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POSSIBILITY OF APPLYING METHODS OF ANALYSIS AND SYNTHESIS OF LINEAR ELECTRICAL CIRCUITS TO SOME NONLINEAR CIRCUITS

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Abstract: *This article discusses the possibility of applying the analysis and calculation methods used in linear electric circuits to certain nonlinear circuits. It is shown that if we abandon the quantitative criteria for the analysis and synthesis of nonlinear circuits using linear principles, some problems in nonlinear electrical engineering can be correctly solved based on linear theory. As an example, the simplest ferroresonant voltage stabilizer is considered, using the method of superposition and the equivalence of ferroresonant circuits in series and parallel connections. The electrical diagram is shown, and a formula for the stabilization coefficient is derived, representing a complex nonlinear function dependent on both linear and nonlinear circuit parameters. Under certain conditions, a simplified formula for calculating the output voltage stabilization coefficient is provided.*

In a circuit where Kirchhoff's laws strictly apply, the method of superposition, which pertains to the analysis of linear circuits, can also be applied to circuits with nonlinear elements. The stabilization of the output voltage of a simple single-phase ferroresonant voltage stabilizer and the characteristics of two ferroresonant circuits with parallel and series connections of passive elements are also presented. Basic calculation formulas are provided as well.

Keywords. *Nonlinear electrical circuit, superposition principle, circuit equivalence.*

Аннотация: *В данной статье рассматривается возможность применения к некоторым нелинейным цепям метод анализа и расчета применяемых в линейных электрических цепях. Показана, что если отказаться от количественных критериев анализа и синтеза нелинейных цепей с помощью линейных принципов, то некоторые задачи нелинейной электротехники можно вполне корректно решить и на базе линейной теории. В качестве примера рассмотрена простейший феррорезонансный стабилизатор напряжения с применением метода суперпозиции (наложения) и эквивалентность феррорезонансных цепей последовательного и параллельного соединений. Показана электрическая схема выведано формула коэффициента стабилизации напряжения представляющий собой сложную нелинейную функцию, завалящую от линейных и нелинейных параметров цепи и при соблюдении определенных условиях показана упрошенная формула расчета коэффициента стабилизации выходного напряжения.*

В цепи где соблюдаются условия при которого строго действует законы Кирхгофа, метод суперпозиции относящейся к анализу линейных цепей также будет применять и в случае цепей с нелинейными элементами. Стабилизации выходного напряжения простейшего однофазного феррорезонансного стабилизатора напряжения и характеристики двух феррорезонансных цепей при параллельных и последовательных соединениях пассивных элементов. А также приведены основных расчетные формулы.

Ключевые слова. *Нелинейная электрическая схема, принцип суперпозиции, эквивалентность схем.*

Annotatsiya: *Mazkur maqolada ayrim noxatli zanjirlarga nisbatan chiziqli elektr zanjirlarida qo'llaniladigan tahlil va hisoblash usulini qo'llash imkoniyati ko'rib chiqilgan. Agar noxatli zanjirlarni chiziqli tamoyillar yordamida tahlil qilish va sintez qilishning miqdoriy mezonlaridan voz kechilsa, ayrim noxatli elektrotexnika masalalarini chiziqli nazariya asosida ham to'g'ri hal qilish mumkinligi ko'rsatilgan. Misol sifatida, superpozitsiya (qatlamlash) usuli qo'llanilgan eng oddiy ferrorezonansli kuchlanish stabilizatori va ketma-ket va parallel ulanishlar bilan ferrorezonansli zanjirlarning ekvivalentligi ko'rib chiqilgan. Elektr sxema ko'rsatilgan va stabilizatsiya koeffitsienti formulasi chiqarilgan, bu koeffitsient chiziqli va noxatli zanjir parametrlariga bog'liq bo'lgan murakkab noxatli funksiyani ifodalaydi. Shuningdek, muayyan shartlar bajarilganda chiqish kuchlanishini stabilizatsiya qilish koeffitsientini hisoblashning soddalashtirilgan formulasi ko'rsatilgan.*

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Zanjirda Kirxgof qonunlari qat'iy amal qiladigan sharoitlarda, chiziqli zanjirlarni tahlil qilishga tegishli bo'lgan superpozitsiya usuli noxatli elementlarga ega zanjirlarda ham qo'llanishi mumkin. Eng oddiy bir fazali ferrorezonansli kuchlanish stabilizatori chiqish kuchlanishini stabilizatsiya qilish va ikki ferrorezonansli zanjirning passiv elementlar ketma-ket va parallel ulanishidagi xarakteristikalar keltirilgan. Shuningdek, asosiy hisoblash formulalari keltirilgan.

