Analysis, Mathematical Model and Simulation of Selected Components of Advanced Technological Solutions of HVDC Architecture of Modern Aircraft Compatible with the Concept of MEA/ AEA

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Abstract**—Conventional voltage of (28V DC, 115V/ 400 Hz AC) in traditional electro-energy power system EPS (*Electric Power System*), used for the "*classic*" aircraft (civilian and military) do not meet the requirements of advanced on-board autonomous power systems ASE (*Autonomous Electric Power Systems*) in the context of a modern system of EPS and a power electronic power system PES (*Power Electronics Systems*). It is dictated first of all by the fact that the concept of a more electric aircraft obliges manufacturers to implement in modern aerospace advanced solutions, among others in the field of high voltage power HVDC (*High Voltage Direct Current*). The subject, and also the purpose of this paper is to introduce the theme of aviation in terms of power HVDC, making its analysis by creating a mathematical model and simulation in software environment of Matlab/ Simulink selected components of the system ASE (EPS, PES) in the context of architecture HVDC in the range of high voltage DC 540V DC (±270V DC), and 350V DC. In the final part of this paper we present the results obtained on the basis of simulations and conclusions in the field of innovative architecture HVDC power in line with the trend of more electric aircraft (MEA/ AEA).**

Index Terms**—mathematical model, architecture HVDC, simulation, More/ All Electric Aircraft (MEA/ AEA)**

I. Introduction

Contemporary advanced aviation technology in the field of civil aviation is undoubtedly related with aviation companies (*Airbus*, *Boeing*), and in the case of military aviation, a leading aerospace corporation in this regard is *Lockheed Martin*. In modern aviation, both in the field of civil aircraft (A-380 and A-350XWB, B-787), as well as in the case of military aviation aircraft in terms of the *Joint Strike Fighter* (JSF) F-35 and F-22 Raptor, consistent with the advanced concept of a more/ all electric aircraft (MEA/ AEA) you can observe the dynamic development of aviation technology in the field of autonomous power systems ASE (EPS, PES) [1], [2].

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The dynamic development of modern on-board autonomous power systems (ASEs) in the context of system architecture (EPS, PES) can be observed both in the implementation of the MET concept (*More Electric Technology*) [3] as well as in the implementation of the *High Voltage Direct Current* (HVDC) in the range of 540V DC (±270V DC) and 350V DC, which will be the subject of considerations and a detailed analysis later in this article [4].

By making a brief introduction to the subject of this paper, it is important to note that the key components of these systems are important within the above systems. As far as the EPS system is concerned, they are primarily sources of electricity generation, both DC and AC. For DC EPS, these include generators, batteries, auxiliary power units APU (*Auxiliary Power Unit*), fuel cells and AC EPS sources include sources in the form of on-board AC electrical machines of variable frequency AC VF (electric generator, integrated starter/ generator set), *Emergency Power Unit* (EPU), emergency air turbine RAT (*Ram Air Turbine*), etc. In the case of PES system, its main components are semiconductor multi- pulse rectifiers (6- , 12- and 18- , 24-) and (36- , 48-) pulse, and even 60- pulse [5], [6]. Consequently, the main components of power systems (EPS, PES) as well as HVDC systems in the range of 540V DC (±270V DC) and 350V DC, which are the domain of mainly military aircraft (JSF F-35, F-22 Raptor), are innovative solutions that are in line with the latest MEA/ AEA aircraft trends.

A. *High Voltage Power Supply System Architecture HVDC 540V DC (±270V DC)*

Technologically advanced modern aircraft, both civil *Airbus* (A-380, A-350 XWB) and *Boeing* (B-787), as well as *Lockheed Martin* military (F-22, Raptor, JSF F-35), according to the current trend of "*More Electric*" (MEA/ AEA), are equipped with on-board networks whose HVDC feed rails are designed for separation and the distribution of high-quality electricity on board a technologically advanced modern aircraft. The above supply rails are used in the field of DC power supply, carrying out various functions, among others, in the case of actuators (executive systems) EMA (*Electro-mechanical Actuation*) and electro-hydraulic actuators EHA (*Electrohyraulical Actuation*). In addition,

