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Research on high voltage DC and AC system integration in line with the electrified aircraft concept

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ABSTRACT

This article presents both an analysis and selected research of key components of modern AAES (PES, EPS) aircraft power supply system based on advanced architecture of high voltage DC system playing an important role in the concept of electrified MEA/AEA aircraft. Selected components of this system have been tested, with special attention paid to the PES system, based, in the high voltage range, on multi-pulse rectifiers. Based on the above, the main aim of the article is to highlight the essence of the functionality of high voltage DC power supply systems implemented on advanced aircraft compliant with the MEA/AEA concept. A special role in this aspect is played by the aviation of military aircraft JSF F-35 and F-22 Raptor of the aviation corporation Lockheed Martin, as well as the civil aviation of leading airlines Airbus in the field of aircraft A-380 and A-350 XWB and Boeing in the field of aircraft Dreamliner B-787, which are fully compatible with the MEA/AEA trend. In the final part of the work, based on the analysis, created mathematical models of selected AAES components (EPS, PES) in the field of PES and selected simulation tests, practical conclusions and observations were formulated.

Keywords: advanced aircraft power supply system AAES, HVDC, more/all electric aircraft, (MEA/AEA), PES, AES.

INTRODUCTION

Modern aviation, i.e. military (Lockheed Martin) in terms of JSF joint strike fighter (JSF) F-35 and F-22 Raptor military aircrafts and, above all, civil aviation (Airbus, Boeing) in field of civil aircrafts (A-380 and A-350 XWB, B-787), according to the constantly evolving concept of electrified more electric aircraft/all electric aircraft (MEA/AEA), is characterized by the dynamic development of advanced on-board power supply advanced aircraft electrical systems (AAES) [1–3].

The above mentioned AAES systems (EPS, PES) are characterized by innovative technological solutions in relation to two main components – the electric power system (EPS) power supply system and power electronics systems (PES) power supply system and its main components - multi-pulse rectifiers, among others (12-, 18- and 24-, 36-) pulse rectifiers in the aspect of high voltage direct current (HVDC) system, which were analysed in detail in this article. The AAES systems, which one of the key functions in the field of high energy direct current HVDC, is the generation, processing and transmission of electricity to the final receivers of the aircraft (systems, installations, equipment, etc.) via the on-board electrical network, are the basic components of the electrical installation of a modern aircraft. The representative of multi-pulse rectifiers of the advanced AAES system in the scope of PES system in aviation is a transformer-rectifier device, commonly referred to as transformer rectifier unit (TRU) rectifier, used primarily in the absence of basic sources of direct current (generator, integrated starter/generator unit) and autotransformer rectifier unit (ATRU) on board of the aircraft.

They are mainly implemented on aircrafts, where the leading power supply system is the AC power supply system of fixed frequency (in the case of conventional aircrafts), and on-board autonomous AC power supply system of variable frequency (in the case of advanced aircrafts), compatible with the MEA/AEA concept. Nowadays, a continuous and dynamic development in the implementation of the HVDC standard in electrical networks of various aircraft can be observed more and more often, including in particular in aircraft compatible with the more electric MEA/AEA concept. Modern on-board electrical networks, in particular those designed in the HVDC system architecture standard, are used, inter alia, to transmit high power over long distances and, most importantly, are used to transmit electrical energy from the central distribution point of the aircraft, supplied by primary on-board sources, which results, among others, in obtaining different short-circuit power and different frequencies of alternating current produced by modern electrical sources and machines [4–5].

Compared to the transfer of AC electricity, DC electricity transmission is characterized by a number of advantages, e.g. transmission losses are reduced by 33%, there is no skin effect, less loss of corona discharge (per crown), transmission power is independent of the distance, the transmission line does not require reactive power compensation and is easy to control energy flow and suppress slow-changing power oscillations in dynamic and emergency states of systems [6–8].

In addition, it should be noted that in an ideal AC electro-energetic power system of a more electric aircraft voltage and frequency constancy is maintained, there is a sinusoidal voltage waveform, no reverse and zero component in the three-phase system and a power factor close to one is obtained. The effects are well known if the values mentioned differ significantly from the nominal values. Increasing number of nonlinear receivers in the form of both converters connected to AC mains (TRU, ATRU) as well as restless receivers, i.e. characterized by repeated sudden load changes (radio navigation and icing equipment, pneumatic systems supply) and asymmetrical receivers (single phase electric machines), causes a significant, generally unacceptable deterioration of the power supply quality and a significant impediment to voltage regulation at various points of energy reception in the electrical equipment of aircraft [9–10].

Additionally, modern technological solutions compatible with the MEA/AEA trend enable the implementation of power electronic systems equipped with modern, microprocessor control systems, having the ability to compensate for interference, introduced into the AC mains, and thus to improve the power quality. Therefore, for example, a conventional reactive power compensator composed of a parallel connection of a fixed capacitor battery and a thyristor inductive current regulator is an adjustable susceptance that enables both power supply of the network and reactive power generation. The quick reaction of the system to the change of the control signal adjusts this system to compensate for rapidly varying reactive powers.

Based on advanced technology of energo-electronics systems, static reactive power compensators have been developed that are equivalent to rotating synchronous compensators. The main system of a static compensator is a converter in a voltage inverter system with bidirectional switches, controlled using the pulse width modulation (PWM) technique. Depending on the sign of the output voltage difference between the inverter and AC mains, reactive power is transferred or taken from the power source. High power and high voltage compensators are built as a cascade connection of single-phase voltage inverters (bridge systems). Such connection allows generation of voltage compensator on the output of voltage with a multi-step waveform with a low content of higher harmonics. An important problem is the compensation of higher harmonics of currents generated by non-linear receivers.

The application also includes energo-electronics active filters, connected in a parallel and serial way. A parallel active filter composed of a voltage inverter connected to the AC mains by a reactor compensates for the strain current generated by the receiver. In turn, a serial filter with a similar topology as the parallel one is connected in series with the power line through the transformer. It compensates for higher harmonics of voltage, coming from higher harmonics of the receiver current [11–12].

Modern technology makes it possible to build AC/DC and DC/AC converters with the functions of linear receivers. Using the PWM technique and multi-pulse (18- and 24-) pulse techniques, it is possible to reduce the current distortion coefficient from the power source total harmonic distortion (THD) to 1–2 [%] in case of the clean power converter (CPC) rectifier [13]. In the following part of this paper, the process of coupling alternating and direct current systems in HVDC architecture is considered, in line with the trend of the MEA/AEA electrified aircraft. In this respect, the converter systems of the PES system based on LCC and CCC technology in the Back-to-Back configuration implemented in the HVDC architecture networks of the aircraft compatible with the MEA/AEA concept were considered.

Research on the power supply of modern aircraft, especially those complying with the MEA/AEA concept, is crucial for the development of civil and military aviation. These studies mainly focus their attention on HVDC systems and complex electronic system components such as multi-pulse rectifiers (12-, 18-, 24-pulse) and TRUs and ATRUs. The selection of these components and the evaluation of their performance contribute to the energy efficiency and reliability of modern aircraft.

