Comparative analysis and simulation of selected components of modern power systems (EPS, PES) of 'classical' aircraft and 'More/ All Electric Aircraft' (MEA/ AEA)

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Abstract— The work deals with the issues of modern architecture of power in the field of electrical power systems EPS (Electric Power Systems) and power electronic power systems PES (Power Electronics Systems), both civil 'classical' aircraft airline concerns Airbus and Boeing (A-320, B-767) and military Lockheed Martin (F-16), as well as civil aircraft more/ fully electric MEA/ AEA (A-380 and A-350XWB, B-787) and military JSF (Joint Strike Fighter) F-35 and F-22 Raptor. Based on the above, the authors conducted a comparative analysis of these systems, with particular emphasis on making the simulation of selected components of individual systems (EPS, PES) including their mathematical models in a dynamic perspective. The main objective of this work was to simulate a range of EPS (synchronous motor) and on the PES converter (48-pulse), presenting their mathematical models and based on them making a comparative analysis of advanced power systems with the trend of MEA/ AEA plane. In the final part, the paper presents the main conclusions arising from the analysis and simulation of selected components of the architecture of power systems (EPS, PES) of 'classical' aircraft and the advanced in line with the new trend of 'MEA/ AEA.

Key-Words: - More/ All Electric Aircraft (MEA/ AEA), Electric Power Systems (EPS), Power Electronics Systems (PES)

1 Introduction

Today, both in the case of civil aviation (Airbus, Boeing), the 'classic' aircraft (A-320, B-767), with particular emphasis on aircraft in line with the new trend in the field of power 'MEA/ AEA' (A-380 and A-350XWB, B-787), as well as in the context of a military aircraft (Lockheed Martin), and in 'conventional' aircraft (F-16) and compatible with the modern trend of MEA/ AEA (JSF F-35, F-22 Raptor), you can see the dynamic development of modern architecture of electrical power systems EPS including high voltage power systems HVDC (High Voltage Direct Current) voltage range ±270V DC (540V DC) for main power of a plane and 350V DC for the power drive unit MEE (More Electric Engine) and power electronic power systems PES [1]. In the context of a brief introduction to this subject it should be noted that the advanced power systems (EPS, PES) used on modern aircraft (airplanes, helicopters), primarily on technologically advanced aircraft, ie. in line with the concept of MEA/ AEA, they belong to a group so called on-board autonomous power systems ASE (Autonomous Electric Power Systems), referred to, among others, as integrated power systems IPS (Integrated Power Systems) [2]. Based on the above, a comparative analysis of selected components of modern power systems (EPS, PES) in the context of the aircraft 'classic' and 'More Electric Aircraft' were carried out according to specific criteria, namely: types of electricity generation systems, their evolution and key sources in terms of power produced by these advanced systems used in today's military and civil aircraft (Fig. 1). Now, in modern aircraft (civil, military) there is an electric power system of power supply DC/ AC, whereby it should be noted that in the most advanced aircraft, both civilian as well as military, there is a tendency in the direction of the architecture of the power supply system of alternating current voltage as leading, using sources of electricity generation in the form of integrally connected team starter/ generator AC variable frequency AS/ G VF (Alternating Starter/ Generator Variable Frequency), whose main purpose is to provide electricity to the subsystem, based on the supply and distribution of electricity PMAD (Power Management and Distribution) resistant to damage [3], [4]. Another trend distinguishing 'classic' aircraft of aircraft consistent with the concept MEA/ AEA, is to replace the power supply on-board electrical network, previously used on 'conventional' aircraft in the form of mechanical, pneumatic and hydraulic energy, by one kind of energy – electricity, which a domain of modern aircraft compatible with the modern concept of power (MEA/ AEA). Therefore, in accordance with input trend of more electric plane, there are expressions such as: optimization of plane energy POA (Power Optimized Aircraft), and with it a more open technology in the field of electricity MOET (More Open Electrical Technology), developed by the Air Airbus company and also innovative solutions were developed in the field of power electronics systems, ie. advanced technology PES (Power Electronics Systems) [5]. In the context of power electronic power systems (PES) their main components play a key role, which are multi-pulse converters (6-, 12- and 18-, 24-pulse), and even 48-pulse, which will be the subject of detailed analysis later in this article.

2 The Architecture of Modern Power Systems (EPS, PES)

2.1 'Classical' civil aircraft (A-320, B-767) in line with the trend 'MEA/ AEA' (A-380 and A-350XWB, B-787)

The development of advanced systems (EPS, PES) of modern aircraft, types of sources (generators) for the generation of electricity and the level generated by their power, in the context considered in this paper airplanes (civil, military) 'classic' and 'More/ All Electric Aircraft' are listed below (Figure 1).

