Study of Multi-Pulse Rectifiers of the PES System in Accordance with the Concept of a More Electric Aircraft

LUCJAN SETLAK, RAFAŁ KOWALIK, WOJCIECH REDO
Department of Avionics and Control Systems
Polish Air Force Academy
ul. Dywizjonu 303 nr 35, 08-521 Deblin
POLAND
l.setlak@wsosp.pl, r.kowalik@wsosp.pl, w.redo@wsosp.pl, http://www.wsosp.pl/index.php/pl/

Abstract— The subject of this paper is to conduct the testing process of multi-pulse rectifiers (6-, 12- and 18-, 24-) impulse of energo-electronic power supply system in terms of the on-board electrical energy power processing of the aircraft (analysis, mathematical model, simulations) in accordance with more and more the growing "more-electric" trend of modern advanced aircrafts. The above trend is referred to in the literature of the subject of research as the concept of "more electric aircraft" or "more electric technology". The primary goal of the paper is to create a transducer model implemented in aviation, i.e. the one that can be considered for use, both on civil aircraft of aviation corporations (Airbus, Boeing) in terms of their hit products (A-380 and A-350XWB, B-787), as well as on military aircraft of the Lockheed Martin corporation (JSF F-35 and F-22 Raptor) compatible with the concept of a partially/fully electric aircraft. Based on the above considerations, in the final part of the paper based on the conducted simulations of selected multi-pulse rectifiers, the simulation processes performed in the Matlab/Simulink program were made and practical conclusions were drawn on this basis.

Key-Words: - study, energo-electronic power supply systems, multi-pulse rectifiers, more/all electric aircraft

1 Introduction

In modern aviation (civilian, military) the trend of increasing dynamics of change is observable in the field of autonomous onboard power supply. It is dictated, among others, by a more and more widely developed concept of a more/all electric aircraft (MEA/AEA), reduced fuel consumption, limitation of emissions of harmful substances due to the ECS (Environmental Control System), improved equipment reliability, easier maintenance, reduced operating costs and thus increased flight safety, etc.

This trend is noticeable primarily in advanced aviation, both in the field of civil aviation (Airbus, Boeing) in the case of aircraft (A-380 and A-350XWB, B-787), as well as in the case of military aviation (Lockheed Martin) in the field of JSF (Joint Strike Fighter) F-35 and F-22 Raptor aircraft. The increasing dynamics of changes in the demand for more electricity (power) exerts a key influence on the dynamically developing concept of a more electric aircraft, including in particular, the dominant role of advanced systems in the production or processing of AC voltage and their main components (rectifiers, converters, etc.), as well as the EPS (Electric Power System) in terms of DC (generator or generators, integrated starter/generator unit, transformer-rectifying devices acting as secondary sources, accumulators as emergency or back-up sources, which are energy storage, super-capacitors, fuel cells, etc.).

Referring to the selected problems of this paper, directly related to the field of energo-electronics in the context of modern energo-electronic power systems PES (Power Electronics Systems) it should be noted that key components of the PES system, i.e. energo-electronic transducers and their basic components, such as multi-pulse rectifiers (6-, 12- and 18-, 24-) impulse, are included in the so-called on-board autonomous electric power systems (ASE). The main component of these systems are power electronics systems (PES) which are among the most important systems, in addition to EPS systems [1], [2].

The preliminary analysis performed in this area in the scope of the dominant role of onboard AC power supply showed that in the case of the power network of modern aircraft, it is based primarily on the 400 Hz increased constant frequency (CF) generator (in the case of "conventional" aircraft) and variable frequency (VF), containing in the range of 390-780 [Hz] (in the case of "More Electric" aircraft).

The on-board power supply network of advanced aircraft according to the new trend, which is the

"More Electric" concept can be based on the power source in the form of a permanent magnet synchronous machine (PMSM) or on an integrated unit in the form of the AC starter/generator VFSG (Variable Frequency Starter Generator), an example of which, together with the main subsystems of an on-board autonomous power supply system ASE, is presented below (Figure 1) [3].

