Advanced Technological Solutions of Key Components of Variable Frequency of Power Supply System ASE of Modern Aircraft in Accordance with the Concept of a More Electric Aircraft MEA

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***Abstract*—The subject of the paper, and thus its objective is to provide innovative solutions in the field of advanced power systems ASE (EPS, PES) of modern aircraft, both the civil aviation (*Airbus, Boeing*) for airplanes (A-380 and A-350XWB, B-787), as well as in relation to the military aviation (*Lockheed Martin*) in the field of the JSF aircraft (*Joint Strike Fighter*) F-35 and F-22 Raptor, which are the domain of advanced aircraft in line with the trend of more electric aircraft. The study analyzes these solutions by creating a mathematical model of selected components (source of electric power, control and regulating equipment, etc.) of variable frequency VF (*Variable Frequency*) of on-board power system, and their exemplary simulations were performed. In the final part of the paper, based on the results of the above considerations, obtained through studies (analysis, simulation) and practical conclusions in the implementation to the advanced aviation technology power supply systems of variable frequency in accordance with the evolving trend of more electric aircraft were presented.**

***Index Terms*—technological solutions, variable frequency, board autonomous power supply system (ASE), more electric aircraft (MEA)**

I. Introduction

In the advanced architecture of the power system of onboard system of modern civil (*Airbus, Boeing*) and military (*Lockheed Martin*), in accordance with the concept of more electric aircraft, a key role is played by the ASE system (EPS PES), based on the components of variable frequency, which are the source of power in the form of a variable frequency generator VFG (*Variable Frequency Generator*) or the integrated unit starter/ AS synchronous generator/ G VF (*Alternating Starter/ Generator of Variable Frequency*) [1], [2]. The proposed in the article solution, due primarily to the simplicity of the architecture of the power system brings many advantages such as low cost of electricity generation, low failure rate, maintenance-free, and greater opportunities for the allocation and distribution of electricity to a greater number of target devices.

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That type of solution, in terms of power, was applied among others in civil aircraft (A-380 and A-350XWB, B-787) and military JSF F-35 and F-22 Raptor. The essence of this type of power system is the change of frequency, which depends on the shaft rotation speed of the electric machine. The scope of the change of frequency has the range of 380 to 720 [Hz]. This system by eliminating the constant rotation speed, has the ability to deliver (transfer) electricity in different voltage ranges, and alternating currents AC [3], [4]. In the most modern solutions in line with the trend of MEA/ AEA, electricity source (generator) is used for the proper functioning of various systems, including anti-icing system, cabin pressurisation, start the drive unit, etc. In the case of use of the system with variable frequency VF (*Variable Frequency*), this energy can be delivered directly to the receivers. The waveforms of the main parameters (voltage, current) are selected by changing the frequency to meet all the requirements necessary to maintain the continuity of work of end equipment (receivers). The overall structure of the system of variable frequency VF is shown in the figure below (Fig. 1).

