Modified Method for Controlling the Switching of the Starter-Generator Phases

Flyur Ismagilov
Ufa state aviation technical university
Department of Electromechanical
Ufa, Russia
user-user-u-user@mail.ru

Viacheslav Vavilov
Ufa state aviation technical university
Department of Electromechanical
Ufa, Russia
s2_88@mail.ru

Alexey Zherebtsov
Ufa state aviation technical university
Department of Electromechanical
Ufa, Russia
zherebtsov@niietkis.ru

Ildus Sayakhov
Ufa state aviation technical university
Department of Electromechanical
Ufa, Russia
isayakhov92@mail.ru

Eugene Zharkov
Ufa state aviation technical university
Department of Electromechanical
Ufa, Russia
eugene0192em@gmail.com

Guzel Zinnatullina
Ufa state aviation technical university
Department of Electromechanical
Ufa, Russia
zinnatullina95@list.ru

Abstract—The purpose of this article is to provide an increase in the efficiency of a starter generator (STG) with a reduced supply voltage of 27 V by modifying the phase switching control method. In this article, a comparison of two methods of phase switching, traditional and with a modified angle, was presented, as a result of which the difference and prospects, as well as the effectiveness of the chosen solution, were clearly shown. Thermal calculations were also performed, which confirmed that the temperature values of the active elements of the starter generator did not exceed the permissible values for the materials used in all operating modes.

Keywords—starter-generator, starter-generator design, starter mode, generator mode, phase switching angle.

I. Introduction

To date, there is a significant development of the aircraft power supply system. A new generation aircraft power systems are expected to be more economical and easier to maintain. The implementation of the stated goals is ensured by the transition to the modern concept of "more electric aircraft" (MEA) by replacing the hydraulic and pneumatic supplies with the electric ones [1-6]. As a result of this transition, there is a need not only to provide electricity to a number of the aircraft main systems, but also to provide engine start, so this article focuses on the design of the starter-generator for such systems. The problem that is often encountered while designing the starter-generator concerns two main functions: providing power to the engines during the start-up and generating energy during the engine's operation. In addition, the starter-generator must provide high efficiency factor, high specific power values, sufficient reliability and minimal weight and size parameters. As we know, the mass of the distribution network, as well as switching and protective equipment, decreases with increasing voltage [7-12], the existing samples of starter-generators are mainly implemented for increased voltage. Therefore, this article explores the possibility of providing a decrease in the mass of the starter-generator at low voltage (27 V).

As a rule, to achieve the required characteristics of electrical machines, it is necessary to select their optimal parameters, which must be linked to the basic requirements for weight, dimensions, reliability, efficiency and cost of the machine. Accordingly, this article discusses a method for improving the efficiency of a starter generator at a low voltage of 27 V by modifying the phase switching control method.

II. Design Features

To evaluate the efficiency of the phase switching control method, the design of the starter-generator for the turbocharger engine of the aircraft was considered. The connection of the starter-generator is implemented through a gearbox with a gear ratio of 2.52, and the base frequency of the turbocharger corresponds to 30257 rpm. In this case, the first mode should provide the turbocharger output to the ignition speed. For this it is necessary to provide a rotation frequency equal to 20 % of the base value of the turbocharger, while the duration of the mode should be no more than 10 s. Taking into account the turbocharger speed and the gearbox characteristics, the ignition frequency for the STG was calculated, which corresponds to a speed of 2400 rpm.

The next mode should provide the turbocharger output to the dry run speed corresponding to the value of ptc=25 %, which when converted to the STG speed corresponds to 3000 rpm, while the torque on the STG shaft should be at least 105 Nm. For all modes, the STG shutdown at the end of the start-up must be provided at ptc=50 %, i.e. at 6000 rpm, while the torque on the STG shaft must be at least 61 Nm. The total operating time of the STG in any mode should not exceed 40 seconds.

The generator mod requires the following: the output power is not less than 14 kW in the frequency ranges from 8885-12367 rpm, the voltage is not less than 27 V, and the STG must provide one and a half times over-current within 5 minutes and a double overload within 10 s. The maximum time of continuous operation in the generator mode is 7 hours, while the STG cooling in the generator mode during operation on the ground and in-flight should be provided by self-ventilation.

The next section describes the process of designing the STG according to the proposed algorithm and suggests a way to increase efficiency by modifying the phase switching control method. In further research, we plan to create a full-size sample and conduct experimental studies of it.