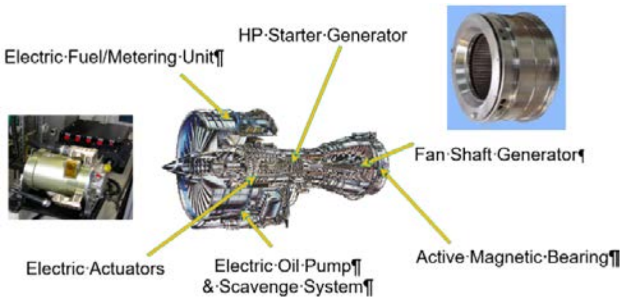

Fig. 1 Example of an integrated synchronous unit motor/3-phase VFSG in the field of a more electric engine (MEE)

The key components of the on-board ASE supply system of modern advanced aircrafts in the PES system in the context of the predominant role of AC power sources are versions of energo-electronic transducers (6-, 12- and 18-, 24-) impulse, which include converters converting electricity AC/DC and DC/DC, are subject to detailed analysis and also subject of research in this article.

2 Analysis of Multi-Pulse Rectifiers in the Field of the PES System in Line with the Concept of MEA/AEA

Electric network of advanced on-board autonomous power supply systems ASE (EPS, PES) of modern aircrafts both civil Airbus (A-380, A-350XWB) and Boeing (B-787), as well as military Lockheed Martin (JSF F-35, F-22 Raptor) is compatible with the concept of partly/all electric aircraft (MEA/AEA). In view of the above, it is necessary to ensure, among others appropriate voltage and DC current of the autonomous power supply system ASE, including in particular in the field of power supply system PES and its main components (rectifiers, autotransformers, etc.) required for the proper operation of electronic equipment, which modern aircraft is equipped with of key aviation companies (Airbus, Boeing, Lockheed Martin) [4], [5].

This type of function in most cases is implemented by the rectifying systems ATRU (Auto Transformer Rectifier Unit) and TRU (Transformer Rectifier Unit), which are based on the configuration of multi-pulse rectifiers (12-, 24- or 48-) impulse. The operation of the rectifier circuits takes place in conditions in which the values of basic parameters (voltage, current) obtained at their outputs are not sufficiently controlled. This phenomenon may result in failure or incorrect operation of the on-board equipment components. This effect can be minimized, among others by using a choke of appropriate inductivity, which will translate into a voltage balance obtained at the output of the multi-pulse rectifier. In a situation where the DC voltage values of both rectifying circuits are equal (in the case of a 12-pulse rectifier), then we deal with the so-called "Transparency" of a system converting AC voltage and current into DC current [6].

In addition, due to the used rectifier (12-, 24- or 48-) impulse system, the converter system has a high content of voltage and current harmonics, so that on the AC side of the AC appropriate filtering systems should be used. Then the filters will only transmit harmonics with the appropriate amplitude value defined in the transformer system. Additionally, it should be noted that voltages and alternating currents AC generated by transformer in a Y-Y-Δ system reach (enter) the input of the rectifier circuit. In the ASE on-board autonomous power system in the scope of the PES system of an advanced aircraft compatible with the concept of a more electric aircraft, the main component responsible for the conversion of AC current and voltage into their fixed counterparts are rectifier circuits. The number of diodes used in the system depends on the efficiency of elimination of undesirable harmonic signals entering the output system of the rectifier. 12- and 24-pulse circuits are most commonly used in aviation.

