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Electrical machines in the military More Electric Aircraft and their impact on the environment

***Abstract**. This paper describes the impact of the More Electric Aircraft (MEA) on the environment and the main advantages the electrified aircrafts can offer. Because of high demand of the MEA on the electrical energy, a new generator need to be designed. The authors propose a novel homopolar starter-generator which could replace both the starter and the generator and could offer higher efficiency and reliability. The principle of work of the new machine has explained and the new machine design has been presented.*

***Streszczenie.** Niniejszy artykuł opisuje wpływ technologii More Electric Aircraft (MEA) na środowisko oraz prezentuje główne zalety jakie mają samoloty wykonane zgodnie z nową technologią. Z powodu dużego zapotrzebowania MEA na energię, konieczne jest zaprojektowanie nowego generatora. Autorzy proponują generator homopolarny, mający również funkcję rozrusznika. (**Silniki elektryczne w wojskowych samolotach typu More Electric Aircraft i ich wpływ na środowisko**).*

Keywords: More Electric Aircraft, starter-generator, homopolar machine.
Słowa kluczowe: More Electric Aircraft, rozruszniko-prądnica, silnik homopolarny.

Introduction

Within the past several years, there has been a tendency to design the on-board airplane systems according to the More Electric Aircraft (MEA) concept. The main idea is to replace the onboard hydraulics and pneumatics installation and devices with corresponding electrical systems. It is believed that replacing only the pneumatic systems, would extract 35% less power from the engines, and in the case of large airplanes could save hundreds of kilograms of weight [1] and consequently dozens of kilograms of fuel. This results in a higher carbon dioxide production. Honeywell claims that the More Electric Architecture will offer significant cost advantages of approximately 30%, especially due to fewer parts (for example no ducting used to pass pressurized air), the integration of key subsystems and multi-use components [2]. Additionally, electric drives are much less maintenance-intensive and less vulnerable than hydraulic systems with their high temperature flammable liquids. This may be important, especially for aircraft in the case of combat. There is also a risk of the oil leakage from the hydraulic systems which results in environment pollution.

The future of the military aircrafts

When aeronautical and aircraft systems are considered, the most important factors are low weight, high reliability, high performance and high efficiency as well as a long life cycle [3]. Currently, the main engine produces energy, which is converted into mechanical (for example, thrust), pneumatics (for example, air conditioning), hydraulics (for example, for flap setting) and electric (for example, board electronics supply). Energy conversion produces losses which are mostly emitted as heat. The losses increase the fuel consumption and the heat increases the so called infrared signature, which is one of the crucial parameters of military aircraft.

In order to introduce the so called “Fly-By-Wire” system, which increases the number of onboard ploughs, a generator or generators with more output power are required.

As the development and the test cycle in the aircraft industry last from several to a dozen of years and the existing generators were developed many years ago, there is a large field for improvement. The final aim is to design and produce an “all-electric-aircraft” but as in the case of the automotive industry, hybrid constructions are introduced first in order that experience is gained and all hydraulic parts are gradually replaced with electric drives. This is the reason why the MEA and other similar projects related to the electrification of aircraft around the world have been launched.

As mentioned before, the MEA demand for the electrical energy comparing to standard airplanes, will significantly increase. The currently used electric net system does not allow distributing the required energy without introducing changes. Generators used in military aircraft (usually two pieces) produce independently a 115VAC with a constant frequency of 400Hz and 28VDC. The second voltage is used for safety critical applications. In order to meet the high energy consumption requirements, a new voltage level has been defined. The 115VAC voltage has been replaced with 270VDC voltage whereas the 28VDC has remained unchanged. The replacement of two separate generators with one machine means higher requirements regarding the reliability and durability.

MEA specification

The newly starter-generator will be coupled with the turbine without any gearbox. It allows avoiding complicated and susceptible-to-damage mechanical parts and reduces the weight. As a consequence of the absence of the gear-box with environment polluting oil, the machine has to be capable of reaching the same rotational speed as the turbine does. It implicates a high requirement regarding the robustness of the machine. The high speed machine which could be suitable for the MEA project would need to have neither sliding contact nor magnets in the rotating machine part.

