Cycloconverter Based on Bridge Circuit for Power Supply Systems of Autonomous Objects

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***Abstract* – This paper presents the method of increasing the input power factor and output voltage fundamental harmonic of the cycloconverter based on bridge circuit and proposed to be used in power generation system of aircraft. The increase of the output voltage fundamental harmonic is achieved by introducing the combined control law. The combined control signal assumes the artificial introduction of components that are multiple of third harmonic by summation the sine wave signal with the triangle wave signal that have three-tuple frequency of fundamental harmonic. The main energy characteristics of the cycloconverter were obtained.**

***Index Terms* – cycloconverter, combined control law, input power factor.**

I. INTRODUCTION

TODAY GOST- 54073-2010 REGULATES the requirements for electrical energy generating systems of the type of "variable speed - constant frequency system" to autonomous objects namely for aircraft. Three-phase ac system should provide the three-phase as well as single-phase power supply with the rated voltage of 115/200 V and the constant nominal frequency of 400 Hz or the variable nominal frequency of 360 ... 800 Hz. Application of the ac systems with dual rated voltage of 230/400 V with the constant frequency of 400 Hz or the variable frequency 360 ... 800 Hz is allowed. The voltage waveform should be sinusoidal. Three-phase ac system must be star-connected with neutral grounded [1].

The structurally of airborne electrical energy generating systems can be constructed on the base of immediate frequency converters with natural commutation (cycloconverter). It can be concluded based on analytical review of domestic and foreign publications [2-5] that application of the electrical energy generating systems with a static frequency converter of the type of "permanent-magnet generator - cycloconverter" based on zero circuit or six-pulse bridge circuits on board of aircraft including special purpose is perspective. Such systems have several advantages:

- there is possible to provide any required quality of generated electricity in static and dynamic modes;
- limit on power of the electrical energy generated channel is absent;
- there is ability to minimize of mass-dimensional parameters of the system;
- the limit on the nature of the load is absent;
- there is the possibility of parallel operation of generating channels, both among themselves and with the land-based sources of electricity;
- there is high efficiency and the possibility of it further increase;
- there is high operational reliability;
- there is resistance to special effects with proper construction of the power circuit.

II. PROBLEM DEFINITION

The main objective of this study is to increase the input power factor of the six-pulse bridge circuit of the cycloconverter which is part of electrical energy generating systems for aircraft.

The object of study is the cycloconverter with combined control law from the sum of fundamental harmonic signal and tripled frequency triangular waveform signal. In this study the control law is understood how the dependence on the thyristor control angle α. It is assumed that introduction of the combined control law will increase the input power factor of the cycloconverter.

III. THEORY

The structural diagram of the cycloconverter power circuits is shown on Fig. 1, where: u_c, i_c - voltage and current supply; m_1 - the number of phases of the mains; w_1 - angular frequency of the mains; u_2, i_2 - voltage and current at the output; m_2 - the number of output phases; w_2 - angular frequency at the output. The cycloconverter produces three-phase output voltage using the identical reverse rectifier converters F_1, F_2, F_3.

The electrical diagram of the cycloconverter power circuits based on bridge circuit is shown on Fig. 2, where: e_{1c}, e_{2c}, e_{3c} – EMF of mains; i_{1c}, i_{2c}, i_{3c} - currents of mains; $V_1 - V_6$ - thyristors of even group; $V_1^{'} - V_6^{'}$ - thyristors of odd group; RRC_A, RRC_B, RRC_C, RRC_0 - reverse rectifier converters; e_{2A}, e_{2B}, e_{2C}, e_{20} - internal EMF of reverse rectifier converters; i_{2A}, i_{2B}, i_{2C} – the output currents; i_{20} - current of the fourth reverse rectifier converter; u_{2A}, u_{2B}, u_{2C} – the output voltages.

The input power factor indicates how much power consumed of the network is transformed into the useful power which ultimately determines the work performed by the load. The input power factor on Fig. 1 in sections C1 and C2 is defined according to the relation:

$$\chi = \frac{P}{S}, \quad (1)$$

where P,S are active and apparent power in sections C_1 and C_2.

Input power factor increases with the amplitude of the fundamental harmonic of the output voltage, which is achieved by the introduction of the combined control law. The combined control signal assumes the artificial introduction of components that are multiple of third harmonic by summation the sine wave signal with the triangle wave signal that have three-tuple frequency of fundamental harmonic.

According to Fig. 3 the nature of change of control angles in the interval [0, π] can be determined using the relation:

$$\alpha_{jCOM(A,B,C)}(\vartheta_2) = \alpha_{jSIN}(\vartheta_2) + \frac{\Delta\alpha_{MIDL}(\vartheta_2)}{2} \quad (2)$$

where $\vartheta_2 = \omega_2 t$.