Kalit so'zlar. *Chiziqli bo'lmagan elektr sxema, superpozitsiya usuli, ekvivalent sxema.*

Introduction

Unlike nonlinear circuits, electrical circuits with linear parameters R, L and C have a much richer list of physical and mathematical descriptions and definitions, a wide range of methods of analysis and synthesis, and therefore disproportionately large areas of application in applied problems of electrical engineering. In turn, physical processes in nonlinear electrical circuits are distinguished by the diversity and complexity of the effects of electromagnetic energy conversion, which are unusual for linear circuits, and are very widely used where it is necessary to perform specific functional transformations of currents and voltages.

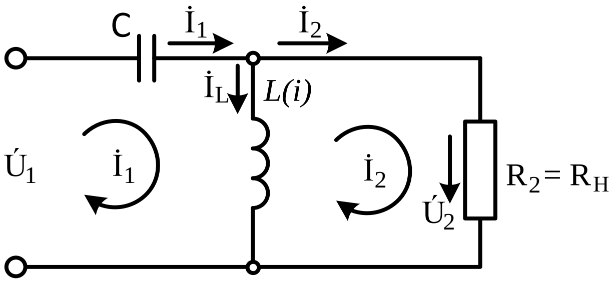
Without going into the details of the classical definition of linear and nonlinear circuits and without considering the issues of generality and differences between them, we will dwell only on some, in our opinion, fundamental theoretical positions and principles inherent in both categories of circuits. We are talking about those principles and concepts common to them that are formally unacceptable for nonlinear electrical circuits, but are very effective in linear ones, namely: the principles of superposition (overlay), reciprocity, reversibility, equivalence of circuits of serial and parallel connections, duality of circuits with sources of EMF and currents [1]. This list could be continued with equally interesting theoretical concepts, but our task includes only a qualitative assessment and comparison of physical phenomena described using known criteria and techniques of a linear chain applied to nonlinear ones.

Research Methods and the Received Results

As will be shown below, the inapplicability of many linear principles to circuits with nonlinear elements is due mainly to the inadequacy of amplitude-frequency and phase relationships in a nonlinear circuit at different levels of voltage (current) amplitude of the power source. However, if we abandon the quantitative criteria for the analysis and synthesis of nonlinear circuits using linear principles, then some problems of nonlinear electrical engineering can be solved quite correctly on the basis of linear theory. As an example, below we consider the calculation of the simplest ferroresonance voltage stabilizer using the superposition method, as well as the equivalence of ferroresonance circuits of serial and parallel connections.

Figure 1 shows a diagram of the simplest single-phase ferroresonance voltage stabilizer with an active load at the output of the circuit. Let's calculate the main operating characteristics and voltage stabilization coefficient

$$K_{cr} = \frac{\Delta U_{\boxdot}}{\Delta U_{\Sigma}} \cdot \frac{U_2}{U_1} - \qquad (1)$$



Drawing 1.

by the loop current method, which is based on the principle of superposition [2]. The basic circuit equations for complex fundamental harmonic currents in this case have the form

$$\dot{I}_1 Z_{11} - \dot{I}_2 Z_{22} = U_1 \qquad (2)$$
$$-\dot{I}_1 Z_{21} + \dot{I}_2 Z_{22} = 0$$

Here: $Z_{11} = j\left(X_{L_{\text{Э}}} - X_c\right)$, $Z_{12} = Z_{21} = jX_{L_{\text{Э}}}\, u\, Z_{22} = R_2 + jX_{L_{\text{Э}}}$

Due to the nonlinearity of the inductive coil L(i), its resistance $X_{L_{\text{Э}}}$ is calculated for equivalent sinusoidal voltage values $u_2 = U_{2m} sin\, Wt$ and current $i_L = I_{Lm} sin\,(Wt - \frac{\pi}{2})$ by approximating the volt-ampere characteristics of the coil using the effective values of the functions

$$I_{L=}\, aU_2 + bU_2^3 \qquad (3)$$

so in our example

$$X_{L_{\text{Э}}} - \frac{U_2}{I_L} = -\frac{1}{a+bU_2^2}$$

(3) is a function of the voltage applied to the coil $U_L = U_2$.
Expressions for the loop currents I_1 and I_2 can be easily obtained from (2) as

$$\dot{I}_1 = \frac{\Delta_{11}}{\Delta} \cdot \dot{U}_1\, u\, \dot{I}_2 = \frac{U_2}{R_2} = \frac{\Delta_{\Sigma\boxdot}}{\Delta} U_{\boxdot}$$

$$\Delta = Z_{11}Z_{22} - Z_{12}^2, \Delta_{11} = Z_{22} u \Delta_{12} = \Delta_{21} = Z_{12} \qquad (4)$$