Table 1. MEA Project Specification

Parameter	Value
Speed range	0 – 12500 rpm
Working speed	6000 – 12500 rpm
Nominal power in generator mode	6 kW
Peak power in generator mode	9 kW for 5 sec
Torque	35Nm at 1500 rpm
	20 Nm at 4000 rpm
Efficiency	>80%
Nominal power in motor mode	>11.5 kW
Weight	<15kg
Overhang torque	<22Nm
Length	<300mm
Diameter	<227mm
Voltage	270VDC 28VDC

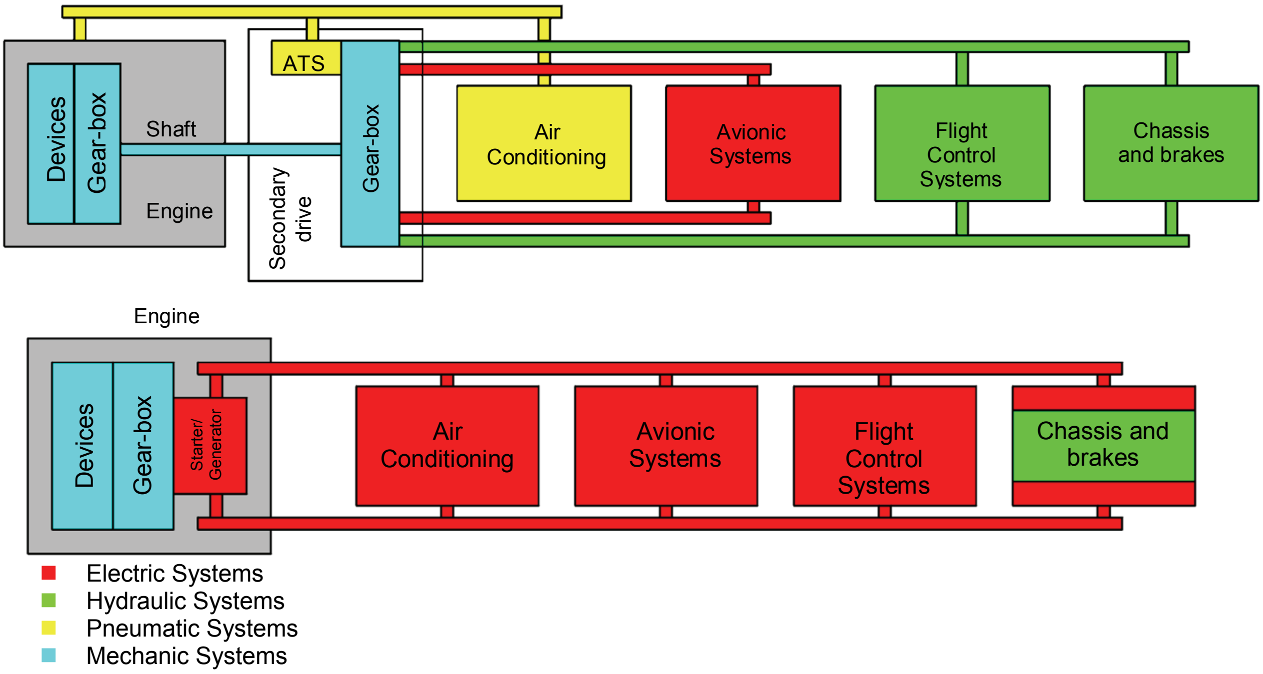

Figure 1. Energy types in a jet airplane [5]

The authors have been involved in the MEA project for over 7 years and developed a novel homopolar machine which was meeting the project requirements [4, 5]. In most currently existing systems, the aircraft engine is started using the so called air-turbine-starter (ATS) also called a pneumatic starter. The air-turbine-starter receives compressed air from an external power source, which can be either mounted on the ground or onboard. These units are usually driven by a small turbine engine. The authors propose a starter which could replace the existing ATS and act as a starter-generator. The homopolar machine has been built and successfully tested at the Military University of Munich [5].

