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Analysis of Subharmonic Oscillations of the Third Order in Three-Phase Circuits with a Separate Ferromagnetic Element

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ABSTRACT: In this paper, we consider the excitation mode of subharmonic oscillations of the third order in a three-phase circuit consisting of active, capacitive and nonlinear inductive elements (the latter have a common magnetic connection), which are analogous to power lines "line - unloaded transformer". A three-phase system is considered, each phase of which consists of a three-phase ferromagnetic element, capacitance and active resistance connected in series. The equations of motion are revealed. It is considered for the analysis of the phenomenon of internal overvoltage caused by the occurrence of subharmonic oscillations in power lines. Also considered is a three-phase system, which each phase consisting of a series-connected three-phase ferro-magnetic element, capacitance and active resistance

KEYWORDS: power lines, subharmonic oscillations, ferromagnetic element, auto-parametric oscillations, electro ferromagnetic circuit, nonlinear circuit, frequency Converter, finite-difference methods, numerical methods, overvoltage phenomena, Weber-ampere characteristics of ferro magnetic element.

I.INTRODUCTION

Currently, in various branches of the electric power industry: automation devices, telemechanics, information and measurement technology, relay protection and others are widely used various kinds of energy converters, the number of phases and frequencies based on the auto-parametric oscillations in three-phase nonlinear circuits with concentrated parameters.

In most cases, the process of excitation of subharmonic oscillations of the second and third order in the electro ferromagnetic circuit by an approximate method, and the transients and the influence of initial conditions on the nature of excitation were calculated numerically. At the same time, when studying specific schemes of auto-parametric frequency converters, there is a need to determine the energy source and consumers, allowing to estimate the levels of energy received from individual circuits of the device at different frequencies.

The phenomena of internal over voltages in power lines (transmission lines), detected due to the excitation of autoparametric oscillations, served as the impetus for a detailed study of the properties of multiphase systems. Equally, the probability of excitation of autoparametric oscillations at a particular frequency depends on the mode and operating conditions of power lines and electricity consumers.

One of the dangerous modes of transmission lines are overvoltages arising from the excitation of subharmonic oscillations, appearing mainly under switching conditions.

To analyze the phenomenon of internal overvoltage caused by the occurrence of subharmonic oscillations in power lines, many authors considered three-phase models of power lines with concentrated parameters. Although this approach did not take into account the distribution of parameters of power lines, the processes carried out in the latter, to some extent reflect the physics of the problem, on the other hand, the analysis of nonlinear oscillations in three-phase circuits, in particular, in the excitation mode of subharmonics, reveals the features and specificity of three-phase systems from the point of view of the theory of circuits [1,2,3,4,5].

Shortened equations are obtained using the averaging method with corresponding phases. From the condition of existence of the periodic solution the phase relations different from the phase relations for three-phase chains with group ferro-magnetic elements are determined. In the stationary mode, the excitation conditions, the region of existence, the dependence of the output values on the parameters of the circuit and the applied action are determined. The stability of the desired solution is also investigated by analyzing the roots of the characteristic equation and the numerical

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implementation of the initial system of nonlinear inhomogeneous second-order differential equations describing the considered chain is given by a qualitative method.

II. RESULTS AND DISCUSSIONS

In the analysis, the following assumption is made: the nonlinear dependence of the Weber-ampere characteristic of a ferro-magnetic element differs from the linear one by an order of μ, where $0 < \mu < 1$

The considered three-phase system, each phase consists of sequentially connected three single-phase ferromagnetic elements, capacitance and active resistance (4,6) is presented in Fig.1. The processes in such a system are described by the following integro-differential equations in matrix form.

$$U = \mathrm{R}i + C^{*}\int idt + w\,A^{*}\dot{\Phi}_{\gamma} \qquad (1)$$

where:

$$\mathrm{R}=\begin{bmatrix} \mathrm{R}_A & -\mathrm{R}_B & 0 \\ 0 & \mathrm{R}_B & -\mathrm{R}_C \\ -\mathrm{R}_A & 0 & \mathrm{R}_C \end{bmatrix}$$

$$C^{*}=\begin{bmatrix} C_A^{-1} & -C_B^{-1} & 0 \\ 0 & C_B^{-1} & -C_C^{-1} \\ C_A^{-1} & 0 & C_C^{-1} \end{bmatrix}$$

$A^{*}=\begin{bmatrix} 1 & -1 & 0 \\ 0 & 1 & -1 \\ -1 & 0 & 1 \end{bmatrix}$ - square special matrices of the strand ν (ν is the number of phases);

u, i, $\int i$dt, $\dot{\Phi_{\nu}}$ - column matrices of instantaneous values of linear voltages of a symmetric source of three-phase voltage, currents of all branches, integrals of current of all branches (phases) and derivative magnetic flows of each rod of three single-phase ferramagnetic element;

