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# ANALYSIS AND SIMULATION OF ADVANCED TECHNOLOGICAL SOLUTIONS IN THE FIELD OF POWER HIGH-VOLTAGE DIRECT CURRENT (HVDC) OF MODERN AIRCRAFT IN LINE WITH THE TREND OF MORE ELECTRIC AIRCRAFT (MEA)

# ANALIZA I SYMULACJA ZAAWANSOWANYCH ROZWIĄZAŃ TECHNOLOGICZNYCH W ZAKRESIE ZASILANIA WYSOKIEGO NAPIĘCIA PRĄDU STAŁEGO (HVDC) WSPÓŁCZESNYCH SAMOLOTÓW ZGODNYCH Z TRENDEM SAMOLOTU BARDZIEJ ELEKTRYCZNEGO (MEA)

Abstract

The subject of the paper is to present innovative technological architecture of the power supply system EPS (Electric Power System) in the field of high voltage power HVDC (High Voltage Direct Current) by conducting a critical analysis of the literature as well as an analysis and simulation of its selected component in line with the trend of more electric aircraft MEA (More Electric Aircraft). The considered advanced technologies relate to the architecture of the power supply system HVDC in the high voltage 540V DC (±270 V DC) and 350 V DC, used for advanced aircraft in line with the trend of MEA/ AEA, in particular for military aircraft made by Lockheed Martin (F-22 Raptor, the JSF F-35). Based on the above, the simulation of sample components of the system architecture of high voltage power HVDC has been made, selected from the group of military aircraft in the area of more electric aircraft 'More Electric Aircraft', which is mainly the domain of advanced military aircraft the JSF (Joint Strike Fighter) F-35 and F-22 Raptor. In the final part, the paper presents the main conclusions arising from the analysis and simulation of selected components of HVDC power system architecture in accordance with the concept of a more electric aircraft.

*Keywords: MEA, power supply systems of high voltage DC (HVDC), electrical machines*

Streszczenie

Przedmiotem niniejszego artykułu jest przedstawienie innowacyjnych rozwiązań technologicznych architektury elektroenergetycznego systemu zasilania EPS (*Electric Power System*) w zakresie zasilania wysokiego napięcia HVDC (*High Voltage Direct Current*) poprzez dokonanie analizy literatury przedmiotu oraz analizy i symulacji wybranego jej komponentu zgodnie z trendem samolotu bardziej elektrycznego MEA (*More Electric Aircraft*). Rozpatrywane zaawansowane rozwiązania technologiczne dotyczą architektury systemu zasilania HVDC w zakresie wysokich napięć 540 V DC (±270 V DC) oraz 350 V DC, stosowanej w zaawansowanych samolotach zgodnych z trendem MEA/AEA, w szczególności samolotach wojskowych koncernu Lockheed Martin (F-22 Raptor, JSF F-35). Dokonano symulacji przykładowych komponentów architektury systemu zasilania wysokiego napięcia HVDC, wybranych z grupy samolotów wojskowych w zakresie samolotu bardziej elektrycznego, będącej domeną głównie zaawansowanych samolotów JSF (*Joint Strike Fighter*) F-35 i F-22 Raptor. W końcowej części referatu przedstawiono główne wnioski wynikające z przeprowadzonej analizy i symulacji wybranych komponentów architektury systemu zasilania HVDC w myśl koncepcji samolotu bardziej elektrycznego.

*Słowa kluczowe: MEA, elektroenergetyczne systemy zasilania wysokiego napięcia prądu stałego (HVDC), maszyny elektryczne*

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## 1. Introduction

After analyzing numerous publications and literature, it can be seen that the More Electric Aircraft (MEA) concept has plenty of branches and solutions. One of its aspects – Power Electronics Systems based on the multi-pulse converters – was presented in our previous publication [1]. This paper indicates and considers another advanced solution compatible with MEA concept – High Voltage Direct Current (HVDC).

