EVALUATION OF THE STABILITY OF THE PARAMETRIC PHASE NUMBER CONVERTER

Ivan Bedritskiy^{1*}, Kamila Jurayeva¹, Laziz Bazarov¹

¹Tashkent state transport university, Department of Power Supply, Adilkhodjayev – 1, Tashkent, 100167, Uzbekistan

Abstract. In the article related issues to the stability assessment of a parametric converter of the number of phases of a ferroresonance nature are analyzed. The areas of change in the characteristic parameters of the converter that guarantee its stable operation are considered.

Introduction

Artificial phase number converters are often used to power automation devices, computer equipment, and radio-electronic equipment, communications equipment, and electrical engineering devices. They are used in cases where the use of multiphase systems meets technical or economic difficulties [1, 2, 3, 4]. The most common devices of this type are three-phase-single-phase converters (so-called balancing devices) and single-phase-three-phase converters, which are used in single-phase circuits for powering three-phase consumers. At the same time, devices based on nonlinear

parametric LC circuits are the most acceptable for powering low-and medium-power consumers [1, 5, 6, 7, 8], having high reliability, relatively low dimensions and weight.

However, devices based on parametric LC circuits can operate in the ferroresonance mode, so they may experience voltage surges (currents). Therefore, it is of interest to study the stability of parametric phase number converters and determine the boundaries of its stable operation.

Statement of a problem

Consider the parametric converter phases according to the scheme in Fig. 1 [9], where: S_1, S_2, S_3 – square section rods of the magnetic core; L_1, L_2, L_3 – the average length of the magnetic lines of the magnetic circuit; $\varphi_1, \varphi_2, \varphi_3$ – instantaneous values of magnetic flux respectively in the cores of the magnetic circuit; g_1, g_2 – active conduction of the primary windings W_1 and W_2 ; W_1, W_2 – number of turns of the primary windings; i_1, i_2 – instantaneous value of current in the primary windings; i_{g1}, i_{g2} – instantaneous value of current in the Taking into account the approximation of the magnetization curve $H = k \cdot b^9$, after some transformations, this scheme is described by a system of equations

transmissibility of primary windings; C_1, C_2 – capacitors, connected in parallel with the primary windings W_1 and W_2 ; i_{c1}, i_{c2} is the instantaneous current in the capacitors; $i = I_m \cdot \sin(\omega t + \psi_i)$ is the instantaneous supply current; $u = U_m \cdot \sin(\omega t + \psi_u)$ is the instantaneous value of the supply voltage; W_3, W_4, W_5 are numbers of turns of the secondary winding of the transducer; Z_1, Z_2, Z_3 – resistance phase of three-phase load of the consumer; U_{1m}, U_{2m}, U_{3m} – voltage artificial phases.

$$\left\{ \begin{array}{l} b_1 \cdot S_1 + b_2 \cdot S_2 - b_3 \cdot S_3 = 0 \\ b_1^9 = \frac{k \cdot L_2 \cdot b_2^9 - i_2 \cdot W_2 + i_1 \cdot W_1}{k \cdot L_1} \\ \left. \begin{array}{l} u = W_1 \cdot S_1 \frac{db_1}{dt} + W_2 \cdot S_2 \frac{db_2}{dt} \\ i = i_2 + i_c + i_{g2} \\ i = i_1 + i_{g1} \end{array} \right\} \right. \quad (1)$$

Fig. 1. Parametric phase number converter

where the instantaneous values of the currents in the branches of the circuit can be found from the expressions

$$\begin{aligned} i_2 &= \frac{k \cdot L_2 \cdot b_2^9}{W_2}; & i_C &= W_2 \cdot C \cdot S_2 \cdot \frac{d_2 b_2}{dt^2}; \\ i_{g2} &= W_2 \cdot g_2 \cdot S_2 \cdot \frac{db_2}{dt}; & i_1 &= \frac{k \cdot L_1 \cdot b_1^9}{W_1}; \\ i_{g1} &= W_1 \cdot g_1 \cdot S_1 \cdot \frac{db_1}{dt}. \end{aligned}$$