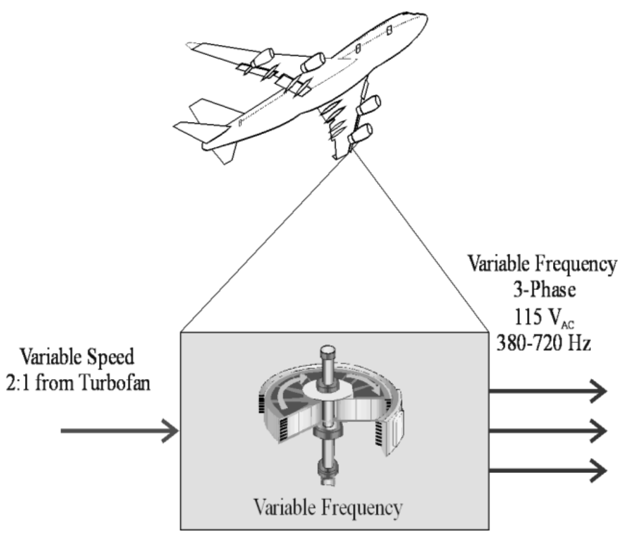

Fig. 1. The general structure of VF power system

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Generator acquires the power needed to start electric machine with mechanical powertrain, which is the turbine engine. Based on the above, it can be assumed that the power system of VF type in the near future, according to the concept of MEA/ AEA, will be the leading system in terms of power of onboard electrical networks of modern aircraft. The basic components of the system may include a main source in the form of brushless generator based on permanent magnets PMSG (*Permanent Magnet Synchronous Generator*) and systems of power electronic converters (inverters) and converters which transform the size of the voltage and AC to DC power [5], [6], [7]. The generator obtains necessary power to boot the electric machine from the motor drive unit, which is the turbine engine and the converter system is responsible for changing the variable frequency VF to constant CF to 400 [Hz]. The figure below (Fig. 2) illustrates a block diagram showing the system of variable frequency VF.

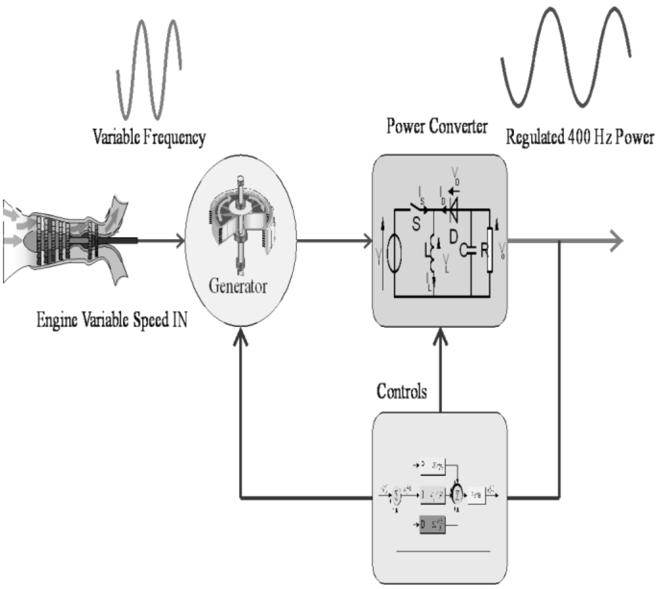

Fig. 2. The scheme of VF power system

In the following sections of the paper mathematical models of selected ASE system components will be analyzed, describing electrical phenomena, occurring in the power system of variable frequency. Moreover, a structure and operation of the VF system will be presented and the concept of the power system in accordance with the concept of a more electric aircraft (MEA) will be proposed based on the examples of solutions used for civil aircraft.

II. Analysis and Mathematical Model of Advanced Technology Solutions of Selected Components of ASE Variable Frequency System According to MEA Concept

A. Analysis of the Modern Technology Solutions of the ASE Power Supply System on the basis of the Variable Frequency Generator VF

In proposed technological solution based on the variable frequency generator, which acts as the primary source on board of a modern aircraft in accordance with the latest trends of (MEA/ AEA), the rotational speed of the electric motor is variable in time and the individual harmonics of AC voltages are derived from a reference frequency of 360- 800 [Hz] with an output voltage of 200 [V].

Furthermore, it should be noted that the variable frequency generator is one of the simplest forms of electricity generation, and at the same time the cheapest and most reliable. In addition, the variable frequency VF of harmonic voltages exerts a significant influence on the other subsystems on board of the aircraft and improves the performance of controllers. The diagram below (Fig. 3) shows the simplest way to produce variable frequency VF.