Both in modern civil (Airbus, Boeing) and military aviation (Lockheed Martin), in terms of aircraft consistent with the concept of the More Electric Aircraft (MEA), you can observe a continuous and dynamic development of the Electric Power System (EPS) architecture. This development can be clearly seen in the field of High Voltage Direct Current (HVDC) and its key component is the Power Electronic System (PES) [1, 2]. Making the introduction to the subject of this paper, it should be noted that modern advanced EPS and PES technology in terms of High Voltage Direct Current (HVDC) relate primarily to the most advanced military aircrafts (F-22 Raptor, JSF F-35). Their domain are high 540 V DC voltages (±270 V DC) and 350V DC [3, 4]. Advanced technological solutions, which are based on the current widely understood development in the field of electrical machines and their related fields (power electronics, electronics), found application in a variety of advanced aviation, particularly in the field of Power Electronics Systems (PES) [5]. The processing of electrical power based on the technologically advanced multi-pulse transducers (converters, inverters) recently became one of the most dynamically developing trends in aviation technology. This is due to the progressive development of the power semiconductor, so that there are new methods for power management of PMS (Power Management System). Therefore, the transducers of electric energy on board of the advanced aircraft as key components of the PES (Power Electronics System) play a key role in the processing methods of DC, including High Voltage Direct Current (HVDC) [6]. Examples of Power Electronics (PE) application used on board of modern aircraft are presented in the table below (Table 1).

In traditional electrical power systems, the concept of high-voltage DC (HVDC) has been known for many years in the context of the transmission of electricity point-to-point. The growing demand for the transmission of large amounts of electricity in modern aircraft, both civilian (A-380, A-350XWB, B-787), and military (F-22 Raptor, JSF F-35) obliged aviation companies to use advanced aircraft electrical systems, consistent with the trend MEA/AEA, high voltage DC (HVDC). Dictated primarily by the fact that HVDC is characterized by many positive properties, it was also planned in further projection of electrical systems of up to 540 V DC (or ±270 V DC also called HVDC) [7].

The first such feature is the reduction of the electric wire cross-section obtained by reduced current flow when transferring the same power supply, resulting in lower weight, which is extremely important in aerospace applications. In addition, it should be noted that the voltage levels can be increased in conventional power networks to increase the transmitted electric power. Another advantage of HVDC system is the reduction of electricity losses due to the higher voltage level and the ability to use the DC network that eliminates reactive power consumption. For these reasons, DC links are used for long-distance point-to-point traditional electrical networks. Furthermore, due to the reduction of losses of the electricity network used on modern aircraft air conditioning, ECS (Environmental Control System) has a lower demand for thermal power (heat). A further advantage of using a DC is the weight cut, as electrical light transducers of AC powering converters must be equipped with passive or active filters, i.e. PFC (Power Factor Correctors), and therefore may be supplied by a sinusoidal current input. This is very important, especially in the case of the high-impedance network, which is onboard aircraft [8, 9].

Table 1

**An example application of power electronics on board modern aircraft [7]**

| Category | Application | Techniques/Circuits |
|---|---|---|
| Energy storage | Battery safety | Battery management system: flyback converters |
| | Charging process | Power factor correction, converter, DC-DC converter |
| Controlling the movement | Actuator | Engine design, motor drive |
| | Fuel pump | Electric pump, motor drive, power converter |
| | Controlling the movement | Power transmitter, vector control, torque control |
| | Chassis | Engine design, motor drive |
| Environment control system | Ventilation | Inverter |
| | Lighting | Electronic ballast, LED |
| | UPS | Inverter, battery charger |
| | Adjusted power factor | Capacitor switching |
| Distribution of electric energy in aviation | Drive | Inverter (DC-AC power converter) |
| | Production of AC | 2-level inverter, resonant converters, phase shift converter |
| | VFCF | Inverter, power factor corrected converter |

## 2. Overview of high voltage HVDC electrical power supply system architecture solutions

In recent years, the aviation industry resigned from the use of traditional 28 V DC voltage and 115 V AC/ 400 Hz power, in exchange using the system of 230 V AC and 270/ 540 V DC. These changes were necessary due to the requirements dictated by increasing demands for electricity, while minimizing the impact of the power lines weight. From the point of view of power management, this trend poses a challenge in terms of design and use of electronic equipment in terms of ELCUs (Electronic Load Control Units), 'smart contactors', SPLS (Smart Programmable Loads and Sources) and BCRU (Battery Charge Regulators Units), intended to provide 28 V DC voltage and recharge onboard battery, permanently connected to the DC network, according to MEA or AEA trend [10]. The figure below (Fig. 1) [11] shows an example of AC-DC converters, built with a transformer and regulator BCRU, which play a key role in the EPS and PES of advanced aircraft.