$$\begin{aligned} \frac{dF}{dt} &= b_1^9 \left(1 + \frac{W_1}{W_2} \right) - b_2^9 \left(\frac{L_2}{L_1} + \frac{W_1 \cdot L_2}{W_2 \cdot L_1} \right) + \frac{db_1}{dt} \left(\frac{W_1' \cdot W_2 \cdot g_1 \cdot S_1 + W_1^2 \cdot g_1 \cdot S_1}{k \cdot L_1} \right) - \\ &- F \left(\frac{g_2 \cdot S_2 \cdot W_2^2 + W_1 \cdot W_2 \cdot g_2 \cdot S_2}{k \cdot L_1} \right). \end{aligned} \quad (3)$$

Express $\frac{db_1}{dt}$ in accordance with (1), we get

$$\frac{db_1}{dt} = \frac{u - W_2 \cdot S_2 \cdot F}{W_1 \cdot S_1}. \quad (4)$$

$$\begin{aligned} A &= W_2 \cdot S_2; \quad B = W_1 \cdot S_1; \quad D = 1 + \frac{W_2}{W_1}; \quad K = \frac{L_2}{L_1} + \frac{W_1 \cdot L_2}{W_2 \cdot L_1}; \quad L = \frac{W_1 \cdot W_2 g_1 \cdot S_1 + W_1^2 \cdot g_1 \cdot S_1}{k \cdot L_1}; \\ M &= \frac{W_2^2 \cdot g_2 \cdot S_2 + W_1 \cdot W_2 \cdot g_2 \cdot S_2}{k \cdot L_1}; \quad N = \frac{W_2^2 \cdot C \cdot S_2 + W_1 \cdot W_2 \cdot C \cdot S_2}{k \cdot L_1} \end{aligned}$$

Taking into account the accepted notation, we get the expression for $\frac{dF}{dt}$

$$\frac{dF}{dt} = \frac{b_1^9 \cdot D - b_2^9 \cdot k + \left(\frac{u - A \cdot F}{D} \cdot L \right) - F \cdot M}{N}. \quad (5)$$

Given that $u = U_m \cdot \sin(\omega t + \psi_u)$, the expression (1) is converted to the form

Let's convert the system (1) to the form required for calculation on the computer, for which we will replace the variables

$$\frac{db_2}{dt} = F; \quad \frac{d_2 b_2}{dt^2} = \frac{dF}{dt}. \quad (2)$$

Express it using the resulting expression $\frac{dF}{dt}$ and after conversion we get

Let's introduce the notation:

$$\left\{ \begin{aligned} \frac{db_1}{dt} &= \frac{U_m \sin(\omega t + \psi_u) - A \cdot F}{B} \\ \frac{dF}{dt} &= \frac{b_1^9 \cdot D - b_2^9 \cdot K + \frac{U_m \sin(\omega t + \psi_u) - A \cdot F}{B} \cdot L - F \cdot M}{N} \\ \frac{db_2}{dt} &= F \end{aligned} \right\} \quad (6)$$

This system of differential equations is used as a basis for studying the stability of the operation of a parametric phase number converter using the Hurwitz method [10, 11].

The concept of the problem decision

We find general expressions for the study of the stability of a parametric phase number converter using elements of the stability theory. A system of differential equations (6) describing the electrical state of a circuit is known. To reduce the number of unknowns, we express F from (2) and substituting it in (6) after the transformation, we get

$$\left\{ \begin{aligned} \frac{db_1}{dt} &= A_1 \cdot U_m \sin(\omega t + \psi_u) - A_2 \cdot \frac{db_2}{dt} \\ \frac{d_2 b_2}{dt^2} &= D_1 \cdot b_1^9 - D_2 \cdot b_2^9 + D_3 \cdot U_m \sin(\omega t + \psi_u) - D_4 \cdot \frac{db_2}{dt} \end{aligned} \right\}, (7)$$

