Models and Simulations of selected Multi-Pulse Rectifiers in terms of Energoelectronic Power System, using Matlab/Simulink in Accordance with the Concept of a More Electric Aircraft

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***Abstract*—The work deals with the issues of new architecture in terms of power multi-pulse rectifiers based on the 12-, 24-, and 48-pulse rectifiers, compatible with the concept of a MEA. The subject of this paper is to present the analysis, the mathematical models and simulations of the operation of a advanced multi-pulse rectifiers, used in the field of energoelectronic power systems PES, both on civil aircraft of aircraft companies Airbus and Boeing (A-380 and A-350XWB, B-787), as well as on military aircrafts of Lockheed Martin (JSF F-35 and F-22 Raptor), compatible with the trend of more electric aircraft. Based on the above, in the final part of the paper the models and analysis of simulation waveforms of considered rectifiers was made and practical conclusions were drawn in terms of advanced power systems PES according to the concept of more electric aircraft.**

Keywords*—models and simulations; multi-pulse rectifiers; power electronics systems; Matlab/Simulink; more electric aircraft

I. Introduction

Currently in modern military aviation (Lockheed Martin) and in civil aviation (Airbus, Boeing, etc.), both for JSF (Joint Strike Fighter) military aircrafts and the F-22 Raptor, as well as in the field of civil aircrafts (A-380 and A-350XWB, B-787), in line with the trend of a more/full electric aircraft (MEA/AEA), you can observe continuous and dynamic development of ASE (Autonomous Electric Power Supply Systems) and their key components, which include the two main power systems. These include the Electric Power System (EPS) and the Power Electronics Systems (PES) [1], [2].

Modern innovative technologies implemented in aviation, based primarily on comprehensive development in terms of electrical machinery and their related fields (power electronics, electronics) have found use in modern aviation, particularly in the use of power electronics (PES), and in particular their main components of advanced multi-pulse rectifiers (6-, 12- and 18-, 24-) and even (48- and 60-) pulses, which will be analyzed in detail in this paper [3].

Energo-electronic converters powered from the onboard electricity network are called rectifiers (converters) in case of processing the AC voltage to a DC voltage and inverters when processing the DC voltage to AC voltage. Based on the literature review of the basic elements of PES, there are two types of transducers, namely transmitters of power sources CSC (Current Source Converters), and transducers of voltage sources VSC (Voltage Source Converters), requiring the use of a high-power filter, necessary to eliminate AC harmonics, in addition to the DC filters.

The process of converting electricity (power) using high-tech converters (inverters) has recently become one of the most dynamically developing trends in aviation technology. In addition, in the case of practical applications, the hitherto used voltage sources, such as DC generators and alternating current generators, and the associated electro-energetic power supply systems (AC and DC power supply systems) are non-economic solutions and technically difficult to implement. Based on the above considered analysis of the 12-pulse, 24-pulse and 48-pulse rectifiers, their mathematical models and the selected simulations have been carried out among others, according to certain criteria, namely: types of processing of electricity systems, their evolution and key sources in terms of power of the modern systems produced by them used on modern aircrafts, both civilian and military (Fig. 1) [4], [5].

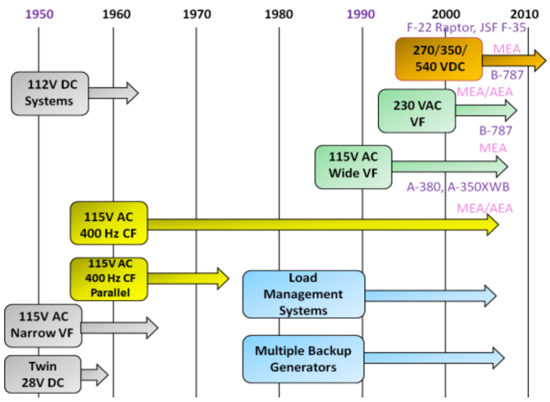

Fig. 1. The evolution of the production/processing of electricity of modern aircrafts (Airbus, Boeing, Lockheed Martin, etc.) [5]

