SWITCHED RELUCTANCE MOTOR WIND GENERATOR SYSTEM

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Abstract: *The work is devoted to the development of a control system for a wind generator with the use of a switched reluctance motor. The search for new structures for the construction of the power unit and control system of electromechanical systems of wind power complexes is an urgent task of today. The most common construction options for such systems include double-fed induction motors and permanent magnet synchronous generators. In the first case there is no possibility of full control of the flow of power transmitted to the network, and in the second case the main disadvantage is the high cost of such an electric machine, which is explained by the use of rare earth materials in its design. The use of a switched reluctance motor as a generator has significant differences compared to similar use of electric machines based on torque generation due to the Lorentz force. A mathematical model of the electromechanical system of a wind generator with a switched reluctance motor in the Matlab / Simulink environment was developed. It was shown by mathematical modeling that when changing the sign of load torque, the machine does not go into braking mode independently, as is the case with other electric machines. This creates considerable difficulties in the operation of such a system, since the transition to brake mode requires a change in control effects on the switched reluctance motor. Features of functioning of the switched reluctance motor in the mode of regenerative braking have been stated. The limits of change of control angles which allow to receive the maximum amount of the generated electric energy and reduction of pulsations of brake torque of the machine have been defined. The structure of the control system of a switched reluctance motor has been developed, which involves the use of a modified speed controller, which divides its output signal into a sign function, which is subsequently used to select the converter control angles, as well as the absolute value used in the operation of the modulation algorithm of the required current magnitude .*

Keywords: *switched reluctance motor; wind generator; current control; control system; electromechanical system; transient process*

Introduction. Formulation of research objectives. The development of technologies has helped to reduce the cost of developing and implementing wind turbines, which has created conditions for making this area more competitive with respect to the use of fossil fuels. Offshore wind energy is currently more competitive per kilowatt compared to new coal / gas plants across most of the EU, Australia, Brazil, Chile, Mexico, New Zealand, also in some Indian and US territories. This trend results in a high proportion of energy generated by wind installations (> 30%) that are integrated into the grid. At the same time, the main tasks and problems that need to be addressed relate to the efficient and reliable use of the existing grid, provided that it is integrated into its structure of renewable energy sources. As wind energy increases, the structure and dynamics of the grid will change significantly in the coming decades. At the same time, the structure of wind turbines is also undergoing significant development as new types of electric machines emerge, with some advantages over existing ones. Typical wind turbines include the use of double-fed induction machines or permanent magnet synchronous machines. The paper proposes to consider the structure and principle of control of an electromechanical system of a wind turbine with switched reluctance motors.

The purpose of this work is to investigate ways of constructing the structure of a control system for a switched reluctance motor in the structure of a wind generator and to study the means of optimal calculation of control angles in order to obtain the maximum amount of electrical energy.

To achieve this goal in the work, we must solve the following tasks:

- to analyze the mathematical description of the switched reluctance motor in order to obtain an analytical relationship between its state variables and the input electrical power;

- to develop a mathematical model of a switched reluctance motor that would allow to study energy performance in the motor and generator mode of operation;

- synthesize an approach to the optimum choice of converter control angles in order to maximize the amount of electricity received.

Analysis of existing structures of wind turbines. Recent trends indicate that wind energy will play an important role in meeting future energy needs in order to reduce dependency on produced fuels and minimize the adverse effects of climate

change. The use of wind energy is the technology that is most actively developed among renewable energy technologies. In the last two decades, wind energy use has been the most promising renewable energy technology through the development of wind turbines, aerodynamics, variable speed generators, power electronics, and microprocessor technology used in control.

Fig. 1 presents a structure of a wind turbine for a constant speed that uses an induction generator with a squirrel-cage rotor connected directly to the grid through a matching transformer. Capacitors are needed to compensate for the reactive power consumed by the induction