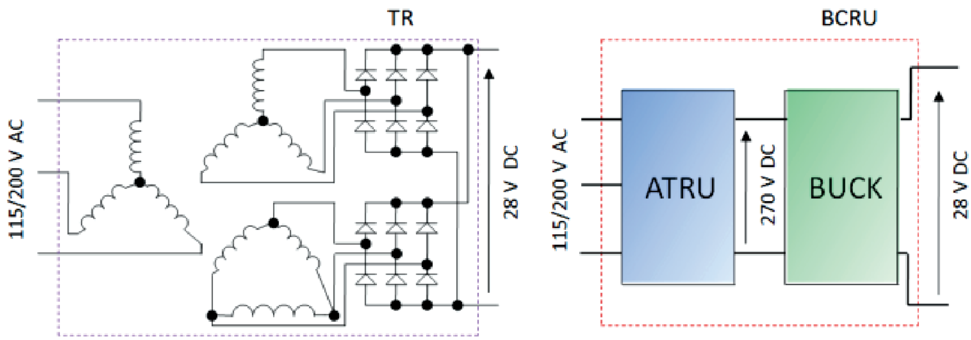


Fig. 1. Example of an advanced technological solution AC-DC converter, used on the Airbus A-380

Electrical Power System (EPS) used on 'traditional' airplanes usually comes down to the use of a combination of 115/200 V AC 400 Hz voltage to meet the needs of the high load receivers as well as high power 28 V DC voltage to supply avionic systems, flight control system and other systems powered by DC voltage. However, due to noticeable need for a significant increase in power of on-board power sources and a continuous and dynamic growth in demand for various types of electric power, the adaptation of the advanced systems for producing electric energy of VF (Variable Frequency) requires the use of advanced power supply systems PES (Power Electronics Systems) serving to convert the generator output to a single high voltage transmission and distribution DC system. It should also be mentioned that it is recommended that the voltage of advanced power electronic power systems PES in the range of DC voltage was 270 V, 350 V or even 540 V. Therefore, the use of high voltage in advanced EPS of DC is dictated primarily by advantages, such as: reduced weight, size and energy loss with an increase in the level of power.

Table 2

**Example of electricity generation system comparison [8]**

| | | Weight | Performance | Reliability |
|---|---|---|---|---|
| **Constant Frequency System (CFS)** | **IDG** | moderate | lowest | average |
| | **DC-Link** | highest | moderate | good |
| | **Cycloconverter** | high | moderate | good |
| **VFS** | | lowest | highest | best |
| **HVDC (270V DC)** | **Brushless DC Generator** | low | moderate | good |
| | **Switched Reluctance Generator (SRG)** | high | moderate | good |

The above table (Table 2) shows the location of the high voltage 270 V DC system (its benefits) in the context of the currently existing types of electrical power generation systems in today's technologically advanced civil (Airbus, Boeing) and military aircraft (Lockheed Martin) [12, 13].

## 2.1. Architecture of high voltage 540 V DC (±270 V DC) power system

Modern aircraft with a high degree of advancement, both civilian Airbus (A-380, A-350XWB) and Boeing (B-787), as well as military Lockheed Martin (F-22 Raptor, the JSF F-35), in line with MEA/AEA have electrical power systems, which, by suppling high voltage DC buses, divide and distribute high-quality electrical power on board modern aircraft. These buses are used to power the DC loads of different purposes, including actuators: electromechanical EMA (Electromechanical Actuation) and electro-hydraulic actuators EHA (Electrohyraulical Actuation). Nowadays, with the developing trend of MEA/AEA and EPS/PES, high-voltage 540 V DC (±270 V DC) systems are considered as standard. The first generation system applies to 270 V DC, while 540 V DC system is a prospective standard. The most advanced aircraft are characterized by a variety of EPS architecture solutions in the range of HVDC, including ±270 V DC (2 phases to ground), 270 V DC (1 phase to ground), ±135 V DC (2 phase to ground) and ±135 V DC (2 phases without ground) [14].

## 2.2. Architecture of high voltage 350 V DC power system

The architecture of this kind in the field of high-voltage 350 V DC applies to advanced MEE (More Electric Engine) technology. The engine uses MEE venting fan in order to protect the engine against the phenomenon of icing, as shown in the figure below (Fig. 2).