Modern aircrafts compatible with the trend of More Electric Aircraft (MEA), whose main systems of processing of electricity in the field of their dynamic development, illustrated in the figure above, are equipped with advanced on-board autonomous power system ASE. This system consists of two key power systems: electric power supply system EPS, whose basic components are generators, integrated assemblies in the form of a starter/generator, batteries, fuel cells, etc., and electro-energetic power supply system PES. The main components of the system PES are primarily multi-pulse rectifiers, such as 12-pulse and 24-pulse, including 48-pulse and even 60-pulse rectifiers, which are the subject of detailed analysis later in the article, as well as other elements which may include: transducers of cycles, transformers, amplifiers blocks of transformers, etc., generally referred to in the literature as electronic systems PE (Power Electronics). These systems in the scope of their activities, which are components of the system are the PES process of using advanced semiconductor devices and components whose key purpose is to control and the processing of one type of energy to another depending on the needs. In other words, electronic systems PE in the power system is able to control both the flow of energy, as well as the types, e.g., AC to DC and the size of the key parameters (current, voltage). The figure below (Fig. 2) shows the block diagram of a energoelectronic power system PES.

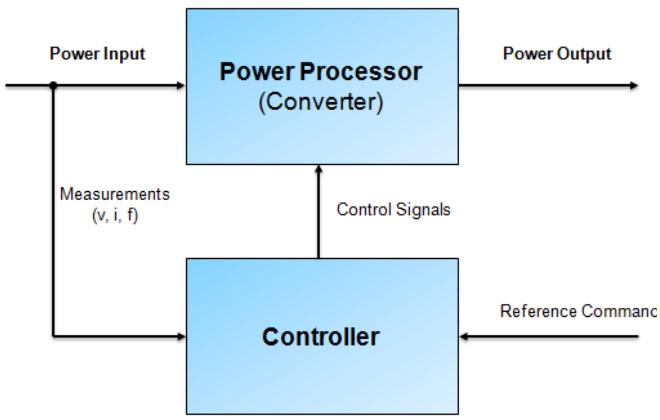

Fig. 2. Block diagram of energoelectronic power system (PES)

Therefore, in the context of energy conversion devices performing the processing power are referred to "converters." Transducers can perform processing functions (AC to DC), a reversal (DC to AC), "bucking" or "boosting" (DC to DC) and converting the frequency (AC to AC). It should also be noted that the processing (conversion) requires the necessary equipment: a control system; semiconductor switches; passive components in the form of capacitors, inductors and transformers, thermal management systems; packaging; safety devices, connectors and attachments DC and AC. This type of equipment is collectively referred to as energy conversion system PCS (Power Conversion System). Later in this paper we have analyzed and created mathematical models of multi-pulse (12-, 24- and 48-) pulse rectifiers selected from groups (6-, 12- and 18-, 24-) and (48- and 60-) pulse [6].

II. The Mathematical Model of Multi-Pulse 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 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. In addition, 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 [7], [8].

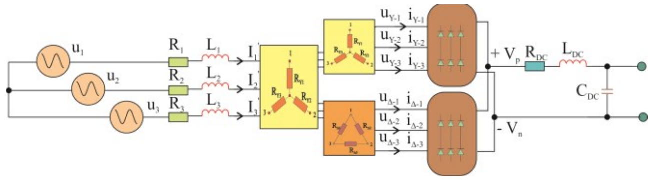

Fig. 3. Wiring diagram of 12-pulse AC/DC rectifier

In other words, the LPF is a low-pass filter, characterized by a specific feature which consists in passing only those frequencies below the signal frequency limit. Essence of the operation of such a system lies in the fact that the input values are alternating AC, and the output are fixed values of the DC. 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 [9], [10], [11]

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

where U_{mp} is the maximum amplitude of harmonic frequencies of voltages produced locally in the 12-pulse rectifier. Assuming that the efficiency of the electric motor PMSM (Permanent Magnets Synchronous Machine) 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 motor, operating in a star configuration

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

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

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

$$u_{\Delta-3} = U_{mp}\sin\left(\omega t - \frac{5\pi}{6} + \frac{\pi}{6}\right) = U_{mp}\sin\left(\omega t + \frac{2\pi}{3}\right)$$