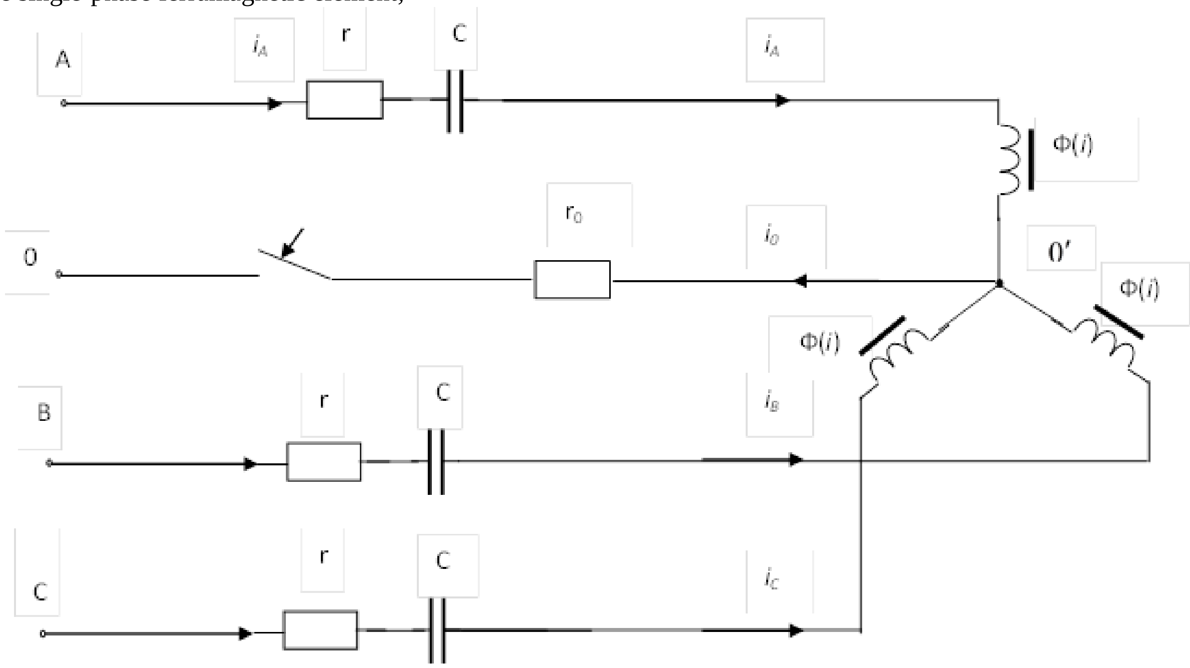

Fig.1. Electro permanent a symmetrical three-phase circuits with series-connected elements R_A,$\mathrm{R}_{B,}$$\mathrm{R}_{C\ И}$ $C_{A,}C_B, C_C$ - respectively active resistances and capacitances in phases.

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Since three single-phase unloaded transformers are considered as a ferromagnetic element (Fig.2), then the current of each of its high-voltage winding and the magnetic field strength of the rods are related by the following relations

$$\mathrm{w}A^{*}i=A^{*}HL \qquad (2)$$

where;

H,L - a column matrix of instantaneous values of the magnetic field strength of the rods of three single-phase ferromagnetic elements and its diagonal matrix of the corresponding average lengths of the rods;

w - the number of turns of the windings of each rod.

Approximating the nonlinear Weber-ampere characteristic of ferromagnetic elements in the form:. [5]

$$i=\alpha\Phi+\beta\Phi^{3}, \qquad (3)$$

Here α and β are the coefficients of the approximating function

And so, given the continuity of currents and magnetic flows in the system, we have the following equation, i.e.

$$\sum_{\nu=1}^{3} i_{\nu=0} \qquad (4)$$

$$W\sum_{\nu=1}^{3} \Phi_{\nu=0} \qquad (5)$$

To reduce equation (2) to a form convenient for further use, we solve it negatively. However, direct resolution is not possible, since the matrix A^* is special. Therefore, the matrix A* is somewhat modified, namely: the elements of the first row of the form with the modified matrix are obtained by subtracting the elements of the third row from the corresponding elements of the first row of the original matrix. The elements of the second line are obtained by subtracting the elements of the second line from the first, etc. After such elementary operations, instead of the matrix A*, we obtain a matrix that has the following form

$$\begin{bmatrix} -2 & 1 & 1 \\ 1 & -2 & 1 \\ 1 & 1 & -2 \end{bmatrix}$$

The resulting matrix can be considered as the sum of two submatrices A and B*, i.e.

$$\mathrm{A}+B^{*}=\begin{bmatrix} 1 & 1 & 1 \\ 1 & 1 & 1 \\ 1 & 1 & 1 \end{bmatrix}+\begin{bmatrix} -3 & 0 & 0 \\ 0 & -3 & 0 \\ 0 & 0 & -3 \end{bmatrix} \qquad (6)$$