$$\text{where } A_1 = \frac{1}{B}; \quad A_2 = \frac{A}{B}; \quad D_1 = \frac{D}{N}; \quad D_2 = \frac{K}{N}; \\ D_3 = \frac{L}{BN}; \quad D_4 = \frac{AL}{BN} - \frac{M}{N}.$$

$$\left\{ \begin{aligned} x\omega \cdot \cos \omega t - y\omega \cdot \sin \omega t &= A_1 \cdot U_m \sin(\omega t + \psi_u) - A_2 (m\omega \cdot \cos \omega t - n\omega \cdot \sin \omega t) \\ -(\omega^2 m + 2\omega \cdot \frac{dn}{dt}) \sin \omega t + (-\omega^2 n + 2\omega \cdot \frac{dm}{dt}) \cos \omega t &= D_1 (x \sin \omega t + y \cos \omega t)^9 - \\ - (D_2 (m \sin \omega t + n \cos \omega t)^9 + D_3 (U_m \sin(\omega t + \psi_u) - D_4 (m\omega \cdot \cos \omega t - n\omega \cdot \sin \omega t) \end{aligned} \right\}$$

Transform the resulting expressions using the harmonic balance method. For the first expression, we have

$$x\omega \cdot \cos \omega t - y\omega \cdot \sin \omega t = A_1 U_m \sin \omega t \cdot \cos \psi_u + \\ + A_1 U_m \cos \omega t \cdot \sin \psi_u - A_2 \omega \cos \omega t + A_2 n \omega \cdot \sin \omega t \quad (10)$$

Equating in (10) the coefficients for $\cos \omega t$ and $\sin \omega t$ we get

$$\begin{aligned} -y\omega &= A_1 U_m \cdot \cos \psi_u + A_2 n \omega \\ x\omega &= A_1 U_m \cdot \sin \psi_u - A_2 m \omega \end{aligned} \quad (11)$$

$$(x \sin \omega t + y \cos \omega t)^9 \approx \sin \omega t (0,5x^9 + 19,7x^7 y^2 + 29,5x^5 y^4 + 19,7x^3 y^6 + 2,5xy^8) + \\ + \cos \omega t (14,8x^8 y + 39,4x^6 y^3 + 29,5x^4 y^5 + 9,8x^2 y^7 + 0,5y^9) \quad (12)$$

$$(m \sin \omega t + n \cos \omega t)^9 \approx \sin \omega t (0,5m^9 + 19,7m^7 n^2 + 29,5m^5 n^4 + 19,7m^3 n^6 + 2,5mn^8) + \\ + \cos \omega t (14,8m^8 n + 39,4m^6 n^3 + 29,5m^4 n^5 + 9,8m^2 n^7 + 0,5n^9) \quad (13)$$

Let us denote the coefficient for $\sin \omega t$ in (12) by X , for $\cos \omega t$ by Y , and in (13) the coefficient for $\sin \omega t$ by M , and for $\cos \omega t$ by N . Taking into account the above

$$\left\{ \begin{aligned} -(\omega^2 m + 2\omega \frac{dn}{dt}) &= D_1 X - D_2 M + D_3 U_m \cos \psi_u + D_4 n \omega \\ -\omega^2 n + 2\omega \frac{dm}{dt} &= D_1 Y - D_2 N + D_3 U_m \sin \psi_u - D_4 m \omega \end{aligned} \right\}. \quad (14)$$

Taking into account (10) and (11), we have a system of algebraic and differential equations for relatively slowly varying amplitudes

$$\left\{ \begin{aligned} -y\omega &= A_1 U_m \cos \psi_u + A_2 n \omega \\ x\omega &= A_1 U_m \sin \psi_u - A_2 m \omega \\ -(\omega^2 m + 2\omega \frac{dn}{dt}) &= D_1 X - D_2 M + D_3 U_m \cos \psi_u + D_4 n \omega \\ -\omega^2 n + 2\omega \frac{dm}{dt} &= D_1 Y - D_2 N + D_3 U_m \sin \psi_u - D_4 m \omega \end{aligned} \right\}. \quad (15)$$