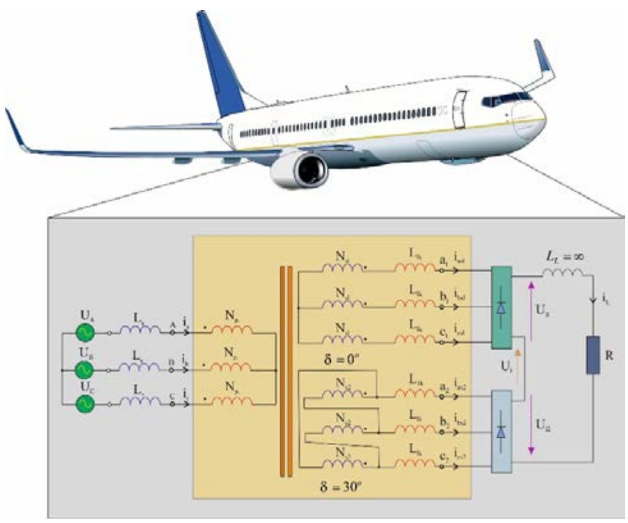

Fig. 2 Block diagram of a 12-pulse rectifier used in the transformer-rectifier TRU [9]

It should be remembered that AC voltage and AC current from a three-phase generator, acting as the main power source on board of a modern aircrafts, is fed into the rectifier circuit input. This means that instead of a single winding for a single pulse for each phase, it is possible to reduce the total number of turns by increasing the number of diodes in the system. The following figure (Fig. 2) presents a typical block diagram of a three-phase rectifier, used in electric networks of modern airplane [7], [8].

When analyzing the transformer-rectifier device (rectifier) of TRU, which is used in aviation, it should be noted that the TRU device retains the properties of a two-half rectifier. In addition, it has special features that are depicted below:

- the middle tap of the transformer winding (or the point of connection of two identical windings) is connected to the mass of the system,
- due to the fact that for each half-period of the transformer's voltage, the current flows only through one diode: the loss of the output voltage caused by the voltage drop on the diode is half as high (i.e. such as for a one-half system),
- this arrangement is not better than the bridge one, because the resistance of the secondary winding increases twice,
- with C filter the voltage at each diode is equal to 2 U_m, so remember to choose diodes with a sufficiently large allowable shut-off voltage.

Independent operation of the units in a bridge connection is ensured by diodes. The output alternating current component of individual systems does not exceed 4%. The value of this current results from the value of the magnetizing current.

The following is a mathematical description of physical phenomena occurring in a 12-pulse rectifier. Assuming that individual harmonics of voltage are shaped by the angle $\frac{2\pi}{3}$, and each diode in the system works based on the established sequence, e.g. 12, 23, 34, 45, 56, 61, hence the value of the DC voltage at the output of the rectifier system is described by the following dependence:

$$U_{DC} = \frac{1}{T}\int_0^T u_L(t)dt \tag{1}$$

where u_L is the voltage value, determined taking into account the load (electronic equipment of the aircraft switched on), U_{DC} constant voltage at the output of the rectifier system.

In view of the above, the average value of the voltage with the load switched on can be written as:

$$U_L = \sqrt{\frac{1}{T}\int_0^T u_L{}^2(t)dt} \tag{2}$$

where U_L is the load voltage.

In turn, the current in the rectifying system can be represented by the expression [10]:

$$i_L(t) = \frac{u_L(t)}{R_L}$$

$$I_{DC} = \frac{U_{DC}}{R_L} \tag{3}$$

$$I_L = \frac{U_L}{R_L}$$

where I_L is the mean value of the current flowing through the load elements (resistive), and I_{DC} is the value of direct current at the output of the rectifier.

Based on the presented mathematical relations, voltage and current values were determined in the 12-pulse rectifier for angle-shaped harmonic signal $\frac{2\pi}{3}$ [11], [12].

$$\begin{aligned} U_{DC} &= \frac{1}{T}\int_0^T u_L(t)dt \\ &= \frac{6}{2\pi}\int_{\frac{\pi}{3}}^{\frac{2\pi}{3}} \sqrt{3}\,U_m \sin(\omega t)dt \\ &= \frac{3\sqrt{3}}{\pi} = 1.654 \cdot U_m \end{aligned}$$

$$\begin{aligned} U_L &= \sqrt{\frac{1}{T}\int_0^T u_L{}^2(t)dt} \\ &= \sqrt{\frac{9}{\pi}\int_{\frac{\pi}{3}}^{\frac{2\pi}{3}} U_m^2 sin^2\,(\omega t)dt} \\ &= 1.655 \cdot U_m \end{aligned} \tag{4}$$

