The Study of Selected Multi-Pulse Rectifiers, used in "Conventional" Airplanes and Aircrafts Compatible with the Concept of a "More/All Electric Aircraft" (MEA/AEA)

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Abstract: - Based on the analysis, mathematical models and simulation of the power of modern aircrafts (conventional, MEA/AEA) in the terms of key components of on-board autonomous power supply system ASE, which are multi-pulse rectifiers (6-, 12- and 18-, 24-) pulse, and even (48-, 60-) pulse, presented in this paper, the main importance of these components of ASE (PES, EPS) system was highlighted. The key objective of the paper is to make an analysis, presentation of the mathematical models and simulation of selected multi-pulse rectifiers, used not only on civil airplanes compatible with the concept of the more/all electric aircraft of Airbus and Boeing airline corporations (A-380 and A-350XWB, B-787) and on military Lockheed Martin JSF aircraft (Joint Strike Fighter) F-35 and F-22 Raptor, but also for "conventional" military aircraft (F-18, F-16) and civilian (A-320, B-777). Additionally, in the final part of the paper, the analysis and exemplary simulations of main components of ASE in the field of PES system (multi-pulse rectifiers) based on mathematical models have contributed to highlighting the key practical applications in terms of the trend of MEA/AEA.

Key-Words: - study (modeling, simulation); multi-pulse rectifiers; more/all electric aircraft

1 Introduction

In modern aircraft, in the context of civil aviation (Airbus, Boeing), taking into account both "conventional" planes (A-320, B-777), as well as so-called civilian more electric aircrafts (A-380 and A-350XWB, B-787) and military aircrafts (Lockheed Martin) in the field of "classic" aircrafts (F-18, F-16) and those in line with the modern trend of More/All Electric Aircraft ("MEA/AEA") Joint Strike Fighter (JSF) F-35 and F-22 Raptor, you can see many significant changes, in particular in the field of on-board Electric Power Systems (EPS). Among other things, you can see the dynamic development of on-board power architectures in terms of Power Electronics Systems (PES), which are key components of the multi-pulse rectifiers (6-, 12-, and 18-, 24-) pulse [1], [2], [3].

At the outset, referring to the selected topics in the field of energy-electronics, connected with the advanced power systems PES, their main components, i.e. electronics transmitters and their essential components, which are multi-pulse rectifiers it should be noted that these systems are among some of the most important systems, except EPS systems. Additionally, they are an essential component of the so-called on-board autonomous electric power systems (ASE), referred to in the literature as well as the so-called integrated power systems (IPS).

Therefore, a co mparative analysis on the types of multi-pulse rectifiers, their analysis in the field of simulation and mathematical models have been carried out, among others, according to certain criteria. These criteria could include types of systems, production/processing of electricity on board of modern aircraft, their dynamic development and the main sources in the field produced by them under the innovative systems, implemented on modern civil and military aircrafts (Fig.1) [4].

Modern aircrafts are equipped with advanced modern power supply systems (EPS), together with the systems of HVDC (High Voltage Direct Current) and power systems of HVAC (High Voltage Alternating Current), power electronics systems (PES) and the innovative avionics systems [5], [6], [7], [8]. Therefore, the main trend of these systems tends in the direction of architecture of board voltage AC as the leading.

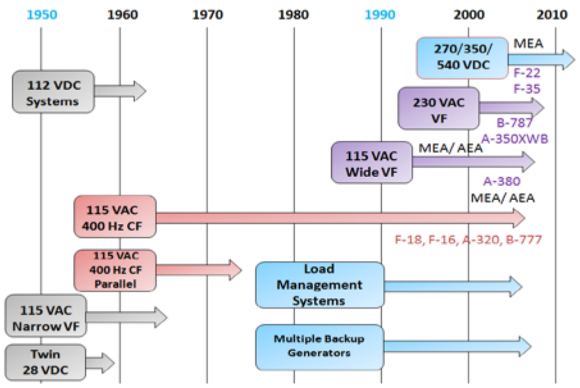

Fig.1. The evolution of the production of electricity of modern ASE (EPS, PES) systems, used on "classic" and "MEA/AEA" aircrafts

Their main idea boils down to the replacement of traditional types of energy and components associated with it (electric, pneumatic, hydraulic and mechanical), by one of its kind - electricity, which is the domain of advanced aircraft and their concept (MEA, AEA and more AEA).