generator. The main disadvantages of using induction generators with a constant speed of rotation are the consumption of reactive power, considerable mechanical loads and poor quality of the generated electricity. In a wind turbine with a constant speed of rotation, fluctuations in wind speed lead to mechanical torque oscillations and lead to fluctuations in electrical power. Thus, power fluctuation data can lead to significant voltage fluctuations in a weak power system. This system does not provide any speed stabilization, it requires considerable power to the power supply, and its mechanical design must be able to withstand high mechanical loads.
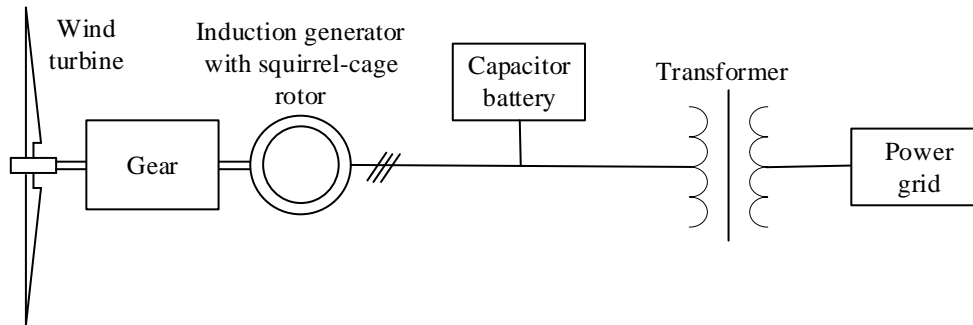

Figure 1. Structure of a wind generator with a constant speed

Currently, wind turbine structures with variable speed are quite popular due to their numerous advantages such as: increasing the amount of electricity generated, maximizing power output, improving efficiency and improving the quality of electricity. Most modern installed

turbines use a double-fed induction generator as a variable-speed wind turbine using a gearbox, as shown in Fig. 2. The advantage of this technology is that a reduced power converter (30% of full power) can be connected to the rotor circuit instead of the stator circuit.
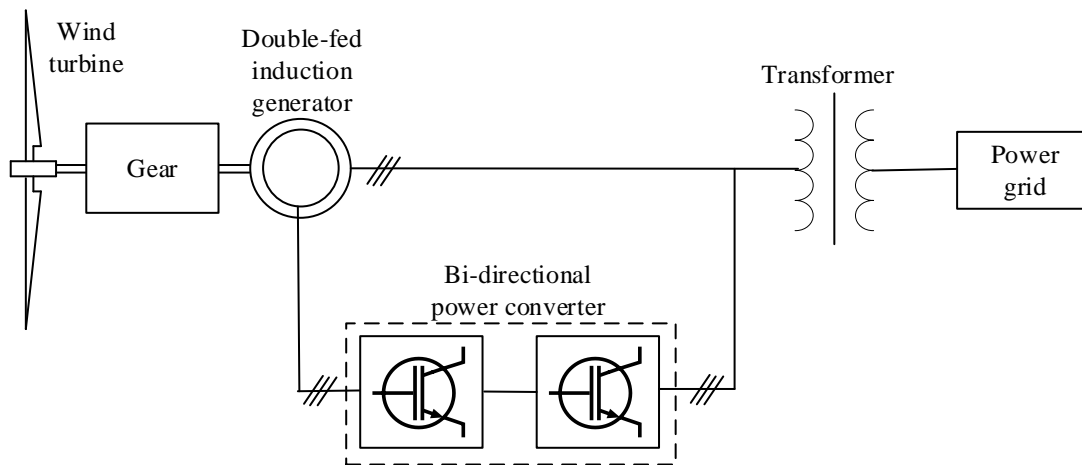

Fig. 2. Structure of variable speed wind turbine based on double-fed induction machine

In this configuration, the stator is directly connected to the power grid and the rotor is

connected to it through a semiconductor converter to control the rotor speed and electrical frequency.

Depending on the size of the frequency converter (which is typically rated at 30% of the rated power of the generator), this circuit is capable of operating over a wide range of speeds. As a rule, the angular velocity range is ± 30% of the synchronous speed, which makes this concept attractive and economically popular. When the generator is operating at supersynchronous speed, electrical power is transmitted to the power grid through the stator and rotor. When the generator is running at sub-synchronous speed, electricity is transferred to the rotor from the grid.

