THE ARCHITECTURE OF THE ON-BOARD POWER SYSTEM OF A MORE ELECTRIC AIRCRAFT

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Resume

Currently, various systems and devices for on-board equipment of modern aircraft are undergoing extensive transformations, particularly in terms of powering electrified aircraft. The main goal of authors of this article was to conduct an analysis of the selected electrified aircraft architecture in the scope of the HVDC system, among architectures in the 540 V voltage range (± 270 VDC) and 350 V, creating a mathematical model and making the necessary tests and simulation studies on the developed model. In the above aspect, article presents selected test results of a proposed system consisting of aircraft generators with changing speeds, which power the bidirectional transistor converters operating in parallel. On the other hand, the energy, generated by generators equipped with a rectifier systems feeds a 0.4/15 kV booster transformer operating at idle. In the final part of the work, based on simulation studies (analysis, mathematical model, tests), important insights are presented and practical conclusions are formulated.

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1 Introduction

Nowadays, modern planes are primarily designed in a context that takes into account the longest possible crossing of distances between various points located on the globe, hence in recent years a new trend has appeared to increase the efficiency and effectiveness of on-board electric systems of the most advanced aircrafts.

Additionally, taking into account the number of innovative avionics systems, including radio receivers on board of a modern aircraft, there was a need to increase the power of the classic electrical network of the aircraft, which in turn resulted in significant energy consumption, including in particular in the field of more/all electric aircraft MEA/AEA (More/All Electric Aircraft). Taking into account the requirements for the production of more useful power by on-board sources of the aircraft's electrical network, the standard of the more electric aircraft MEA/AEA was developed, which is now being implemented to an increasing number of constructed aircrafts [1-3].

In the design process, the main factor determining the efficiency of the developed standard was dictated primarily by improving the operational reliability of on-board electrical equipment, which in turn led to increased reliability of the entire aircraft. In conclusion, the concept of MEA has proven its worth in the following factors: efficiency of the entire aircraft, increase in its reliability and reduction in fuel consumption, and thus reduced the operating costs, as well [4-6].

In addition, the flexibility and economy of the aircraft have increased. The main power components that significantly affect the operation of the electricity network in accordance with the MEA trend are on-board sources in the form of synchronous permanent magnet generators PMSG (Permanent Magnets Synchronous Generator), switchable reluctance starters/generators SR S/G (Synchronous Reluctance Starter/Generator) by using a starter/generator unit, powered by voltage of 270 VDC and AS S/G (Alternating Synchronous Starter/Generator).

The above on-board power sources are the key components of an autonomous system for generation, division and distribution of electricity. The complete electricity generating system, in accordance with the concept of a more electric aircraft, consists of: constant speed drive CSD (Constant Speed Drive), integrated drive generator IDG (Integrated Drive Generator) and a component responsible for producing constant rotational speed at variable frequency VSCF (Variable Speed Constant Frequency). Analyzing individual power generation systems, it should be noted that the VSCF system is characterized by greater efficiency compared to the CSD/IDG system, because the subunits associated with the VSCF system can be deployed in various places on the aircraft as opposed to the CSD/IDG system, where its mechanical elements, including the electro-hydraulic transmission must be close to the engine [7-8].

In addition, in the event of a power system failure, replacement or repair in the case of the VSCF system is problem-free, which translates into proper maintenance of the electrical network operation during the flight. The electrical network of the aircraft requires the supply of DC and alternating AC; therefore, it is necessary to use devices that convert AC voltage and AC current into DC values. Usually, passive rectifiers, made of semiconductor diodes or active switching elements, such as thyristors, are most often used. Both elements generate additional harmonic signals, which reduce the efficiency of the generator. Undesired signals, in the form of harmonics, can be eliminated by using the passive filters or active filters [9-10].

This paper presents a complete simulation model, mapping the actual on-board electrical network model in the field of power electronics systems PES (Power Electronics Systems) meeting the requirements of the more electric aircraft (MEA/AEA) concept.

The simulation model was created for advanced aircraft power supply systems in the scope of on-board power source (generator), performing work based on the method of creating rotational speed and variable frequency of the VSCF system. The output power of the on-board electricity network is 90 kVA per transmission channel of the power supply network (in aircraft compliant with the MEA there are two) [11-12].

In the developed model, it was assumed that experimental tests will be carried out for various combinations of end devices (the so-called loads), alternating AC and direct DC. In the case of avionic systems supplied with DC current, it should be remembered to maintain a constant value of useful power and continuous maintenance of DC current.

The undesirable harmonic signals and noise appearing in the system were eliminated by using a high-pass filter HPF (High-pass Filter), which was placed behind the generator system [13-15].

2 Analysis and mathematical model of selected components of the on-board power system architecture according to the concept of a more electric aircraft

By entering the analysis process and creating a mathematical description (model) of selected key components of the on-board autonomous power system, in accordance with the MEA trend, it should be noted that the basic elements of the considered system are the generator or integrated starter/generator unit in the scope of the EPS system and alternating current converter to direct current AC/DC for the PES system.

In addition, in the case of analyzing on-board electro-energetic networks of modern aircraft, two types of AC networks should be considered. The first of these is a network based on an alternating current AC generator with a fixed (stabilized) frequency of 400 Hz (in the case of conventional aircraft) or on an integrated unit in the form of an AC starter/generator with variable (non-stabilized frequency) of 360-900 Hz (in the case of electrified aircraft), which changes at a speed proportional to the angular velocity of the main engine shaft.

Additionally, it should be added that the above type of electro-energetic power network is usually based on a 3-phase 200 V network (classic civil and military aircraft) and a 3-phase 115 V network (Airbus) or 230 V network (Boeing), for advanced civil and military aircraft compatible with the MEA concept.

The second type of network is the electro-energetic power network based on electromechanical or electronic converters requiring, due to their design solution, high frequency and voltage [16-18].

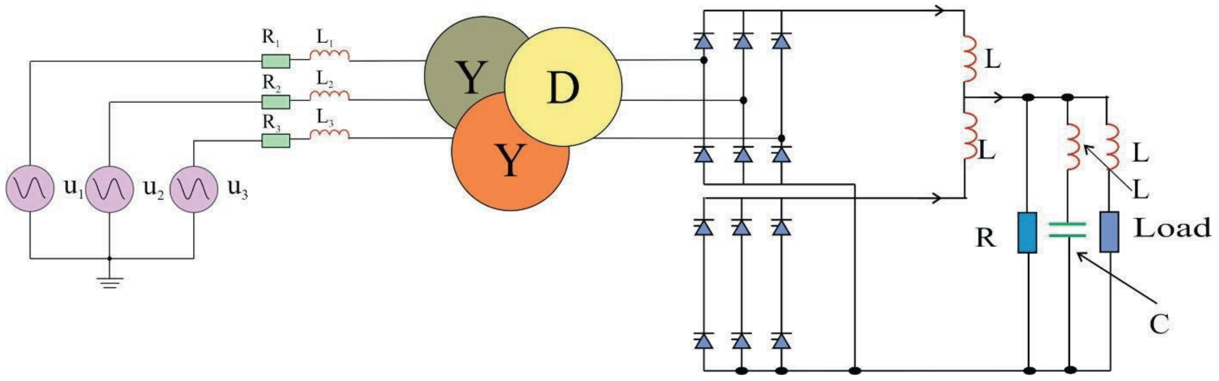

***Figure 1** A block diagram of a TRU system using a 12-pulse rectifier*

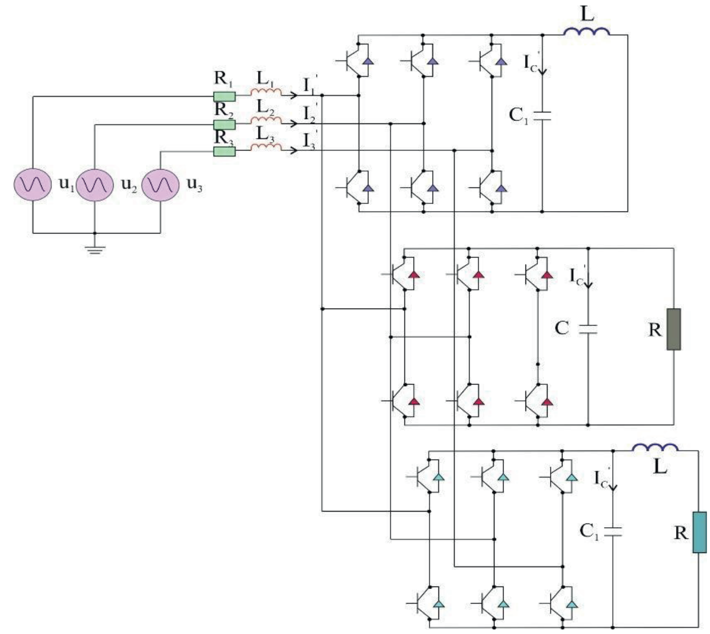

***Figure 2** Method of controlling the DC voltage for different types of loads*

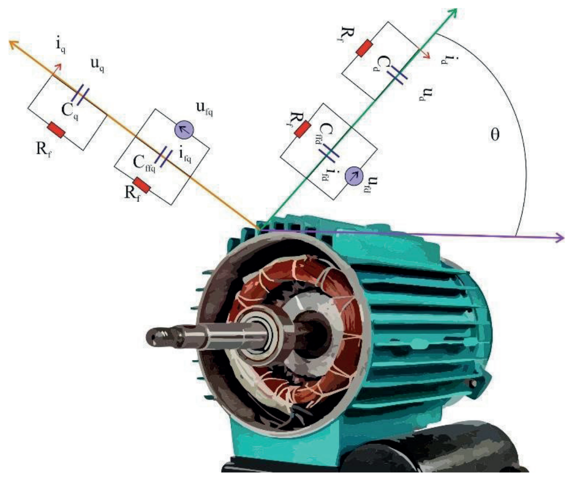

***Figure 3** Block diagram of the generator with an additional electrical circuit*

2.1 Analysis of on-board power sources in accordance with the MEA/AEA concept

The complete airplane power system includes an internal combustion engine, an electric starter and various types of generators, which are treated as integrated drive units. In addition to the specified components, responsible for the process of electricity generation and conversion, there is also a rectifier unit, useful power controllers, pneumatic actuators, anti-icing systems and various elements of systems and subsystems, having an indirect impact on the operation of the aircraft's on-board electrical network.

The general block diagram of the on-board electricity network in the scope of the PES system, compatible with the MEA concept, is shown in the Figure 1.

Subsequently in the analysis, it should be noted that due to switching on the start-up system, the AC voltage and current generation process is performed, which are then converted into DC values. This system is characterized by maintaining the final power at the output of the generating system. In the next range, an electric engine, operating in the variable rotational speed range provides the required value of the input power to the generator.

This operation is carried out as a result of maintaining a constant value of the rotational speed at the output of the generator. The output voltage, obtained at the PMSG synchronous generator output, is shaped by a frequency in the range from 400 to 800 Hz.

The main components, responsible for implementation of the AC conversion operations into DC current, are multi-pulse rectifier circuits in the form of 6-, 12- and 24-pulse rectifiers. The simulation tests used a rectifier built of 12 semiconductor diodes. In total, all the components in the system form transformer-rectifier devices in the form of TRU (Transformer Rectifier Unit), the general diagram of which for different types of loads is shown in Figure 2 [19-22].

The TRU system is characterized by a high power factor, with minimal distortion of harmonic voltage and current signals THD (Total Harmonic Distortion) at 13%. As a result, power losses occurring in the rectifier are negligible. Furthermore, the rectifier circuit is supplied through a three-phase transformer connected in the star-star-delta *Y/Y/D* configuration (Figure 1).

The method of connecting the transformer ensures supplying the voltage shifted in phase by an angle of 30° for the 12-pulse rectifier. The output voltage on the TRU rectifier (270 VDC) is regulated by the generator current and the electromagnetic field generated by the generator by means of the feedback proportional controller PI (Proportional-Integral Controller).

The capacitor, present in the rectifier system, serves to smooth the DC end voltage. All the types of loads supplied with DC current are connected to an adjustable 270 VDC power bus through special DC/DC converters, which is illustrated in the Figure 3.