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modern technology is gradually being introduced through innovative development of the MEA/ AEA concept, more open technology in the field of electricity MOET (*More Open Electrical Technology*) and optimization of power (electric energy) of the modern aircraft POA (*Power Optimized Aircraft*). As a consequence of this, there is a continuous and dynamic development of modern power systems ASE (EPS, PES), while high-voltage systems of 540V DC (±270V DC) are considered as the standard in modern aviation technology, while the first generation concerns 270V DC system, while systems in the high voltage 540V DC are so-called future standard, according to the trend of more AEA.

The HVDC high-voltage system architecture of modern on-board autonomous power supply systems ASE in the 540V DC range (±270V DC) should be considered in terms of analysis of power systems that are part of the ASE system, i.e., the electric energy power supply system EPS (*Electric Power System*) and the power electronics supply system PES (*Power Electronic System*). Based on a literature review, the basic components of the EPS system are considered and analyzed through complexity criteria and interactions and relationships that maximize the efficiency of the entire power system on a contemporary aircraft. Consequently, in innovative technology solutions, integrated units in the form of starters/ AC generators of VF (*Variable Frequency*) are used, which provide essential input parameters for the main engine and high-quality power to secondary non-propulsion systems of modern aircraft in line with the trend of MEA/ AEA [7], [8].

Modern EPS power supply systems are equipped in various functional components, as shown in the figure below (Fig. 1).

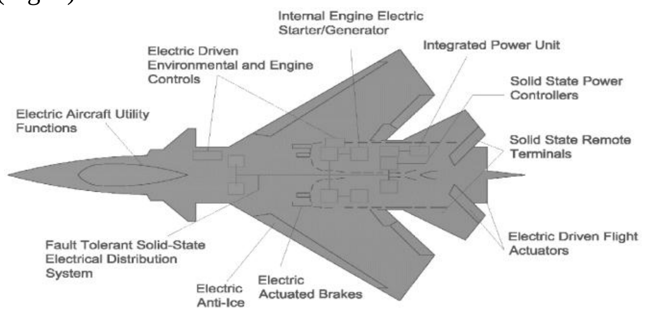

Fig. 1. An example of a modern technological solution of the power supply system ASE (EPS, PES), based on the JSF F-35 military aircraft in accordance with the MEA/ AEA concept [9], [12]

Key components include a combustion engine ICE (*Integral Combustion Engine*); electric set, starter/ generator S/ G (*Starter/ Generator*), integrated with drive systems; semiconductor power controllers; electrically driven flight control actuators; electric frost protection system; electrically operated brakes; fault-tolerant (failure-free) semiconductor power management system; electrically driven installation of environmental protection ECS (*Environmental Control System*) and engine control.

In summary, the HVDC power supply systems in the 270V DC range used in modern airplanes are characterized by the following important symptoms: the correct power source for the voltage applied to the multi-pulse transmitters, intended for the specific power supply (loads) of the aircraft; easy to provide power types of rails with battery backup and regeneration (recovery) of power from the electric actuators to the return rail. Contemporary high-advanced aircraft, both civil *Airbus* (A-380, A-350 XWB) and *Boeing* (B-787), as well as military *Lockheed Martin* (F-22 Raptor, JSF F-35) in line with the trend of MEA/ AEA are equipped with electric power lines that the supply HVDC rails distribute high-quality electricity on board of a modern aircraft (Fig. 1). In addition, the most advanced aircraft are characterized by a variety of variants of modern EPS architecture in the range of HVDC high voltage, 270V DC (2 phases with ground), 270V DC (1 phase with ground), ±135V DC (2 phases with ground) and ±135V DC (2 phases without ground) [10].

B. HVDC High Voltage Power Supply Architecture 350V DC

The power architecture of this kind of HVDC system in the range of 350V DC deals with the more advanced technology of more engine MEE (*More Electric Engine*), in line with the trend of MEA/ AEA. An example of such a technological solution is the *Rolls-Royce* Trent 500 drive motor, equipped with electrical components, shown in the figure below (Fig. 2).

