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# THE POSSIBILITY ANALYSIS OF POWER INCREASE EFFICIENCY IN GENERATING DEVICES FOR ONBOARD RADIO-ELECTRONIC MEANS

*A generalized analysis of a high frequency key generator is conducted. This analysis allows the power indicators estimation of the generator in a wide frequency range, and in scheme parameters.*

*Keywords: key generator, on-board system, resonance inverter.*

In the issues of space development there is an important one of power supply maintenance for independent objects; these objects are intended for long-term presence in orbit or in interplanetary space. One of the working capacity maintenance ways of long-term space objects is the increase in power efficiency for the basic consumers – onboard electronic systems. This particularly concerns powerful generating devices for communication purposes.

For powerful radio devices the biharmonic mode generator had been widely used. With the advent of powerful solid-state electronics application, duple schemes of consecutive resonant inverters (class generators "D") [1] came into exploitation.

The possibility of energy conversion efficiency increase with an upset loading, was discovered by E. P. Khmelnitskiy in the 1960s [2]. In foreign sources, generators of such type were known as class E generators, as in Russian they were identified as key generators with a forming contour [3]. Despite the fact that class E generators provide high energy conversion efficiency for limited key modes frequencies, in a variety of causes their application is limited, and they are still on the stage of experiment. The scheme analysis for a wide range of frequencies and scheme parameters generally, has a lower result.

A simplified scheme of the generator is presented in figure 1, where AE is the active element (transistor, lamp) working in the *key* mode; VD is a diode that provides recuperation of energy of jet elements in an opened key; $L$, $C$ are the elements of a contour, defining the form of pressure on AE; $L_k$, $C_k$ are the loading contours, which have been adjusted to the frequency of operating pressure.

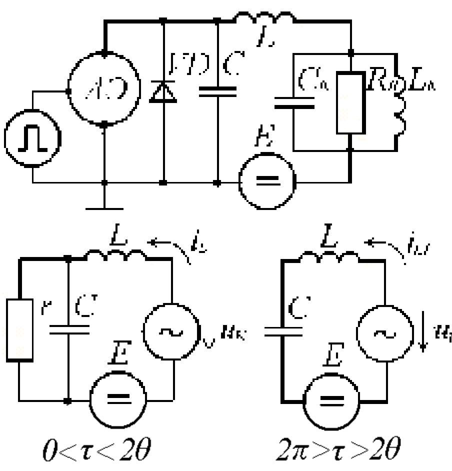


Fig. 1. Scheme of the generator

Supposing, that the unlocking and locking of AE is completely defined the by operating pressure ($U_k$), we will present the investigated generator in two equivalent schemes; they will show the processes happening in the generator in open and closed conditions of the AE. Here $u_к = U_к \sin(\tau + \varphi)$; $\tau = \varphi t$; $2\theta$ – an angle corresponding to the time during which the AE is open; $i_{L1}$, $i_L$ – currents in the external chain of the generator for corresponding equivalent schemes.

The differential equation for equivalent schemes becomes:

$$\frac{d^2 i_L}{d\tau^2} + \frac{1}{r\omega C}\frac{di_L}{d\tau} + \nu^2 i_L = \frac{\nu^2 E}{r} - U_k\left(\frac{\nu^2 \sin(\tau+\varphi)}{r} + \frac{\cos(\tau+\varphi)}{\omega L}\right), \quad (1)$$

$$\frac{d^2 i_{L1}}{d\tau^2} + \nu^2 i_{L1} = -\frac{U_k}{\omega L}\cos(\tau+\varphi). \quad (2)$$

The solution for these equations can be written down the following way:

$$i = \sigma + \xi\varepsilon_1 \cos(\tau+\varphi) - \xi\varepsilon_2 \sin(\tau+\varphi) + I_{11}e^{p1\tau} + I_{12}e^{p2\tau}..., \quad (3)$$

$$i_1 = I_{21}\cos\nu(\tau-2\theta) + I_{22}\sin\nu(\tau-2\theta) - \frac{1}{\nu^2-1}\xi\cos(\tau+\varphi), \quad (4)$$

$$U = -\xi\varepsilon_1 \sin(\tau+\varphi) - \xi\varepsilon_2\cos(\tau+\varphi) + p_1 I_{11}e^{p1\tau} + p_2 I_{12}e^{p2\tau},$$

$$U_1 = \nu I_{22}\cos\nu(\tau-2\theta) - \nu I_{21}\sin\nu(\tau-2\theta) + \frac{1}{\nu^2-1}\xi\sin(\tau+\varphi). \quad (5)$$

