Technological Solutions of Selected Components of Energo-electronic Power Supply System PES in the Field of AC/DC/DC Processing in Accordance with a Trend of More Electric Aircraft

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***Abstract*—**This article presents selected solutions for the basic components of the energo-electronic power supply system PES, which are multi-pulse (6-, 12- and 18-, 24-) impulse rectifiers, with particular emphasis on AC/DC/DC processing. The multi-pulse rectifier solutions are used in modern military aviation, both of the Lockheed Martin company and its latest JSF F-35 and F-22 Raptor aircrafts, as well as in the civil aircrafts architecture of the Airbus and Boeing companies in the field of their hit products (A-380, A-350XWB and B-787), consistent with the concept of a more electric aircraft. The main goal of the article is to develop a mathematical model in the field of AC/DC/DC processing and simulation of selected multi-pulse rectifiers, implemented on modern aircrafts. Based on the above, the final part of the work presents important practical conclusions resulting from the analysis and simulation tests of key components of the PES system, i.e. selected multi-pulse rectifiers.

***Keywords*—**technological solutions, energo-electronic power supply system, more electric aircraft, AC/DC/DC processing

I. Introduction

NOWADAYS we can observe a gradually increasing dynamics of changes in the use of the main components of energo-electronic power supply systems PES (Power Electronics Systems), which include multi-pulse rectifiers, especially in the field of AC/DC and DC/DC processing.

The above solutions in the scope of using the main PES system components, i.e. multi-pulse (6-, 12- and 18-, 24-) impulse rectifiers, have found wide application both in civil aviation (A-380 and A-350XWB, B-787), as well as in military aviation in the field of JSF (Joint Strike Fighter) F-35 and F-22 Raptor aircrafts. The subject of this article, which are multi-pulse rectifiers of AC/DC/DC transducers included in the ASE (Autonomous Electric Power Supply System) on-board system, are the key components of the PES system [1], [2].

The basic and, at the same time, very important in particular in the functional context of the above system are transducers, primarily in the field of AC/DC/DC processing. Power electronic converters supplied from on-board electricity networks of modern aircrafts are referred to as multi-pulse converters when the AC voltage is converted into DC voltage and inverters when the DC voltage is converted to alternating current AC.

In addition, it should be noted that in practical applications, previously used voltage sources such as direct current generators and alternating current generators or integrated VFSG (Variable Frequency Starter Generator) AC units as well as related electro-energetic power systems (AC and DC power supply networks) are uneconomic and technically difficult to implement. An exemplary application of selected components of power electronics (Power Electronics), used on board a modern aircraft is presented below (TABLE I).

TABLE I. Example of application of selected power electronics components on board of a modern aircrafts [3]

Category	Application	Technology/Circuits
Energy storage	Battery safety	Battery management system: flyback converter
	Charging process	Power factor correction, transducer, DC/DC converter
Displacement control	Actuator	Engine design, engine drive
	Fuel pump	Electric pump, motor drive, power converter
	Displacement control	Power converter, vector control, torque control
	Landing gear	Engine design, engine drive

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Service of the environment	Ventilation	Inverter
	Lighting	Electronic ballast, LED
	UPS	Inverter, battery charger
	Corrected power factor	Switching capacitor
Distribution of electricity in aviation	Drive	Inverter (DC/AC power converter)
	AC power generation	2-level inverter, resonant converters, phase shift converter
	VFCF	Inverter, corrected power factor of the converter

In the further part of this paper, the analysis and simulation of selected multi-pulse rectifiers, compatible with the concept of more electric MEA (More Electric Aircraft) aircraft were made. In addition, a mathematical model in the field of AC/DC and DC/DC processing has been presented, as well as methods for regulating the speed and torque of a Permanent Magnets Synchronous Machine (PMSM) permanent magnet machine in a DC system have been characterized [4].