The square matrix A in expression (6), whose elements are only positive ones, is special and has special significance for a three-phase system, since the products of the columns of the current matrices and the magnetic fluxes on A form the zero matrix, i.e., the

$$Ai = 0, \qquad w\,A\Phi_{\nu} = 0. \qquad (7)$$

Taking into account (7) and (1.6) from the expression (1.2) we find the current

$$i = \frac{1}{w}(\mathrm{B}^{*-1}\mathrm{A\,H\,L} + \mathrm{H\,L}) \qquad (8)$$

If the diagonal matrix of the average lengths (l) of the rods of three single-phase ferromagnetic elements is represented as consisting of two diagonal submatrices in the form of the following sequential transformation

$$\mathrm{L} = \begin{bmatrix} L_1 & 0 & 0 \\ 0 & L_2 & 0 \\ 0 & 0 & L_3 \end{bmatrix}=\begin{bmatrix} L_1 & 0 & 0 \\ 0 & L_1[(k-1)+1] & 0 \\ 0 & 0 & L_1 \end{bmatrix}=$$

$$= L_1\left(\begin{bmatrix} 1 & & \\ & 1 & \\ & & 1 \end{bmatrix}+\begin{bmatrix} 0 & & \\ & (\mathrm{k}-1) & \\ & & 0 \end{bmatrix}\right)=L_1(1+\mathrm{k})$$

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where: k = $L_2 L_1^{-1}$ - the ratio of the average lengths of the rods, the expression (8) when substituting the expression (3) takes the form convenient for further use:

$$i = \frac{l_1}{\text{ω}}\left(\alpha C\Phi + \beta C\Phi^3 - \frac{1}{3}\beta A\Phi^3\right) \qquad (9)$$

where:

$C = 1 + \kappa - \frac{1}{3}A\kappa = \begin{bmatrix} 1 & -(\kappa-1)/3 & 0 \\ 0 & (2k+1)/3 & 0 \\ 0 & -(k-1)/3 & 1 \end{bmatrix}$ - a square nonsingular matrix of the ratio of average rod lengths of three single-phase ferromagnetic elements.

Expressing the line voltages of the power supply through phase and introducing notation R_A =n $R_B = m R_C$ u $C_A = nC_B = mC_C$ and then having done elementary transformations over the matrices of parameters (R, C^*) of the original equation (1) similarly to the transformation of the matrix A*, we write the equation of motion (1) in the form

$$-3u - R_A(A + C)i + \frac{1}{C_A}(A + E)\int i\,dt + w\,D(A + B^*)\dot{\Phi}, \qquad (10.)$$

Where, u is a column matrix of instantaneous values of phase voltages of a symmetric three-phase voltage source;

G, E-square matrices, the elements of which are the coefficients taking into account the ratio of the electrical parameters of the system i.e.

$$G = \begin{bmatrix} -3 & (n-1) & (m-1) \\ 0 & -(2n+1) & (m-1) \\ 0 & (n-1) & -(2m+1) \end{bmatrix};$$

$$E = \begin{bmatrix} -3 & -(k-1)/k & -(g-1)/g \\ 0 & -(k+2)/k & -(g-1)/g \\ 0 & -(k-1)/k & -(g+2)/g \end{bmatrix}.$$

The expression (9) is substituted in (10) and after some mathematical transformations passing to the new time $\tau = \frac{wt}{\chi}$,, where is the order of subharmonic oscillations, we obtain a system of nonlinear differential equations in matrix form of the following form

$$\ddot{\Phi} + \frac{\chi^2\alpha a}{w^2 C_1}G'\Phi + \frac{\chi^2\beta a}{w^2 C_1}(G' + G'')\Phi^3 + \frac{\chi r\alpha a}{w}E'\dot{\Phi} + \frac{\chi r\beta a}{w}(3E' + E'')\Phi^2\dot{\Phi} = d\boldsymbol{\chi}\dot{u} \quad (11)$$

where: $G' = B^{*-1}GC$, $G'' = -\frac{1}{3}B^{*-1}GA$, $E' = B^{*-1}ED$, $E'' = -B^{*-1}EA$ - square matrix of order λ

III. CONCLUSION

The last equation is the equation of motion of the three-phase system, presented in Fig.1. [6] in the special case at K = k = g =m=n=1, this equation easily turns into the equation of a symmetric three-phase system with group ferromagnetic elements. In addition, the resulting equation (11) allows you to write the equations for each phase separately, containing terms with the second derivatives of the induction of the respective phases and the first derivatives of the induction of all phases, etc.

The above algorithm for deriving the equation of motion allows us to obtain equations of some kind in the "standard" form, which are not subject to any preliminary transformation when using the averaging method.

The obtained nonlinear differential equations for symmetric three and multiphase basic electroferromagnetic circuits allow us to consider the process of excitation of autoparametric oscillations at different frequencies in both steady-state and transient modes.

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