The novelty of this research lies in its focus on HVDC technology, which enables reduced energy losses, improved voltage stability and efficient power transmission over long distances. The studies show that direct current (DC) has lower energy transport losses than traditional alternating current (AC) systems, offers better regulation of energy flow and is more resilient to voltage fluctuations. In addition, HVDC systems eliminate the need for reactive power compensation and reduce the occurrence of oscillations under dynamic and emergency conditions.

The idea of the MEA/AEA concept increasingly requires modern technologies, which causes greater interest in research in this field. The implementation of HVDC in the on-board networks of modern aircraft, both military and civilian, is a breakthrough step towards full electrification of aircraft.

Research has proven that the use of HVDC technology in power systems brings significant energy savings and improved reliability of on-board systems, which is important in the face of the growing demand for more ecological and energy-efficient solutions in aviation.

In the area of military aviation, innovative solutions can be seen in the power systems used in Lockheed Martin aircraft, such as the F-35 and F-22 Raptor, which fully use HVDC technology in accordance with the MEA/AEA concept. In the aviation industry, airlines such as Airbus (A-380, A-350 XWB) and Boeing (B-787 Dreamliner) are successfully implementing innovative solutions related to power systems, which is key to improving energy efficiency and reducing CO2 emissions. The research carried out is also of great importance in the context of the development of power electronic technologies, especially microprocessor control systems that allow for the compensation of disturbances introduced into the AC network. Thanks to advanced control algorithms, systems such as reactive power compensators and active filters contribute to improving the quality of power supply in aircraft, which is crucial for the operational reliability of all on-board systems.

In the context of practical application, this research focuses on mathematical modeling and simulation of selected components of on-board power systems, which enables a thorough understanding of the complex phenomena occurring during the transmission and transformation of electrical energy. Simulation tests conducted in the Matlab/Simulink environment for HVDC/MEA systems allowed for the identification of key parameters affecting the performance and reliability of on-board systems.

This type of research is also very important for the future of aviation, which is increasingly moving towards total electrification. The use of HVDC technology not only enhances energy efficiency, but also allows for the introduction of more advanced solutions, such as multi-level power electronic converter systems, characterized by lower harmonics and greater reliability.

To sum up, what is new in the conducted research is the implementation of advanced technologies in aviation power systems, which not only improves energy efficiency, but also reduces pollutant emissions and increases the reliability of modern aircraft. Implementing the HVDC standard and advanced power electronic components in line with the MEA/AEA concept creates new opportunities for the future of aviation, highlighting the importance of ongoing research.

COUPLING OF AC AND DC SYSTEMS IN HVDC ARCHITECTURE ACCORDING TO MEA/AEA CONCEPT

According to research, the use of multi-pulse rectifiers (12-, 18- and 24-) pulse in the power systems of modern aircraft leads to high energy efficiency while minimizing energy losses. It was confirmed that thanks to advanced filtering of current and voltage harmonics and transformers, it is possible to maintain high power quality and stable operating parameters of on-board devices.

One of the key conclusions from the analysis was that HVDC systems are characterized by significantly lower energy losses compared to conventional AC systems. This is due to the elimination of reactive power and resonances, which in turn affects the greater reliability of on-board systems in dynamic and emergency conditions. The research has shown that the use of TRU and ATRU rectifiers in HVDC systems reduces harmonic distortions, which translates into effective power supply of electronic and power electronic devices on board an advanced aircraft.

Studies have also shown positive effects of using HVDC technology in aircraft compliant with the MEA idea. F-35 and F-22 aircraft are excellent examples where the use of HVDC systems has allowed to save a lot of energy and increase the efficiency of the entire power supply system. In the case of air transport, Airbus A-380 and Boeing B-787 Dreamliner effectively use this technology, which leads to reduced emissions and increased flight capabilities.

Computer studies to evaluate voltages and currents in HVDC systems confirmed that they are stable under extreme conditions, such as overloads or faults. One of the main findings was that these systems are able to quickly recover from disturbances, which indicates their high reliability. The use of advanced reactive power compensation and harmonic filtering techniques made it possible to achieve this.

Another important observation is the potential for efficient integration of HVDC systems with existing AC networks on aircraft. By using AC/DC converters and active filters, both types of networks can be efficiently integrated, which affects the flexibility of the power systems and improves their reliability. Studies have shown that HVDC systems can operate with AC networks without the need for advanced compensation devices, thus increasing their operational potential.

The next important result was the investigation of the potential of integrating HVDC systems with alternating current networks on board aircraft. The simulation showed that using special power electronics solutions, such as AC/DC converters and active filters, both types of networks can be efficiently connected, increasing the flexibility and energy efficiency of MEA/AEA aircraft. In summary, the experiments confirmed that HVDC technology is applicable in modern aviation. With advanced multipulse rectifiers and HVDC systems, energy efficiency, reliability and emission reduction in modern aircraft can be increased.

With regard to high voltage direct current HVDC solutions in on-board power supply networks compatible with the concept of an electrified aircraft in the system of combining AC and DC network structures into one uniform system, it is required to use appropriate transformer systems. Transformer systems based on the converter structure are powered from one side using a rectifier circuit connected to a high voltage DC transmission line and systems converting the inverter voltage into the high voltage of the receiving system, which is illustrated in the figure below (Fig. 1).

It should be noted that in the above solution, the power losses during the transfer process are smaller than with the alternating current AC, and besides, non-synchronous systems can be combined with one another. Converter transformers provide galvanic isolation of DC and AC systems. In addition, due to the cooperation of the transformer with the converter, odd harmonics of current appear in windings (5, 7, 13 and

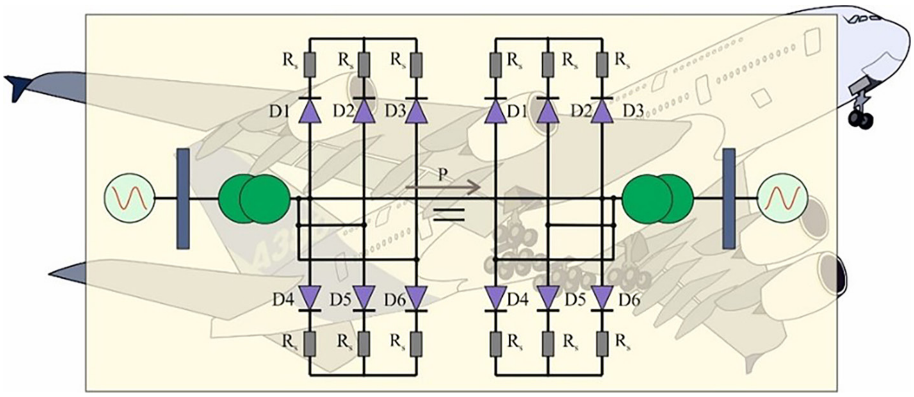

Figure 1. Architecture of the HVDC system in the field of voltage and current transmission of an on-board aircraft electrical network compliant with the concept of MEA/AEA

higher), which are the cause of additional - load losses [14–15]. The problems mentioned concern, in particular, the functionality of the 12-pulse rectifiers in which specific harmonics of both AC and DC current accur during the operation.