The following designations are accepted here: $i = i_L\frac{\omega L}{E}$, $i_1 = i_{L1}\frac{\omega L}{E}$, $u = \frac{L}{E}\frac{di_L}{d\tau}$, $u_1 = \frac{L}{E}\frac{di_{L1}}{d\tau}$, $p_1 = -\frac{1}{\omega r C}$, $p_2 = -\frac{1}{\sigma}$ – roots of the characteristic equation (1); $\nu^2 = \frac{1}{\omega^2 LC}$, $\sigma = \frac{\omega L}{r}$, $\xi = \frac{U_k}{E}$, $\varepsilon_1 = \frac{p_1^2 - (\nu^2-1)}{p_1 + (\nu^2-1)^2}$, $\varepsilon_2 = \frac{\sigma\nu^4}{p_1^2 + (\nu^2-1)^2}$, $I_{11}, I_{12}, I_{21}, I_{22}$ – integration constants.

Supposing that the generator mode had been established, we will define the integration constants, using the current continuity principle in inductance and in capacity pressure of contour LC:

$$i(0) = i_1(2\pi); i(2\theta) = i_1(2\theta), \quad (7)$$

$$u_c = u_{c1}(2\pi); u_c(2\theta) = u_{c1}(2\theta) \quad (8)$$

Here $U_c = E - U_k - U_L$. (9)

On the basis of (3)–(6) in conditions (7)–(9) we will receive:

$$I_{11} = A_1 + \xi(B_{11}\sin\varphi + B_{12}\cos\varphi);$$
$$I_{12} = A_2 + \xi(B_{21}\sin\varphi + B_{22}\cos\varphi);$$
$$I_{21} = A_3 + \xi(B_{31}\sin\varphi + B_{32}\cos\varphi);$$
$$I_{22} = A_4 + \xi(B_{41}\sin\varphi + B_{42}\cos\varphi). \quad (10)$$

In the last expressions the following designations are accepted:

$$A_1 = \frac{a_2 b_3 - a_3 b_2}{a_1 b_2 - a_2 b_1}; \; A_2 = \frac{a_3 b_1 - a_1 b_3}{a_1 b_2 - a_2 b_1};$$
$$B_{11} = \frac{a_2 b_{41} - a_{41} b_2}{a_1 b_2 - a_2 b_1};$$
$$B_{12} = \frac{a_2 b_{42} - a_{42} b_2}{a_1 b_2 - a_2 b_1};$$
$$B_{22} = \frac{a_{42} b_1 - a_1 b_{42}}{a_1 b_2 - a_2 b_1};$$
$$B_{21} = \frac{a_{41} b_1 - a_1 b_{41}}{a_1 b_2 - a_2 b_1};$$
$$a_1 = 1 - e^{2p1\theta}\cos 2\nu(\pi-\theta) - \frac{p_1}{\nu} e^{2p1\theta}\sin 2\nu(\pi-\theta);$$
$$a_2 = 1 - e^{2p2\theta}\cos 2\nu(\pi-\theta) - \frac{p_1}{\nu} e^{2p2\theta}\sin 2\nu(\pi-\theta);$$
$$a_3 = \sigma[1 - \cos 2\nu(\pi-\theta)];$$
$$a_{41} = -\varepsilon_2 + q_1\cos 2\nu(\pi-\theta) + \frac{1}{\nu} q_2 \sin 2\nu(\pi-\theta);$$
$$a_{42} = \varepsilon_2 - q_2\cos 2\nu(\pi-\theta) + \frac{1}{\nu} q_1 \sin 2\nu(\pi-\theta);$$
$$b_1 = -p_1[1 - e^{2p1\theta}\cos 2\nu(\pi-\theta) + \frac{p_2}{\nu} e^{2p1\theta}\sin 2\nu(\pi-\theta)];$$
$$b_2 = -p_2[1 - e^{2p2\theta}\cos 2\nu(\pi-\theta) + \frac{p_1}{\nu} e^{2p2\theta}\sin 2\nu(\pi-\theta)];$$
$$b_3 = -\frac{p_1}{\nu}\sin 2\nu(\pi-\theta); \qquad \varepsilon_3 = \varepsilon_1 + \frac{1}{\nu^2-1};$$
$$b_{41} = \varepsilon_2 - q_1\cos 2\nu(\pi-\theta) + \nu q_2 \sin 2\nu(\pi-\theta);$$
$$A_3 = \sigma + A_1 e^{2p1\theta} + A_2 e^{2p2\theta};$$
$$A_4 = \frac{p_1}{\nu} A_1 e^{2p1\theta} + \frac{p_2}{\nu} A_2 e^{2p2\theta};$$
$$B_{31} = B_{11} e^{2p1\theta} + B_{21} e^{2p2\theta} - q_1;$$
$$q_1 = (\varepsilon_3 \sin 2\theta + \varepsilon_2 \cos 2\theta);$$
$$B_{32} = B_{12} e^{2p1\theta} + B_{22} e^{2p2\theta} - q_2;$$
$$q_2 = (\varepsilon_3 \cos 2\theta - \varepsilon_2 \sin 2\theta);$$
$$B_{41} = \frac{1}{\nu}(p_1 B_{11} e^{2p1\theta} + p_2 B_{21} e^{2p2\theta} - q_2);$$
$$B_{42} = \frac{1}{\nu}(p_1 B_{12} e^{2p1\theta} + p_2 B_{22} e^{2p2\theta} - q_1).$$