In simulation tests, it was assumed that the maximum DC load value is 5.6 [kW], and the voltage transfer process is controlled by the PI controller. All the DC/DC converters in the system are of a conventional type, which are based on IGBT (Insulated Gate Bipolar Transistor) elements [23-26].

2.2 A mathematical model of AC/DC conversion for different positions of permanent magnets of an electric machine

The structure of the on-board autonomous power system architecture, compatible with the MEA concept in the mathematical modelling process, was considered in the form of a simplified model, which includes key components responsible for generating the on-board electricity, i.e. a PMSG (Permanent Magnet Synchronous Generator) and a rectifier system responsible for the conversion process of alternating voltage AC to direct DC, which in the aviation application is transformer-rectifier unit TRU (Transformer Rectifier Unit).

The basic component, subjected to the analysis, is the arrangement and position of the rotor in the stator at the moment of shaping the magnetic field. The stator circuits are considered to be a system of two axes through which electric current flows. The components responsible for generating the magnetic field were modelled by appropriate connection of resistive and capacitive elements. Thanks to this approach, the proposed solution significantly improves the efficiency of the entire system, control of the useful and reactive power balance, as well as effectively performs the power division operation, depending on the current load on board of the modern aircraft.

In addition, a system for dividing and distributing electricity, together with AC/DC converters, allows more freedom in the field of more efficient power control in AC and DC circuits. This process is expressed based on the equations presented later in this article. The presented model takes into account the direct relationship between the sides of AC and DC, responsible for AC voltage and AC power generation, as well as the DC voltage and current [27-28].

In the mathematical analysis process, the assumption was made that the electric generator would be treated as a synchronous machine with permanent magnets of an arcuate shape. This type of construction is referred to as SMPMSG (Surface Mounted Permanent Magnet Synchronous Generator). The analyzed generator uses permanent magnets with rare earth dopants, NdFeB type (very strong neodymium magnets) [29-30].

These magnets are mounted on the inner side of the rotor yoke, which simultaneously acts as the hull of an external generator. The number of magnetic poles of the generator was determined in the design process in accordance with the mathematical expression $2p = 40$. In addition, in order to further simplify the design of the synchronous generator, it was assumed that in the stator winding the number of grooves per pole and phase was equal to $q = 1$. The nominal frequency of the generator is $f_N = 400$ Hz, as a typical frequency in aerospace applications.

The rotor is supplied with the DC voltage, which generates a specific electric field, responsible for induction of electric charge in the circuit. The intensity of the electric field, and the rotational speed occurring in the electrical machine PMSM (Permanent Magnet Synchronous Machine), are expressed in terms of the capacitance of the capacitor in the DC circuit.

The following figure shows a block diagram of the analyzed synchronous generator with a defined electric circuit based on permanent magnets. For the electric circuit, the current equation in the synchronous generator stator circuit can be represented as:

$$\begin{aligned} i_d &= \frac{dQ_d}{dt} - Q_q \frac{d\theta}{dt} - \frac{u_d}{R}, \\ i_q &= \frac{dQ_q}{dt} - Q_d \frac{d\theta}{dt} - \frac{u_q}{R}, \\ i_0 &= \frac{dQ_0}{dt} - \frac{u_d}{R}, \end{aligned} \tag{1}$$

where: i_d, i_q, i_0 are the current in the axes d, q and 0, respectively, Qd, Qq are the electric charge present in the electric circuit in the axes d, q and 0, respectively and R is the resistance included in the generator electrical circuit.

In addition, the parameters u_d, u_q, u_0- determine the voltage values in the stator circuit. The sizes with the lower index f refer to the electric field appearing in the analyzed system. The electric charge flowing in the electric circuit of the synchronous generator at any time is determined b:

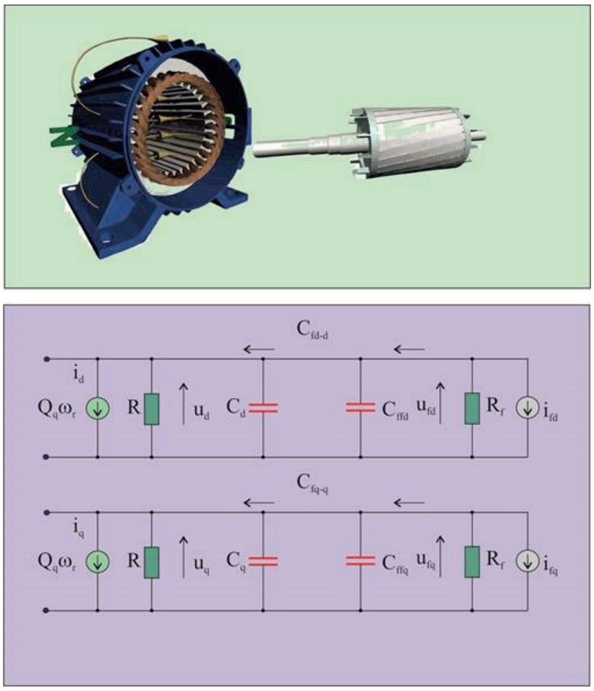

Figure 4 *Substitute diagram of electric circuit of the PMSG synchronous generator*

$$\begin{aligned} &Q_d = -C_d u_d + C_{fd-d} u_{fd} i_d = \\ &= \frac{dQ_d}{dt} - Q_q \frac{d\theta}{dt} - \frac{u_d}{R}, \\ &Q_d = -C_d u_d + C_{fd-d} u_{fd} Q_q = -C_q u_q + \\ &+ C_{fq-q} u_{fq} Q_0 = -C_0 u_0, \\ &Q_q = -C_q u_q + C_{fq-q} u_{fq} i_q = \\ &= \frac{dQ_q}{dt} - Q_q \frac{d\theta}{dt} - \frac{u_q}{R}, \\ &Q_0 = -C_0 u_0 i_0 = \frac{dQ_0}{dt} - \frac{u_d}{R}, \end{aligned} \tag{2}$$

where: C_{fd-d} and C_{fq-q} are equivalent capacities between the rotor and the stator in the *d–q* axes, respectively, in turn, by $C_{fq-q} v_{fq}$ is the value of the electric charge transferred from the rotor to the stator was defined.

Next, the current equations for the rotor for the *d–q* axis were determined as [31-33]:

$$\begin{aligned} i_{fd} &= \frac{dQ_{fd}}{dt} - \frac{u_{fd}}{R_f}, \\ i_{fq} &= \frac{dQ_{fq}}{dt} - \frac{u_{fq}}{R_f}, \end{aligned} \tag{3}$$

where: quantities Q_{fd} and Q_{fq} - were determined by the following relationships:

$$\begin{aligned} Q_{fd} &= C_{ffd} u_{fd} - \frac{3}{2} C_{fd-d} u_d, \\ Q_{fq} &= C_{ffq} u_{fq} - \frac{3}{2} C_{fq-q} u_q, \end{aligned} \tag{4}$$

where: C_{ffd}, C_{ffq} describe the rotor capacities in the *d–q* axes.

In the next stage of mathematical considerations, an attempt was made to normalize variable quantities that characterize the work of a synchronous generator, such as: frequency of voltage operation and current.

The mentioned parameters were related to the stator transformation relative to the *d–q* axes during the synchronous machine operation. The complete equations, describing the physical phenomena occurring during the operation of the synchronous generator, the block diagram of which is depicted in the Figure 4, are as follows:

$$\begin{aligned} i_d &= \frac{dQ_d}{dt} - Q_q \omega - \frac{u_d}{R}, \\ i_q &= \frac{dQ_q}{dt} - Q_d \omega - \frac{u_q}{R}, \\ i_0 &= \frac{dQ_0}{dt} - \frac{u_0}{R}, \\ i_{fd} &= \frac{dQ_{fd}}{dt} + \frac{u_{fd}}{R}, \\ i_{fq} &= \frac{dQ_{fq}}{dt} + \frac{u_{fq}}{R_f}, \end{aligned} \tag{5}$$

where:

$$\begin{aligned} Q_d &= -C_d u_d + C_{fd-d} u_{fd}, \\ Q_q &= -C_q u_q + C_{fq-q} u_{fq}, \\ Q_0 &= -C_0 u_0, \\ Qf_d &= C_{ffd} u_{fd} + C_{fd-d} u_d, \\ Qf_q &= C_{ffq} u_{fq} + C_{fq-q} u_q,. \end{aligned} \tag{6}$$

Simplified substitute scheme of a synchronous generator is shown in Figure 4 with an additional circuit improving the control of the power generated by the apparatus, using for this purpose the phase locked loop PLL (Phase Locked Loop).

An arc-shaped permanent magnet generator, placed in the stator, was modelled in the Matlab/Simulink programming environment and a series of simulations were performed, out of which one of the most optimal solutions was chosen for the on-board electrical network of a more electric aircraft in accordance with the MEA concept [34-35].

3 The results of simulation tests of the proposed architecture of the on-board power system according to the concept of MEA/AEA

The correctness of the constructed model has been verified by comparing the simulation results to the mathematical model presented in the previous subsection. Analogical symmetrical disturbances were introduced in individual harmonics of voltages and currents in both models and the time waveforms were compared.

Figure 5 shows the waveforms for a three-phase short circuit in point 2.1 (Figure 1), and Figure 6 for a step change of the voltage setpoint. The waveforms for both models show good compatibility. Models of voltage and current regulation systems, for various generators, are presented in publications [36-38].

In the next stage of testing, the analysis process was carried out in terms of the key characteristics and the effect of frequency variation on the main parameters and performance of an on-board power generation source, such as an AC generator, and an analysis of the effect of frequency variation on behaviour and performance of the generator was carried out (Figures 7-18).

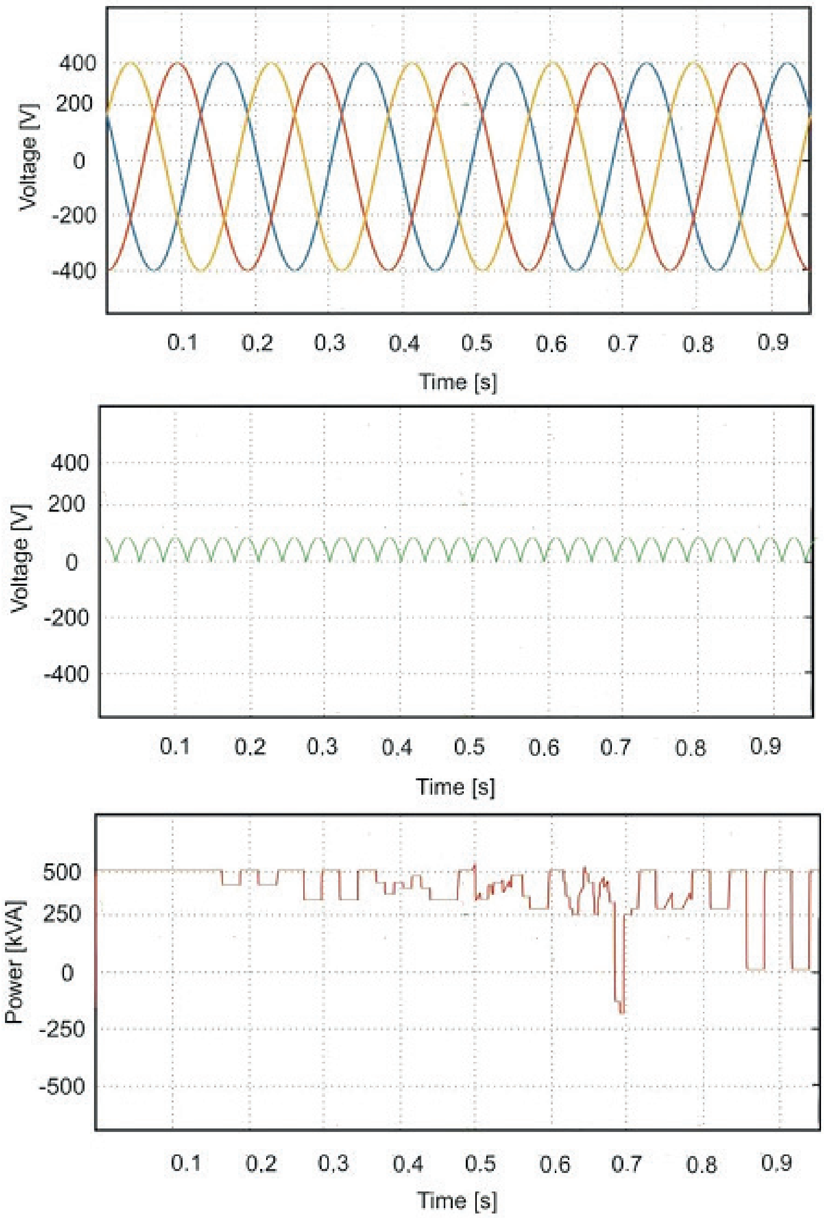

Figure 5 *Waveforms of voltage components and power of an on-board aircraft power source for a coil load and a resistor in accordance with the concept of MEA*

