Weight saving in the electrical distribution systems of aircraft using innovative concepts

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Weight Saving in the Electrical Distribution Systems of Aircraft Using Innovative Concepts

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Abstract: There is a growing need for an electrical generation and distribution system for modern commercial aircraft. In the field of aviation, there is a trend towards 'more electric aircraft', which implies the substitution of the hydraulic and pneumatic systems by electrical ones. This trend, in effect, results in an increasing demand for energy. In aircraft construction, there is a state-of-the-art inflexible point-to-point supply of loads based on a complex and expensive electric load analysis. Connecting the load to different feeders during flights is not possible because of rigid wiring.

The article introduces modern concepts for improving the electrical distribution system—namely feeder balancing and phase balancing. These methods involve utilizing intelligent switching nodes based on power semiconductor devices. The concepts allow for a reallocation of electrical loads on different power feeders. The article will also present an analysis of the integration of a multifunctional fuel cell system with a focus on the necessary changes in the electrical network of an aircraft. In less than a decade's time, commercial aircraft could use low-temperature fuel cells to substitute the auxiliary power unit and the ram air turbine, which is used in ground phases and in cases of turbine failure. Using fuel cells could aid in constructing a completely different layout of the electrical network implementing a ±270 V DC voltage level. The increasing electrical demand of aircraft requires an energy-efficient power supply network.

1. INTRODUCTION

Since 2012, all airliners taking off from or landing in Europe have been required to participate in the emissions trading, whereby they need to pay for their CO_2 fabrication. Moreover, the price of fossil fuels is projected to rise in the coming years. The optimum utilization of the electrical network capacities leads to cost efficiency improvement for aircraft, thereby reducing emissions. Since electrical power accounts for only 0.2 % of the whole engine power in cruise flight phase, the energy saving will not be very high. However, reducing the weight of the electrical network has a significant impact. A reduction of one kilogram of weight saves US$4,500 for a midrange aircraft over a 20-year operation period [1]. Figure 1 illustrates that many hydraulic, mechanical and pneumatic components of conventional aircraft can be replaced by electrical ones in modern aircraft.

Since power feeders are seldom completely utilized, in-flight measurements have shown the possible benefits of optimizing the distribution grid. One of the on-going projects at the Department of Electrical Power Systems at Helmut Schmidt University is the research on ‘Flexible and energy-efficient aircraft power-supply systems’ for the development and analysis of new aircraft architectures for power feeder and phase balancing.

The auxiliary power unit (APU) installed in the rear of a commercial aircraft, which is used during ground operations and in cases of emergency, is mainly responsible for the noise and CO_2 emissions at airports. Latest developments in the field of fuel cells systems improving the efficiency and reliability can lead to a substitution of the APU. Research on installing a fuel cell system into the electrical structure is undertaken in the project ‘Cabin Technology and Multifunctional Fuel Cell Systems’ at Helmut Schmidt University.

2. CONVENTIONAL ELECTRICAL GRIDS OF AIRCRAFT

This section discusses the conventional electrical grid in an aircraft and gives an overview of the state of the art. In general, the electric grid comprises the generation, transmission, distribution, protection devices as well as the monitoring parts.

2.1. Electrical Energy Generation

Customarily, airliners use a main bus voltage of 115 V in a three-phase system to distribute electrical energy. Latest aircraft use also 230 V_{AC} to reduce the currents and the needed cable diameters [2]. An aircraft usually has two or four jet engines to produce the thrust. A synchronous generator is installed on the same shaft to produce the electrical energy. On most airliners, the AC frequency is fixed at 400 Hz using a constant speed drive device. Using higher frequencies reduces the size of the transformers. If the frequency is too high, the skin effect causes the resistance of the conductor to increase. Depending on the angular velocity of the engine, modern aircraft have a variable frequency in the range of 360…800 Hz, which helps to avoid the heavy and maintenance-intensive constant speed drives [3]. In order to supply the DC loads, the AC voltage is converted into 28 V_{DC} using a transformer and a rectifier circuit unit.

2.2. Electrical Energy Distribution

The energy produced by the generators is transmitted via the generation route to the primary electrical power distribution centre (PEPDC), which is located at the front of an aircraft. Flight-critical loads, high power consumers as well as the secondary power distribution boxes (SPDBs) are supplied through the PEPDC. Cabin and cargo loads are supplied through the SPDBs, which are placed in each cabin section of an aircraft to avoid long wiring in the cabin loads. An electrical distribution line or feeder is connected to at least one SPDB per aircraft side, whereas each SPDB is usually connected to more than one feeder [4]. The fuselage, which is usually made of conductive aluminium and is used as the return path for the current, also provides protection from lightning. Load segregation is important for reasons of safety and so flight-critical loads have distinct paths from cargo and cabin loads. In addition, the generators from one side never supply energy to the other side of the aircraft in normal operation. But each generator is able to provide the whole aircraft with electrical power in case of an outage. It is for this reason that they have to be oversized. Figure 2 illustrates the conventional distribution system of a modern aircraft.

