Comparative Analysis and Simulation of Selected Components of Modern on-board Autonomous Power Systems (ASE) of Modern Aircraft in line with the Concept of MEA/ AEA

Lucjan Setlak, Rafał Kowalik

***Abstract*— The subject of this paper is to present the most advanced technology on-board autonomous power systems (ASE) in the field of modern power systems (EPS, PES) of modern aircraft. Given that the largest function in terms of the trend of More Electric Aircraft (MEA) is attributed to civil aviation, the main (fully justified) role in this paper will be assigned to civil aircraft of the key aviation companies (Boeing, Airbus). Innovative technological solutions presented are based on the analysis of literature and comparative analysis and simulation in software environment MATLAB/ Simulink of selected components of the architecture of power systems EPS and PES. Based on the above, exemplary simulations of selected components of power system (EPS, PES) were conducted, selected from the group of civilian aircraft companies Airbus (A-380, A-350XWB) and Boeing (B-787) compatible with the trend of more/ full electric aircraft (MEA/ AEA). In the final part, the paper presents the main findings resulting from both the comparative study of selected components of the power systems architecture (EPS, PES) of modern aircraft, and the simulation of sample components of ASE architecture in accordance with the concept of a more electric aircraft.**

***Index Terms*— More Electric Aircraft (MEA), Autonomous Electric Power Systems (ASE), Electric Power Systems (EPS), Power Electronics Systems (PES)**

I. Introduction

In modern aviation, both civil (*Airbus, Boeing*), in the field of aircraft consistent with the concept of a more/ full electric aircraft MEA/ AEA (A-380 and A-350XWB, B-787) and in military aviation (*Lockheed Martin*) in the field of aircraft compatible with the trend of MEA, for example *Joint Strike Fighter* (JSF) F-35 and F-22 Raptor, you can see the dynamic development of modern on-board autonomous power systems (ASE) in the context of systems architecture (EPS, PES) [1], [2]. When making a short introduction to the subject of this paper it should be noted that modern advanced solutions of air power systems EPS and PES, including in the field of supply of *High Voltage Direct Current* (HVDC) relate primarily to the most advanced aircraft (civilian and military). The basis for these solutions is the current development in the field of electrical machines and their related fields (power electronics, electronics), which found a variety of uses in modern aviation, in particular in the field of *Power Electronics Systems* (PES) [3]. The processing of electricity (power) through a technologically advanced multi-pulse transducers (6-, 12-, and 18- and 24- pulse) has recently become one of the fastest growing trends in aviation technology implemented.

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Similarly, in the case of *Electrical Power Systems* (EPS), which together with the PES are key components of autonomous power systems (ASE), you can observe innovative technological solutions in this area, e.g. switched reluctance starters/ generators in the form of team starter/ generator powered by a high voltage of 270 [V] DC and sources, which are synchronous generators based on permanent magnet PMSG (*Permanent Magnet Synchronous Generator*) [4].

II. Components of Autonomous Power System ASE (EPS, PES) Compatible with Trend of MEA/ AEA

A. *The general structure of modern power systems*

The concept of electrified power systems MEAPS (*More Electric Aircraft Power Systems*), which is used in advanced aircraft constructed in recent years, depending on demand, allows optimum production, processing and management of power supply in terms of its distribution to the various electrical components. These systems are characterized by high efficiency generated in real time and through infrastructure, technology-based intelligent solutions for equipping the supply system the hardware modules responsible for directing and controlling the generated voltage and current. Thanks to the technology discussed its continuous expansion is possible, by which the modern power systems (EPS, PES) are gaining new functions by modifying the software on the respective control devices mounted on modern aircraft. All sources in the form of real and simulated generators connected to the on-board electrical network according to the concept MEA provide current control generated voltage and current transmitted to the receivers. Advanced power supply systems (EPS, PES) provide power in the real-time of appropriate quality of electricity necessary to power aircraft systems, which could include e.g. hydraulic or electromechanical system which provide full functionality of actuators included in these systems.