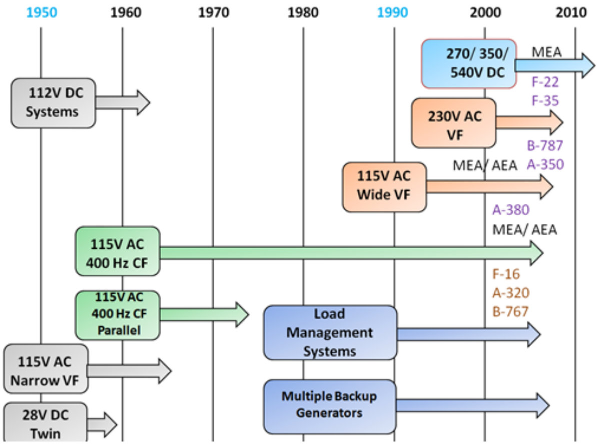

Fig. 1 Evolution of EPS aircraft ‘classic’ and ‘MEA/ AEA’ [6], [7]

Now, in modern aviation, both civil aircraft 'classic' (A-320, B-767) and 'More/ All Electric Aircraft' (A-380 and A-350XWB, B-787) and in the case of military aircraft 'classic' (F-16) and 'More/ All Electric Aircraft' (JSF F-35, F-22 Raptor), there are the following systems for the generation of electricity on board of the plane, illustrated in the following figure (Figure 2).

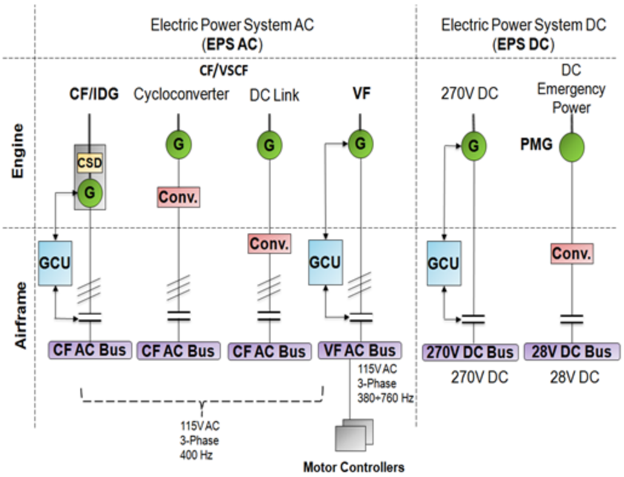

Fig. 2 Types of systems generating electricity on board aircraft 'classic' and 'MEA/ AEA' [6], [7]

2.2 Military aircraft 'classic' (F-16) and in line with the trend of 'MEA/ AEA' (JSF F-35, F-22 Raptor)

Changes in the dynamic development in the field of electrical machines and its related fields of electronics and power electronics are closely linked to the implementation of the concept of more electric plane MEA (More Electric Aircraft), applied not only to civil aircraft (Airbus, Boeing), but also for military aircraft (Lockheed Martin), which was established under the project MOET or in the near future, the concept of fully electric aircraft AEA (All Electric Aircraft). According to the above concept of the basic subsystems of the JSF F-35, such as a subsystem of hydraulic cylinders of flight control EHA (Electohydrostatic Actuators) subsystem of gear motor driving the fuel pump and the air-driven subsystem of environmental pollution control of aircraft ECS (Environmental Control System) are powered electrically by an electric drive motor. The major component of EPS system, which is a set of starter/ generator AS/ G is designed to supply electric power subsystem PMAD shatterproof. In addition, it should be noted that in the modern aviation advanced technology plays increasingly frequent role in the field of high-voltage HVDC (± 270V DC, 350V DC) [6].

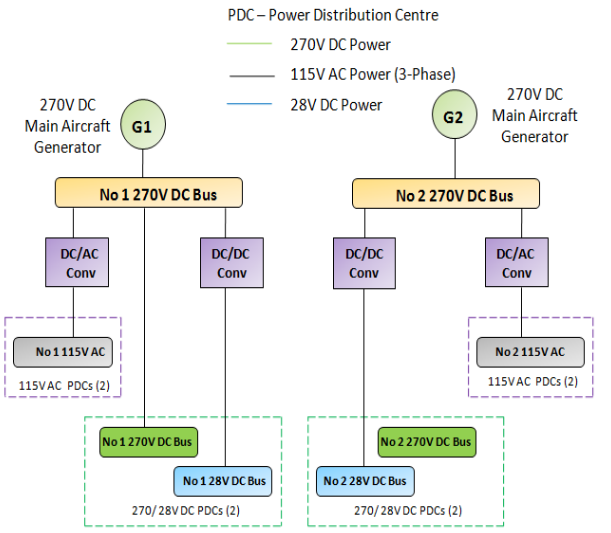

Fig. 3 Simplified diagram of EPS system military aircraft F-22 Raptor [8]

For example, in military aircraft F-22 Raptor voltage of 270V DC is used to power not only specific components of the EPS, as is in the case of advanced civil aircraft (A-380 and A-350XWB, B-787), but also acts as the main power system of aircraft, which has been illustrated in the figure above (Fig. 3).