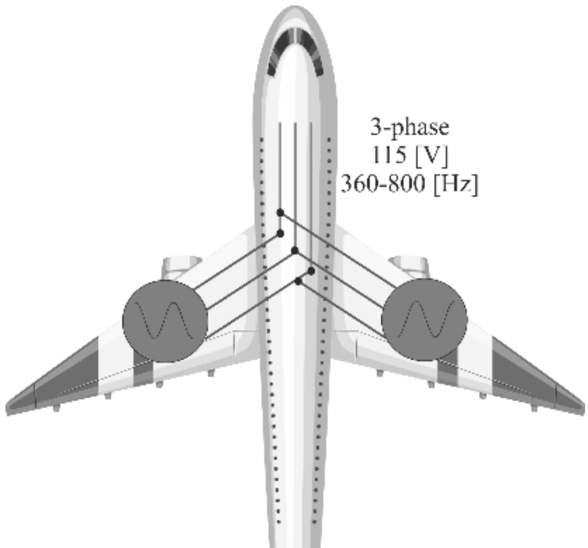

Fig. 3. The illustrative system for producing variable frequency of VF system

Electricity in onboard autonomous power supply system ASE (EPS, PES) based on VF system is generated due to the variable frequency produced by a generator of variable frequency VFG and the frequency range of harmonic signals of AC voltage will change in proportion to the rotational speed of the rotor of electric drive. Transmission of 3- phase voltage is carried out through two feed rails (right and left VFG). The next figure (Fig. 4) shows the method for transmitting variable frequency voltage signals VF.

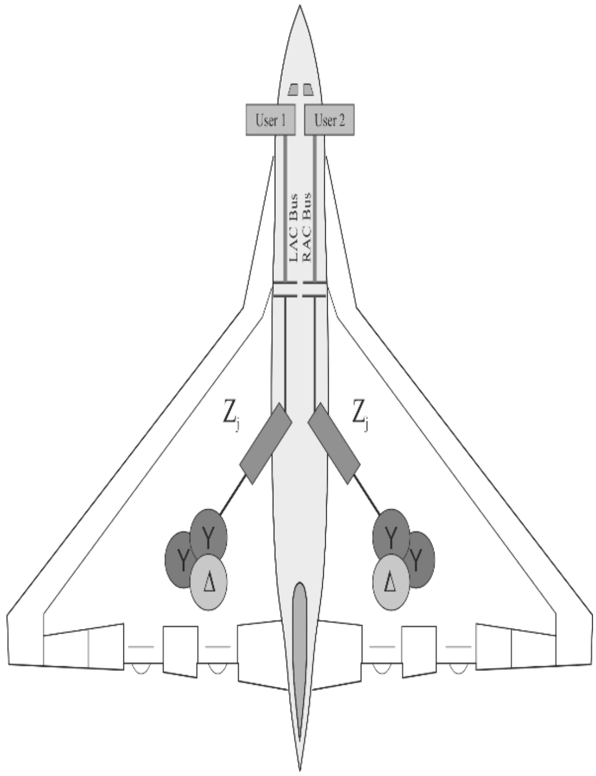

Fig. 4. The illustrative system of harmonic signals transfer of 3- phase voltage current generated by the VF

Where: Z_f- is the total impedance of the electrical system of VF for each power rail; X_f- this is the reactance of the VF system and VF, and R_f- is the resistance of the VF circuit.
In turn, the figure below (Fig. 5) shows the methods of power supply using a 3- phase network in the on-board ASE electrical system of a more electric aircraft.