Transform the system (15) with respect to the derivatives of slowly varying amplitudes, for which we express y and x from the first two expressions (15), respectively. Receive

$$y = \frac{A_1 U_m \cos \psi_u - A_2 n}{\omega}; \quad x = \frac{A_1 U_m \sin \psi_u - A_2 m}{\omega}. \quad (16)$$

Transform (7) using the method of slowly varying amplitudes, assuming that the unknown b_1, b_2 can be represented as follows

$$\begin{aligned} b_1 &= x \sin \omega t + y \cos \omega t \\ b_2 &= m \sin \omega t + n \cos \omega t \end{aligned}, (8)$$

where x, y, m, n are the amplitudes of the desired oscillations that change slowly over time. We find the derivatives and given that x, y, m, n change slowly over time, we get the first approximation

$$\left\{ \begin{aligned} \frac{db_1}{dt} &= x\omega \cdot \cos \omega t - y\omega \cdot \sin \omega t \\ \frac{db_2}{dt} &= m\omega \cdot \cos \omega t - n\omega \cdot \sin \omega t \\ \frac{d_2 b_2}{dt^2} &= -(\omega^2 m + 2\omega \cdot \frac{dn}{dt}) \sin \omega t + (-\omega^2 n + 2\omega \cdot \frac{dm}{dt}) \cos \omega t \end{aligned} \right\}. \quad (9)$$

Substituting (9) in (7) we get

For the second expression, we are binomial $(x \sin \omega t + y \cos \omega t)^9$ and $(m \sin \omega t + n \cos \omega t)^9$ transform by the Newton binomial. In the obtained expressions of the degree $\cos \omega t$ and $\sin \omega t$, we convert to the sum of harmonics in the first degree and without taking into account even harmonics, as well as harmonics higher than the first, we have

notation and comparing the coefficients for $\sin \omega t$ and $\cos \omega t$, we transform the resulting expression using the harmonic balance method, we get the system

$$\text{Denote } C = \frac{A_1 U_m \cdot \cos \psi_u}{\omega}; \quad S = \frac{A_1 U_m \cdot \sin \psi_u}{\omega}.$$

Substitute (16) in the last two expressions of (15), taking into account the newly adopted notation. Since X and Y are functions of x and y , with the new substitution they will become functions of m and n . Receive

$$X_{nm} = 0,5(s - A_{2m})^9 + 19,7(s - A_{2m})^7(-c - A_{2n})^2 + 29,5(s - A_{2m})^5(-c - A_{2n})^4 + \\ + 19,7(s - A_{2m})^3(-c - A_{2n})^6 + 2,5(s - A_{2m})(-c - A_{2n})^8 \quad (17)$$

$$Y_{nm} = 14,8(s - A_{2m})^8(-c - A_{2n}) + 39,4(s - A_{2m})^6(-c - A_{2n})^3 + \\ + 29,5(s - A_{2m})^4(-c - A_{2n})^5 + 9,8(s - A_{2m})^2(-c - A_{2n})^7 + 0,5(-c - A_{2n})^9 \quad (18)$$

By substituting (17) and (18) into the two lower equations of the system (15) after transformations, we obtain a system of differential equations with respect to derivatives of slowly varying amplitudes m and n :

$$\left\{ \begin{aligned} \frac{dn}{dt} &= \frac{-D_1 X_{nm} + D_2 M - D_3 U_m \cos \psi_u - D_4 \cdot n - \omega m}{2\omega} - \frac{D_4 \cdot n - \omega m}{2} \\ \frac{dm}{dt} &= \frac{D_1 Y_{nm} - D_2 N + D_3 U_m \sin \psi_u - D_4 \cdot m + \omega n}{2\omega} - \frac{D_4 \cdot m + \omega n}{2} \end{aligned} \right\} \quad (19)$$