II. Analysis and Mathematical Model of Selected Multi-Pulse Rectifiers in the Field of AC/DC/DC Processing

Referring to the research subject of this article, it should be noted that drive systems with squirrel-induction motors supplied by voltage converters are currently the largest group of AC regulated AC drives used in industry, including the aviation industry. The voltage inverter is an integral topological part of the frequency converter and provides the ability to control the flow of electrical energy and the electromagnetic torque of the electrical machine EM (engine/generator). During braking, the kinetic energy of the rotating shaft after the conversion in the EM (engine/generator) into electrical energy is transferred to the intermediate circuit of the frequency converter and is stored in a capacitor connected to this circuit. In the case when the value of this energy is large, it is necessary to transfer it to other aircraft circuits. Otherwise, there may be an excessive increase in the voltage in the intermediate circuit, dangerous for elements of the power electronics systems (PES) and motor circuits [5], [6].

In the classical AC/DC/DC converters, an additional network-switched thyristor rectifier is used (Fig. 1). During braking, the rectifier is in the inverter operating mode, enabling the return of energy to the electrical network of the aircraft. The most beneficial solution from technical and economic reasons is the use of AC/DC network converter with bi-directional electricity flow. This converter, called the PWM (Pulse Width Modulation) rectifier, is a power electronics device with internal commutation and pulse control. In addition, the AC/DC power converter along with the appropriate control system ensures the consumption of currents from the power supply network, similar in shape to sinusoidal waveforms, practically with no reactive power consumption (power factor *cosφ* close to oneness).

By entering the process of determining the mathematical relations describing the physical phenomena occurring in the ASE on-board autonomous power supply system (EPS, PES) in the field of electricity management of modern aircraft, compatible with advanced solutions of the concept of more electric aircraft (MEA/AEA), special attention should be paid to two cycles of AC voltage and AC harmonics conversion into DC and conversion of voltage and current with a defined DC current value to a different DC current value, i.e. in the AC/DC/DC processing range.

To this end, the solution shown in the drawing below (Fig. 1) was used, in which the topology of a three-phase AC/DC converter with an LCL filtering system is depicted. The aforementioned subunit in the structure of the electrical network responsible for the transformation of voltage and current is responsible for the elimination of noise and distorted harmonics [7], [8].

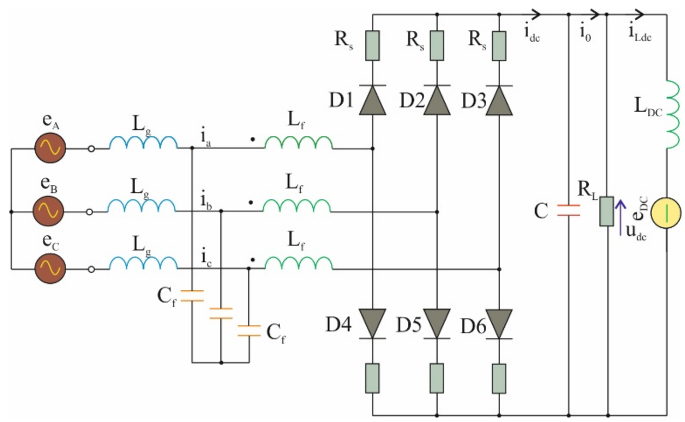

Fig. 1 Block diagram of a three-phase AC/DC converter

It should be noted that the use of the LCL filter solution is justified by a much higher attenuation (60 dB/dek) compared to an L-type filter (20 dB/dek), which translates into a reduction in the overall size and cost of the inverter [9].

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In the presented block diagram, it is assumed that the parameter u_{DC} means the voltage value at the load output, and e_{DC} is the value of the source voltage at the output of the DC converter.

In turn, by L_{DC} the inductance of the choke was determined in the load circuit with a DC voltage source, which prevents the occurrence of a starting current in the system. In addition, the quantities, L_g and L_f are respectively the input and output inductance of the filter system, and C_f the capacity of the capacitor that is part of the filter.

In the presented system, the phenomenon of removing current and voltage harmonics in the low frequency range occurs. This process is closely related to the filter system assuming that the total inductance in the filter is $L = L_g + L_f$. respectively. In this way, you can obtain mathematical relationships showing physical phenomena occurring in the filter as well as the entire converter system. In addition, it should be added that in the mathematical analysis the value of capacitor capacitance C_f was omitted due to the fact that the entire filtration process occurs in the low frequency range.

