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Study of subharmonic oscillation processes in ferroresonance circuits

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Abstract. The article presents a general theory of the analysis of subharmonic oscillations at a frequency of 25 Hz in three-phase Ferro resonance circuits with common magnetic conductors. The abbreviated equations are obtained by averaging with the corresponding phases. From the condition of the existence of a periodic solution, the phase and amplitude ratios of the excited oscillations are determined, which differ from three-phase circuits with a separate ferromagnetic element. In steady-state mode, the excitation conditions and the area of existence are determined depending on the parameters of the circuit, the bias current and the applied action. The stability of the solution of the initial system of nonlinear second-order differential equations is also studied by analysing the roots of the characteristic equation using a qualitative method. In the theory of nonlinear electrical circuits, the analysis of the physical processes occurring in three-phase Ferro resonance circuits during the excitation of second-order subharmonic oscillations is of particular importance in the design and creation of various converter devices.

1 Introduction

Ensuring Subharmonics are harmonics that have frequencies smaller than the base frequency. In energy systems, under certain conditions, the emergence of currents of subharmonic frequency is observed. Subharmonic frequencies include frequencies below: the primary frequency is divided by some positive integer N, i.e. 1/n, for example, if the generator's primary frequency is 50 Hz, while the subharmonic frequency is 25 Hz (1/2) and 16.6 Hz (1/3). Inductive resistances are used to limit the magnitude of the harmonic oscillations that occur in nonlinear chains, as inductive resistance affects the current. Similarly, sequentially connected linear capacitance resistors are used to increase the actual power by canceling part of the inductive resistance. However, as with sequential linear capacitance when resistances are compensated, some solutions can cause new problems in the system. When capacitors are used as a sequential element in a transmission line, subharmonic currents with frequencies below the main ones are formed [1,2,3]. Extensive research has been conducted, and the effects of subharmonic currents are devastating. Despite the fact that currently there are many publications on the study of subharmonic fluctuations in three-phase chains, the processes in them are analyzed only on the basis of experimental studies. According to the results of the

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analysis, a theoretical analysis was carried out of processes in three-phase chains as an analogue of single-phase chains, which could not reveal the quantitative and qualitative side of processes in three-phase chains. This in turn involves solving nonlinear systems of non-uniform differential equations with reciprocal phase displacements in three-phase chains. These equations describe nonlinear three-phase systems [4,5,6]. On the other hand, in all available literature, subharmonic oscillations are studied in three-phase chains where each phase uses separate ferromagnetic elements. The excitation of subharmonic oscillations in three-phase ferromagnetic element three-phase chains with a magnetic relationship between phases in common ferromagnetic spindle chains has not yet been sufficiently studied [7,8]. This cited document examined the mode of excitation of subharmonic oscillations of the third order in a three-phase chain consisting of linear active, capacitive and nonlinear inductive elements with a common magnetic connection, which is an analogue of the "line unloaded Transformer" Power Line, and obtained equations of motion [9]. Using the averaging method with the corresponding phases Shortened equations. From the condition for the existence of a periodic solution, phase relations are determined that differ from the phase relations for three-phase circuits with group ferromagnetic elements. In the stationary mode, the excitation conditions, the areas of existence, the dependence of the output values on the parameters of the circuit and the applied action are determined. In general, subharmonic oscillations in three-phase chains can be excited in chains consisting of nonlinear inductive resistance and capacitance in chains for the purpose of accumulating a certain amount of energy in their elements necessary to excite and hold their oscillation at a given frequency [10,11,12,13,14]. However, from a practical point of view, electro ferromagnetic chains that are capable of working to a large capacity during energy exchange occur, which are autoparametric oscillatory circuits that are of great interest. In chains where ferromagnetic elements are connected in series with linear capacitances, a large amount of energy is stored in the excitation process when building for switchgear equipment and can generate circuits that can be used effectively to create them [15,16]. In this regard, the issues of developing methods and theory for calculating subgarmonic energy modifiers, which can be used as the basis for engineering calculations of specific devices, have also been studied separately [17,18,19]. Of even greater practical importance is the creation of devices based on multiphase subharmonic chains with electro ferromagnetic vibrational chains, mainly: two-phase and three-phase devices. These, unlike existing energy modifiers, which are mainly based on single-phase nonlinear circuits, have phase-discrete properties, are reliable and convenient to operate. [20,21,22].