Taking into account the specific values of the linear and nonlinear parameters of the circuit,

we have [3-4].

$$\dot{I}_1 = \frac{(R_2 + jX_{L_{\text{Э}}})\dot{U}_1}{X_{L_{\text{Э}}}X_c + jR(X_{L_{\text{Э}}} - X_c)} = \frac{\left[(a+bU_2^2) + jg_2\right]\dot{U}_1}{g_{2_{\text{Э}}}X_c + j\left[1 - aX_c - bX_cU_2^2\right]} \qquad (5)$$

$$I_2 = \frac{-jg\dot{U}_1}{X_{L_{\text{Э}}}X_{\text{c}} + jR_2(X_{L_{\text{Э}}} - X_c)} = \frac{-j\dot{U}_1}{X_{\text{c}} + jR_2\left[1 - aX_c - bX_{\text{c}}U_2^2\right]} = \frac{-jg\dot{U}_1}{g_{2_{\text{Э}}}X_{\text{c}} + j\left[1 - aX_c - bX_{\text{c}}U_2^2\right]} \qquad (6)$$

From (3) you can go to the main operating characteristic of the stabilizer U2= ʃ1 (*U1*) or *U1*= ʄ2 *(U2)*:

$$\dot{U}_2 = -\frac{\dot{U}_1}{(1-\alpha \mathrm{Xc}-bXcU_2^2)-\mathrm{f}g_2\mathrm{Xc}} = \frac{\dot{U}_1}{(\alpha \mathrm{Xc}+bXcU_2^2-1)+jg_2X_c}, \qquad (7)$$

$$\dot{U}_1 = \left(\alpha X_c\dot{U}_2 + bX_c\dot{U}_2^3 - \dot{U}_2\right) + jg_2X_cU_2 \qquad (8)$$

The relationship between the modules of the vectors $\dot{U}_1$ and $\dot{U}_2$ has the form

$$U_1 = \sqrt{(\alpha X_c + bX_cU_2^2 - 1)^2 + g_2^2X_c^2 \cdot U_2} \qquad (9)$$

Equation (6) makes it possible to analytically express one of the most important parameters of the stabilizer - the stabilization coefficient

$$K_{cm} = \frac{\Delta U_1}{U_1} : \frac{\Delta U_2}{U_2} \cong \frac{dU_1}{dU_2} \cdot \frac{U_2}{U_1} \qquad (10)$$

Let's write it down

$$K_{cm} = \frac{dU_1}{dU_2} \cdot \frac{U_2}{U_1} = \frac{2bX_sU_2^2(\alpha X_c+bX_cU_2^2-1)}{(\alpha X_c+bX_cU_2^2-1)^2+g_2^2X_c^2} + 1 \qquad (11)$$

As you can see, the output voltage stabilization coefficient is a complex nonlinear function that depends on the linear and nonlinear parameters of the circuit and the voltage U2 at the circuit output. However, if we take into account that $U_2 = \ const$ as a stabilized quantity, $g_2X_c \ll \alpha X_c + bX_cU_2^2 - 1$ (or $g_2 \ll \alpha + \mathrm{b}U_2^2 - \omega C$), then (7) can be simplified and reduced to the form

$$K_{cm} = \frac{2bX_cU_2^2}{aX_c+bX_2U_2^2-1} + 1 = \frac{2b\mathrm{U}_2^2}{a+b\mathrm{U}_2^2-\omega\mathrm{C}} + 1 \ (11, \mathrm{a})$$

From (7,a) it follows that the stabilization coefficient is greater, the larger the capacitance C and the smaller the linear approximation coefficient α, i.e. the flatter the UL(IL) curve in the saturation zone. Using (5) you can also determine two critical voltage values [5-9].