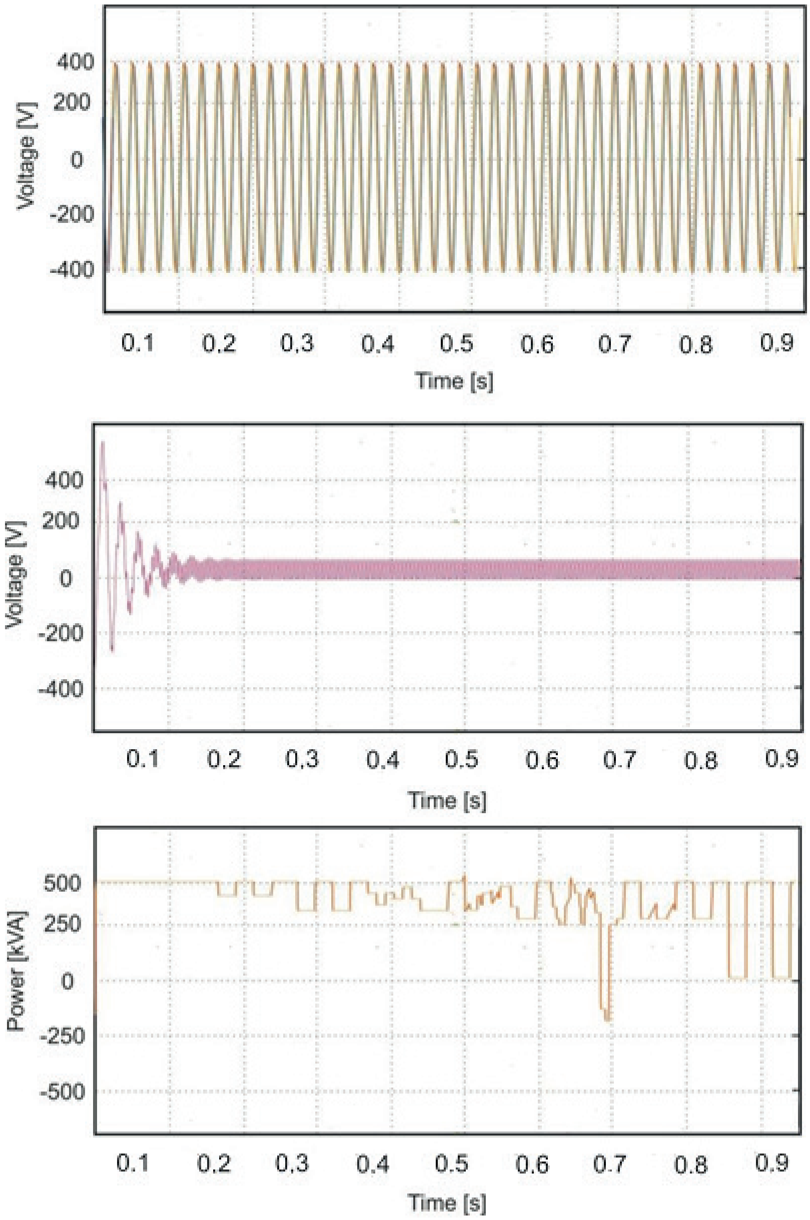

Figure 6 *Waveforms of voltage and power components of an on-board aircraft power source for load of coil, resistor and capacitor in accordance with the MEA concept*

From the below waveforms of Figures 7-12 (for 400 Hz frequency) and Figures 13-18 (for 800 Hz frequency), respectively, it can be seen that the tested generator in the AAES system of an electrified aircraft, according to the MEA trend, during the single operation with a linear receiver R, for a rotor speed of 1000 rpm, gives off electrical power P = 20 kW at the phase-to-phase voltage V_{LL} and current I = 5.1 A. It should be noted that such conditions would occur, among others, in the case of direct connection of the generator with operating avionic equipment of a modern aircraft.

In many practical applications, the synchronous generator is connected to a 3-phase 12-pulse rectifier, which can be the case, for example, when using the generator to power the DC loads, charge batteries or when operating the generator with a rigid network via a frequency converter. It should be noted here that the 12-pulse rectifier is a resistive load, however, non-linear in nature, in turn, both the current and voltage at the output terminals of the generator operating with a diode rectifier are significantly distorted, as can be observed in selected graphs (Figures 11-13 and Figure 15).

In addition, due to additional harmonics in the spatial-temporal distribution of induction in the gap and additional harmonics in the current, in a generator operating with a rectifier there are additional losses in the magnetic circuit and increased losses in the windings, which results in significantly lower efficiency of the generator and higher temperature rises in the electric machine compared to operation on a resistive linear load with the same input power.

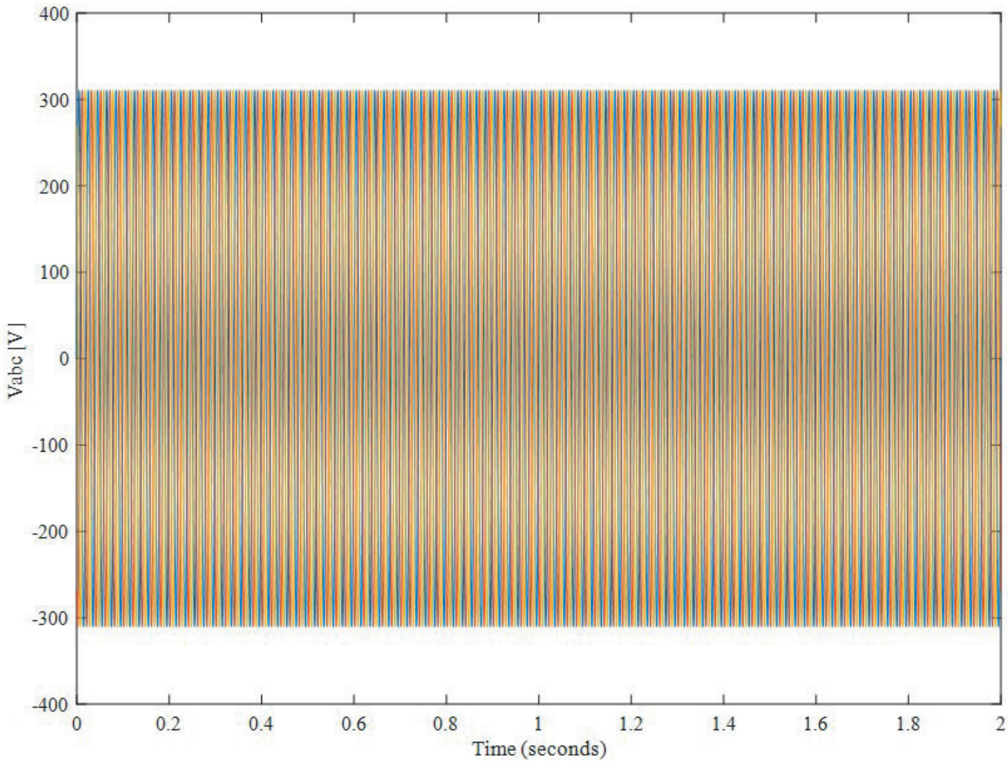

Figure 7 *Voltage waveforms of the 3-phase on-board aircraft power source according to the MEA concept*

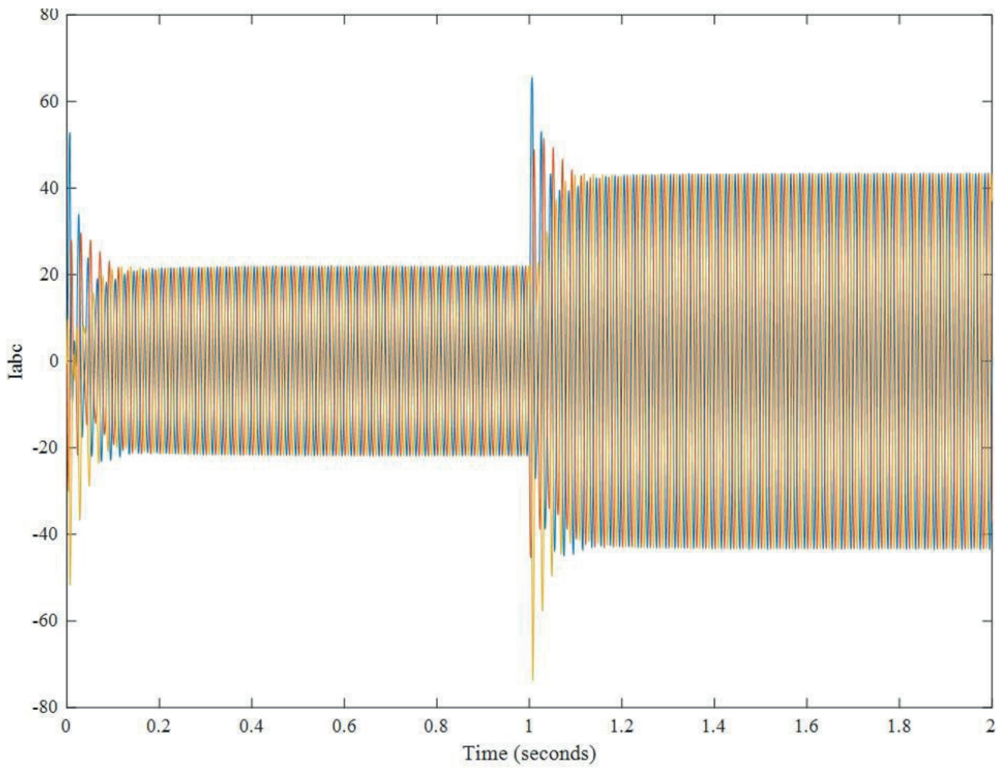

Figure 8 *Current waveforms of the 3-phase on-board aircraft power source according t o the MEA concept*