Therefore, the rated power, obtained from the PMSM 90 kW, direct 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 $\alpha \le \theta < \varphi$

$$\begin{aligned} L_{ac}\frac{di_{\Delta-1}}{dt} &= -R_{ac}i_{\Delta-1} + u_{\Delta-1} - V_p \\ L_{ac}\frac{di_{\Delta-2}}{dt} &= -R_{ac}i_{\Delta-2} + u_{\Delta-2} - V_n \\ L_{ac}\frac{di_{\Delta-3}}{dt} &= -R_{ac}i_{\Delta-3} + u_{\Delta-3} - V_n \\ L_{ac}\frac{di_{Y-1}}{dt} &= -R_{ac}i_{Y-1} + u_{Y-1} - V_p \\ L_{ac}\frac{di_{Y-2}}{dt} &= -R_{ac}i_{Y-2} + u_{Y-2} - V_p \\ L_{ac}\frac{di_{Y-3}}{dt} &= -R_{ac}i_{Y-3} + u_{Y-3} - V_n \end{aligned} \tag{4}$$

In a further step of analysis obtained

$$\begin{gathered} i_{\Delta-1} = -(i_{\Delta-2} + i_{\Delta-3}) \\ i_{Y-1} = -i_{Y-2} \\ i_{Y-3} = 0 \\ i_{Y-1} + i_{\Delta-1} = I_{DC} \end{gathered} \tag{5}$$

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

$$\begin{aligned} L_{ac}\frac{di_{\Delta-1}}{dt} &= -R_{ac}i_{\Delta-1} + u_{\Delta-1} - V_p \\ L_{ac}\frac{di_{\Delta-3}}{dt} &= -R_{ac}i_{\Delta-3} + u_{\Delta-3} - V_n \\ L_{ac}\frac{di_{Y-1}}{dt} &= -R_{ac}i_{Y-1} + u_{Y-1} - V_p \\ L_{ac}\frac{di_{Y-2}}{dt} &= -R_{ac}i_{Y-2} + u_{Y-2} - V_n \end{aligned} \tag{6}$$

Therefore, after appropriate transformations obtained

$$\begin{gathered} i_{\Delta-1} = -i_{\Delta-3} \\ i_{\Delta-2} = 0 \\ i_{Y-1} = -i_{Y-2} \\ i_{Y-1} + i_{\Delta-1} = I_{DC} \\ i_{Y-1} = i_{\Delta-1} = \frac{1}{2}I_{DC} \\ i_{Y-3} = 0 \end{gathered} \tag{7}$$

Subsequently, using the mutual relations between equations (4) and (5), 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 (6) and (7), resulting in

$$\begin{aligned} V_p - V_n &= \frac{6}{7}u_{\Delta-1} + \frac{3}{7}(u_{Y-1} - u_{Y-2}) - \frac{6}{7}R_{ac}I_{DC} \\ &\quad - \frac{6}{7}L_{ac}\frac{dI_{DC}}{dt} \qquad \alpha \le \theta < \varphi \\ V_p - V_n &= \frac{1}{2}(u_{\Delta-1} - u_{\Delta-3}) + \frac{1}{2}(u_{Y-1} - u_{Y-2}) - R_{ac}I_{DC} \\ &\quad - L_{ac}\frac{dI_{DC}}{dt} \quad \varphi \le \theta < \alpha + \frac{\pi}{6} \end{aligned} \tag{8}$$

Substituting equation (2) and (3) to the mathematical equation (8) obtained

$$\begin{aligned} V_p - V_n &= \frac{6+\sqrt{3}}{7}U_{mp}\sin\left(\theta + \frac{2\pi}{3}\right) - \frac{6}{7}R_{ac}I_{DC} \\ &\quad - \frac{6}{7}L_{ac}\frac{dI_{DC}}{dt} \qquad \alpha \le \theta < \varphi \\ V_p - V_n &= \frac{1}{2}\left[\sqrt{3}U_{mp}\cos\theta + \sqrt{3}U_{mp}\sin\left(\theta + \frac{2\pi}{3}\right)\right] \\ &\quad - R_{ac}I_{DC} - L_{ac}\frac{dI_{DC}}{dt} \quad \varphi \le \theta < \alpha + \frac{\pi}{6} \end{aligned} \tag{9}$$

where I_{DC} is the DC at output side of the rectifier circuit.

