Balance of DFIA active powers depending on operating modes.

$$P_1 = 1.5U_1 I_{1x};\ Q_1 = -1.5U_1 I_{1y};\ Q_2 = 1.5\left(U_{2y} I_{2x} - U_{2x} I_{2y}\right);$$
$$P_m = T_e \omega_m = T_e \frac{(1-s)\omega_1}{p};\ P_2 = 1.5\left(U_{2x} I_{2x} + U_{2y} I_{2y}\right. \quad (8)$$

Electromagnetic losses are calculated by the expression

$$\Delta P = I_1^2 R_s + I_2^2 | R_r \quad (9)$$

These equations can be used to model DFIA in Mathlab (**Figures 17–19**).
We present the main characteristics obtained on the model.
Assessing the properties of DFIA in the generator mode, we can draw the following conclusions:

1. The area of unstable operation is in a rather narrow zone of positive slides.

2. At $U_{2m} \leq U_1$ in the sliding range from 0 to −1, the reactive power consumed from the network is mainly positive (inductive).

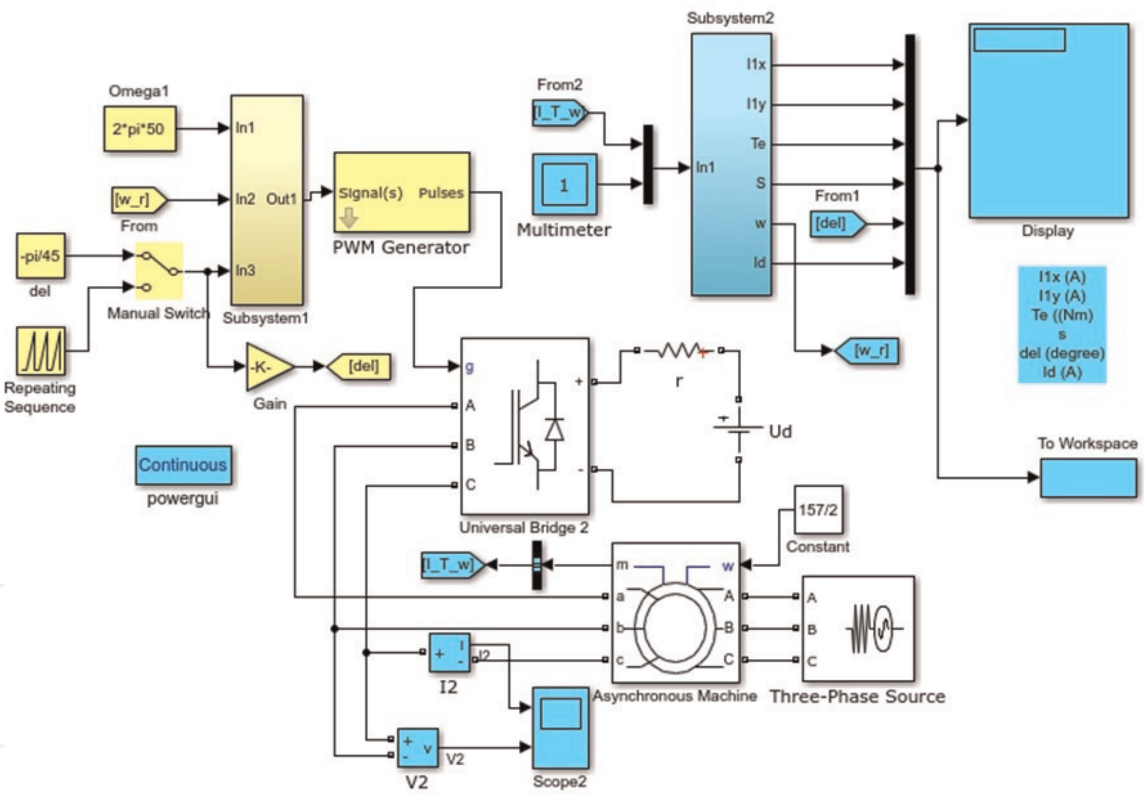

Figure 17.
Virtual laboratory setup for DFIA studies with independent controlling.

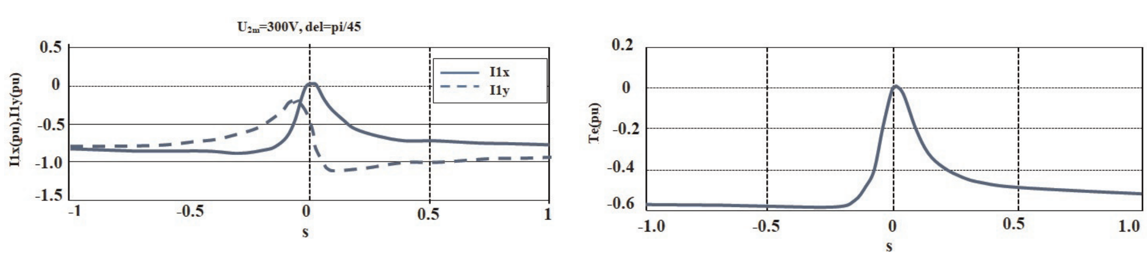

Figure 18.
Electromagnetic and electromechanical characteristics of DFIA with independent control in generator mode at $U_{2m} < U_1$.

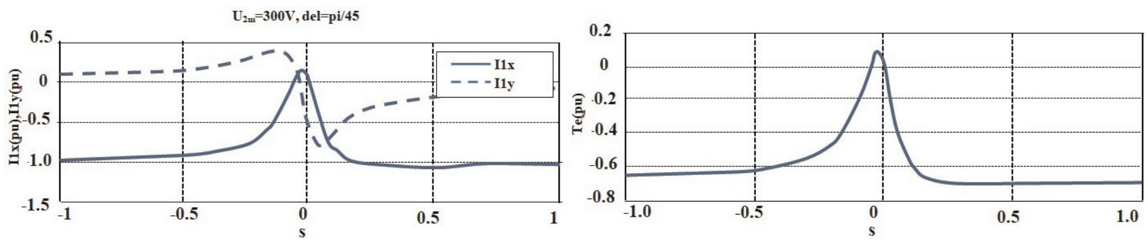

Figure 19.
Electromagnetic and electromechanical characteristics of DFIA with independent control in generator mode at $U_{2m} > U_1$.

3. At $U_2 > U_1$ in the sliding range from 0 to −1, the reactive power consumed from the network is always negative (capacitive).