2.3. Emergency Energy Systems

In some cases, the grid has to be supplied from sources other than the main generators. This situation occurs during ground operations and in cases of engine loss. In these cases, an auxiliary power unit (APU) and often a ram air turbine (RAT) are integrated into the aircraft grid [5]. Batteries bridge the time from the engine loss to the activation of the APU or RAT. If all systems fail, the batteries supply power to the most essential parts for a short period of time. The DC voltage produced by the batteries is then converted into 115 V_{AC} to provide for flight-critical loads. Modern fuel cell systems can replace the APU and RAT, and can downsize the batteries. The first application area for the fuel cells will be the substitution of the APU. Thus, pollution and noise during ground operations can be reduced.

2.3.1. Auxiliary Power Unit

The auxiliary power unit—a combustion turbine producing 115 V_{AC}—is typically located at the back of the aircraft. 28 V_{DC} can be generated through a rectifying unit. During flights, electrical power for the aircraft is generated by the main engines. The efficiency can exceed 40 %. During ground operations, the main engines are shut off and the conventional APU takes over the electrical energy supply. This kerosene-operated turbine is very noisy and inefficient. Hence, the efficiency of the conventional APU is only about 10 %. Additionally, a large part of the total emissions at an airport is caused by the APU [6]. Nowadays, many airports have strict regulations for using the conventional APU to limit environmental repercussions.

2.3.2. Ram Air Turbine

During an emergency and APU loss, the RAT can be ascended. The RAT is a small wind turbine installed under the airfoil to generate power in case of turbine loss. During the descent of an aircraft, the RAT utilizes the airstream to generate rotational mechanical energy, which the integrated generator then converts into hydraulic power and in modern aircraft, into electrical energy of 115 V_{AC}.

2.4. Protection Devices

Protection devices are an integral component of the electrical grid to ensure safety of operations and high reliability. In order to protect the electrical network and the loads, fuses and circuit breakers are installed. If a short circuit occurs, the current path of the fuse is opened. The advantage of the circuit breakers lies in their reset ability. As a result, this bimetal technology is more commonly used. If the resetting is possible via a remote, the device is called a remote-controlled circuit breaker (RCCB). The loads with current smaller than 15 A, on the other hand, are nowadays switched and protected against high temperature and short circuit by solid state power controllers (SSPC) in the latest breeds of aircraft. SSPCs use power semiconductors such as MOSFETs and microcontrollers. They can be remote-controlled and programmed for different trip values. The electronic triggering is faster than that of the circuit breakers. An SSPC can imitate the behaviour of a fuse, which is illustrated in Figure 3. At an adjustable high current, the SSPC trips (Region 1), while lower currents can appear for a longer time before it trips (Region 2) [7]. Moreover, SSPCs can be modified to realize the switching node concepts introduced in chapter 3.

3. MODERN CONCEPTS

The concepts of phase and feeder balancing, which are to be introduced in the next sections, are aimed at increasing the performance of the electrical grid. These concepts are applicable to commercial loads only. Flight-critical loads are not incorporated due to safety reasons. Commercial loads are non-critical part of the loads, which would not affect safety during any of the flight phases. Still, these concepts remain highly reliable because of the fact that disturbance could lead to flight delays, flight cancellation or in-flight turn-backs. Phase and feeder balancing have limited applicability on each side because they are not allowed to connect different grids. The generators supply power to their own grid without interconnecting with other generator grids.

An electric load analysis shows the potential to reduce weight in the electrical generation and distribution system. Using a power management system ensures that the network does not get overloaded at any point in time. Without this concept, a high power demand of the loads or a fault could activate a fuse, thereby opening the power supply line. In case of a high energy demand, the load management turns the consumers off. Therefore, load segregation is used on a priority basis. Some loads, such as thermic loads, can be turned off or dimmed for a certain time, whereas others can be activated at different times. For example, using coffee machines at different times reduces the demand for power. Temporarily disconnecting these loads does not result in discomfort for passengers [8].