The wiring diagram of the transformer system is shown in the figure below (Fig. 2) with 12-pulse system valves. On the side of the AC mains power supply, there are no higher harmonics of the mentioned rows, because they close through the windings of both transformers, increasing the load losses. The 5th harmonic can reach up to 20% of the basic harmonic. At the AC/DC converting station, there is in principle the possibility of converting the current to any frequency imposed by the AC system.

As shown in Figure 5 (p. 8), the voltages on the valve side are offset by 30°. Rectified voltage in idle state is

$$U_{DC} = \frac{6\sqrt{2}}{\pi} U_{AC} \cos\alpha \quad (1)$$

where: U_{DC} – DC voltage along serially connected valves in bridges, U_{AC} – phase-to-phase voltage on the transformer side (effective value), α – ignition delay angle (control angle).

As a result, for $\alpha = 0$, the voltage is $U_{DC} = 2.7\ U_{AC}$, while in the case of a load the voltage is respectively $U_{DC} = (2.4 - 2.5)\ U_{AC}$. The winding on the valve side, in the bottom grounded bridge, is located on about 1/4 of the potential of the DC line, and the windings on the valve side for the upper bridge, on the level 3/4 of the line potential. The voltage distribution between the constant and liquid insulation of the transformer at the alternating current AC has a capacitive character. This means that the distribution of the voltage and intensity of the electric field is determined, among others permeability of materials. At direct current, this distribution is determined by the resistivity of the materials. Due to the fact that the resistivity of the solid insulation is much larger than the transformer oil, almost all of the voltage is deposited on the solid insulation [16–17].

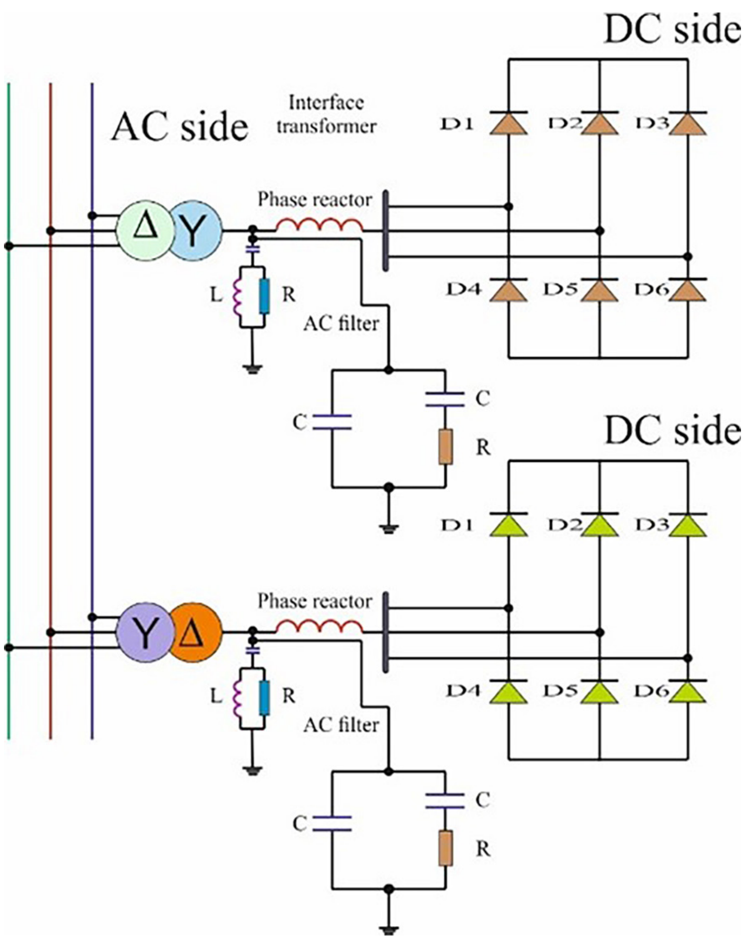

Figure 2. 12-pulse rectifying system HVDC used in aircraft electrical networks compliant with the concept of MEA/AEA

Consequently, HVDC transformers have much higher proportions of solid insulation (almost three times more) compared to AC transformers. Up-to-date DC transmission systems are designed for ±600 kV voltage. The transformers are equipped with tap-changers on the upper voltage (UV) side to regulate the secondary voltage. Additionally, it is necessary to carefully check the impedance of transformer short-circuits. Deviation impedance between individual phase windings can not be greater than ± 3% from the average value. This requirement results from the need to eliminate higher harmonics in the 12-pulse bridge system. Current converters are built using six-pulse bridges. In modern systems, two six-pulse bridges are connected in series to twelve-pulse bridges in order to increase DC voltage and improve energy quality by eliminating harmonic parts.

These two rectifying systems (bridges) require a voltage source, shifted in relation to each other by 30 electrical degrees, which is implemented through the connection of windings of the transformers that supply the Wye, while the other one into the Delta [18]. During the twelve-pulse operation there are characteristic harmonics in the alternating current AC ($12n \pm 1$) and in the direct DC voltage ($12n$), where: n = 1, 2, 3, ... Moreover, thanks to the twelve-pulse operation, no filters associated with six-pulse operation are required, including 5th and 7th harmonics [19–21].

CONVERTER SYSTEMS IN THE FIELD OF THE PES SYSTEM USED IN AIRCRAFT HVDC NETWORKS CONSISTENT WITH THE MEA/AEA CONCEPT

Energo-electronic power converters (transducers) supplied from on-board electricity networks are called rectifiers (converters) in the case of converting AC voltage into DC voltage and inverters when they convert DC voltage into AC voltage. Applied in more electric aircraft systems in the implementation of the HVDC standard, they may differ in terms of construction and control system. The basic structure of the network converter is a two-level converter (Fig. 3).

It has three pairs of keys working alternately. The advantage of such a converter is, among others, its low construction cost. However, it has a number of disadvantages such as: the need to use filters on the output, due to the content of a large number of higher harmonics in the output voltage and that its semiconductor keys are working on the input voltage. In the case of using three-level converters with six pairs of semiconductor keys, such a technological solution from the economic point may prove more beneficial (Fig. 4).

This is due to the fact that the output filters are smaller and the semiconductor keys work at half of the input voltage. Subsequent solutions of multi-level converters approximate the shape of the output voltage to a sinusoidal, with the simultaneous increase in the construction costs of such devices. Depending on the needs, there are also parallel connection systems with a common or separate DC source, with continuous or alternating operation [22–23].

The choice of the appropriate system is conditioned, among others, by analysis of key parameters such as: THD factor, power losses, financial possibilities, etc. Semiconductor keys in inverters used in HVDC systems are mostly thyristors or IGBT (Insulated Gate Bipolar Transistor) transistors.