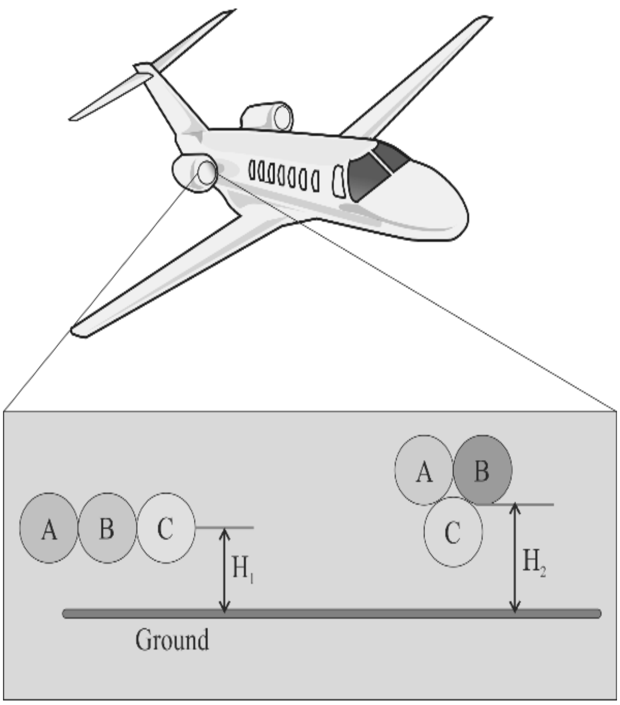

Fig. 5. The illustrative system of signal transmission in VF system in two possible combinations

During the design process of the power supply of modern aircraft, consistent with the trend of MEA/ AEA, you should pay special attention to the energy performance of all key components (devices, systems, components, parts, etc.), included in a comprehensive on-board autonomous power supply system in the field of EPS system and the PES system. This will allow you to get the best performance and the efficiency of the power supply of each component, which are the aircraft equipment. In addition, you should also remember that the main power bus, responsible for the transmission of voltages and currents of 3- phase should have a very high resistivity. Additionally, at this stage, the appropriate configuration and placement of the supply cables for the target receiver systems is essential.

B. Mathematical Model of Variable Frequency Generator

By following the mathematical description of the physical phenomena occurring in the electric machine process, which is responsible for the production of variable frequency harmonics, the first step is to define the motor for the placement of permanent magnets in the coordinate system in the context of polarization of *d* and *q*. Subsequently, taking into account the complexity of the mathematical model in the case of three-phase motor, powered by AC voltage, it has been simplified that mathematical analysis will be carried out in a similar fashion to DC. Therefore, during the process of deriving mathematical equations the principle of magnetic field balancing should be observed in the electrical circuit, and to take into account the lack of variability of the power values of the signals produced by the electric machine both before and after the transformation of the permanent magnet position in the defined coordinate system. During the operation of the electric motor, the permanent magnets in the center rotate at constant angular velocity.

Taking into account the above, the process that takes place during the generation of voltage signals inside an electrical machine in a particular coordinate system whose center is at the center of the permanent magnet *d-q* can be described by the following equations [8], [9]:

$$\begin{aligned} u_{ds} &= R_s i_{ds} + \frac{d\psi_{ds}}{dt} - \omega_e \psi_{qs} \\ u_{qs} &= R_s i_{qs} + \frac{d\psi_{qs}}{dt} - \omega_e \psi_{ds} \\ u_{dr} &= R_r i_{dr} + \frac{d\psi_{dr}}{dt} - (\omega_e - \omega_r)\psi_{qr} \\ u_{qr} &= R_r i_{qr} + \frac{d\psi_{qr}}{dt} - (\omega_e - \omega_r)\psi_{dr} \end{aligned} \tag{1}$$

Where: R_s and R_r- denote the resistance of the stator and the rotor respectively; ω_e- angular velocity of the electric motor; in turn, ω_r- defines the angular velocity of the rotor. In the state of short circuit in the electric motor on the rotor element the condition $u_{dr} - u_{qr} = 0$ is fulfilled.
Equations of magnetic flux in the motor circuit with permanent magnets in the coordinate system *d-q* can be written as [10]:

$$\begin{aligned} \psi_{qs} &= L_s i_{qs} + L_m i_{qr} \\ \psi_{ds} &= L_s i_{ds} + L_m i_{dr} \\ \psi_{qr} &= L_r i_{qr} + L_m i_{qs} \\ \psi_{dr} &= L_r i_{dr} + L_m i_{ds} \end{aligned} \tag{2}$$