3 Comparative Analysis and Dynamic Mathematical Model of the Selected Components of Modern Power Systems (EPS, PES)

3.1 Synchronous motor teams AS/ G VF (Alternating Starter/ Generator Variable Frequency) EPS system in accordance with the trend of MEA/ AEA

Currently, the main source of electricity generation used in most of the aircraft both civilian and military (large and small) is a synchronous motor (starter) three-phase alternating current team AS/ G VF. It should be noted that in modern aerospace majority of electric drives, are synchronous motors of permanent magnet PMSM (Permanent Magnet Synchronous Motor). In addition, the above type of engine works most efficiently in a situation where high dynamics of the object in which it was placed is required, small pulsations of electrodynamic momentum and a large speed range. Mathematical record of phenomena occurring in a synchronous motor with permanent magnets is as follows. In considering dynamics of the supply system (frequency inverter voltage) was omitted. This is due to the high switching frequency of power transistors, which is typically 10-20 [kHz]. Therefore the frequency converter has a much shorter time constants than analyzed synchronous motor. The dynamic mathematical model of induction motor cage, stored in the rotating speed of ω^K coordinate system according to [9], [10], [11], [15], [16] and [21] can be represented in the following form:

$$u_s = R_{si_s} + \frac{d\Psi_s}{dt} + j\omega^K\Psi_s \tag{1}$$

$$0 = R_{sR_s} + \frac{d\Psi_R}{dt} + j(\omega^K - p_b\omega_m)\Psi_R \tag{2}$$

$$\Psi_s = L_s i_s + L_\mu i_R \tag{3}$$

$$\Psi_R = L_R i_R + L_\mu i_s \tag{4}$$

The method of vector control induction motor SVM-DTC (Direct Torque Control - Space Vector Modulation) (1) uses a mathematical model of the motor rotating synchronously with the stator flux vector coordinates. This means writing equations of engine using the spatial vector method [9], [10], [11], [15], [16] and [21], wherein an actual axis coordinate system is the stator flux:

$$\Psi_s = \Psi_{sd} + j\Psi_{sq} = |\Psi_s| = \Psi_s \tag{5}$$

This approach leads to the following equations [2], [10]:

$$u_{sd} = R_s i_{sd} + \frac{d\Psi_s}{dt} \tag{6}$$

$$u_{sq} = R_s i_{sq} + \omega_{ms}\Psi_s \tag{7}$$

$$0 = R_R i_{Rd} + \frac{d\Psi_{Rd}}{dt} + j(p_b\omega_m - \omega_{ms})\Psi_{Rq} \tag{8}$$

$$0 = R_R i_{Rq} + \frac{d\Psi_{Rq}}{dt} + j(\omega_{ms} - p_b\omega_m)\Psi_{Rd} \tag{9}$$

$$\Psi_s = L_s i_{sd} + L_\mu i_{Rd} \tag{10}$$

$$0 = L_s i_{sd} + L_\mu i_{Rd} \tag{11}$$

$$\Psi_{Rd} = L_R i_{Rd} + L_\mu i_{sd} \tag{12}$$

$$\Psi_{Rq} = L_R i_{Rq} + L_\mu i_{sq} \tag{13}$$

$$M_e = \frac{3}{2} p_b \Psi_s i_{sq} \tag{14}$$

$$J\frac{d\omega_m}{dt} = M_e - M_m \tag{15}$$

In the above equations in the following markings are used: i_{sd}, i_{sq} – longitudinal and transverse component of the stator current vector, stored in a moving coordinate system associated with Ψ_s, L_R – inductance of the rotor, L_S – stator inductance, L – mutual inductance, R_R – rotor resistance, R_S – stator resistance, p_b – the number of pole pairs of the motor, ω_m – the angular velocity of rotor, ω_{ms} – pulsation (speed) stream Ψ_s. The following figure (Figure 4) shows a simplified block diagram of the power supply system of the F-16 aircraft.