Homopolar machine

A homopolar machine is an A.C. excited synchronous machine, equipped with an armature and excitation winding on the stator side of the air-gap. The machine is equipped with a rotor divided axially and each of the rotor's salient poles in each rotor part has the same polarity. The homopolar flux produced by a ring-formed excitation winding flows axially through the rotor shaft and closes through the stator teeth and stator yoke. In the figure 2 the principle of operation of a homopolar machine is presented [6].

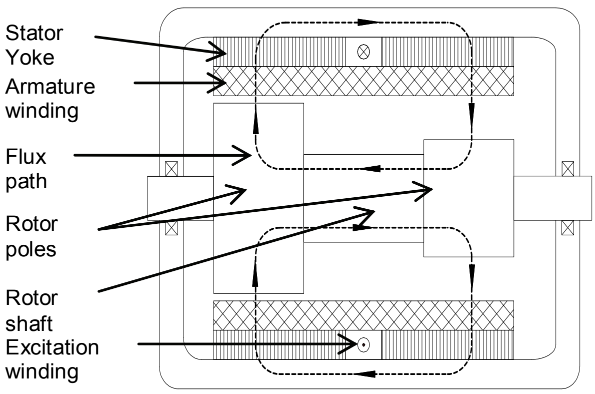

Figure 2. Principle of operation of a homopolar machine

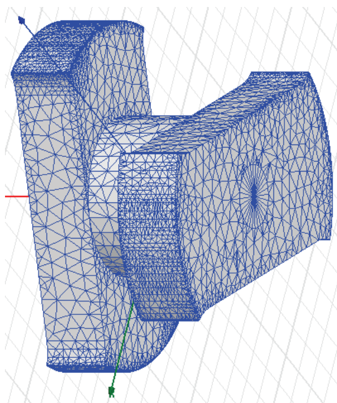

Figure 3. Rotor of a homopolar machine

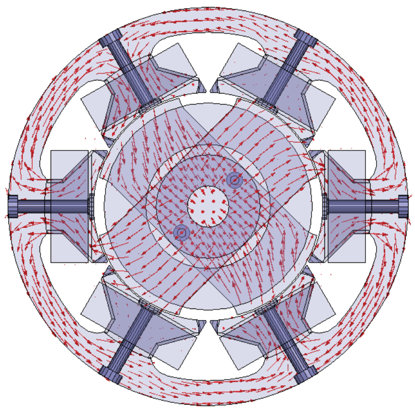

Figure 4. Flux distribution in a homopolar machine

Because of the fact that both excitation and armature windings are on the stator side and do not rotate with the rotor, no sliding contact is required and the total machine can be reduced. It makes the construction very robust and this kind of machine is especially intended for high speed applications. The stator winding carries sine wave currents although there are examples in the literature of homopolar machines with square wave currents [7]. The windings, as in the case of a PM machine, can be realized as a concentrated or lap winding. When using a concentrated winding, the winding can be produced in two different ways. It can go along the whole machine whereas the stator poles have to be mechanically 90° rotated against each other; another possibility is to divide the armature windings axially into two parts, rotate them 90° electrically and keep the rotor poles non-rotated against each other. The second solution would require more copper, increase the reliability but its cost and weight as well.

The homopolar machine is rarely discussed in the literature although it combines many advantages of reluctance and PM machines. It has neither an excitation winding nor magnets rotating with the rotor, and compared to a reluctance drive, it has additional excitation. Due to this fact, not only reluctant torque, but also much higher electromagnetic torque can be produced and additionally, the excitation can be freely adjusted. Due to the absence of magnets, there is no risk of demagnetization of magnets. Additional important criteria when choosing the right machine for this project were:

- High temperature resistance – there is hot air from the turbine, which may disqualify some machine types.
- Low production cost – this criterion is important in every industry branch. Although in the aircraft industry the project budget is higher than in almost any other industry branch, the machine has to be cost optimized.
- High failure tolerance – most of the airplane on-board systems are redundant. As the main source of electrical energy, the machine has to be extremely reliable.