The change control angles law for the three output phases of the cycloconverter at the sinusoidal control signal ($j=1,2,3$, which corresponds to the output phases A, B and C) [6]:

$$\alpha_{jSIN}(\vartheta_2) = \frac{\pi}{2}\left\{1 - M \sin\left[\vartheta_2 - (j-1)\frac{2\pi}{3}\right]\right\}. \quad (3)$$

The combined additive:

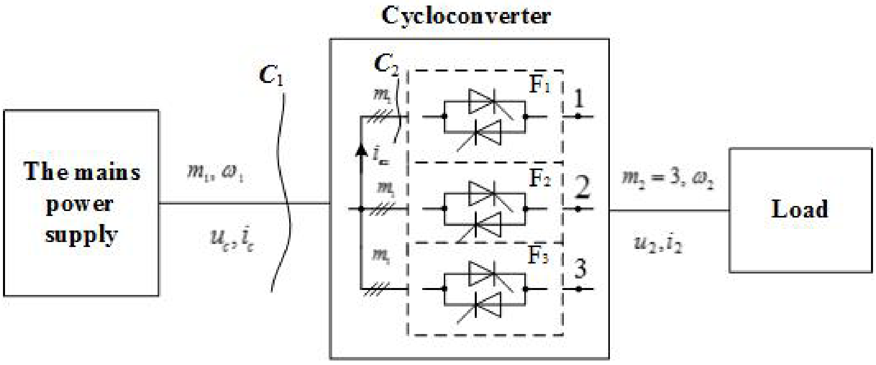

Fig. 1 The structural diagram of the cycloconverter power circuit

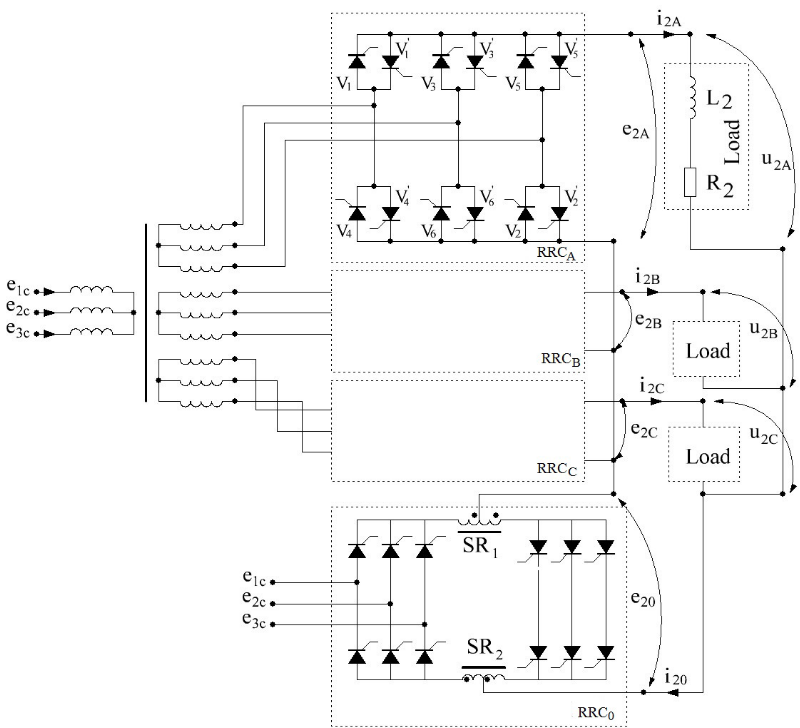

Fig. 2 The electrical diagram of the cycloconverter power circuit

$$\Delta\alpha_{MIDL}(\vartheta_2) = Midl\{\alpha_1(\vartheta_2), \alpha_2(\vartheta_2), \alpha_3(\vartheta_2)\} \quad (4)$$

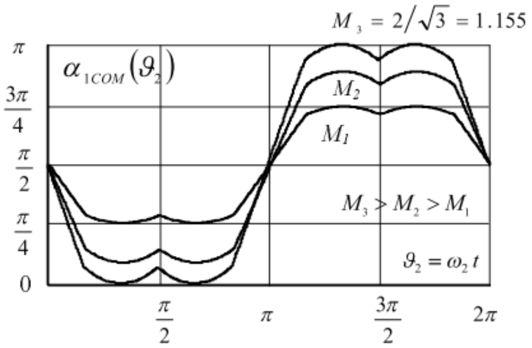

Fig. 3 Combined control law

Nature of the change of the combined additive in time is shown on Fig.4.