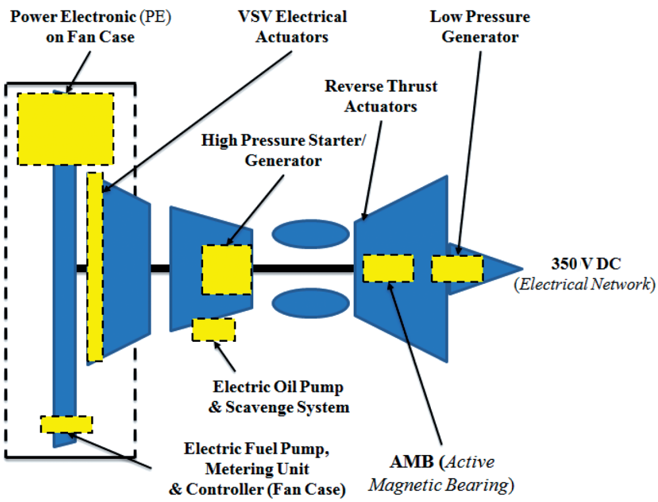


Fig. 2. Arrangement of the basic components of MEE engine Trent 500 [10]

One of these components of the upgraded Trent 500 plus engine, made in the MEE technology, is a bleed air fan used to protect the engine against the phenomenon of icing. The key components of the Trent 500 Rolls-Royce engine are: HPSG (High Pressure Starter/Generator) that provides power of 150 kVA (Permanent Magnet), PEM (Power Electronics Module) providing 350 V DC voltage to the engine and ME (more-electric) components of aircraft, electric fuel pumps, electric motors of VSV (Variable Stator Vanes) and other items, as shown in the Fig. 3.

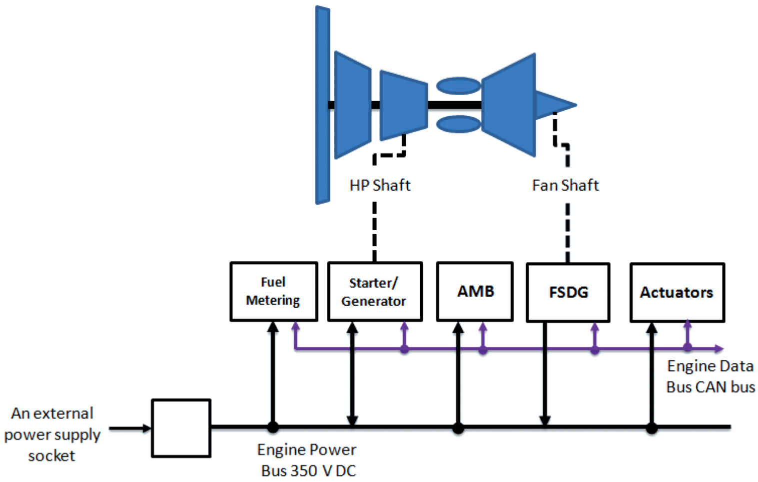


Fig. 3. Main components of the electric MEE engine – Trent 500 Rolls-Royce [10]

In the context of the EPS architecture analysis in the range of high voltage of 350 V DC, the most important component is the electric bus with voltage of 350V DC. On the other hand, starter/generator mounted on the HPSG shaft (High Pressure Starter/Generator), used to start the engine, is powered by 350 V DC from on-board batteries or an external power source. After starting the engine, this unit provides a voltage of 350 V DC to engine bus through PEM (Power Electronics Module) to power subsystems, such as: fuel dosing, AMB (Active Magnetic Bearing) and actuators, which are connected to the data exchange CAN bus (Controller Area Network bus). It should also be noted that in the case of a running engine, the generator operates as a FSDG (Fan Drive Shaft Generator), which also becomes the source of the 350 V DC voltage.

## 3. Analysis of HVDC electrical power system architecture in line with the MEA trend

The development of current electrical power systems (EPS) in generating, switching and the security of electrical power followed with the development of technological progress in this field. These innovative solutions have an impact on the traditional powering systems that have existed for many years, probably since World War II. These changes have resulted in the availability of new technologies and equipment, which in turn made advanced concepts of the systems credible, or provided resources for advanced concepts of systems, such as MEA/AEA, EPS/PES, HVDC, etc.