Consider a gearless wind turbine based on a permanent magnet synchronous generator with variable speed. In this configuration, the generator's rotor is directly connected to the turbine's rotor without the use of gearbox, and the generator is connected to the power grid / load via a power converter that is rated at full power, as shown in Fig. 3.
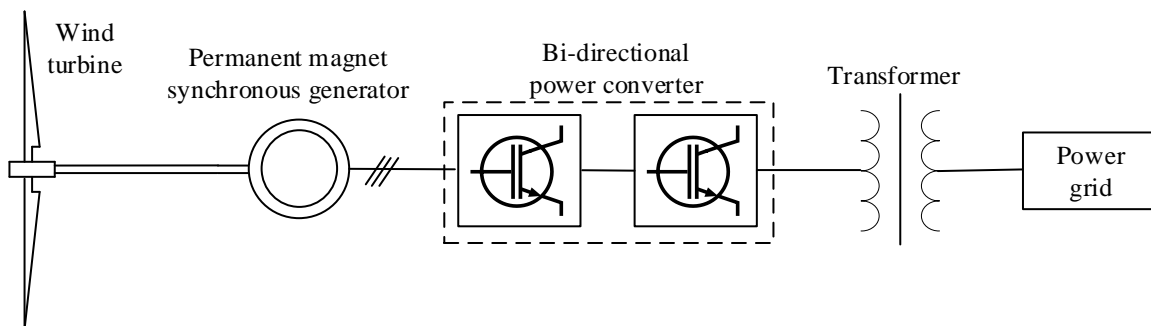

Fig. 3. Direct-drive gearless generator based on permanent magnet synchronous generator

This configuration is most suitable for full power control since it connects to the power grid through a power converter. The permanent magnet synchronous generator used in this scheme is a low-speed generator with a corresponding number of pole pairs capable of producing high torque at low speed. The power converter is designed for the full power of the generator and can transmit power to the electrical power grid throughout the speed range. The power semiconductor converter used in this scheme has two main tasks: to operate as an energy buffer (DC link) for power fluctuations caused by the wind installation, and to smooth transients coming from the power grid. This structure enables the synthesis of active and reactive power control systems.

The main properties of wind turbines based on a permanent magnet synchronous generator:
• gearless operation and increased reliability;
• simple structure, smaller size and cost;
• low mechanical and electrical losses;
• higher power factor and efficiency;
• absence of any requirements for the supply of reactive power;
• higher cost and higher power converter losses;
• there is no need for any external excitation.

This type of wind turbine has better reliability than the system based on double-fed induction generator, has better efficiency and is simpler. At the same time, the requirements for generating reactive power can be met by appropriate control of the power converter, both for the double-fed induction generator and for the direct drive wind turbine with the full-rated power converter.

As already mentioned, the most popular types of electric machines used in the structure of wind turbines are double-fed induction machines and permanent magnet synchronous generators. However, switched reluctance motor can also be considered as a good alternative because they have high energy efficiency when changing angular speed over a wide range. However, it is important to note the significant advantages of such a generator, which are the majority of mechanical strength and reliability, high efficiency, low cost of manufacture due to the absence of permanent magnets in the structure of the machine. The disadvantages of such a system can be attributed to the presence of torque oscillations, acoustic noise, the need to install a position sensor, as well as the development of a system that is able to provide high efficiency and reliability of the wind generator in a wide range of changes in its angular speed. This is the solution to the last question.

Synthesis of mathematical model of electromechanical system with switched reluctance motor. The difficulty of solving this question is that the switched reluctance motor is a significantly nonlinear object, and therefore it is impossible to obtain an analytical equation that would link the power generated by the machine to the parameters of motion of the mechanical part, as well as the signals of the control system.

In [5], mathematical modeling was performed using a number of design parameters of the generator and control system signals to determine the output power. The authors formulated requirements for the operation of the maximum power tracking system, which allows optimizing the operation of the generator.

In [6] authors investigated the influence of control angles in order to stabilize the voltage in the DC link of the converter. An algorithm for optimizing generator power when operating at high angular speeds is presented in [7]. In [8], a study of this question was performed when the voltage in the DC link was changed. Changes in efficiency, copper losses of the machine and generator power output are presented.

The system of optimization of operation of the switched reluctance generator at low and high speeds, which allows to obtain angles of turning on and off the phases of the machine, was presented in [9, 10]. However, the practical implementation of such an algorithm requires the presence of a very powerful digital signal processor in the control system structure to determine the on and off angles in real time. However, the study of generator efficiency at variable wind speed has not been addressed in this paper.

In [11] authors presents a system for controlling the power of a switched reluctance generator at low speeds by changing the values of control angles.