A. Mathematical model of a multi-pulse rectifier in the field of AC/DC processing

In a rectifier system operating in the AC/DC converter range, the on-board AC three-phase source supplies electrical energy (power) to the TRU (Transformer Rectifier Unit) by using a bi-directional DC converter. Having the above in mind, we can see that the discussed system works in the feedback loop, so that the equation defining the voltage distribution on the side of the system responsible for generating the DC voltage and DC can be written in the following form [10], [11]:

$$L\frac{di_x}{dt} + R_s i_x = e_x - u_x = e_x - (u_x N + u_{N0}) \tag{1}$$

where e_x is the value of the AC voltage source, and i_x is the phase current present in the analyzed system.
Hence, the mathematical notation of both quantities is as follows:

$$\begin{cases} e_x = E_m \cos\left(\omega t - \frac{2\pi k}{3}\right) \\ i_x = I_m \cos\left(\omega t - \frac{2\pi k}{3}\right) \end{cases} \tag{2}$$

where E_m is the amplitude of the triode voltage, I_m means the value of the AC current amplitude, in turn the parameter is denoted as k =0, 1, 2 and x = a, b, c, and ω is the frequency of a three-phase system expressed in w rad/s.

In the discussed system, it is possible to convert the neutral voltage and the grounding voltage, which have been expressed in the following form:

$$\begin{aligned} u_{xN} &= u_{dc} \cdot S_x \\ u_{N0} &= -\frac{u_{dc}}{3} \sum_{x=a,b,c} S_x \end{aligned} \tag{3}$$

where S_x is the switching function specified by the following relationship:

$$S_x = \begin{cases} 1, & S_{xp} \text{ is on and } S_{xp} \text{ is off} \\ 0, & S_{xp} \text{ is on and } S_{xp} \text{ is off} \end{cases} \tag{4}$$

By substitution of equations (3) and (4) for mathematical relationship (1) was obtained:

$$L\frac{di_x}{dt} + R_s i_x = e_x - u_{dc}\left(S_x - \frac{1}{3}\sum_{x=a,b,c} S_x\right) \tag{5}$$

The resulting DC current can be expressed as the sum of the three-phase currents present in the system [12], [13]:

$$i_{dc} = S_a i_a + S_b i_b + S_c i_c \tag{6}$$

Subsequently, by grouping differential equations, they can be formulated in a matrix equation, reflecting all current and voltage relationships occurring in the analyzed system:

$$\begin{cases} L\begin{bmatrix} \frac{di_a}{dt} \\ \frac{di_b}{dt} \\ \frac{di_c}{dt} \end{bmatrix} + R_s \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} = \begin{bmatrix} e_a \\ e_b \\ e_c \end{bmatrix} - u_{dc} \begin{bmatrix} S_a - \frac{1}{3}\sum_{x=a,b,c} S_x \\ S_b - \frac{1}{3}\sum_{x=a,b,c} S_x \\ S_c - \frac{1}{3}\sum_{x=a,b,c} S_x \end{bmatrix} \\ C\frac{du_{dc}}{dt} = [S_a, S_b, S_c] \cdot \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} - \frac{u_{dc}}{R_L} - i_{Ldc} \end{cases} \tag{7}$$

When the power control system is switched on in the aircraft, the stationary coordinate system is transformed into two coordinate systems depending on the position of the magnets
d-q in the AC three-phase AC generator, which is depicted in the figure below (Fig. 2).