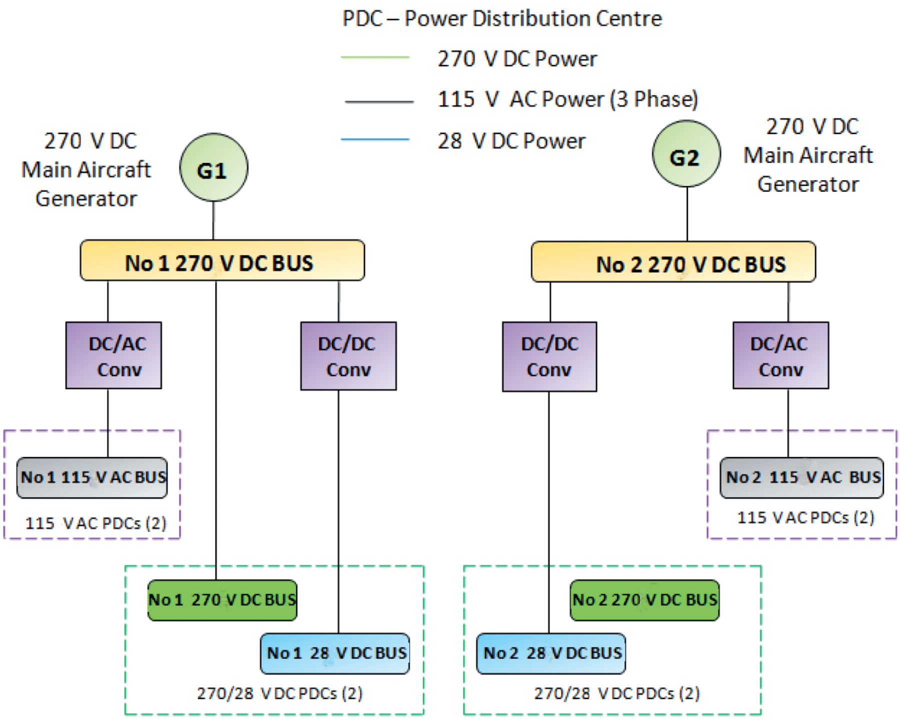


Fig. 4. A simplified EPS system diagram of military aircraft F-22 [12]

Innovative concepts of electrical power system EPS include the following key elements: ELMS (electrical load management system), VSCF (variable speed constant frequency) – Cycloconverter, 270 V DC systems and the MEA [15]. Analyzing the 270 V DC system architecture for a high-voltage HVDC, it should be noted that the system of 270 V DC is used not only as power supply for certain components of an EPS (civilian aircraft), but also it is used as a main power source for advanced military aircraft (F-22 Raptor, the JSF F-35).

Fig. 4 shows a diagram of simplified EPS system diagram of military aircraft F-22 Raptor. US Air Force aircrafts, using 270 V DC EPS in the range of HVDC are: F-22 Raptor and F-35 Lightning II from Lockheed Martin company, which utilize 270 V DC system as the main power system. Application of 270 V DC system is an extrapolation of circumstances to departure the 28 V DC system to the 115 V AC system, namely: reducing the size of the current wires thus minimizing the weight, voltage drop and power dissipation. There are also several disadvantages associated with the usage of the 270 V DC of high voltage HVDC system, which could include: high cost, the usage by the technical staff, in the field of air services, of traditional 28 V DC and 115 V AC voltage, and that the use of higher voltages extracts greater reliance on techniques and implementation methods of isolation, to avoid power interruption. For this reason, the US military has done a lot of projects, development programs and demonstration. Some of them were designed for greater use of electricity on board of combat aircraft, possibly to replace conventional energy obtainable from secondary sources and hydraulic actuators, or at least to substantially increase them. The determination of these changes is more in line with the trend of More Electric Aircraft (MEA), and therefore may lead to a much larger, if not total use of electrical power in aircraft electrical systems. In addition, the use of HVDC systems in military aircraft poses a threat in the context of the increased possibility of a fire phenomenon, resulting from damage to the aircraft, made of composite materials in the form of carbon (carbon-fiber) during combat operations. In addition, care should be taken to reduce the phenomenon of sparkling at high altitudes or in difficult conditions (humidity, salinity, etc.) in tropical and marine environments. It should also be noted that there is also a potential mortal danger to the technical staff during service. Therefore, all these factors must be taken into account during the design stage and the production of advanced aircraft.