4. In case of significant sliding, the DFIA is a source of torque.

This property is extremely useful when performing the DFIA generator function when the shaft speed varies widely.

6. DFIA design basics

The design of complex technical systems such as DFIA in the digital age should be based on the application of nonlinear programming techniques for synthesis and analysis.

There are a large number of CAD systems for the analysis of electromagnetic and thermal state of electric machines. Application of the Ansys software package will be shown below.

For the synthesis of electric machines, there are no fully developed techniques. Developers are forced to form a design system for each new type of machine.

DFIA operates in a wide range of mechanical and electrical loads. For its effective operation in all modes, it is necessary to determine the optimal geometry of the magnetic system and the anchor windings.

It should be noted that the problem of optimal design of electric machines remains quite complex and not fully solved [5, 12–18]. This is due to the choice of optimization method, the formalization of independent variables and the definition of quality indicators of the electric machine. Until now, the optimal design problems remain very important and relevant in electrical engineering.

6.1 Problem statement of optimal design of DFIA

Optimizations should be understood as the process of selecting the best option for a large number of possible options. Indicators of the quality of the best option are the optimality criteria. As a rule, there are several optimality criteria in the computational model, and in the most General case there is a need to solve a multi-criteria problem. It should be noted that the solution of multi-criteria problem is quite difficult. This is due to the fact that the optimality criteria are in a contradictory relationship. Improvement of one criterion leads to deterioration of others. So the increase in efficiency leads to an increase in the mass and volume of the product, the improvement of the output voltage parameters to the complication of electronics, cost reduction to a decrease in reliability. The experience of optimal design in electrical engineering shows that the task of multi-criteria optimization is quite complex. It is poorly formalized. The existing methods of its solution are

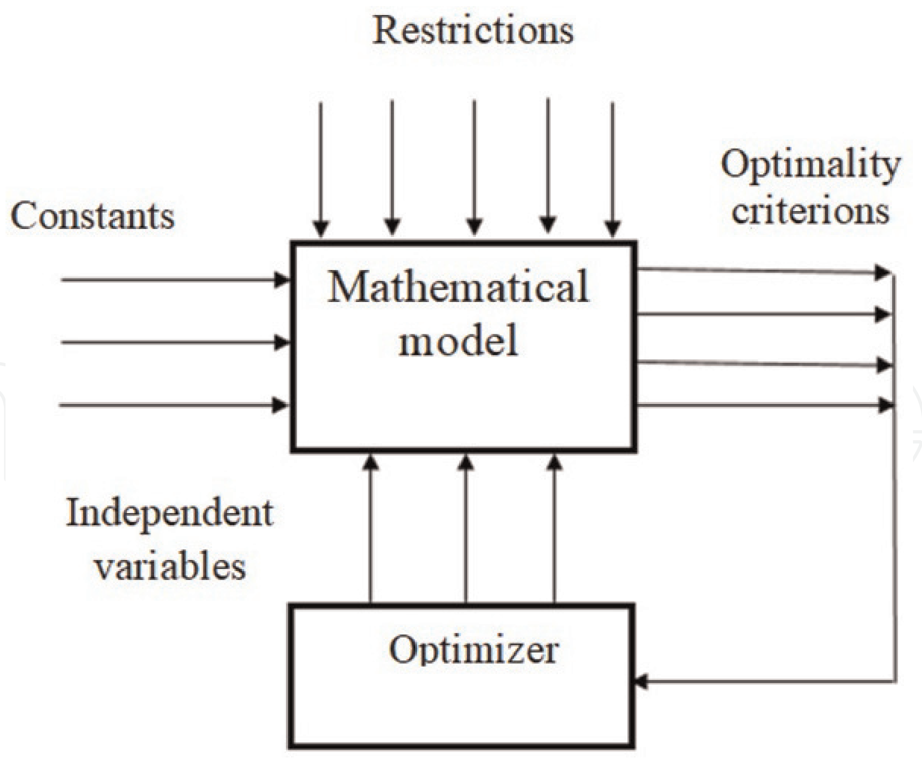

Figure 20.
Block diagram of the single-criterion optimization problem.

subjective and the success of their application depends on the experience of the developer. For this reason, we formulate a one-criterion optimization problem for the generator. Practice shows that such problems are solved successfully and efficiently. It should be noted that the optimality criterion can be changed depending on the current project situation.

We formulate the problem of single-criterion optimization of DFIA in the classical formulation [2, 3]: for the given parameters (specific performance, materials, initial data of the technical task), under the given restrictions, it is necessary, making a search of independent variables by a certain algorithm, to determine the geometry that would provide the extreme value of the selected criteria. There can be several optimality criteria, but depending on the project situation one is chosen for optimization.

The flowchart of the single-criterion optimization problem is shown in **Figure 20**.

The data of the technical task are taken as constants in the problem.

As constraints are the technical requirements for dimensions and permissible loads.

As criteria of optimality it is possible to accept the quality indicators which have received the greatest distribution in practice, for example: the minimum mass of active materials; the minimum volume of magnetic system, the maximum possible at the set electromagnetic loadings of efficiency.

The choice of independent variables is a separate and rather complex task.

6.2 Selecting independent variables for the optimization problem

The independent variables for the optimization problem must meet the following basic requirements:

- they should be visual and have a clear physical meaning;
- they should be effective, that is, their change should bring the calculation closer to the optimal design in the minimum number of iterations;

- they should have clear boundaries of change, it is desirable that the optimum is not on the border. This will make it difficult to choose optimization methods.

Analysis of the characteristics of the DFIA generator shows that its energy efficiency and specific energy performance are less dependent on specific linear dimensions, such as the height and width of the slot, the size of the back of the stator and inductor. To a greater extent, the energy of the machine depends on the ratio of the areas of the active zones, for example, the ratio of the cross-sectional area of the anchor to the cross-sectional area of the machine, the ratio of the area of the slotted zone to the area of the anchor, the ratio of the area of the slots to the area of the slotted zone, etc. Selecting these relative parameters as independent variables is very convenient. They have clear boundaries of change from 0 to 1, show the optimal ratio of the active zones involved in the energy conversion; their optimal values vary in a small range when the size changes over a wide range.

The idea of using these variables is not new. It was used for the synthesis of traction motors of rolling stock [22], and later, for the development of design methods of valve torque DC motors [3]. However, for dual power generators, this technique has not previously been used. Let us give these variables the term "generalized variables", which reflect their physical nature, and define them for DFIA.