2 Comparative Analysis and Mathematical Model of Multi-Pulse Rectifiers of "Conventional" Aircraft and Aircraft consistent with the Concept of "MEA/AEA"

2.1 Comparative Analysis of the Multi-Pulse Rectifiers (6-, 12- and 18-, 24-) and (48-, 60-) Pulse as regards the PES System

Example of a comparative analysis of multi-pulse rectifiers and their mathematical models are presented basing on the rectifiers (12- and 24-) pulse selected from the group of (6-, 12- and 18-, 24-) pulse rectifiers.

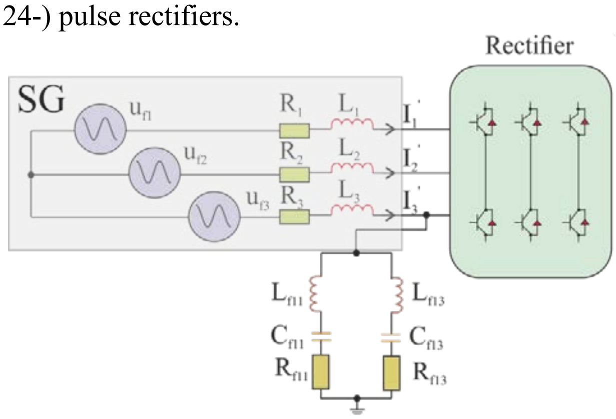

Fig.2. Exemplary block diagram of PES system consistent with the concept of MEA/AEA

These rectifiers and their mathematical models were compared with the 48-pulse rectifier selected from the group of (48- and 60-) pulse rectifiers (Fig.1). The figure below illustrates the modern architecture of the power system, used on the most advanced aircrafts (Airbus, Boeing) as regards the PES, which is also the main component of the on-board autonomous power systems ASE. A main power supply of 3-phase AC of this architecture is an electric machine (motor/generator) that uses permanent magnets instead of rotor windings. It is referred to in the literature as a PMSM (Permanent Magnets Synchronous Machine). For practical applications it is used for electronic control of the excitation with integrated power inverter and rectifier, sensor and electronics inverter. It should be noted that the 3-phase AC voltage, in particular its individual harmonics in addition to the desired signals (practical) also contains undesired signals as mutual interference, noise, etc., which must be eliminated or reduced.

Therefore, in the structure of the rectifier, using multi-pulse rectifiers (12- and 24-) pulse, set of filters was applied, developed on the basis of two parallel-connected RLC elements. This kind of solution in the final stage will eliminate some unwanted signals, affecting the final shape of the waveform of the output voltage of the multi-pulse rectifier. As a result, basing on a block diagram of the power system architecture in terms of PES system, mathematical notation of physical phenomena of the power of MEA/AEA for the voltage at the input of the energy-electronic transducer unit AC/DC will take the following form [9], [10]

$$u_1 = U_m \sin\left(\omega t + \frac{\pi}{2}\right)$$
$$u_2 = U_m \sin\left(\omega t - \frac{\pi}{6}\right) \quad (1)$$
$$u_3 = U_m \sin\left(\omega t - \frac{5\pi}{6}\right)$$

Basing on the above expression (1), we see that the waveform shape (waveform), which shows the input voltage of the same amplitude U_m, is different only by phase shift value. In the case of the voltage flowing through the filter unit, mathematical notation (model) takes the following form [11]

$$u_{f1} = u_1 + R_1 i_1 + L_1 \frac{di_1}{dt}$$
$$u_{f2} = u_2 + R_2 i_2 + L_2 \frac{di_2}{dt} \quad (2)$$
$$u_{f3} = u_3 + R_3 i_3 + L_3 \frac{di_3}{dt}$$

After adoption of the initial assumptions and determinations, where u_1, u_2 and u_3 are voltages of

3-phase AC generated by an open circuit at the terminals of the electric machine PMSM with a maximum value of the amplitude U_m; u_{f1}, u_{f2} and u_{f3} determine the value of voltage in the electrical filter circuit RLC and ω indicates the angular speed of the electric machine PMSM.

Therefore, the total resistance in the analyzed circuit is expressed as the sum of the resistances of elements, included in the electric machine PMSM and the resistance of the wires connecting the various components of the power PES system in accordance with a trend of MEA/AEA.

