Control system of mutually coupled switched reluctance motor drive of mining machines in generator mode

A S Ivanov, I Yu Kalanchin and E E Pugacheva

Siberian State Industrial University, 42 Kirova Street, Novokuznetsk, 654007, Russia

E-mail: sibiuprk@gmail.com

Abstract. One of the first electric motors, based on the use of electromagnets, was a reluctance motor in the XIX century. Due to the complexities in the implementation of control system the development of switched reluctance electric machines was repeatedly initiated only in 1960 thanks to the development of computers and power electronic devices. The main feature of these machines is the capacity to work both in engine mode and in generator mode. Thanks to a simple and reliable design in which there is no winding of the rotor, commutator, permanent magnets, a reactive gate-inductor electric drive operating in the engine mode is actively being introduced into various areas such as car industry, production of household appliances, wind power engineering, as well as responsible production processes in the oil and mining industries. However, the existing shortcomings of switched reluctance electric machines, such as non-linear pulsations of electromagnetic moment, the presence of three or four phase supply system and sensor of rotor position prevent wide distribution of this kind of electric machines.

1. Introduction

Switched reluctance machines are one of the most promising types of electrical machines. Because of simple design and low cost they are more often used both in everyday life and in various industries. Noteworthy is the fact that such machines are capable of working both in engine mode and in generator mode. For each mode of operation own control system with a certain algorithm of operation is needed, which mainly depends on the operating angles. Operating are the angles of rotor position relative to the stator, under which either the excitation of the stator coils occurs or their disconnection. To make the control system of the switched reluctance machine work more efficiently, it is necessary to determine with an accuracy at which angle value of the rotor position the induction profile has the maximum and minimum values.

The rotor and stator of a switched reluctance electrical machine are made of electrical steel, and only the stator poles have windings that are placed around the tooth, while the rotor is free of windings, magnets and a brush-collector device [1]. The windings of one stator phase are connected in series and located diametrically opposite each other. There are different configurations of valve inductor-reactive machines. They depend on the number of stator and rotor teeth, they can be 6/4, where 6 is the number of stator poles and 4 rotor poles, and configuration can be 8/6 and 10/8. The appearance of a switched reluctance machine 8/6 is shown in figure 1.
The main advantages of a switched reluctance machine can be attributed to the simplicity of design, since the rotor consists only of electrical steel and the winding of phases are located only on the stator teeth, the absence of expensive rare-earth metals in the structure, operation at high speeds and temperatures and high reliability [2].

However, besides these advantages the switched reluctance machines have a number of serious disadvantages. A three-phase or four-phase power supply system is required depending on the configuration of the electrical machine, providing alternate excitation of the stator windings to create a rotating electromagnetic field. The disadvantages also include non-linear characteristics of these machines, high pulsations of electromagnetic moment and electromagnetic flow.

The principle of mutually coupled switched reluctance machine is based on the fact that ferromagnetic bodies in the external magnetic field are oriented so that the magnetic flux penetrating them is maximized, i.e. when the stator phase is excited, the nearest rotor poles tend to assume an aligned position with respect to the stator poles [3].

When the rotor poles move relative to the excited phases of the stator, the induction profile varies periodically from maximum to minimum. At the agreed position, when the stator pole aligned with the rotor pole, the electromagnetic induction assumes the maximum value, and if the poles are unaligned the induction tends to a minimum. The dependence of the magnitude of induction profile on the rotor position relative to the stator is shown in figure 2 [4].

When excitation of stator windings at the time of mismatching of rotor and stator poles a negative electromagnetic moment is created, which entails the generation of electrical energy in the network. However, a negative electromagnetic moment can also cause the stop of electrical machine; thus, an external source is required to maintain the necessary constant speed for different loads. The functional scheme for controlling the excitation of a switched reluctance generator is shown in figure 3 [5].