Substituting the values of integration constants (10) in equations (3)–(6), we will receive the description of an inductance current and pressure for the established generator mode.

For the definition of the generator's power indicators it is necessary to define the current of the first loading harmonic and the current consumed from the power supply.

$$I_1 = \sqrt{I_{1s}^2 + I_{1c}^2} = \frac{I_{1s}}{\cos\varphi} = \frac{I_{1c}}{\sin\varphi}, \text{ где } tg\varphi = \frac{I_{1c}}{I_{1s}}. \quad (11)$$

Here:

$$I_{1s} = \frac{1}{\pi}\int_0^{2\theta} i_L \sin\tau\, d\tau + \frac{1}{\pi}\int_{2\theta}^{2\pi} i_{L1}\sin\tau\, d\tau =$$
$$= \frac{E}{\pi\omega L}\left(\int_0^{2\theta} i\sin\tau d\tau + \int_{2\theta}^{2\pi} i_1 \sin\tau d\tau\right) =$$
$$= \frac{E}{\pi\varpi L}[A_5 + \xi(B_{51}\sin\varphi + B_{52}\cos\varphi)]; \quad (12)$$
$$I_{1c} = \frac{1}{\pi}\int_0^{2\theta} i_L \cos\tau\, d\tau + \frac{1}{\pi}\int_{2\theta}^{2\pi} i_{L1}\cos\tau\, d\tau =$$
$$= \frac{E}{\pi\varpi L}[A_6 + \xi(B_{61}\sin\varphi + B_{62}\cos\varphi)]. \quad (13)$$

Parameters $A_5, A_6, B_{51}, B_{52}, B_{61}, B_{62}$ are defined by the following expressions:

$$A_5 = \frac{1}{\pi}[\sigma(1-\cos 2\theta) + \frac{A_1}{1+p_1^2} d_{12} +$$
$$+ \frac{1}{\nu^2-1}(A_3 d_{13} + A_4 d_{14})];$$
$$B_{51} = \frac{1}{\nu^2-1} + \frac{1}{\pi}[\varepsilon_3(\frac{\sin 4\theta}{4} - \theta) + \varepsilon_2(\frac{\cos 4\theta}{4} - \frac{1}{4}) +$$
$$+ \frac{B_{11}}{1+p_1^2} d_{11} + \frac{B_{21}}{1+p_2^2} d_{12} + \frac{1}{\nu^2-1}(B_{31} d_{13} + B_{41} d_{14})];$$
$$B_{52} = \frac{1}{\pi}[\varepsilon_2(\frac{\sin 4\theta}{4} - \theta) - \varepsilon_3(\frac{\cos 4\theta}{4} - \frac{1}{4}) +$$
$$+ \frac{B_{11}}{1+p_1^2} d_{11} + \frac{B_{22}}{1+p_2^2} d_{12} + \frac{1}{\nu^2-1}(B_{32} d_{13} + B_{42} d_{14})];$$
$$d_{11} = 1 - e^{2p1\theta}(\cos 2\theta - p_1 \sin 2\theta);$$
$$d_{12} = 1 - e^{2p2\theta}(\cos 2\theta - p_2 \sin 2\theta);$$
$$d_{13} = \cos 2\nu(\pi-\theta) - \cos 2\theta;$$
$$d_{14} = \sin 2\nu(\pi-\theta) + \nu \sin 2\theta;$$
$$A_6 = \frac{1}{\pi}[\sigma \sin 2\theta + \frac{A_1}{1+p_1^2} d_{21} +$$
$$+ \frac{A_2}{1+p_2^2} d_{22} + \frac{1}{\nu^2-1}(A_3 d_{23} + A_4 d_{24})];$$
$$B_{61} = \frac{1}{\pi}[\varepsilon_3(\frac{\cos 4\theta}{4} - \frac{1}{4}) - \varepsilon_2(\frac{\sin 4\theta}{4} + \theta) +$$
$$+ \frac{B_{11}}{1+p_1^2} d_{21} + \frac{B_{21}}{1+p_2^2} d_{22} + \frac{1}{\nu^2-1}(B_{31} d_{23} + B_{41} d_{24})];$$
$$B_{62} = -\frac{1}{\nu^2-1} + \frac{1}{\pi}[\varepsilon_2(\frac{\sin 4\theta}{4} + \theta) + \varepsilon_3(\frac{\cos 4\theta}{4} - \frac{1}{4}) +$$
$$+ \frac{B_{12}}{1+p_1^2} d_{21} + \frac{B_{22}}{1+p_2^2} d_{22} + \frac{1}{\nu^2-1}(B_{32} d_{23} + B_{42} d_{24})];$$
$$d_{21} = -p_1 + e^{2p1\theta}(p_1 \cos 2\theta + \sin 2\theta);$$
$$d_{22} = -p_2 + e^{2p2\theta}(p_2 \cos 2\theta + \sin 2\theta);$$
$$d_{23} = \nu \sin 2\nu(\pi-\theta) + \sin 2\theta;$$
$$d_{24} = \cos 2\theta - \cos 2\nu(\pi-\theta).$$

The electricity consumed from the source:

$$I_0=\frac{1}{2\pi}\int_0^{2\theta}\frac{U_c}{r}d\tau=\frac{1}{2\pi}\int_0^{2\theta}\frac{E-U_k-U_L}{r}\times$$

$$\times d\tau=\frac{E_a}{2\pi\omega L}\int_0^{2\theta}\sigma[1-\xi\sin(\tau+\varphi)-u]d\tau \qquad (14)$$

$U$ is defined by expression (5).

Result of the integration (14):

$$I_0=\frac{E_a\sigma}{2\pi\varpi L}\{2\theta+\xi[\cos(2\theta+\varphi)-\cos\varphi](1-\varepsilon_1)+$$
$$+\xi\varepsilon_2[\sin(2\theta+\varphi)-\sin\varphi]+$$
$$+I_{11}(1-e^{2p1\theta})+I_{12}(1-e^{2p2\theta})\}. \qquad (15)$$

The efficiency of the first harmonic is defined by the known parity [3]

$$\eta=\frac{1}{2}\xi\frac{I_1}{I_0}. \qquad (16)$$

$$\text{As } \xi=\frac{U_k}{E}=\frac{I_1R_н}{E}=\frac{I_{1s}R_н}{\cos\varphi}, \qquad (12)$$

that agrees $\xi=\dfrac{R_н[A_5+\xi(B_{51}\sin\varphi+B_{52}\cos\varphi)]}{\omega L\cos\varphi}$. (17)

On the other hand,

$$tg\varphi=\frac{I_{1c}}{I_{1s}}=\frac{A_6+\xi(B_{61}\sin\varphi+B_{62}\cos\varphi)}{A_5+\xi(B_{51}\sin\varphi+B_{52}\cos\varphi)}. \qquad (18)$$

The system of the transcendental equations (17), (18) allows us to define the required value of o.