Also, the mathematical notation of occurring phenomena is as follows

$$R_{z1} = R_{f11} - R_{f13} \tag{3}$$

Analyzing the architecture of the PES system for the case of inductance in the filter circuit, as illustrated in the Fig.2, a mathematical notation takes a similar form

$$L_{z1} = L_{f11} - L_{f13} \tag{4}$$

After adoption of the following indications and assumptions for analysis in the field of power architecture PES, where i_1, i_2 and i_3 are the values of the currents in a 3-phase set for the branch base from 1 to 3; $I_p^{'}$ is the electric current that occurs at the rectifiers input, which is responsible for the performance of key functions, which is to transform the voltage and AC on t he DC power (AC/DC), implemented by the TRU (Transformer Rectifier Unit).

Based on the above, and taking into account the above equation (1) - (4) you can determine the equations describing all physical electrical phenomena in the considered filtering circuit. Therefore [12], [13]

$$L_{f11}\frac{d^2 i_{f11}}{dt^2} + R_{f11}\frac{di_{f11}}{dt} + \frac{1}{C_{f11}} i_{f11} = \frac{du_f}{dt} = L_{f13}\frac{d^2 i_{f13}}{dt^2} + R_{f13}\frac{di_{f13}}{dt} + \frac{1}{C_{f13}} i_{f13} \tag{5}$$

$$i_{f11} + i_{f13} = I_f = I_p^{'} - I_p$$

where L_{f11}, C_{f11} and L_{f13}, C_{f13} are respectively the inductance and capacitance on the respective elements L, C in the filter circuit in each branch of the circuit concerned.

It should also be noted that this filter is designed to filter individual harmonics (in our case harmonics of 11 and 13 are filtered). Additionally, as in the case of EPS supply system for an electric machine PMSM, also in the case of a PES system there is the resistance of the filter present in the circuit architecture, which is denoted by R_{f11} and R_{f13}. The individual harmonic voltages of the current are produced by the 12-pulse rectifier selected from the group of multi-pulse rectifiers (6-, 12- and 18-, 24-) pulse [14], which a more detailed analysis will be presented later in this paper.

2.2 The Mathematical Model of Selected Multi-Pulse Rectifiers 12-Pulse Rectifiers

By joining the mathematical description of physical phenomena occurring at the output rectifier (defining a mathematical model), the initial assumptions were made, where $I_1^{'}$, $I_2^{'}$ and $I_3^{'}$ represent electric currents flowing through the rectifier unit configuration, respectively in the three branches of the 3-phase system.

Analyzed system for which mathematical considerations were carried out is illustrated in the figure below (Fig.3). The structure of the following type of rectifier circuit is realized as two rectifier bridges (6 diodes each), whose operation is based on the conversion of AC to DC current.

In the system there is a straightening processing of AC voltages, which are further fed to the rectifier circuit via the 2 secondary windings.

Additionally, at the output of rectifier filter of LPF type was applied (Low-pass filter), whose key function is to eliminate signals (in our case the harmonic voltages below the cut-off frequency) and damping signals above the limit frequency.

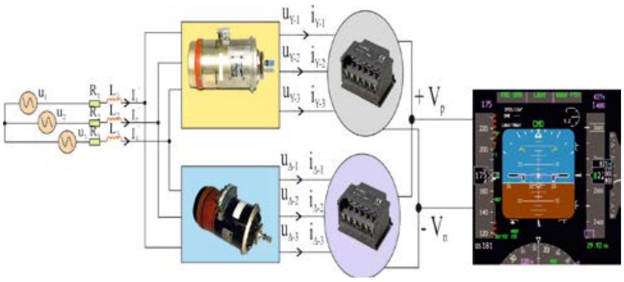

Fig.3. Wiring diagram of 12-pulse AC/DC rectifier

The process carried out by the bridge rectifier in terms of its ongoing functions can be written in a mathematical way using non-linear differential equations, which are presented in the following relationships [15], [16]

$$\begin{aligned} u_{f1} &= U_{mp}\sin\left(\omega t + \frac{\pi}{2}\right) \\ u_{f2} &= U_{mp}\sin\left(\omega t - \frac{\pi}{6}\right) \\ u_{f3} &= U_{mp}\sin\left(\omega t - \frac{5\pi}{6}\right) \end{aligned} \tag{6}$$

where U_{mp} it is the maximum amplitude of harmonic frequencies of voltages produced locally in the 12-pulse rectifier.