Performance of a mutually coupled switched reluctance machine in the generator mode depends on its control strategy, which consists in the correct switching of power electronic devices. It is necessary to determine carefully the excitation angles to ensure continuous operation of the generator and to maximize its efficiency. It should be noted that with increasing excitation current, the output power will increase comparable to the speed increase. Consequently, the value of the output power will depend both on the angular speed and on excitation voltage.
However, because of the nonlinear characteristics of mutually coupled switched reluctance machines, it is difficult to determine the optimal control system [4]. The most effective way is to determine the optimal angles of the rotor poles relative to the stator poles for windings excitation, which allows the pulsations of the electromagnetic moment to be reduced and the energy efficiency of the switched reluctance generator to be increase. Currently, there are various combinations of excitation angles that can produce the maximum output power.

The control strategy, based on the determination of excitation angles, can be divided into three groups:

- fixed angles of switching on and switching off;
- fixed angles of switching on and varying angles of switching off (and vice versa);
- varying angles of both switching on and off.

Input values of the controller are current, voltage, as well as the angle of rotor position. The output signals from the programmable logic controller are transmitted to the predetermined angles of position rotor to the voltage converter for switching on and switching off the excitation circuit.

2. Methods of research

Rapidly developing information technologies alongside with digital computing allow complex mathematical problems to be solved, as well as physical and mathematical modeling to be performed. At present, numerical methods for modeling electromagnetic fields are widely used. These methods are based on spatial and spatial-temporal discretization. Their main advantage is sufficiently accurate results obtained taking into account the properties of materials and the geometric shape of the bodies [6]. The main requirement of the numerical method is the statement of boundary conditions of the calculated domains.

To study electromagnetic fields of mutually coupled switched reluctance generator FEMM program is used, since it is freely distributed and has a fairly convenient interface.

FEMM is a complex of programs designed to solve low-frequency electromagnetic problems in a two-dimensional plane. At the moment, this program is focused on solving linear and nonlinear magnetostatic problems, linear electrostatic problems, as well as static heating problems. FEMM includes three parts that make up this software:

- Interactive shell (FEMM.EXE). It consists of a 2D design system in which the investigated object is constructed, for each element of which certain material properties and boundary states are assigned. In 2D design environment, DXF files built in programs such as AutoCAD or KOMPAS 3D can be imported. The results of solutions can be reflected in the form of contours and density plots. The program also allows the field in its various points to be explored by the user, as well as the values of physical quantities of interest to be determined.
- The next component of the software (TRIANGLE.EXE) allows the solution area you to be discredited into the set of triangles required for the solution with the help of finite element method.
- The main part of this complex is solvers (FKERN.EXE) for magnetic; (BELASOLV.EXE) for electrostatic tasks. Each of the solvers uses a set of files that describes the problem

![Control system of excitation of a mutually coupled switched reluctance generator.](image)

Figure 3. Control system of excitation of a mutually coupled switched reluctance generator.
under investigation and produces a solution of partial differential equations preliminarily divided into domains (triangles) in order to obtain the necessary values within the solution domain of investigated field.

To study the electromagnetic field of a switched reluctance generator using CAD KOMPAS 3D, a model of mutually coupled switched reluctance machine with 8 stator poles and 6 rotor poles is created having the following main parameters: stator diameter 174 mm, stator pole height 23 mm, rotor pole height 16 mm and air gap 0.5 mm. Next, the model is imported into FEMM environment in DXF format, previously specifying the solution of magnetic problem. After that, assign materials for each element of the model, as well as determine the stator coils to which the current will be fed. The contours of the figures should be closed, otherwise the calculation will be unreliable [7].

Figure 4. Screenshot of the FEMM interface.

Figure 1 shows FEMM interface, where the solution sequence of electromagnetic problem can be seen. First, the profile of the object under investigation is constructed, then the solution domain is discretized. After the solution is completed, magnetic flux lines are constructed, as well as the density of its distribution, sections with large density values have a darker color. Besides, it is possible to determine the values of flux linkage, magnetic flux, magnetic field induction and also the electromagnetic moment. To determine the working angles, it is necessary for different rotor positions relative to the stator, and also for different current values, to obtain the values of flux linkage for the constructed model [8].