From the conducted analysis we can see, that direct calculations of the generator's power indicators are rather labor-consuming, because of the bulky calculations and the impossibility of an analytical solution for this system of equations (17), (18).

Therefore in each separate case it is expedient to resort numerical methods by using computer calculations.

As an example, we have executed the PEVM energy conversion efficiency calculation. The generator for the special case is $\theta = 90°$ and $R_H = 5r$.

Figure 2 shows the generator's energy conversion efficiency dependence from the frequency and the $LC$ contour parameters on a plane of variables ($p_1, p_2$).

As a first approximation $|p_1|\approx\dfrac{1}{\omega rC}$; $|p_2|=\dfrac{r}{\omega L}$; $p_1p_2=\dfrac{\omega_0}{\omega}$; $\omega_0=\dfrac{1}{\sqrt{LC}}$.

In the frequency characteristics of the generator's energy conversion efficiency it is possible to receive surface construction planes (figure 2), corresponding to specific relation values of $\dfrac{p_2}{p_1}$; energy conversion efficiency schedules. The function $\dfrac{1}{p_2}=\dfrac{\omega L}{r}$ is presented in figure 3.

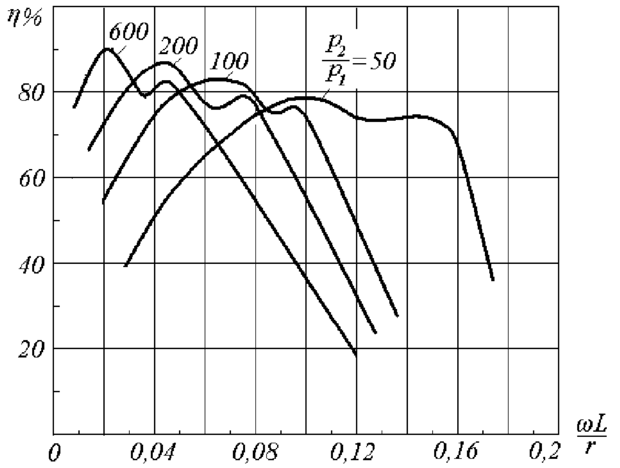


Fig. 3. Frequency characteristics of the generator

Here as in figure 2, the special case $\theta = 90°$ and $R_H = 5r$ is considered.

The conducted analysis states that direct calculations of the generator's energy features are rather complicated. The reason for this is the excessive calculation size and the analytical impossibility of solving equation systems (17), (18).

It is advisable to use numerical methods together with calculating devices for each case.

In conclusion we can say that it is possible to considerably increase the generator's energy conversion efficiency; in comparison with standard power converters, the energy conversion efficiency of which does not exceed 40...60 % for high frequencies.