Assuming that the efficiency of the electric machine PMSM is equal to one, and by adopting at a later stage of consideration that the converter converts the voltage from both the lower and upper voltage harmonics, a process of operation of the rectifier can be represented as mathematical notation as follows.

For an electric machine, operating in a star configuration

$$
\begin{aligned}
u_{Y-1} &= u_{f1} = U_{mp}\sin\left(\omega t + \frac{\pi}{2}\right)\\
u_{Y-2} &= u_{f2} = U_{mp}\sin\left(\omega t - \frac{\pi}{6}\right)\\
u_{Y-3} &= u_{f3} = U_{mp}\sin\left(\omega t - \frac{5\pi}{6}\right)
\end{aligned} \tag{7}
$$

On the other hand, in the case of an electric machine PMSM operating in a triangle we get the following relationship

$$
\begin{aligned}
u_{\Delta-1} &= U_{mp}\, sin\left(\omega t + \frac{\pi}{2} + \frac{\pi}{6}\right) = U_{mp}\, sin\left(\omega t + \frac{2\pi}{3}\right)\\
u_{\Delta-2} &= U_{mp}\, sin\left(\omega t - \frac{5\pi}{6} + \frac{\pi}{6}\right) = U_{mp}\, sin(\omega t)\\
u_{\Delta-3} &= U_{mp}\sin\left(\omega t - \frac{5\pi}{6} + \frac{\pi}{6}\right) = U_{mp}\sin\left(\omega t + \frac{2\pi}{3}\right)
\end{aligned} \tag{8}
$$

Therefore, the rated power, obtained from the electric motor 90 kW, DC current is relatively small. In such circumstances, the phase angle φ of the carrier harmonic voltage is smaller than $\frac{\pi}{6}$, and the harmonic frequencies for the low and high range do not overlap, hence the equations for the electric circuit of the multi-pulse rectifier take the following form.

For the case of the phase angle $\alpha \le \theta < \varphi$

$$
\begin{aligned}
L_{ac}\frac{di_{\Delta-1}}{dt} &= -R_{ac}i_{\Delta-1} + u_{\Delta-1} - V_p\\
L_{ac}\frac{di_{\Delta-2}}{dt} &= -R_{ac}i_{\Delta-2} + u_{\Delta-2} - V_n\\
L_{ac}\frac{di_{\Delta-3}}{dt} &= -R_{ac}i_{\Delta-3} + u_{\Delta-3} - V_n\\
L_{ac}\frac{di_{Y-1}}{dt} &= -R_{ac}i_{Y-1} + u_{Y-1} - V_p\\
L_{ac}\frac{di_{Y-2}}{dt} &= -R_{ac}i_{Y-2} + u_{Y-2} - V_p\\
L_{ac}\frac{di_{Y-3}}{dt} &= -R_{ac}i_{Y-3} + u_{Y-3} - V_n
\end{aligned} \tag{9}
$$

In a further step of analysis obtained

$$
\begin{aligned}
i_{\Delta-1} &= -(i_{\Delta-2} + i_{\Delta-3})\\
i_{Y-1} &= -i_{Y-2}\\
i_{Y-3} &= 0\\
i_{Y-1} + i_{\Delta-1} &= I_{DC}
\end{aligned} \tag{10}
$$

where $\alpha = \omega t$ defines the initial angle of the alternating voltage obtained at the output of the PMSM, therefore α is the phase angle of the alternating voltage signal after passing through the initial stages of the rectifier and filtering circuit; i_Δ, i_Y alternating currents measured at the input of the rectifier; L_{ac} and R_{ac} are respectively the inductance and resistance occurring in a rectifier.

On the other hand, V_p and V_n indicate negative or positive value of DC voltage nodes.