6.3 Definition of generalized variables for DFIA

For the asynchronous-synchronous machine, it is convenient to allocate 6 generalized variables:

1. Variable f_s shows how much of the cross-sectional area of the electric machine without shaft is occupied by the total machine cross section (**Figure 21**);

$$f_s = \frac{S_{ring}}{S_{circle}} = \frac{S_{machine\ cross\ section\ without\ shaft}}{S_{total\ machine\ cross\ section}}; \tag{10}$$

2. Variable f_a reflects the ratio of area of the rotor cross section by the area of total machine cross section (**Figure 22**)

$$f_a = \frac{S_{rotor\ cross\ section}}{S_{total\ machine\ cross\_section}}; \tag{11}$$

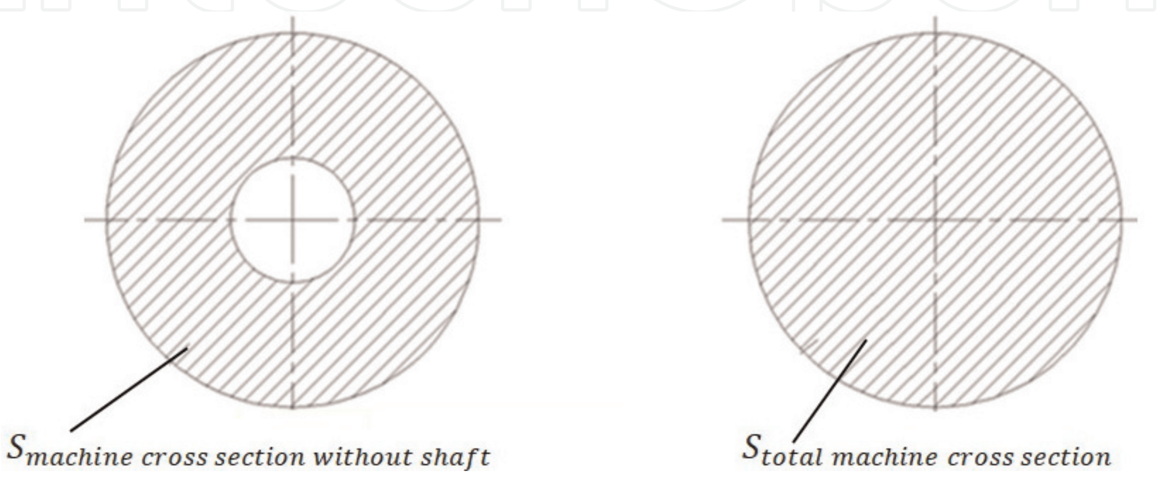

Figure 21.
Variable f_s.

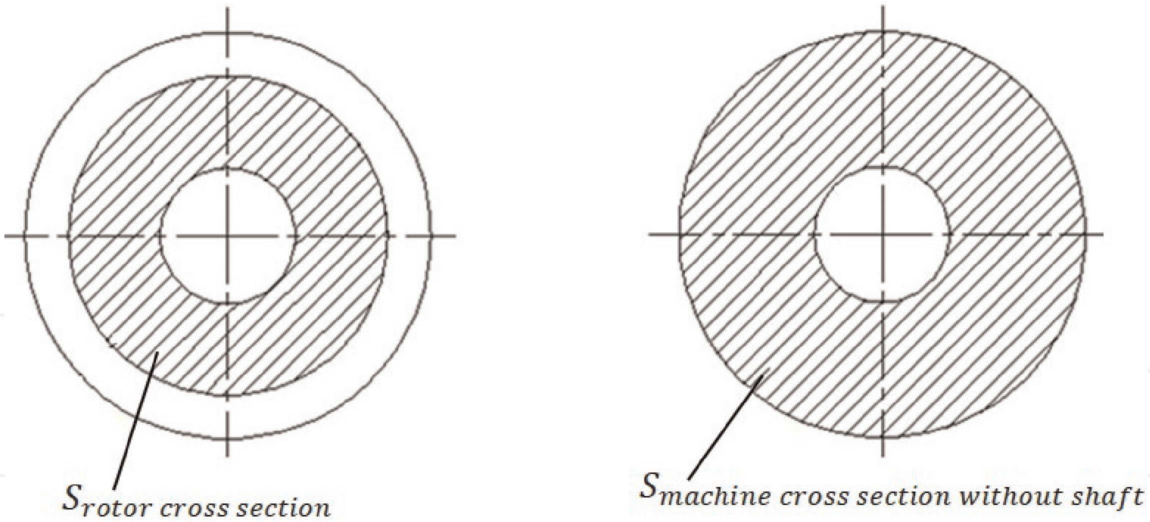

Figure 22.
Variable f_a.

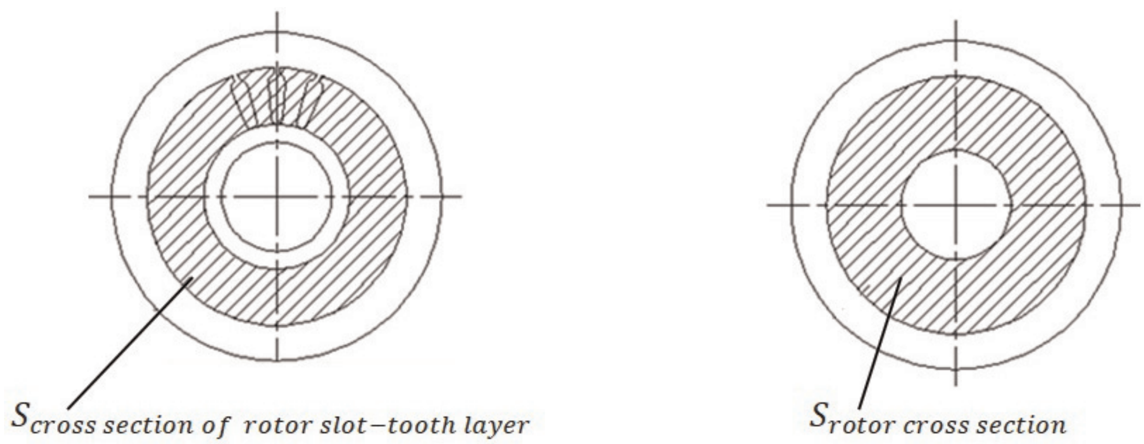

Figure 23.
Variable f_{es}.

