Electrodynamic speed stabilizer for emergency wind power unit of an aircraft

A A Shirokov¹, V V Tishkov¹, M V Zdorova¹ and V A Kaliy²

¹ Moscow Aviation Institute (National Research University), 4, Volokolamskoe shosse, Moscow, 125993, Russia
² JSC Technodinamika, 35/5, ul. Bolshaya Tatarskaya, Moscow, 115184, Russia
E-mail: shirokovanton96@gmail.com

Abstract. In this paper, a new technical solution is proposed for a deeper and faster speed stabilization of an emergency aviation wind power unit (EAWPU) using an electromagnetic brake. The principle of the electromagnetic brake operation is considered and a simplified block diagram of the aircraft emergency power supply system is presented. An example of the design electromagnetic brake for installation on an EAWPU is proposed, and the results of a finite element analysis magnetic field and current density in the rotating part of the electrodynamic speed stabilizer are presented. The study of various materials and the thickness of the electromagnetic brake rotor is carried out in order to find the highest value of the braking torque. The main dependences of the braking torque on the excitation current, the rotor thickness and the EAWPU rotation speed are obtained. The simulation of the thermal processes electromagnetic brake is carried out in order to find the maximum temperature of the rotor, according to the results of which the temperature dependences on the rotor speed are constructed at different excitation currents of the electromagnetic brake.

1. Introduction
Improving the reliability of aircraft power supply system is one of the main tasks for the development of aviation technology, including for promising more electric and fully electric aircraft [1]. Currently, power redundancy on board the aircraft is widely used, as well as additional emergency generation systems are used, which include batteries and emergency aviation wind power units [2]. Emergency systems provide power to the devices and systems that are needed to land the aircraft during the failure of other generation systems [3].

The conventional EAWPU consists of a brushless synchronous alternator, an air turbine driven by an oncoming air flow, and a centrifugal regulator [4]. The centrifugal regulator stabilizes the speed of rotation by changing the angle of rotation of the blades. This regulator, due to its low speed, is not able to fully stabilize the rotor speed of rotation, but is only able to limit the range of its changes. Therefore, strict requirements are imposed on piloting an aircraft with a released generator wind turbine.

As a new technical solution for deeper and faster stabilization of the EAWPU shaft speed, this paper examines the possibility of using an electromagnetic brake.

2. General Description
The principle of the electromagnetic brake (EMB) operation is based on the Faraday’s law. It describes the process of the eddy currents appearance in a rotating metal disk in the presence
of an alternating and constant magnetic field [5, 6]. The proposed EMB (figure 1) consists of a movable metal body of the wind turbine, a fixed magnetic core and coils [7, 8]. When a direct current is applied to the coils, an electromagnetic excitation field is created, which penetrates the metal body of the wind turbine. While rotation, the magnetic field created by the coils becomes quasi-static for the rotating body and produces of eddy currents in it. The interaction of magnetic fields leads to the appearance of a braking torque. The flow of eddy currents is accompanied by the release of heat in the rotating body of the wind turbine [9]. The EMB is mechanically connected to the generator rotor and the wind turbine, so the resulting electromagnetic moment counteracts the aerodynamic moment of the EAWPU rotor impeller.

Figure 1. Electromagnetic brake design.

A simplified block diagram of the emergency power supply system is shown in figure 2. It consists of a wind turbine, an electromagnetic brake, a synchronous machine with permanent magnet excitation (SMPM), a control system and electrical loads.

Figure 2. Simplified block diagram of an emergency power supply system.
To maintain a stable rotation speed of the EAWPU rotor, the proposed control algorithm can be used: at the output of the generator, the voltage level and frequency are measured, and when the voltage value deviates from a required value due to the increased revolutions of the generator shaft, the current in the windings of the EAWPU braking device increases. As the current increases, the braking torque increases, which reduces the shaft speed to the desired value. In the case of a voltage drop at the output of the generator, the current in the coils of the brake device decreases and the rotation speed of the generator shaft increases. This algorithm of EAWPU operation release the pilot from constant monitoring of the flight speed in emergency mode.

When switched on, the EMB creates an additional braking torque, which, thereby, prevents an increase in the speed of rotation of the generator shaft [10]. Speed, efficiency and flexibility of regulation can be noted as the advantages of this design of the brake.

The EMB acts on the balance of moments on the generator shaft, so the braking moment is directly included in the equation of the generator rotor motion:

\[ J \frac{d\Omega}{dt} = M_{dr} - M_{el} - M_b, \]

where \( J \) is the moment of inertia the rotating parts of EAWPU; \( \Omega \)—angular speed of rotation of the rotor; \( M_{dr} \)—torque drive; \( M_{el} \)—electromagnetic torque of the generator; \( M_b \)—braking torque generated by EMB:

\[ M_b = \oint_v r \times (j(v) \times B) \, dV, \]

where \( j \) is the current density in the EMB rotor; \( B \) is the magnetic field induction.

3. Results of magnetic field calculation and EMB characteristics

The value of braking torque depends on magnitude of the magnetic field induction and the current density in the rotating part of the EMB, so modelling was performed to estimate the value of these parameters and find the value of the braking torque.