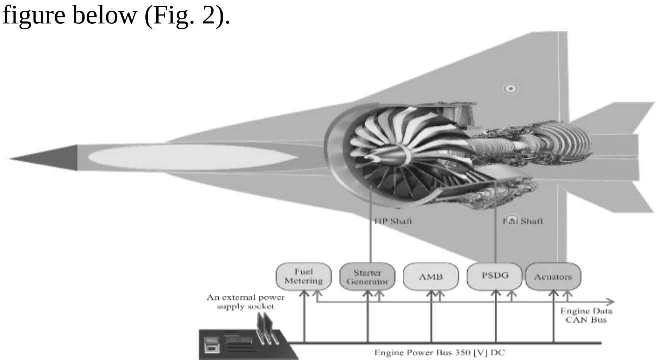

Fig. 2. The basic electrical components of the MEE [11], [12]

Based on the above drawing, it is noted that the main component of the HVDC power system architecture in the 350V DC range is the 350V DC electric rail. The integrated unit starter/ generator is mounted on a high pressure shaft HPSG (*High Pressure Starter/ Generator*). It is used to start the engine and is powered by a 350V DC battery or external power source. Once the engine has started, the integrated S/ G unit provides 350V DC on the motor bus via the *Power Electronics Module* (PEM) for powering subsystems which can include, among others, fuel metering, active magnetic bearing AMB (*Active Magnetic Bearing*) and executive systems. In addition, it is noted that when the engine is running, the generator of low pressure FSDG (*Fan Shaft Drive Generator*) also operates, which is also the source of the HVDC system in the 350V DC range.

II. Analysis and Mathematical Model of Selected Technology Solutions of HVDC Architecture According to the Trend of More Electric Aircraft MEA/ AEA

A. Analysis of Selected Technology Solutions in HVDC Architecture

Classical (conventional) HVDC systems are a combination of high voltage DC, implemented through the transmission system in the form of converter stations and overhead lines or cable DC. Today, there are many well-

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known configurations of these systems, which generally are classified into two groups: systems "*Back-to-Back*" (BTB), which are used to connect systems AC, operating asynchronously and systems of distance (remote) for power transmission. Typically, there are two separate stations, each of them (depending on the direction of power transmission) may act as a rectifier or inverter. Furthermore, in the BTB systems, which inserts DC, both types of converters are located in the same source of electrical power. In the case of aircraft in the field of on-board power system ASE (EPS, PES), the role is performed by the main on-board source of aircraft (generator, integrated starter/ generator).

On the basis of the literature review it can be seen that in connections HVDC are used two basic topologies of converters, i.e. inverter current CSCs (*Current Source Converters*), which include converters CSC switching network, natural, known as LCC (*Line Commutated Converters*) and the second topology in the form of voltage converters (*Voltage Source Converters*) for forced commutation FCC (forced commutated Converters). HVDC systems with the use of converters operating as current sources CSC are conventional systems, referred to as "*classical HVDC*", while HVDC systems from converters working as the voltage source of VSC systems are modern.

In the most advanced civil aircraft (*Boeing, Airbus*) and military (*Lockheed Martin*), consistent to the concept of MEA/ AEA, there are various possible solutions of architecture in the field of high voltage HVDC.

Architecture ±270V DC of power supply is used in practical applications, such as in the form of a power system EPS of plane using the system with fuel cells (*Fuel Cell*), which is used to carry out similar functions, which served as a conventional auxiliary power unit APU (*Auxiliary Power Unit*) driven by the turbine. The use of this type of solution has been implemented for practical use mainly due to the fact that, since the efficiency supplied by the APU is generally lower than 20 [%], and characterized by undesirable noise and emission of exhaust gas from the aircraft engine [13]. As the oldest, and thus the conventional solution in the use of converters are assumed LCC converters, which sample diagrammatic view is shown in the figure below (Fig. 3). It should also be noted that the high-voltage HVDC realized on the basis of converters LCC, have the ability to transfer the greatest power values.