All of the presented research combines the fact that the switched reluctance machine in them is considered as a source of alternating voltage with constant amplitude without taking into account the influence of the characteristics of the wind generator and changes in wind speed. It is known that for each operating wind speed there is a certain maximum value of power that can be obtained by the generator. And that should be a tactic in developing a control system for a switched reluctance machine. Therefore, the task of the control system is to calculate the control angles of the inverter that feeds the machine, both in the case of operation at low and at high angular speed, to maintain its operation at the point of maximum power generated.

A mathematical model in the Matlab / Simulink environment was developed to investigate the modes of regenerative braking of a valve jet engine. The general appearance of the model is presented in Fig. 4.

Its main components are:

• switched reluctance motor - model of switched reluctance motor with 6/4 stator and rotor pole configuration;

• power converter - a subsystem of the power semiconductor converter that feeds the motor (Fig. 5);

• current Reg - motor current control subsystem that controls a semiconductor converter in order to maintain a given current value in the winding of a switched reluctance motor during its active state (Fig. 6);

• CPUg S-Function - a switched reluctance motor control subsystem implemented in the form of an S-file and generates, in accordance with the set angles, the active state signals of the corresponding phase of the engine.
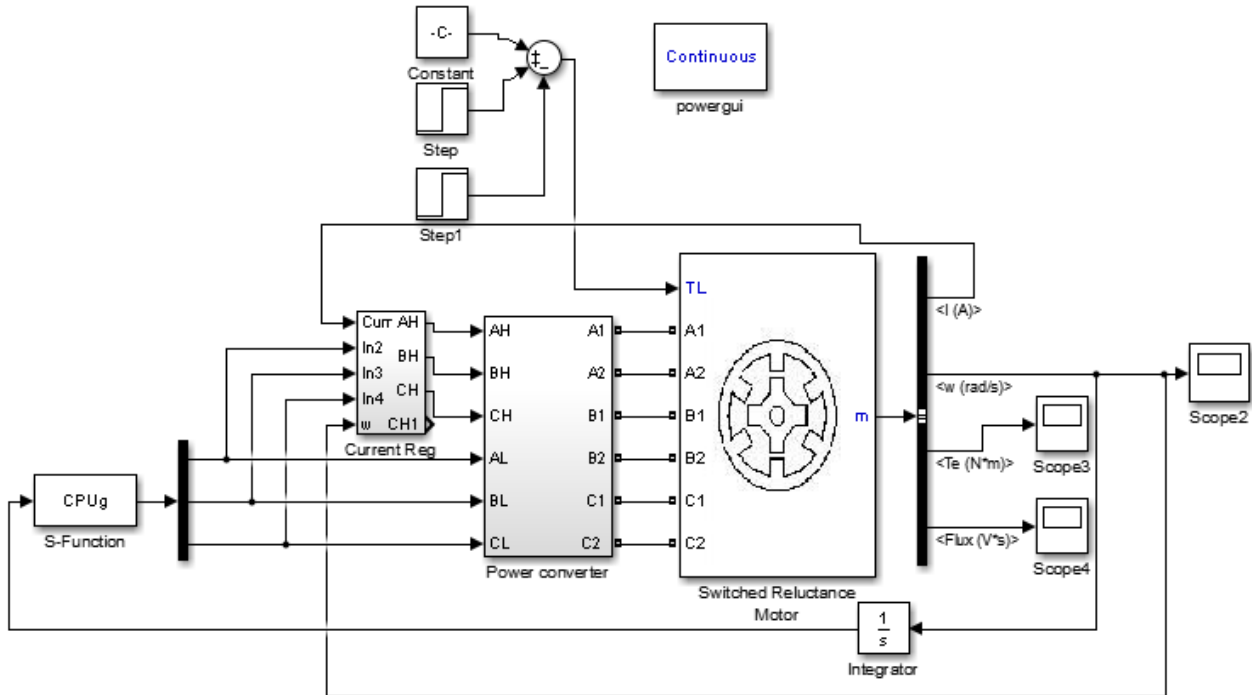
Figure 4. General view of mathematical model of electromechanical system with switched reluctance motor in Matlab / Simulink environment
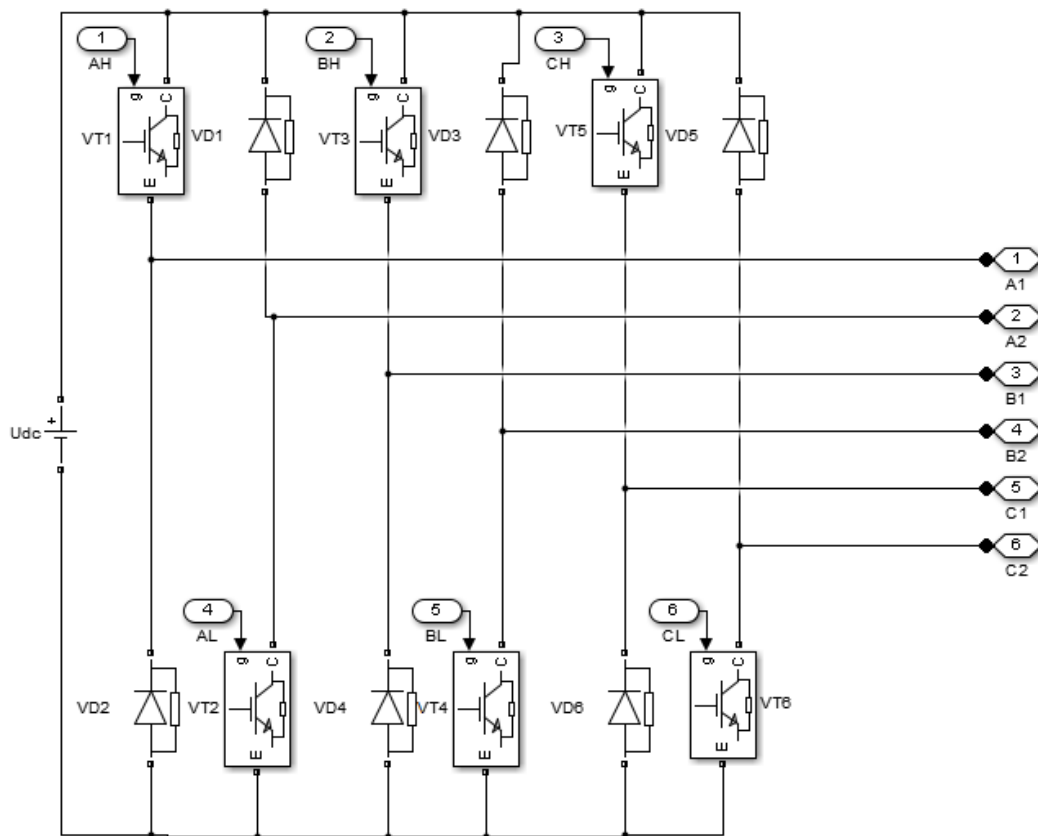