III. The Design of the Starter-Generator

The characteristics of the projected STG obtained analyti-

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cally are presented in Table I. A drawing of the active part is shown in Fig. 1.

TABLE I. STG CHARACTERISTICS

Parameter	Values
Power, kW	up to 40
Rotation speed, rpm	up to 12000
Supply voltage, V	27
Permanent magnets type	Sm_2Co_{17}, H=850 kA / m, B_r=1.08 T
Stator magnetic core material	49K2FA
Number of turns	2
Phase resistance, Ohms	0.00020307
The number of stator slots	36
Number of rotor poles	12
Active length, mm	120
Stator magnetic circuit weight, kg	2.87
Rotor magnetic circuit weight, kg	0.903
Winding weight, kg	1.32
PM weight, kg	0.98
Act. parts weight, kg	6.09

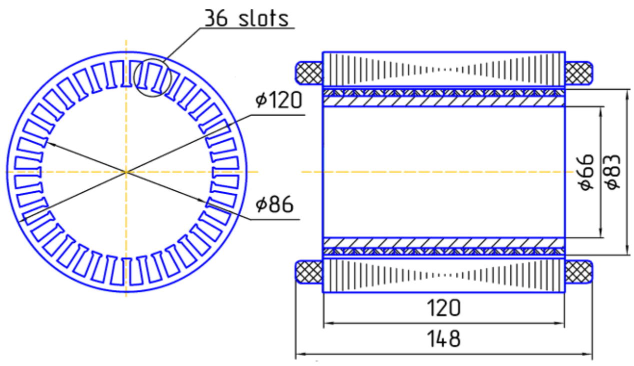

Fig. 1. STG active part drawing

These characteristics were obtained in the STG by changing the phase switching angle from the standard 120 to 156 degrees. At the same time, it was possible to achieve an increase in the efficiency of the STG, in order to show the results clearly, this STG was simulated in the Ansys software package, taking into account the use of a standard control system with a shift angle of 120 and a control system with a shift of 156 degrees.

The results of the STG analysis in several operating modes are presented below. Table II shows the results of the electromagnetic calculation in the starter mode; the shaft rotation speed is 1200 rpm.

Table III shows the results of the electromagnetic calculation in the starter mode; the shaft rotation speed is 2400 rpm.

Table IV shows the results of the electromagnetic calculation in the starter mode; the shaft rotation speed is 3000 rpm.

Table V shows the results of the electromagnetic calculation in the starter mode; the shaft rotation speed is 6000 rpm.

TABLE II. THE RESULTS OF THE CALCULATION OF THE ELECTRIC MOTOR AT A SPEED OF 1200 RPM

Parameter	Short-term mode	
	Commut ation 120^0, el. grad.	***Commut ation 156^0, el. grad.***
Output power, kW	13.52	14.59
Rotation speed, rpm	1200	
Supply voltage, V	27	
Inverted supply voltage, V	15.1	14.1
Phase current, A	3390.7	3356
Linear current load, kA/m	150.6	149
Heat factor (A·j), A/sm·A/mm^2	63734	62254

TABLE III. THE RESULTS OF THE CALCULATION OF THE ELECTRIC MOTOR AT A SPEED OF 2400 RPM

Parameter	Short-term mode	
	Commut ation 120^0, el. grad.	***Commut ation 156^0, el. grad.***
Output power, kW	26.27	29.14
Rotation speed, rpm	2400	
Supply voltage, V	27	
Inverted supply voltage, V	19.2	18.2
Phase current, A	3268	3388
Linear current load, kA/m	146	150.4
Heat factor (A·j), A/sm·A/mm^2	60123	63770

According to the analysis, the use of 156^0 commutation allows you to get a higher torque at the same voltage, due to the fact that the switching keys are open to transmit the supply voltage for a longer time, which leads to the fact that the phase windings of the STG are energized longer. Another advantage of using 156^0 commutation is the improved shape of the current curve, which minimizes losses in permanent magnets and steel. The current form for 156 and 120-degree commutation at a speed of 6000 rpm are shown in Fig. 2 and Fig. 3.

In addition to the comparative analysis, the tables above show that the starter mode provides the output of the turbocharger to the ignition speed since the required speed and torque values meet the requirements specified in the task.

To confirm the reliability and operability, a thermal analysis of the STG was performed in the starter mode.