3. Variable f_{er} shows the ratio of the area of cross section of rotor slot-tooth layer by the area of rotor cross section (**Figure 23**);

$$f_{es} = \frac{S_{cross\ section\ of\ \ rotor\ slot-tooth\ layer}}{S_{rotor\ cross\ section}}; \tag{12}$$

4. Variable f_{zr} reflects the ratio of the area of cross section of rotor slots by the area of cross section of rotor slot-tooth layer (**Figure 24**)

$$f_{zr} = \frac{S_{cross\ section\ of\ \ rotor\ slots}}{S_{cross\ section\ of\ rotor\ slot-tooth\ layer}}; \tag{13}$$

5. Variable f_{es} shows the ratio of the area of stator slot-tooth layer by the area of stator cross section (**Figure 25**);

$$f_{es} = \frac{S_{cross\ section\ of\ \ stator\ slot-tooth\ layer}}{S_{stator\ cross\ section}}; \tag{14}$$

6. Variable f_{zs} reflects the ratio of the area of cross section of stator slots by the area of cross section of stator slot-tooth layer (**Figure 26**);

$$f_{zs} = \frac{S_{cross\ section\ of\ \ stator\ slots}}{S_{cross\ section\ of\ \ stator\ slot-tooth\ layer}}; \tag{15}$$

Once again, we emphasize the visibility and clear physical meaning of the introduced generalized variables.

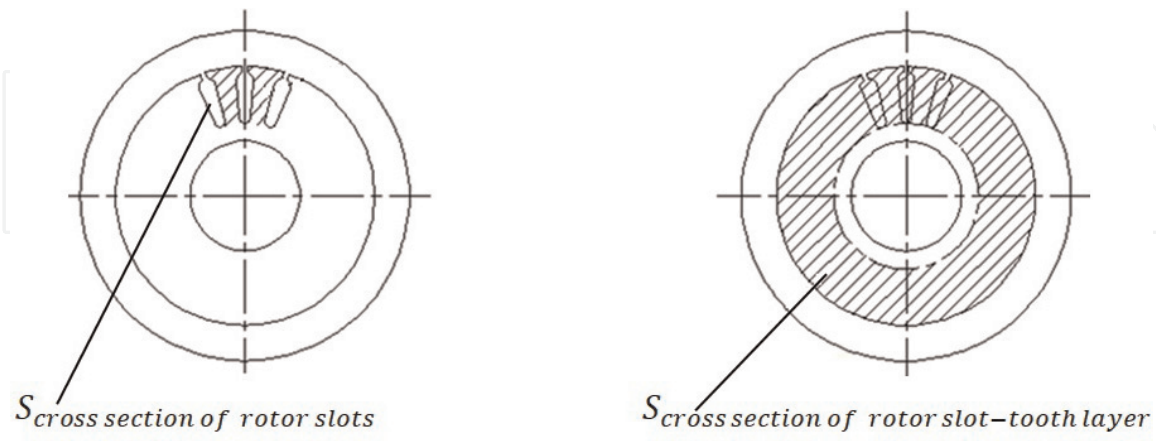

Figure 24.
Variable f_z.

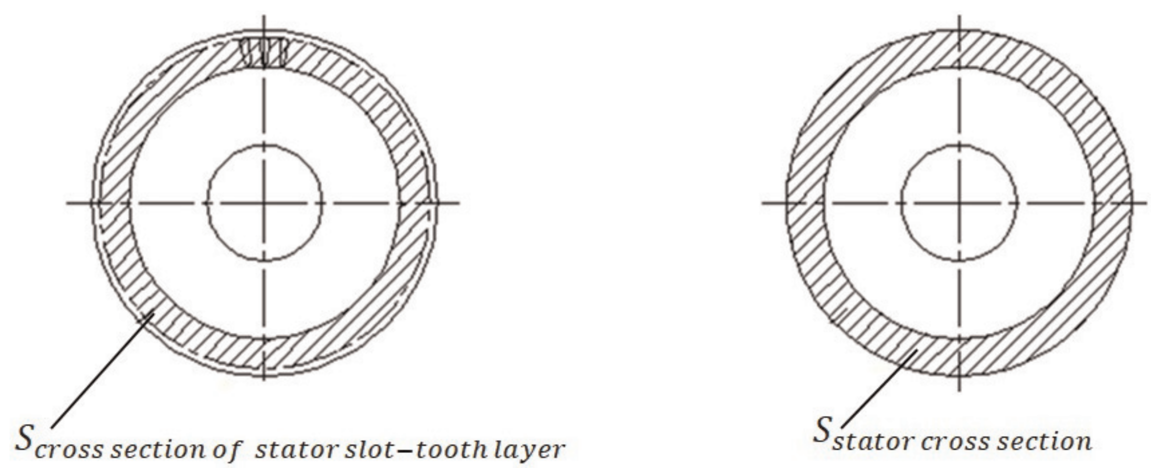

Figure 25.
Variable f_{er}.

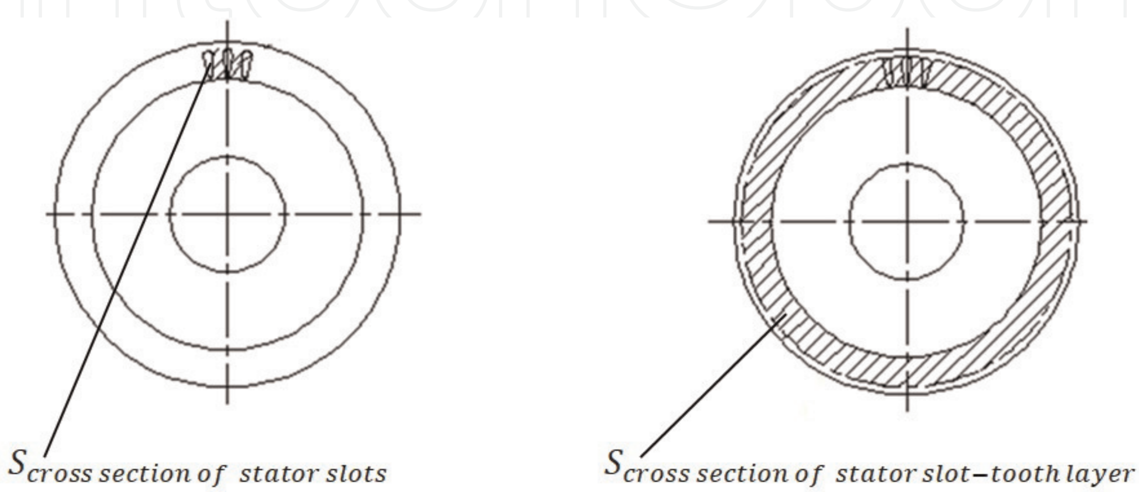

Figure 26.
Variable f_{zr}.