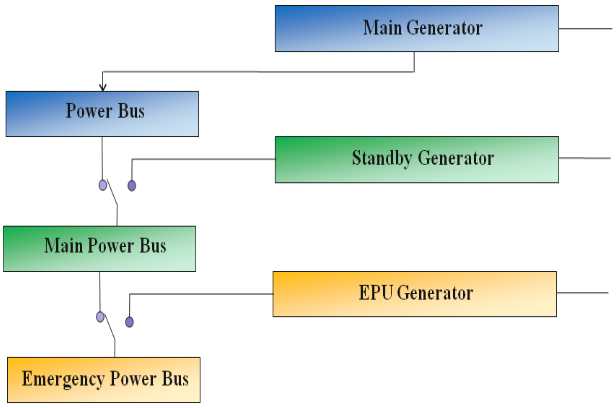

Fig. 4 Simplified power system of F-16 electrical installation

3.2 48-Pulse Transmitter of Power Electronic Power System PES in Accordance with the Trend of MEA/ AEA

For the currently used power electronics supply systems PES elements responsible for the conversion of the AC to DC power, multi-pulse transmitters are in most cases used in 12-pulse or 24-pulse rectifiers. However, in the literature [14], [22] developed models of 48-pulse rectifiers can be found. One such characteristic of the sensor is the ability to produce significantly less harmonic distortion of the output voltages, and less likelihood of loss of power in the system, as was in the case of 6-, 12- and 18- and 24-pulse rectifiers. The results presented in the literature [13], [22] from the contained simulation it can be seen that instability of 48-pulse rectifier is possible resulting from overloading the system and the possibility of changes in the voltage harmonics. Emerging incompatibilities indirectly can be eliminated by using suitably phased voltage three-phase system of 7.5°, this value will provide valuable full operation of 48-pulse rectifier. Also, be sure to make symmetrical movements of all three voltages produced by the transformer windings. Transmitter model shown in Figures 5-6 consists of four identical 12-pulse rectifiers, associated with four 12-pulse transformer windings with offset. Generally speaking, the 48-pulse converter phase shifts are implemented in the following way, two voltage transformers are offset by the value of 3.75° is connected directly to the 24-pulse rectifiers. Same situation is in the next two transformers. The basic element of the power supply is AC transformer. The transformer at 400 Hz (the frequency used in aviation) under load drops occur in the output voltage caused by the resistance of the primary winding and a secondary resistance of the core losses and leakage inductance of the primary winding and secondary (particularly for high power transformers). Transformer manufacturers usually provide only the basic parameters of the transformer: the power output on the secondary winding, rated primary voltage, secondary voltage at the maximum load resistance, the secondary winding current at maximum load.

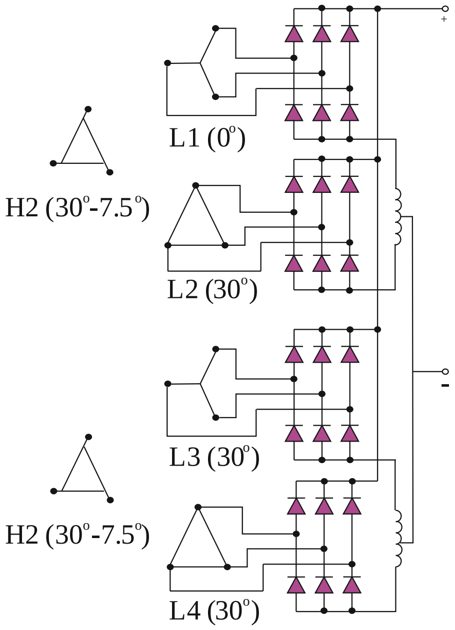

Fig. 5 Block diagram of the 48-pulse rectifier in supply system of F-16 electrical installation (part with the generator harmonic signal with a phase of 0° and 30°)

In the presented system, you can see the connectors and transformer circuits 24- pulse rectifiers in the final result from the 48-pulse rectifier. Modeled system can be used in devices or systems supplying high voltage applications with high power without the use of filtering systems due to the treatment of its very low harmonic distortion arising from the side that produces alternating current. It should be noted that the output voltages from the system are characterized by standard values of the harmonics of, respectively, n = 48r + 1, where r = 0, 1, 2, 3, i.e. 47, 49, 95, 98 with typical sizes of 1/ 47, 1/ 49 and so on respectively as the system that produces DC voltage.