3.1. Phase Balancing

The return current of the electrical three-phase AC system flows through the structure of the fuselage, which is usually made of conductive aluminium. No cables are used as return line in aircraft for weight-saving purposes. A symmetric three-phase system generally does not have return current. The voltage drop over the structure is zero, which means that the only voltage drop is the one through the path from the primary electrical energy distribution to the loads. When the asymmetric in the three-phase system increases —e.g. due to different single-phase loads in a three-phase system—the return current becomes higher. Not only does it cause more electrical power losses but also increase the voltage drop. This has to be compensated through the feeders leading to further electrical power losses as well as through more weight owing to the necessary overdesign of the feeders. Figure 4 shows different scenarios of loads leading to return current because of different amplitudes or different phases. Also single-phase loads can be arranged in such a way that the return current is zero but the phases are unequally utilized (Fig. 4 c).

These considerations have led to the concept of phase balancing. It is aimed at the elimination or minimization of the return current of the three-phase system. Figure 5 shows left the conventional rigid connection between the phases and the loads and right the new flexible possibility to connect single-phase loads to either one of the phases via a three-fold switch. The concept of phase balancing is even more interesting to consider in case the aircraft fuselage is made of carbon-fibre-reinforced polymer (CFRP) material. When it comes to a poorly conducting fuselage, there are different possibilities for the return current grid: one approach involves installing additional cables for the layout of the return current network, which would increase the weight of the distribution system. Another would be implementing a metal braiding into the CFRP fuselage. A good solution is using the existing conductive structure of the aircraft. These elements have to be interconnected with a short cable. However, they increase the weight of the aircraft only very slightly. Phase balancing would lead to a minimum layout of the metal braiding and return cables, thereby saving weight. Also the voltage drop over the return path can be reduced and thereby the primary voltage drop is allowed to be higher, leading to smaller cable diameter.

One method of realizing the phase balancing concept is the use of known technologies from the conventional power supply such as flexible alternating current transmission system (FACTS). The reactive current part, which has to be compensated for, is fed out of phase into the network by these systems. Nevertheless, due to the high switching rate, this technology is not suitable for use in aircraft. A more suitable way to realize phase balancing is the implementation of a reallocation procedure for the single-phase loads. This implies in the first place that each single-phase load needs the option to be supplied by each of the three phases of the power system (Figure 6). The threefold-switches measure the input voltages and the currents and by that they can determine the phase shift of the loads. For n single-phase loads (Z_1 … Z_n), $3{\cdot}n$ solid state power controllers

(SSPC) are necessary. For each instant of time, the status of the SSPCs can be merged into a [3 x n] matrix, indicating the allocation of the loads in the three-phase system. With the help of the measured values of the phase currents as well as the phase-to-phase voltages, there are several ways of computing the degree of asymmetry. A low return current can be achieved using non-linear optimization techniques like genetic algorithm. Hence, the degree of asymmetry is lowered to a minimum and this state is preserved until the happening of the next event, i.e. either automatic or manual turning on and off of a single phase load [9].

3.2. Feeder Balancing

The usual architecture of the electrical grid of an aircraft comprises a primary and several secondary power distribution boxes (SPDBs). Due to reliability reasons, the SPDBs are supplied from multiple feeders from the PEPDC. Three criteria have to be fulfilled by the feeders: the minimum sizes for a specific voltage drop, maximum temperature and the protection devices have to meet the requirements [10]. Based on an electrical load analysis, the single-phase loads are allocated to one of the phases of the two or more feeders, which supply the SPDB. The usage of the loads varies by phase, as a result of which the different feeders do not conduct the same current most of the time.

Currently, the feeders are designed for the maximum current appearing during a flight. In consequence of this sizing on maximum power, the expected demand of all attached loads is used. Overloads that might occur during a normal flight are thus avoidable. However, measurements show that the maximum current appears only for a short time during a flight. The operational power is much smaller. If a feeder carries its maximum current, the other feeders usually do not.

Another concept using smart switching nodes is feeder balancing, which is also considered in this article. Feeder balancing is meant to reduce the feeder diameter and thereby to save weight. To symmetrize the current flowing through all feeders, intelligent switching nodes could switch loads from one feeder to another. This, along with its ability to connect each single load to all phases of a feeder, would lead to high granularity. The disadvantage, on the other hand, would be the high demand for switches and the additional cable length to extend all feeders to the SPDBs. Figure 7 illustrates feeder balancing using an additional box between the contact terminal blocks (CTBs) and the SPDBs. This is one possible topology that offers a low number of switches but rough granularity. Switching on lower levels or even the SSPC level offers much higher granularity. On the other hand, the number of necessary switches is higher. Feeder balancing is not limited to AC feeders; the DC feeder of the cabin and cargo can be symmetrized in the same way.