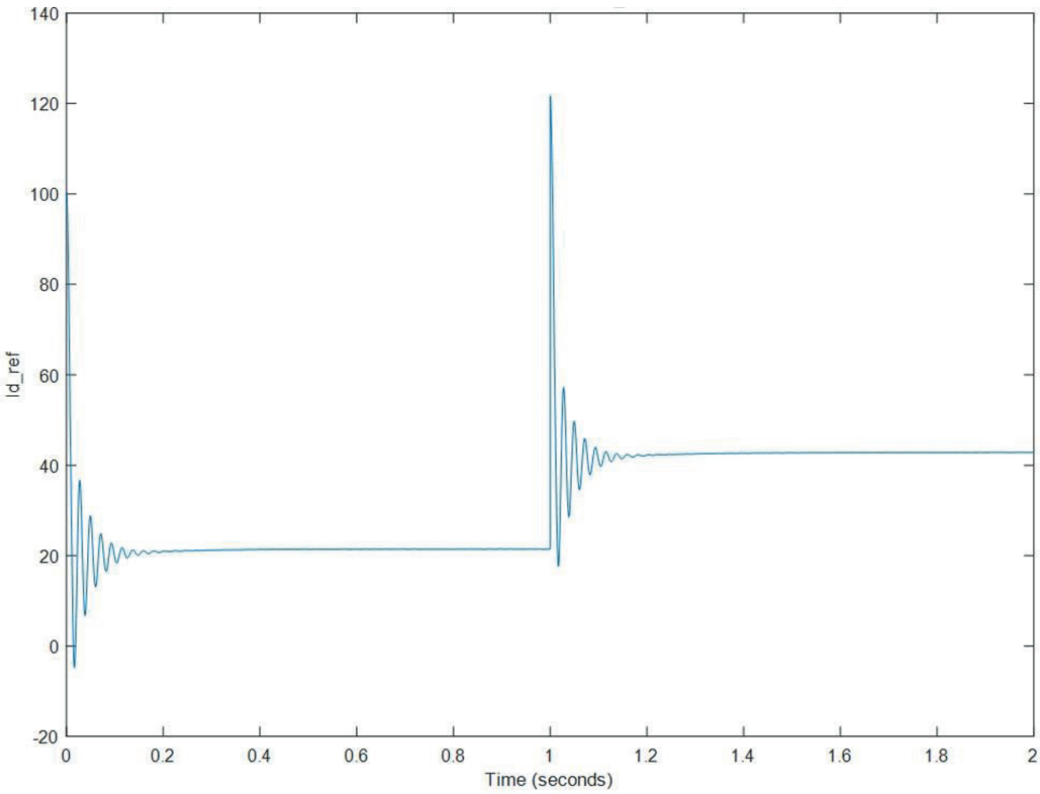

Figure 9 *Current waveform of the 3-phase AC generator in the d–axis of rotor position*

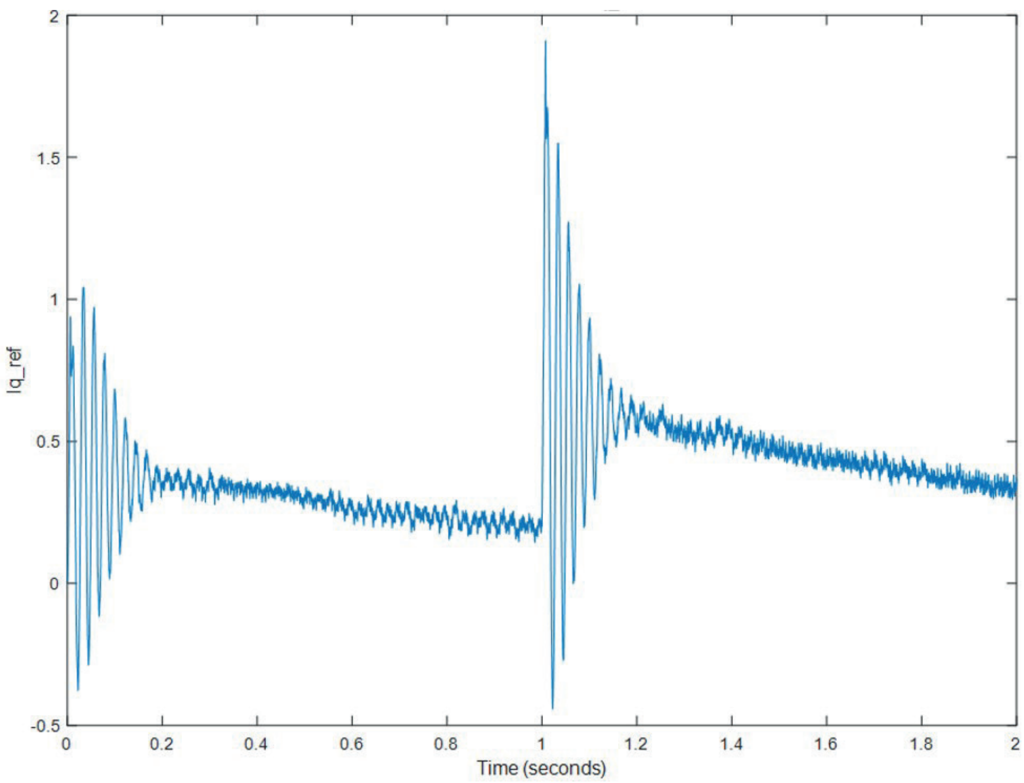

Figure 10 *Current waveform of the 3-phase AC generator in the q–axis of rotor position*

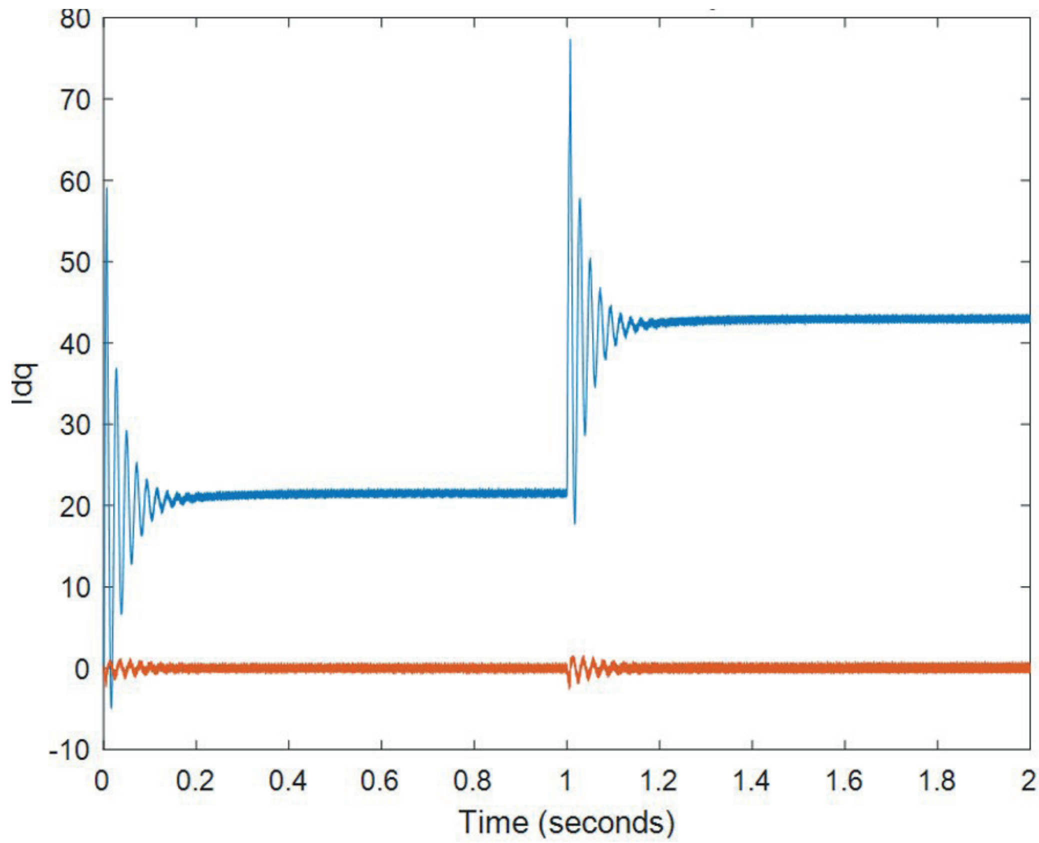

Figure 11 *Current waveform of the 3-phase AC generator in the d–q axis of rotor position*

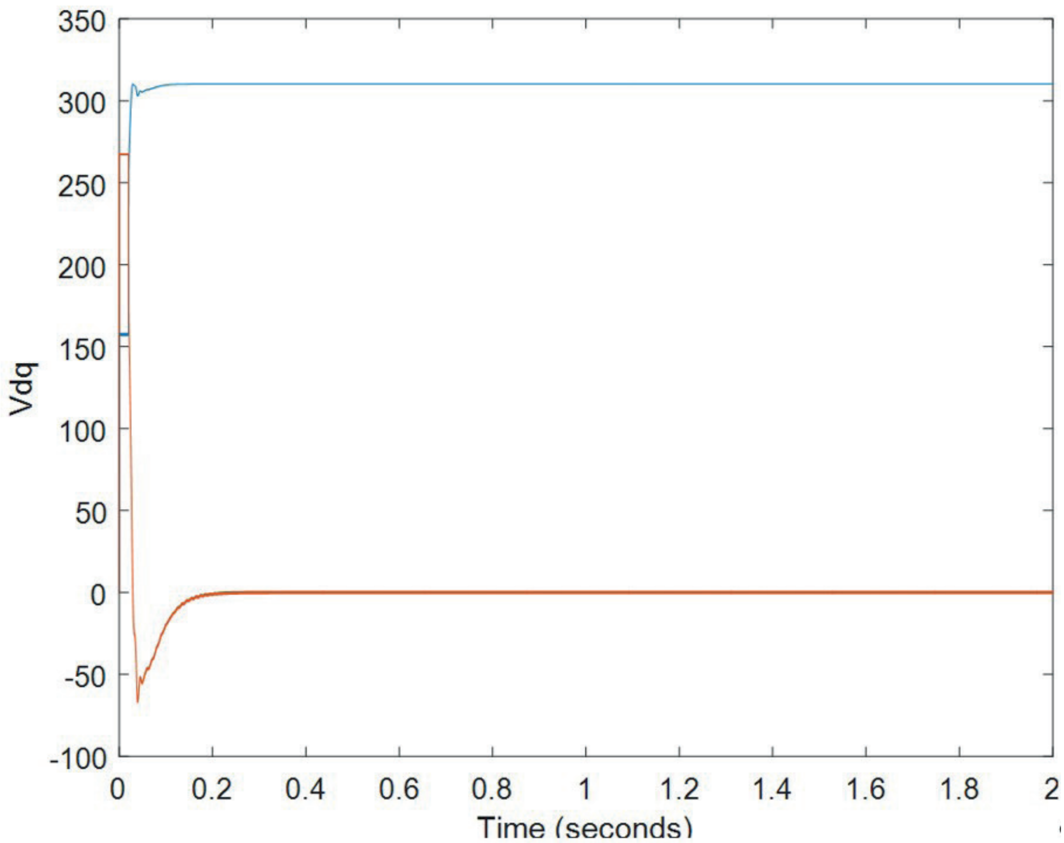

Figure 12 *Voltage waveform of the 3-phase generator in the d–q axis of rotor position*

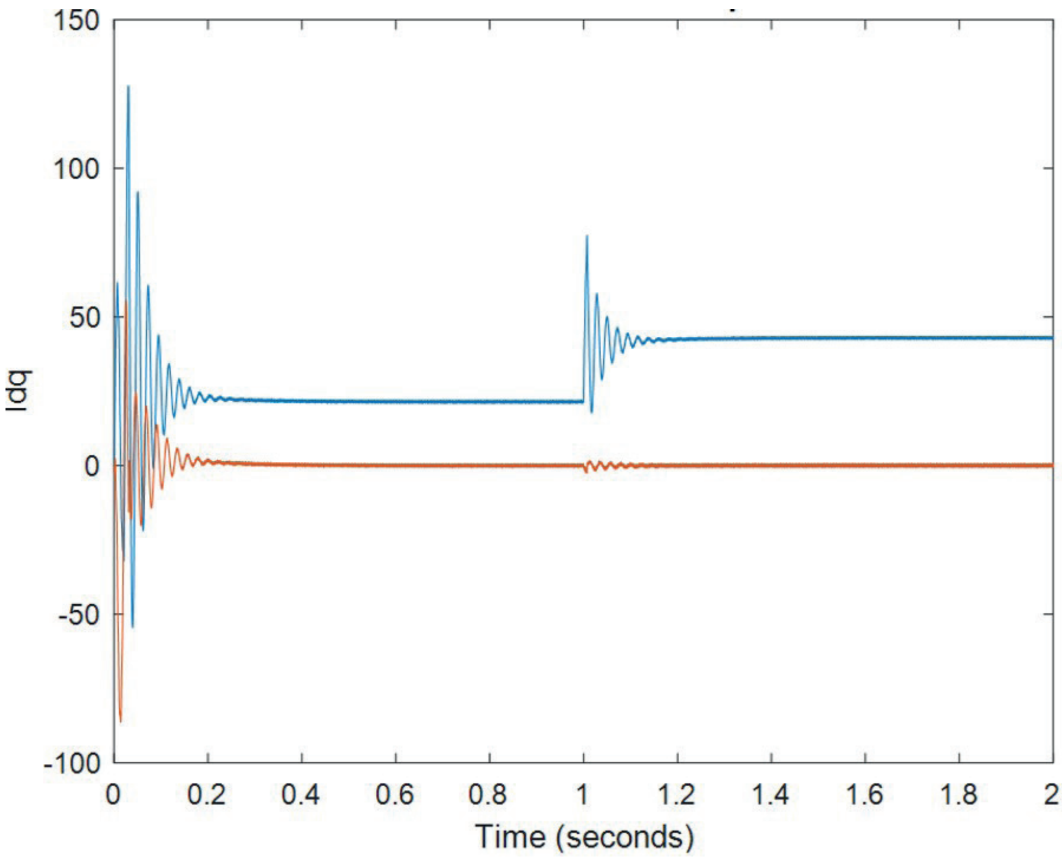

Figure 13 *Current waveform of the 3-phase generator in the d–q axis of rotor position*