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Where: L_m - is the mutual inductance between the stator windings and the rotor in the *d-q* system; L_s - stator inductance; L_r - rotor inductance.
The moment in the coordinate system *d-q* is described by the equation:

$$T_e = n_p L_m \left(i_{qs} i_{dr} - i_{ds} i_{qr} \right) \quad (3)$$

In the case when the rotor is rotating synchronously (at the same speed), the conditions $\psi_{dr} = \psi_r$ and $\psi_{qr} = 0$, occur, hence, the moment can be presented as follows:

$$T_e = n_p \frac{L_m}{L_r} \left(i_{qs} \psi_{dr} \right) \quad (4)$$

Where: n_p - defines a pair of poles of permanent magnets of the electric motor.
Apart from the friction between the rotor and the stator and taking into account the changing situation in the created electromagnetic field inside the electric drive, you can define the motion equation in the following form:

$$T_e = T_L + \frac{J}{n_p} \frac{d\omega_r}{dt} \quad (5)$$

Where: T_L - is the moment of the load, and J – moment of the inertia of the system.

III. Results of Simulation Research of Selected Components of Advanced Technology Solutions of Variable Frequency System According to MEA Concept

Using mathematical equations and block diagrams of the VF system, a model of VF system was developed in the programming environment of Matlab/ Simulink (Fig. 6). The proposed block diagram assumes that the rotation speed of the electric motor shaft ranged between 1300 - 1400 [r/min].

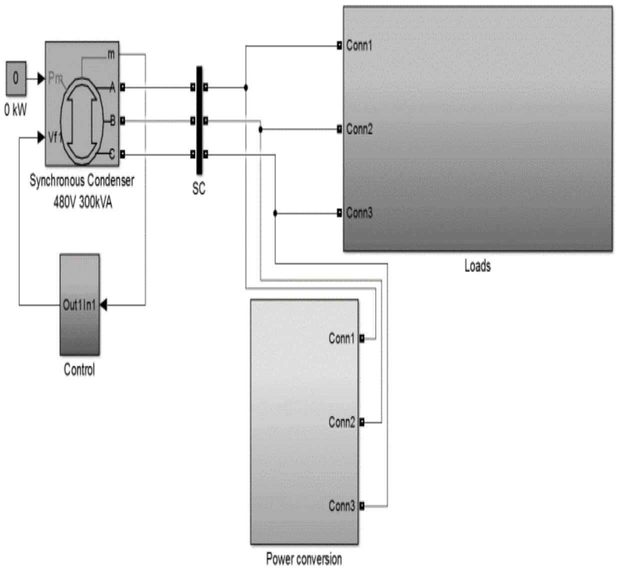

Fig. 6. Block diagram of the VF power system in Matlab/ Simulink

Production of voltage in the VF system was performed for three different frequencies 300, 350, 400, and 450 [Hz]. The basic parameters for which observations of designed system were made are voltage and AC waveforms received at the VF system output, as shown in the graphs below (Fig. 7-8).