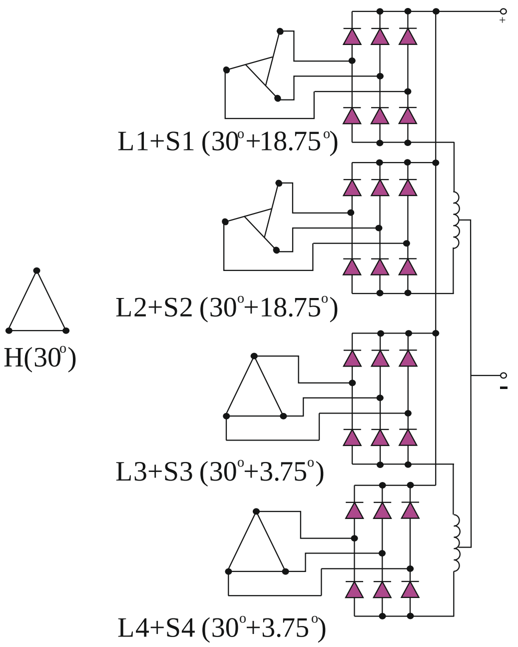

Fig. 6 Block diagram of the 48-pulse rectifier supply system of F-16 electrical installation (part with the generator of harmonic signal with a phase of 30°, 18.75° and 3.75°)

The lower range of the harmonic voltage is 48. With this information in mind the authors attempted to test how 48-pulse rectifier behaves in the electrical power supply system of more electric aircraft. In addition, in the development of a simulation model in Matlab/ Simulink it was tested how a 48-pulse rectifier reacted to the phase shift change in the voltage transformer

3.3 The Mathematical Model of The 48-Pulse Converter in Power System PES Based on Example of TRU Rectifier Transformer

Description of occurring physical phenomena and mechanisms of action (mathematical model) 48-pulse transmitter can be summarized as follows [14]. The system is divided into four main components, wherein each unit for the 12-pulse converter and the main attention was focused on the mathematical description (Fig. 5-6). Thus, the voltage generated by the first 12-pulse rectifier is described by the equation:

$$\begin{aligned} U_{AB12}(t)_1 = 2\big[&V_{AB1}\sin(\omega t+30^\circ) \\ &+V_{AB11}\sin(11\omega t+195^\circ) \\ &+V_{AB13}\sin(13\omega t+255^\circ) \\ &+V_{AB23}\sin(23\omega t+60^\circ) \\ &+V_{AB25}\sin(25\omega t+120^\circ) \\ &+\cdots\big] \end{aligned} \quad (16)$$

In a second 12-pulse rectifier output voltage switches as follows:

$$\begin{aligned} U_{AB12}(t)_2 = 2\big[&V_{AB1}\sin(\omega t+30^\circ) \\ &+V_{AB11}\sin(11\omega t+15^\circ) \\ &+V_{AB13}\sin(13\omega t+75^\circ) \\ &+V_{AB23}\sin(23\omega t+60^\circ) \\ &+V_{AB25}\sin(25\omega t+120^\circ) \\ &+\cdots\big] \end{aligned} \quad (17)$$

For the third rectifier unit equation voltage at its output is shown as:

$$\begin{aligned} U_{AB12}(t)_3 = 2\big[&V_{AB1}\sin(\omega t+30^\circ) \\ &+V_{AB11}\sin(11\omega t+285^\circ) \\ &+V_{AB13}\sin(13\omega t+345^\circ) \\ &+V_{AB23}\sin(23\omega t+240^\circ) \\ &+V_{AB25}\sin(25\omega t+300^\circ) \\ &+\cdots\big] \end{aligned} \quad (18)$$

The last equation defining the output voltage of the rectifier 12-pulse of the fourth pulse component of the 48-pulse converter is as follows:

$$\begin{aligned} U_{AB12}(t)_4 = 2\big[&V_{AB1}\sin(\omega t+30^\circ) \\ &+V_{AB11}\sin(11\omega t+105^\circ) \\ &+V_{AB13}\sin(13\omega t+165^\circ) \\ &+V_{AB23}\sin(23\omega t+240^\circ) \\ &+V_{AB25}\sin(25\omega t+300^\circ) \\ &+\cdots\big] \end{aligned} \quad (19)$$

The four mathematical equations for recording of the physical phenomena occurring in a 12-pulse rectifier in particular relates to shift the AC voltage at the output of the system described by equations (3) - (6) is inserted in series to the respective secondary windings of the transformers. As a result, the total value of the AC voltage at the 48-pulse rectifier output is:

$$\begin{aligned} U_{AB12}(t)_{48} = &U_{AB12}(t)_1 + U_{AB12}(t)_2 \\ &+ U_{AB12}(t)_3 + U_{AB12}(t)_4 \end{aligned} \quad (20)$$

After the summation operation obtained:

$$\begin{aligned} U_{AB12}(t)_{48} = 8\big[&V_{AB1}\sin(\omega t+30^\circ) \\ &+V_{AB47}\sin(47\omega t+150^\circ) \\ &+V_{AB49}\sin(49\omega t+210^\circ) \\ &+V_{AB95}\sin(95\omega t+330^\circ) \\ &+V_{AB97}\sin(97\omega t+30^\circ) \\ &+\cdots\big] \end{aligned} \quad (21)$$