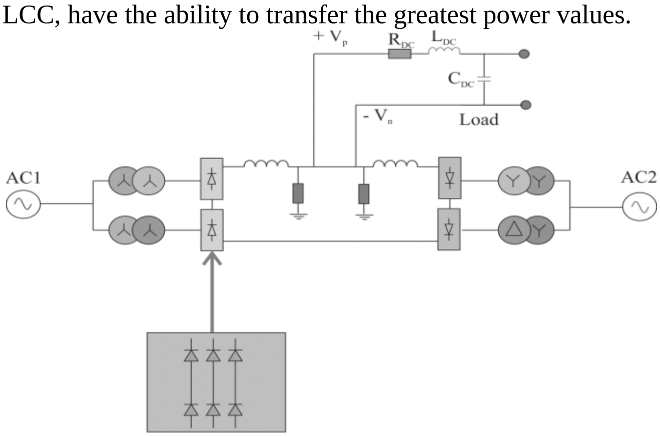

Fig. 3. Block diagram of the LCC system (using a 12- pulse bridge)

B. Mathematical Model of Selected Technology Solutions for HVDC Architecture

The selected technology solution of today's modern aircraft, both civilian (*Airbus*, *Boeing*) as well as military (*Lockheed Martin*) is an autonomous on-board ASE power system for PES. In this type of system, responsible for the implementation of high voltage transmissions, processed by the AC/ DC multi-pulse rectifier system in the HVDC range, the most important condition for obtaining the required parameters is to provide the correct input power at the output of the rectifier and the appropriate selection of the electronic components that make up the AC/ DC converter. The optimum solution for obtaining the required voltage signals is the use of a bridge system that is responsible for converting AC to DC. This process in the rectifier circuit is realized by means of a specialized converter system.

In view of the above, the operation of the DC side circuit can be represented by the voltage equation on the rectifier side:

$$U_{D0} = \frac{3\sqrt{2}}{\pi} \cdot B \cdot T \cdot U_{AC} \quad (1)$$

and

$$U_{DR} = U_{D0} \cos\alpha - \frac{3}{\pi} \cdot X_L \cdot I_D \cdot B \quad (2)$$

where: B - is the number of bridge circuits involved in the transmission of signals from the transformer; U_{AC}- the voltage value obtained by the transformation process on the AC side of the transformer, i.e. mean square value RMS (*Root Mean Square*); X_c- reactance of each bridge in the rectifier circuit, which is: $X_L = \omega \cdot L$.
On the other hand, DC voltage on the inverter side can be expressed as:

$$U_{DI} = U_{D0} \cos\gamma - \frac{3}{\pi} \cdot X_L \cdot I_D \cdot B \quad (3)$$

and

$$U_{DI} = U_{D0} \cos\beta - \frac{3}{\pi} \cdot X_L \cdot I_D \cdot B \quad (4)$$

Based on the presented equations describing the operation of the rectifier circuit and the inverter, it can be stated that both systems having significant functions in HVDC high voltage generation work together and are controlled one after another in a particular loop.
The next step defines the DC current flow from the rectifier side towards the inverter. The record (mathematical model) of this phenomenon is as follows:

$$I_D = \frac{U_{dor}\cos\alpha - U_{doi}\cos\gamma}{R_{cr} + R_L + R_{ci}} \quad (5)$$

In turn, the output power of the rectifier is derived from the following expression:

$$P_{dr} = U_{dr} \cdot I_d \quad (6)$$

In the next step of processing the voltage and current signals, the output power of the inverter is determined by the following expression:

$$P_{di} = U_{di} \cdot I_d = P_{dr} - R_L I_d^2 \quad (7)$$

Voltage and DC currents are evaluated by means of the angle of the voltage and AC and controlled by a transformer. A simplified HVDC system for which mathematical considerations were performed is shown in the figure below (Fig. 4).