6.4 The determination of the geometry of DFIA using generalized variables

The above six generalized variables allow us to accurately calculate the basic dimensions of the magnetic circuit of the DFIA but for the product of this calculation it is necessary to set the initial parameter from which the further calculation will be made. As this parameter, it is most convenient to take the outer diameter of the stator of the electric machine, since most often this parameter is set by the terms of reference.

Taking as the initial parameter the outer diameter of the stator of the electric machine simple mathematical transformations allow from expressions (10),(11), (12), (13), (14), (15), print the equations that determine the basic geometric dimensions of the magnetic circuit of the double-feed machine (see **Figure 27**):

1. Variable f_s allows determining the diameter of the hole in the rotor (16):

$$Din = Dout \times \sqrt{1 - f_s}, \tag{16}$$

where *Dout* is the outer diameter of the stator;

2. Variable f_a allows determining the diameter of the rotor Da (17):

$$Da = Dout \times \sqrt{1 - f_s + f_a \times f_s}; \tag{17}$$

3. The variable f_{er} allows determining the height of the groove of the rotor h_{zr} (18):

$$h_{zr} = 0.5 \times Dout \times \left(\sqrt{1 - f_s + f_a \times f_s} - \sqrt{1 - f_s + f_a \times f_{er} + f_a \times f_s}\right.; \tag{18}$$

4. The variable f_{zr} allows defining the width of the groove of the rotorb_{zr} (19):

$$b_{zr} = \frac{\pi \times Dout \times f_{zr}}{2 \times z_p} * \left(\sqrt{1 - f_s + f_a \times f_s} + \sqrt{1 - f_s + f_a \times f_{er} + f_a \times f_s}\right., \tag{19}$$

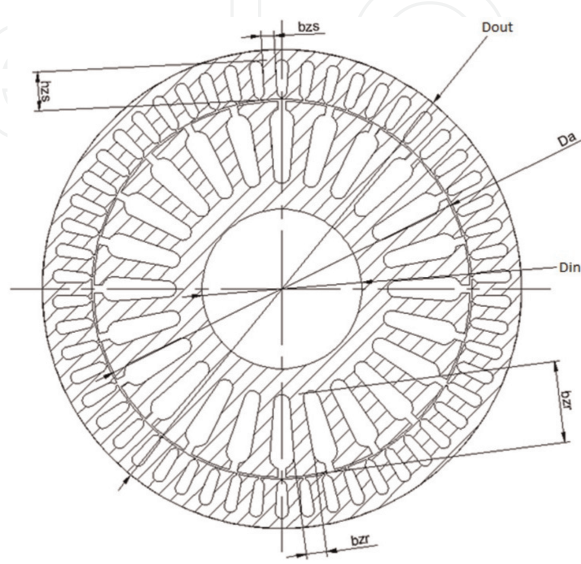

Figure 27.
Cross-sectional sketch of DFIA.

where z_p is the number of rotor slots;

5. The variable f_{es} allows determining the height of the stator slot h_{zs} (20):

$$h_{zs} = 0.5 \times \left(\sqrt{f_{es} \times Dout^2 - (Da + 2 \times \delta)^2 \times \left(f_{es} + 1\right)} - Da - 2 \times \delta, \qquad (20)$$

where δ is the air gap;

6. The variable f_{zs} allows determining the width of the stator groove b_{zs} (21):

$$b_{zs} = \frac{f_{zs} \times f_{es} \times \pi \times \left(Dout^2 - (Da + 2 \times \delta)^2\right)}{4 \times z_s \times h_{zs}}, \qquad (21)$$

where z_s is number of stator slots.

Thus, for a known outer diameter and given generalized variables defined by expressions (10–15), the transverse geometry of DFIA can be uniquely determined. On the basis of the accepted variables, a mathematical model of the generator was developed, which was used to optimize the geometry of a number of wind power plants based on DFIA. As a block optimizer used an algorithm that combines the method of coordinate-wise descent Gauss-Seidel with the Fibonacci method.

The main advantage of the generalized variables is their visibility, due to the fact that they have a clear physical meaning and can independently act as criteria for the quality of the electric machine. The second advantage is that the generalized variables have a fixed range of changes [0;1], which allows to apply optimization algorithms to the mathematical model [5, 18], built on the basis of these variables.

On the basis of this technique and with the use of the algorithm, DFIA with output power of 10 kV, line voltage 380 V and synchronous speed of 50 rpm with the required optimality criteria—maximum efficiency and minimum weight—was calculated . The calculation time of the program written in Delphi for six independent generalized variables was about 30 seconds, which is quite acceptable.

7. Analysis of the results of geometry optimization

At the stage of DFIA synthesis the method of substitution schemes was used, which contains equations in integral form. This is due to the fact that a simplified calculation model is required for optimization. This model should allow the calculation of a large number of options to select the best option.

A thorough analysis of the results after optimization is required. This analysis should use accurate methods. The finite element method is such an accurate method [2–4, 8–18, 23].

The software package Ansys Electronics Desktop allows you to perform analysis of electromagnetic and fields in an electric machine. The application of the program for the analysis of DFIA is shown below.

The data of alternator is:

Rated output power, (kW)	10
Rated voltage, (V)	380
Frequency, (Hz)	50
Rated speed, (RPM)	60

DOI: http://dx.doi.org/10.5772/intechopen.89255

Mass, (kg)	1200
Outline sizes (mm*mm)	1260*320

The calculation in Maxwell Ansys can be divided into three stages:

1. Analysis of the model using the RMxprt;

2. Analysis of the model using Maxwell2D on the basis of already created models in RMxprt;

3. Analysis of the model using the Maxwell3D on the basis of the model created in RMxprt.

The program Ansys Electronics Desktop has a very developed interface. This makes it easier to use.

At the first stage, when working with RMxprt, it is enough to fill in special forms. They include geometrical dimensions, winding data and nominal parameters of the machine. The mathematical model of calculation is made on the basis of a method of schemes of substitution therefore are carried out within 1 min. The program calculates all the necessary parameters and characteristics.

At the second stage, the program automatically creates a 2D model of the generator, splits it into finite elements, sets the boundary conditions and current loads. To simplify the calculations, the program determines the axial symmetry and solves the problem of calculating the field taking into account the periodicity condition. The resulting characteristics are obtained by multiplying the results by the number of symmetric fragments.