## 4. Simulation of rectifying systems used in aircraft in compliance with 'More Electric Aircraft' concept

The below figure (Fig. 5) shows an ATRU (Auto-Transformer Rectifier Unit), which was used, among others, on the Boeing B-787 Dreamliner. It consists of a source of electrical energy in the form of a 230 V AC VF bus, ATU (Auto Transformer Unit) processing voltage from source into 4 voltage groups of 3 phase shifted in phase with each other by 15 degrees, a 24-pulse converter, consisting of four 6-pulse transducers and the system load in the form of resistance [16, 17].

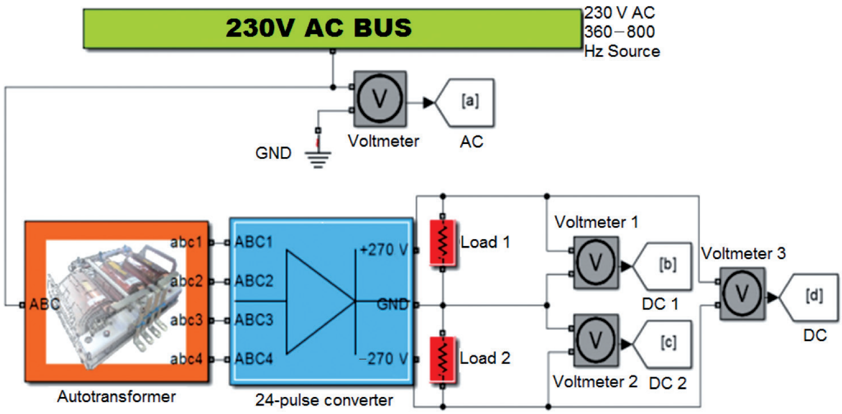


Fig. 5. Block diagram of the auto-transformer rectifier ATRU HVDC ±270 V DC in the Simulink

The measuring system consists of 4 voltmeters measuring voltage of power source and voltage of output channels: +270 V, –270 V and 540 V, as shown on each graph (Fig. 6–9).

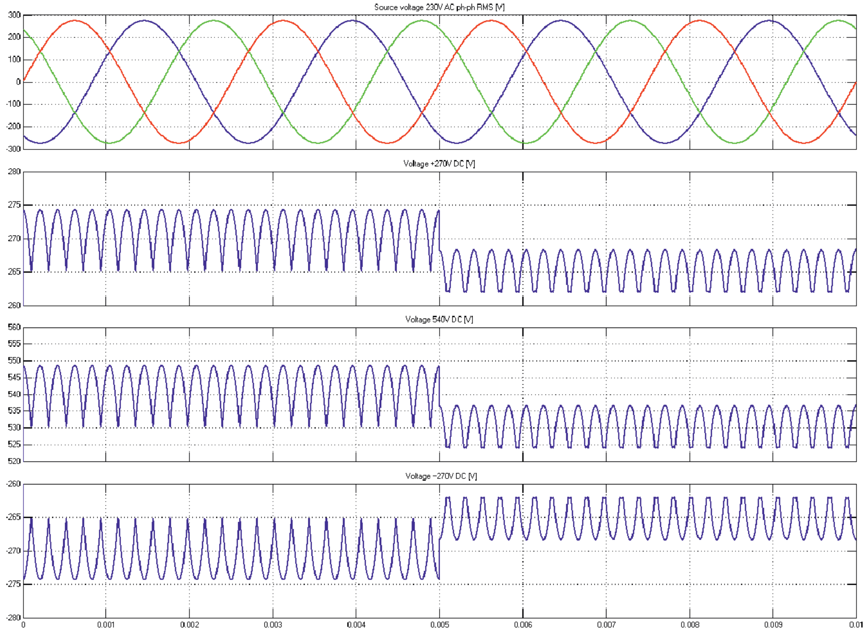


Fig. 6. Chart of source 230 V AC voltage, and output voltages of ATRU (±270 V DC, 540 V DC) $f$ = 400 Hz (10 kVA load added in 0.005 s) in the Simulink