2 Materials and methods

The conditions of excitation and the nature of the processes of the agro-industrial complex in such circuits depend not only on the parameters of the elements, the degree of nonlinearity of the PV, the initial conditions, but also on the structure and methods of connecting the elements, the symmetry of the system and the magnitude of the input effect. In three-phase systems, depending on the amplitude, the applied voltage, initial conditions and parameters of the third-order subharmonic oscillations circuit are excited with different amplitude-phase relations and phase alternation, sharply violating the symmetry of the system. Let us consider the steady-state mode of third-order subharmonic oscillations in symmetric three-phase ferroresonance circuits using frequency-energy relations. The Weber-ampere characteristic of a nonlinear inductance (identical in all phases) is approximated by a cubic two-term of the third degree (1):

$$i_v = a\Phi_v + b\Phi_v^3 \tag{1}$$

Taking the law of change in the fluxes created by the current of nonlinear inductance, in the form of (2):

$$\Phi_v = \Phi_v \cos\left[wt + \phi_1 + \left(\frac{1-v}{9}\right)2\pi\right] + \Phi_{3vm}\cos\left[3wt + \phi_3 + \left(\frac{1-v}{3}\right)2\pi\right] \quad (2)$$

To analyze the excitation of third-order subharmonic oscillations in three-phase electro ferromagnetic oscillatory circuits, substitute (1) in (3)

$$i_v = A_{1v}\cos\left[wt + \phi_1 + 2\pi\left(\frac{1-v}{9}\right)\right] + B_{1v}\cos\left[3wt + \phi_3 + 2\pi\left(\frac{1-v}{3}\right)\right] +$$
$$+A_{2v}\sin\left[wt + \phi_1 + 2\pi\left(\frac{1-v}{9}\right)\right] + B_{2v}\sin\left[3wt + \phi_3 + 2\pi\left(\frac{1-v}{3}\right)\right] \quad (3)$$

Where:

$$A_{1v} = a\Phi_{1m} + b\Phi_{1m}\left[\frac{3}{4}\Phi_{1m}^2 + \frac{3}{2}\Phi_{3m}^2 + \frac{3}{4}\Phi_{1m}\Phi_{3m}\cos(3\phi_1 + \phi_3)\right]$$
$$A_{2v} = \frac{3}{4}b\Phi_{1m}^2\Phi_{1m}\sin(3\phi_1 + \phi_3)$$
$$B_{1v} = a\Phi_{3m} + b\Phi_{1m}\left[\frac{3}{4}\Phi_{3m}^2 + \frac{3}{2}\Phi_{1m}^2 + \frac{1}{4}\Phi_{1m}^2\cos(3\phi_1 + \phi_3)\right]$$
$$B_{2v} = \frac{1}{4}b\Phi_{1m}^3\sin(3\phi_1 + \phi_3) \quad (4)$$

In expression (3), terms that differ in frequency from ω and 3ω are ignored for simplicity. Using the conclusions about the possible variants of excitation of subharmonic oscillations circuit in three-phase circuits, we will use the initial data and express the currents of individual phases, while we assume that the components of the subharmonic flows are shifted by angles of 0°, 40°, 80°, and the fundamental harmonic flows are symmetrical and constitute a direct sequence system.

3 Results and discussion

To determine the area of existence and critical values of the circuit parameters at which the steady-state mode of subharmonic oscillations can still exist in three-phase ferroresonance circuits, consider equations (3). To do this, square them and add them up. The instantaneous value of the voltage in the nonlinear inductance, taking into account (2), is expressed as (5):

$$U_1 = \frac{d\phi}{dt} - aw\Phi_{1m}\sin(wt + \phi_1) - 3b\Phi_{3m}\sin(3wt + \phi_3) \quad (5)$$

Let's write down the voltage and current in a complex form and we can solve. As a result, we obtain expressions that determine the relationship between the squares of the amplitudes of the fundamental harmonic flux and subharmonics. Taking into account the phase relations in the three-phase circuits given in 3, we obtain in general terms the following equations for each phase (6):

$$36\Phi_{3v}^4 + 27\Phi_{3v}^2\Phi_{1v}^2 + 9\Phi_{1v}^4 - 2N_v\Phi_{2v}^2 - N_v\Phi_{1v}^2 + \frac{16}{9b^2}N_v[K_v + 1] = 0 \quad (6)$$

Where, the values $\mathbf{N_v}$ and $\mathbf{K_v}$ summarized in Table 1.

Table 1. Dependence of coefficients N_v and K_v on Phase Shift angles.