All the criteria mentioned in the previous paragraph predispose only certain machine types to meet the project requirements. For a direct comparison, 3 standard type machines (reluctance, permanent magnet and synchronous) and the previously mentioned homopolar machine have been chosen and thoroughly analyzed.

Starter-generator requirements

When designing a starter-generator, the braking torque produced during short-circuit, is a challenging issue. Short-circuit may appear either in the power electronic unit or directly in the machine. Depending on the kind of short-circuit and the machine design the braking torque may increase with the machine speed. This means that in the event of fault, the braking torque may be very high at high turbine speed [8]. This may lead to safety critical situations. The ideal starter-generator should exhibit no or very low braking torque after a short-circuit fault. Induction and reluctance machines produce no braking torque even if all phases of the machine are short-circuit. In the case of a short-circuit in the armature winding of a homopolar machine, as long as it is possible to switch off the excitation, braking torque will not exist. It has been proved that both induction and reluctance machines can be designed to produce a certain torque level even if one phase does not work; one means to achieve this is to increase the number of phases to more than three (please refer to [8] in the case of the reluctance machine). The inappropriate design of a PM machine may cause an increase in braking torque and it can even reach a higher value than the rated torque. It is possible to design the machine in the way that the braking torque is reduced to 10% of the nominal torque [9]. However, the problem will not be solved completely. Since the main causes of the occurrence of braking torque are the permanent magnets, the easiest way to avoid braking torque would be to demagnetize them.

The ideal starter-generator should have a possibly low weight to torque and volume to torque ratio. Most of the comparisons found in the literature claim that an SRM and an induction machine of the same output would have similar sizes with a slight advantage of an SRM machine. PM machine would be much better than the other two machines in both categories. Most of the comparisons have been made for the inner rotor PM machine. The outer rotor PM machine should be expected to achieve even better results. All the reports mentioned do not compare the homopolar machine with standard machines. The only known report which directly compares homopolar and PM machines describes the homopolar machine as having a slightly worse power/mass ratio than the PM machine [10].

Noise is also an important aspect when choosing the right drive for a military aircraft. In the case of a starter-generator it is not the most important criterion but the noise has to be kept on a reasonable level and it's important from the environmental point of view. The asynchronous machine is known for its low-noise operation. The PM machine can reach the induction machine level, but the design has to be carefully considered and usually the machine performance has to be sacrificed. Because of the less aerodynamic shape of the rotor poles of the homopolar machine and a small axial distance between the rotor poles and the excitation winding, the homopolar machine is expected to be louder than the PM machine. The SRM is definitely the loudest of all four machines. The source of the noise has been described in one of the previous sections.

The operation environment of a starter-generator is very rough. It would be affected by dust, water and vibration and heat produced by the turbine. This means that the ideal machine drive should be very robust and would make the reluctance and homopolar machine as the most interesting solution. Also the induction machine does not have any part which can be easily destroyed. The permanent magnets in PM machine are prone to vibrations and high temperatures and may be demagnetized in unfavorable conditions. Because of the high vertical forces, a possibly large air-gap would be an advantage. In this case the PM and the homopolar machine would win by a clear margin, as they have the largest air-gap of all the machines compared. The SRM requires the smallest air-gap and the induction machine air-gap size is placed between both opponents. The choice of SRM would probably require stiffer and more expensive bearings, due to high radial forces acting on the rotor. Because of the large PM and homopolar machine air-gap, the manufacturing tolerances may also be slightly larger.

The costs of the machine manufacturing depends on many factors but the price of the PM machine, because of the use of high remanence rare earth magnets, will definitely be the highest. Due to a very simple construction and concentrated winding, the SRM should be the cheapest to manufacture. Induction and homopolar machine costs would be between those of the two other machines.