3.3. Lightweight Fuel Cell Integration

The reduction of pollutant emissions and hence the increasing of the efficiency is one of the major challenges for the aviation industry. One idea in the context of executing the More Electric Aircraft concept is the replacement of the traditional kerosene fired Auxiliary Power Unit (APU) by a Multifunctional Fuel Cell System (MFFCS). A Fuel Cell (FC) system operates noiselessly and the efficiency can reach more than 50 %, compared to the 10 % efficiency of the conventional APU. A MFFCS provides further applications that could be used in modern aircraft. The main benefits include the ridding of kerosene dependency, water generation, the tank and cargo inerting, the resultant reduction of ground support [11] and the fire suppression system. Furthermore, the RAT-based emergency system could be replaced by a fuel cell system. Figure 8 schematically illustrates a possible design of the installation point of the fuel cell system in the tail of an aircraft.

In comparison with conventional APUs, a FC stack provides a load-dependent DC voltage. The electrical power of the FC stack is the result of stack current and voltage. The stack voltage is equal the sum of the single-cell voltage. DC/DC converters can be used to transform the variable FC output voltage into the level of constant High-Voltage Direct Current (HVDC). Using a ±270 V_{DC} grid makes it possible to use two different voltage levels, namely 270 V_{DC} and 540 V_{DC}. To achieve a lightweight electrical fuel cell system one approach is to use a step down (buck) converter with an additional electrical bypass, related to an optimal FC output voltage. When the FC output voltage is equal or within the allowed HVDC limits the FC can be connected directly with a bypass to the HVDC grid. Due to the allowed wide voltage range (30 V_{DC}) of the HVDC onboard grid the electrical DC/DC converter structure can be designed solely to 30 % of the maximum rated power. Figure 9 shows the typical polarization curve of a fuel cell stack with the allowed voltage limits, maximum power point of the overall system and the maximal converter designed point [12].

The polymer electrolyte membrane (PEM) fuel cell is the preferred type of fuel cell technology for use on aircraft. The benefits of the low-temperature fuel cell are better dynamics and higher-power density compared to other fuel cells. The PEM's operation temperature is in the range of 60–80°C. In the coming years, the high temperature polymer electrolyte membrane (HTPEM), which has an operation temperature of up to 180°C, could be an interesting alternative [13].

The PEM stack must be supplied with hydrogen (H_2) and oxygen (O_2). The oxygen is drawn from the environment air to save the weight of the oxygen gas bottle. To achieve the required pressure, an air compressor is used. Although the dynamics of the PEM is very high, it might fail to supply all connected consumers sufficiently. Measurements have shown that large load steps are difficult to handle, as a result of which the voltage in the electrical grid would break down. Investigations have shown that different solutions for the improvement of the fuel cell dynamics are possible.

Despite the use of an intelligent power management, the fuel cell system could integrate additional short-time energy storage (STES). For this reason a STES based on supercapacitors (SC) are connected to the FC System. To prevent an oversizing of the energy storage the minimum capacity to achieve the power quality for a worst case scenario can be determined by an innovative mathematical approach [14]. Consequently, the hybridization of the weight optimized MFFCS leads to satisfactory dynamics and it fulfils the required power quality of the overall system which is presented in Figure 10.

4. CONCLUSIONS

Phase balancing minimizes the electrical return current. Feeder balancing can reduce the diameter of the power feeders. The two concepts can be regarded separately, but an all-embracing view leads to more synergetic effects. Modern power semiconductors are capable of handling switching operations necessary for both concepts. An intelligent load management (LM) is necessary for avoiding overloads but the rate the LM has to deactivate loads can be reduced using phase and feeder balancing.

Using a fuel cell system together with a high-voltage DC distribution network can result in synergetic effects. New-generation aircraft already use high-voltage DC networks. Using DC instead of AC has the following advantages—it obviates the need for reactive power and can weight-optimize electrical converters. As a result, the currents are lower and the diameter of the feeder can be reduced. To change the voltages to different levels, switching converters are needed. Hence, to compensate for the harmonies produced power factor correction devices need to be used.

Concepts like phase and feeder balancing are necessary for aircraft. They can be implemented in updated versions of existing aircraft by modifying their existing structures. However, safety analyses need to be accomplished to ensure safe operations at any state.