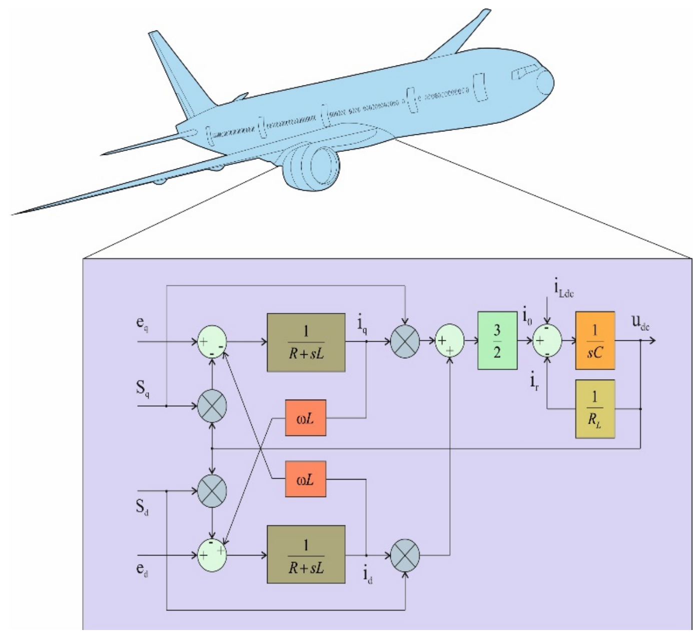

Fig. 2 Block diagram of the power control system in the electrical network of the aircraft in accordance with the concept of MEA

As a result, it was obtained:

$$\begin{cases} L\begin{bmatrix} \frac{di_d}{dt} \\ \frac{di_q}{dt} \end{bmatrix} + R_s \begin{bmatrix} i_d \\ i_q \end{bmatrix} = \begin{bmatrix} e_d \\ e_q \end{bmatrix} + \begin{bmatrix} 0 & \omega L \\ -\omega L & 0 \end{bmatrix} \cdot \begin{bmatrix} i_d \\ i_q \end{bmatrix} - \begin{bmatrix} S_d \\ S_q \end{bmatrix} u_{dc} \\ C\frac{du_{dc}}{dt} = \frac{3}{2}\begin{bmatrix} S_d & S_q \end{bmatrix} \cdot \begin{bmatrix} i_d \\ i_q \end{bmatrix} - \frac{u_{dc}}{R_L} - i_{Ldc} \end{cases} \tag{8}$$

where e_{dq} are the qualities of the input voltage source of the converter system.

B. Mathematical model of a multi-pulse rectifier in the field of AC/DC processing

In the case when the analyzed system is switched into the inverter operation mode, the DC power source supplies power to the converter, followed by the reverse transformation process from the DC to the AC side.

Thus, the mathematical notation in the form of a differential equation will be presented in the following way [14], [15], [16]:

$$\begin{cases} L\begin{bmatrix}\frac{di_a}{dt}\\ \frac{di_b}{dt}\\ \frac{di_c}{dt}\end{bmatrix}+R_s\begin{bmatrix}i_a\\ i_b\\ i_c\end{bmatrix}=u_{dc}\begin{bmatrix}S_a-\frac{1}{3}\sum\limits_{x=a,b,c}S_x\\ S_b-\frac{1}{3}\sum\limits_{x=a,b,c}S_x\\ S_c-\frac{1}{3}\sum\limits_{x=a,b,c}S_x\end{bmatrix}-\begin{bmatrix}e_a\\ e_b\\ e_c\end{bmatrix}\\ C\frac{du_{dc}}{dt}=-[S_a,S_b,S_c]\cdot\begin{bmatrix}i_a\\ i_b\\ i_c\end{bmatrix}-\frac{u_{dc}}{R_L}+i_{Ldc}\end{cases} \tag{9}$$

In the next step of analysis, using the Park's transformations, equation (9) can be presented as follows:

$$\begin{cases} L\begin{bmatrix}\frac{di_d}{dt}\\ \frac{di_q}{dt}\end{bmatrix}+R_s\begin{bmatrix}i_d\\ i_q\end{bmatrix}=\begin{bmatrix}S_d\\ S_q\end{bmatrix}u_{dc}+\begin{bmatrix}0 & \omega L\\ -\omega L & 0\end{bmatrix}\cdot\begin{bmatrix}i_d\\ i_q\end{bmatrix}-\begin{bmatrix}e_d\\ e_q\end{bmatrix}\\ C\frac{du_{dc}}{dt}=\frac{3}{2}\begin{bmatrix}S_d & S_q\end{bmatrix}\cdot\begin{bmatrix}i_d\\ i_q\end{bmatrix}-\frac{u_{dc}}{R_L}+i_{Ldc}\end{cases} \tag{10}$$

C. Methods of regulating speed and torque of PMSM electric machine in a DC system

The system controlling the frequency inverter can implement different algorithms. Each of them provides a different functionality and properties of the drive unit, as illustrated in the drawing below (Fig. 1). The easiest and the most commonly used is the scalar U/f algorithm.