$U_1 = U'_1 \ u \ U_1 = U''_1$, at which ferroresonant current surges occur

$$\ll up \gg \ -by \ U_1 = U'_1 \ u \ \ll down \gg \ -by \ U_1 = U''_1. \qquad (12)$$

To do this, in the first case we perform the operation

$$[Re\dot{U}_1]'_{U^2} = 0 = \alpha X_c + 3bX_cU_2^2 - 1, \qquad (13)$$

Where do we have $U'_2 = \frac{\sqrt{\omega C - a}}{3} \rightarrow U'_1$ (upward jump), and in the second –

$$Re\dot{U}_1 = 0 = \alpha X_c + bX_cU_2^2 - 1,$$

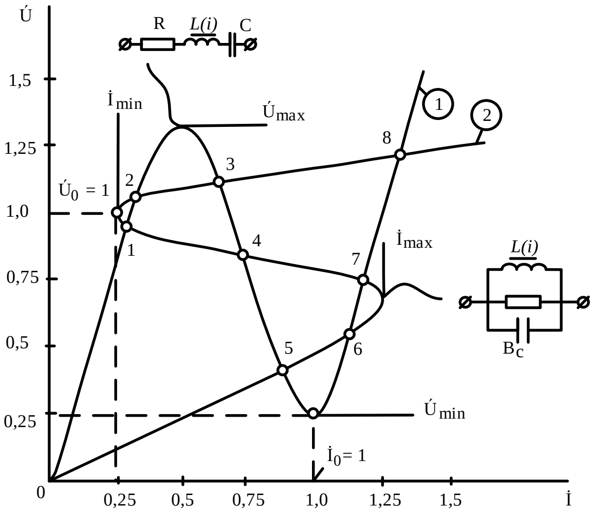
Where do we have $U''_2 = \frac{\sqrt{\omega \mathrm{C} - a}}{\mathrm{b}} \rightarrow U''_1$ (jump down).

From the above, we can draw the following conclusion that the superposition method, common in the analysis of linear circuits, can also be used in the case of circuits with nonlinear elements, if the conditions are met under which Kirchhoff's law strictly applies in the circuit [10-16].

The following example includes signs of equivalence of ferroresonant circuits of serial and parallel connections.

When applied to a linear two-terminal network, the principle of equivalence of two circuits means that regardless of the method of connecting their elements (series, parallel or series-parallel or series-parallel), the current I consumed by them from the voltage source U must be identical in magnitude and phase[17]. Thus, a series circuit with elements R, XL, and XC and impedance $Z = R + j(X_L - X_C)$ is considered equivalent to a parallel circuit with elements g, bL and bc and impedance Y=g-j($b_L - b_C$) if the condition Z*Y = 1 is met (in this case I=YU=U:z, $\varphi_{\text{зкв}} = arctg\frac{X_L - X_C}{R} = arctg\frac{b_L - b_C}{g}$). Now let's turn to characteristics 1 and 2 of two ferroresonant circuits of serial and parallel connections (Fig. 2), built for convenience of analysis in relative units of voltages and currents. The circuit elements are selected so that the extreme values of parallel ferroresonance currents are equal to the extreme values of series voltages, i.e.

$$I_{max} = U_{max}, \qquad I_{min} = U_{min}.$$



Drawing 2.

Discussion

From a comparison of the current-voltage characteristics 1 and 2 it is clear that formally the modulus of the total resistance of a series circuit is equal to the inverse value of the modulus of the total conductance of a parallel circuit at all points of intersection of characteristics 1, 2, ..., 8. But circuits can be equivalent in a linear sense be only at intersection points 2, 3, 6 and 7, where the impedances of the two circuits are equal not only in magnitude, but also in the nature of the phase shifts between voltage and current. In fact, at points 1, 4 and 5 - φ_1>0, φ_2> 0, and at point 8 - φ_1<0 and φ_2>0, i.e. the inductive mode of a series circuit corresponds to the capacitive mode of a parallel circuit or vice versa. This does not take into account the fact that of the equivalent modes, only 3 is unstable for a series circuit, and point 7 is unstable for a parallel circuit.

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ALGORITHMS AND SOLUTION TO THE PROBLEM OF PARAMETRIC IDENTIFICATION OF THE GAS COMPOSITION OF THE ATMOSPHERE

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Abstract. *This article discusses the problem of identifying the gas composition of the atmosphere, which has important practical significance and allows us to illustrate the advantages of the proposed regularizing solution algorithms. Every ear, human industrial activity increasingly aggravates the problem of environmental protection. Among the diverse human impacts on nature, air pollution occupies a special place. Every ear, up to 500 thousand various pollutants are emitted into the atmosphere. In this regard, the task of monitoring the composition of the atmosphere is very relevant. Numerical studies of the problem of identifying the gas composition of the atmosphere have*

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