In the following subsections of this chapter the topologies of classical line commutated converters (LCC) and their modifications in the form of capacitor commutated converters (CCC)

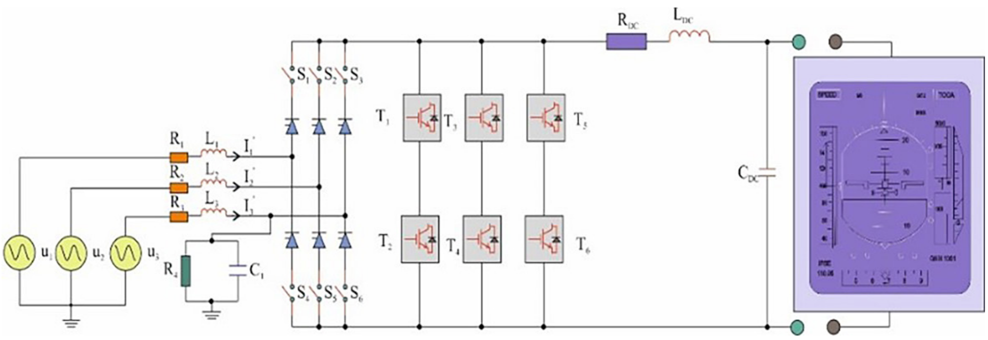

Figure 3. A two-level energo-electronic converter for an aircraft electrical network system in accordance with the HVDC/MEA concept

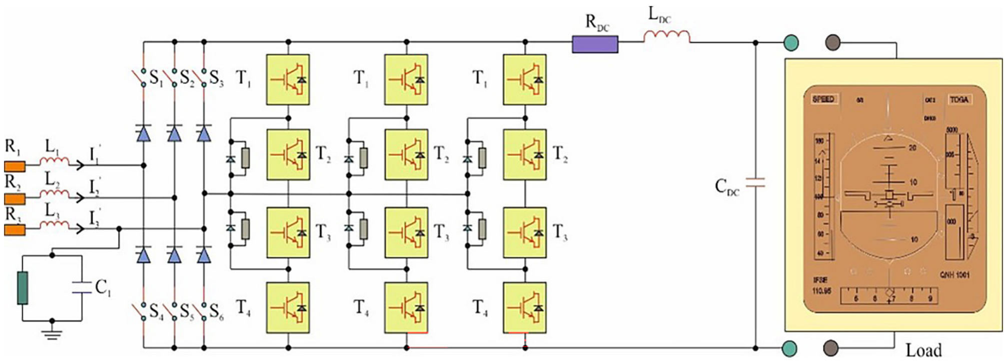

Figure 4. A three-level energo-electronic converter for an aircraft electrical network system in accordance with the HVDC/MEA concept

were considered. The topology of these converters in aviation was applied when connecting systems operating asynchronously, mainly through back-to-back systems.

An aircraft HVDC system converter in accordance with the MEA/AEA concept in LCC technology in the back-to-back configuration

The AC/DC and DC/AC energo-electronic converters are implemented through multi-stage electricity processing in the Back-to-Back System configuration (Fig. 5) are located in the same place, as it is not necessary to transmit energy in the HVDC system. These systems usually connect two unsynchronised energy systems or energy systems at different frequencies locally [24–25].

This type of solution is much easier to construct than the HVDC system transfer station, however, when choosing a DC voltage level, it is not necessary to take into account the optimum values that are usually considered for the HVDC (cable) transmission lines and is relatively low. Other simplifications in the construction of the system also include solutions in which the system with the reactor is only present in the DC circuit and the system with the connectivity between the two converters that takes place only locally [26–28].

Constituent components of converters in the AC/DC/AC converter circuit with DC intermediate circuit are their two types: AC/DC network converter (power rectifier) and DC/AC converter, i.e. engine converter, which due to the construction solution is a circuit voltage source inverter (VSI) or current source inverter (CSI) current inverter system. Converters powered from a power source with LCC natural power commutation are the most commonly used AC/DC/AC conversion solutions used in the world power industry in the area of high power and high voltage. They are considered as a classic solution. In the context of multi-pulse rectifiers, being components of converters (transducers) in the

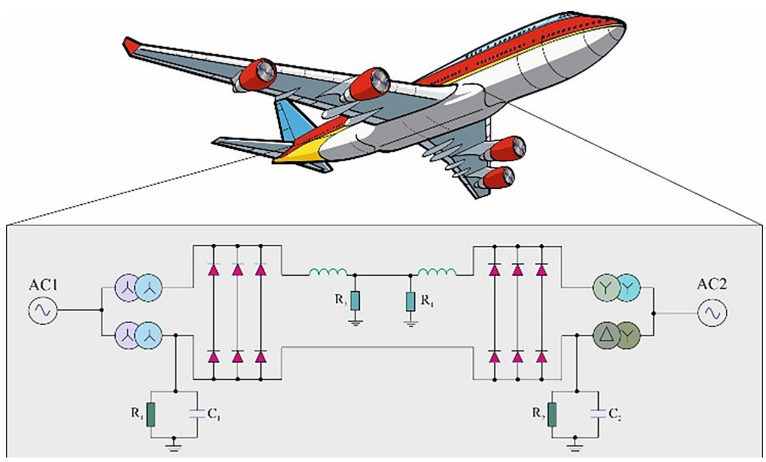

Figure 5. Basic diagram of the back-to-back configuration built from LCC topology converters for the aircraft electrical network system according to the HVDC/MEA concept

field of PES energo-electronic power system, they have found application in various types of industry. They are used in the automotive and maritime industry, applications related to renewable energy sources, and above all in aviation and space-related applications, defined by the common concept of electrical systems for aircraft, railway and ship propulsion (ESARS). Its main idea boils down to replacing traditional types of energy and related elements (electrical, pneumatic, hydraulic and mechanical), into one type of power supply, namely using electricity, which is the domain of advanced aircraft and their concepts (MEA, AEA and more AEA) [26]. The basic elements of energo-electronics in the field of the PES system in the case of converters made in LCC technology are thyristors [29–30].

These elements are usually connected in series or, if required, also in parallel, creating so-called thyristor valve, enabling operation at very high voltages, reaching a level of several hundred kV. The technology of building converters, based on the LCC topology, is well known in the field of energo-electronics and outperforms the efficiency of transducers based on phase-controlled thyristors (PCT), where the short circuit power of the PCT electro-energetic power line must be at least twice as high as installed power converters. In addition, these converters cannot power the passive network. LCC converters which require a relatively rigid voltage source due to commutation, which takes place between its phases, and therefore the short-circuit power of the installed converters may be lower.

In summary, LCC converters require a rigid voltage source to enable natural mains commutation depending on the 3-phase power supply voltage to ensure proper operation. It should be noted that proper functionality of the operation of such systems is only possible with AC mains current, which is decelerated in relation to the voltage, as a result of which the conversion process requires reactive power, the demand of which is met by compensating devices: in the form of filters, capacitors, etc., while surplus or shortage of power must be supplied from AC mains. In addition, changing the direction of power flow, in systems based on LCC converters, requires changing the polarization of the system, in both converter systems.