For the case of the phase angle $\varphi \le \theta < \alpha + \frac{\pi}{6}$

$$
\begin{aligned}
L_{ac}\frac{di_{\Delta-1}}{dt} &= -R_{ac}i_{\Delta-1} + u_{\Delta-1} - V_p\\
L_{ac}\frac{di_{\Delta-3}}{dt} &= -R_{ac}i_{\Delta-3} + u_{\Delta-3} - V_n\\
L_{ac}\frac{di_{Y-1}}{dt} &= -R_{ac}i_{Y-1} + u_{Y-1} - V_p\\
L_{ac}\frac{di_{Y-2}}{dt} &= -R_{ac}i_{Y-2} + u_{Y-2} - V_n
\end{aligned} \tag{11}
$$

Therefore, after appropriate transformations obtained

$$
\begin{aligned}
i_{\Delta-1} &= -i_{\Delta-3}\\
i_{\Delta-2} &= 0\\
i_{Y-1} &= -i_{Y-2}\\
i_{Y-1} + i_{\Delta-1} &= I_{DC}\\
i_{Y-1} = i_{\Delta-1} &= \frac{1}{2}I_{DC}\\
i_{Y-3} &= 0
\end{aligned} \tag{12}
$$

Subsequently, using the mutual relations between equations (9) and (10), mathematical equations have been derived which determine the values of currents in the analyzed system. The obtained mathematical relations in the next step were inserted into equations (11) and (12), resulting in

$$V_p - V_n = \frac{6}{7}u_{\Delta-1} + \frac{3}{7}(u_{Y-1} - u_{Y-2}) - \frac{6}{7}R_{ac}I_{DC} - \frac{6}{7}L_{ac}\frac{dI_{DC}}{dt}$$

$$\alpha \le \theta < \varphi$$

$$V_p - V_n = \frac{1}{2}(u_{\Delta-1} - u_{\Delta-3}) + \frac{1}{2}(u_{Y-1} - u_{Y-2}) - R_{ac}I_{DC} - L_{ac}\frac{dI_{DC}}{dt} \quad \varphi \le \theta < \alpha + \frac{\pi}{6} \tag{13}$$

Substituting equation (7) and (8) to the mathematical equation (13) obtained:

$$V_p - V_n = \frac{6+\sqrt{3}}{7}U_{mp}\sin\left(\theta + \frac{2\pi}{3}\right) - \frac{6}{7}R_{ac}I_{DC} - \frac{6}{7}L_{ac}\frac{dI_{DC}}{dt}$$

$$\alpha \le \theta < \ddot{o}$$

$$V_p - V_n = \frac{1}{2}\left[\sqrt{3}U_{mp}\cos\theta + \sqrt{3}U_{mp}\sin\left(\theta + \frac{2\pi}{3}\right)\right] - R_{ac}I_{DC} - L_{ac}\frac{dI_{DC}}{dt} \tag{14}$$

$$\varphi \le \theta < \alpha + \frac{\pi}{6}$$

where I_{DC} the DC at output side of the rectifier circuit. Thus, the voltage and current can be expressed as

$$R_{DC}I_{DC} + L_{DC}\frac{dI_{DC}}{dt} = (V_p - V_n) - U_{DC}$$
$$I_{DC} = C_{DC}\frac{dU_{DC}}{dt} + I_{Load} \tag{15}$$

where R_{DC} is the total resistance of electronic elements, located in the electrical system after rectifier so-called load, while L_{DC} and C_{DC} mark inductance and capacitance in the circuit of the rectifier. Substituting expression (15) to (14) were obtained

$$U_{DC} + R_1C_{DC}\frac{dU_{DC}}{dt} + L_1\frac{d^2U_{DC}}{dt^2} = \frac{6+\sqrt{3}}{7}U_{mp}\sin\left(\theta + \frac{2\pi}{3}\right) - R_1I_{Load} - L_1\frac{dI_{Load}}{dt} \tag{16}$$

$$-\frac{\pi}{4} \le \theta < \varphi - \frac{\pi}{4}$$

$$V_{DC} + R_2C_{DC}\frac{dU_{DC}}{dt} + L_2\frac{d^2U_{DC}}{dt^2} = \frac{1}{2}\left[\sqrt{3}U_{mp}\cos\theta + \sqrt{3}U_{mp}\sin\left(\theta + \frac{2\pi}{3}\right)\right] - R_2I_{DC} - L_2\frac{dI_{DC}}{dt}$$

$$\varphi - \frac{\pi}{4} \le \theta < -\frac{\pi}{12}$$

where

$$R_1 = R_{DC} + \frac{6}{7}R_{AC}$$
$$L_1 = L_{DC} + \frac{6}{7}L_{AC} \tag{17}$$
$$R_2 = R_{DC} + R_{AC}$$
$$L_2 = L_{DC} + L_{AC}$$

2.3 The Mathematical Model of Selected Multi-Pulse Rectifiers 24-Pulse Rectifiers

An analysis and determining of the mathematical model of the 24-pulse rectifier it should be noted that the mathematical model of presented earlier 12-pulse rectifier AC/DC has one major drawback in that the voltage or current signals in the form of harmonic waves can not reduce (alleviate) upper harmonics.