B. *Key components of the power supply system EPS compatible with the trend of MEA/ AEA*

On board of modern aircraft, there are several sources (generators), generating electricity. The primary source of power are the main generators (Main generator) driven directly or through the gears with the aircraft jet engine. Depending on the power required to install one or two generators attributable to a jet engine. In the back of the plane there is auxiliary generator APU (*Auxiliary Power Unit*). Auxiliary power unit APU is used to power the airplane in the event of failure of the main generators or

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when parked at the airport. In addition, both the main generators and auxiliary power unit APU can work as motors and can be used to start jet engines. In the case of faults, if they are damaged main generators and auxiliary power unit APU, the most important aviation installations (eg. Avionics systems) are supplied from the emergency generator driven by an air turbine RAT (*Ram Air Turbine*) pull-out of the fuselage. As emergency generators low-power generators 5-15 [kVA] are usually used excited by permanent magnets. Under the conditions of the ground when the aircraft main engines do not work, aircraft electrical installation is powered from the airport power GPU (*Ground Power Unit*).

Modern power source in the form of a three-stage generator designed to generate aircraft electricity, consistent with the concept MEA/ AEA comprises three electric machines mounted on a common shaft (Fig. 1) [5].

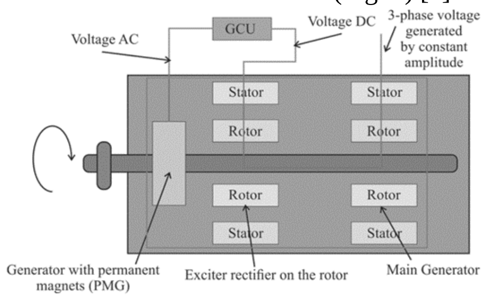

Fig. 1 Block diagram of a modern three-stage generator of electricity used in airplanes in line with the concept of MEA/ AEA

Main generator, which serves as the main power supply of the plane is a classic three-phase synchronous motor in which the coil winding is located on the rotor and the armature winding on the stator. Furthermore, due to high performances in terms of rotor speed, the generator rotor is constructed as a generally cylindrical and the coil winding is distributed in nurseries. Nurseries are protected by special wedges in order to protect the winding against centrifugal forces. In addition, front connections of rotor windings are enclosed by non-magnetic metal rings. In the case of salient pole rotors in the space between the poles are aluminum wedges, whose task is to improve the conditions of the cooling coil winding. Damping cages are at nurseries located on the surface of the pole pieces (salient pole machines) or in the space of so-called large tooth (cylindrical machines).

When analyzing the power supply system EPS used in advanced aircraft in accordance with the concept of MEA/ AEA, due to its complexity this article focused only to the making of the supply voltage. This procedure is carried out in most cases by a synchronous generator AC. Now, in modern power supply systems of aircraft permanent magnet synchronous systems PMSG are used. The generators are characterized by high efficiency and high reliability of operation. In addition, synchronous generators with permanent magnets PMSG can be built from a large number of pole pairs (as low speed) and can be operated without the need for mechanical transmission. The rest of this article presents a mathematical model of synchronous generator.

C. Mathematical model of synchronous generator used in power systems compatible the trend plane MEA/ AEA

While modeling the synchronous generator based on a permanent magnet, the following simplifying assumptions were adopted [5]-[8]: symmetry of 3-phase windings of the armature, the linearity of the magnetic circuits of the generator, the omission of eddy currents and magnetic hysteresis, sinusoidal electromotive force (SEM), induced the armature windings, no windings in the rotor damping. A mathematical model of the synchronous generator PMSG is reached on the transformation of equations described by the phase coordinates of vector equations machine in which the components of a vector are expressed in a rectangular coordinate system (d, q) rotating with an electrical angular speed of the rotor of the generator and the axis D is aligned with the axis the magnetic flux of permanent magnets, as illustrated in the figure below (Fig. 2).

