Voltage regulation characteristics of a two-pack synchronous generator with combined excitation

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Abstract. The design, principle of operation, method for determining the inductance and the algorithm for plotting the voltage regulation characteristics of a two-packet synchronous generator with a combined excitation are described in this article. Characterization and inductance calculation were carried out for a prototype having a power of 11 kW, number of phases - 3, frequency of induced EMF in the AC winding - 550 Hz, number of pole pairs - 11.

1. Introduction
In recent years, due to the development of unmanned vehicles, electric batteries and electronics, the demand for autonomous sources of constant voltage has increased.

DC voltage generators are capable of generating constant voltage. These machines have a commutator. Due to the complexity of the design of the commutator and frequent switching plates, the commutator significantly reduces the reliability of the machine, increases its cost, and complicates maintenance.

Also synchronous machines operating with a rectifier can be used as direct current sources. Classical synchronous generators are equipped with an excitation winding located on the rotor of the machine. It’s possible to regulate the main magnetic flux by having an excitation winding. However, in that case, the machine has a sliding contact, which reduces its reliability and complicates maintenance.

The generator considered in this article has a combined excitation, which allows it to work with the excitation winding turned off, and with it turned on. The excitation winding is located on the stator between the packages and has no sliding contacts (figure 1). Thus, this machine has the following advantages:

1. Increased reliability relative to DC machines and synchronous machines in the classic version.
2. Lower power of the excitation winding due to the presence of permanent magnets.
3. Increased utilization of magnetic induction compared with an axial inductor machines [2].
4. The ability to control the main magnetic flux.

2. Problem statement
Voltage regulation characteristics are necessary for the development of an automatic excitation system. It is assumed that this generator will work with the rectifier and its load will be only active. But because of its own inductance, the load of the generator will be active-inductive. Due to the unusual design and the presence of the constant component of magnetic induction in the magnetic conductor, there are no expressions for valuation the inductance along two axes. This article presents one of the methods for valuation of the inductance for this generator.
3. Theory

3.1. Description of the design
Figure 1 shows the constructions of the generator. The stator consists of laminated packages fixed in a frame and an excitation winding installed between the packages. The rotor also consists of two laminated packages in the slots of which magnets with radial magnetization are installed. Magnets have opposite magnetization vectors in different packages. Packages mounted on a molded liner and are shifted relative to each other on the pole pitch. So that both rotor packages have the same polarity. Magnetic flux does not pass through the end shield and parasitic air gaps, as is the case in a single-package construction [2].

This generator has the following characteristics: 11 pole pairs, power 11 kW and rotor speed of 3000 rpm. Making of this generator with classical type winding will lead to diminishment teeth-slots area, which will cause a decrease in specific values (this is due to the need to a lower fill factor) and complicates the production technology [5]. Therefore, the machine is made with a fractional slot concentrate winding.

![Generator Construction](image)

**Figure 1.** Construction of the generator

3.2. Principles of operation
When the excitation winding is turned off, most of the flow generated by the magnets passes along the contour: the magnet of the first rotor package - air gap – teeth of the first stator package – frame – teeth of the second package of the stator – air gap – iron pole of the second package of the rotor – liner. A smaller part of the flow is closed radially, as in classical synchronous machines with permanent magnets. When the excitation winding is turned on, the magnetic flux created by DC winding is directed oppositely to the flow from the magnets and passes along the contour: the frame – teeth of the first package of the stator – iron pole of the first package of the rotor – liner – iron pole of the second package of rotor – teeth of the second package of the stator. The equivalent circuit of the magnetic circuit is shown in Figure 2. Thus, the flux of permanent magnets decreases slightly, but the flux passing through the pole increases and the constant component of the magnetic induction in the air gap decreases. By changing the MMF of the excitation winding, it is possible to control the magnetic flux passing through the pole.

3.3. Valuation of inductance
Generator inductance is calculated by numerical simulation of the magnetic field. Inductance – the coefficient of proportionality between the current flowing in a circuit and the flux linkage created by this current through the surface, the edge of which is the circuit [1]:

![Image](image)
The d axis coincides with the axis of the pole, in other words the magnetic resistance in this case is minimal, respectively the magnetic resistance of the q axis is maximum. Figure 3 and 4 show the location of the rotor relative to the stator, corresponding to the minimum and maximum magnetic resistance. By knowing the value of the phase flux linkage at given rotor positions and taking into account the flux created by permanent magnets, it is possible to determine the inductance of the generator along the d and q axes:

\[
L = \frac{\psi}{I} \quad (1).
\]

By calculating the three-dimensional magnetic field by the finite element method in the ANSYS program, it is possible to determine these flows and calculate the inductance.

In equation (2) \( \psi_A' \) - phase flux linkage created by permanent magnet and phase current, \( \psi_A^* \) - phase flux linkage created by only permanent magnet, \( I_A \) - amplitude value of the phase current.