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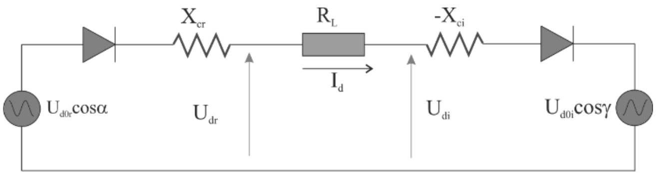

Fig. 4. HVDC Power transmission on the DC side

C. HVDC System Architecture in accordance with MEA/ AEA Concept

With the development of advanced aviation technology, the demand for various types of avionics has increased in terms of functions, including: modern radio technology, mechatronics, flight control systems, etc., which are important systems of modern aircraft [14], [15]. Progress in this area obliged constructors (engineers) to develop modern on- board electrical networks in terms of load requirements.

At this stage, the key task is, among others, taking into account the optimization process of the on-board architecture of the electrical network, i.e., optimizing the power of an aircraft POA (*Power Optimization Aircraft*), and developing appropriate procedures (algorithms) responsible for the production, distribution and transfer of power on board of a modern aircraft. The proposed solution should be based on combining the various functions of electrical equipment (sources) that produce voltage and current in the onboard electrical systems of a modern aircraft, taking into account different power ranges specified by the voltage (28V, 270V) in individual phases of flight of a modern aircraft. One of the design solutions is the on-board electrical system used on a *Boeing 787* aircraft, characterized by the applied environmental control system ECS (*Environment Control System*) that includes a function module which, during the engine start-up process, from the inverter of converter based on the PWM method, DC voltage and DC signals are supplied. This solution is of great interest primarily because it is compatible with particular specifications, that is, the previously used standards TS (*Technical Standards*) of an electric network.

Based on the analysis of the subject literature, in the publication [16] the authors propose a solution consisting in the use of parallel rectifier systems consisting of three 3-phase PWM inverters. For example, four inverters with AC active power of 30 [kVA] can be combined with interleaving (*phase-phase*) with inductors to achieve quadruple frequencies in switching range equivalent to 25 [%]. Therefore, in each circuit inverter has a power of 120 [kVA].

A completely different solution is the use of an HVDC system, whose main task is to connect the main power sources that produce the voltage and current to the electrical storage devices, such as the supercapacitor, which is actually a hybrid system consisting of a classical condenser, battery and electrolyte. Such appliances provide many benefits in terms of electricity generation and are complementary to traditional sources.

Considering the case of a full power unit failure, we note that during this transition between the normal and the emergency states, that is, between the primary and the emergency work, they are running in a smooth manner, virtually imperceptible by electrical appliances and by the operator of these devices. This kind of transitional process in conventional (classical) solutions, was realized by the hydraulic network of the aircraft (in the field of hydraulic energy), where the energy storage device was a source in the form of RAT air turbine, which is a component of the equipment of a more electric aircraft. The drawings below, illustrate examples of such technological solutions, namely Fig. 5 shows the general structure of the onboard electrical network using HVDC system, with GCU (*Generator Control Unit*), which secures the proper operation of the onboard power source in the form of a generator or an integrated starter/ generator set, and Fig. 6 shows the principle of operation of this system.

