Synchronous generators for traction mechanisms

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Abstract. This article shows the principle of operation, experimental characteristics, comparison with other types of generators, functional diagrams of an electric generator set based on a field regulated reluctance machine. Attention is drawn to the high specific performance and favorable performance characteristics of these power generating sets. The simplicity of the design ensures high manufacturability of the electric machine, the non-contact design in combination with a “cold” winding-free rotor increases the reliability of the bearings and the entire machine, the ability to make the rotor massive (the rotor poles and the shaft are from one solid billet) significantly increase it strength and lateral stiffness. Also it allows obtaining high angular velocities and large moment overloads. Small control powers along the excitation circuit with a sufficiently high speed of this channel contribute to the achievement of high accuracy of maintaining a given voltage at favorable mass and dimensional parameters of the electric power plant.

1. Introduction

Autonomous installations for the production of electricity are operated in difficult conditions. Therefore, contactless design of the generator is often not only a desirable, but a prerequisite for design. Non-contact motors have high specific power indicators. They made on the basis of a field regulated reluctance machine (FRRM) [1]. Meanwhile, the operation of this machine in generator mode has its own characteristics and advantages, which are discussed below.

There are various design options for electric generators for an autonomous network. Typically, the vehicle electrical system is powered by a parallel-connected battery and a direct current generator, which is driven by an internal combustion engine. As the main source of electricity, collector DC generators are used. Alsothere are valve generators with a rotor with permanent magnets [2]. The brush-collector assembly is the main drawback of collector generators and leads to a decrease in the service life of the generator, lower reliability, unfavorable mass-dimensional characteristics. Permanent magnet generators are characterized by complex manufacturing technology, instability of parameters, increased power of output voltage stabilization devices, and high cost.

The inductor generators have reliable rotor [3]. However, they are characterized by the unsatisfactory use of an electric machine on steel due to unidirectional (pulsating) magnetic flux and poor mass-dimensional parameters.

Induction motors are characterized by simplicity [4], but are practically uncontrollable.

Non-contact synchronous generators with an exciter and a rotating rectifier, with a multiphase winding of the armature (stator) and a power multiphase rectifier at the generator output [5] also find application. However, the placement on the rotor of a rotating field winding and rectifier diodes reduces the mechanical reliability of the generator and does not allow obtaining high angular rotational speeds of the rotor [6].
2. Materials and Methods

Studies of generators can be carried out by the electromagnetic method. Electromagnetic method for detecting local faults and active steel sections stator core with increased losses. Control is carried out with ring magnetization with low magnetization induction (0.02-0.05 T). It allows detecting all damage inter-sheet insulation, both on the surface and in the core, capable of causing unacceptable heating during operation or during testing of stator steel with induction of 1.0 - 1.4 T. Electromagnetic control of inter-sheet insulation of active steel of turbogenerator stators runs on a stopped machine with the rotor pulled out. The generator must be expanded, the phases of the winding are open [7].

The magnetizing winding is powered by a step-down transformer of 12V or 36V with a power of at least 1000 VA. The rated voltage of the step-down transformer and the number of turns of the magnetizing winding are specified based on local conditions and ensuring induction on the back in the range of 0.02-0.05 T.

As is known [8], the FRRM has excitation winding that are located opposite the interpolar gaps and have a full step. The electric motor has the same windings. They alternately play the role of either working windings or excitation windings, depending on where at a given moment of time they are located: opposite the pole or the interpolar gap [9]. Meanwhile, when the electric machine operates in generator mode, the valves of the switch connected to the working windings operate in natural switching mode. Therefore, it is advisable to constructively separate the chains of the windings of the workers, which do not require artificial switching of the valves and, therefore, can be connected to an uncontrolled rectifier, and the field windings, which are connected to the output of a controlled converter. Choosing the length of the pole arc of the corresponding conduction time of the valves (usually 120 degrees), it is possible to rationally coordinate the parameters of the motor and the converter [10].

Figure 1 shows a sectional view of an example of a three-phase generator, when in the grooves of the stator located in the planes A - a, B - b, C - c, spatially shifted by 120 degrees, the main (power) windings connected to the star are placed [11].

Also there are additional field windings made with a full step on the stator in the same way in the planes X - x, Y - y, Z - z. They are made according to a half-wave scheme. Therefore, in each of the grooves, two half-windings included are back-to-back [12].

Other versions of the windings in the generator are possible, for example, with a different number of phases, with a different number of phases of the power and excitation windings, located not in different, but in the same stator slots.

The rotor has a clearly polar design and does not carry any windings [13].

Power windings connected to a star through an uncontrolled rectifier made according to a three-phase bridge circuit are connected in parallel with the battery to the on-board DC network. Field windings are connected to the exciter outputs.