The EMB characteristics were determined with the following parameter values:
- \( D_s = 138 \text{ mm} \)—outer diameter of the stator;
- \( D_r = 148 \text{ mm} \)—outer diameter of the rotor;
- \( \delta_0 = 4 \text{ mm} \)—nominal thickness of the outer rotating shell (case);
- \( l_\delta = 50 \text{ mm} \)—active axial length;
- \( \delta = 1 \text{ mm} \)—equivalent to the air gap;
- \( w = 144 \)—number of turns of the field winding;
- \( a_c = 1 \text{ mm}^2 \)—square cross section of elementary conductor winding;
- \( b_m = 20 \text{ mm} \)—the width of the magnetic pole of the stator;
- \( h_m = 20 \text{ mm} \)—the height of the pole of the magnetic circuit of the stator;
- \( I_v = 10 \text{ A} \)—the nominal current of the field winding;
- \( n = 8000 \text{ rpm} \)—rated speed.

Initially, the EMB model was built with a rotating massive steel rotor [9]. The results of the finite element analysis of the magnetic field and the current density distribution are shown in figure 3. Two conclusions can be formulated from this calculation: 1) the magnetic induction in the stator does not exceed the permissible for the selected steel type; 2) significant eddy currents occur in the rotor, which are necessary to create a braking torque at the rated speed.

The main characteristics of EMB are: adjustment—this is the dependence of the braking torque on the current of the field winding at a constant speed, as well as working-the dependence of the braking torque on the rotation speed at a constant current in the field winding [11]. These dependences obtained as a result of the calculation for different rotor materials are shown in figure 4.

In order to find the highest value of the braking torque, various EMB rotor materials were studied. As can be seen from figure 4(b), aluminium and copper have a significantly lower value of the braking torque and its peak is shifted to the region of lower speeds from the nominal one. This is due to the lower magnetic permeability of these materials compared to electrical steel, which requires an increase in the magnetomotive force required to create eddy currents in the
rotor. Therefore, despite the large weight of the steel rotor, the energy efficiency of creating braking torque with this material is the highest. Based on this criterion, electrical steel for the rotating part of the EMB was selected for further analysis.

According to figure 4, in the part of the curve that lies after the maximum braking torque, the following effect is observed: with an increase in the flight speed and, accordingly, the speed of rotation, the value of the braking torque decreases, which leads to the formation of a positive feedback. This further increases the speed of the EMB and reduces the value of the braking torque, which is unacceptable. Therefore, to provide a margin for regulation, it is necessary to increase the field winding current. The dependences of the braking torque on the speed at different values of the excitation current are shown in figure 5.

Based on the presented characteristics, it can be concluded that the greatest margin for regulation (at a speed of rotation of up to 10,000 rpm) is provided at an excitation current of 20 A.
Figure 5. Dependence of the braking torque on the rotation speed.

Figure 6. Dependence of the braking torque on the thickness of the steel shell.

The thickness of the steel shell is an important design parameter that directly affects the value of the braking torque and the mass of the EMB. Figure 6 shows the dependence of the braking torque on the thickness of the steel shell.

As can be seen from figure 6, the optimal thickness of the steel shell is 4 mm. The low value of the braking torque at a thickness of less than 3 mm is associated with an increase in the EMB rotor induction over 2 T and saturation of steel. However, it is impractical to use a larger thickness due to the increase mass and reduction of the current layer at high speeds of rotation of the EMB rotor.

4. Calculation results of the rotor temperature

During the operation of the electromagnetic brake, significant eddy currents occur in the rotor, which leads to large heat emissions. To find the maximum temperature in the EMB rotor, the thermal processes were modeled by the finite element method.

Figure 7. Temperature distribution in the EMB.
The temperature distribution was calculated at the values of the field winding current from 5 to 20 A. The used material has a critical temperature, at which the properties change. In this case, the use of the selected steel as the material for the rotor is possible only up to a temperature of 700°C.

After all the parameters were set, the thermal distribution was calculated at an excitation current of 10 A. The results of this calculation are shown in figure 7.

The average temperature in the rotor is 180°C, which is an acceptable value for the selected steel type. The uniform temperature distribution is associated with high values of the EMB rotation speed and the speed of the blown air. A parametric analysis of the thermal fields at different excitation currents is also carried out and the dependences of the temperature in the rotor on the rotation speed is constructed, which is shown in figure 8.

![Figure 8. Dependences of the temperature in the rotor at different rotation speed.](image)

Figure 8 shows that the rotor temperature at different values of the excitation current does not exceed the permissible values. Therefore, the developed device for stabilizing the speed of rotation under the selected operating conditions can be used at excitation currents of more than 20 A.

5. Conclusion

The results of EMB parameters calculating showed that the application of the proposed method makes it possible to significantly increase the control range of the EAWPU rotation speed in comparison with existing methods. A finite element analysis and study of various EMB rotor materials was carried out, as a result of which it can be concluded that the most appropriate use of EMB with a rotor made of electrical steel is due to the greater energy efficiency of the control.

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