Let's denote m and n in steady-state modes by m_0 and n_0 . Substituting their steady-state values in (19) instead

of m and n , and equating them $\frac{dn}{dt} = 0$; $\frac{dm}{dt} = 0$, we obtain a system of algebraic equations:

$$\left\{ \begin{aligned} \frac{-D_1 X_{nm}(0) + D_2 M(0) - D_3 U_m \cos \psi_u - D_4 n(0) - \omega m(0)}{2\omega} - \frac{D_4 n(0) - \omega m(0)}{2} &= 0 \\ \frac{D_1 Y_{nm}(0) - D_2 N(0) + D_3 U_m \sin \psi_u - D_4 m(0) + \omega n(0)}{2\omega} - \frac{D_4 m(0) + \omega n(0)}{2} &= 0 \end{aligned} \right\} \quad (20)$$

Solving the system (20), we can find the steady-state values of the amplitudes m_0 and n_0 .

$n = n_0 + \Delta n$. Taking into account the above, we obtain from (20)

Let the perturbation result in small increments of the oscillation amplitudes Δm and Δn , i.e. $m = m_0 + \Delta m$,

$$\left\{ \begin{aligned} \frac{d(n_0 + \Delta n)}{dt} &= \frac{-D_1 \cdot X_{\left(\begin{smallmatrix} n_0 + \Delta n \\ m_0 + \Delta m \end{smallmatrix}\right)} + D_2 \cdot M_{\left(\begin{smallmatrix} n_0 + \Delta n \\ m_0 + \Delta m \end{smallmatrix}\right)} - D_3 U_m \cos \psi_u}{2\omega} - \frac{D_4 (n_0 + \Delta n) - \omega (m_0 + \Delta m)}{2} \\ \frac{d(m_0 + \Delta m)}{dt} &= \frac{D_1 \cdot Y_{\left(\begin{smallmatrix} n_0 + \Delta n \\ m_0 + \Delta m \end{smallmatrix}\right)} - D_2 \cdot N_{\left(\begin{smallmatrix} n_0 + \Delta n \\ m_0 + \Delta m \end{smallmatrix}\right)} + D_3 U_m \sin \psi_u}{2\omega} - \frac{D_4 (m_0 + \Delta m) + \omega (n_0 + \Delta n)}{2} \end{aligned} \right\}$$

We expand the values $\frac{d(n_0 + \Delta n)}{dt}$ and $\frac{d(m_0 + \Delta m)}{dt}$ from the last expression to the Taylor series in small increments of Δn and Δm , and because of their

smallness, we restrict the summands with the first powers of Δn and Δm . For the specified decomposition, we find the partial derivatives:

$$\begin{aligned} \frac{dX_{nm}}{d_m} &= 4,5(s - A_{2m})^8 \cdot A_2 + 137,9(-c - A_{2n})^2(s - A_{2m})^6 \cdot A_2 + \\ &+ 147,5(-c - A_{2n})^4(s - A_{2m})^4 \cdot A_2 + 59,1(-c - A_{2n})^6(s - A_{2m})^2 \cdot A_2 + 2,5(s - A_{2m})(-c - A_{2n})^8 \cdot A_2 \\ \frac{dX_{nm}}{d_n} &= -39,4(-c - A_{2n})(s - A_{2m})^7 \cdot A_2 - 118(-c - A_{2n})^3(s - A_{2m})^5 - \\ &- 118,2(-c - A_{2n})^5(s - A_{2m})^3 \cdot A_2 - 20(-c - A_{2n})^7(s - A_{2m}) \cdot A_2 \\ \frac{dY_{nm}}{d_m} &= 118,4(-c - A_{2n})(s - A_{2m})^7 \cdot A_2 + 236,4(s - A_{2m})^5(-c - A_{2n})^3 \cdot A_2 + \\ &+ 118(s - A_{2m})^3(-c - A_{2n})^5 \cdot A_2 + 19,6(s - A_{2m})(-c - A_{2n})^7 \cdot A_2 \\ \frac{dY_{nm}}{d_n} &= -14,8(s - A_{2m})^8 A_2 - 118,2(-c - A_{2n})^2(s - A_{2m})^6 \cdot A_2 - \\ &- 147,5(-c - A_{2n})^4(s - A_{2m})^4 \cdot A_2 - 68,6(-c - A_{2n})^6(s - A_{2m})^2 \cdot A_2 - 4,5(-c - A_{2n})^8 \cdot A_2 \\ \frac{dM_{nm}}{d_m} &= 4,5m^8 + 137,9n^2 m^6 + 147,5n^4 m^4 + 59,1n^6 m^2 + 2,5n^8 \cdot \\ \frac{dM_{nm}}{d_n} &= 39,4m^7 n + 118m^5 n^3 + 118,2n^3 m^5 + 20mn^7 \cdot \\ \frac{dN_{nm}}{d_m} &= 118,4mn^7 + 2326,4n^3 m^5 + 118n^5 m^3 + 19,6n^7 m \cdot \end{aligned}$$