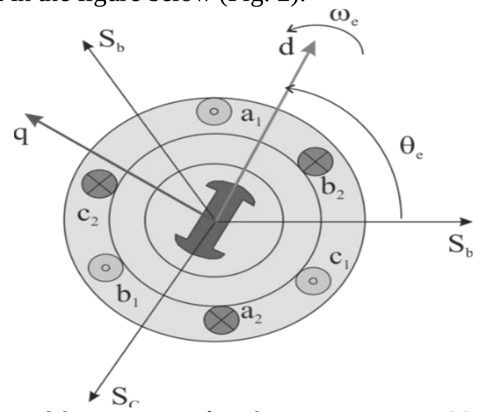

Fig. 2 Section and the axis system of synchronous generator PMSG

The equations of mathematical model of the synchronous generator with permanent magnets (PMSG) expressed in system (d, q) [9], [10] represent the following relationships:

$$u_{sd} = -R_s i_{sd} - L_d p i_{sd} + \omega_e L_q i_{sq} \quad (1)$$

and

$$u_{sq} = -R_s i_{sq} - L_d p i_{sq} + \omega_e L_d i_{sd} + \omega_e \psi_{PM} \quad (2)$$

where

$$\omega_e = p_b \omega_m, \quad p = \frac{d}{dt} \quad (3)$$

u_{sd}, u_{sq} – armature voltage vector components in the axis d and q; i_{sd}, i_{sq} – vector components of armature currents in the d-axis and q; L_d, L_q – inductance of the armature winding axis d and q; ψ_{PM} – stream of permanent magnets; R_s – resistance of the phase windings of the armature; ω_e, ω_m –electrical and mechanical angular speed of the generator rotor; p_b – number of pole pairs of the generator; p –the operator of differentiation with respect to time t.

Interpretation of peripheral equations of mathematical model of synchronous generator based on a permanent magnet (PMSG) is shown in the figure below (Fig. 3).

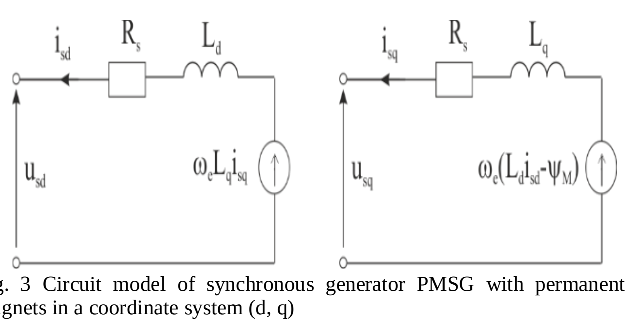

Fig. 3 Circuit model of synchronous generator PMSG with permanent magnets in a coordinate system (d, q)

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On the other hand, the equation of the electromagnetic torque of the generator is expressed in the following relationship:

$$M_e = \frac{3}{2} p_b \left[\psi_{PM} i_{sq} + \left(L_d - L_q \right) i_{sd} i_{sq} \right] \quad (4)$$

For cylindrical machines, and when the inductance L_d and L_q are equal, the electromagnetic torque equation simplifies to the form:

$$M_e = \frac{3}{2} p_b \psi_{PM} i_{sq} \quad (5)$$

A block diagram showing the concept of aircraft power in accordance with the concept of MEA/ AEA with generator PMSG shown below (Fig. 4). In this system, to the 3-phase stator winding of the generator PMSG 3-phase AC converter is attached, the converter is called a converter machine CM. In addition, the circuit includes three rectifier circuits used to convert the AC voltage or current for the voltage or current and the conductor rail. These elements allow the connection of DC receivers to the plane power supply. In the intermediate circuit DC and AC 3-phase inverter is turned which is used for speed control of 3-phase electric motor by changing the frequency and voltage supply. Additionally, the inverter can reduce the starting current of the motor and reduction of dynamic loads in the drive.

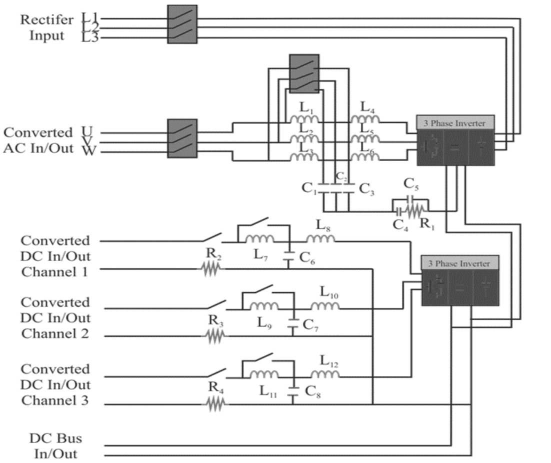

Fig. 4 Block diagram of an aircraft power system in accordance with the concept of MEA/ AEA