Therefore, the process of leveling the harmonics that occur in currents that power rectifiers AC/DC, is a very important issue.

This task is performed by the rectifiers of higher orders: (24-, 36- and 48-) pulse or even 60-pulse. In addition, reducing the proportion of higher harmonics is achieved, among others, using active filters, working with high switching frequency, which, however, are not suitable for use in high power systems. In addition, the 24-pulse rectifier allows for higher currents of distorted power in relation to the 36-pulse rectifier.

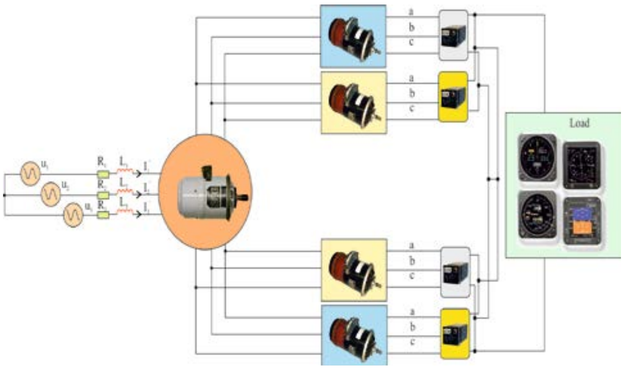

Fig.4. Wiring diagram of 24-pulse AC/DC rectifier

In the figure above (Fig.4) are examples of solutions containing two 3-phase rectifier bridge circuits, showing the behavior of the 24-pulse rectifier. The envisaged 24-pulse system consists of two circuits of 12-pulse rectifier, creating a network bridge 1 and 2.

The system is supplied with 3-phase electric motor, the input current of the 24-pulse rectifier can be described as

$$i_{a1} = \sum bn \cdot \sin n(\pi t + \varphi) = \sum_{n=1,3,5} \left[\frac{4I_{DC}}{n\pi} \cdot \cos\frac{n\pi}{6}\right] \sin n\left(\omega t + \frac{\pi}{24}\right) \quad (18)$$

Example

$$i_{a2} = \sum_{n=1,3,5} \left[\frac{4I_{DC}}{n\pi} \cdot \cos\frac{n\pi}{6}\right] \sin n\left(\omega t + \frac{\pi}{8}\right)$$

$$i_{a3} = \sum_{n=1,3,5} \left[\frac{4I_{DC}}{n\pi} \cdot \cos\frac{n\pi}{6}\right] \sin n\left(\omega t - \frac{\pi}{24}\right) \quad (19)$$

$$i_{a4} = \sum_{n=1,3,5} \left[\frac{4I_{DC}}{n\pi} \cdot \cos\frac{n\pi}{6}\right] \sin n\left(\omega t - \frac{\pi}{8}\right)$$

For the opposite side dependencies take the form of

$$i_{c1} = \sum_{n=1,3,5} \left[\frac{4I_{DC}}{n\pi} \cdot \cos\frac{n\pi}{6}\right] \sin n\left(\omega t + \frac{17\pi}{24}\right)$$

$$i_{c2} = \sum_{n=1,3,5} \left[\frac{4I_{DC}}{n\pi} \cdot \cos\frac{n\pi}{6}\right] \sin n\left(\omega t + \frac{19\pi}{24}\right)$$

$$i_{b4} = \sum_{n=1,3,5} \left[\frac{4I_{DC}}{n\pi} \cdot \cos\frac{n\pi}{6}\right] \sin n\left(\omega t - \frac{19\pi}{24}\right) \quad (20)$$

$$i_{b3} = \sum_{n=1,3,5} \left[\frac{4I_{DC}}{n\pi} \cdot \cos\frac{n\pi}{6}\right] \sin n\left(\omega t - \frac{17\pi}{24}\right)$$

Each phase angle of the AC harmonic wave consists of the phase angle of the current in the main branch and the phase angle occurring in the side branch, which takes the form of mathematical notation

$$i_{a0} = (i_{c1}k_2 + i_{b3}k_2) \cdot \cos\frac{13\pi}{45} + (i_{c2}k_4 + i_{b4}k_4) \cdot \cos\frac{37{,}5\pi}{180} \quad (21)$$