The current values are as follows [13], [14, [15]:

$$I_{DC} = \frac{\sqrt{3}U_m}{R_L}\sqrt{\frac{2}{\pi}\left(\frac{\pi}{6}+\frac{\sqrt{3}}{4}\right)}$$

$$I_L = \frac{\sqrt{3}U_m}{R_L}\sqrt{\frac{1}{\pi}\left(\frac{\pi}{6}+\frac{\sqrt{3}}{4}\right)} \tag{5}$$

The AC voltage and current waveforms supplied to the 12-pulse rectifier are shown in the figures below (Figs. 3-4).

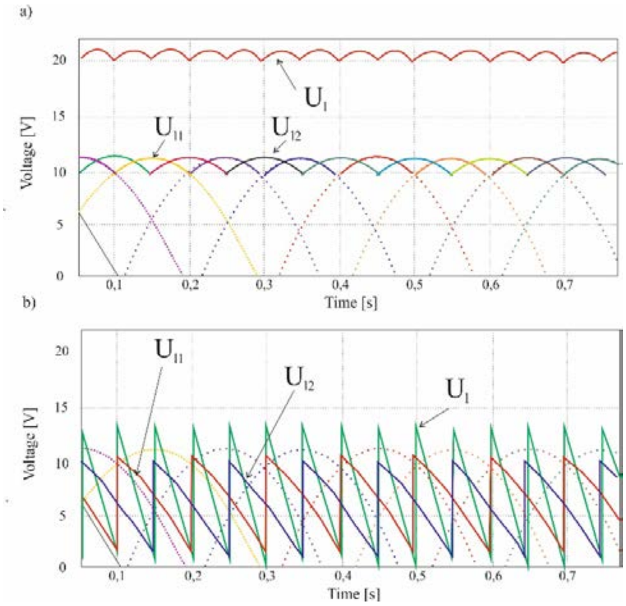

Fig. 3 Harmonics of AC voltage and current in the TRU rectifier system

The voltage and three-phase AC waveforms presented in Fig. 3 and Fig. 4 supplied to the rectifying system, responsible for transforming the magnitude into their DC equivalents, are characterized by only the change of the phase shift of individual harmonics. This applies to both voltage and current waveforms, on the basis of which we can see uniform shifts of individual harmonic signals by an angle of 30°. In addition, from the analysis of individual charts, one can also conclude that there is no change in the amplitude of the voltage signals and currents, which remains at a fixed level despite making changes in the load of the rectification system used on modern aircrafts.

The curve marked in red is the current flowing through the capacitor diode. The output voltage waveform $U_{wy}(t)$ is marked with green. Analyzing the individual waveforms illustrated in the above figure, we can see the between-peak rate ripple value *"U_{tpp}"* on it. In addition, it can be seen from the analysis of the output voltage waveform that the discharging time of the capacitor is much longer than the charging time, so even with low resistance loads (high load current) the capacitor will be largely discharged and there will be high ripple values at the output.