Another component of the autonomous power supply system (ASE), which shall be analyzed will be multipulse rectifier, which is a key element of power electronic power system (PES). A typical solution to the power supply system (PES), which is used in aviation is a system containing a generator of high frequency 400 [Hz] of AC voltage, DC voltage generator or generators, battery as a backup source (energy storage). Nominal values of mentioned voltage sources (effective AC and DC average) contain generally to a maximum rated voltage of AC generator, that is U_{NAC} (usually U_{NAC} = 400 [V]). Energy conversion of AC high frequency voltage is obtained by adopting the multi burst rectifier. The average value of rectified voltage that can be achieved by three phase bidirectional (bridge) filter capacitance of a capacitor with a very large volume, the value of the amplitude of the line voltage reduced by the voltage drops across the diodes, and about ½ of the amplitude of the output ripple voltage [11], [12].

$$U_{d0} = \sqrt{2} U_{NAC} \quad (6)$$

Applying a filter capacitor of the capacitive of a very large capacity rectifier output produces a pulse of current from the mains, and so generation of odd harmonics, the fundamental component has a frequency of 400 [Hz] (Fig. 4-5). In real terms the average value of the rectified voltage is reduced by voltage drop on the conductive semiconductor elements (LEDs). This decline is a fraction of a percent, and the computational analysis usually ignores it. This value is also lower because of the existing output voltage ripple caused by the pulse charge and discharge the output capacitor. For the idle state when the supply voltage (effective value) U_{NAC} = 400 [V] voltage is rectified the U_{d0} = 540 [V]. In addition, the voltage of 540 [V] is generally much larger than the rated voltage receivers, should therefore be reduced (lowered) by means of pulse voltage converters DC/ DC buck. The aircraft power supply systems can be operated receivers DC with different voltages. Supply of these receivers is also possible through the use of controlled rectifiers directly from the AC mains. In this case, depending on the required power rectifiers may be used for both single and three phase. However, it seems optimal use of thyristor rectifier bridge 12T thyristor or diode-6T-6D. Also, you should take into account the occurrence of the rectifier circuits, alternating current mains with a frequency of 400 [Hz], the increased voltage drop at the output in connection with the commutation (greater commutation reactance) and the distortion of the line current flowing to the rectifier. These systems have trays (magazines) of electricity DC - batteries. The solution of the power supply system with a frequency of 400 [Hz] in the case under consideration is shown in Fig. 5. In addition, it should be noted that if the receivers AC and/ or DC require adjustment or stabilize the voltage, the system must be the extension of another regulatory converters. This problem is much less complicated for DC receivers because after rectification of AC voltage you can directly perform the adjustment procedure on a DC voltage of DC/ DC buck, which is controlled by pulse width modulation system of the PWM (*Pulse Width Modulation*) [13], [14].

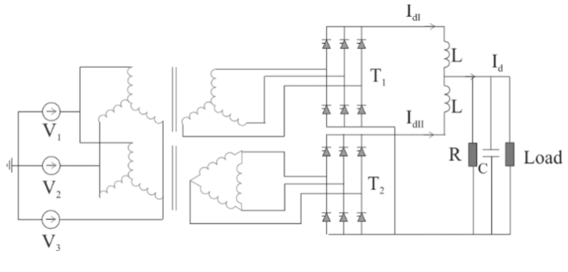

Fig. 5 12-pulse thyristor rectifier

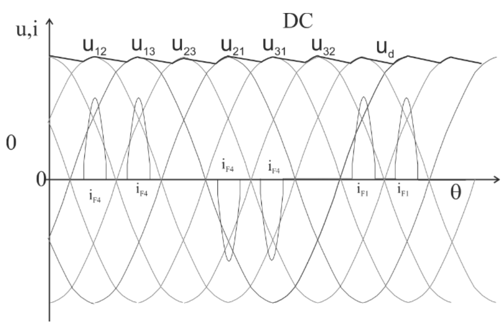

Fig. 6 Characteristic current waveforms of one phase in a bridge rectifier 12D with the filter capacitance C, i_1= = $i_{F1} - i_{F4}$

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For the AC receivers, requiring adjustment of electrical parameters (voltage, current, frequency), it is possible to use more complex system. Similarly to AC supply at a frequency of 50 [Hz], it must be converted into AC voltage to a DC voltage by a rectifier, preferably a diode with a filter capacitor C and then transforming the AC voltage using a voltage inverter in a three-phase bridge twelve-transistor system controlled pulse width modulation PWM.