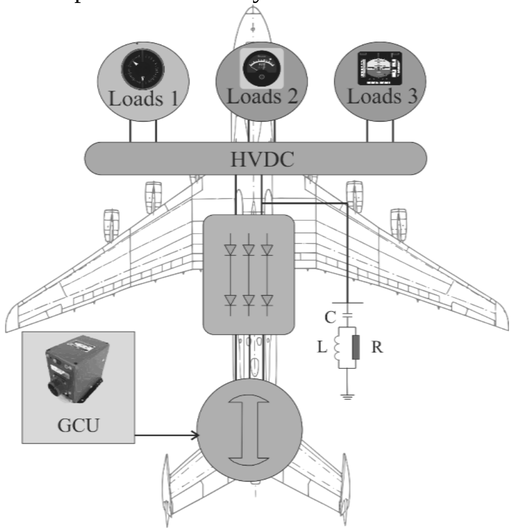

Fig. 5. General structure of HVDC on-board electrical system

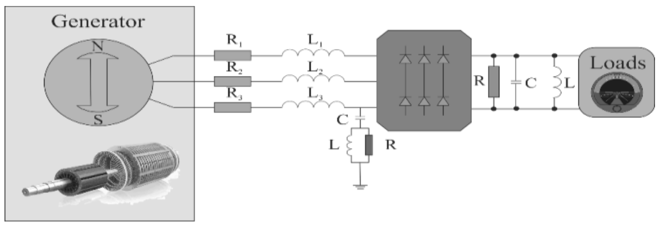

Fig. 6. The process of signal transmission of HVDC system

The essence of operation of the onboard electrical network of the aircraft using HVDC system is based on the fact that the main power source in the form of a synchronous generator together with a controlled excitation process produces a 3- phase AC current, which in the next step is fed to multi-pulse rectification systems, e.g., (6- , 12- , 18- , 24-) pulses, after having passed through the filter system via a filter (mainly capacitive), designed to improve the output parameters of the rectifier circuit. Subsequently, the signals are transmitted to the inverters, which will be further transformed so that, in the final stage, power the end devices (systems, devices, installations, etc.). The only drawback (disadvantage) of the presented solution is the loss of power in the processed (transformed) waveforms of voltages and currents. In turn, undoubtedly the great advantage of the HVDC system is the reduction of weight of electrical machines EM (*Electrical Machines*) to 30 [%], which is of great importance for aviation [17], [18]. The following figure (Fig. 7) illustrates an exemplary functional diagram of an HVDC on- board electrical system in accordance with the trend of the more electric aircraft MEA/ AEA.

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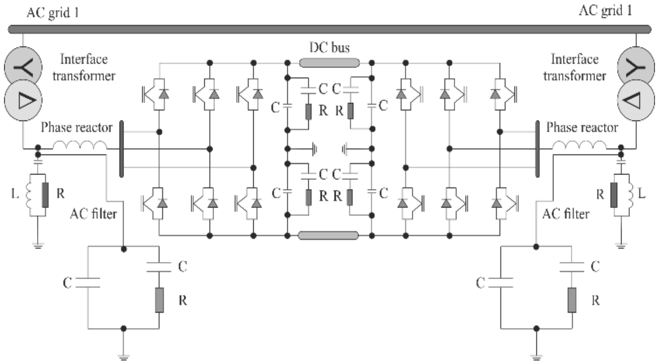

Fig. 7. Example of a functional diagram of the electrical network of HVDC system of a more electric aircraft [18]

The above system consists of two different 3-phase alternating current sources, AC, which operate in the equivalent electrical systems of the aircraft connected by a DC bus feeder via a link in the form of two inverters connected to the DC bus. At a later stage in dealing with issues related with the implementation of the HVDC system for advanced on-board ASE systems (including the physical model) illustrated in Figures 6-7, based on the electromagnetic transient states in relation to the *d-q* planes in the synchronous generator, were defined equations describing the states, which are presented in the following form:

$$\begin{cases} L\dfrac{di_d}{dt} + i_d R - \omega i_q = u_{cd} - u_{sd} \\ L\dfrac{di_q}{dt} + i_q R - \omega i_q = u_{cq} - u_{sq} \end{cases} \quad (8)$$

where: ω- is angular velocity; u_{cd} and u_{cq}- denote respectively the voltage components in the transducer on the reactor transducer side (choke); and u_{sq} and u_{sd}- the voltages on the component side of the inverter.