When analysing the functionality of LCC converters, it should be noted that the process of controlling thyristors used in current converter systems has certain limitations due to the fact that they can only be switched on. In systems based on LCC converters, their main components, i.e. thyristor valves, require a network frequency for proper operation, and through the control angle there is a possibility of changing their voltage level. By using this type of solution, it is possible to achieve higher efficiency and faster control within the scope of the considered AAES power system.

Additionally, by changing the angle of control of the converter, changing in the range from 0 to 90 electrical degrees (rectifier operation) and from 90 to 180 degrees (inverter operation), it is possible to adjust the voltage on both sides of the HVDC system link, obtaining a change in power flows, so that the greater the angle of control, the smaller is the value of direct voltage at the output of the system [31-33].

The main advantages of LCC converters are, among others, operating factors and their relatively low cost. In modern aviation, LCC converters are used as LCC converters in back-to-back configuration, characterized by a different type of direct current transmission. Such a solution is based on the fact that in this type of solution both the rectifier and the inverter are located within the same power system in the HVDC architecture, which allows the use of a common control system, cooling and other for both converters. Furthermore, in systems based on LCC converters in back-to-back configuration, a lower voltage is required because the transmission of electricity takes place within the on-board electricity grid (no distance transmission of energy), so there are no typical transmission losses. Therefore, systems of this kind are used for connecting systems operating asynchronously and enable improvement of stability of weak transmission lines and improvement of rocking damping [34–35].

An aircraft HVDC system converter in accordance with the MEA/AEA concept in CCC technology in the back-to-back configuration

The key difference between LCC and CCC converters, being a modification of LCC converters, lies in the way they are incorporated into the system, namely: between the transformer and the thyristor switch, the capacitor is incorporated in series. Such a solution ensures that the reactive power required by the system is delivered depending on the load. Capacitor commutated converters are a modification of the classic LCC converters.

Compared with network commutation converters, natural LCC are a more modern solution, used, among others, in the on-board electrical networks of a more electric aircraft, in which a high impedance of the so-called weak networks is required, while in the structural field the key elements, which are capacitors, are connected in series between the transformer and the thyristor connector (Fig. 6).

This type of solution has many advantages, among others, thanks to such implementation, consisting in the fact that the capacitor was connected in series between the transformer and the thyristor link, the reactive power required by the system is provided, depending on the load, i.e. the capacitors directly supply reactive power to the system as the load power increases. It also allows reducing the dimensions, improving the commutation process in the case of weak networks, improving the voltage stability and preventing the zero current component flow. It should be mentioned that the converters of this topology, due to their advantages, are used in connecting electro-energetic system nodes with small short-circuiting powers.

A typical converter station includes converters depending on the topology: LCC, VSC or CCC, matching transformers, control equipment and cooling medium, higher harmonic filters. LCC and CCC converters are based on valves switched by a current signal, mainly thyristors, while VSC converters on valves fully controllable, switched by a voltage signal – transistors [36–38].

CONVERTER SYSTEMS IN THE FIELD OF THE EPS SYSTEM USED IN AIRCRAFT HVDC NETWORKS CONSISTENT WITH THE MEA/AEA CONCEPT

In the case of HVDC system configuration, adapted to the electrical network of the aircraft in accordance with the MEA/AEA trend, particular attention should be paid to the occurrence of low oscillation frequencies occurring on the generator rotor axis or integrated starter/generator. Generator as the main power source of the aircraft in the HVDC system is responsible for the generation of AC voltage and AC sinusoidal current.

An analogous situation occurs in the case of the process of controlling the inter-object oscillation, coming from other electrical machines included in the on-board electrical network in accordance with the concept of a more electric aircraft MEA. The full scope of mathematical operations (mathematical model) describing

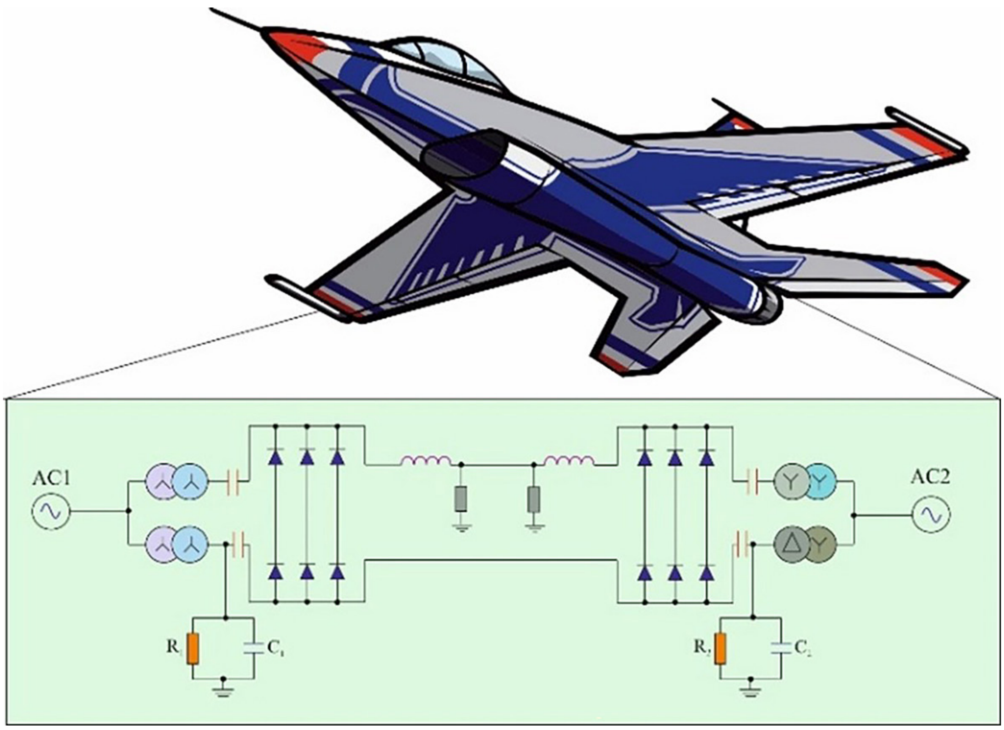

Figure 6. Basic diagram of the back-to-back configuration built from LCC topology converters for the aircraft electrical network system according to the HVDC/MEA concept