To test the generator, the following numerical experiment was carried out: the different rotation frequency of the generator shaft (0, 10, 60 and 100) rpm was set.

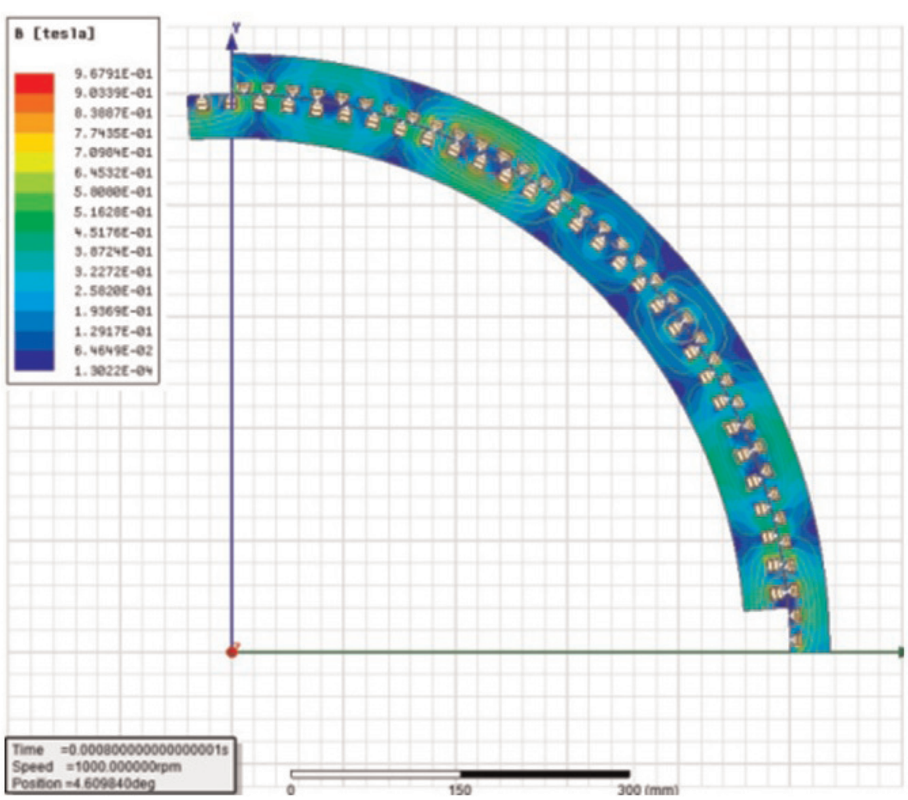

Figure 28.
The analysis of the magnetic field at frequency of rotation of 10 rpm.

For these speeds, the frequency of the excitation winding supply and the current in the excitation winding were selected so that the nominal voltage was obtained at the generator output.

The results of the analysis are presented below (**Figures 28–31**).

Tables 2 and **3** show the main electrical parameters of the generator obtained experimentally.

The results of the numerical experiment show that the output voltage and power have stable values when the rotation frequency of the generator shaft changes from a braked state to 10 RPM. It is very important for wind turbines.

Thus, the main problem of wind power to obtain standard parameters of electricity at different wind speeds is solved through the use of DFIA.

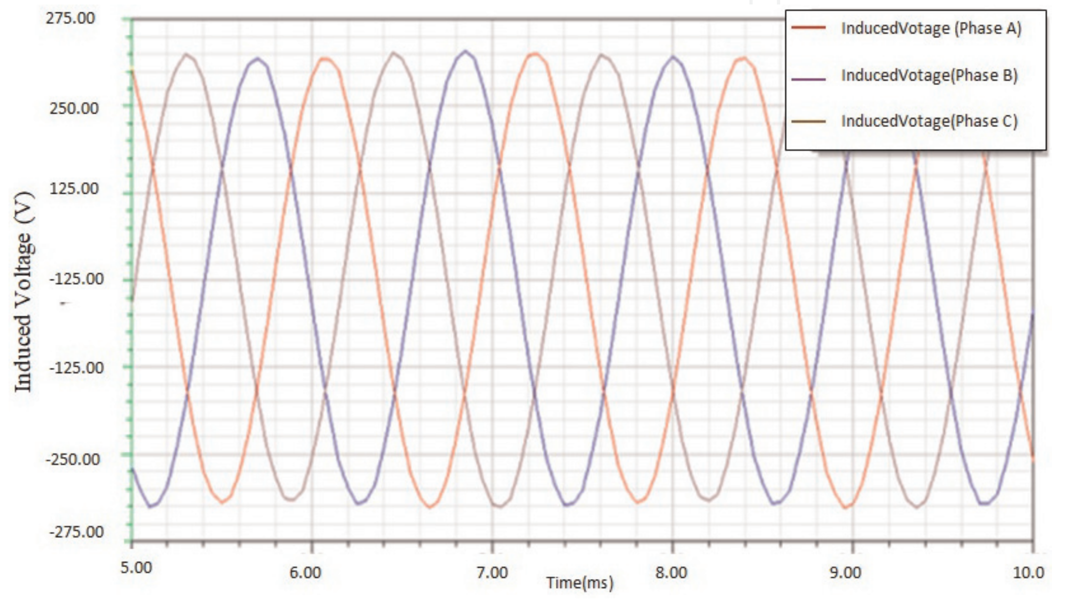

Figure 29.
EMF of anchor winding (10 rpm).