Figure 5. A subsystem of a semiconductor converter for powering a switched reluctance motor
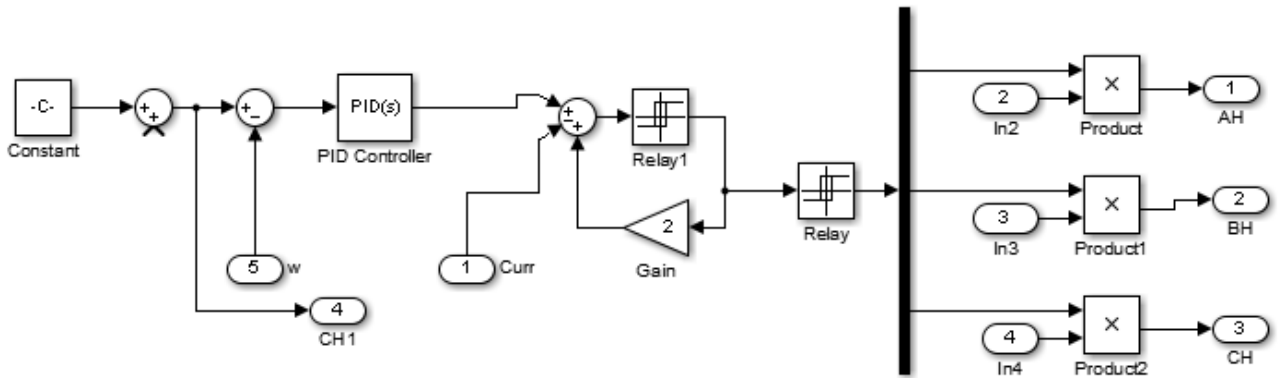
Figure 6. The current control system of the phases of the switched reluctance motor

Investigation of regenerative braking modes when changing control angles. We perform simulation of transition to regenerative braking mode without changing the power parameters. As is known, any electric machine based on the use of Lorentz force is able to enter the mode of regenerative braking automatically when the sign of the load torque is changed due to the fact that the value of the EMF generated by the motor becomes greater than the magnitude of the applied voltage. However, the functioning of the switched reluctance motor is based on other principles,

which leads to differences in the implementation of the transition to brake mode.