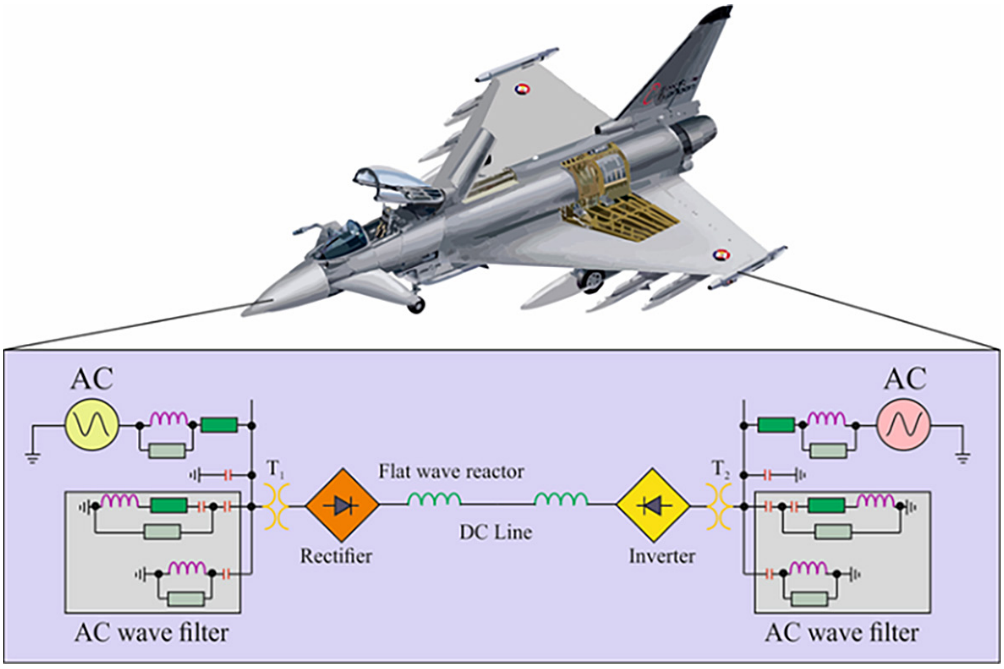

Figure 7. A two-range power supply system with parallel equalization lines for AC/DC converters of the aircraft electrical network in accordance with the HVDC/MEA concept

electrical phenomena occurring in the on-board electrical network of the HVDC/MEA system should be considered in two aspects [39–40].

The first one refers to the generator work analysis, in particular the evaluation of the rotor and stator operating condition. A significant role in this respect is played by the angular velocity occurring on the tested object. At this stage, input signals are generated which are responsible for controlling the circuits that shape harmonic signals at low frequencies. The second aspect concerns the description by means of mathematical equations of phenomena occurring on components, responsible for the transformation of three-phase AC voltage and current into their respective DC fixed values.

Therefore, in view of the above information, it can be assumed that the HVDC/MEA system works in two areas of power supply operation of the aircraft with AC/DC converter lines connected in parallel, as shown in the above figure (Fig. 7). The angle and speed of the rotor in areas A and B are defined by [41–42]. Thus, for the area A

$$\omega_A = \frac{\sum_{i\epsilon A} M_i \omega_i}{M_A},\ \delta_A = \frac{\sum_{i\epsilon A} M_i \delta_i}{M_A},\ M_A = \sum_{i\epsilon A} M_i \quad (2)$$

and for area B

$$\omega_B = \frac{\sum_{i\epsilon B} M_i \omega_i}{M_B},\ \delta_B = \frac{\sum_{i\epsilon B} M_i \delta_i}{M_B},\ M_B = \sum_{i\epsilon B} M_i \quad (3)$$

where: M_k, δ_k and ω_k ($k = i,j$) – are respectively the moments of inertia, angle and velocities occurring on the rotor k – of the generator in relation to the center of the inertial (COI) reference frame in other words place of fixing.

The kinetic energy in the analysed system reflects the relative fluctuations between the two rotors of the generator. It should be noted that some of the energy represents the relative movement of the generator inside areas A and B. The mathematical notation is as follows:

$$E_k = \frac{1}{2} \cdot M_{eq} \omega_{eq}^2,\ M_{eq} = \frac{M_A M_B}{M_A + M_B},\ \omega_{eq} = \omega_A - \omega_B \quad (4)$$

The energy function for the system shown in Fig. 7 can be written as Eqution 5.

$$E_k = \frac{1}{2} \cdot M_{eq} \omega_{eq}^2 + \int_{\delta_s}^{\delta_{eq}} P_{COI} d\delta_{eq},\ P_{COI} = \\ = \frac{\left(M_A \sum_{i\epsilon A} P_{ei} - M_B \sum_{j\epsilon B} P_{ei}\right) - \left(M_A \sum_{i\epsilon A} P_{mi} - M_B \sum_{j\epsilon B} P_{mi}\right)}{M_A + M_B} = P_e - P_m \quad (5)$$

The Equation 5 reflects the lack of equilibrium of the electromotive forces of both generators in the HVDC/MEA system, δ_s – is the value δ_{eq} at the stable point of operation of the generators, determined in the obtained state of equilibrium.

Next, it is necessary to eliminate electromechanical oscillations in the HVDC/MEA system, which generate a large amount in the electrical network of the aircraft and reduce the energy function. As a result, the HVDC/MEA system connector can be controlled from the condition $E_k < 0$.

$$E_k = \left(M_{eq}\frac{d\omega_{eq}}{dt} + P'_{COI}\right)\frac{d\delta_{eq}}{dt} - P_{mod}\frac{d\delta_{eq}}{dt} \quad (6)$$

where: P_{mod} – it is a modulated DC voltage signal, and $P'_{COI} = P_e - P_{m\,+}\,P_{mod}$ – is the output power of the HVDC/MEA system, in the case of transmission of DC modulated signals.

The first part of the expression (6) is responsible for the generator power balance and is 0. The energy derivative present in the HVDC/MEA system is determined by the second expression of the equation. Finally, it can be written:

$$P_{mod} = K \cdot \omega_{eq}, K > 0 \quad (7)$$

COMPUTER SIMULATIONS OF SELECTED COMPONENTS OF THE HVDC/MEA SYSTEM AND ANALYSIS OF THE OBTAINED SIMULATION RESULTS

The transformer rectifier unit (TRU) simulation method is based on multi-pulse rectifiers that convert alternating current to direct current in the electrical onboard networks of modern aircraft. The tests were carried out on a 12-pulse rectifier, which converts a three-phase AC voltage of 380 V and a frequency of 400 Hz into a fixed DC voltage. The simulation was designed to investigate the characteristics of the TRU system and its ability to provide a stable power supply under operating conditions typical of modern electric aircraft.

During the design of the TRU system, provision was also made for the use of harmonic filters to reduce current and voltage interference generated by the rectifier. It should be noted that such filters remove unwanted harmonics, resulting in the production of more stable DC signals at the rectifier output, which in turn improves the quality of power supply in on-board systems.

The TRU rectifier used in the simulation improves the operation of HVDC systems by converting AC to DC with minimal energy consumption. This system plays an important role in modern aircraft compliant with the MEA/AEA concept, where the demand for a stable DC source is particularly high.

Studies have shown that combining a 12-pulse TRU rectifier with appropriate filters can significantly reduce current interference and improve the quality of the delivered electricity. This is particularly important during flight, when the load changes dynamically and interference from other systems on board can occur.

As a result, the simulation showed that the use of TRU rectifiers in HVDC is the best solution for modern power systems on board modern aircraft to enable these systems to meet the increasing energy efficiency and reliability requirements of advanced electric aircraft such as the Boeing B-787 Dreamliner and Airbus A-380.