Thus, the voltage and current can be expressed as

$$\begin{gathered} R_{DC}I_{DC} + L_{DC}\frac{dI_{DC}}{dt} = (V_p - V_n) - U_{DC} \\ I_{DC} = C_{DC}\frac{dU_{DC}}{dt} + I_{Load} \end{gathered} \tag{10}$$

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 (10) to (9) were obtained

$$\begin{aligned} &U_{DC} + R_1C_{DC}\frac{dU_{DC}}{dt} + L_1\frac{d^2U_{DC}}{dt^2} \\ &\quad = \frac{6+\sqrt{3}}{7}U_{mp}\sin\left(\theta + \frac{2\pi}{3}\right) - R_1I_{Load} \\ &\quad - L_1\frac{dI_{Load}}{dt} \qquad -\frac{\pi}{4} \le \theta < \varphi - \frac{\pi}{4} \\ &V_{DC} + R_2C_{DC}\frac{dU_{DC}}{dt} + L_2\frac{d^2U_{DC}}{dt^2} \\ &\quad = \frac{1}{2}\Big[\sqrt{3}U_{mp}\cos\theta \\ &\quad + \sqrt{3}U_{mp}\sin\left(\theta + \frac{2\pi}{3}\right)\Big] - R_2I_{DC} \\ &\quad - L_2\frac{dI_{DC}}{dt} \quad \varphi - \frac{\pi}{4} \le \theta < -\frac{\pi}{12} \end{aligned} \tag{11}$$

where

$$\begin{gathered} R_1 = R_{DC} + \frac{6}{7}R_{AC} \\ L_1 = L_{DC} + \frac{6}{7}L_{AC} \\ R_2 = R_{DC} + R_{AC} \\ L_2 = L_{DC} + L_{AC} \end{gathered} \tag{12}$$

III. THE MATHEMATICAL MODEL OF MULTI-PULSE 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.

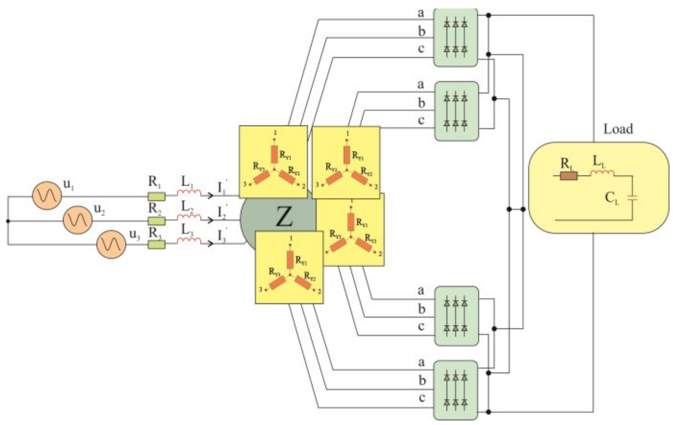

Fig. 4. Wiring diagram of 24-pulse AC/DC rectifier

This task is performed by the rectifiers of higher orders: 24-, 36- and 48- 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. Additionally, the 24-pulse rectifier allows for higher currents of distorted power in relation to the 36-pulse 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 three-phase electric motor, the input current of the 24-pulse rectifier can be described as [12], [13]

$$i_{a1} = \sum bn \cdot \sin n(\pi t + \varphi) = \sum_{n=1,3,5} \left[\frac{4I_{DC}}{n\pi} \cdot \cos\frac{n\pi}{6}\right] \sin n\left(\omega t + \frac{\pi}{24}\right) \tag{13}$$

Example

$$\begin{aligned} i_{a2} &= \sum_{n=1,3,5} \left[\frac{4I_{DC}}{n\pi} \cdot \cos\frac{n\pi}{6}\right] \sin n\left(\omega t + \frac{\pi}{8}\right) \\ i_{a3} &= \sum_{n=1,3,5} \left[\frac{4I_{DC}}{n\pi} \cdot \cos\frac{n\pi}{6}\right] \sin n\left(\omega t - \frac{\pi}{24}\right) \\ i_{a4} &= \sum_{n=1,3,5} \left[\frac{4I_{DC}}{n\pi} \cdot \cos\frac{n\pi}{6}\right] \sin n\left(\omega t - \frac{\pi}{8}\right) \end{aligned} \tag{14}$$