Thus, ultimately the output voltage generated by the neutral 48-pulse rectifier can be written as:

$$U_{AB12}(t)_{48} = \frac{8}{\sqrt{3}} \sum_{n=1}^{\infty} V_{AB1} \sin\Big(n\omega t + 18.75^{\circ} n - 18.75^{\circ} i\Big) + \cdots \tag{22}$$

where: n = (48r ± 1), r = 0, 1, 2, … . A voltage $U_{BN12}(t)_{48}$ and $U_{CN12}(t)_{48}$ having a sine wave-like shape, are offset with an angle of 120° and 240° degrees relative to the voltage $U_{AB12}(t)_{48}$.

4 Examples of Simulations of Selected Components (EPS, PES), used for Advanced Aircraft in line with the Concept of More Electric Aircraft MEA/ AEA

The main objective of carrying out computer simulations of selected components, which included a synchronous motor and 48-pulse converter, was to assess the performance of modern power systems (EPS, PES), used in advanced aircraft in use today, both civilian and military. Therefore, the authors have made an exemplary analysis of the operation of the electric drive in modern power systems (EPS, PES) aircraft in accordance with the trend of More Electric Aircraft and their comparison. Given the complexity of both these power systems, particular attention is focused on two components that play an important role in modern electrical systems of the aircraft. These are three-phase synchronous motor PMSM and the elements responsible for the processing of AC to DC current (multi-pulse converters). Computer simulations were carried out in the computer program Matlab/ Simulink. At the beginning fixed parameters are defined that will be used in computer simulations performed. Thus, one used relative units related to the rating of the three-phase synchronous motor with permanent magnets R_s = 0,2 [Ω], L_d = L_q = L_s = 0,0085 [H], Ψ_f = 0.175 [Vs], p = 4.

The following illustrations show the models of power 3-phase synchronous motor AC (Fig. 6) and the transformer rectifier (Fig. 7) TRU (Transformer Rectifier Unit), made in Matlab/ Simulink.

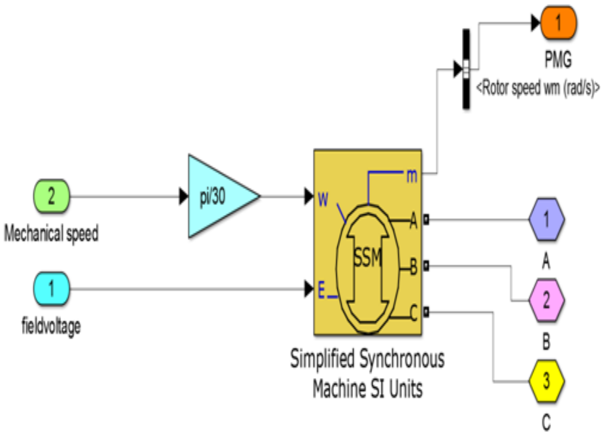

Fig. 7 PMSM motor model in Matlab/ Simulink

In the pad motor the following values of parameters were defined characterizing his work: Power output (Power Generation) 100 [kVA], operating frequency f = 400 [Hz], line-to-line voltage of 200 [V].

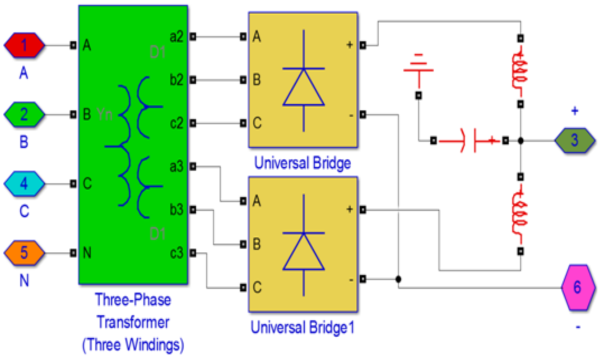

Fig. 8 TRU model component in Matlab/ Simulink

Received at this stage of simulation research results in a waveform of voltages and currents are shown in a number of the following illustrations (Fig. 9-16). On the other hand, comparative analysis of modern power systems (EPS, PES), in accordance with the trend of MEA/ AEA has been made on two stages of the electrical system of the aircraft. The first relates to the parameters of the output of synchronous AC motor, while the second concerns the size of the generated output transducers AC/ DC.