$$\frac{dN_{nn}}{d_n} = 14,8m^8 + 118,2m^6n^2 + 147,5m^4n^4 + 68,6m^2n^6 + 4,5n^8.$$

Insert the values m_0 and n_0 of the steady state mode into the found expressions and enter the notation

$$\begin{aligned} \frac{dX_{nn(m=m_0, n=n_0)}}{d_m} &= X_1; \frac{dX_{nn(m=m_0, n=n_0)}}{d_n} = X_2; \frac{dY_{nn(m=m_0, n=n_0)}}{d_m} = Y_1; \frac{dY_{nn(m=m_0, n=n_0)}}{d_n} = Y_2; \\ \frac{dM_{nn(m=m_0, n=n_0)}}{d_m} &= M_1; \frac{dM_{nn(m=m_0, n=n_0)}}{d_n} = M_2; \frac{dN_{nn(m=m_0, n=n_0)}}{d_m} = N_1; \frac{dN_{nn(m=m_0, n=n_0)}}{d_n} = N_2 \end{aligned} \quad (21)$$

We also denote

$$X_{nn(m=m_0, n=n_0)} = X_0; Y_{nn(m=m_0, n=n_0)} = Y_0; M_{nn(m=m_0, n=n_0)} = M_0; N_{nn(m=m_0, n=n_0)} = N_0 \quad (22)$$

Substituting expressions (21) and (22) for derivatives after transformations, we obtain a system of equations that takes into account increments

$$\begin{aligned} \frac{D_1 \cdot X_{(m_0+\Delta m; n_0+\Delta n)}}{2\omega} + \frac{D_2 \cdot M_{(m_0+\Delta m; n_0+\Delta n)}}{2\omega} - \frac{D_3 \cdot U_m \cos \psi_u}{2\omega} - \frac{D_4(n_0+\Delta n)}{2} - \frac{\omega(m_0+\Delta m)}{2} = \\ = \frac{D_1 X_0}{2\omega} + \frac{D_2 M_0}{2\omega} - \frac{D_3 U_m \cos \psi_u}{2\omega} - \frac{D_4 n_0}{2} - \frac{\omega m_0}{2} + \\ + \Delta m \left(\frac{D_1 X_1}{2\omega} + \frac{D_2 M_1}{2\omega} - \frac{\omega}{2} \right) + \Delta n \left(\frac{D_1 X_2}{2\omega} + \frac{D_2 M_2}{2\omega} - \frac{D_4}{2} \right); \end{aligned} \quad (23)$$

Given that $\frac{d(m_0+\Delta m)}{dt} = \frac{d\Delta m}{dt}$, $\frac{d(n_0+\Delta n)}{dt} = \frac{d\Delta n}{dt}$,

expression (23) is written as

$$\left\{ \begin{aligned} \frac{d\Delta m}{dt} &= \left(\frac{D_1 X_1 + D_2 M_1}{2\omega} - \frac{\omega}{2} \right) \Delta m + \left(\frac{D_1 X_2 + D_2 M_2}{2\omega} - \frac{D_4}{2} \right) \Delta n \\ \frac{d\Delta n}{dt} &= \left(\frac{D_1 Y_1 + D_2 N_1}{2\omega} - \frac{\omega}{2} \right) \Delta m + \left(\frac{D_1 Y_2 + D_2 N_2}{2\omega} - \frac{D_4}{2} \right) \Delta n \end{aligned} \right\}. \quad (24)$$