For the opposite side dependencies take the form of

$$\begin{aligned} i_{c1} &= \sum_{n=1,3,5} \left[\frac{4I_{DC}}{n\pi} \cdot \cos\frac{n\pi}{6}\right] \sin n\left(\omega t + \frac{17\pi}{24}\right) \\ i_{c2} &= \sum_{n=1,3,5} \left[\frac{4I_{DC}}{n\pi} \cdot \cos\frac{n\pi}{6}\right] \sin n\left(\omega t + \frac{19\pi}{24}\right) \\ i_{b4} &= \sum_{n=1,3,5} \left[\frac{4I_{DC}}{n\pi} \cdot \cos\frac{n\pi}{6}\right] \sin n\left(\omega t - \frac{19\pi}{24}\right) \\ i_{b3} &= \sum_{n=1,3,5} \left[\frac{4I_{DC}}{n\pi} \cdot \cos\frac{n\pi}{6}\right] \sin n\left(\omega t - \frac{17\pi}{24}\right) \end{aligned} \tag{15}$$

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 [14]

$$i_{a0} = (i_{c1}k_2 + i_{b3}k_2) \cdot \cos\frac{13\pi}{45} + (i_{c2}k_4 + i_{b4}k_4) \cdot \cos\frac{37{,}5\pi}{180} \tag{16}$$

Hence, the current in the first phase A is

$$i_{ax} = (i_{a1} + i_{a3})k_1 \cdot \cos\frac{7{,}5\pi}{180} + (i_{a2} + i_{a4})k_3 \cdot \cos\frac{22{,}5\pi}{180} \tag{17}$$

Where input current of the electric motor is expressed by the formula

$$i_a = i_{ax} - i_{a0} \tag{18}$$

Next, by making a Fourier transform of equation (18) obtained

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

where I_{DC} is 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

$$\begin{aligned} A_n \\ = \frac{2I_{DC24}}{n\pi} \\ \cdot \left(\cos\frac{n\pi}{6}\right) \cdot \Big[\cos\frac{1}{24}n\pi k_1 \\ + \cos\frac{1}{8}n\pi k_3 - \cos\frac{17}{24}n\pi k_2 - \cos\frac{19}{24}n\pi k_4\Big] \end{aligned} \tag{20}$$

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

IV. The Mathematical Model of Multi-Pulse 48-Pulse Rectifiers

For the currently used energoelectronic power system (PES) elements responsible for the conversion of the AC/DC power, are multi-pulse transducers, and in most cases 12- or 24-pulse rectifiers are used. However, in the scientific literature [7], [15] developed models of 48-pulse rectifiers can be found. The results presented in the literature [8], [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 3-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 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 (EPS, PES) power supply systems, especially in the field of PES used in advanced aircraft. However, due to limitations in the volume of this paper to 6 pages, the authors were unable to provide in-depth comparative analysis and simulations of 12- and 24-pulse power electronics rectifiers [16]. Considerations in this area have been made in other papers [6], [17], including the mathematical model of the 48-pulse rectifier [17]. Authors have confined themselves only to the analysis and simulation of 48-pulse rectifiers in the context of 12- and 24-pulse rectifiers. The mathematical considerations presented in this paper have contributed to both the development of a complete electrical system in the Matlab/Simulink program 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 mathematical models (Figs. 3 to 4).

V. Examples of Simulations of Selected Multi-Pulse Rectifiers in Accordance with Concept of MEA

Exemplary computer simulations of selected multi-pulse (12-, 24-, and 48-) pulse rectifiers were performed in a Matlab/Simulink programming environment, whose primary purpose was to determine the voltage waveforms obtained at the output of 12-, 24-, and 48-pulse rectifiers. Essential tests were performed for electrical systems with RL load. Values of magnitudes that represent the load on the measuring systems (electronic equipment with which aircraft are equipped) have been selected to reflect the actual operating conditions.