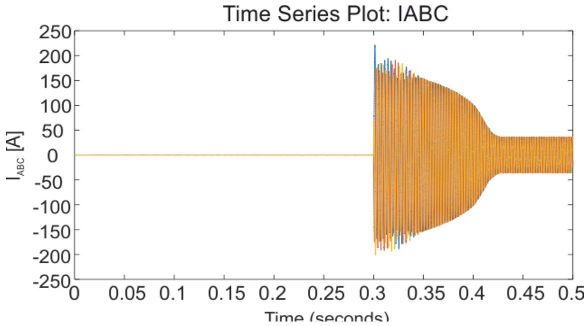

Fig. 9 Course of output current in a ABC three-phase synchronous motor PMSM

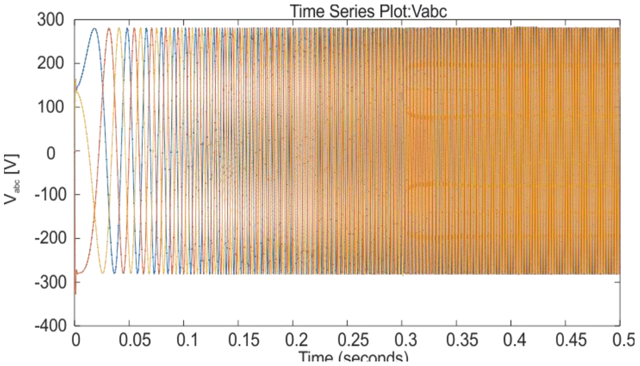

Fig. 10 The course of the output voltage in a ABC three-phase synchronous motor PMSM

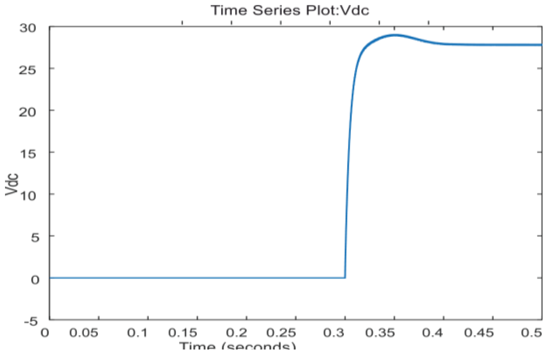

Fig. 11 Decrease in the voltage cross the Transformer and Transformer Rectifier Unit (TRU): 28 Vdc, 4 kW

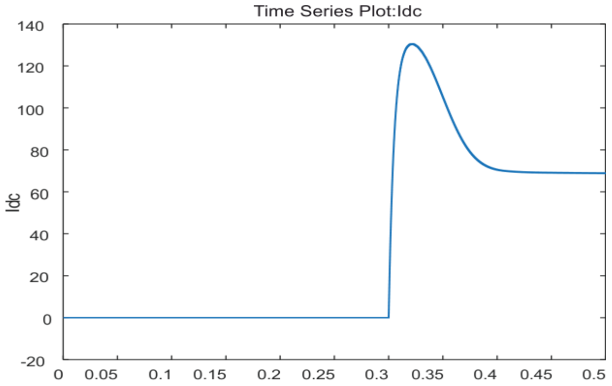

Fig. 12 The decrease in current on the element Transformer and Transformer Rectifier Unit (TRU): 28 Vdc, 4 kW

The next stage of the analysis was simulation of synchronous motor to assess the performance of the power supply system in accordance with the concept of PES MEA/ AEA. The test values in this case were the voltage and current waveforms on the three-phase TRU (48-pulse rectifier system), and the observations of the effect of the starter was carried out at the time of switching. The results obtained at this stage of the study are presented below (Fig. 13-16).

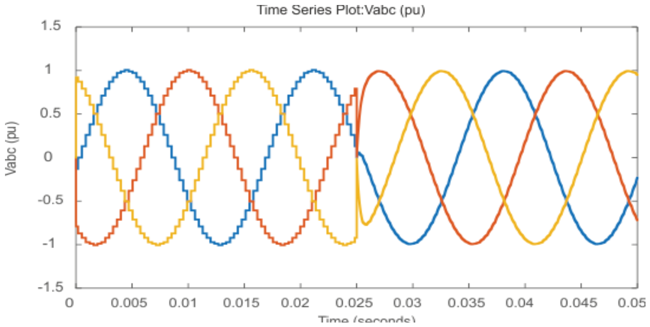

Fig. 13 The course of tension in the TRU in accordance with the concept of MEA/ AEA for the angle of the voltage harmonic 7.5°