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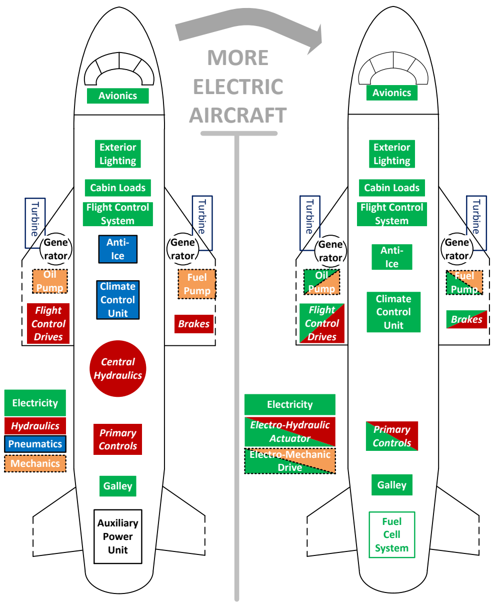

Fig. 1 More electric aircraft substituting pneumatic, hydraulic and mechanical systems

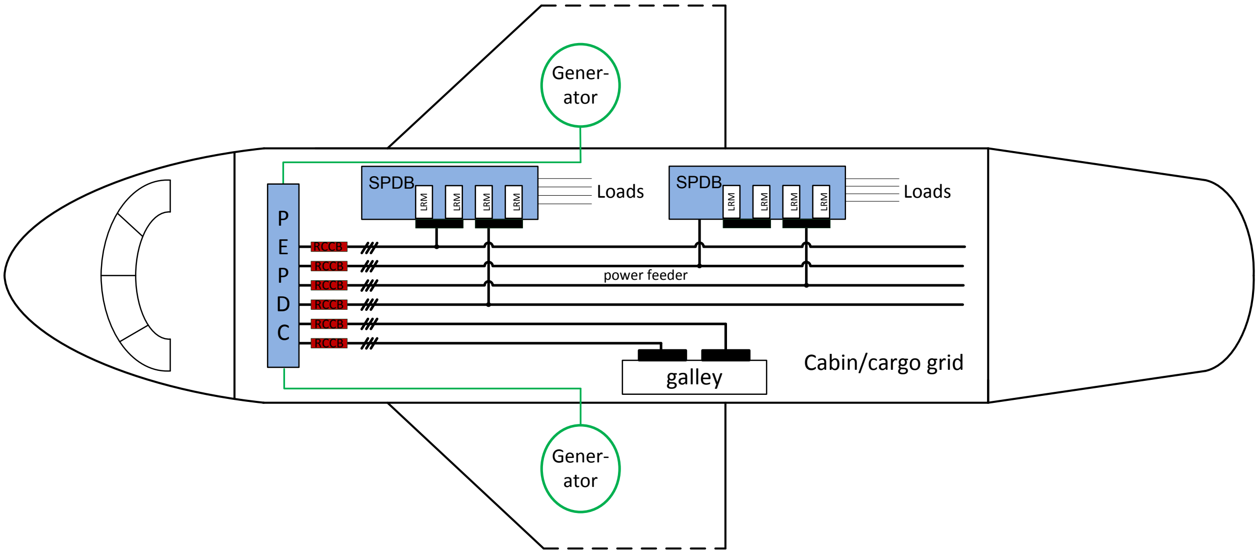

Fig. 2 Conventional electrical distribution system in a modern aircraft

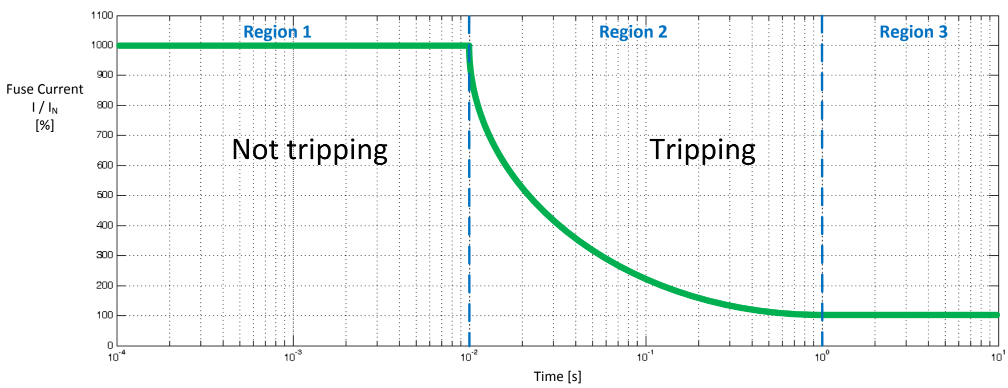

Fig. 3 Typical trip curve for solid state power controllers

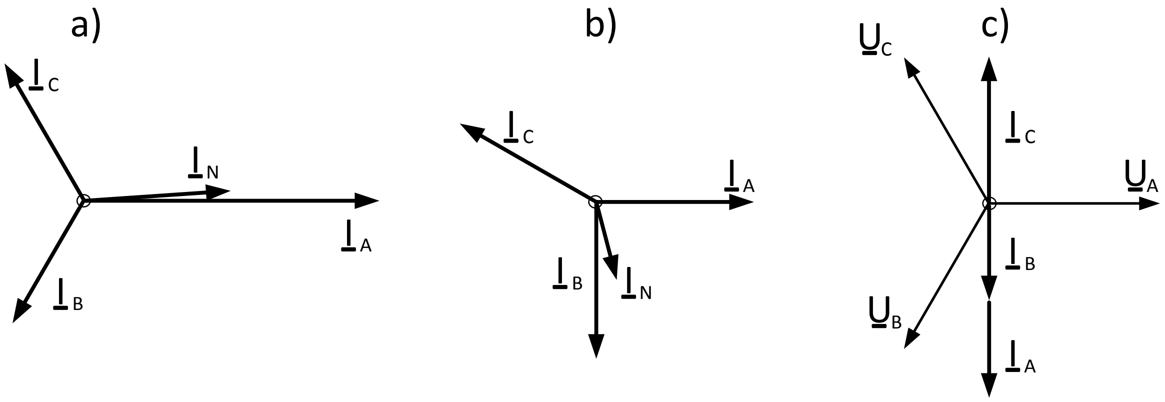

Fig. 4 Examples of different loads for a three-phase system a) different amplitudes b) and different phase shifts leading to return current and c) unequally utilized phases without a return current