The rotational speed is controlled by changing the frequency of the motor's windings (Fig. 3). In order to maintain a relatively constant torque, in proportion to frequency changes, the voltage supplied to the PMSM electrical machine (engine) terminals is also changed [17], [18].

In addition, it should be noted that the U/f frequency converter does not regulate the speed, but only the frequency of the motor supply voltage. Due to the occurrence of the slip phenomenon, i.e. the difference between the speed of rotation of the magnetic field in the electric motor and the rotational speed of the motor shaft, hence the rotational speed of the motor shaft is not strictly proportional to the frequency.

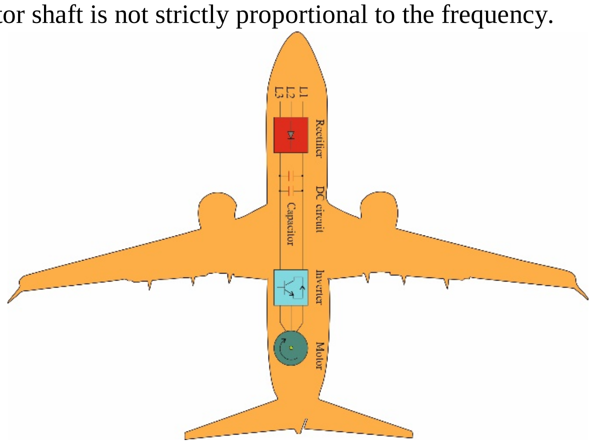

Fig. 3 General scheme of the frequency converter

Additionally, it should be added that frequency converters with the U/f algorithm are used in applications that do not require precise speed control and where the load torque decreases with the speed or is relatively constant in the entire range of its changes.

III. Results of Simulation Tests of Selected Multi-Pulse Rectifiers in the Field of AC/DC/DC Processing in Accordance With the MEA Concept

The simulation tests were performed for the control system of the AC/DC/AC double-sided converter shown in the following figures (Figs. 4-8). The parameters of the induction motor, supply network and intermediate circuit used in the tests are given in TABLE II.

TABLE II Parameters of simulation model

Parameters of squirrel-cage induction motor:	
P_N= 10 kW	J = 0,067 kg-m^2
U_{1fN} = 220 V	R_s = 0,4937 Ω
I_{1fN} = 20,5 A	R_r = 0,3756 Ω
ω_N = 152 rad/s	Ls_σ = $L_{r\sigma}$ = 2,9mH
p_b = 2	L_m = 51,9mH
Parameters of the supply network and DC circuit:	
e_2 = 230 V	L_g = 30mH
f_B = 50 Hz	C_d= 15mF
R_g = 0,1 Ω	

The control system of the voltage inverter maintains the set value of the angular velocity ω_{ref} = 100 rad/s.