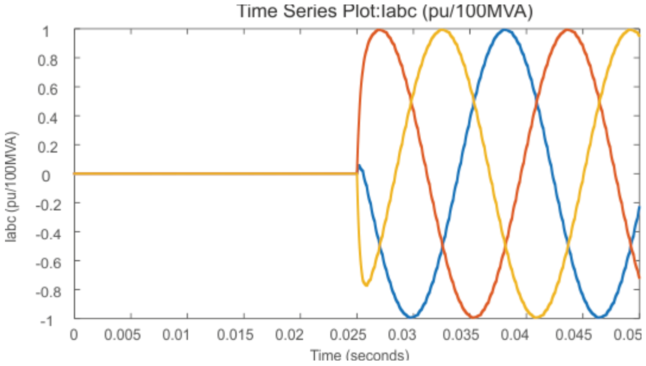

Fig. 14 The course of the current in the TRU in accordance with the concept of MEA/ AEA for the angle of the voltage harmonic 7.5°

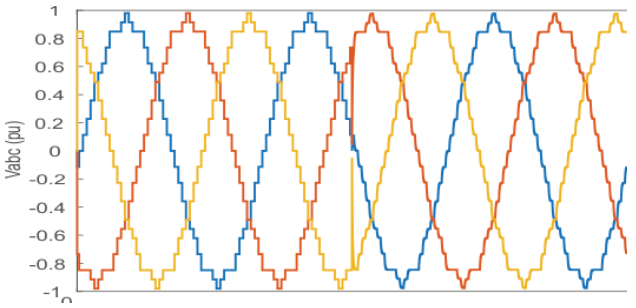

Fig. 15 The course of tension in the TRU in accordance with the concept of MEA/ AEA for the angle of the voltage harmonic 30°

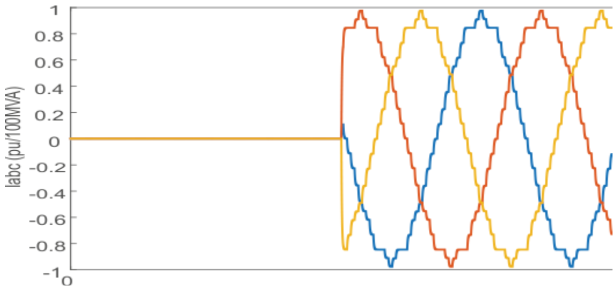

Fig. 16 The course of the current in the TRU in accordance with the concept of MEA/ AEA for the angle of the voltage harmonic 30°

5 Conclusion

Based on the results of field tests of PMSM motors, their simulation-computer models can be upgraded, which differ from the traditional ones by greater accuracy and are designed to develop and test simulation of complex drive systems. Based on this calculation results and measurements of the simulation model of modern power systems (EPS, PES) it can be stated that, the systems which comply with the concept of MEA/ AEA, based on the provided graphs showing voltage and current waveforms (Fig. 9-10) are characterized by a higher efficiency of operation than it is in the case of systems used on 'classical' aircraft. In addition, the voltage of the synchronous motor induced by permanent high-power magnet stabilizes much faster and sets the appropriate value. The same situation is in the case of currents waveform. The efficiency of this engine, and the power factor particularly are stable and have a maximum value in a very large range of variations in the load. Many modern current regulators are based on a peripheral model, while contemporary solutions in the field of computer simulation techniques allow in a very precise way to determine the parameters of the electric machine and take into account the phenomena occurring in it in the synthesis of the regulator at the stage of its design.

A very important power system, used in aviation (except EPS system) is an energo-electronic power system PES, which is a leading component of the multi-pulse converters (eg. TRU). From the presented simulation performed in Matlab/ Simulink it is clear that the use of 48-pulse converter in a power supply system of modern aircraft from the user point of view is very attractive and effective in the configuration intended for processing high-voltage AC to DC.

In modern power systems (EPS, PES) every step of the AC voltage AC power into DC power is carried out by sub-12-pulse rectifiers, which are the proper configuration of 24-pulse rectifier circuit with its own voltage response. Two sets of 24-pulse connection harmonic transform of phase by 7.5° from each other, which in turn ensures proper operation of the 48-pulse converter (Fig. 13-14). Furthermore, in this system in a situation where we are dealing in various types of loads, supply system will alleviate the problem of voltage instability. On the other hand, changing the phase angle of the voltage to a value of 30° makes the end result a waveform voltage and current is significantly distorted than in the previously discussed case, which could mean unstable operation of all electrical devices, with which a particular aircraft is supplied (Figure 15-16). This effect is an effect of mutual harmonic voltages generated by the generator.

In summary, the stabilization voltage transformer rectifier subassembly TRU using a 48-pulse rectifier systems using 12-chip connected in common with each other when the voltage phase of the harmonic 7.5°, produced by the AC power as a result of simulations proceeded positively. The results confirmed the validity of established concepts, with the proviso that when the voltage phase of 30° respectively, the results were unsatisfactory, and the voltage waveform revealed a lot of distortion that adversely affect the power system TRU.

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