D. Processing of AC/ DC using multi-pulse converters

The main element of the processor AC/ DC in most modern power systems, including in particular in the field of PES and compatible concept MEA/ AEA are 12-pulse converters, which block diagrams are shown in Fig. 6 and 7 [13]. The power factors and harmonic components of the voltage can be improved by using phase shift of the voltage by 30° in the mode switching star-delta ($\Delta \rightarrow Y$), or by adding the autotransformer which produces a voltage offset by the same angle.

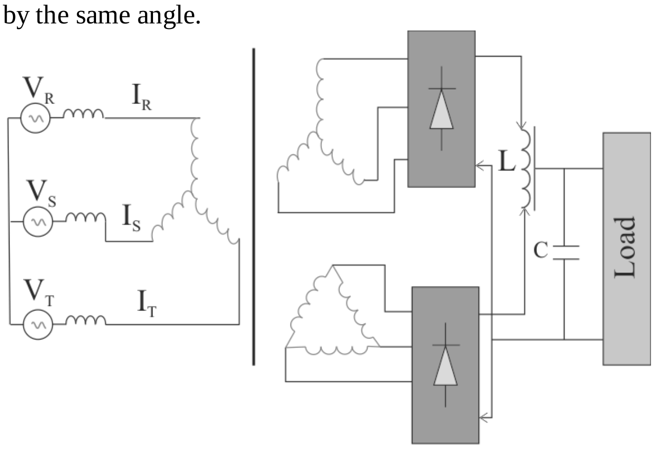

Fig. 7 Conventional 12-pulse AC/ DC converter. Δ-Y isolated transformer

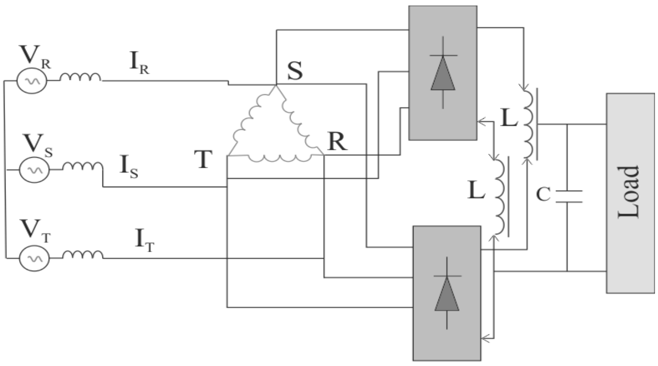

Fig. 8 Conventional 12-pulse AC/ DC converter. Autotransformer phase shifted

It should also be noted that the voltage obtained at the output AC/ DC converter is not controllable. Process in 12-pulse converter can be controlled by making the conversion operations LEDs to thyristors. The functional diagram of the discussed embodiment is shown in Fig. 8 and 9. In addition, it should be noted that the flowcharts shown in Fig. 8 and 9 are equivalent. On the other hand, Fig. 10 shows a general block diagram of AC/ DC converter including the star-delta ($\Delta \rightarrow Y$) switching.

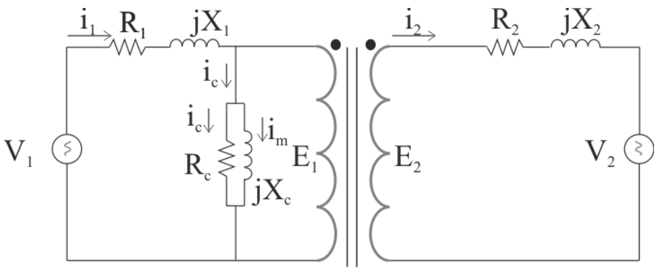

Fig. 9 Equivalent circuit diagram of Δ-Y transformer AC/ DC converter

The mathematical description of the scheme switches as follows:

$$v_{ST} = L_1 \frac{di_s}{dt} - M_1 \frac{di_{R3}}{dt} + M_2 \frac{di_{R1}}{dt} \tag{7}$$

$$E_A = M_1 \frac{di_s}{dt} - L_2 \frac{di_{R2}}{dt} + M_3 \frac{di_{R1}}{dt} \tag{8}$$

$$E_B = M_2 \frac{di_s}{dt} - M_3 \frac{di_{R2}}{dt} + L_3 \frac{di_{R1}}{dt} \tag{9}$$

where: L_1, L_2 and L_3, are the inductances, and M_1, M_2 and M_3 are mutual inductances of electrical circuit.