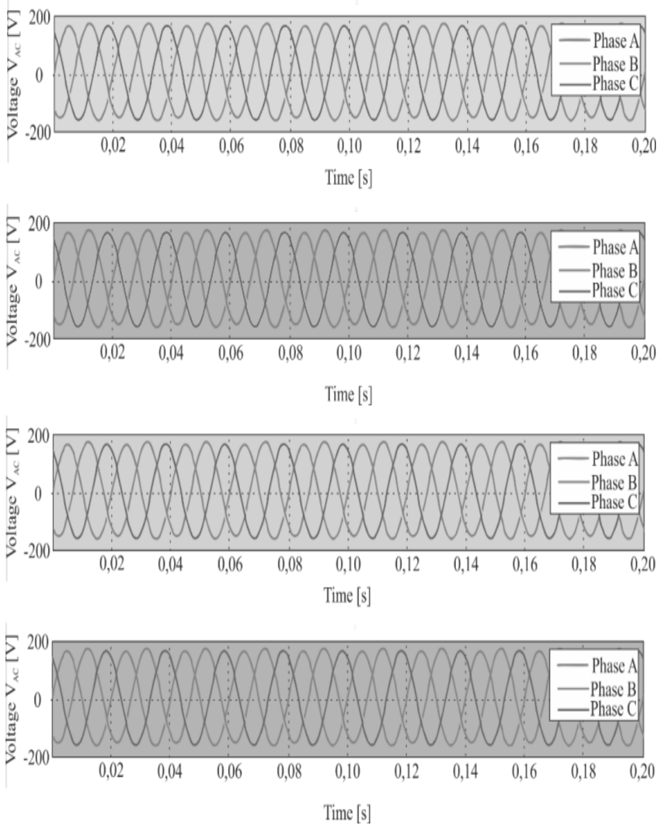

Fig. 7. Three-phase voltage waveform at the output of four different frequencies a) 300 [Hz], b) 350 [Hz], c) 400 [Hz], and d) 450 [Hz]

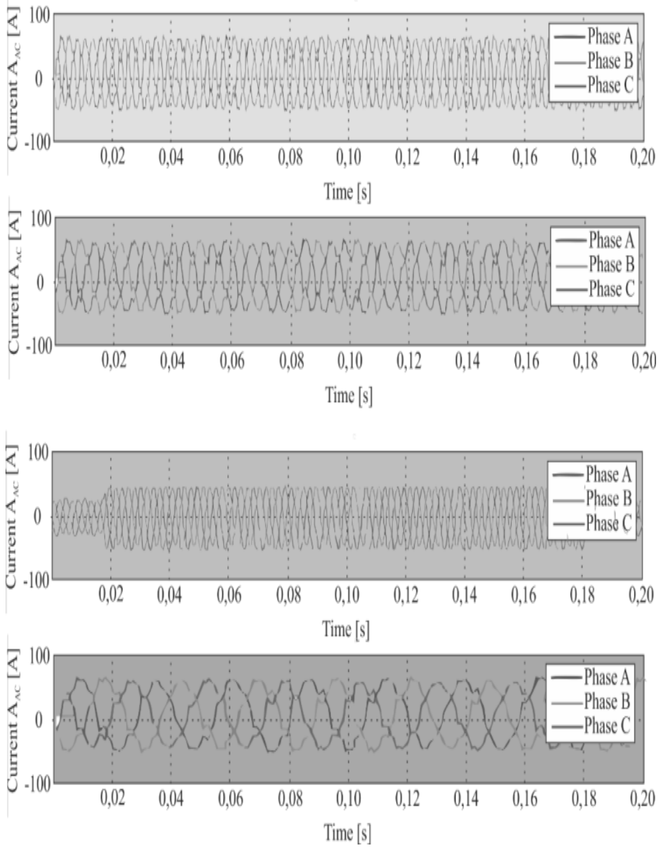

Fig. 8. Three-phase current waveform at the output of four different frequencies a) 300 [Hz], b) 350 [Hz], c) 400 [Hz], and d) 450 [Hz]

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From the graphs shown above (Figs. 7-8), it can be seen that it is produced by the main three-phase alternating current AC source of AC variable frequency VF sinusoidal voltage signal for individual harmonics shifted by a phase angle in the range from 0 to 60^o, then further alternating voltage signals are generated with phase shift in the range of 60^o to 120^o.

It should be noted that the whole process was carried out for different frequency ranges produced in the loop, namely for frequencies: 300 [Hz], 350 [Hz], 400 [Hz] and 450 [Hz]. In addition, the adopted concept of the system allows the generation of additional frequencies at the VF variable frequency system output.