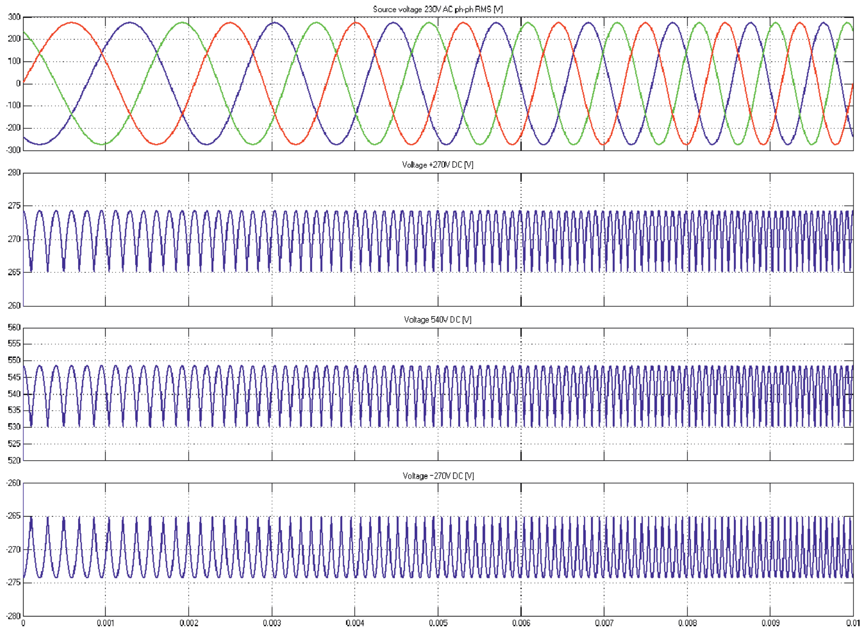


Fig. 7. Graph of source 230 V AC voltage, and output voltages of ATRU (±270 V DC, 540 V DC) $f$ = 400÷800 Hz in the Simulink

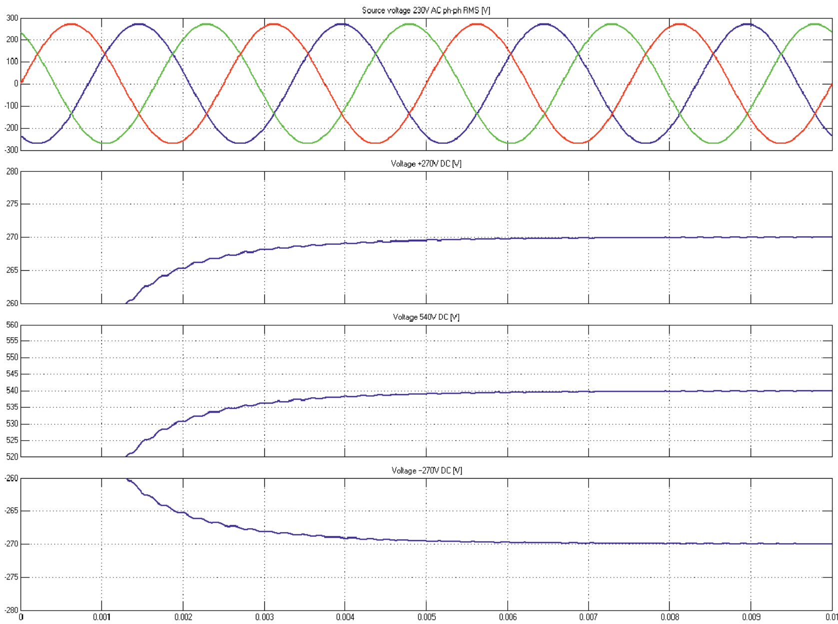


Fig. 8. Chart of source 230 V AC voltage and output ATRU voltages (±270 V DC, 540 V DC) after adding a capacitance in the Simulink