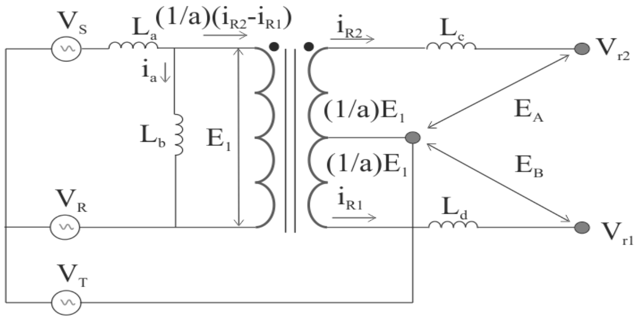

Fig. 10 Equivalent circuit of autotransformer connected AC/ DC converter

In the case of the autotransformer the mathematical relations describing the block diagram presented in Fig. 9 are as follows:

$$v_{ST} = (L_a + L_b)\frac{di_s}{dt} - \frac{L_b}{a}\frac{di_{R2}}{dt} + \frac{L_b}{a}\frac{di_{R1}}{dt} \tag{10}$$

$$E_A = \frac{L_b}{a}\frac{di_s}{dt} - \left(\frac{L_b}{a^2} + L_c\right)\frac{di_{R2}}{dt} + \frac{L_b}{a^2}\frac{di_{R1}}{dt} \tag{11}$$

$$E_B = \frac{L_b}{a}\frac{di_s}{dt} - \frac{L_b}{a^2}\frac{di_{R2}}{dt} + \left(\frac{L_b}{a^2} + L_d\right)\frac{di_{R1}}{dt} \tag{12}$$

Assuming that $L_2 = L_3$ and $M_1 = M_2$, the inductance L_a, L_b, L_c and L_d may be expressed as:

$$\begin{gathered} L_a = (1-K)L_1 \\ L_b = KL_1 \\ L_c = L_d = (1-K)L_2 \end{gathered} \tag{13}$$

Consequently it was achieved:

$$E_A = \frac{1}{a}(v_{ST} - i_s j\omega L_a) - i_{R2} j\omega L_c \tag{14}$$

$$E_B = \frac{1}{a}(v_{ST} - i_s j\omega L_a) + i_{R2} j\omega L_c \tag{15}$$

$$v'_{R1} = v_R - E_B = v_{R1} - j\omega L_c(a i_s + i_{R1}) \tag{16}$$

$$v'_{R2} = v_R - E_A = v_{R2} - j\omega L_c(a i_s + i_{R2}) \tag{17}$$

Ignoring the excitation current of the equations (14) and

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(15) were obtained:

$$v'_{R1} = v_{R1} + j\omega L_c(i_{R2} + 2i_{R1}) \quad (18)$$

$$v'_{R2} = v_{R2} - j\omega L_c(2i_{R2} + i_{R1}) \quad (19)$$

III. Results of simulation testing of selected components ASE (EPS, PES)

Examples of simulations of the selected components of on-board autonomous power supply system (ASE) have been made in the field of power supply system (EPS) on the example of the key element of the architecture of the EPS, which is the contactless brushless generator, based on permanent magnets (PMG) and in the field of power electronics power supply system (PES) on the example of the basic elements of architecture PES, which are multi-pulse converters. In the context of the key components of ASE civil aircraft (*Airbus, Boeing*), in particular for the generator (Fig. 11), and multi-pulse transmitters (Fig. 14), simulation models were developed created in a software environment Matlab/ Simulink.