Exemplary simulation tests were carried out in the Matlab/Simulink programming environment, on the basis of which a mathematical model of the HVDC/MEA system was developed, based on a 12-pulse rectifier system. The tests were carried out for three phase voltage of 380 V and frequency 400 Hz. The input voltage waveforms were shaped by changing the AC voltage generated by the transformer. The value of the AC voltage is "rectified" by a 12-pulse rectifier subunit. At both ends of the feed line, a filter is used, whose main purpose is to "smooth out" the final harmonic signals by using the inductance coil L_d = 0.5. H. This element together with the condenser implements a high-pass filter, which is built into the lines of the AC mains power supply on the rectifier side.

The above solution ensures obtaining the appropriate value of reactive power and eliminates distortions in individual harmonics of AC current and three-phase voltage. In turn on the rectifier side, DC current values are generated, which are responsible for the complete control of the HVDC/MEA system. It should be noted that the results obtained from the computer simulations show only a small part and refer only to the TRU and auto-transformer rectifier unit (ATRU) systems included in the electrical installation, consistent with the concept of a more electric aircraft MEA/AEA [43–49].

Based on the analysis of voltage and current waveforms for the HVDC/MEA system, illustrated in the above graphs (Figs. 8–11), interactions between the HVDC/MEA LCC system can be observed. For example, this system, which during the process of returning to the initial operating conditions after the occurrence of disturbances in the form of propagation of occasional overvoltages and commutation turns or interaction of control systems, increases the reactive power consumption in the AC system (including filters and capacitor batteries in the converter station), from which this power is delivered. The component performing the process of changing the reactive power value is the voltage source converter (VSC), which directly transforms the time waveform of the electric current.

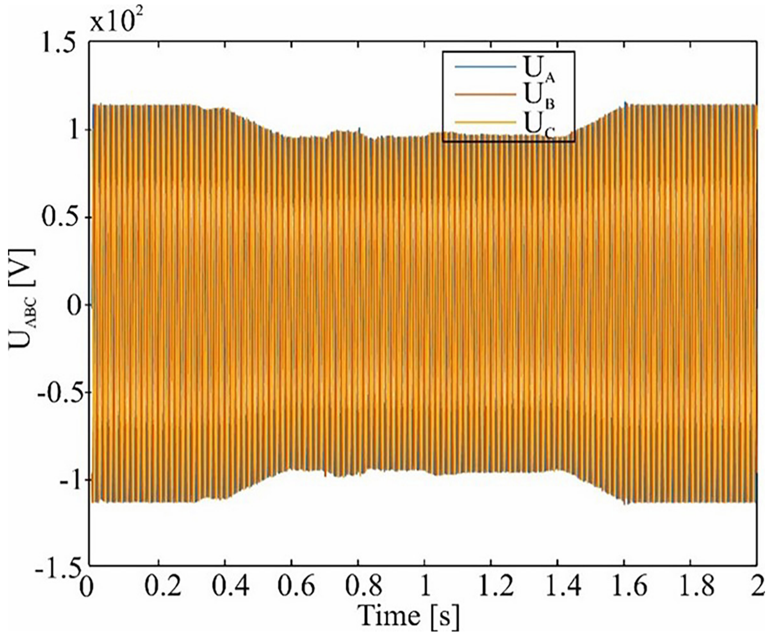

Figure 8. Voltage waveforms for the TRU rectifier circuit system for the aircraft electrical system in accordance with the HVDC/MEA concept on the AC side

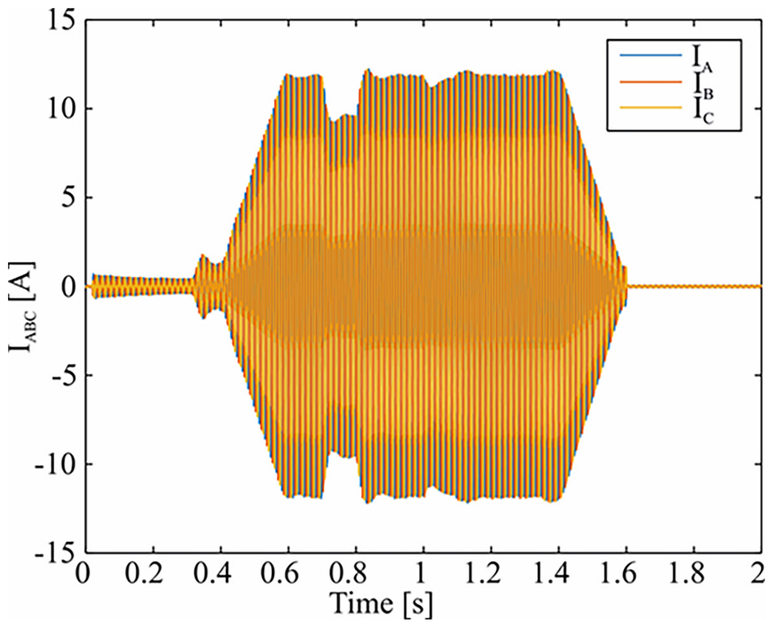

Figure 9. Current waveforms for the TRU rectifier circuit system for the aircraft electrical system in accordance with the HVDC/MEA concept on the AC side

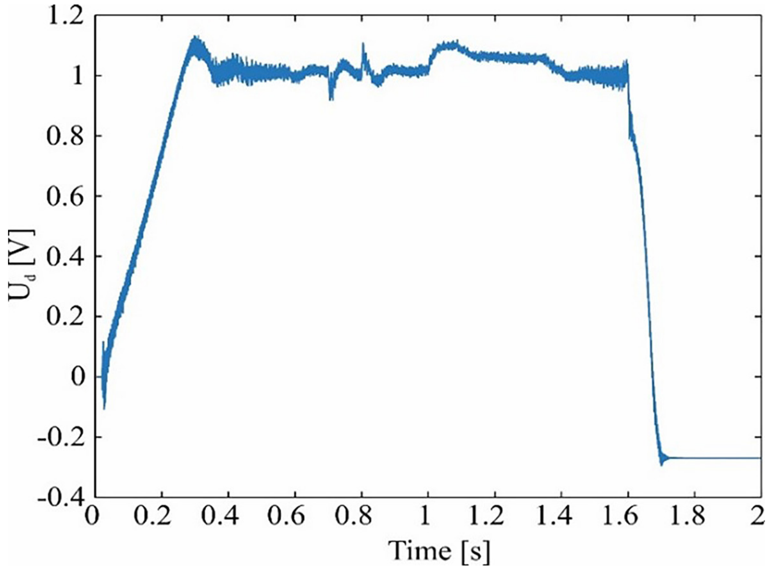

Figure 10. Voltage waveforms for the HVDC rectifier circuit system for the aircraft electrical system in accordance with the HVDC/MEA concept on the AC side