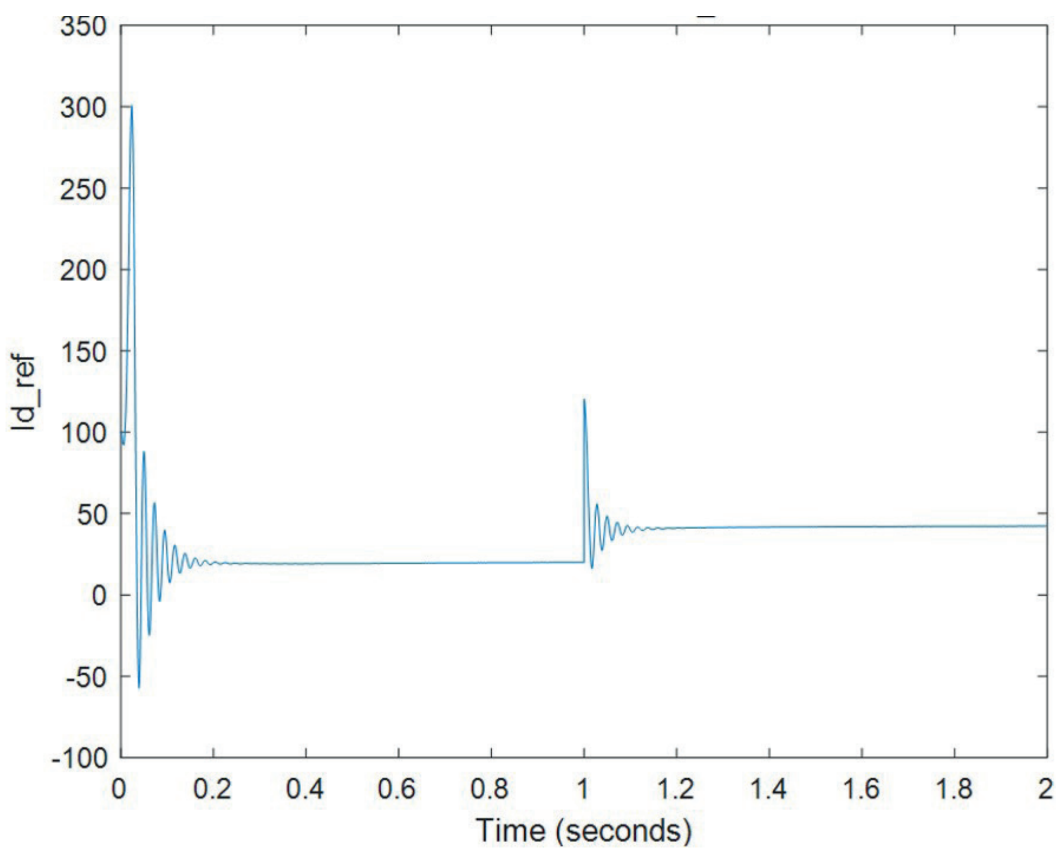

Figure 14 *Current waveform of the 3-phase AC generator in the d–axis of rotor position*

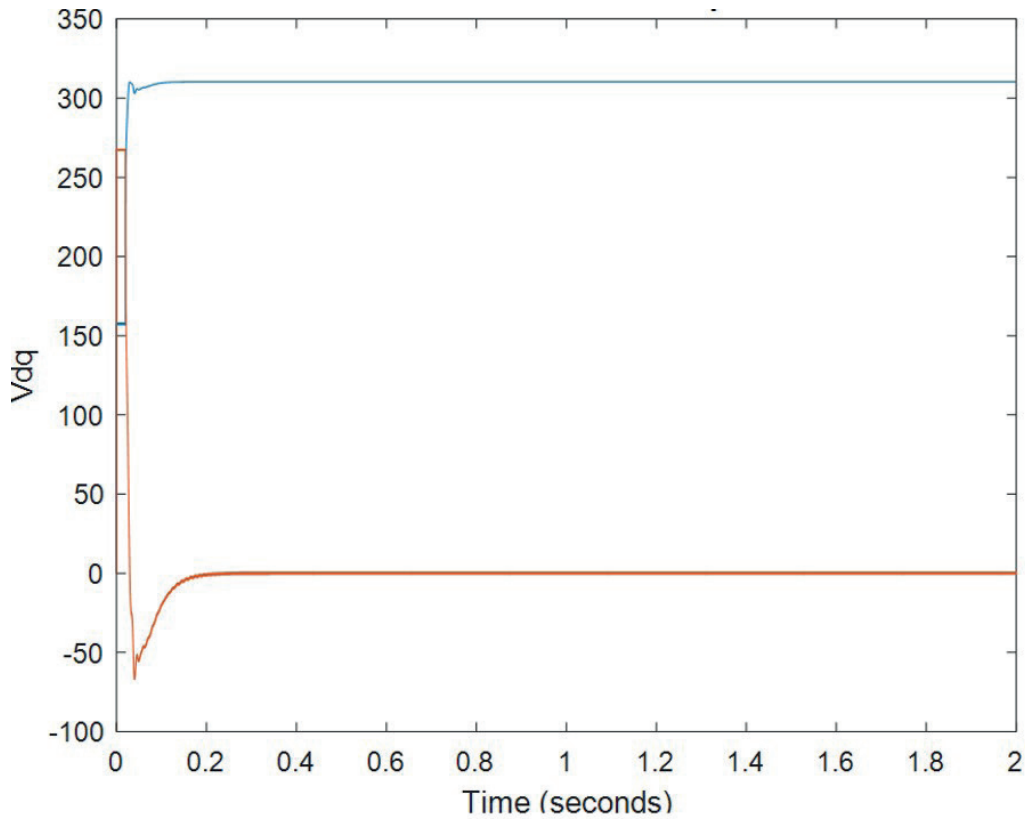

Figure 15 *Voltage waveform of the 3-phase AC generator in the d–q axis of rotor position*

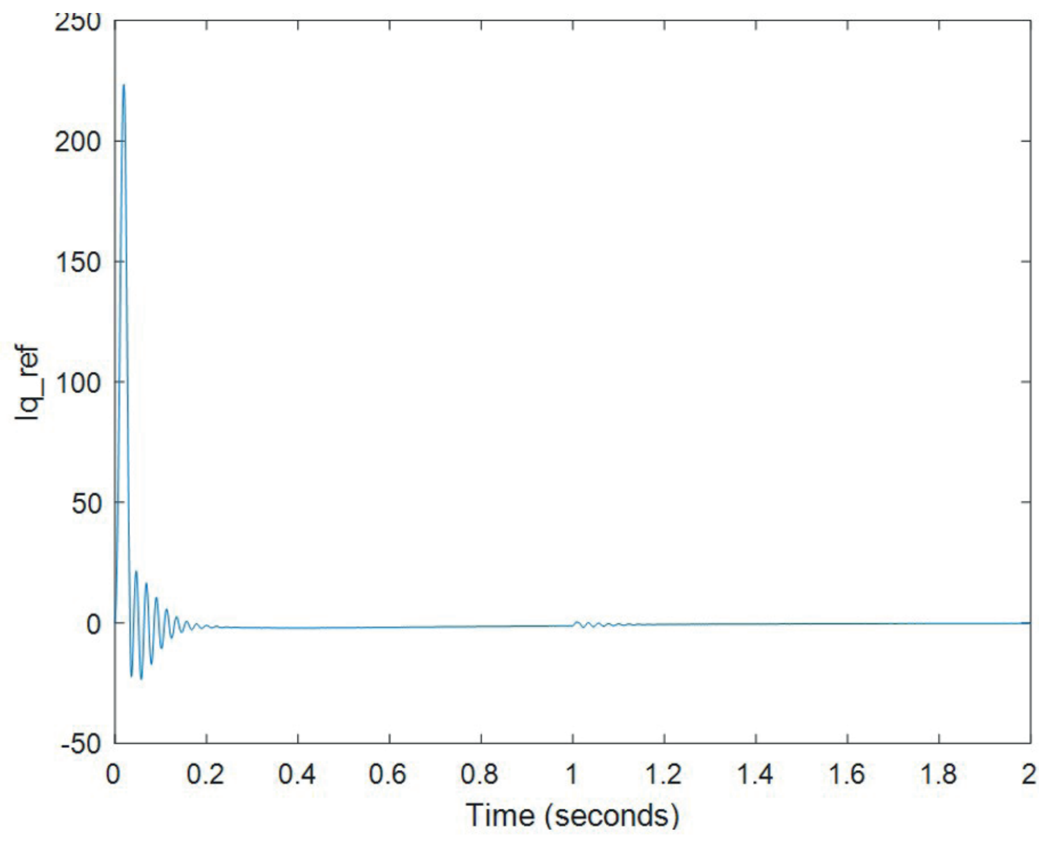

Figure 16 *Current waveform of the 3-phase AC generator in the q–axis of rotor position*

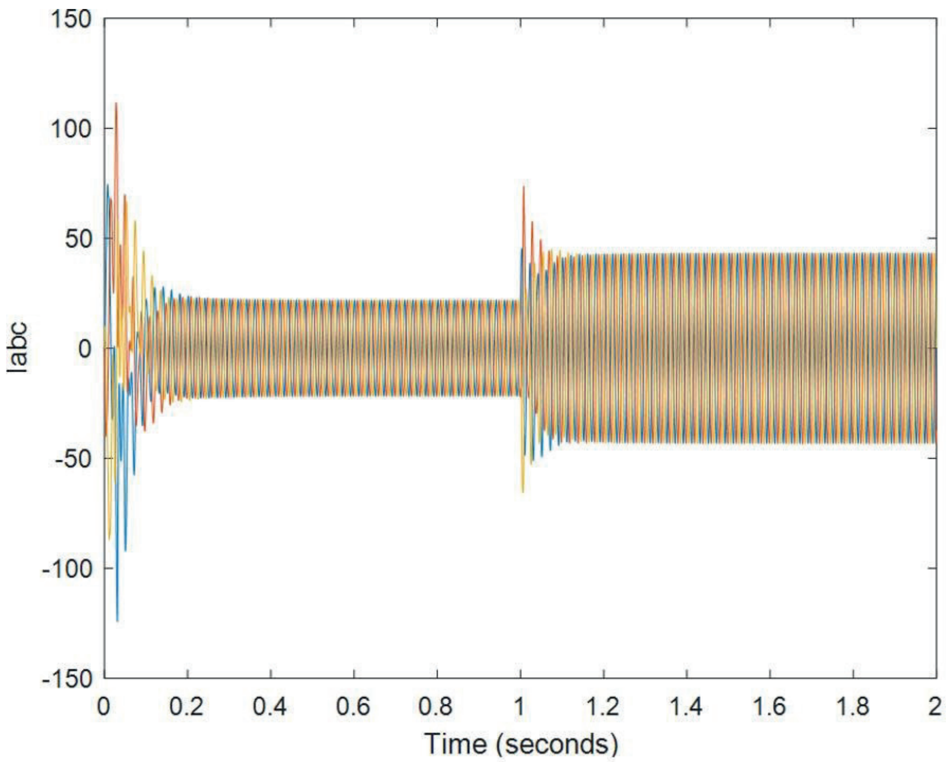

Figure 17 *Current waveforms of the 3-phase on-board aircraft power source according to the MEA concept*