The simulation of the motor has been conducted with load increasing at t = 0.25 s and change the sign of the load torque at time t = 0.5 s. As it can be seen from the graphs (Fig. 7), when switching to regenerative braking, the motor speed starts to increase infinitely. This is due to the fact that the torque created by the motor drops to zero, and under the action of dynamic torque created by the load, there is an increase in the speed. Consider the principle of current control of a switched reluctance motor.
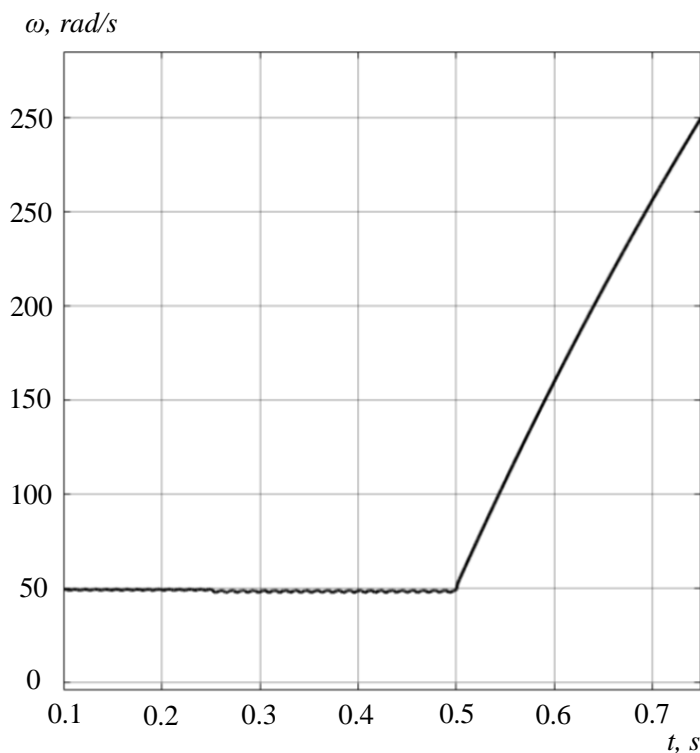

Figure 7. Graph of switched reluctance motor speed at load increasing at t = 0.25 s and change of sign of load torque at time t = 0.5 s
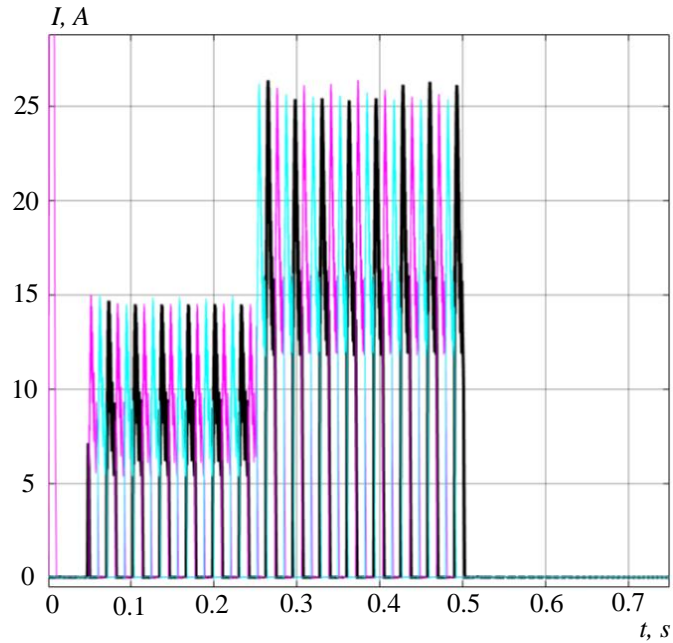
Figure 8. Graph of switched reluctance motor current at load increasing at t = 0.25 s and change of sign of load torque at time t = 0.5 s