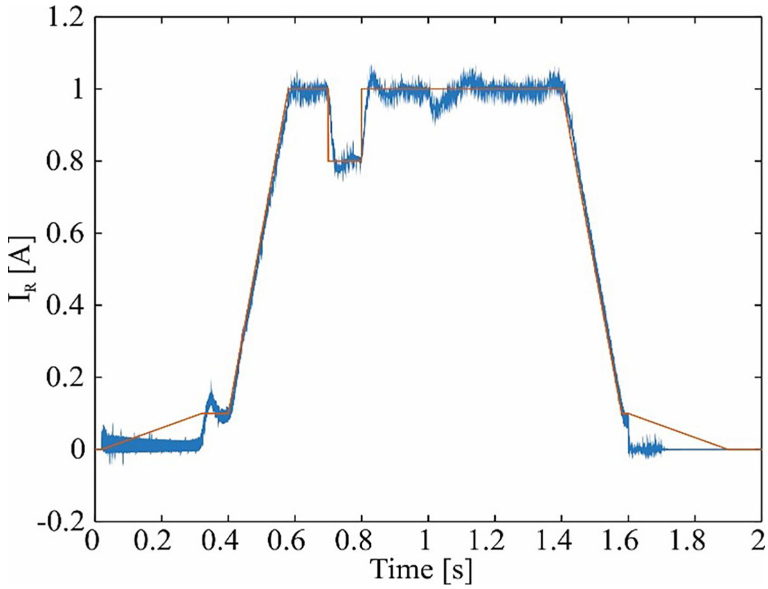

Figure 11. Voltage and current waveforms for the TRU rectifier circuit system for the aircraft electrical system in accordance with the HVDC/MEA concept on the DC side

CONCLUSIONS

On the basis of the conducted review and analysis in the field of the research subject, it should be noted that the development of power electronics devices in the PES system and high power systems contributes to increasing the share of HVDC/MEA systems in modern electro-energetic systems, including AAES on-board advanced power systems (PES, EPS), used in advanced aircraft in accordance with the concept of a more electric aircraft MEA/AEA.

The article presents the idea of TRU transformer-rectifier unit operation and ATRU rectifier autotransformer used in modern aviation power systems. For this purpose, simulation tests were conducted for a three-phase voltage of 380 V with a constant (stabilized) frequency of 400 Hz.

Conclusions from the analysis of modern on-board power systems on MEA/AEA-compliant aircraft show the significant benefits of HVDC technology. The use of advanced rectifier systems, such as multi-pulse TRU and ATRU rectifiers, is key to improving the energy efficiency and reliability of onboard power systems. One of the main findings of the study was the confirmation that HVDC systems are more energy efficient than traditional AC systems. HVDC technology reduces the need for reactive power compensation, leading to lower energy losses during transmission and improved voltage stability in on-board networks. Through the use of advanced current and voltage harmonic filtering, these systems reduce electromagnetic interference, which directly improves the reliability of on-board equipment, especially in difficult situations and emergency conditions.

The study showed that important components of HVDC systems, such as multi-pulse (12-, 18-, 24-) pulse rectifiers, are key to improving power quality in MEA/AEA-concept aircraft. Through analysis in Matlab/Simulink, it has been possible to accurately identify the parameters affecting the efficiency of the systems. For example, the use of rectifier transformers (TRUs and ATRUs) allows alternating current (AC) to direct current (DC) to be converted efficiently with minimal energy losses, which is important for the advanced technologies used in today's aircraft.

Another important insight is the potential ability to effectively integrate HVDC systems with the AC networks already in operation on aircraft. Through the use of AC/DC converters and active filters, both types of networks can be effectively integrated, which affects the flexibility of power systems and improves their reliability. Studies have shown that HVDC systems can operate with AC networks without the need for sophisticated compensation devices, resulting in increased operational potential.

From the perspective of the future of aviation, the findings of the study indicate that HVDC systems will make a significant contribution to the development of electric aircraft. The introduction of higher voltages in onboard systems and the use of modern power electronic converters will allow for increased energy efficiency and reduced emissions. In particular, HVDC technology creates new opportunities for the development of more environmentally friendly and energy-efficient aircraft, which is crucial for future aviation projects.

The results of the computer simulations and mathematical modelling carried out confirmed the effectiveness of the proposed technological solutions. Thanks to mathematical modelling, it was possible to accurately determine the operating parameters of power supply systems and detect potential risks associated with their use. For example, research has shown that the use of advanced control algorithms in HVDC systems enables rapid restoration of system stability after disturbances, which is crucial for the safe operation of modern aircraft.

It should be noted that despite the many advantages of HVDC systems, there are also some difficulties associated with their introduction, as evidenced by studies. The need to establish standards and regulations for the interoperability of different brands of equipment is one of the key challenges for the future development of this technology. In order to electrify aircraft to their full potential, consistent technical standards will need to be established that allow HVDC systems to function smoothly under different operating conditions.

In conclusion, the analysis has shown that HVDC technology is suitable for use in modern air transport. The results of the simulation and mathematical analyses show many advantages related to increased energy efficiency, reliability of on-board systems and reduced emissions. The use of HVDC technology offers new prospects for future aviation projects to be greener and more energy efficient, in line with global sustainability trends.

It should be noted that in real on-board autonomous ASE power supply systems in the field of the PES system, ATRU autotransformers with a three-phase 115 V voltage (for Airbus A-380, A-350 XWB) or 230 V (in the case of airplanes Boeing B-787) are used and variable frequency (VF), in the range of 360-800 Hz. In advanced HVDC electrical networks, the ATRU rectifier autotransformer should have a high density of electricity (power). It is used to convert 3-phase voltage with variable frequency 230 V AC VF/115 V AC VF or 3-phase constant frequency voltage 115 V AC 400 Hz (in the case of conventional aircraft) at the input.

In addition, it is also designed to convert to a double voltage at the output equal to ± 270 V DC (additive voltage 540 V DC). Another purpose is to transform electricity of the HVDC power source using unregulated AC/DC converters for on-board electrical energy conversion during the autotransformer voltage switching process. TRU rectifier is a representative of AC/DC converters used in aviation [45-46].

Nowadays, in this area there is a growing dynamics of changes and continuous progress in the field of achieved nominal parameters and improvement of reliability of designed systems (among others by limiting the number of elements in voltage stacks). In addition to the well-known LCC topology converters, which constitute the largest share in the electricity market, there is an increase in the number of applications, currently being in the phase of intensive work and development, VSC topology.

Additionally, circuits with voltage converters allow for a significant expansion of the existing functionalities (e.g. enable supply of passive networks or independent regulation of active and reactive power). The intensification of research on complex systems, including multi-station ones, is noticeable.

The development of offshore wind farms and the growing number of DC connections make the HVDC systems likely to create a DC backbone network in the future. The construction of such networks is, however, connected with the necessity of proper regulation and standardization of technical and functional requirements regarding DC connections.

However, the current progress in the standardization of HVDC systems is not enough. The proper development of HVDC connections should strive to create the possibility of cooperation between devices from different manufacturers, allowing for proper competition on the electro-energetic market.

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