Mutual relations between the voltage u_{cd} and the voltage u_{cq} is expressed by:

$$\begin{cases} u_{cd} = M\cos\theta \dfrac{u_{dc}}{2} \\ u_{cq} = M\sin\theta \dfrac{u_{dc}}{2} \end{cases} \quad (9)$$

where: M- is the amplitude of the three- phase current i_{abc}; θ- is the angle of phase shift of the voltage u_{abc}, responsible for the HVDC system. Equation (9) describes transition states on the AC side. Next, using the theory of instantaneous reactive power in a DC block, one can present it in the form:

$$u_{dc} i_{dc} = \frac{\frac{1}{2} d(u_{dc}^2)}{dt} + \frac{3}{2} u_{sd} i_d + \frac{3L}{4}\left(\frac{di_d^2}{dt} + \frac{di_q^2}{dt}\right) \quad (10)$$

In addition, mathematical dependence (10) describes physical phenomena occurring on the DC side of the HVDC system.

III. Results of Simulation Research of Selected Components of Advanced Technology Solutions of HVDC Architecture According to the Concept of MEA/ AEA

The following figures (Fig. 8-11) are examples of voltage and current waveforms for the HVDC system voltages of 270V DC and 115V DC obtained from the system of converters LCC (*Line Commutated Converters*) [19],[20].

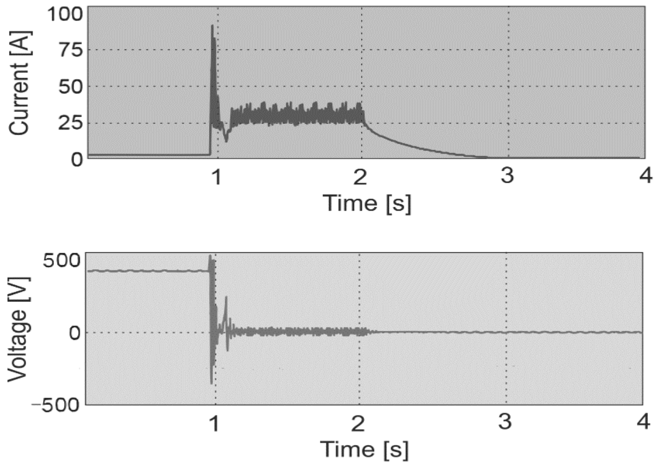

Fig. 8. Voltage and current waveforms for the HVDC 270V DC obtained from the system LCC

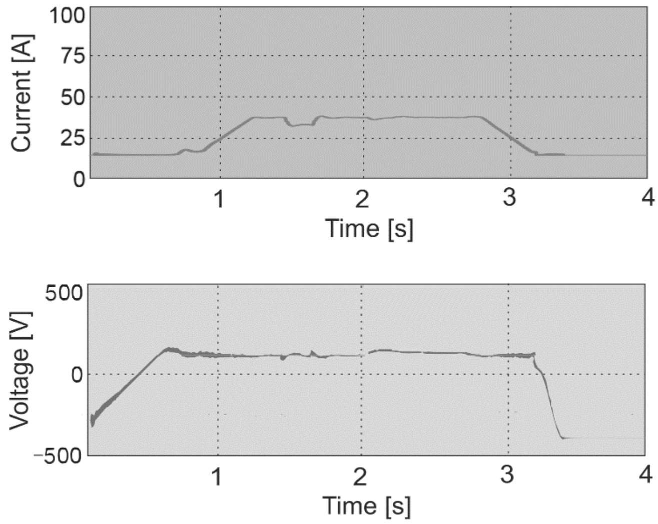

Fig. 9. Voltage and current waveforms for the HVDC 270V DC system obtained from system LCC on the side of the DC voltage at the frequency of 500 [Hz]