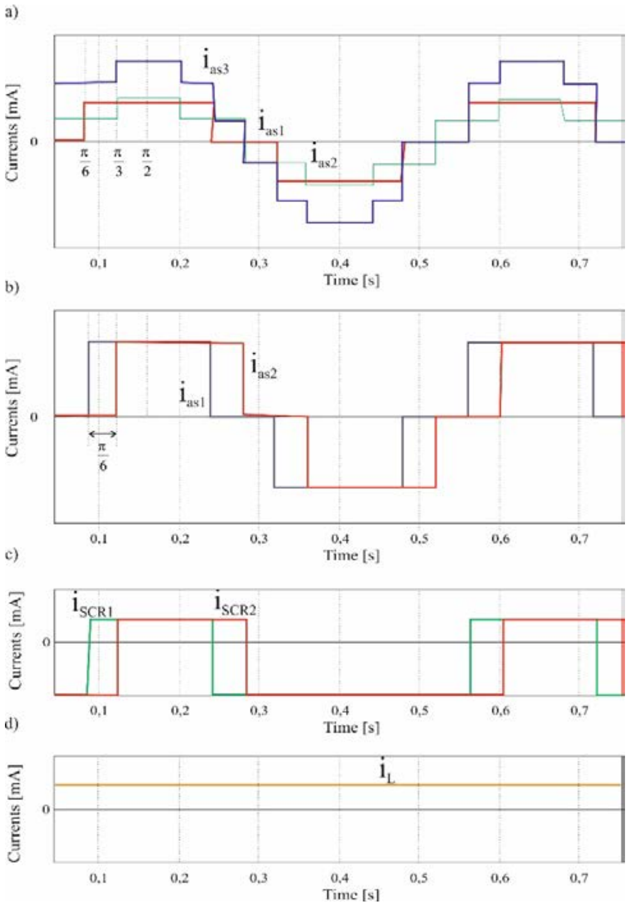

Fig. 4 Harmonics of AC currents in the TRU rectifier system after the AC/DC conversion process

In turn, the one-half rectifier system can be used only where there are small load currents and where they do not play a significant role of ripple output voltage. The mean values of voltage and current at the output of the rectifying system were marked in blue.

3 Mathematical Model of Harmonics Removal in the Rectifier System

Mathematical analysis describing the process of elimination of distortion of harmonic signals from voltage and AC currents in a rectifier system should be considered in two ranges of transformer operation generating voltage and alternating current in three different phases - 30 and + 30 degrees.

The block diagram for which mathematical considerations were performed is shown in the figure below (Fig. 5).

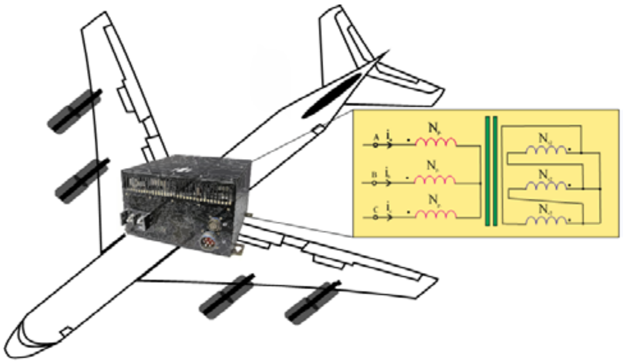

Fig. 5 Block diagram of the AC power supply system in the TRU rectifier system

$$i_{1a} = I\left[\cos(\omega t) - \frac{1}{5}\cos 5(\omega t) + \frac{1}{7}\cos 7(\omega t) - \frac{1}{11}\cos 11(\omega t) + \frac{1}{13}\cos 13(\omega t) - \cdots\right]$$

$$i_{1c} = I\left[\cos(\omega t + 120°) - \frac{1}{5}\cos 5(\omega t + 120°) + \frac{1}{7}\cos 7(\omega t + 120°) - \frac{1}{11}\cos 11(\omega t + 120°) + \frac{1}{13}\cos 13(\omega t + 120°)\right] \quad (6)$$

where I is the value of the AC current amplitude supplied to the rectifier circuit input.

In the case when the winding coefficient of the autotransformer is $\frac{1}{\sqrt{3}}$ then a Fourier series for quality i_{2a_ph} *and* i_{2c_ph} by [16]

$$i_{2a\_ph} = \frac{I}{\sqrt{3}}\left[\cos(\omega t) - \frac{1}{5}\cos 5(\omega t) + \frac{1}{7}\cos 7(\omega t) - \frac{1}{11}\cos 11(\omega t) + \frac{1}{13}\cos 13(\omega t) - \cdots\right], \quad (7)$$

$$i_{2a\_ph} = \frac{I}{\sqrt{3}}\left[\cos(\omega t + 120°) - \frac{1}{5}\cos 5(\omega t + 120°) + \frac{1}{7}\cos 7(\omega t + 120°) - \frac{1}{11}\cos 11(\omega t + 120°) + \frac{1}{13}\cos 13(\omega t + 120°)\right]$$