Hence, the current in the first phase *A* is

$$i_{ax} = (i_{a1} + i_{a3})k_1 \cdot \cos\frac{7{,}5\pi}{180} + (i_{a2} + i_{a4})k_3 \cdot \cos\frac{22{,}5\pi}{180} \quad (22)$$

Where input current of the electric machine PMSM is expressed by the formula

$$i_a = i_{ax} - i_{a0} \quad (23)$$

Further, by making a Fourier transform of equation (23) obtained

$$i_a = 2 \cdot \sum_{n=1,3,5} \left[\frac{4I_{DC}}{n\pi} \cdot \cos\frac{n\pi}{6}\right] \sin(n\omega t) \cdot \left[\cos\frac{1}{24}n\pi k_1 \cdot \cos\frac{\pi}{24} + \cos\frac{1}{8}n\pi k_3 \cdot \cos\frac{3\pi}{24} - \cos\frac{17}{24}n\pi k_2 \cdot \cos\frac{7\pi}{24} - \cos\frac{19}{24}n\pi k_4 \cdot \cos\frac{5\pi}{24}\right] \quad (24)$$

where: I_{DC} a DC in the 6-pulse rectifier and amounts $I_{DC} = \frac{I_{DC24}}{4}$ and I_{DC24} is output current of 24-pulse rectifier.

On the other hand, the amplitude of the N-th harmonic signal is defined as

$$A_n = \frac{2I_{DC24}}{n\pi} \cdot \left(\cos\frac{n\pi}{6}\right) \cdot \left[\cos\frac{1}{24}n\pi k_1 + \cos\frac{1}{8}n\pi k_3 - \cos\frac{17}{24}n\pi k_2 - \cos\frac{19}{24}n\pi k_4\right. \quad (25)$$

In the case of 24-pulse rectifier total distortion factor THD for harmonics 23 and 25 is 5.09%.

2.4 The Mathematical Model of Selected Multi-Pulse Rectifiers 48-Pulse Rectifiers

For the currently used power electronics supply systems PES elements responsible for the conversion of the AC to DC power, are multi-pulse sensors, and in most cases 12-pulse or 24-pulse rectifiers are used. However, in the scientific literature [9], [15] developed models of 48-pulse rectifiers can be found.

The results presented in the literature [10], [15] contained the simulation from which 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 inconsistencies can be eliminated indirectly by using the appropriately phased voltage in three-phase system of 7.5°, this value will provide valuable full effect of a 48-pulse rectifier.

Also, be sure to correct functioning of the rectifier to make symmetrical movements of all three voltages produced by the transformer windings. The remainder of the paper are examples of simulations of multi-pulse rectifiers of 12-and 24-pulse and their comparison with the 48-pulse rectifiers was made.

The mathematical considerations presented in this article have contributed to both the development of a complete electrical system in the Matlab/Simulink and their implementation in this environment for a more efficient operation of the rectifier circuit. Also, they largely reflect the actual operating conditions of the rectifier in the on-board electrical network.

In turn, the change of phase AC was obtained based on the received AC phase shift values, in the context of the presented mathematical models [17].

3 Simulation of Selected Multi-Pulse Rectifier of "Conventional" Aircraft and Aircraft consistent with the Concept of "MEA/AEA"

3.1 Simulation of 12- and 24-Pulse Rectifiers

The basic purpose of accomplishing simulations of selected components, including in particular the multi-pulse (12-, 24-, and 48-) pulse rectifiers, was to evaluate their effectiveness in modern ASE power supply systems in the field of PES used in advanced aircraft. However, due to limitations in the volume of this paper, the authors were unable to provide in-depth comparative analysis and simulations of (12-and 24-) pulse power electronics rectifiers. Considerations in this area have been made in other articles [2], [17]. Authors have confined themselves only to the analysis and simulation of 48-pulse rectifiers in the context of (12- and 24-) pulse rectifiers.

3.2 Simulation of 48-Pulse Rectifiers

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 (Figs.5 to 8).