Figure 5. Magnetization curve.
In figure 5 it can be seen that the flux linkage values depend on the rotor position relative to the stator. When the rotor pole and the stator pole are aligned the maximum induction value is observed (figure 6) [9]. When operating in the generator mode, the excitation of stator phase must be performed at the moment when the rotor pole moves past the stator tooth, i.e. at 6°-15° from the aligned rotor position. When the machine is operating in engine mode, excitation occurs at the minimum induction value, while the stator and rotor poles are in unaligned position, i.e. with rotor position 25°-36°.

Thus, the software for solution of electromagnetic problems using the finite element method allows us to determine the main characteristics of the examined machine at the modeling stage without creating a prototype. Due to the complex of programs Finite Element Methods Magnetics the sections of rotor position were determined in which the magnetic circuit has the maximum and minimum values of electromagnetic induction for determining the working angles of a mutually coupled switched reluctance electrical machine.

3. Results and discussion
On the basis of the results obtained, a mutually coupled switched reluctance electric machine was constructed on which various operating modes are currently being investigated. This electric machine has a power of 2.2 kW and 3 feeding phases. The appearance of the mutually coupled switched reluctance machine, rotor and stator are presented in figures 7 and 8, respectively. The investigated electric machine functions both in the engine mode and in generator mode.

Figure 9 shows the transient processes of electromagnetic torque, obtained as a result of computer simulation by the program complex Infolytica, at rotor speeds of 600, 750 and 800 rpm. The figure shows that the torque pulsations are minimal at a rotation speed of 750 rpm.

Also, using computer simulation the efficiency of the developed inductor-reactive electric machine was determined (figure 10). The maximum efficiency value of 0.86 is achieved at a rotor speed 1200 rpm.
Figure 8. (a) appearance of the stator, (b) appearance of the rotor of mutually coupled switched reluctance machine.

Figure 9. Graph of the torque of the examined mutually coupled switched reluctance machine.

Since the mutually coupled switched reluctance electric drive is structurally more simple and more technologically efficient for manufacturing, maintenance and repair, it has a lower cost price; has got increased energy efficiency and higher overload capacity in comparison with asynchronous and synchronous engines, constant power in a wide range of rotational speeds, which is crucial for responsible equipment in mining, oil and gas, processing industries.

One of the latest developments of the company Le Tourneau Technologies, Inc. is the world’s largest loader included in the Guinness Book of Records, L-2350, 6.7 m high and 20.3 m long, weighs 266 tonnes and can lift 72 tons of cargo in a bucket with capacity of 40.5 m³. The cost of one such loader is 7.6 million USD [10]. As the traction motor of motor-wheel a switched reluctance engine of 400 kW is used, which transmits the torque to the wheel through the planetary gear. Compared with the DC traction motor the service interval of the unit has increased from 500 to 20 000 h, only the bearings are replaced.
Figure 10. Graph of the performance factor of examined mutually coupled switched reluctance machine.

The manufacturer of construction and agricultural machinery American Deere&Company (Molin, Illinois, USA) in 2011 presented at the international exhibition ConExpo in Las Vegas a 944K diesel quarry loader with an engine 500 hp/367.5 kW with a hybrid electric transmission based on switched reluctance-technology [11].

4. Conclusions
Mutually coupled switched reluctance motors have several advantages over frequency-controlled asynchronous electric AC motors, machines with synchronous electromagnetic excitation and excitation from permanent magnets. At present, application of switched reluctance machines, operating in the generator mode, in the sphere of wind power engineering, as well as in the automotive industry are are carried out.

Mutually coupled switched reluctance machines can reduce the cost of electricity generation through wind farms, improve the energy efficiency of various production processes, and reduce maintenance costs due to its simple and reliable design [12]. The existing shortcomings of these electric machines hinder their wide spread and require prompt elimination.

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