Options	Phase	Start of phase	N_v	K_v
1	A	0^0	$\frac{K_q - a}{b}$	$\frac{K_p}{K_q - a}$
	B	40^0	$\frac{0.643K_p + 0.766K_q - a}{b}$	$\frac{0.766K_p + 0.643K_q}{0.643K_p + 0.766K_q - a}$

	C	80^0	$\frac{0.984K_p + 0.173K_q - a}{b}$	$\frac{0.173K_p + 0.984K_q}{0.984K_p + 0.173K_q - a}$
2	A	0^0	$\frac{K_q - a}{b}$	$\frac{K_p}{K_q - a}$
	B	80^0	$\frac{0.984K_p + 0.173K_q - a}{b}$	$\frac{0.173K_p + 0.984K_q}{0.984K_p + 0.173K_q - a}$
	C	160^0	$\frac{0.939K_p + 0.342K_q - a}{b}$	$\frac{0.342K_p + 0.939 + K_q}{0.939K_p + 0.342K_q - a}$
3	A	0^0	$\frac{K_q - a}{b}$	$\frac{K_p}{K_q - a}$
	B	160^0	$\frac{0.939K_p + 0.342K_q - a}{b}$	$\frac{0.342K_p + 0.939 + K_q}{0.939K_p + 0.342K_q - a}$
	C	320^0	$\frac{0.643K_p + 0.766K_q - a}{b}$	$\frac{0..766K_p + 0.643 + K_q}{0.643K_p + 0.766K_q - a}$

Each equation of this system is an equation for the connection of the square of the flows of the main and sub harmonic components $\Phi^2_{3v}$and Φ^2_{1v} in ferromagnetic elements and is the equation of the second-order curve. By solving from it, it is possible to determine the critical parameters of the phase elements, the active resistance and the capacitance of the circuit. Expression (5) is the conditions for the existence of a subharmonic oscillation mode for each phase in three-phase circuits. It can be seen from the inequalities that the conditions for the existence of subharmonic oscillations for each phase are different and are determined by the parameters of the circuit. If conditions (5) are met, the second-order curves describe real ellipses located in the first square of the plane Φ^2_{3v} 0 Φ^2_{1v}. The coordinates of the ellipse centers are determined by the formula: for a phase shift of 0°,40°, 80° we get:

$$\Phi^2_{301} = \frac{2}{7}\left(\frac{K_p}{K_q - a}\right) \tag{7}$$

$$\Phi^2_{101} = \frac{4}{7}\left(\frac{K_p}{K_q - a}\right) \tag{8}$$

$$\Phi^2_{302} = \frac{2}{7}\left(\frac{0.643K_p + 0.766K_q - a}{b}\right) \tag{9}$$

$$\Phi^2_{102} = \frac{4}{7}\left(\frac{0.643K_p + 0.766K_q - a}{b}\right) \tag{10}$$

$$\Phi^2_{303} = \frac{2}{7}\left(\frac{0.984K_p + 0.173K_q - a}{b}\right) \tag{11}$$

$$\Phi^2_{103} = \frac{4}{7}\left(\frac{0.984K_p + 0.173K_q - a}{b}\right) \tag{12}$$

Graphical interpretations of equations (5) corresponding to the steady-state mode of third-order subharmonic oscillations for the mode of excitation of subharmonic oscillations with a phase shift of 0°, 40°, 80°.According to the table, the excitation conditions for different phases differ from each other, because K1, K2 and K3 are different. Different K1 correspond to their ellipses, from which it can be seen that in each particular case, the regions of existence by the input effect of $\Delta\Phi^2_{3vM}$and the amplitudes of the excited subharmonic oscillations differ from each other. The use of the frequency-energy method for the analysis of subharmonic oscillations in three-phase ferroresonance circuits is possible only when used in the power ratios of the phases and phase relations of the corresponding ones. The use of the energy method, regardless of the characteristics of the frequency-converting element, simplifies the computational algorithm for compiling the equations of the established process of the agro-industrial complex both in the division mode and in the frequency multiplication mode (derivation of the equations of motion of the system, approximate the solution of shortened equations).

4 Conclusion

In conclusion, it can be said that in three-phase ferroresonance chains with a common ferromagnetic element, a nonlinear equation of motion is induced, allowing to obtain an equation that takes into account the processes in the common ferromagnetic element in contrast to ferroresonance chains made up of individual ferroromagnetic elements. Even in three-phase ferroresonance chains with a three-phase ferromagnetic element, subharmonic oscillations excite in hard and soft modes. It has been found that ferroresonance, composed of separate ferroromagnetic elements, excites simultaneously in all phases in contrast to chains. In three-phase ferroresonance chains with a common three-phase ferromagnetic element, subharmonic oscillations appear in a wider range than in three-phase ferroresonance chains consisting of separate ferromagnetic elements, which allows for wide applications in mnogoustoychivian elements.

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