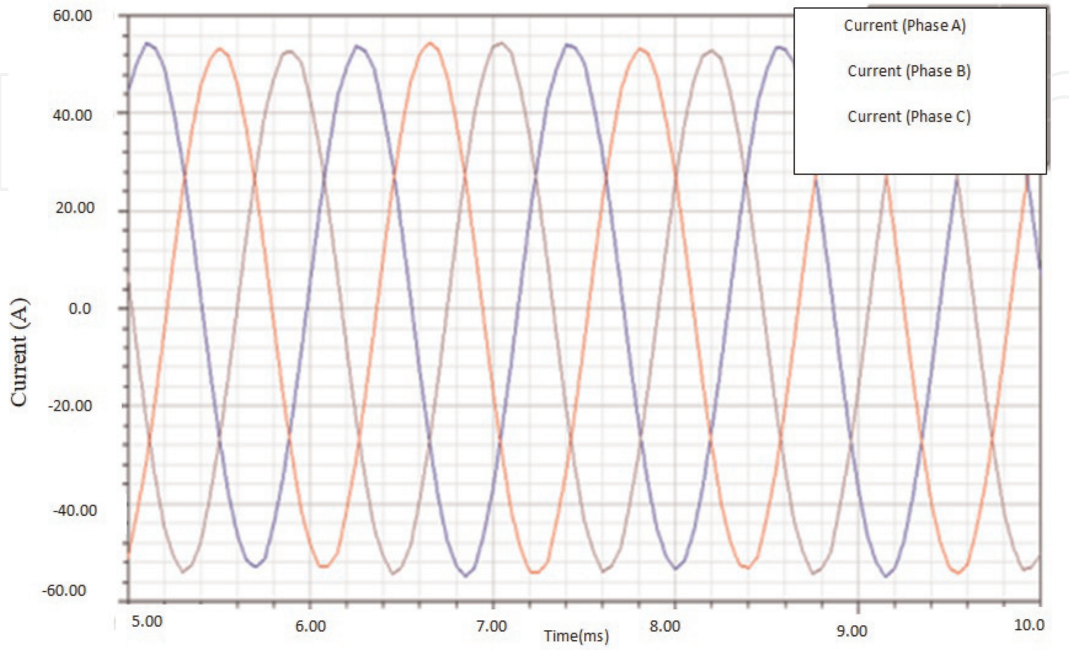

Figure 30.
Anchor currents (10 rpm).

DOI: http://dx.doi.org/10.5772/intechopen.89255

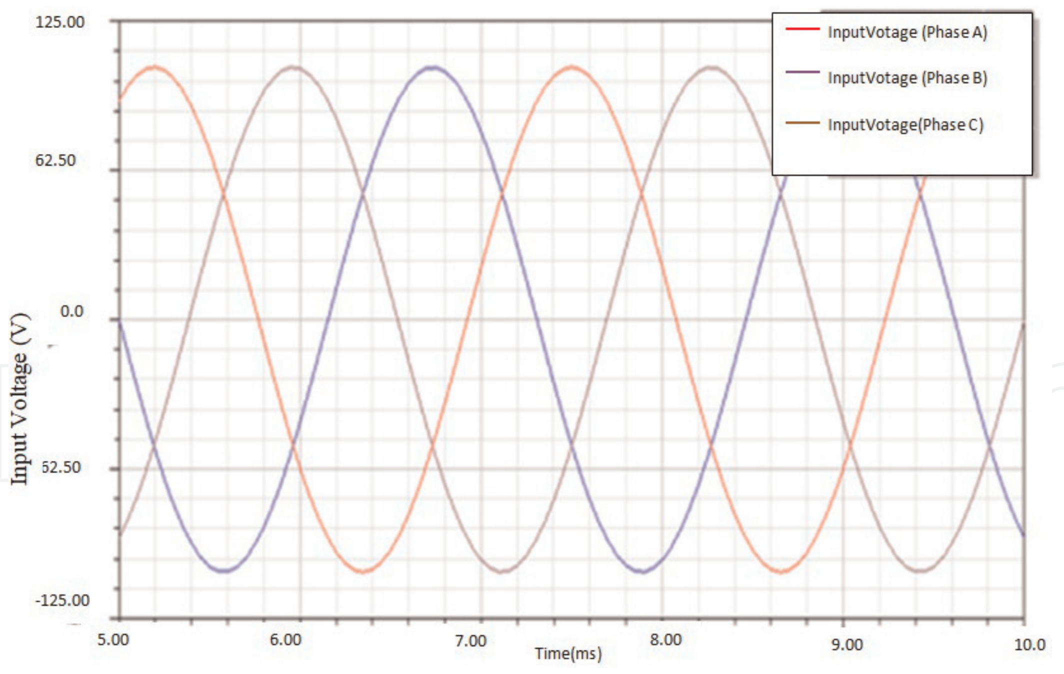

Figure 31.
The voltage of the exitating winding (10 rpm).

Rotational speed, rpm	Stator voltage (RMS), V	Load current (RMS), A	Excitation winding voltage (RMS), V	Excitation winding current(RMS), A
0	236	15.05	148.0	26.3
10	235	14.95	137.0	26.25
60	232	14.43	74.5	26.0
100	233	14.59	2.8	31.85

Table 2.
Generator voltages and currents depending on speed.

Rotational speed, rpm	Output power, kW	Excitation power, kW	Mechanical power on shaft, kW	Total power, kW	Efficiency
0	10.65	11.67	0.00	11.54	0.912
10	10.54	10.78	0.55	21.03	0.93
60	10.05	5.81	4.55	19.72	0.97
100	10.20	0.267	10.03	19.41	0.99

Table 3.
Generator p depending on speed.

8. The solving of the problem of an accumulation with using the concept of DFIA

Wind power plants must be highly reliable. This is due to the fact that the generator is located at high altitude, works in different climatic zones, and it is very difficult to carry out repair work in these conditions.

This requirement makes the supply of electricity to the rotor without sliding contact.

In the proposed generator, a second built-in electric machine is used to solve this problem.

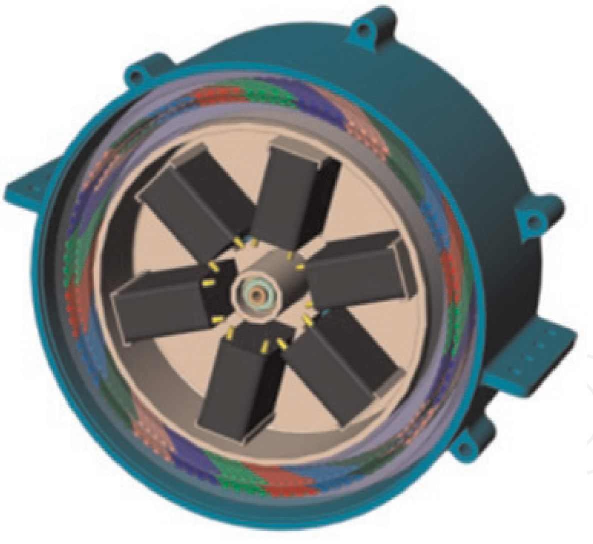

Figure 32.
DFIA design with built-in rechargeable batteries.

But it is possible to apply another technical solution. Batteries can be used to power the electrical circuits of the rotor if placed on a rotating part (**Figure 32**). In this case, the exiting alternator can be excluded. The battery pack will additionally function as a storage device [4].

