Power Systems

Yuan Jiang
Qing Li

Vacuum Circuit Breaker for Aviation Variable Frequency Power System

Theory and Application of Arc in Electrical Apparatus

Science Press
Beijing

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Power Systems

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Yuan Jiang
School of Automation
and Electrical Engineering
University of Science
and Technology Beijing
Beijing, China

Qing Li
School of Automation
and Electrical Engineering
University of Science
and Technology Beijing
Beijing, China

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Preface

In more electric aircrafts, electricity is generated by a frequency-varying generator and the current frequency is in the range of intermediate frequency (IF) 360–800 Hz, which is called a variable frequency (VF) power supply system. As the frequency and current increase, the breaking process becomes difficult and hence new circuit breakers are required to ensure the safety of the aircraft. Vacuum circuit breakers have been widely used in civil power systems, and are potentially suitable for application in the power supply system for aircrafts. Current breaking in vacuum circuit breaker is a systematic theory to study the physical processes that occur between two contacts, related to many fields, such as electric, mechanic, materials, computational technology, and so on. The goal of the research is to improve the reliability of breaking process and the life of the vacuum circuit breaker under the premise of meeting the economic and safety benefits.

This book focuses on the vacuum circuit breaker in variable intermediate frequency power supply system, mainly involving characteristics of current interruption and breakdown, as well as arc theory. In this book, the relevant theories, devices, tests, simulation, and experimental methods of the vacuum circuit breaker in variable intermediate frequency conditions are introduced in detail. The effect of frequency on characteristics of vacuum arc and the mechanism of breaking and post-arc breakdown under different operating conditions are discussed.

Combined with the practical application, the effect of contact structure on the breaking characteristics, such as arc mode, arc pinch, and magnetic field in a vacuum circuit breaker are analyzed, and the test technology of VF vacuum circuit breaker is proposed. The post-arc breakdown problems, involved in the voltage spike, marginal effect on field emission, and sputtering of macroscopic particles, are deeply discussed by the aspects of basic theory, research methods, and simulation. The whole book (or part of the chapters) can be used as a textbook or reference for graduate and senior undergraduates.

I would like to thank my wife, Ms. Qian Zhang, for her contribution to the translation of this book and her support for my scientific research.

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Due to the limited level of the author, there are still some shortcomings in the book, please correct.

Beijing, China Dr. Yuan Jiang

The original version of the book was revised: Funding information has been updated. The correction to this book is available at https://doi.org/10.1007/978-981-33-4781-6_6

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Introduction

1.1 More/All-Electric Aircraft and Aviation Power Systems

1.1.1 More/All-Electric Aircraft

As a strategic industry, aviation industry is an important symbol of science and technology, industrial base, and comprehensive strength, and has been highly valued and given priority to development by all countries worldwide. With the application of new technologies such as electromechanical actuators and power by wire (PBW), the onboard load capacity has been greatly improved. While the power consumption has been increased and the power supply quality and reliability have been improved, the existing power system is unable to meet the power demand, thus promoting the development of large capacity aviation power supply system. Facing the future, the secondary power system of aircraft will gradually be unified into the electric power system, from the traditional multi-energy system such as mechanical energy, hydraulic energy, and pneumatic energy. That is named more/all-electric aircraft. Electrification has the advantages of low fuel consumption, high reliability, high maintainability, and high energy conversion efficiency, as well as is an important way to support green aviation and the development trend of aviation industry. Since 1990, the Department of Defense and NASA in the USA have been conducting demonstrations and research on more/all-electric aircraft. By 2012, they have completed the improvement of the generation form and power level of the DC power supply system for F-22 and F-35 aircraft in three stages. Currently, the MTA program is being promoted to achieve Megawatt generation power of Tactical Aircraft [1, 2]. Since 2013, "Three Musketeers" in China have made their first successful flights, among which the large conveyer Y-20 and the large passenger aircraft C919 have adopted more electric technology.

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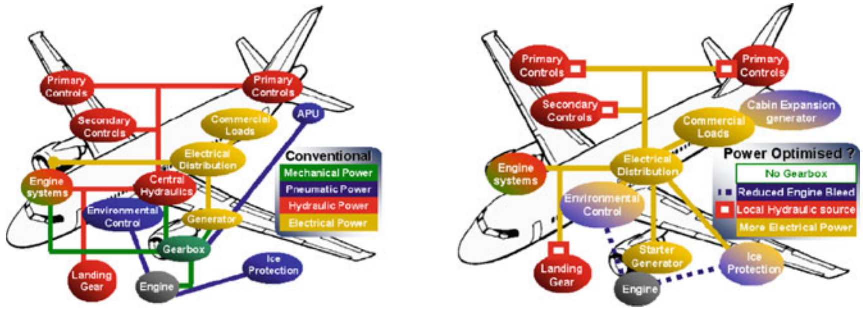


(a) Schematic of conventional power distribution **(b) A potential optimized architecture**

Fig. 1.1 Energy systems in conventional and more electric aircraft

In the energy system of traditional aircraft and more electric aircraft, as shown in Fig. 1.1, the traditional aircraft secondary energies include mechanical power, pneumatic power, hard power, and electrical power. The main secondary energy of more electric aircraft is electric energy and PBW technology is adopted, and hydraulic energy is used in local parts [3, 4].