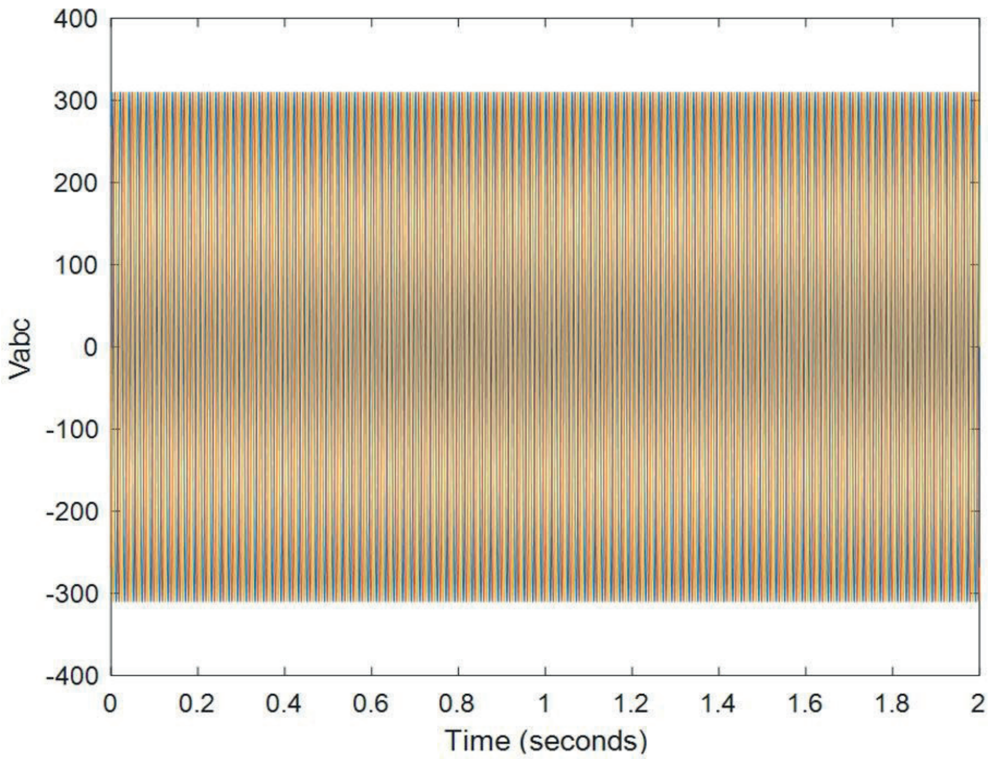

Figure 18 *Voltage waveforms of the 3-phase on-board aircraft power source according to the MEA concept*

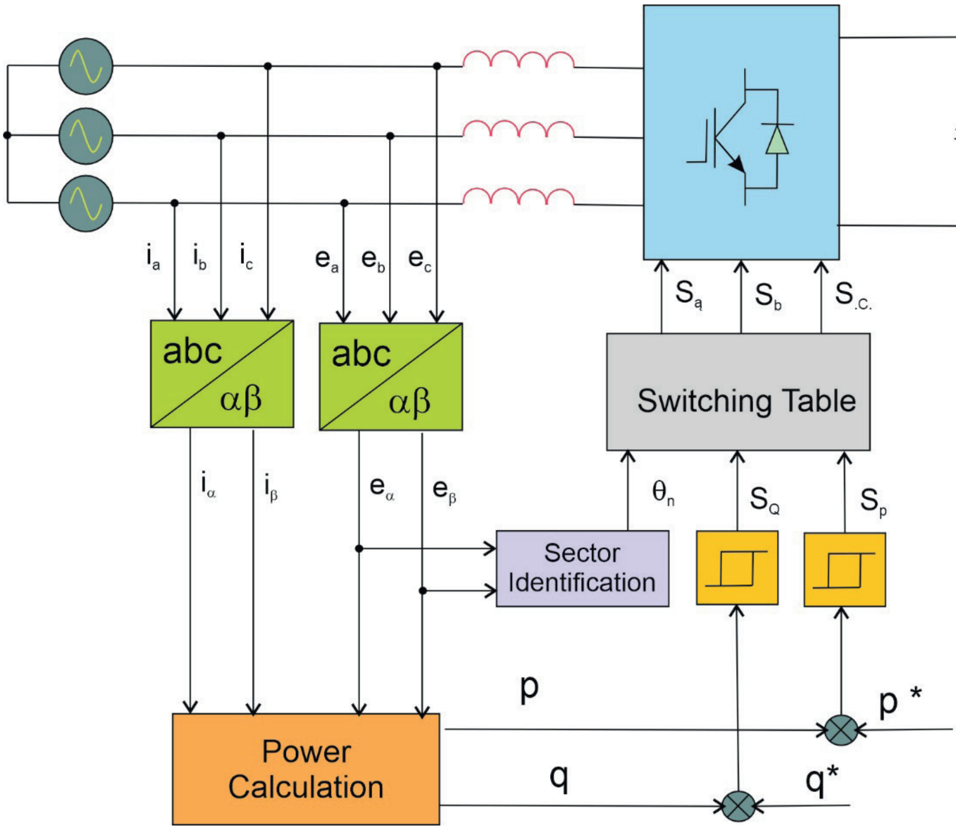

Figure 19 *Scheme of the control system of a self-excited synchronous generator*

4 The results of simulation studies of the control system

For the purposes of the tests, the control systems of two different types of generators were programmed in such a way that the first generator on the switchgear rails is switched on via a 24-pulse generator converter. When the generator is switched on the converter buses, it has the priority of the leading generator, i.e., the amplitude and frequency of the voltage produced by it takes precedence and applies to the entire aircraft power grid. On the other hand, the control system, connected to the bidirectional converter of the second synchronous generator until it is switched on the rails, works in the so-called "island" manner.

Operation in this mode involves the process of regulating the amplitude of the voltage and frequency of the mains converter of the synchronous generator to specific values that allow it to be synchronized with the voltage on the rails of the system. At the moment when the voltage and frequency of the mains converter of the generator to be connected, and the generator already connected to the rails, are equal, the synchronization system signals that the second generator is ready to be connected to the rails. After switching to parallel operation, it becomes impossible to maintain the regime of island operation, since in such an operating algorithm it is not possible to efficiently distribute active and reactive power between the operating generators.

In the presented control system, information on the value of the rotational speed and the current rotor position angle comes from the measurement of sinusoidal voltages at the output of the generator (u_a, u_b, u_c). By studying the transitions of the voltage values through zero, information about the frequency and speed of the generator as illustrated in Figure 19 in Chapter 3. For this reason, there is no need for additional computational means in the form of software simulators or machine state observers.

The operation of the power electronic system with a synchronous generator is briefly presented below. For a synchronous converter generator to be switched on and controlled, the capacitors of the intermediate circuit of the converter must be pre-charged. In turn, for this to be possible, a switch controlled by a sufficiently high value of the DC voltage U_{DC} must turn on.

In the system under consideration, the contactor turns on when the rotational speed of the synchronous generator reaches a value of about 885 rpm. As the rotational speed of the generator increases, the DC voltage of the DC link, denoted as U_{DC}, also increases. Through an appropriate control algorithm executed in the processor, it is possible to raise the DC voltage to about 690 V from the moment the contactor that charges the capacitors of the intermediate circuit is switched on. It should be noted that an important advantage of the circuit in question is the absence of pre-charging of capacitors from external sources.

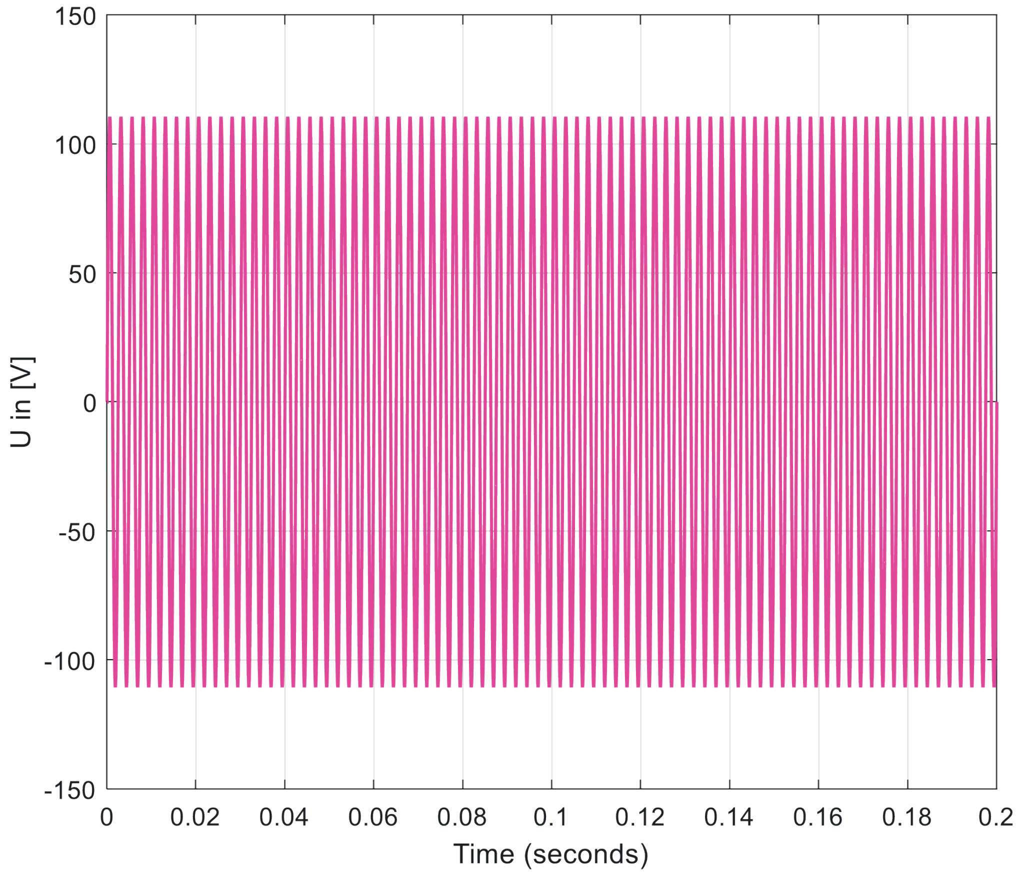

Figure 20 *Voltage waveform on the generator before switching on the control signal*

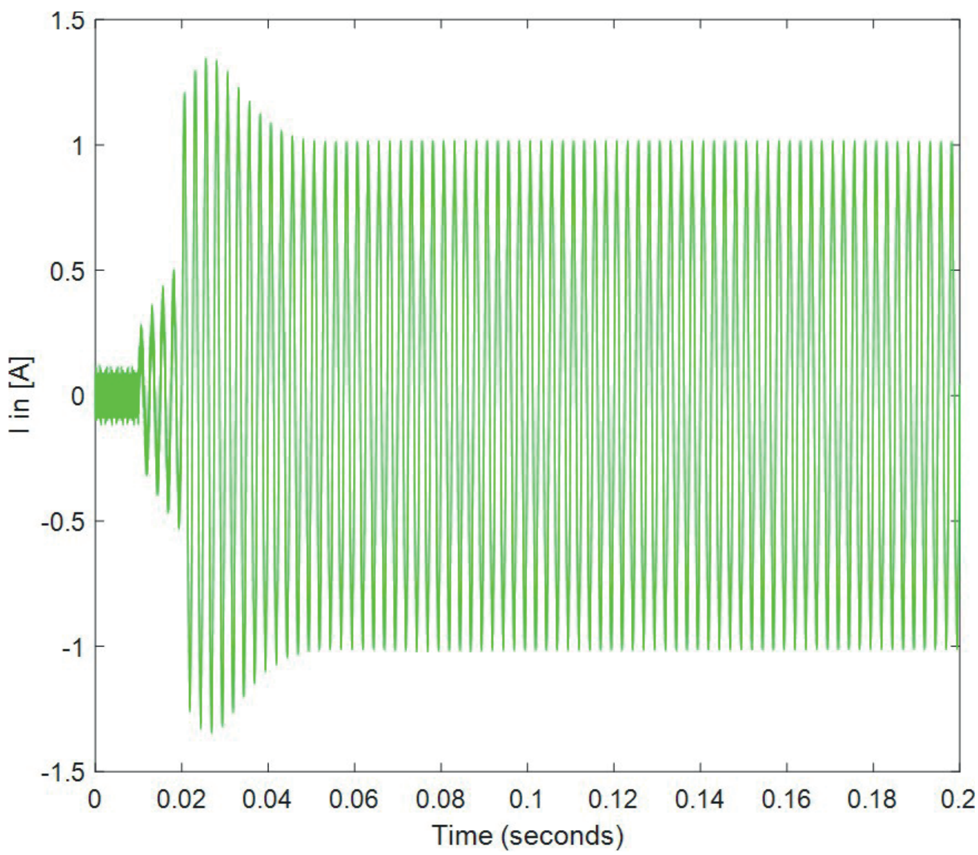

Figure 21 *Current waveform on the generator before switching on the control signal*