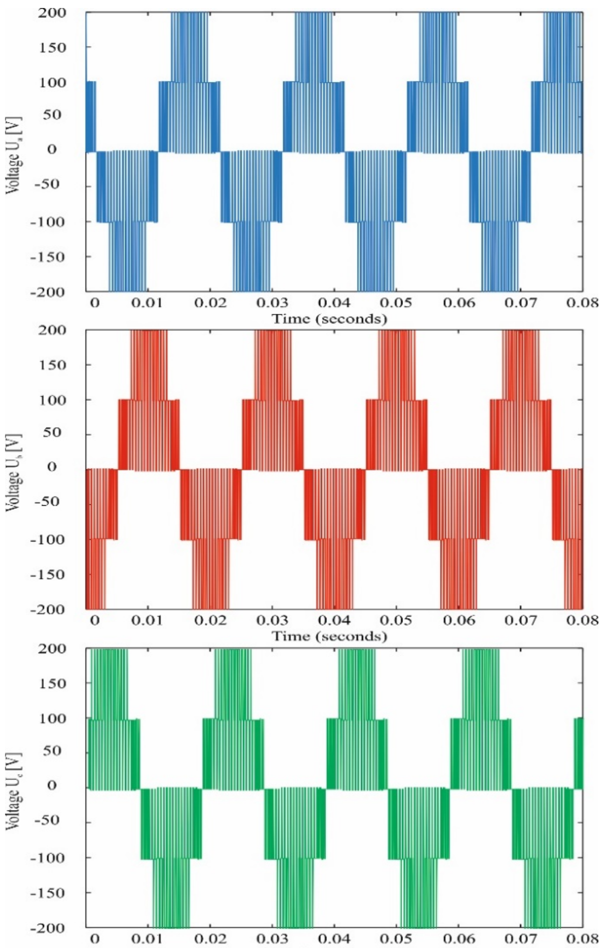

Fig. 4 Voltage waveforms generated at the AC/DC/DC output

Figure 4 presents graphs showing the content of higher harmonics in voltage waveforms, obtained from the TRU rectifier circuit shown in Fig. 1. The presented graphs reflect the content of higher harmonics in voltage waveforms with a sinusoidal supply. Based on the analysis of individual charts, we can observe both a small (less than 1%) value of the harmonic amplitude 5 of the supply voltage, as well as a low content of 5, 7 harmonics of the supply current (engine current).

In turn, on the basis of the analysis of the diagrams from Figure 5, showing the content of higher harmonics at the power supply from the power electronic converter, we can notice a very high content of higher harmonics of the current consumed by the converter from the power network of the aircraft. Also the content of higher harmonics in the other waveforms is increased in relation to the sinusoidal supply, namely: for frequency equal to 400 Hz, 5, 9, 16 and 17, the harmonic has a higher value, and for power supply with frequency 450 Hz, an increase in 5, 7 , 9, 13, 17 harmonics of the engine voltage can be observed.

It should also be noted that the change of the power source from sinusoidal to the converting causes a decrease in the efficiency of the engine: by 6% for power supply with frequency. In view of the above, the obtained current time waveform of the system's source in the field of AC/DC/DC processing of supply shown in Fig. 5 is sufficiently close to the sinusoidal variable waveform. Simulation studies of the implemented model were performed in terms of the behavior of the rectifier system at the change of load for a constant voltage level and for changes in the voltage level of the capacitor at a constant load current. The entire simulation research process was performed at the maximum load of the aircraft's electrical network.