Permanent magnets in the PM machine have certainly one great advantage − in an aircraft where more efficiency and energy saving is reflected in lower fuel consumption and less heat radiation, the use of PM eliminates the need of an additional excitation field and consequently, an additional energy source. On the other hand, the excitation field produced by magnets cannot be varied. This causes high hysteresis and eddy current losses when no high torque is required and gives a low speed range at constant power if surface mounted magnets are used. That is why, for the envisaged application a rotor construction with buried magnets is favorable. Mechanical field weakening methods are known (for example, the mechanical axial displacement of the rotor) but they are complex and usually expensive.

Because of the operation principle of the induction machine, more heat is generated in the rotor than in the case of a SRM or a PM machine and the removal of heat from the rotor is a challenging task. On the other hand much higher rotor operating temperatures are permissible for SRM, homopolar and induction machines [11].

A very important criterion when choosing a machine for starter-generator is its easiness of being excited with low voltage at high speeds. This may be important, when the main circuit collapses and only the 24V board battery is available. In this case only the reluctance machine will cause problems [8].

All the drives presented have many advantages and some of them have at least one crucial disadvantage concerning their application as a starter-generator. In the case of a PM machine, a severe disadvantage would be the braking torque which arises in the case of a fault and its susceptibility to high temperatures. The induction machine has a low power density, large end windings and the heat removal from rotor may cause difficulties. Also the excitation problem at high speeds is a significant problem. The same applies to the SRM which additionally has a high torque ripple. In addition, the SRM, PM and homopolar machine require a precise position sensor. It has to be mentioned that for all the machine types considered, sensorless control methods are known, but it is very doubtful whether the entire operation range can be controlled in the required quality without a sensor. Sensor breakdown is the most critical for SRM, PM and homopolar motor, whereas the induction motor can be driven in open-loop control by a voltage-frequency command.

It can be seen, that also the less popular and less known homopolar machine can be an interesting alternative.

Comparison of electrical machines

To conclude, the main characteristics of the four electrical machines compared in this report with respect to the requirements of the application as starter-generator drive are summarized in the table 2.

When looking at this table it can be seen that the only machine which does not have any feature which could disqualify it as a starter-generator is the homopolar machine.

Table 2. Evaluation of the most important parameters of machines used as a starter-generator in aircraft

	Reluctance machine	Asynchronous machine	PM machine	Homopolar machine
Power density	+	++	+++	++
Efficiency	+	++	+++	++
Costs	++	++	-	+
Reliability	+++	++	+	+++
High speed ability	++	+	+	++
No braking torque in the case of fault	++	++	-	++
Easiness of excitation at high speeds	-	++	+++	+++
Overhang torque	+	-	+++	+
Total:	11	12	12	16

+++ - 3 points; ++ - 2 points; + - 1 point; - Exclusion criterion

The final homopolar machine version meeting all project requirements is presented in the figure 5.

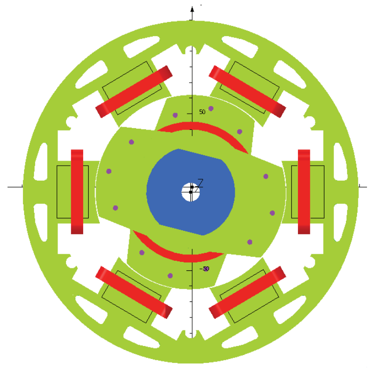

Figure 5. The final version of the homopolar machine

Summary

After all, the More Electric Aircrafts are lighter and more energy-efficient than conventional aircrafts, offer a significant fuel reduction and therefore their negative impact on the environment is much lower than in the case of the conventional aircrafts. They seem to be the only way of keeping the humankind flying in a fuel-efficient manner and without further environmental damage. The novel hompolar starter-generator presented by the authors is the first step to create an environment friendly aircraft.

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