Hence the Fourier series for i_{2a} was defined as

$$i_{2a} = i_{2a\_ph} - i_{2c\_ph} = I\left[\cos(\omega t - 30°) - \frac{1}{5}\cos 5(\omega t + 30°) + \frac{1}{7}\cos 7(\omega t - 30°) - \frac{1}{11}\cos 11(\omega t + 30°) + \frac{1}{13}\cos 13(\omega t - 30°)\right]$$

(8)

$$i_{2a\_ph} = \frac{I}{\sqrt{3}}\left[\cos(\omega t + 120°) - \frac{1}{5}\cos 5(\omega t + 120°) + \frac{1}{7}\cos 7(\omega t + 120°) - \frac{1}{11}\cos 11(\omega t + 120°) + \frac{1}{13}\cos 13(\omega t + 120°)\right]$$

In the next stage of the mathematical analysis, derivations were made describing the process of removing distortion in harmonic AC current waveforms for a 12-pulse rectifier. The mathematical notation of the Fourier series for current i_{as1} is determined by [17]

$$i_{as1} = 1{,}1I_L\left[\cos(\omega t) - \frac{1}{5}\cos 5(\omega t) + \frac{1}{7}\cos 7(\omega t) - \frac{1}{11}\cos 11(\omega t) + \frac{1}{13}\cos 13(\omega t) - \cdots\right], \quad (9)$$

For the current determination i_{as2}, you can save:

$$i_{as1} = 1{,}1I_L\left[\cos(\omega t - 30°) - \frac{1}{5}\cos 5(\omega t * -30°) + \frac{1}{7}\cos 7(\omega t - 30°) - \frac{1}{11}\cos 11(\omega t - 30°) + \frac{1}{13}\cos 13(\omega t - 30°) - \cdots\right], \quad (10)$$

Assuming that the voltage ratio at the transformer terminals is $\frac{V_{AB}}{V_{a1b1}} = \frac{V_{AB}}{V_{a2b2}} = 2$, hence the current expressed in equation (3) can be represented as [18], [19]

$$i_{as1}{}' = \frac{1{,}1I_L}{2}\left[\cos(\omega t) - \frac{1}{5}\cos 5(\omega t) + \frac{1}{7}\cos 7(\omega t) - \frac{1}{11}\cos 11(\omega t) + \frac{1}{13}\cos 13(\omega t) - \cdots\right] \quad (11)$$

And current i_{as2}

$$i_{as2}{}' = \frac{1{,}1I_L}{2}\left[\cos[(\omega t - 30°) + 30°] + -\frac{1}{5}\cos[5(\omega t - 30°) + 30°] + \frac{1}{7}\cos[7(\omega t - 30°) + 30°] - \frac{1}{11}\cos[11(\omega t - 30°) + 30°] + \frac{1}{13}\cos[13(\omega t - 30°) + 30°] - \cdots\right], \quad (12)$$

Then, taking into account the equations (5) and (6), you can determine the total current i_a in the 12-pulse rectifier system:

$$i_A = i_{as1}{}' + i_{as2}{}' = 1{,}1I_L\left[\cos(\omega t) - \frac{1}{11}\cos 11(\omega t) + \frac{1}{13}\cos 13(\omega t) - \frac{1}{23}\cos 23(\omega t) - + \cdots\right] \quad (13)$$

Hence, the 5, 7, 17 and 19 harmonics in the AC current are equal to zero, and harmonics 11 is the lowest.

4 Results of Selected Simulations of the Multi-Pulse Rectifiers in the Field of PES System According to MEA/AEA Trend

Based on the analysis and simulation tests performed on the exemplary 12-pulse multi-pulse rectifier, the simulation study results presented below were obtained (Figs. 6-8).