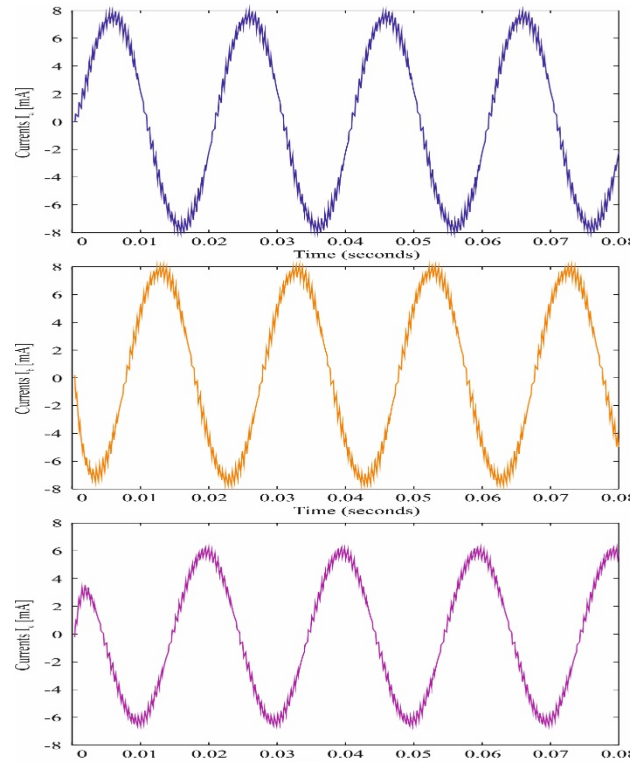

Fig. 5 Current waveforms generated at the AC/DC/DC output

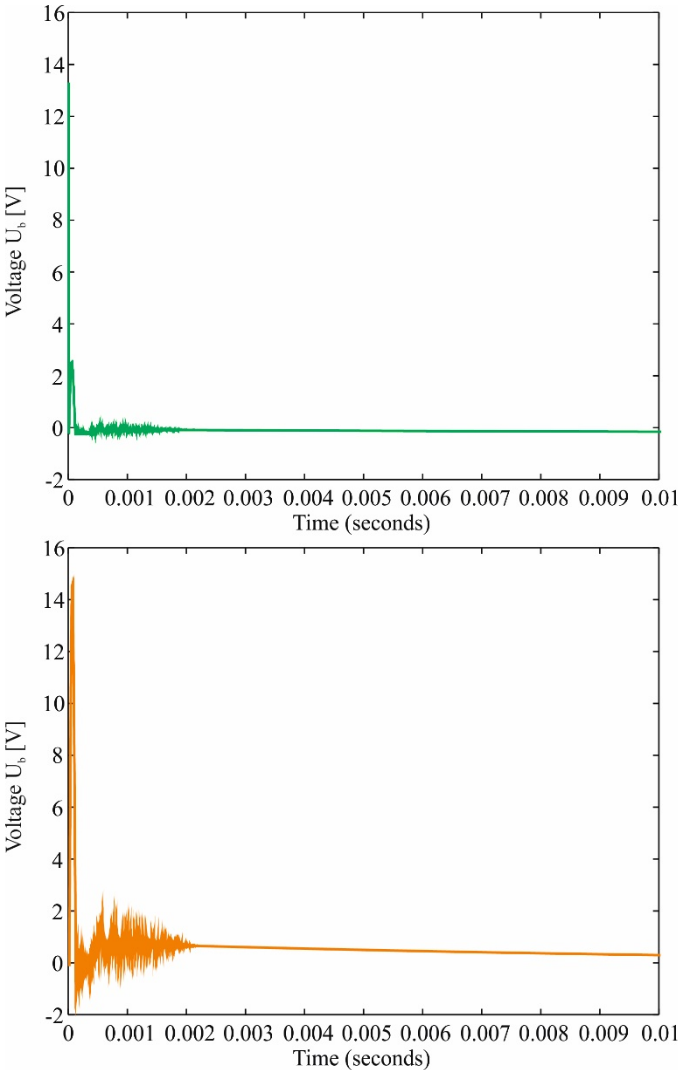

Fig. 6 Voltage waveforms generated at the DC/DC output at different starting angle δ =0^o and δ =30^o for the U_a component

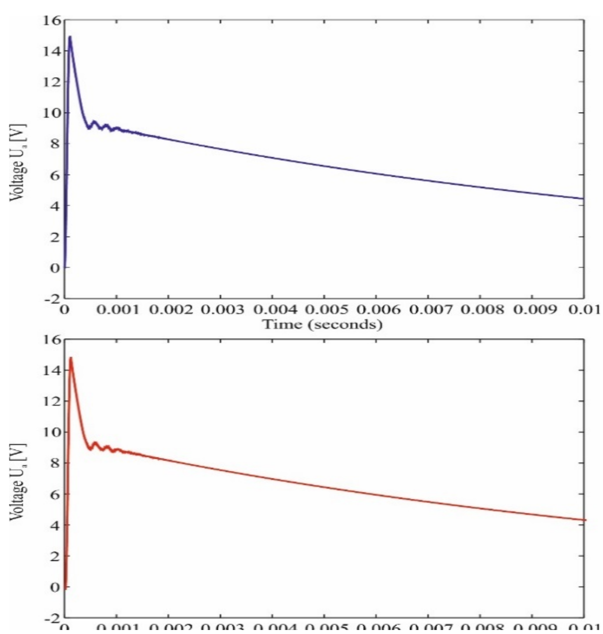

Fig. 7 Voltage waveforms generated at the DC/DC output at different initial angle δ =0^o and δ =30^o for the U_b component