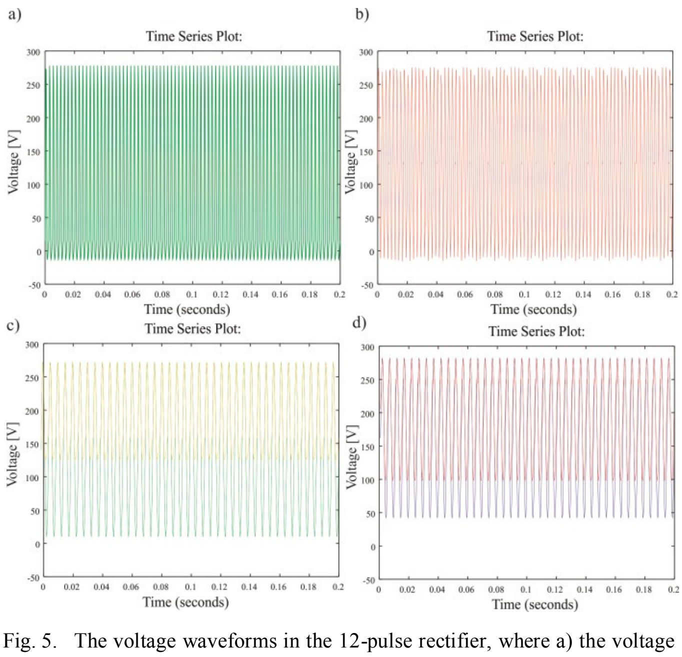

Fig. 5. The voltage waveforms in the 12-pulse rectifier, where a) the voltage at the input of the rectifier at a load R = 100Ω, and L = 0.01H; b) the voltage at the input of the rectifier at a load R = 1000Ω and L = 0.02H; c) the voltage at the output of the 12-pulse rectifier with R = 100Ω, and L = 0.01H; d) the voltage at the output of the 12-pulse rectifier with R = 1000Ω and L = 0.02H

The studies in the Matlab/Simulink development environment were conducted for two different loads. The first step of the analysis was done with the assumption R = 100Ω and 0.01H. On the other hand, the second part of the simulations was carried out for technical parameters of R = 1000Ω and L = 0.02H respectively. Figs. 5 to 7 illustrate the waveforms of the mains voltage and current taken from the mains at the joint of the multi-pulse inverter and the additive voltage of the individual phases of 3-phase voltage, i.e. phase A, B and C, in the case of the activated electrical load on the side of the mains of the aircraft in line with the MEA concept.

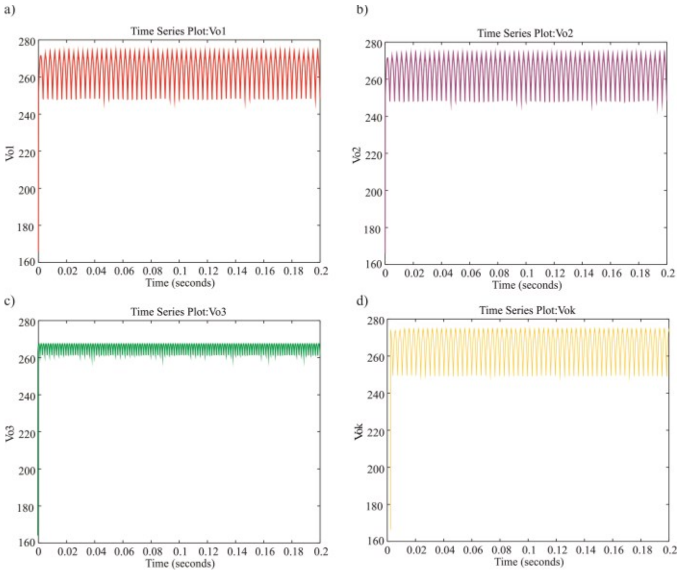

Fig. 6. Waveforms of AC voltage at the output of 24-pulse rectifier, where a) A - first harmonic; b) B - a second component; c) C - third harmonic; d) the total voltage waveform at the output of 24-pulse rectifier (sum of a + b + c)