From the graph of current (Fig. 8) it is visible that when the torque sign changes, the current in the windings of the switched reluctance motor drops to zero, despite the connection to the windings of the corresponding voltage. At the same time there is a fall of the motor torque to zero (Fig. 9).
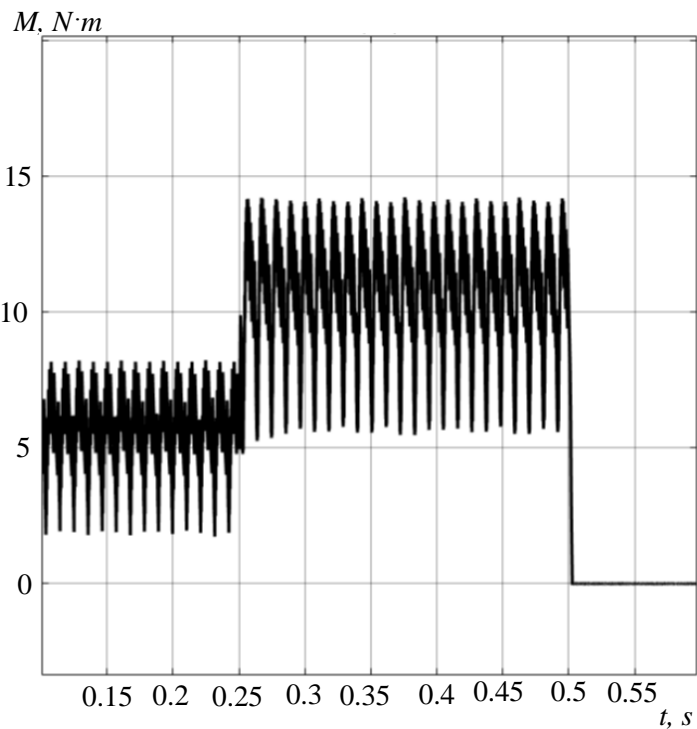

Fig. 9. Graph of switched reluctance motor torque at load increasing at t = 0.25 s and change of sign of load torque at time t = 0.5 s

For the phase of the switched reluctance motor, the equation made by Kirchhoff's second law has the following form [12]:

$$i(\theta_m)R + \frac{d\psi}{dt} = u,$$

де R – active winding resistance, $\psi = f(i, \theta_m)$ – the flux of the winding, which depends on the current flowing through it and the angle of rotation of the rotor by the so-called magnetization curve of the machine.

Consider the processes of energy conversion in switched reluctance motor. In view of such a simple design, it may seem that the processes of torque generation and energy conversion are also quite simple, but unfortunately this is not true. Energy conversion processes are analyzed using a single-phase machine to establish the connection between the power source, the magnetic field energy in the air gap, and the mechanical energy on the shaft of the machine. It is necessary to take into account the saturation of the magnetic system at the desired level. At the same time, losses in copper and steel can be neglected, as they will, although they affect the overall efficiency of energy conversion processes, but do not make a significant impact on the principles of torque generation and energy conversion.

When neglecting losses in copper machines, the previous equation can be written in the following form:

$$\frac{d\psi}{dt} = u.$$

Analyzing the derived equation, we obtain:

$$\frac{d\psi}{dt} = \omega \frac{d\psi}{d\theta} = \omega \frac{d(Li)}{d\theta} = L\frac{di}{dt} + \omega i \frac{dL}{d\theta}.$$

The last component can be referred to as the engine's EPC:

$$e = \omega i \frac{dL}{d\theta}.$$

Multiplying both parts of the equation by Kirchhoff's second law by the amount of current yields instantaneous electrical power at the input of the circuit:

$$ui = i^2R + Li\frac{di}{dt} + \omega i^2 \frac{dL}{d\theta}.$$

The rate of change of energy stored in the machine can be estimated as follows:

$$\frac{dW_m}{dt} = \frac{d}{dt}\left(\frac{Li^2}{2}\right) = \frac{i^2}{2}\frac{dL}{dt} + Li\frac{di}{dt} =$$
$$= \frac{i^2\omega}{2}\frac{dL}{d\theta} + Li\frac{di}{dt}.$$