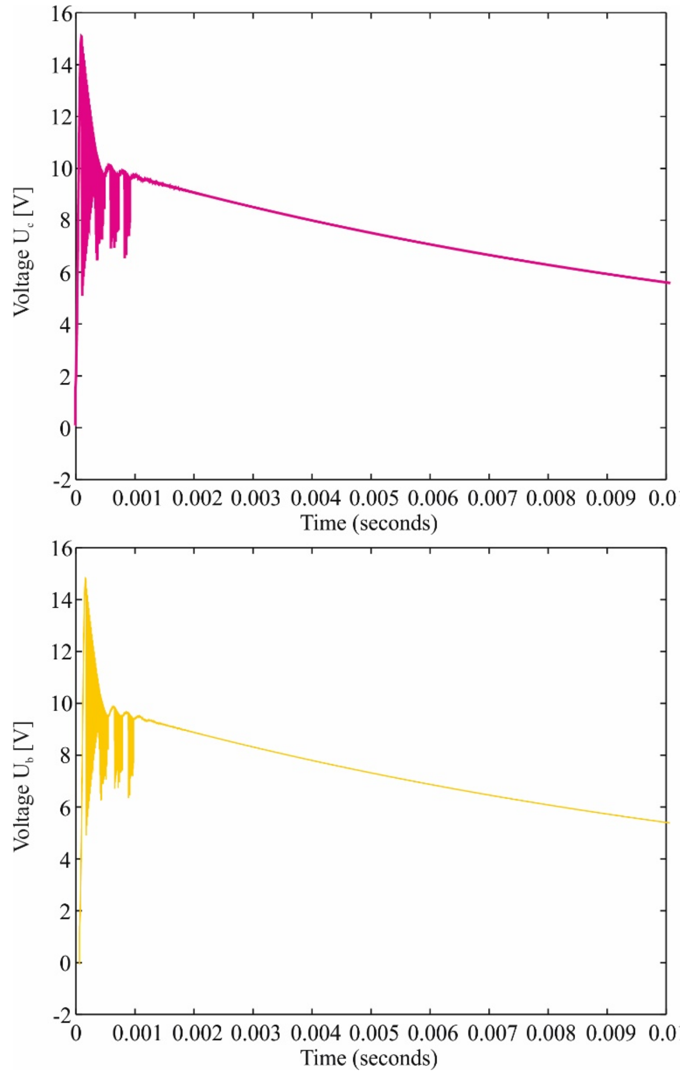

Fig. 8 Voltage waveforms generated at the DC/DC output at different initial angle δ =0^o and δ =30^o for the U_c component

Summing up, the simulation results shown in Figs. 6-8 indicate that with a constant set voltage the control system maintains the preset charge of the capacitor to 100V, the maximum over-regulation value does not exceed 6V, and when charged to a voltage equal to 480V, it does not exceed 3V
(Fig. 8).

IV. Conclusion

The paper presents the analysis of vector control with an induction drive with a frequency converter in a double-sided AC/DC/AC converter system. The use of a double-sided converter provides four-quadrant operation of the drive system with the possibility of regenerating the braking energy to the mains. A double-sided modulated AC/DC/AC converter using appropriate control methods ensures the consumption of network currents with waveforms similar to a sine wave.

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At the same time, the control system ensures that the inverter can operate at any adjustable value of the *cosφ* power factor. Then the drive system is characterized by the reactive power compensation properties consumed by receivers installed nearby.

The AC/DC/DC conversion processing system proposed in the article with regulated intermediate circuit voltage allows fluent voltage regulation in the 50-550 [V] range. Due to the voltage reduction, the amplitude of the current ripple is reduced, so that the waveform of the sampled average value is milder.

During operation of the system, when the value of the capacitor voltage changes, the current value deviates from the set value, however, this phenomenon may be reduced using the tunable PID (proportional-integral-derivative) algorithm, the regulator used in control systems, taking into account the current voltage value. The controller of this type consists of three parts: proportional, integral and differentiating, whose key goal is to maintain the output value (in our case voltage) at a given level, i.e. set value [19], [20].

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