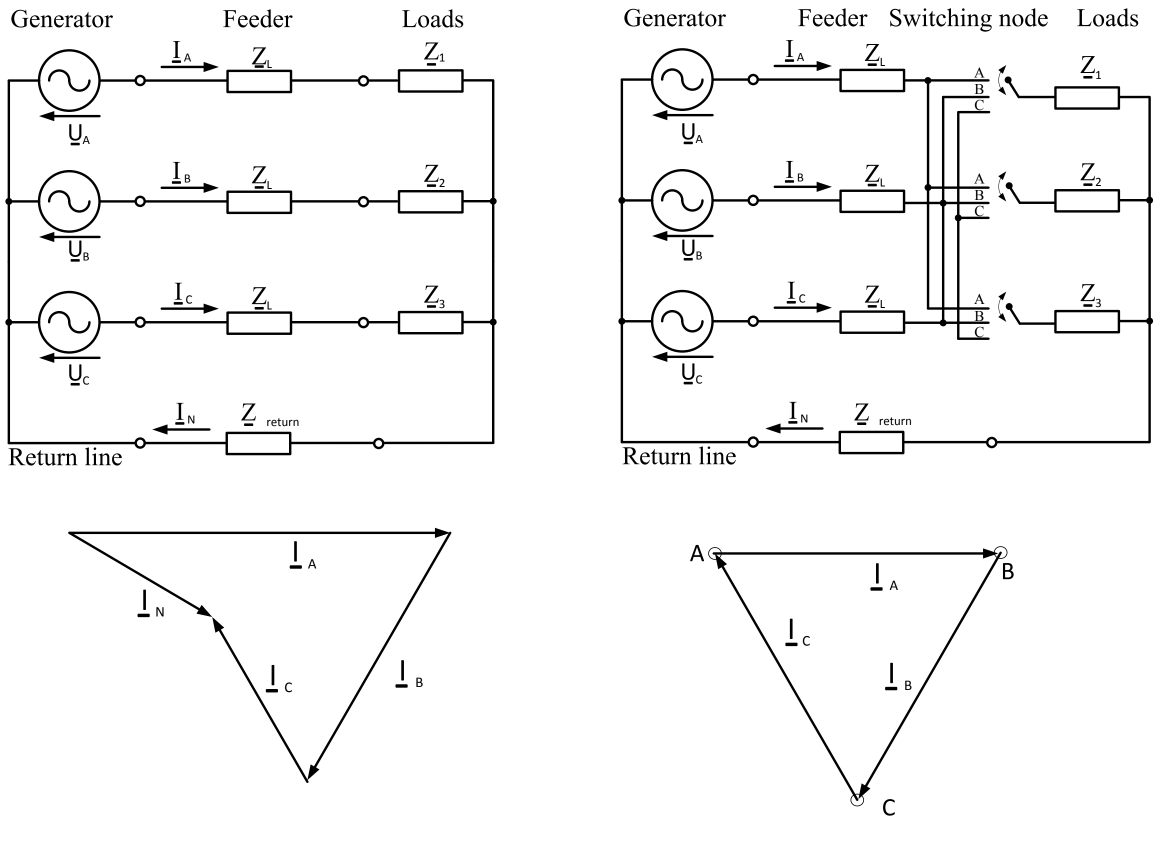

Fig. 5 Phase balancing concept on-board an aircraft

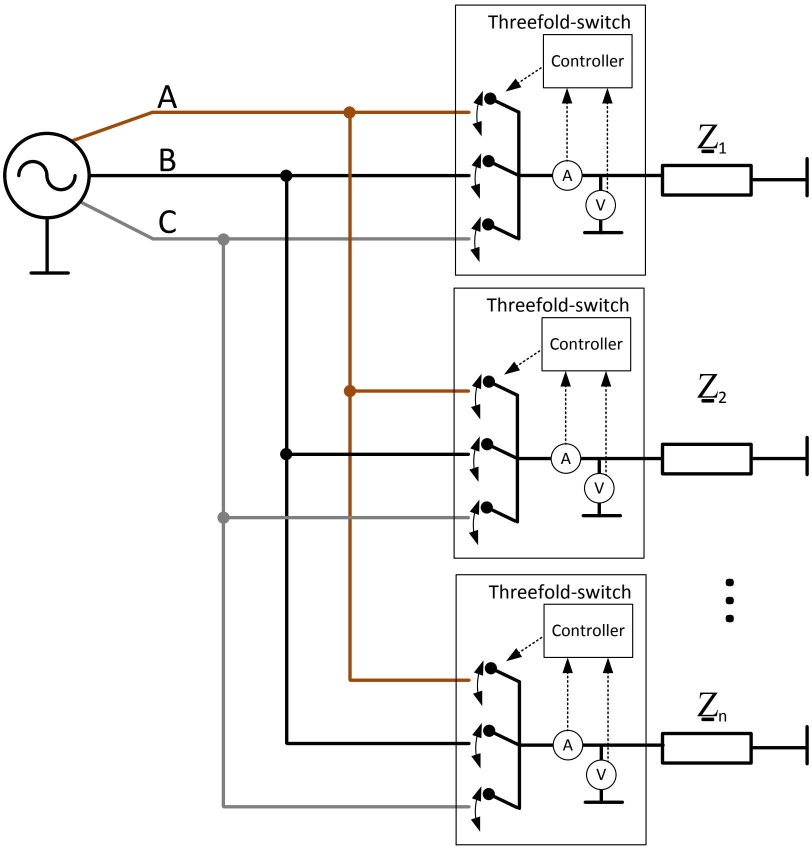

Fig. 6 Procedure for phase balancing with threefold-switches

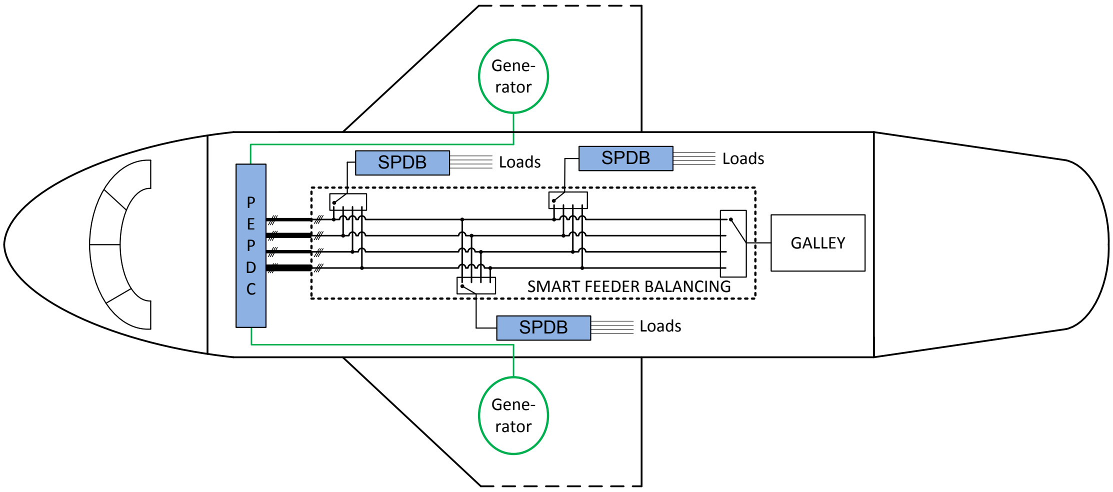