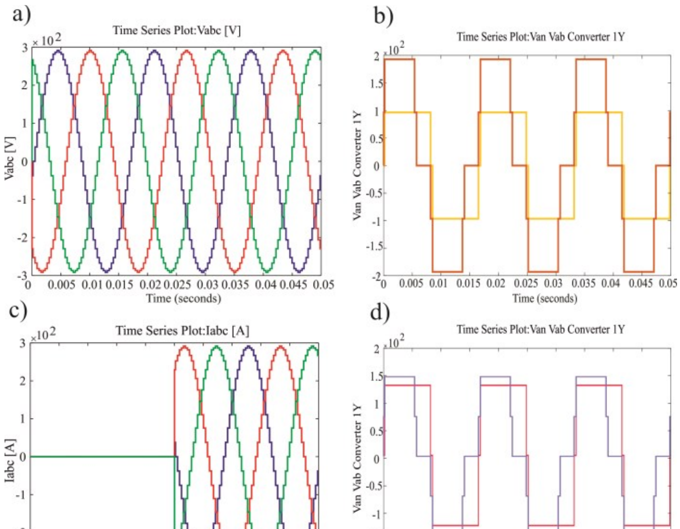

Fig. 7. a) and c) Voltage and current waveform at the output of a 48-pulse rectifier in three-phase mains; b) and d) phase-to-phase voltage waveform in the rectifier at the Y connection for the angle of $7{,}5^0$ and 30^0

In addition, it should be noted that an electric system with a load of RL can simultaneously provide a filtration system. The main purpose of the filter module is to compensate for the impact of the wreckage and to raise the mains voltage at the load, and the appropriate control of the active filtration system is required to obtain the correct shape and amplitude of the current introduced through the phase-to-phase rectifier. It should also be noted that when the filter is switched on, there may be high frequency oscillations in the waveforms of both the current and the voltages of the on-board network. Elimination of these oscillations requires the development of advanced control methods, and the selection of the optimal transformer gearbox can provide a reduction in the voltage or currents of the filter depending on the application used.

Based on the analysis of the above drawings we can observe that the current drawn from the mains supply is sufficiently close to the sinusoidally variable waveform. In the current paper the authors attempted to highlight the influence of the deformation of the supply voltage on the work of the comparable 12-, 24- and 48-pulse systems. In a 12-pulse system, the correct operation occurs only with purely sinusoidal supply, the deformation of the supply voltage not only results in an increase in the total THD in the straight-up voltage, but above all the emergence of a predominant harmonic up to 6, including the voltage at the most unfavorable variant of the supply voltage.

In turn, in the 24-pulse system, 24 harmonic in the straight-up voltage dominates (predominates) only when powering the rectifier transformer with purely sinusoidal voltage. The zigzag system works properly both in parallel and in serial-to-parallel connection of rectifiers, with a ripple coefficient of straightened-up voltage THD is negligible and reaches only a few percent. In addition, the deformation of the supply voltage by the variants accepted in the calculations causes the harmonic up to 6 to be several dozen times higher than the harmonic 24, which means that the system operates as a 6-pulse. The most spectacular effect of deformed supply voltage is shown in Fig. 6.

IV. CONCLUSIONS

In the time waveform of the current and the voltage taken from the power source for the rectifiers circuit (12-, 24- and 48-) impulse practically no harmonic occur and if it comes to that, they are strongly suppressed (Figs. 6a to 6b). The presented simulated results performed in Matlab/Simulink program show high efficiency and close to oneness power factor.

In addition, simulation studies have shown that increasing the number of steps by means of a modulator causes 12-pulse systems to show the properties of (24- and 48-) pulse systems, which explains the lesser effect of the rectifier on the mains. The conducted simulations of the electrical system with load showed a significant improvement in the shape of the mains current, approximating its waveform to the sinusoidal.

Analysis of the results of the simulated tests confirmed that the systems responsible for converting the three-phase voltage in the electrical network of the aircraft are operating properly and the resulting time waveforms are sufficiently close to the theoretical results [6], [17]. Therefore, three-phase 12-, 24- and 48-pulse rectifiers can be used in any three-phase voltage system, both with neutral wire and without neutral wire. In addition, the output voltage shows very low ripple (compared to bridge rectifiers). Energy of power sources is used to the greatest extent, which is especially important for high power devices such as advanced power supply systems of the aircraft [18], [19]. The various types of rectifier systems discussed in the article can be used wherever the power output of the device is smoothly regulated, and therefore also in the case of a more electric aircraft. In addition, they provide a significant reduction in the level of higher harmonics in the supply voltage waveforms with minor potential interference from the other electronic components of the rectifier circuit.

REFERENCES

[1] I. Moir, A. Seabridge, "Design and Development of Aircraft Systems," Second Edition, John Wiley & Sons, Ltd., 2013.

[2] L. Setlak and R. Kowalik, "Mathematical modeling and simulation of selected components on-board autonomous power supply system (ASE), in accordance with the concept of a more electric aircraft (MEA)," 18th International Scientific Conference on Electric Power Engineering (EPE), Kouty nad Desnou, Czech Republic, pp. 1-6, IEEE 2017.