Denote

Realization of the concept

From (26) we make a characteristic equation, for which we express Δm from the upper expression (26) and substitute the lower expression (26). Reducing the resulting expression by Δn , after transformations we get $P^2 - P(\alpha + \delta) - \alpha \cdot \delta - \gamma \cdot \beta = 0$

According to the Hurwitz criterion, for the attenuation of Δm and Δn , the conditions must be met:

$$-(\alpha + \delta) > 0; (\alpha \cdot \delta - \gamma \cdot \beta) > 0 \quad (27)$$

In expression (27), we replace the inequality signs with equal signs, express the value of α from the first expression, after substitution in the second expression, and after conversion, we get an expression for a function whose points lie on the interface between stable and unstable modes of operation of the chain

$$\alpha = \sqrt{-\gamma \cdot \beta} \quad (28)$$

To get real values of α , it is necessary that the root expression is equal to zero or greater than zero, therefore, combinations of γ and β are possible only with different signs.

In the fig. 2 shows a graph of dependencies $\alpha = \sqrt{-\gamma \cdot \beta}$, which are surfaces located above the second (S1) and fourth (S2) quadrants.

$$\begin{aligned} \alpha &= \frac{D_1 X_1 + D_2 M_1}{2\omega} - \frac{\omega}{2}; \quad \beta = \frac{D_1 X_2 + D_2 M_2}{2\omega} - \frac{D_4}{2}; \\ \gamma &= \frac{D_1 Y_1 + D_2 N_1}{2\omega} + \frac{\omega}{2}; \quad \delta = \frac{D_1 Y_2 + D_2 N_2}{2\omega} - \frac{D_4}{2}. \end{aligned} \quad (25)$$

Algebraize (24) and taking into account (25), we get

$$\begin{aligned} P \cdot \Delta m &= \alpha \cdot \Delta m + \beta \cdot \Delta n \\ P \cdot \Delta n &= \gamma \cdot \Delta m + \delta \cdot \Delta n \end{aligned} \quad (26)$$

Under 27, function points, lying under the surfaces S1 and S2 ($\alpha < \sqrt{-\gamma \cdot \beta}$) are points of unstable operation of the device, the points belonging to the surfaces S1 and S2 ($\alpha < \sqrt{-\gamma \cdot \beta}$) characterize the work chain on the border of stable and unstable regions, and the points lying above the surfaces S1 and S2 ($\alpha < \sqrt{-\gamma \cdot \beta}$) – characterize the work of the circuit in the stable area.

There are two possible modes of operation at the stability boundary:

1) when $-\gamma = \beta$ or $-\beta = \gamma$, when one value of α corresponds to one combination of γ and β (the mode point is located on the curves OA or OA'), belonging to the surfaces S1, S2, respectively, and in this combination of γ and β in the chain, it is impossible to change the parameters abruptly;

2) for $\gamma > -\beta$ or $\beta > -\gamma$, when one value of α corresponds to two combinations of γ and β , and there are two points B and B' of possible unstable equilibrium, and in the chain there are possible abrupt changes in parameters.

Fig.2. Graph of dependencies $\alpha = \sqrt{-\gamma \cdot \beta}$

Conclusion

1. Studies of the stability and operation of the device with the scheme in Fig.1 when the parameters $C_1, C_2 = 10 - 30 \text{ mkF}$, $W_1, W_2 = 300 - 450$ turns, $g_1 = 0,0015 \text{ Om}^{-1}$, $g_2 = 0,0015 - 0,05 \text{ Om}^{-1}$ are varied, the results obtained on the basis of expression (28) show that the periodic process at the fundamental frequency in this circuit is stable.
2. Changing the resistances Z_1, Z_2, Z_3 of the phase number converter loads from 0 (short circuit) to ∞ (idle) does not affect the stability mode.
3. From the point of view of stability theory, the circuit is suitable for the development of real devices, in particular, for parametric frequency converters.

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