Fig. 7 Smart feeder balancing on-board an aircraft

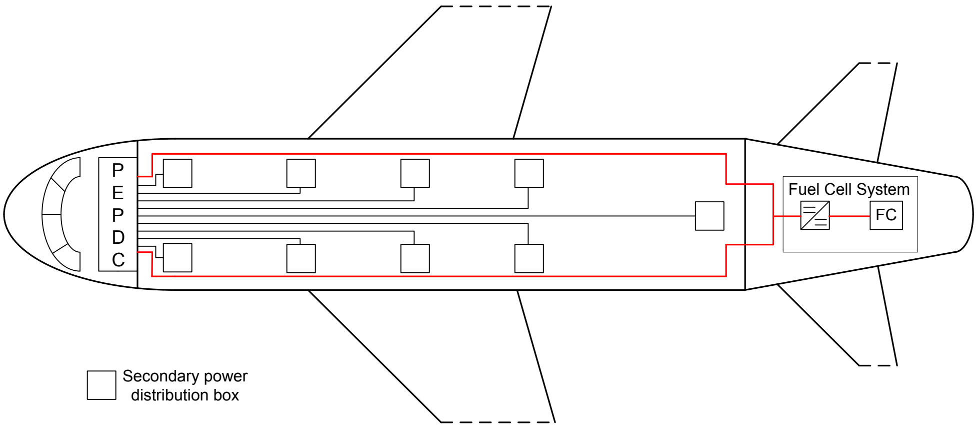

Fig. 8 Possible integration point of a fuel cell system in a modern aircraft

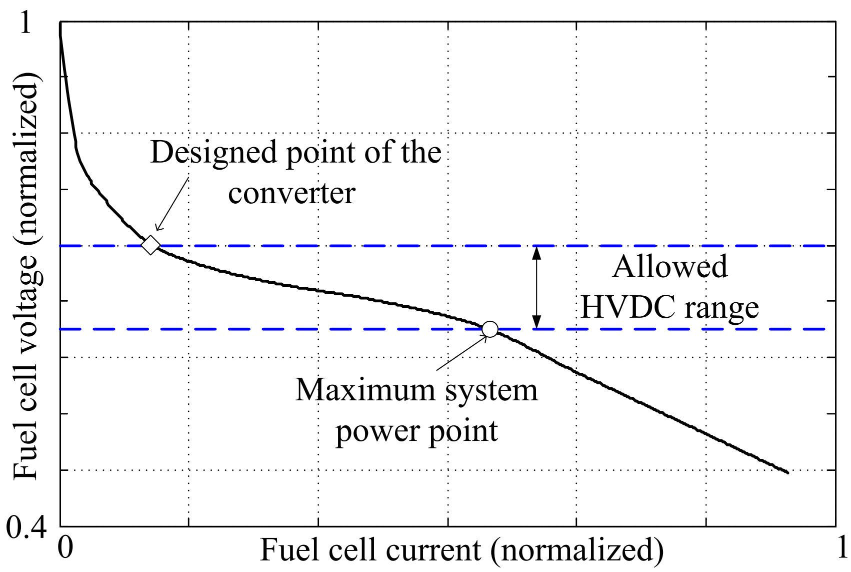

Fig. 9 Typical stationary current-voltage characteristics