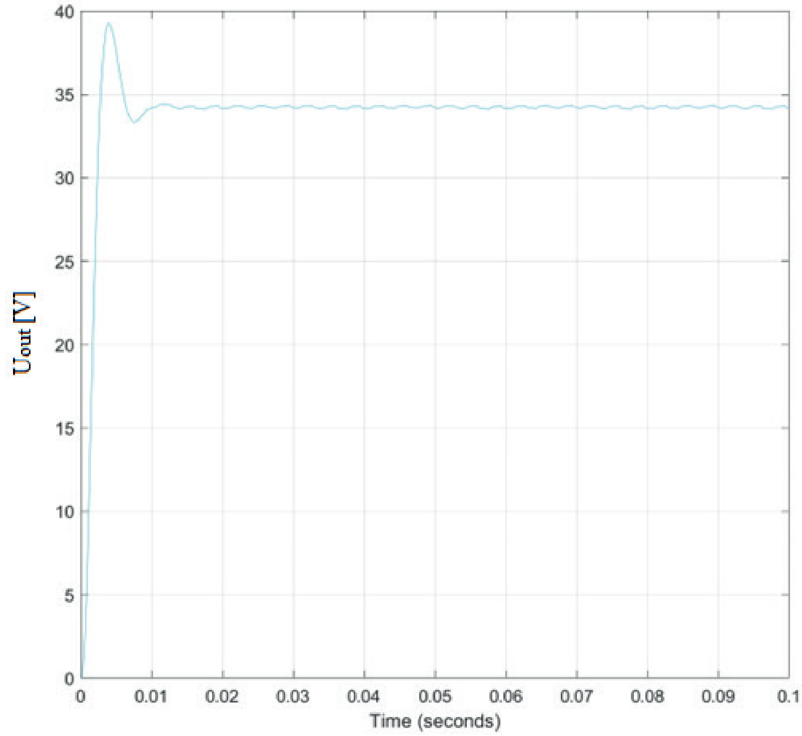

Figure 22 *Voltage DC waveform at the input of the converter with control signal*

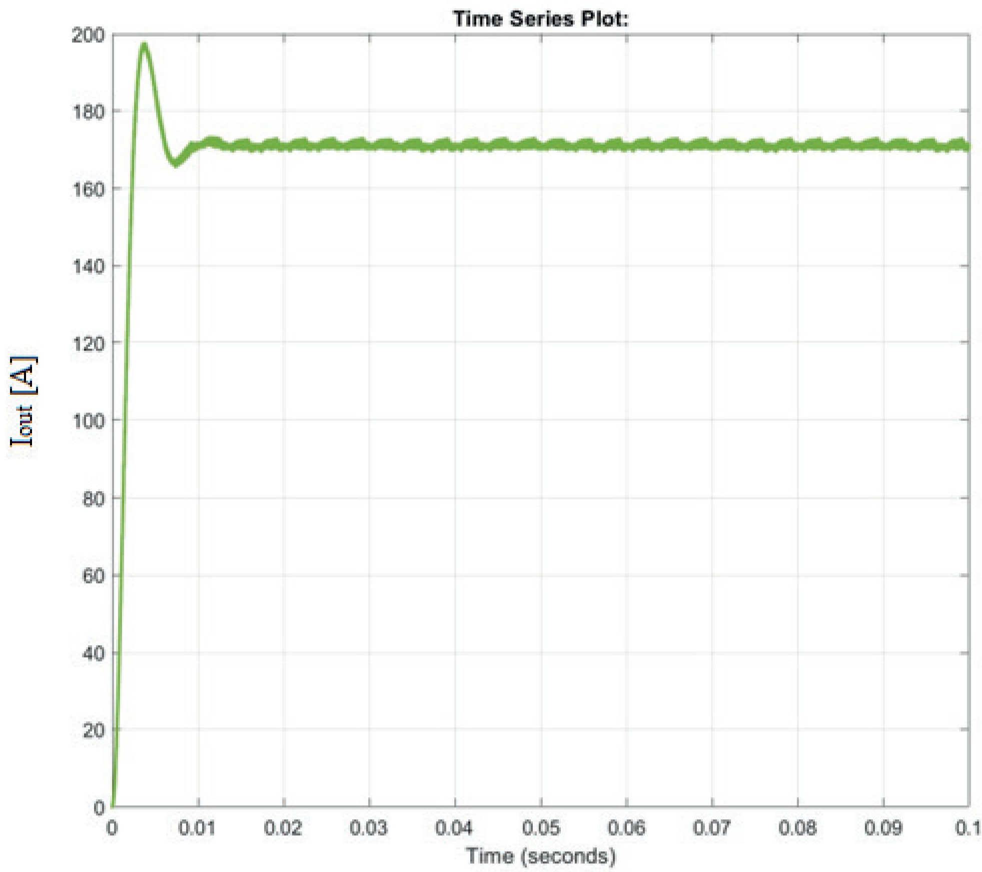

Figure 23 *DC current waveform at converter input with control signal*

4.1 Control of converter operation

Converters, transferring the energy from the intermediate circuit capacitors of the power grid converter, provide two modes of operation. In the case of a single generator operation, the converter has the task of controlling and regulating the voltage amplitude and frequency. When there is a need to switch on and synchronize another generator for parallel operation, the algorithm changes. The frequency of the converter of the connected generator is automatically adjusted to equalize its value with the frequency of the generator (or generators) switched on the buses.

The same happens with the amplitude of the output voltage, that is, when the synchronization conditions are met, the generator switch is turned on and the generator-converter system begins to work in parallel with other sources connected to the network. In the case of switching on, the algorithm controlling the operation of the converter changes under the influence of the signal informing about switching on the buses, and the system begins to work in the program implementing active and reactive power distribution. For the correct operation of the power distribution controllers, continuous information about the frequency of the network voltage is necessary. In the presented solution, a software-based PLL (Phase Locked Loop) circuit was used for frequency control. As a result of the PLL algorithm, the signal processor obtains information about the frequency and phase angle of the voltage, which makes it possible to regulate the amplitude and phase shift values of the output voltage.

Figures 21-23 show that there are uneven loads in generators with the total active and non-active power, and thus also current, both in the states of dynamic load changes and in static states. It should be noted that from the above-mentioned waveforms it is not possible to determine small differences in the values of the AC voltage and current waveforms on the input side of the rectification system. The values of the current at the input of the rectification system (Figure 23) are determined by the control program executed by a specialized Matlab/Simulink software module in real time, in parallel operation of both aircraft generators. The generator carrying out the procedure of distributing the power for the various loads of the aircraft's electrical network takes on a predetermined value of the load, while the remainder (if any) is protected by the second generator.

In this way, it is shown that the requirements of the current regulations for asymmetrical loads are so vague that by meeting the regulations on the permissible value of the ratio of the symmetrical component of the order opposite to the rated current, it is possible to force different current spreads in the windings of the generator. Those distributions cause the occurrence of different values of power losses in the windings, and thus different heating of the windings.

Due to the fact that during the three-phase loads on a generator the value of the ratio $I_d/I_n = 0.1$ depends on many variables, when connecting a load, it is difficult to predict at what values of currents in individual windings the required value of this ratio will be obtained.

5 Conclusions

The developed model of the generator with the excitation and voltage regulation system makes it possible to conduct tests and analyses any asymmetrical states of the generator and excitation system (Figures 1-4). This is a new solution, previously not used in studies of excitation systems.

In this respect, a discrete model of the control system, with the real sampling time and full mapping of measurement systems, was applied. The developed model of the system, based on diodes, allows the mapping of real waveforms in excitation systems (Figures 5-6).

The generator described in the article was made in the Matlab/Simulink programming environment, and simulation studies of the generator for various states of operation are currently underway. It should be noted that the preliminary test results indicate the correctness of the adopted solutions, both in terms of the obtained electrical parameters of the generator and its mechanical design.

From the simulations carried out can be observed that changing the frequency of the generator results in minimizing the tapping torque, which is an unfavorable phenomenon that causes current pulsations when changing the rotor position, and thus interferes with its operation, which was successfully reduced to about 2.5% of the rated torque.

The preliminary results of the tests carried out in this article also indicate the correctness of the calculated power waveforms in the aircraft's electrical network. The investigated efficiency of the generator, when operating with a 12-pulse rectifier and with a generated power of 20 kW, is about 81%. It should be noted that in the case of using the solution in the form of a 6-phase armature winding (2x3 phases), an additional increase in the rated power of the generator of about 3.4% was obtained, and the power losses in the armature winding are reduced by the same amount.

In turn, each of the three-phase windings eliminates the third harmonic in the line-to-line voltage, while the three-phase system, formed from the transformation of the 2x3-phase system, eliminates the fifth and seventh harmonics of the voltage.

In addition, it should be noted that a hybrid excitation generator, when operating alone, has the ability to smoothly stabilize the voltage with changes in load power. In addition, the alternator, when operating on the power grid, can be synchronized with the grid like any machine with electromagnetic excitation, and during the steady-state operation has the ability to continuously regulate the reactive power transferred to the grid. The excitation winding of the generator is characterized by the low copper mass, thus the power loss in the excitation winding is small.

The proposed power electronic system worked stably and, what should be emphasized, was characterized by the high speed of operation and regulation, in the case of abrupt changes occurring in the circuit. The 15 kV quality of the voltage produced by the transformer on the converter side, measured with a higher harmonic content tester, showed that the THD (Total Harmonic Distortion) averaged 2.3% with a value of 2.4% of the input voltage. The output voltage, measured on the converter side, came from measurements with voltage transformers, that is, it was smoothed, which resulted in an improved voltage shape.

The presented system allows free distribution of active and reactive power and long-term cooperation of electricity sources, such as electric generators of various types operating at variable speeds. The developed method of switching on the transformer made it possible to significantly simplify the system and allowed the replacement of electrical components by program code, which increased the reliability of the entire system. Further work will include studies of the stability of the presented systems under rapid load changes across the power range.