The control method proposed allows to expand the linear range of the input sine wave of $2/\sqrt{3} = 1.155$ times. Fig.3 shows that harmonics with frequencies $(6k-3)\omega_2$ (where k = 1,2,3 ...) in the combined additive $\Delta\alpha_{MIDL}(\vartheta_2)/2$ are present. Such harmonics will produce of similar components in the output voltage of the cycloconverter. Since the harmonics with frequencies $(6k-3)\omega_2$ (where k = 1,2,3 ...) create a zero sequence of output voltage it can be compensated by adding the reverse rectifier converter (RRC_0) in the zero load wire that generates a voltage as shown on Fig. 2. The control law for optional reverse rectifier converter chosen in the form:

$$\alpha_0(\vartheta_2) = \frac{\Delta\alpha_{MIDL}(\vartheta_2)}{2} \cdot \Im(M) \quad (5)$$

where $\Im(M)$ is the function that takes into account of variation of the transmission gate of rectifier converters RRC_A, RRC_B, RRC_C at harmonic with the frequency $(6k-3)\omega$, depending on the modulation depth M.

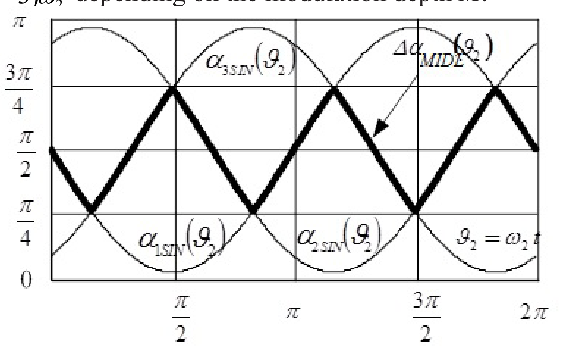

Fig. 4 The nature of change of the combined additive in time

According to Fig. 2 the output voltages of the cycloconverter will be defined as:

$$u_{2j} = e_{2j} + e_{20}, \; j = A, B, C \quad (6)$$

It is seen from Fig.2 that the fourth reverse rectifier converter $RRC_{0\ operates}$ in a joint control mode. This operating mode requires the installation of the smoothing reactors SR_1 and SR_2 to limit the equalization currents flowing inside the kit. Worth noting that the smoothing reactors also perform the function of limitations of the zero sequence current that occurs under the action of the zero sequence voltage:

$$u_{20} = \frac{1}{3}(u_{2A} + u_{2B} + u_{2C}) = \frac{1}{3}(e_{2A} + e_{2B} + e_{2C}) - e_{20}. \quad \mathbf{(7)}$$

The oscillogram of the output voltage of phase A in relative units $u_{2A}/\sqrt{6}E_c$ where E_c - the effective value of the mains voltage shown on Fig.5.

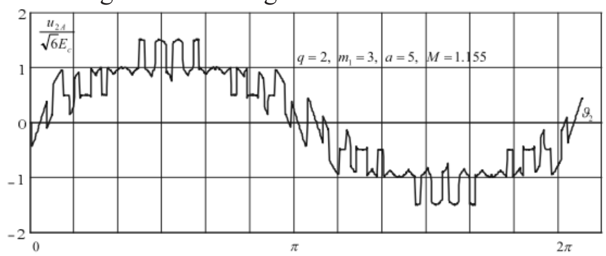

Fig.5 The output voltage of the cycloconverter ohase A with multiplicity frequency $a=\omega_1/\omega_2=5$

The waveform of the zero sequence voltage in relative units $u_{20}/\sqrt{6}E_c$ shown on Fig. 6. The amplitude-frequency spectrum of a signal specified is shown in Fig. 7.

The expression for the effective value of the output voltage fundamental harmonic is given by:

$$E_{2(1)}(q, m_1) = \frac{qm_1}{\pi}\sin\frac{\pi}{m_1} 2\left\{ J_1\left(M\frac{\pi}{2}\right) J_0\left(M\frac{3\sqrt{3}}{16}\right) + \left[J_2\left(M\frac{\pi}{2}\right) - J_4\left(M\frac{\pi}{2}\right)\right] J_1\left(M\frac{3\sqrt{3}}{16}\right)\right\} E_c \quad (8)$$

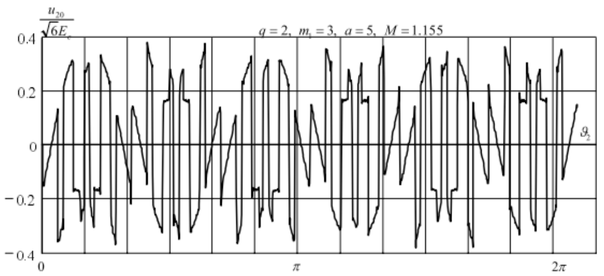

Fig. 6 The zero sequence voltage

The plot of this dependence is shown on Fig. 8. It is noteworthy that the maximum value of the fundamental harmonic for a given control law up higher on 8-15% than the sinusoidal control signal.