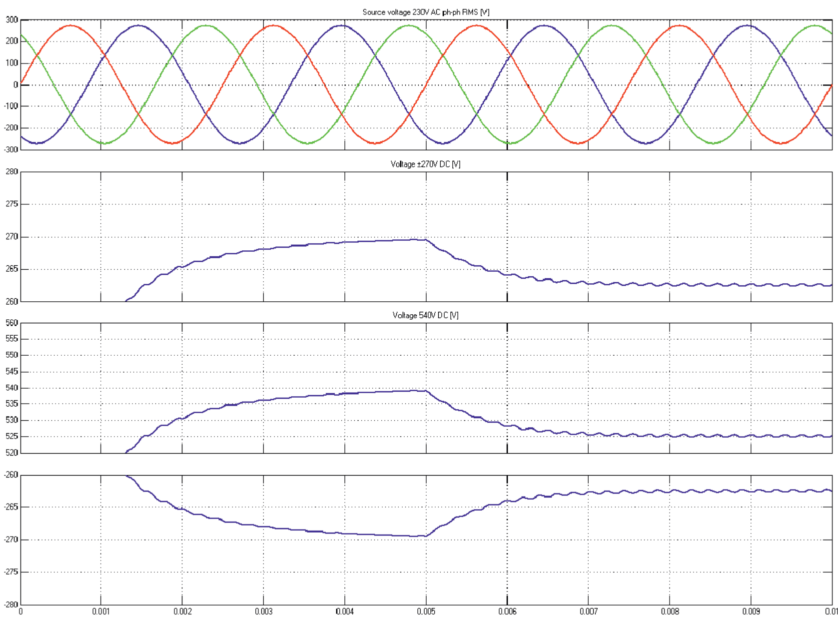


Fig. 9. Chart of source 230 V AC 400 Hz voltage and stabilized output ATRU voltages (±270 V DC, 540 V DC) with load added in 0.005 s in the Simulink

The three-phase AC source voltage is first processed by the autotransformer to 4 groups of the AC voltage phase-shifted relative to each other at 15 degrees. Each group of the AC voltage goes to one of the four 6-pulse converters, in which the AC voltage is converted into a DC voltage. 6-pulse converters are connected in parallel to form an advanced 24-pulse converter. This solution allows for a significant reduction in output ripple voltage, which in turn feeds the individual instruments and actuators.

The voltage supplied to ATRU is 230 V AC variable frequency in the range of 360÷800 Hz, depending on the speed of the motors driving AC alternators. Assuming that the nominal AC frequency is 400 Hz, normal operation of the EPS system was simulated. In the graph (Fig. 6), it can be observed that at this frequency output ±270 V DC voltage ripple is approx. 9 V (ripple factor approx. 3.3%), while for 540 V DC output voltage ripple is approx. 18 V (ripple factor approx. 3.3%). In the 0.005 s of simulation, there was a 10 kVA load connected to the system. The voltage of all channels dropped by 1.85%.

The operation of the system with increasing AC frequency: from 400 Hz to 800 Hz, was also simulated (Fig. 7). After analyzing the graphs, it can be seen that, despite changes in the frequency, the output voltage is maintained at the nominal values.

The graphs (Fig. 8 and Fig. 9) show working of the system after adding a capacitance. As can be observed, the electrical inertia of the system increased, which allowed to maintain much more precise voltage levels with very small ripples. Also, after adding a load to the system, output voltage value dropped by 2.8%.

## 5. Summary and conclusions

Based on our review of the literature, the general analysis and examples of ATRU of HVDC ±270 V DC simulations in the Simulink, it can be assumed that the innovative technological solutions of the HVDC system architecture in the field of high voltage 540 V DC (±270 V DC) and 350 V DC, used on advanced aircraft (Airbus, Boeing, Lockheed Martin), have the ability to standardize the future aerospace applications. The conducted simulations of selected components of HVDC (+270 V, –270 V and the voltage 540 V) system based on ATRU showed that despite the analysis for different frequencies (from 400 to 800 Hz), the output voltage of HVDC was maintained at nominal values with small ripple level. However, interestingly, a suitable capacitance at the output causes a much smoother voltage level. Adding a load to the system appears in decreased output voltage due to the source internal resistance. It means that this system needs a voltage regulator to keep the voltage at the same level regardless of connected loads. It should also be noted that the analyzed autotransformer rectifier ATRU is characterized by a high density of electrical power, it is designated for transformation of three-phase, variable frequency voltage (230 V AC VF) or three-phase voltage with a fixed frequency (115 V AC 400 Hz) at the input. Its task is to transform to the dual output voltage of ±270 V DC (i.e. the differential voltage of 540 V DC). Additionally, ATRU converts electrical power of HVDC from the source, using the unregulated AC-DC converters during the process of switching voltage of the autotransformer. Summarizing the above, it should be mentioned that the implementation of the system architecture of the HVDC power supply of the 540 V (±270 V DC), and 350 V DC voltages plays a key role in the most advanced aircraft in accordance with the current and future trend of the MEA/ MEE and AEA and more AEA.

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