The most important task in modeling the rectifier system in the Matlab/Simulink programming environment is the correct selection of the transformer, which must take into account many factors affecting the operation of the PSU (power supply unit), which include, among others:

- acceptable range of mains voltage changes, that is 230V ± 10%,
- voltage drop on the rectifier,
- output voltage loss, resulting from the influence of internal resistance of transformer windings,
- the output power of the PSU and power losses on individual elements of the PSU.

To fully understand the significance of the internal resistance R_w of the transformer, it is best to analyze an example comparing the work of a transformer loaded with load resistance R_l and the work of the transformer in the power supply system with two-half rectification, loaded with the same resistance R_l (Fig. 5).

In addition, the internal resistance of the R_w transformer affects the key parameters of the rectifier system, which among others include:

- drop of transformer output voltage under load,
- peak diode conduction current in the PSU system, and what is connected with it, also on the value of diode voltage drop.

In the proposed simulation model, it was assumed that the capacitor, resistor and coil were assumed to be the load.

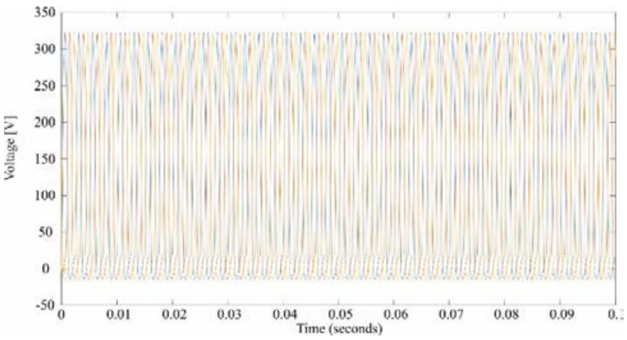

Fig. 6 Voltage waveforms generated at a different starting angle $\delta = 0^\circ$

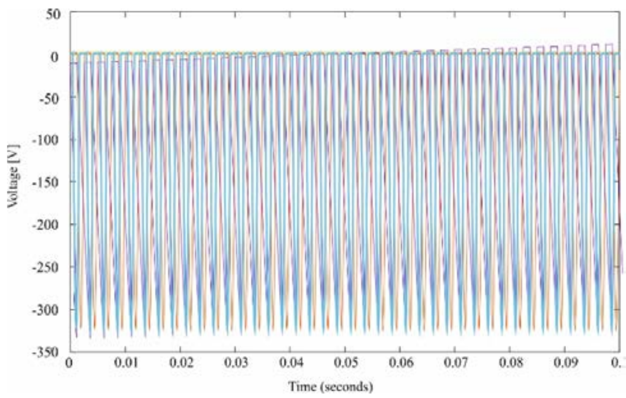

Fig. 7 Voltage waveforms generated at a different starting angle $\delta = 30^\circ$

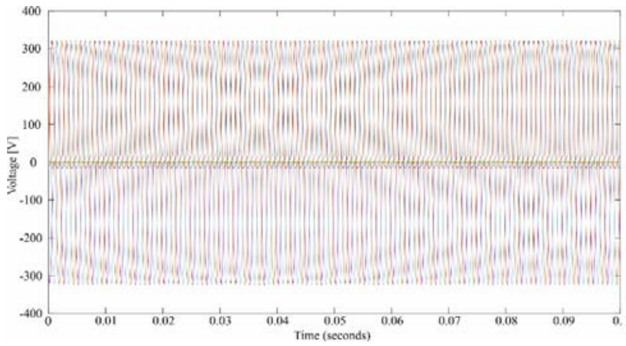

Fig. 8 Voltage waveforms generated at a different starting angle $\delta = 60^\circ$

Figures 6-8 show the oscillograms of voltages and currents recorded during the tests. The diagrams show sinusoidal waveforms of voltages and currents. During this research, the engine was powered via an inductive controller from the power network (frequency 400 Hz) and directly from a three-phase synchronous generator (frequency 400 Hz).