The directions of currents in all stator windings correspond to those indicated instantaneous position of the rotor of the generator [14].
Carrying out the function of the position of the rotor switching currents in the phase excitation windings, provide spatial circular motion of the magnetomotive excitation force along the circumference of the air gap of the machine [15]. This magnetomotive force moves synchronously with the rotating rotor of the generator. Due to this joint rotational motion of the generator rotor and the magnetomotive excitation force, continuous excitation of the generator in the longitudinal direction is achieved [16].

3. Results

The chains of the working windings can be made both according to the well-known three-phase bridge circuit, and the "star - reverse star" scheme with equalization reactor. Although the second option leads to a slight increase in winding copper, but with the same number of valves as in the bridge circuit, it allows obtaining a double rectified current with half the total voltage drop across the rectifier circuit valves, which is important for electric power plants having a small on-board voltage, for example 12 or 28 V.

Excitation circuits can be performed in the same way as typical circuits of power circuits of valve-induction motors [5]. Figure 2 shows windings are turned on according to a half-wave circuit: positive half-waves of phase excitation currents pass through windings 1, 3 and 5 through switches VT1, VT3 and VT5, and negative half-waves pass through windings 2, 4 and 6 through switches VT2, VT4 and VT6. The winding circuits are identical, therefore, only the winding circuits 1 and 6 are shown in the diagram (Fig. 2). The excitation winding circuits 1 ... 6, arranged uniformly along the stator bore and having a full pitch, include transistors VT1 ... VT6, which form commutator (switch) of the phase currents of the excitation of the generator. The rotor is magnetized along the longitudinal axis and always in the same direction, as a function of the angle of rotation of the rotor. Transistors of those phases of the excitation circuit are opened, the windings of which are located at a given moment in time opposite the interpolar gap of the rotor. In series with the field winding circuits, a VT transistor is turned on, which operates in pulse-width modulation mode and acts as an adjustable excitation current source. Diodes VD, VD1 ... VD6 reduce switching overvoltages at power transitions of transistors in the forward direction.
Figure 2. Functional diagram of generator excitation circuits.

The shaft of the synchronous generator is mechanically connected with the shaft of the primary internal combustion engine, the angular velocity of which can vary in the range up to 1: 4 or more. Maintaining a given voltage value is carried out by changing the excitation current of the generator. It is most difficult to suppress the generator ripple voltage ripple. They are caused, first of all, by the uneven rotation of the shaft due to the pulsed nature of the operation of the internal combustion engine. The amplitude of the velocity pulsations can reach up to 5% in the operating mode of the engine and even up to 20% or more at light loads. Another cause of reverse pulsations is the heterogeneity of the magnetic resistance of the stator iron along its bore. This is due to the fact that the stator iron packet is burdened from sheets of cold rolled steel, which has different magnetic permeabilities along and across the rolling direction. Experimental measurements performed on AC electric machines with a power of 0.5 ... 5.0 kW and the number of pole pairs 1 ... 3 indicate the ripple level within 10 ... 30% of the average voltage value. The greatest ripple is observed in electric machines with a small number of pole pairs.

4. Discussion

Suppression of reverse pulsations by traditional L-C filters is inefficient, as they are designed for high (hundreds of Hz) frequencies. However, as shown by experimental data taken at a stand where FRRM (0.25 kW, 28 V, 6 A, 1500 rpm) was used as a generator, it is possible to suppress reverse voltage ripples by means of controls. This is confirmed by the frequency characteristics of the voltage control loop (VCL), which in an open system (Fig. 3, curve 1) have a band of uniform transmission of frequencies on the reference signal no more than 100 rad / s. In a closed system (Fig. 3, curve 2), it is possible to expand the frequency bandwidth to 800 ... 1000 rad / s. In fig. 3b shows the amplitude frequency response of the voltage control loop perturbation. It has two branches: ascending (in the frequency range up to $\omega \approx 300...400$rad / s), where the periodic effect is attenuated by the voltage control loop, and decaying (at higher frequencies), where the feedback action is already ineffective, and the attenuation of periodic disturbances only an LC filter in the power circuit is possible. In the region of the extremum, the magnitude of the dynamic error is maximum. Here, voltage feedback due to the inertia of the voltage control loop is already ineffective, and strengthening the influence of the L-C filter requires an increase in the dimensions of its elements. Meanwhile, even these frequencies are attenuated by the combined operation of the VCL and filter by 30 ... 50 times.
5. Conclusions
The simplicity of the design ensures high manufacturability of the electric machine, the non-contact design in combination with a “cold” winding-free rotor increases the reliability of the bearings and the entire machine, the ability to make the rotor massive (the rotor poles and the shaft are from one solid billet) significantly increase its strength and lateral stiffness. Also it allows obtaining high angular velocities and large moment overloads. Small control powers along the excitation circuit with a sufficiently high speed of this channel contribute to the achievement of high accuracy of maintaining a given voltage at favorable mass and dimensional parameters of the electric power plant.

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