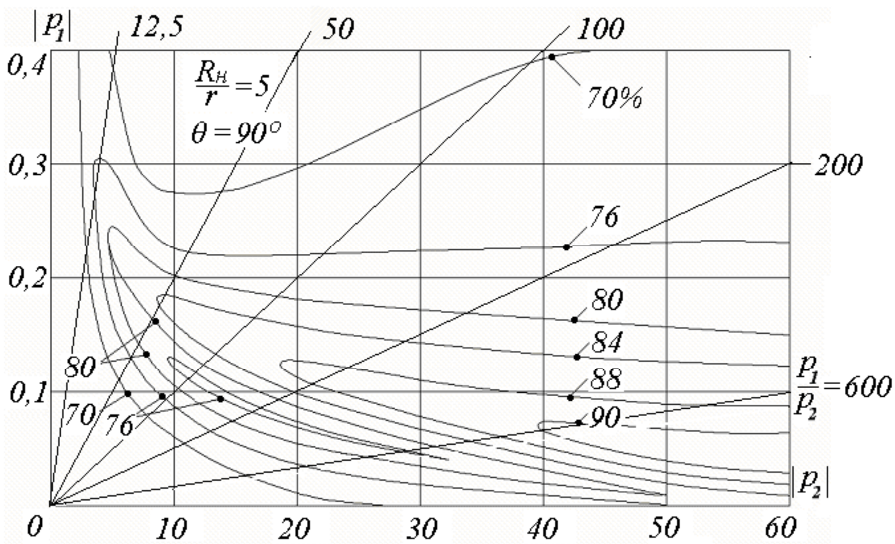


Fig. 2. Energy conversion efficiency of the generator

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# DEVELOPMENT OF MECHANICAL TEST PROCEDURE FOR THE FUEL BELLOWS TANKS

*The mechanical qualification and acceptance test requirements are considered for the fuel bellows tanks. Some procedural mistakes taking place during these tests are described.*

*Keywords: spacecraft, tank, storage and feed unit, mechanical tests, resonance.*

For decades the fuel storage/feed units based on the bellows tanks are successfully used in the monopropellant propulsions of the domestic spacecrafts (SCs). In order to use the fuel storage units for new generation SCs (i. e. to be exposed higher mechanical loads) there was a necessity to perform supplemental mechanical tests to prove their durability.

SC hardware ground test plan includes the acceleration, vibration and shock tests [1; 2]. The tests levels are based on the data obtained from hardware operating conditions analysis, equipment mass and its allocation on the SC.

The storage and feed unit (SFU) manufacturer has to procure off-the shelf tanks from other supplier and then has to equip it with supplemental hardware in order to obtain the SFU as an item of SC propulsion.

During the SFU development testing, bellows of two tanks were corrupted (along an external crimp weld) when they were exposed to mechanical environment. This damage occurred directly along the weld, and not in an area around the weld; it was typically if the weld was well done i. e. this damage designated an insufficient quality of the join. It is necessary to note that such welds in the tanks are critical because they influence the strength of the whole assembly; the thickness of weldment isn’t great, while the total length of weld may be hundreds of meters long. However, all the delivered tanks for the integration of the SFUs have passed the acceptance tests at the manufacturer’s site.

In order to analyze the failures of tank bellows and to generate the levels of durability and acceptance tests, supplemental mechanical tests of two SFUs had been conducted. This work is meant to review all the test results and to identify the possible procedural mistakes that have made it impossible to detect manufacturing flaws during the acceptance tests of tanks.

**Test Objectives.** During the test campaign it was necessary to achieve a set of mutually complementary objectives:

– to detect the rupture sources of tank bellows;
– to develop a technique for determination of low eigenfrequencies of the bellows located inside a tank;
– to estimate an influence of test procedure on the test data;
– to confirm or exclude an influence of the test hardware (fixture, tools, control system, etc) to the test results;
– to update the durability/acceptance test levels for tank and SFU.

**Test equipment and mechanical loads.** The following mechanical tests were performed:

– resonance search within a frequency range of 5 Hz to 2,000 Hz with level of 0,5 g and a scanning rate of 2 octave/min;
– sine vibration within a frequency range of 5 Hz to 2,000 Hz with levels of 1 to 12 g;
– random vibration within a frequency range of 20 Hz to 2,000 Hz with levels of 0.02 to 0.2 $g^2$/Hz;
– quasi-static loads with levels of ±10 g;
– shocks with levels of ±40 g.

The test specifications were generated proceeding from the SFU operation conditions at levels of the SC and in compliance with an approach as described in [3; 4]. They have met the requirements as established in [1; 2]. The tests were conducted in few phases changing the levels and duration of loading. The following equipment was used:

– centrifuge C-400;
– shock test bench ST-800;
– vibration shaker LDS V894/440.

Beforehand, the test equipment and test fixture were subjected to approval. The equipment’s low eigenfrequency is about 1,000 Hz. All the test hardware corresponded to the test standards according to the test specification accuracy and provided the mechanical loading of the SFU and was measured with the following tolerances:

– vibration acceleration amplitude: ±10 %;
– vibration acceleration power spectral density: ±6 dB;