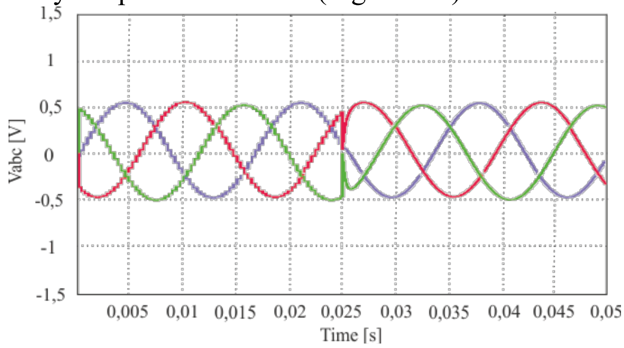

Fig.5. Voltage waveform in the TRU in accordance with the concept of MEA/AEA for the angle of the voltage harmonic 7.5°

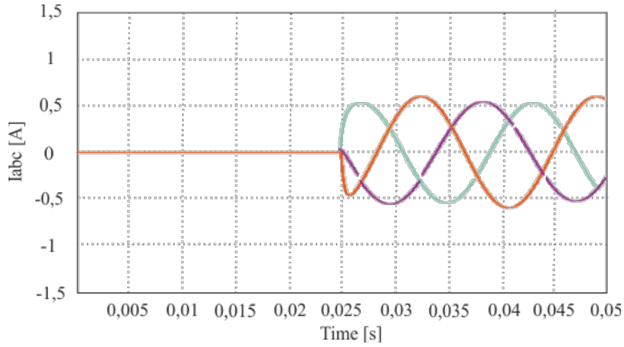

Fig.6. The waveform of the current in the TRU in accordance with the concept of MEA/AEA for the angle of the voltage harmonic 7.5°

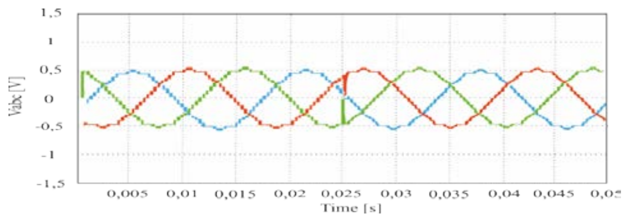

Fig.7. Voltage waveform in the TRU in accordance with the concept of MEA/AEA for the angle of the voltage harmonic 30°

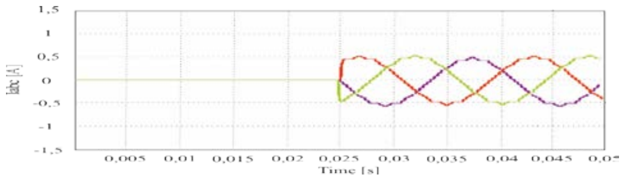

Fig.8. The waveform of the current in the TRU in accordance with the concept of MEA/AEA for the angle of the voltage harmonic 30°

In the shown graphs there is a noticeable jump of waveforms of AC currents for the time of 0.025 s which is caused by the switching of the rectifier circuit. At the same time load receivers were connected. In addition, during the initial phase of the simulation process, the phase angle of the alternating AC voltage was determined [17].

4 Conclusion

Based on results of calculations and measurements of the simulation model of modern power systems ASE in terms of the system PES it can be concluded that the systems comply with the concept of a MEA/AEA, based on the presented graphs showing voltage and current waveforms (Figs.7 to 8) they have a h igher efficiency of operation than in the case of systems used on "classical" aircrafts.

From the presented simulation performed in Matlab/Simulink it is clear that the use of a 48-pulse rectifier in the power supply system of modern aircraft to the user is very attractive and effective in the configuration intended for processing high-voltage AC to DC.

In modern systems, the ASE power as regards the PES, each step of the conversion of the AC voltage to DC voltage is performed by sub-unit of 12-pulse rectifiers which in the proper configuration are the rectifier of 24-pulse circuit with its own response voltage.

In addition, the two 24-pulse circuits convert the voltage harmonics in phase by 7.5° from each other, which in turn ensures the correct operation of the 48-pulse transmitter (Figs.5 to 6). Additionally, in this system when we are dealing in various loads, system power will level a problem of voltage instability.

In turn, changing the phase angle of voltage at a value of 30° makes the final effect of the voltage waveform and currents be significantly distorted than in the previously discussed case, which could affect unstable operation of all electrical devices, which specific plane is supplied with (Figs.7 to 8).

This effect is connected with mutual harmonic voltages generated by the primary power source in the form of a electric machine PMSM (motor, generator) [16], [17].

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