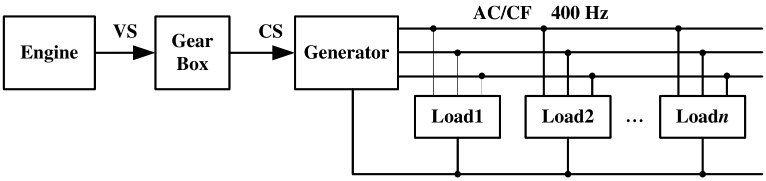
1.1.2 Aviation Power System

1.1.2.1 Aviation AC Power System

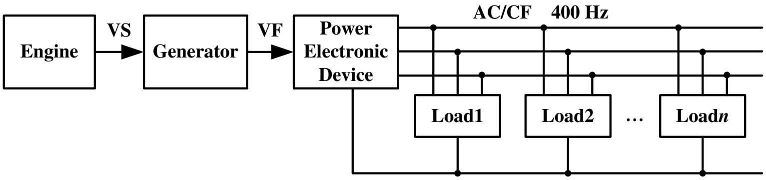
The AC power systems currently used in more electric aircraft, including constant speed and constant frequency (CSCF), variable speed and constant frequency (VSCF), and variable speed and frequency conversion (VSVF), are shown in Fig. 1.2.

Most of the traditional AC power generation systems in aviation use CSCF power supply scheme with an intermediate frequency (IF) of 400 Hz. The aviation generator is connected to the engine through the constant speed mechanical transmission device to make the power frequency stable. However, the device is large and inefficient. The CSCF power system has the following problems: large volume of mechanical structure, low efficiency, low reliability, large amount of maintenance tasks, etc. It is difficult to increase capacity further. In the world, the maximum capacity developed is 150 kVA, and the maximum installed capacity is 120 kVA for Boeing B777 aircraft. In China, the maximum capacity developed is 90 kVA and the maximum installed capacity is 60 kVA.

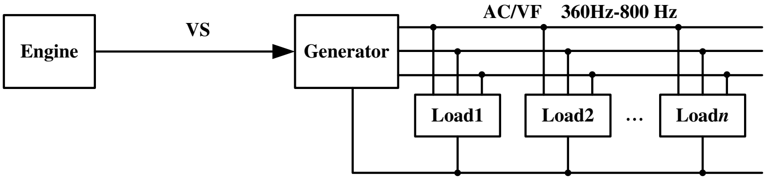
Compared with the CSCF power system, there are some advantages for the VSCF power system, such as no constant speed device, no high stress mechanical/hydraulic components, or easily worn parts. It overcomes the disadvantages of constant speed device, which has high reliability, good maintenance, and low life cycle cost. It is highly efficient at generating electricity, increasing efficiency by 10%. At the same



(a) CSCF power system



(b) VSCF power system



(c) VSVF power system

Fig. 1.2 AC power system for more electric aircraft

time, the power quality is better, and the voltage precision is higher, and the voltage transient is smaller. Unfortunately, there are also some new technical problems. For example, constant frequency is realized by power electronic devices. Due to the limited power, the capacity is generally 40 kVA, and the capacity on MD-90 aircraft is 60/75 kVA, which has reached the limit, and the temperature requirement of the installation environment is strict. There is a problem of compatibility with low power factor loads, such as inductive and capacitive loads. Therefore, the VSCF power system has been used as auxiliary power for a while in B777, and all of them have been replaced already.

The most advanced aviation variable frequency (VF) generator can connect the generator to the engine, making the frequency of the power supply system variable IF 360–800 Hz. The VF AC power supply system is composed of an alternator and controller, which has only one transformation process. The alternator is directly driven by the engine motor box, without a constant speed transmission mechanism or constant frequency power electronic device. The system has the characteristics of simple structure, lightweight, small volume, high power density, high reliability, low life cycle cost, good maintainability, and high energy conversion efficiency. However, there are also some technical challenges, such as for load adaptation, resulting in an increase in the volume and weight of electrical equipment,

Table 1.1 AC power system structures of typical more electric aircraft

Aircraft model	Main generator capacity (kVA)	Line voltage (V)	Main generator frequency (Hz)	APU capacity (kVA)	APU frequency (Hz)	Emergency power capacity (kVA)
A320ME	4 × 75	200	360–800	2 × 120	400	2 × 80
A380	4 × 150	200	360–800	2 × 120	400	70
B787	4 × 250	400	360–800	2 × 225	400	10

and the addition of controllers. According to the public information, the more electrification of large aircraft adopts the AC power generation with variable frequency scheme (the frequency range is 360–800 Hz). The typical representatives are the large airliners Airbus A380 and Boeing B787 [4]. The VSVF power capacity of A380 is 600 kVA, the line voltage is 200 V, and four 150 kVA alternators are driven by the main engine. Boeing B787 is closer to all-electric aircraft, with a total VSVF power capacity of 1.4 MVA and line voltage of 400 V. The main engine drives 4 × 250 kVA AC starters/generators, and the auxiliary power unit drives 2 × 225 kVA AC starters/generators. In addition, both the Y-20, a large transport aircraft developed in China, and the C919, a large passenger aircraft developed under the auspices of COMAC, have adopted VSVF power supply (Table 1.1).

1.1.2.2 Aviation HVDC Power System

With the increase of power consumption, power quality, and reliability, the traditional 28 V low-voltage DC power supply has been unable to meet the needs of modern aircraft, which promotes the development of the 270 V high-voltage DC (HVDC) power supply system.

The transmission lines of HVDC power system are light in weight, simple in structure, high in power density, high in energy conversion efficiency, and easy to realize uninterrupted power supply, which has become the first choice of power supply system for military aircraft. For example, F-22, F-35, and reconnaissance/attack helicopters RAH-66 are all equipped with HVDC power systems. The F-14A, S-3A, and anti-submarine aircraft P-3C are also partially powered by HVDC. For civil aircraft, although the main power supply of Boeing B787 is the VF alternator, 4 × 150 kW power supply with ±270 V is formed through the rectifier and other power electronic devices (Table 1.2).