A review of electrified propulsion system concepts for advanced aircraft

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Abstract. The active development of electrical technology provided leeway to creating fundamentally new configurations of propulsion systems and novel aerodynamic layouts of aircraft. Currently, this area of science is in the initial stage of development, but thanks to its huge potential, the number of projects with new propulsion system configurations is growing annually at an exponential rate. A classification of new types of propulsion system configurations is presented in order to understand its wide variety. Beneficial and negative impacts of each configuration are presented.

1. Introduction
The International Civil Aviation Organization (ICAO) predicts that air traffic will double by 2035 [1]. The existing air transport network is not capable of providing such a high level of traffic. To achieve this goal, it will be necessary to increase the aircraft fleet, as well as the number of airports and their capacity, which will inevitably lead to stricter environmental requirements for promising aircraft in terms of noise and emissions.

Over the past 15 years noise standards have been tightened by a total of 17 decibels (Figure 1).

![Figure 1. ICAO noise standards [2]](image)

In terms of emissions of harmful substances by international airlines, the standards have tightened by almost 50% over the past 15 years.

In 2020 and 2030, ICAO plans to reduce NOx emissions by 45% and 60% relative to the 2008 ICAO CAEP/6 standards (Figure 2).
After 2022, it is also possible that additional regulations to reduce emissions of harmful substances in the upper atmosphere will be imposed: NOx – up to 5-10 g/kg of fuel, CO2 – by 10-20% or more of the achieved level, depending on the type of aircraft.

One of the ways to significantly improve the environmental performance of aircraft is to increase their electrification level. The first studies in this area appeared in the second half of the twentieth century. In this regard, in the early 1990s the concept of "more electrical aircraft" emerged on the international scene and implied the replacement of heavy and difficult to control pneumatic and hydraulic onboard systems and components with electrical ones. This step allowed to reduce the weight and size characteristics of a number of aircraft units and increase their efficiency.

The main difference between the More Electric Aircraft concept and the traditional aircraft is as follows:

- the air bleed offtake system to the cabin air conditioning system and the anti-icing system of the wing are excluded, instead, electric-driven compressors are used;
- instead of hydraulic and pneumatic drives of mechanization and landing gears, electric drives are used;
- the power of electrical energy generated on board increases significantly.

At a certain period, the concept was also called the All-Electric Aircraft (AEA) [4]. But at present, this term means an aircraft with an all-electric propulsion system.

Unfortunately, electrification of aircraft onboard systems alone is not capable of meeting the environmental objectives set by ICAO. Therefore, the next stage in the development of science and technology was the electrification of its propulsion system (PS). Thus, in 2018 about 100 projects with new propulsion system configurations were recorded, and in 2019 this number reached 200. In order to understand the wide range of differences in PS this study classifies the configurations of new types of propulsion systems into several types.

Today, the following types of propulsion systems are distinguished [5,6]:

- a traditional propulsion system based on gas turbine or aircraft piston engines;
- an all-electric propulsion system;
- a turboelectric propulsion system;
- a hybrid propulsion system.

The following sections of this paper analyze each type in more detail.

2. Types of propulsion systems

2.1. Traditional propulsion system

A traditional propulsion system is a power package in which a fuel-air mixture acts as a primary source of energy, and mechanical energy sufficient to create the necessary thrust of a given aircraft in all flight modes is provided by one or several thermal engines (Figure 3).
2.2. **All-electric propulsion system**

An all-electric propulsion system (AEPS) is a power package in which electrochemical energy sources (ECES) and/or energy storage act as the primary energy source, and the mechanical energy sufficient to create the necessary thrust of a given aircraft in all flight modes is reproduced by means of one or more electric motors (EM) rotating air propellers (Figure 4). In international terminology, this type of propulsion system is also referred to as a "Pure electrical propulsion system", "Full electrical propulsion system" (or All-electric propulsion system) or "Universally-electric electrical propulsion system".

As a rule, the following are used as an energy source:

- primary electrochemical energy sources (non-rechargeable);
- secondary electrochemical energy sources (rechargeable batteries);
- fuel cells;
- capacitors.

2.3. **Turboelectric propulsion system**

A turboelectric propulsion system (TEPS) is a power package in which a fuel-air mixture acts as a primary source of energy, and mechanical energy sufficient to create the necessary traction of a given aircraft in all flight modes is reproduced by means of electric motors that rotate the propellers or when
used together with one or more thermal engines (Figure 5). In international terminology, this type of PS is called a "Turboelectric propulsion system".

There are two types of TEPS:

- an all-turboelectric propulsion system (Figure 5a);
- a partially turboelectric propulsion system (Figure 5b).

In the first case, all the chemical energy of the fuel is converted into electrical energy by means of serial connection of the thermal engine to the generator. In the second case, only part of the energy is converted into electrical energy, and the rest of the energy is used to generate thrust. In international terminology, this propulsion system is called a "Partially turboelectric propulsion system".

![a) All-turboelectric propulsion system  b) Partially turboelectric propulsion system](image)

**Figure 5.** Types of turboelectric propulsion systems

### 2.4. Hybrid propulsion system

A hybrid propulsion system (HPS) is a power package in which two or more types of energy sources and/or energy storage units are used as a primary energy source. Usually, the simultaneous use of both a thermal engine and an electrochemical source is meant. The mechanical energy sufficient to create the necessary thrust of a given aircraft in all flight modes is reproduced by means of electric motors or when they are used together with one or more thermal engines. In international terminology, this type of power plant is commonly called a "Hybrid propulsion system".

Depending on the connection diagram of electrical machines to the thermal engine, there are serial and parallel HPS circuits.

A serial HPS is a hybrid configuration in which a thermal engine and an electrochemical source act as the main energy sources, and the mechanical energy sufficient to create the necessary thrust of a given aircraft in all flight modes is reproduced by means of electric motors (Figure 6). In international terminology, this type of power plant is commonly referred to as a "Serial hybrid propulsion system" or a "Full serial hybrid propulsion system". Such a propulsion system differs from a turboelectric one as it has an electrochemical source or energy storage. Usually, the thermal engine operates in all flight modes and its power is sufficient to ensure the cruising flight mode, but insufficient to ensure takeoff. The electrochemical source is primarily designed to increase power during takeoff and climb.
Figure 6. Serial hybrid propulsion system

A parallel HPS is a hybrid configuration in which both a thermal engine and electric machines are used to generate mechanical power sufficient to create the required thrust of a given aircraft in all flight modes. Figure 7 shows one of the possible configurations of a parallel HPS. In international terminology, this type of propulsion system is referred to as the "Parallel hybrid propulsion system".

In addition to the above listed types other HPS include serial-parallel HPS, partially serial and partially-parallel and other configurations.

Figure 7. Parallel hybrid propulsion system

3. Conclusion

This study presents a classification of existing electrified configurations of propulsion systems, depending on their composition and the connection diagram of nodes and systems. An assessment of the potential advantages and disadvantages of each PS configuration shows that the application of one or another configuration directly depends on the level of development of electrical technologies and the tactical and technical requirements for the aircraft.

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