[3] Haitham Abu-Rub, M. Malinowski, K. Al-Haddad, "Power Electronics for Renewable Energy Systems," Transportation, and Industrial Applications, First Edition, John Wiley & Sons Ltd., 2014.

[4] K. Emandi, M. Ehsani, "Aircraft power systems: technology state of the art, and the future trends," Aerospace and Electronic Systems Magazine, IEEE, 2000.

[5] I. Moir, A. Seabridge, "Aircraft Systems: Mechanical, Electrical, and Avionics Subsystems Integration," Third Edition, John Wiley & Sons, Ltd., 2008.

[6] L. Setlak, E. Ruda, "Review, Analysis and Simulation of Advanced Technology Solutions in Power Electronics Systems (PES) of More Electric Aircraft," World Academy of Science, Engineering and Technology, Vol: 9, No: 10, 2015.

[7] B. Singh, S. Gairola, B.N. Singh, A. Chandra, and K.A. Haddad, "Multi-pulse AC-DC Converter for Improving Power Quality: A Review IEEE Transactions," On Power Delivery, Vol. 23, No. 1, January 2008.

[8] S. Raghuvanshi, N. Singh, "Comparative analysis of 36, 48, 60 pulse AC-DC Controlled Multipulse Converter for Harmonic Mitigation," International Journal of Advanced Research in Computer Engineering & Technology (IJARCET), Volume 3, Issue 4, April 2014.

[9] G. Gong, U. Drofenik, J.W. Kolar, "12-Pulse Rectifier for More Electric Aircraft Applications," ETH Zurich, Power Electronic Systems Laboratory, ICIT 2003.

[10] S. Bozhko, T. Wu, Y. Tao, and A. G.M, "More-Electric Aircraft Electrical Power System Accelerated Functional Modeling," in International Power Electronics and Motion Control Conference, Ohrid, Republc of Macedonia, 2010.

[11] A. Hernadi, T. Taufik, and Anwari M., Modeling and Simulation of 6-Pulse and 12-Pulse Rectifiers under Balanced and Unbalanced Conditions with Impacts to Input Current Harmonic," Second Asia International Conference on Modelling & Simulation, 2008.

[12] Wu B., "High-Power Converters and AC Drives," IEEE Press, John Wiley & Sons, Inc., Publication 2006.

[13] A.O. Monroy, H. Le-Huy, C. Lavoie, "Modeling and Simulation of a 24-pulse Transformer Rectifier Unit for More Electric Aircraft Power System:, Electrical Systems for Aircraft, Railway and Ship Propulsion (ESARS)," 2012.

[14] A.O. Monroy, H. Le-Huy, C. Lavoie, "Modeling and Simulation of a 24-pulse Transformer Rectifier Unit for More Electric Aircraft Power System:, Electrical Systems for Aircraft," Railway and Ship Propulsion (ESARS), 2012.

[15] M.S. El-Moursi, A.M. Sharaf, "Novel Controllers for the 48-Pulse VSC STATCOM and SSSC for Voltage Regulation and Reactive Power Compensation," IEEE Transactions On Power Systems, Vol. 20, No. 4, November 2005.

[16] K-N. Areerak, S.V. Bozhko, G.M. Asher, and D.W.P. Thomas, "Stability Analysis and Modelling of AC-DC System with Mixed Load Using DQ-Transformation Method," Cambridge, UK, 29 June-2 July, pp. 19-24, 2008.

[17] L. Setlak, R. Kowalik, "Review, comparative analysis and simulation of selected components of modern power systems (EPS, PES) of 'classical' aircraft and 'More/All Electric Aircraft' (MEA/AEA)," WSEAS Transactions on Power Systems, Volume 11, 2016.

[18] Z. Yang, J. Qu, J. Ma, and X. Shi, "Modeling and Simulation of Power Distribution System in More Electric Aircraft," Hindawi Publishing Corporation, Journal of Electrical and Computer Engineering Volume, Article ID 847624, 7 pages, 2015.

[19] Vinod Vashram Vadher, "Mathematical Modelling of Aircraft Electrical Power Systems", Doctoral Thesis, Loughborough University of Technology 1981.