It is possible to determine the coefficients of harmonic distortion ν_{U2} and output voltage $k_{\tilde{A}U2}$ knowing the value of the fundamental harmonic of the output voltage and the effective value of the voltage. Calculations indicate that the coefficient of distortion in the combined control law on the 1-1.5% less than the sinusoidal control signal.

We obtain the expression of the current value of the current I_2, which is equal to the effective current value of the fundamental harmonic taking the assumption that the load current is sinusoidal:

$$I_2 = I_{2(1)} \tag{9}$$

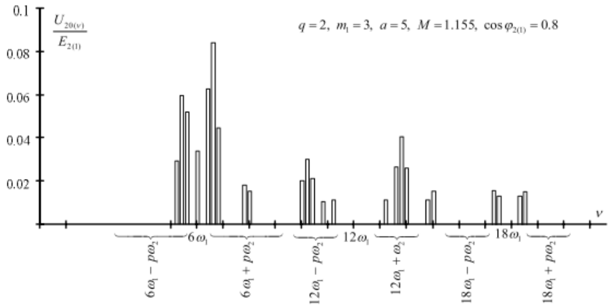

Fig. 7 The amplitude-frequency spectrum of the zero sequence voltage

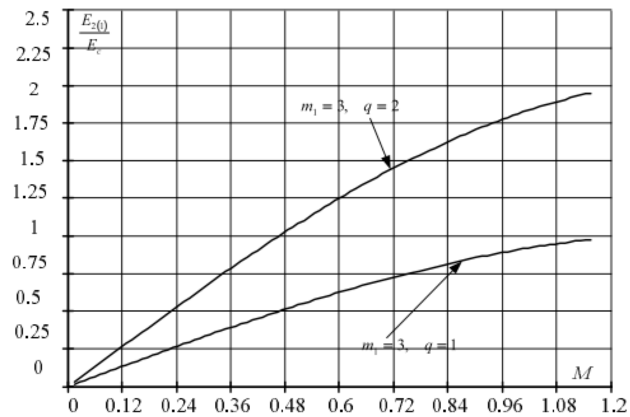

Fig. 8 The dependence of the effective value of the output voltage on the modulation depth

Then assuming that the efficiency of the cycloconverter is equal to unity and the load is balanced the input power factor in the general case and the single-phase mode will be determined according to the relation:

$$\chi_{1COMB}^{q,m_1} = \frac{P_{in}}{S_{in}} = \frac{E_{2(1)} I_{2(1)} \cos\phi_{2(1)}}{m_1\, E_c\, I_{in}} =$$
$$= \frac{\sqrt{qm_1}}{\pi} \sin\frac{\pi}{m_1} 2\left\{ J_1\left(M\frac{\pi}{2}\right) J_0\left(M\frac{3\sqrt{3}}{16}\right) + \right.$$
$$\left. + \left[J_2\left(M\frac{\pi}{2}\right) - J_4\left(M\frac{\pi}{2}\right)\right] J_1\left(M\frac{3\sqrt{3}}{16}\right)\right\} \cos\phi_{2(1)}, \tag{10}$$

where S_{in} и P_{in} – active and full power to the cross section C_2, $cos\varphi_{2(1)}$ is the angle of shear of the first harmonic of the load current from the first harmonic of the output voltage of the cycloconverter. The plot of the expression obtained is shown on Fig. 9.

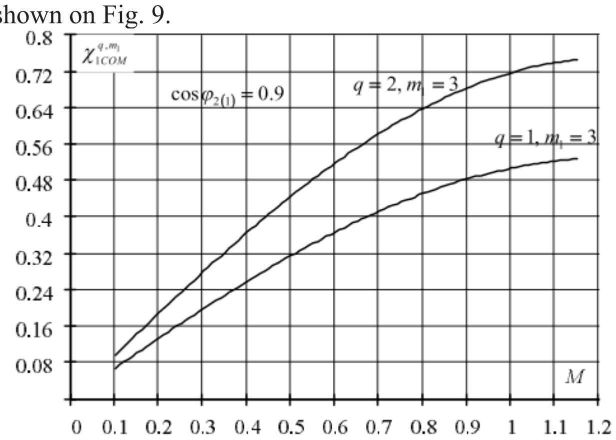

Fig. 9 The dependence of the input power factor from the modulation depth

Let us define the input power factor of the cycloconverter in section C_1. The research [6] is shown that the effective value of the current mains Ic in the C1 cross section for the bridge circuit can be determined according to the following expression:

$$I_c = \sqrt{2}\, I_{2(1)} \sqrt{1 + 2\ \xi(M, \cos\phi_{\ 2(1)}}, \tag{11}$$

where:

$$\xi\left(M, \cos\varphi_{\ 2(1)}\right) = \left(0.965M - 0.079\right)\cos\varphi_{\ 2(1)} - 1.138M + 0.821;$$

Then, the power factor of the cycloconverter will determined as:

$$\chi_{3COMB} = \frac{P_c}{S_c} = \frac{m_2\, E_{2(1)} I_{2(1)} \cos\phi_{2(1)}}{m_1\, E_1\, I_c} \frac{\sqrt{3}\, \chi_{1COMB}^{2,3}}{\sqrt{1 + 2\ \xi(M, \cos\phi_{\ 2(1)})}}, \tag{12}$$

where P_c, S_c are active and full power to the cross section C_1; $\chi_{1COMB}^{2,3}$ is the power factor for the bridge circuit of the C_1 cross-section.

The dependence of the input power factor of the C1 cross section on the modulation depth is shown on Fig. 10. The dependence of the input power factor of the C1 cross-section on the changes of the shift angle of the first harmonic of the load current relative to the first harmonic of the output voltage of the cycloconverter shown on Fig. 11.

Comparing the input power factor $\chi_{3COMB}^{2,3}$ with the same coefficient at the sinusoidal control law [7] It is evident that in the case of combined control law the input power factor greater than 14.5% with a modulation depth M=0.2, and greater than 8.5% with maximum modulation depth, which corresponds M=1 to a sinusoidal law and $M = 2/\sqrt{3}$ to a combines law.

V. CONCLUSIONS

According to the results of this work can be said that the maximum value of the fundamental harmonic of the output voltage at the combined control law above 8-15% higher

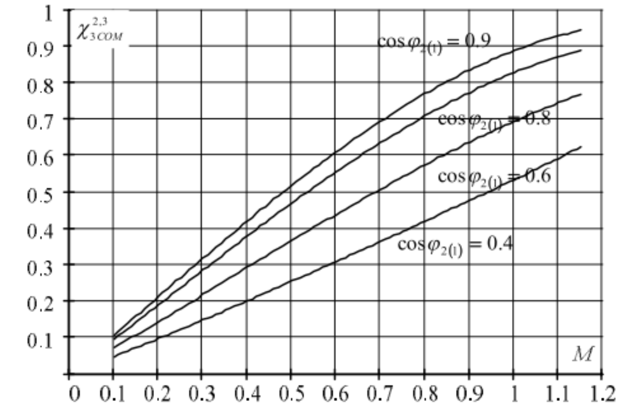

Fig. 10 The dependence of the input power factor (C1 cross section) on the modulation depth

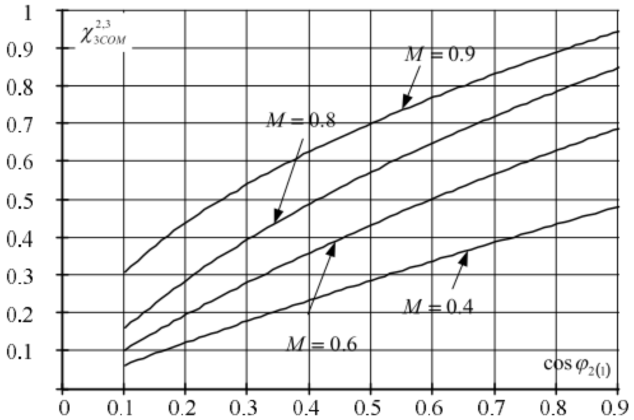

Fig. 11 . The dependence of the input power factor at the changes of the shift angle of the first harmonic of the load current relative to the first harmonic of the output voltage

than for a sinusoidal control signal. However, the application such a control law requires the installation of the optional reversing converter RRC_0. The distortion factor at the combined control law by 1-1.5% less than with a sinusoidal control signal. At the combined control the input power factor on the C1 cross-section section at the maximum modulation depth is larger by 8.5% compared to sinusoidal control law. The cycloconverter circuit proposed meets the requirements of GHOST - 54073-2010 [26] and can be used as a frequency converter for electrical energy generating systems of aircraft.

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