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Conflicts of interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

References

[1] MOIR, I., SEABRIDGE, A. *Military avionics systems* [online]. West Sussex: John Wiley and Sons, Ltd., 2006. ISBN 9780470016329, eISBN 9780470035467. Available from: https://doi.org/10.1002/0470035463.fmatter

[2] ABDEL-FADIL, R., EID, A., ABDEL-SALAM, M. Electrical distribution power systems of modern civil aircrafts. In: 2nd International Conference on Energy Systems and Technologies: proceedings [online]. 2013. Available from: http://www.afaqscientific.com/icest2013/22-Eid76.pdf

[3] SETLAK, L., KOWALIK R. Model and simulation of permanent magnets synchronous machine (PMSM) of the electric power supply system (EPS), in accordance with the concept of a more electric aircraft (MEA). *ITM Web of Conferences* [online]. 2018, **16**, 03004. eISSN 2271-2097. Available from: https://doi.org/10.1051/itmconf/20181603004

[4] FORSYTH, A., ABDEL-HAFEZ, A. A review of more-electric aircraft. 13th International Conference on Aerospace Sciences and Aviation Technology ASAT - 13: proceedings [online]. 2009. Available from: https://doi.org/10.21608/ASAT.2009.23726

[5] BROMBACH, J., LUCKEN, A., NYA, B., JOHANNSEN, M., SCHULZ, D. Comparison of different electrical HVDC-architectures for aircraft application. In: Electrical Systems for Aircraft, Railway and Ship Propulsion ESARS: proceedings [online]. IEEE. 2012. ISBN 978-1-4673-1370-4, eISBN 978-1-4673-1371-1. Available from: https://doi.org/10.1109/ESARS.2012.6387380

[6] LUCKEN, A., BROMBACH, J., SCHULZ, D. Design and protection of high voltage DC on-board grid with integrated fuel cell system on toward optimized electrical networks electric aircraft. In: Electrical Systems for Aircraft, Railway and Ship Propulsion ESARS: proceedings [online]. IEEE. 2012. ISBN 978-1-4673-1370-4, eISBN 978-1-4673-1371-1. Available from: https://doi.org/10.1109/ESARS.2010.5665245

[7] MOIR I., SEABRIDGE, A. *Aircraft systems: mechanical, electrical, and avionics subsystems integration*. 3rd ed. West Sussex: John Wiley and Sons, Ltd., 2008. ISBN 978-0-470-05996-8.

[8] EMANDI, K., EHSANI, M. Aircraft power systems: technology state of the art, and the future trends. *Aerospace and Electronic Systems Magazine* [online]. 2000, **15**(1), p. 28-32. ISSN 0885-8985, eISSN 1557-959X. Available from: https://doi.org/10.1109/62.821660

[9] MLOT, A., LUKANISZYN, M., KORKOSZ, M. Influence of an end-winding size on proximity losses in a high-speed PM synchronous motor. In: 2015 Selected Problems of Electrical Engineering and Electronics WZEE: proceedings [online]. IEEE. 2015. Available from: https://doi.org/10.1109/WZEE.2015.7394026

[10] RAGHUVANSHI, S., SINGH, N. Comparative analysis of 36, 48, 60 pulse AC-DC controlled multipulse converter for harmonic mitigation. *International Journal of Advanced Research in Computer Engineering and Technology (IJARCET)*. 2014, **3**(4). ISSN 2278-1323.

[11] MOHAN, N., UNDERLAND, T. M., ROBBINS, W. P. *Power electronics: converters, application, and design*. West Sussex: John Wiley and Sons, 1989. ISBN 0-471-58408-8.

[12] KAZMIERKOWSKI, M. P., BLAABJERG, F., KRISHNAN, R. *Control in power electronics*. Academic Press Series in Engineering. USA: Elsevier Science, 2002. ISBN 0-12-402772-5.
[13] SETLAK, L., KOWALIK, R. Mathematical modelling and simulation of selected components on-board autonomous power supply system (ASE), in accordance with the concept of a more electric aircraft (MEA). In: 18th International Scientific Conference on Electric Power Engineering EPE: proceedings [online]. IEEE. 2017. eISBN 978-1-5090-6406-9. Available from: https://doi.org/10.1109/EPE.2017.7967337
[14] ZHAO, X., GUERRERO, J. M., WU, X. Review of aircraft electric power systems and architectures. In: IEEE 2014 International Energy Conference ENERGYCON: proceedings [online]. eISBN 978-1-4799-2449-3. Available from: https://doi.org/10.1109/ENERGYCON.2014.6850540
[15] ERRAMI, Y., OUASSAID, M. Modelling and control strategy of PMSG based variable speed wind energy conversion system. In: International Conference on Multimedia Computing and Systems ICMCS: proceedings [online]. 2011. ISBN 978-1-61284-730-6, eISBN 978-1-61284-730-6. Available from: https://doi.org/10.1109/ICMCS.2011.5945736
[16] MOUNI, E., TNANI, S., CHAMPENOIS, G. Comparative study of three modelling methods of synchronous generator. In: IEEE 32nd Annual Conference on Industrial Electronics: proceedings [online]. 2006. eISBN 978-1-5090-9155-3, p. 1551-1556. Available from: https://doi.org/10.1109/IECON.2006.347987
[17] BOZHKO, S., WU, T., TAO, Y., ASHER, G. M. More-electric aircraft electrical power system accelerated functional modelling. In: International Power Electronics and Motion Control Conference: proceedings [online]. 2010. ISBN 978-1-4244-7856-9, eISBN 978-1-4244-7855-2. Available from: https://doi.org/10.1109/EPEPEMC.2010.5606894
[18] ROBOAM, X. New trends and challenges of electrical network embedded in “more electrical aircraft”. In: Proceedings of the IEEE International Symposium on Industrial Electronics ISIE’11: proceedings [online]. IEEE. 2011. ISBN 978-1-4244-9310-4, eISBN 978-1-4244-9312-8, p. 26-31. Available from: https://doi.org/10.1109/ISIE.2011.5984130
[19] SETLAK, L., KOWALIK R. Modern technological solutions in generation, transmission and distribution of electricity in “conventional” vs. “more electric” aircrafts. In: 2017 Progress in Applied Electrical Engineering PAEE: proceedings [online]. IEEE. 2017. eISBN 978-1-5386-1528-7. Available from: https://doi.org/10.1109/PAEE.2017.8009008
[20] ABDEL-HAFEZ, A. Power generation and distribution system for a more electric aircraft - a review. In: *Recent advances in aircraft technology*. AGARWAL, R. (ed.). China: In-Tech, 2012. ISBN 978-953-51-0150-5, p. 289-308.
[21] ABU-RUB, H., MALINOWSKI, M., AL-HADDAD, K. *Power electronics for renewable energy systems. Transportation, and industrial applications* [online]. 1st ed. John Wiley and Sons, Ltd., 2014. ISBN 9781118634035, eISBN 9781118755525. Available from: https://doi.org/10.1002/9781118755525
[22] GONG, G., DROFENIK, U., KOLAR, J. W. 12-pulse rectifier for more electric aircraft applications. In: IEEE International Conference on Industrial Technology ICIT: proceedings [online]. 2003. ISBN 0-7803-7852-0. Available from: https://doi.org/10.1109/ICIT.2003.1290816
[23] ERRAMI, Y., OUASSAID, M. Modelling and control strategy of PMSG based variable speed wind energy conversion system. In: International Conference on Multimedia Computing and Systems ICMCS: proceedings [online]. IEEE. 2011. ISBN 978-1-61284-730-6, eISBN 978-1-61284-732-0. Available from: https://doi.org/10.1109/ICMCS.2011.5945736
[24] SETLAK, L., KOWALIK, R. Model study and simulation of selected components of on-board power supply system ASE in the range of EPS and PES systems of a modern aircraft, compatible with the concept of more electric aircraft. In: IAENG Transactions on Engineering Sciences: Special Issue for the International Association of Engineers Conference`s 2016: proceedings [online]. Vol. II. 2018. ISBN 978-981-3230-76-7, eISBN 978-981-3230-78-1, p. 344-359. Available from: https://doi.org/10.1142/9789813230774_0025
[25] AREERAK, K-N., BOZHKO, S. V., ASHER, G. M., THOMAS, D. W. P. Stability analysis and modelling of AC-DC system with mixed load using DQ-transformation method. In: 2008 IEEE International Symposium on Industrial Electronics: proceedings [online]. IEEE. 2008. ISBN 978-1-4244-1665-3. Available from: https://doi.org/10.1109/ISIE.2008.4676898
[26] MONROY, A. O., LE-HUY, H., LAVOIE, C. Modelling and simulation of a 24-pulse transformer rectifier unit for more electric aircraft power system. Electrical Systems for Aircraft, Railway and Ship Propulsion ESARS: proceedings [online]. IEEE. 2012. ISBN 978-1-4673-1370-4, eISBN 978-1-4673-1372-8. Available from: https://doi.org/10.1109/ESARS.2012.6387383
[27] WU, B., NARIMANI, M. *High-power converters and AC drives* [online]. Hoboken, New Jersey: IEEE Press, John Wiley and Sons, Inc., Publication, 2006. ISBN 9781119156031, eISBN 9781119156079. Available from: https://doi.org/10.1002/9781119156079
[28] SKVARENINA, T. L., PEKAREK, WASYNCZUK, S. O., KRAUSE, P. C. Simulation of a more-electric aircraft power system using an automated state model approach. In: Intersociety Energy Conversion Engineering

Conference: proceedings [online]. IEEE. 1996. p. 133-136. ISBN 0-7803-3547-3. Available from: https://doi.org/10.1109/IECEC.1996.552859

[29] SETLAK, L., KOWALIK, R. Mathematical model and simulation of selected components of the EPS of the aircraft, providing the operation of on-board electrical equipment and systems in accordance with MEA/AEA concept. In: 2017 Progress in Applied Electrical Engineering PAEE: proceedings [online]. IEEE. 2017. eISBN 978-1-5386-1528-7. Available from: https://doi.org/10.1109/PAEE.2017.8009007

[30] MAKAROV, D., KHARITONOV, S., ZINOVIEV, G., SIDOROV, A.V. Variable frequency generation system for aircraft. In: 2014 IEEE Energy Conversion Congress and Exposition: proceedings [online]. IEEE. 2014. ISSN 2329-3721, eISSN 2329-3748. Available from: https://doi.org/10.1109/ECCE.2014.6953496

[31] LATAWIEC, K., STANISLAWSKI, R., LUKANISZYN, M., CZUWARA, W., RYDEL, M. Fractional-order modelling of electric circuits: modern empiricism vs. classical science. In: 2017 Progress in Applied Electrical Engineering PAEE: proceedings [online]. IEEE. 2017. eISBN 978-1-5386-1528-7. Available from: https://doi.org/10.1109/PAEE.2017.8008998

[32] SETLAK, L., KOWALIK, R., REDO, W. The study of permanent magnets synchronous machine (PMSM) of the autonomous electric power supply system (ASE), compatible with the concept of a more electric aircraft (MEA). *ITM Web of Conferences* [online]. 2018, **16**, 03001. eISSN 2271-2097. Available from: https://doi.org/10.1051/itmconf/20181603001

[33] WHEELER, P., CLARE, J., BOZHKO, S. Regeneration in aircraft electrical power systems. In: SAE Power Systems Conference: proceedings. SAE. 2010.

[34] SETLAK, L., KOWALIK, R., REDO, W. Mathematical models and simulation of key multi-pulse rectifiers in field of autonomous electric power supply system, using Matlab/Simulink programming environment compatible with the concept of a more electric aircraft (MEA). In: 2017 European Conference on Electrical Engineering and Computer Science EECS: proceedings [online]. IEEE. 2017. eISBN 978-1-5386-2085-4. Available from: https://doi.org/10.1109/EECS.2017.75

[35] MALDONADO, M. A., KORBA, G. J. Power management and distribution system for a more-electric aircraft (MADMEL). *Aerospace and Electronic Systems Magazine* [online]. 1999, **14**(12), p. 3-8. ISSN 0885-8985, eISSN 1557-959X. Available from: https://doi.org/10.1109/62.811084

[36] WEIMER, J. A. Electrical power technology for the more electric aircraft. In: 12th AIAA/IEEE Digital Avionics Systems Conference: proceedings. IEEE. 1993. p. 445-450.

[37] YANG, Z., QU, J., MA, J., SHI, X. Modeling and simulation of power distribution system in more electric aircraft. *Journal of Electrical and Computer Engineering* [online]. 2015, **2015**, 847624. Available from: https://doi.org/10.1155/2015/847624

[38] SETLAK, L., KOWALIK, R. Analysis, mathematical model and simulation of selected components of advanced technological solutions of HVDC architecture of modern aircraft compatible with the concept of MEA/AEA. In: The World Congress on Engineering and Computer Science 2017: proceedings. 2017. ISBN 978-988-14047-5-6, p. 327-332, 2017.