Visible AC voltage waveforms for each phase A, B and C in all analyzed characteristics are slightly distorted. This is due both to the lack of (disappearance) of rotational speed control as well as to the phenomenon of saturation of the core in the electrical machine EM (*Electrical Machine*). In addition, the harmonic distortion of the AC voltage for the three phases is also influenced by the frequency generated by the VF variable frequency system itself and by the value of the supply voltage of the unit responsible for the process of shaping (forming) the frequency. Also, you should remember that the frequency change process (throughout its range) depends on the rotor speed of the electrical machine.

In the analyzed system the decisive influence on the obtained values of the AC voltage is the value of the magnetizing current occurring in the electrical machine. The presented VF system concept also allows for significant, and also very important savings in terms of the quality of electricity produced by the power units, it also allows for more efficient use of electricity by controllers for its distribution and transmission to the on-board target elements of a modern aircraft. Distortion (disorder) in AC harmonic voltage in the VF system can be eliminated or possibly lowered by using an appropriate LC low-pass filter combination to smooth the current amperage and voltage change.

In addition, the various stages of generating variable frequency signals can be controlled by a PWM (*Pulse-Width Modulation*) inverter, a method of adjusting the current or voltage signal, with fixed parameters (amplitude, frequency), which consists in changing the signal fill according to the rule that as the rotor speed rises, the frequency rises.

In conclusion, both the essence of the presented in this article solution, as well as its main advantage, is the invariability of the power emitted (transmitted) in the individual harmonics of AC voltage. On the other hand, undoubtedly the disadvantage of the VF system in question is the distortion of the AC voltage waveforms at the very beginning of the VF unit startup due to the occurrence of vortex currents in the electrical machine, which adversely affect the efficiency of the electrical equipment.

IV. Conclusion

The paper presents the results obtained from carried out simulations in the Matlab/ Simulink programming environment in terms of the variable frequency EPS power supply system of modern aircraft in accordance with the concept of more electric aircraft MEA show that the proposed solutions in the ASE (EPS, PES) autonomous power supply systems contribute to significant improvements in the quality of the electricity supplied and have the ability to expand existing electrical systems with new modules that manage the flow and accumulation of electricity. On the basis of graphs depicting the waveform of the AC voltage (Fig. 7-8) it can be seen that the frequency change slightly affects the shape of a sine wave and amplitude. Furthermore, the phase shifts for each signal of the AC to a particular frequency are the same.

In other words, the basic parameters of the waveform in the form of amplitude and duration remain constant values for the individual harmonics of voltage and the period of the sinusoidal wave. On the other hand, for an AC waveform at the output of the system, it shows a marked change of frequency of the terminal signals. In addition, we see that the phase shifts for the signal generated in the range 300 - 400 [Hz] are different. Based on the above it can be concluded from the set of numerical simulation, that it is possible to generate an AC voltage of 115V AC nominal value which is contained in the working range of the variable frequency power system VF, comprising in the range of 108 - 120V AC.

In addition, it is important to note that the key advantage of the variable frequency VF system being considered is the short duration of the short circuit in the generator current circuit, which results in better rectifier performance. Another very significant advantage of the VF variable frequency system is the low short-circuit current level in the electrical machine, which is illustrated in the individual graphs (Fig. 7-8).

Another positive effect resulting from the use of the generator as the main on-board source responsible for sending signals with variable frequency are the benefits that affect the mass of the system along with all the equipment of the modern aircraft. This is primarily due to the higher level of the induced power value of the generator. In addition, it should be remembered that all harmonic voltages generated by the generator are mutually synchronous, as can be seen from the analysis in the previous subsections of the article, including in particular, based on the results obtained from the simulations. This solution substantially improved the reliability of the on-board power supply system of the aircraft.

In addition, based on the analysis undertaken, mathematical considerations and review of available studies in the literature [11], [12], [13] dedicated to key components of ASE system in the subject of research, in the final version of the paper a model of the selected component in terms of EPS and PES system will be developed in accordance with the concept of a more electric aircraft.

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