of a fuel cell stack (polarization curve) with the allowed HVDC limits

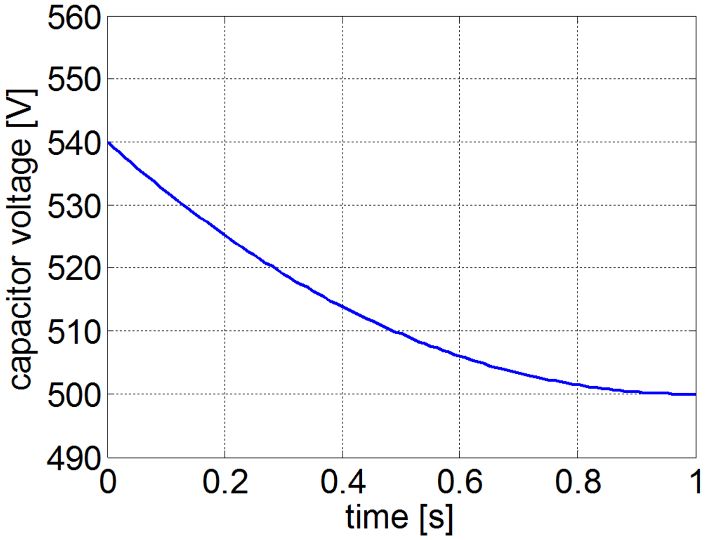

Fig. 10 Voltage drop on the HVDC bus during a large load step with an integrated SC; the capacitor voltage does not drop below $500V_{DC}$