In practice it is impossible to use windmills without energy storage devices. It is necessary for us to have a stable energy supply but wind has unstable action.

Nowadays the storage batteries are the acceptable energy storage devices taking in consideration the reliability and cost. The double-fed alternator allows combining two concepts (creating the standard energy and storage energy) at one device. In sketch, it is possible to see that the rotor has enough place for allocation the batteries (**Figure 32**).

These batteries can solve two problems. They are:

- The electric energy storage.
- The supplying the electric energy to electronic control system. This solution allows extending the limits of the windmill working operation. Indeed, for short time, it is possible to use windmill with fixed rotor when we have no wind.

9. Conclusion

Nowadays the development of windmill industry is holding back by one serious problem. It is very difficult to transform with high efficiency the nonstandard energy to the standard energy. The using of the induction alternators or the synchronous alternators cannot solve this problem with good results. As a rule in this case we have low efficiency, complex design and high total cost. The problem is becoming more difficult when you make attempt to build the row of windmills from small power to big power (10 kW–1 MW). The concept of the DFIA proves to be very effective for solving windmills problems. It is possible to transform the nonstandard energy in to the standard energy with high efficiency. Windmills may operate as stand-alone or grid tied. It is possible to build the row of windmills with the same design. But the main reason of the application the DFIA is the low total cost of windmill and electronic control system. The new design of this concept is presented. The concept is confirmed by the complex engineering calculations and the manufacturing of the prototypes.

This concept can be used for design of windmill row with output power up to 1 MW.

Author details

Sergey Gandzha* and Anton Kotov
South Ural State University, Chelyabinsk, Russia

*Address all correspondence to: gandja_sa@mail.ru

References

[1] Altshuller GS. Find an Idea. 3-e Izd., EXT. Petrozavodsk: Scandinavia; 2003. (in Russian)

[2] Gandzha S, Aminov D, Kosimov B. Application of digital twins Technology for Analysis of brushless electric machines with axial magnetic flux. Proceedings-2018. Global Smart Industry Conference CloSIC. 2018

[3] Gandzha S, Aminov D, Kosimov B. Design of Brushless Electric Machine with axial magnetic flux based on the use of Nomograms. In: Proceedings - 2018 International Ural Conference on Green Energy. UralCon; 2018

[4] Gandzha S, Belonozhko A. Development of electrical energy storage device using direct-acting fuel cells based on methanol. In: Proceedings - 2018 International Ural Conference on Green Energy. UralCon; 2018

[5] Stemmler H, Omlin A. Converter controlled fixed-frequency variable-speed motor/alternator. Presented at the IPEC '95, Japan; 1995

[6] Bogalecka E. Dynamics of the power control of double fed induction alternator connected to the soft grid. In: Proc. IEEE Int. Symp. Ind. Electron. Budapest; 1993. pp. 509-513

[7] Lauw HK, Weigand CH, Marckx DA. Variable-Speed Wind System Design: Final Report. Washington, DC, Rep. DOE/BP/99893-TI: U.S. Dept. of Energy; 1993

[8] Gandzha S, Kiessh I, Aminov D. Development of engineering technique for calculating magnet systems with permanent magnets. In: Proceedings - 2018 International Conference on Industrial Engineering, Applications and Manufacturing. ICIEAM; 2018

[9] Gandzha S, Kiessh I. Selection of winding commutation for axial gap machines with any phases. In: Proceedings - 2018 International Conference on Industrial Engineering, Applications and Manufacturing. ICIEAM; 2018

[10] Gandzha S, Andrey S, Andrey M, Kiessh I. The design of the low-speed brushless motor for the winch which operates in see-water. In: International Multidisciplinary Scientific GeoConference Surveying Geology and Mining Ecology Management. SGEM; 2017

[11] Gandzha S, Kiessh I. The high-speed axial gap electric alternator is the best solution for a gas turbine engine. In: International Multidisciplinary Scientific GeoConference Surveying Geology and Mining Ecology Management. SGEM; 2017

[12] Gandzha S. The application of the double-fed alternator for the solving of the wind power problems. In: International Multidisciplinary Scientific GeoConference Surveying Geology and Mining Ecology Management. SGEM; 2017

[13] Gandzha SA, Sogrin AI, Kiessh IE. The comparative analysis of permanent magnet electric machines with integer and fractional number of slots per pole and phase. Procedia Engineering. 2015; **129**:408-414

[14] Gandzha SA, Kiessh IE. Application brushless machines with combine excitation for a small and medium power windmills. Procedia Engineering. 2015;**129**:191-194

[15] Gandzha S, Kiesh I. A proposal of doubly-fed alternator for windmill application. In: 2016 2nd International Conference on Industrial Engineering. Applications and Manufacturing (ICIEAM). IEEE Conferences; 2016. pp. 1-3

[16] Gandzha SA, Kiessh IE. Varible speed power. Procedia Engineering. 2015;**129**:731-735

[17] Gandzha SA, Sogrin AI, Kiessh IE. The comparative analysis of permanent magnet electric machines with integer and fractional number of slots per pole and phase. Procedia Engineering. 2015; **129**:408-414

[18] Gandzha SA. Modelling of permanent magnet direct current motor with electromagnetic reduction. In: Gandzha SA, editor. Collection of Papers of Software Users Sixth Conference CAD_FEMGmbH (20–21 April 2006). Moscow; 2006. pp. 358-360

[19] Kurochka AL. Synthesis of optimal machines of direct and pulsating current on the basis of aggregated variables. In: Kurochka AL, editor. Electromechanics. Vol. 6. Izv. Higher. Educational Institution; 1976. pp. 608-617. (in Russian)

[20] Botvinnik MM. Asynchronous Synchronous Machine. Moscow, Leningrad: Gosenergoizdat; 1960. 70 p. (in Russian)

[21] Slezhanovsky OV. In: Slezhanovsky OV, Dackowski LH, Kuznetsov IS, et al., editors. Systems of Subordinate Regulation AC Motor Drive with Brushless DC Converters. Moscow: Energoatomizdat; 1983. (in Russian)

[22] Herman-Galkin SG. Virtual Laboratories of Semiconductor Systems in Mathlab-Simulink Environment: Textbook. LAN Publishing House; 2013. 448 p. (in Russian)

[23] Cingoski V, Murakawa R, Kaneda K, Yamashita H. Automatic mesh generation in finite element analysis using dynamic bubble system. Jornal of Applied Physics. 1997;**81**(8 Pt 2): 4085-4087