TABLE IV. THE RESULTS OF THE CALCULATION OF THE ELECTRIC MOTOR AT A SPEED OF 3000 RPM

Parameter	Short-term mode	
	Commut ation 120^0, el. grad.	***Commut ation 156^0, el. grad.***
Output power, kW	28.7	33.12
Rotation speed, rpm	3000	
Supply voltage, V	27	

Parameter	Short-term mode	
	Commut ation 120⁰, el. grad.	*Commut ation 156⁰, el. grad.*
Inverted supply voltage, V	20.2	19.2
Phase current, A	2788	3029
Linear current load, kA/m	123.8	134.5
Heat factor (A·j), A/sm·A/mm^2	43082	50706.5

TABLE V. THE RESULTS OF THE CALCULATION OF THE ELECTRIC MOTOR AT A SPEED OF 6000 RPM

Parameter	Short-term mode	
	Commut ation 120⁰, el. grad.	*Commut ation 156⁰, el. grad.*
Output power, kW	25.5	39.3
Rotation speed, rpm	6000	
Supply voltage, V	27	
Inverted supply voltage, V	25	25
Phase current, A	1108	1696
Linear current load, kA/m	49.2	149
Heat factor (A·j), A/sm·A/mm^2	6814	15941

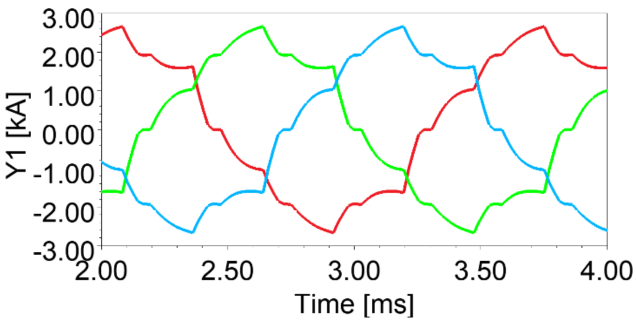

Fig. 2. The phase currents shape with commutation at 156 degrees

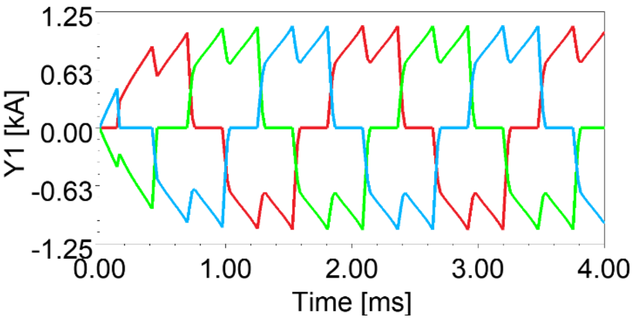

Fig. 3. The phase currents shape with commutation at 120 degrees

The thermal calculation was carried out in the transition process. The electric machine starts three times: failed start, dry run, start. Promotion to the ignition frequency occurs in 6 seconds, then the electric machine operates for 25 seconds at a frequency of 6000 rpm and a torque of 64 Nm. In the dry run mode, the electric machine reaches a frequency of 3000 rpm in 6 seconds and then operates at a torque of 105 Nm for 40 seconds. The ambient temperature is assumed to be 50 ^{0}C, the pressure is atmospheric. Fig. 4 shows the result of the thermal calculation.

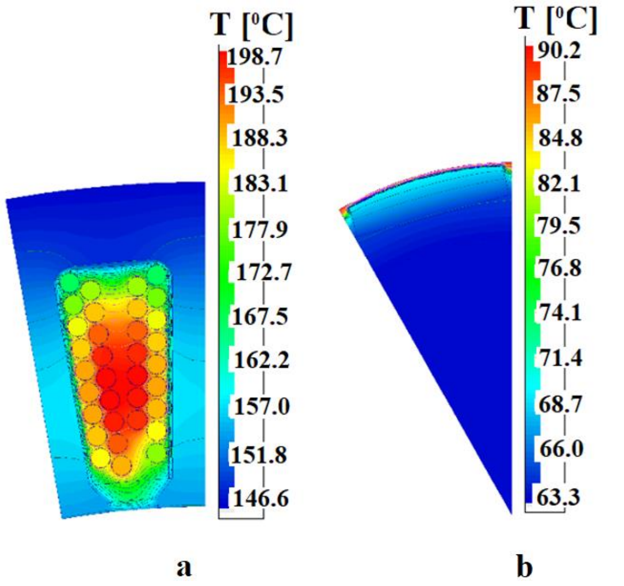

Fig. 4. Results of the thermal calculation of the starter: a) stator winding in the groove, b) permanent magnet rotor