In accordance with the law of energy conservation, the mechanical power on the motor shaft $M_e\omega$ is equal to the power consumed by the network minus the power losses on the active resistance i^2R and the energy stored in the magnetic system of the machine. So,

$$M_e = \frac{p}{\omega} = \frac{ui - i^2R - \frac{d}{dt}\left(\frac{Li^2}{2}\right)}{\omega} =$$
$$= \frac{(i^2R + Li\frac{di}{dt} + \omega i^2\frac{dL}{d\theta}) - i^2R - (\frac{i^2\omega}{2}\frac{dL}{d\theta} + Li\frac{di}{dt})}{\omega}$$
$$= \frac{i^2}{2}\frac{dL}{d\theta}.$$

Therefore, the switched reluctance motor torque moment is proportional to the square of the current and the rate of change of the inductance profile $\frac{dL}{d\theta}$. From the same equation we can conclude that the torque sign does not depend on the direction of current flow, since the value i^2 is always positive. Nevertheless, a reversal of the winding voltage is still necessary in order to return the coupling level to zero at the end of each pulse. To implement this, a back voltage must be applied to the winding to ensure $d\psi/dt < 0$. Therefore, the possibility of reversing the direction of torque exists if the current is supplied at the stage of reducing the value of inductance.

Let's change the control angles of the switched reluctance motor in the mathematical model under study. To do this, we will make some changes to the structure of the control system (Fig. 10) so that, depending on the output signal of the speed controller, the operating mode of the motor is determined: motor or generator. In the future, the system will use the absolute value of this signal to perform the functions of receiving key control signals in order to modulate the required current value.
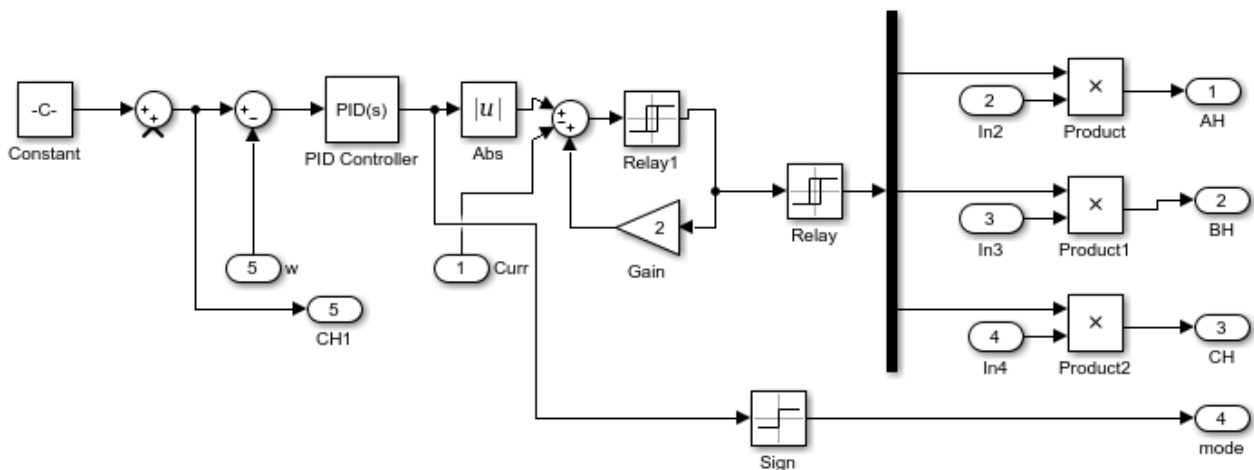
Fig. 10. Modified mathematical model of the current control of a switched reluctance motor

Conclusions. In this work, a theoretical generalization and solution of the actual scientific and technical problem of synthesis of a control system of a switched reluctance motor in the composition of a wind turbine installation has been made.

The most significant scientific and applied results, conclusions and recommendations are as follows:

1. Features of functioning of the switched reluctance motor in the mode of regenerative braking are stated. The limits of change of control angles which allow to receive the maximum amount of the generated electric energy at reduction of pulsations of brake moment of the machine has been defined.

2. The structure of the control system of a switched reluctance motor has been developed, which involves the use of a modified speed controller, which divides its output signal into a sign function, which is subsequently used to select the control angles of the converter, as well as the absolute value used in the operation of the modulation algorithm required magnitudes of current.

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