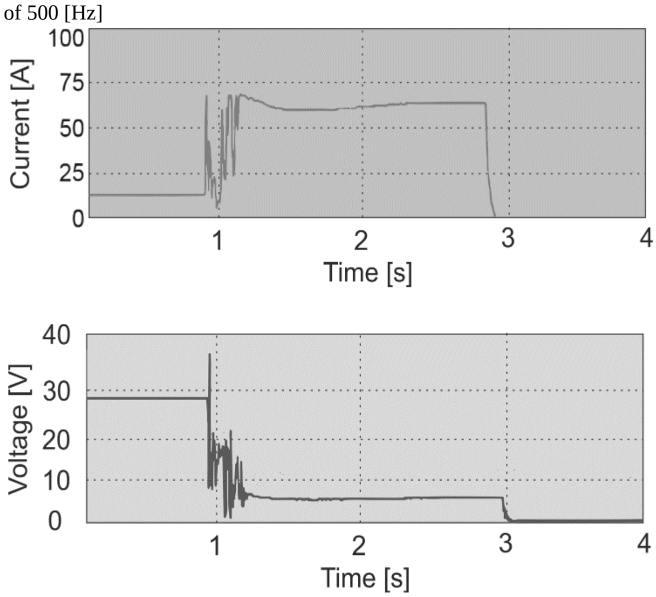

Fig. 10. Voltage and current waveforms for the HVDC 115V DC obtained from the system LCC

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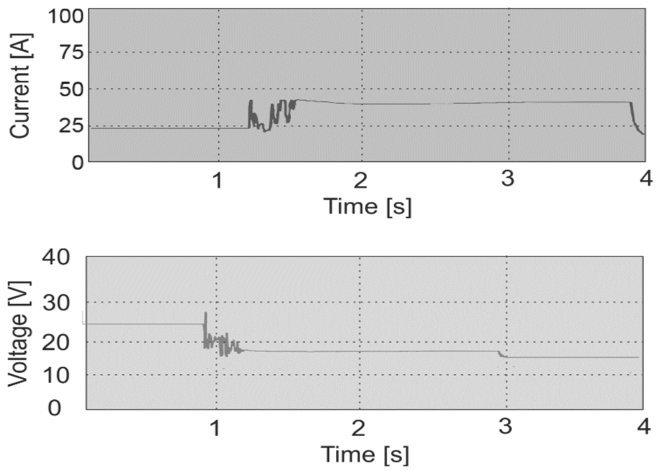

Fig. 11. Voltage and current waveforms for the HVDC 270V DC system obtained from the system LCC on the side of the DC voltage at the frequency of 350 [Hz]

IV. Conclusion

Based on a review of the subject literature in the field of architecture HVDC 540V DC (±270V DC), and 350V DC, performing their overall analysis and exemplify the simulations of the key components of ASE system in the field of PES, it can be assumed that such technological solutions are possible to use in the context of the standard in future aviation applications. Selected sample simulations were performed for the basic components of the ASE on-board power supply system in the field of PES, namely HVDC high voltage systems, realized basing on LCC converters. It should be noted here that the article presents only the preliminary modeling process of HVDC systems and their results from computer simulations were carried out for stationary and transient states.

The results obtained on the basis of the simulations performed in the Matlab/ Simulink programming environment indicate that in high HVDC voltages it is possible to convert efficiently high AC voltages to their respective DC constant values. Visible errors in relation to the waveforms of voltages and currents derived DC characteristics result from the rapid emission of the AC harmonic current and voltage variables. In addition, it should be added that the ”*wobbles*” observed in the charts are also influenced by time-varying loads of target aircraft components (devices, installations, receivers, etc.). When analyzing the voltage and current waveforms in terms of system architecture of HVDC 270V DC and 115V DC for the two selected frequencies 350 and 500 [Hz] (Fig. 8-11), it can be observed that in a situation in which there are ”*wobbles*” of the current value, the waveform of the voltage increases rapidly, then gradually decreases to a dangerously low level (critical level).

This is due to the occurrence of a capacitor discharge phenomenon occurring during the conversion of AC values to DC values. The discharge phenomenon contributes to the voltage drops in the electrical circuit that transmits DC voltage, but the signal strength is not deteriorating.

The solution described in the article is characterized by many advantages, among others, optimizing and improving the efficiency and effectiveness of on-board electrical network of autonomous power supply system ASE (EPS, PES). In addition, the technical solution in the field of HVDC allows mutual integration and relations between components (subassemblies) which are responsible for the quality of produced electricity and the elements in DC power supply. In addition, the results presented in the article from made simulations and selected mathematical models can contribute to the further development of board electrical network architecture in the field of HVDC of modern aircraft.

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