TABLE VI. THE RESULTS OF THE CALCULATION OF THE GENERATOR MODE AT FREQUENCY OF 8885 RPM

Parameter	Value		
Rotation speed, rpm	8885		
Mode	nominal	1.5 times overload	2 times overload
Load voltage, V	23.03	21.8	20.53
Current to the load, A	697.8	1090	1579
Output power of the rectifier kW	16.07	23.76	32.4
Phase current, A	549.6	884.3	1214
Current density, A/MM^2	6.86	11.1	15.15
Linear current load, kA/m	24.4	39.45	53.92
Total losses, W	409.4	760.4	1253
Electric machine efficiency, %	97.5	96.9	96.3

TABLE VII. THE RESULTS OF THE CALCULATION OF THE GENERATOR MODE AT FREQUENCY OF 12367 RPM

Parameter	Value		
Rotation speed, rpm	12367		
Mode	nominal	1.5 times overload	2 times overload
Load voltage, V	33.97	32.77	31.3
Current to the load, A	485.2	728.3	1042
Output power of the rectifier kW	16.48	23.87	32.6
Phase current, A	385.6	571.7	819.4
Current density, A/MM^2	4.8	7.14	10.2
Linear current load, kA/m	17.1	25.4	36.39
Total losses, W	416	567	843
Electric machine efficiency, %	97.5	97.7	97.4

As can be seen from Fig. 4, the peak temperature is reached during dry run, at which the maximum temperature of the grooved part of the winding is 198,7 ^{0}C, and a maximum temperature for the surface of permanent magnets is 90,2 ^{0}C.

In addition to the starter mode, the developed STG has a generator mode, the requirements for which were described earlier in the article.

Table VI shows the results of the electromagnetic calculation of an electric machine in generator mode at a frequency of 8885 rpm, table VII a frequency of 12367 rpm.

It will be necessary to use a step-up converter to provide an output voltage of 27 V, at a reduced speed. Changing the configuration of the STG, so that the voltage meets the requirements of the technical specifications is impossible because increasing the induced voltage in the generator mode will not allow you to achieve the desired value of the torque in the starter mode.

The efficiency of the STG is confirmed by the thermal calculation shown in Fig. 5.

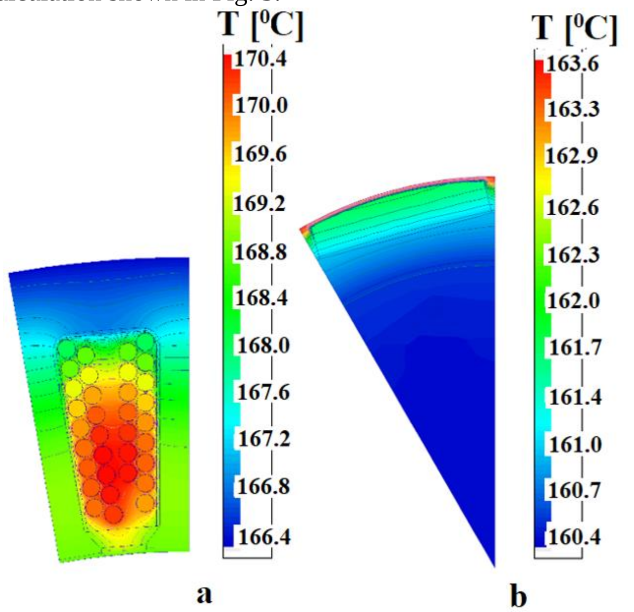

Fig. 5. The dependence of the load voltage on the power: a) stator winding in the groove, b) permanent magnet rotor

As can be seen from Fig. 5, in the steady-state mode, the peak temperature of the stator winding was 170.4 ^{0}C.

The presented calculation results show the efficiency of the electric machine. The electric machine produces the required power in the starter and generator modes, while the maximum winding temperature does not exceed the maximum permissible value of 220 ^{0}C , the mass of the active part STG was 6.09 kg.

IV. Conclusion

The article studies the possibility of providing an increase in the efficiency of the starter generator at a low voltage of 27 V by modifying the phase switching control method. The characteristics of the starter generator were considered taking into account the use of a standard control system with a shift angle of 120 degrees and a control system with a shift of 156 degrees. By changing the phase switching angle from the standard 120 to 156 degrees, it was possible to increase the efficiency of the starter generator used in the turbocharger engine of the aircraft.

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