The obtained results were presented as oscillograms of voltages and currents supplying the 12-pulse rectifier system (supply network voltage and current absorbed by the system) as well as the engine voltage and the current drawn by the engine. Voltages supplying the inverter have a sinusoidal shape - it is the shape of the three-phase network voltage, while the voltage supplying the engine has a distorted waveform. The current consumed by the power electronic converter has the distorted (impulse) shape figure 5.

In addition, figures 6-8 show the content of higher harmonics in voltage and current waveforms with a sinusoidal supply. Based on the analysis, we can observe a small, less than 1% amplitude value 5 of the harmonic of the supply voltage and also a low content of 5, 7 harmonics of the supply current (engine current).

The obtained simulation results indicate that the voltage and current values obtained at the DC rectifier circuit output can be used in the process of optimization of systems in the scope of AC/DC/DC processing. In addition, the choice of TRU rectifier system parameters (number of diodes in the system) will allow for hastening of the design process of the automatic generator adjustment system installed in the onboard electrical network of advanced aircraft (Airbus, Boeing, Lockheed Martin) developed in accordance with the concept of a more electric aircraft MEA/AEA [20], [21].

In the case where the transformer works with the rectifier in the same way as depicted in the above figure (Fig. 2), the operation of the rectifier system is as follows.

In this system, current I that flows out from the transformer is not only dependent on the load R_l, but also on the output resistance of the transformer R_w. Additionally, this current only flows in a short time interval and appears when the voltage on the discharging capacitor drops (decreases) so much that the instantaneous voltage of the transformer will be greater than the capacitor voltage by a voltage drop across the two diodes of the bridge rectifier (approx. $2 \times 0{,}7$V) to allow conduction of the bridge. Then the capacitor will be charged with the current impulse (compare Fig. 3b from Fig. 3).

As can be observed on the waveforms, the value of the current I charging capacitor is much higher than for the first one (Fig. 3). With such a large current value flowing through the secondary winding of the transformer, the voltage drop on the internal resistance is much higher than in the basic system. Therefore, a higher current causes a significant drop in the output voltage of the transformer (green line in Fig. 4).

It would seem that it is better to use "rigid" transformers (with low resistance of windings), but this in turn will cause more current flowing through the rectifier bridge, causing an increase in voltage drop on the conducting diodes (even twice). For typical LEDs from the 1N4001 ... 1N4007 family, this will mean increasing the voltage drop from 0.7V (even 1V at 1A) to approx. 1.5V, which for the Graetz bridge system will provide a reduction of the output voltage of the PSU even by 3V in relation to the input voltage.

5 Conclusion

The presented results of simulation tests confirm positive features of the analyzed 12-pulse rectifier system in terms of the increase of the output voltage and energy efficiency of the system. In addition, they also confirm the possibility of improving the shape of the current drawn from electrical network of the aircraft in a certain range, depending on its inductance. It should be noted, however, that the effect of this inductance on the resonance frequency of the auxiliary circuit for the flow of the third harmonic of the current requires a precise selection of the inductance of the filtering main rectifier, which is a major disadvantage of this solution. In the absence of information about the inductance value of the electricity network, optimal design of the system for the most favorable current distortion factor is difficult.

The loading of the rectifier with a capacitive filter causes a significant increase in the amplitudes of the primary harmonic and the first two higher harmonics in the phase current of the power source. At a continuous current of the receiver there is the phenomenon of current commutation between the valves of the sequentially conducting phases, resulting from the presence of inductance in the alternating current circuit (inductance of the transformer's dissipation and the supply line). The commutation taking place in time corresponding to the commutation angle μ causes the reduction of the average value of the output voltage. Knowledge of the commutation angle is an important issue in the case of inverter rectifier operation at angles approaching 180^o.

Additionally, 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 [22], [23]. 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 multi-pulse rectifier circuit.

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 [24]. Therefore, three-phase 12-, 24- and even 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).

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