A. *Synchronous generator with permanent magnets (PMSG) in the field of component EPS*

In the generator were considered: permanent magnets, bearing the abbreviation PMG, excitation coil (*Exciter Generator*), rectifier TRU (*Transformer Rectifier Unit*), the main generator (*Main Generator*) and generator protection unit GCU (*Generator Control Unit*). The above-mentioned components ASE in the range of EPS are shown below in the block *Generator systems*.

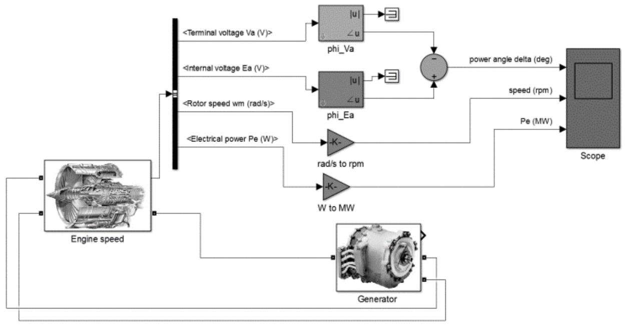

Fig. 11 Block diagram of the generator used in More Electric Aircraft (MEA) in the Simulink program

In making an example simulation in terms of EPS, special attention was paid to the 3-phase voltage waveforms, and in particular, how they run during a process of setting power to a plane and what shape they take when loaded, wherein the load condition was simulated in the computer simulation by the change in the resistance value. In addition, it should be added that the phase angle for the course was 120°.

Analyzing these waveforms (Fig. 12-13) one will notice that all three harmonics ("waves") of voltages take the same value for each phase of AC generator. This fact testifies to the same conditions of the generator. The amplitudes of all three wave forms of 3-phase are identical in the two simulated cases. Furthermore, according to need, frequency of the generator can be appropriately selected, which is a good solution of supply test systems or seat for analyzing phenomena taking place in the generator of induced synchronous permanent magnet.

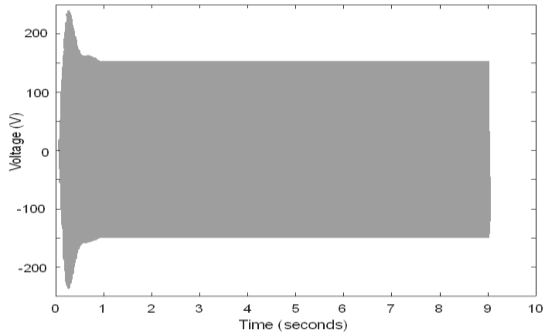

Fig. 12 Voltage in the main generator with a load of 15 [kΩ]

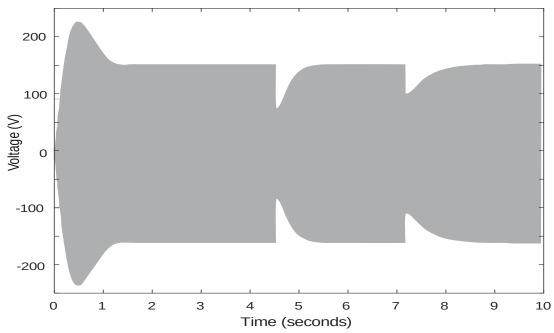

Fig. 13 Voltage in the main generator at variable load included in the range of 10-22 [kΩ]

B. *Multi-pulse transmitters in the field of component PES*

Another solution, which was simulated is selected component ASE in the range of power electronic power system (PES). The basic elements of the PES, on which attention was focused is a 12-pulse rectifier, consisting of 12 LEDs bridged connected and the power supply unit, in our case they are three reactors. The block diagram of the rectifier made in the Simulink is shown below (Fig. 14).