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**Figure 2.** Equivalent circuit of the magnetic circuit

In accordance with Figure 2 \( R_f \) and \( R_s \) - reluctance of the frame and the sleeve, \( R_{t1} \) and \( R_{t2} \) - reluctance of the teeth of the stator and rotor, \( R_\delta \) - reluctance of the air gap, \( R_m \) and \( R_{om} \) - reluctance of the permanent magnet and its stray flux, \( R_a \) - reluctance of the stator back, \( F_m \) and \( F_e \) - MMF of the permanent magnet and excitation winding.
3.4. Mathematical description of the generator

Creating a mathematical description of any electric machine begins with the compilation of a system of differential equations that determine the behavior of the processes inside the machine. The calculation and formulation of equations of the machine were carried out in a rotating coordinate system. In this case, for a synchronous machine with a combined excitation description has the following form:

\[
\begin{align*}
\frac{d}{dt}i_d &= \frac{1}{L_d}U_d + \frac{R}{L_d}i_d + \frac{L_q}{L_d}p \cdot \omega \cdot i_q, \\
\frac{d}{dt}i_q &= \frac{1}{L_q}U_q + \frac{R}{L_q}i_q + \frac{L_d}{L_q}p \cdot \omega \cdot i_d - \frac{\psi \cdot p \cdot \omega}{L_q}, \\
M_e &= 1.5 \cdot p \cdot \left(\psi \cdot i_d + \left(L_d - L_q\right) \cdot i_d \cdot i_q\right).
\end{align*}
\]

In accordance with the system of equations (3): \(L_d\), \(L_q\) - generator inductance along the d and q axes; \(R\) - active phase resistance of the stator winding; \(\psi\) - flux linkage of the phase; \(p\) - number of pole pairs; \(\omega\) - rotary speed of the rotor.

With the help of this system of equations, a structural scheme of the machine was compiled in the Matlab/Simulink software package. A feature of the scheme is that it is implemented using both standard blocks of the Simulink library and Simscape. In scheming of the machine, it was assumed that the speed of the engine driving the generator rotor is constant over time.
4. Experimental results
Simulation of the three-dimensional magnetic field was carried out in the ANSYS program. According to the simulation results, the values of the flux linkages necessary for the calculation of inductance were determined. The results are shown in Table 1.

The distribution curves of the magnetic induction in the air gap and their harmonic compositions were also obtained (Figures 5-6).

Table 1. Parameters for inductive calculation

| Parameter                                                                 | Value      |
|---------------------------------------------------------------------------|------------|
| Phase flux linkage at maximum magnetic reluctance created by phase current and magnets | 0.0094 Wb  |
| Phase flux linkage at maximum magnetic reluctance created by phase current and magnets | 0.00011 Wb |
| Phase flux linkage at maximum magnetic reluctance created by phase current and magnets | 0.0017 Wb  |
| Phase flux linkage at maximum magnetic reluctance created by phase current and magnets | -0.0069 Wb |
| Amplitude value of armature winding current                                | 309.1 A    |

Figure 5. a – the distribution curve of the magnetic induction in the air gap with excitation winding is off; b – the harmonic composition of this curve.

Figure 6. a – the distribution curve of the magnetic induction in the air gap with excitation winding is on; b – the harmonic composition of this curve.
5. Discussion of results
As seen in figures 5-6, with the excitation winding off, the constant component of the magnetic induction in the air gap is larger than the amplitude of the main harmonic. When the excitation winding is turned on, the constant component is almost completely compensated, and the amplitude of the main harmonic increases. According to the values of flux linkage (Table 1), inductances were determined along the q and d axes ($L_q = 13.79 \times 10^{-6}$ H, $L_d = 15.02 \times 10^{-6}$ H) and a set of voltage regulation characteristics was constructed (Figure 7).

![Figure 7. Set of the voltage regulation characteristics](image)

6. Conclusion
The article describes the design and principle of operation of a two-pack synchronous generator with combined excitation. The method for calculating inductances along the q and d axes is presented. The calculation of the three-dimensional magnetic field in the ANSYS program was also carried out, the results of the calculation are presented in the graphs of the distribution of magnetic induction in the air gap. For the obtained inductance values, voltage regulation characteristics were constructed.

To construct regulating characteristics, it is necessary to construct the characteristic curve of the main harmonic of the flux linkage on the excitation current. When constructing this plot, one may encounter a number of difficulties caused by the design features of the generator and the presence of the constant component of magnetic induction. The development of an algorithm for constructing this graph may be the goal of further research.

References
[1] Voldek A I 1978 Electrical machines (Leningrad: Energiya) 832
[2] Dombur L E 1984 Axial inductor machines (Riga: Zinatne) 247
[3] Shevchenko A F, Pristup A G 2016 Electric machines with permanent magnets (Novosibirsk: Izdatelstvo NGTU) 64
[4] Kroneberg U N, Gomzyakov V B, Zhibinov A S 1971 “Two-Pack Generator with Combined Excitation News of Tomsk Polytechnic University 212
[5] Bukhgolc U G, Komarov A V, Shevchenko A F, Shevchenko L G 1996 Multipolar synchronous machines with fractional slot windings part 1, (NGTU: Novosibirsk)
[6] Bukhgolc U G, Komarov A V, Shevchenko A F, Shevchenko L G 1996 Multipolar synchronous machines with fractional slot windings part 2, (NGTU: Novosibirsk)
[7] Bespalov V Ya, Kotelene N F 2006 Electrical machines (Moskow: Akademiya) 320
[8] Kacman M M 2003 Electrical machines (Moskow: Vysh. shk.) 469
[9] Tapia J A, Leonardi F, Lipo T A, 2001 Consequent Pole Permanent Magnet Machine With Field Weakening Capability *IEEE International Electric Machines and Drives Conference, IEMDC* 126-131.

[10] Tapia J A, Leonardi F, Lipo T A 2003 Consequent-Pole Permanent Magnet Machine With Field-Weakening Capability *IEEE Transactions on Industry Applications* **39** **6** 1704-1709.