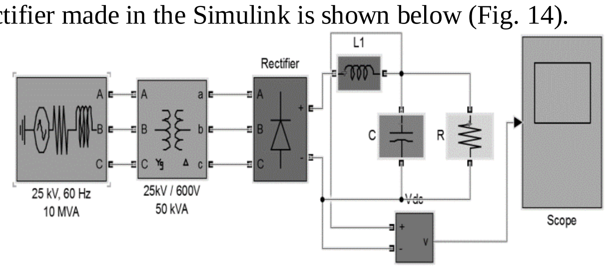

Fig. 14 Block diagram of the rectifier used in the ASE in the range of PES

These chokes supply terminals (Conn2, Conn3, Conn4) in a three-phase voltage offset each other at an angle of 30°. LEDs on the way back to DC current bridges d1, d2, d3, d4 are to make work of the bridges independent from each other, and the output current from the bridge, for example *id_g1* was equal to the return current *id_d1*. On the other hand, coupled inductors provide the corresponding bridges 3-phase voltage offset each other by 30°. In this way, they meet the requirements of the 12-pulse mutual offset at an angle of 60°/ 2 = 30° the voltages of the bridges. The values of each parameter for which the simulations were carried out are as follows: U_N = 120 [V], f_N = 410 [Hz], P_o = 12 [kW]. In addition, simulations studied voltage waveforms at the output of the rectifier, and examples of the results are shown in the following figures (fig. 15-17).

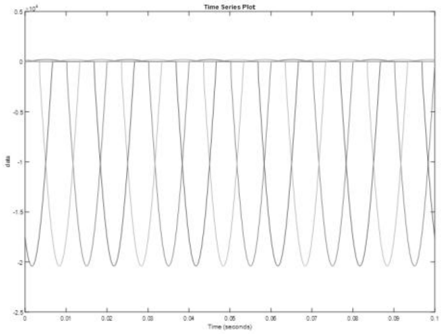

Fig. 15 The course of the voltage at the output of rectifier diodes

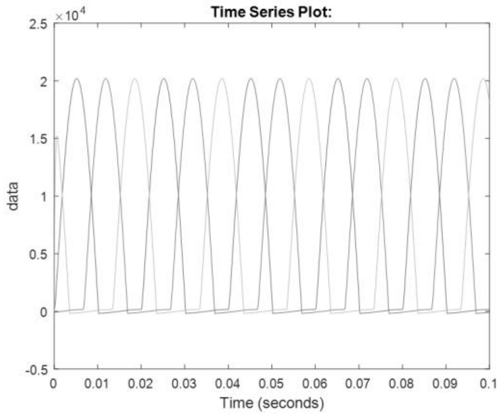

Fig. 16 The course of the voltage at the output of three-phase system

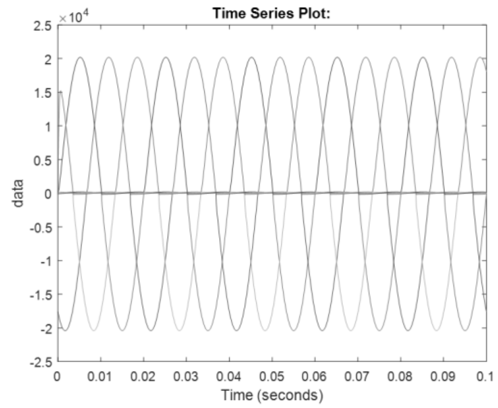

Fig. 17 The course of the voltages at the output of rectifier

IV. Conclusions

In the presented figures concerning the results of computer simulations carried out it was observed that the output harmonic voltages are confined by amplitude of the input signal of low frequency. The amplitude of this pulse depends on the content of the component opposite to the voltage supply. Additional pulsation reduces the efficiency of straightening alternating voltage, as indicated by the analysis of harmonic pulsations of rectified voltage as a function of the content component of the reverse order of the power supply. It should also be noted that the symmetrical supply voltages in all phases of the power rectifier device are identical and have the same duration (movement). Component of reverse order does not significantly affect the value of the average rectified voltage. Impact-sequence of opposite voltage has a negative impact on working conditions of rectifier devices. This asymmetry causes:

– increase in the rectified voltage pulse;
– reduction of the permissible DC power system due to reduced component of the rms current in the windings of the transformer.

In the simulation tests have shown that the pair of the power values of 10 [kW] in the power system of 12-pulse rectifier, applied in the context of aircraft power supply circuit in the field of PES, experimental results obtained show a high efficiency and low harmonic current, which can be used in a wide operating range. In addition, 12-pulse rectifier guarantees a constant output voltage and constant amplitude and output power level. An additional advantage of the use of this solution in *More Electric Aircraft* (MEA) is a high reliability and low complexity of the components utilized in a complete power system.

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