



ICECET'25 CONFERENCE PROCEEDINGS

3-6 July 2025



STATISTICAL DETAILS FOR ICECET 2025

Submitted papers: **2078**

Accepted papers: **771**

Acceptance ratio: **37%**

Total registered papers: **720 from 79 different countries**

Physical Poster presentation: **28**

Physical Oral presentation: **230**

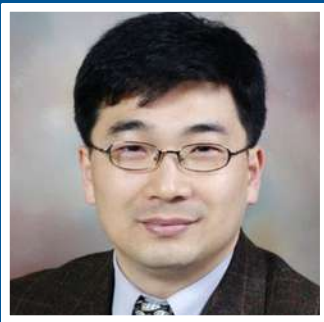
Online presentation: **462**

Total physical participants: **300+ from 55 different countries.**

The papers have been submitted to IEEE for publication.

KEYNOTE

Prof. Dr. Hee-Cheol Kim
Inje University, South Korea



Dr. Hee-Cheol Kim Ph.D. in Numerical Analysis and Computing Science from Stockholm University, Sweden. He is a senior professor in the Department of Computer Engineering and as the Head of the Institute of Digital Anti-Aging Healthcare at Inje University, South Korea. He is the President of the Korea Institute of Information and Communication Engineering (KIICE) research society and the Co-Chair of the IEEE International Conference on Advanced Communication Technology (ICACT). He also leads the Smart Computing Research Laboratory. His research interests encompass medical image processing, pathology image analysis, natural language processing, computer vision, text mining, bioinformatics, the metaverse, blockchain, and federated learning.

Title: Revolutionizing Healthcare with AI: Innovations in Medical Imaging and Clinical Decision-Making

Abstract: Artificial Intelligence (AI) is revolutionizing healthcare by enhancing diagnostic accuracy, optimizing treatment strategies, and improving patient outcomes. This keynote will explore cutting-edge AI techniques applied in medical imaging and clinical decision-making, focusing on deep learning, computer vision, natural language processing (NLP), and federated learning. Convolutional Neural Networks (CNNs) and Vision Transformers (ViTs) have significantly advanced automated disease detection and segmentation in radiology and digital pathology, improving efficiency and consistency. Generative AI techniques, such as diffusion models and generative adversarial networks (GANs), enable data augmentation and synthetic image generation, addressing challenges like data scarcity and bias. Large language models (LLMs) and NLP techniques play a crucial role in clinical text analysis, aiding in automated medical report generation and disease prediction from electronic health records (EHRs). Additionally, federated learning ensures privacy-preserving AI model training across multiple institutions, fostering collaboration while maintaining data security. This keynote will discuss these AI-driven advancements, explore challenges such as interpretability, bias, and regulatory compliance, and highlight future directions for AI-powered healthcare.

KEYNOTE

Prof. Dr. Raffaele Carli
Politecnico di Bari, Italy



Raffaele Carli received his Laurea degree in Electronic Engineering with honours in 2002 and his PhD in Electrical and Information Engineering in 2016, both from Politecnico di Bari, Italy. From 2003 to 2004, he was a Reserve Officer with Italian Navy. From 2004 to 2012, he worked as System and Control Engineer and Technical Manager for a multinational company in the space and defense sector. Currently, Dr. Carli is an Associate Professor in Systems and Control Engineering at Politecnico di Bari, where he is the technical lead for the Decision and Control Laboratory (coordinated by prof. Mariagrazia Dotoli) within the Department of Electric and Information Engineering (<http://dclab.poliba.it/>). He has held national qualifications as a Full Professor since 2023. Since 2022, he has served as Vice-Coordinator of the National PhD program in Autonomous Systems (<http://dausy.poliba.it/phd/>). Dr. Carli serves on the editorial board of IEEE (Institute of Electrical and Electronics Engineers) journals as an Associate Editor for IEEE Transactions on Automation Science and Engineering (awarded 2023 and 2024 Best Associate Editor) and IEEE Transactions on Systems, Man, and Cybernetics. He is also an active member of the conference editorial boards of various events sponsored by IFAC (International Federation of Automatic Control) and IEEE, including those sponsored by the IEEE Control Systems Society (CSS), IEEE Robotics and Automation Society (RAS), and IEEE Systems, Man, and Cybernetics Society (SMCS). His organizational roles include positions on the committees of several IEEE conferences, such as Young Career Chair of the 2017 IEEE International Conference on Automation Science and Engineering, Publication Co-chair of the 2015 IEEE International Conference on Automation Science and Engineering, Tutorial Co-chair of the 2023 IEEE International Conference on Systems, Man and Cybernetics, Finance Chair and Special Session Chair of the 2024 IEEE International Conference on Automation Science and Engineering.

He also serves as General Chair of the upcoming IFAC Workshop on Smart Energy Systems for Efficient and Sustainable Smart Grids and Smart Cities (SENSYS 2025) and the Publicity Chair of the 2026 IEEE International Conference on Industrial Electronics and Applications. An IEEE Senior Member since 2022, Dr. Carli currently serves as the Mentorship Subcommittee Chair of the Membership and Student Activities Committee within the IEEE SMCS for the 2023-2024 and 2025-2026 terms. Additionally, he currently serves as the Secretary of the IEEE Italy Section Chapter CS23 of the CSS for the 2025-2026 term. Dr. Carli has authored over 120 printed international publications (Google Scholar profile: <https://scholar.google.it/citations?user=OvXT8Y0AAAAJ&hl=en>). His research focuses on developing decision and control techniques for modeling, optimizing, managing, and controlling complex, large-scale systems, particularly in smart frameworks such as industry and energy. He received the 2024 IEEE Italy Section SMCS Chapter Award for Excellence in Early Career Research. For additional information, visit: <http://dclab.poliba.it/people/raffaele-carli/>

Title: Optimal Solar Tracking for Sustainable Crop Cultivation and Energy Generation in Agrivoltaics

Abstract: Rural energy communities play a crucial role in driving sustainable development through the integration of agriculture and energy systems. In this context, the talk focuses on agrivoltaics, an innovative approach that blends photovoltaic technology with agricultural practices to optimize land use efficiency and enhance resource sustainability in rural areas. The talk specifically explores two scenarios: rural photovoltaic farms and integrated agrivoltaic plants, with a keen emphasis on optimizing layout and system performance. Detailed analysis of objectives and system modeling methodologies is provided for each scenario, alongside simulation results from practical applications, offering insights into agrivoltaics' potential impact on energy production and agriculture sustainability.

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past CONFERENCES



ICECET - 2021
09-10 December, 2021
Cape Town - South Africa
Virtual



ICECET - 2022
July 20-21-22, 2022
Prague, Czech Republic
Virtual and Physical



ICECET - 2023
November 16-17, 2023
Cape Town - South Africa
Virtual and Physical



ICECET - 2024
July 25-27, 2024
Sydney, Australia
Virtual and Physical

Next Conference

ICECET'26

Rome, Italy

06-08
JULY
2026

<https://www.icecet.com/2026>

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PAPERS

Exact calculation of resonant frequency in a real parallel RLC circuit

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Abstract— We study a parallel oscillating circuit consisting of an inductance and a capacitance connected in parallel. It is often assumed that such a circuit is ideal, i.e., the inductance has no internal resistance and there is no current leakage through the capacitor. For such an ideal circuit, the phenomenon of current resonance is well studied, and all the quantities arising in this case have been calculated. However, for a real, not ideal circuit, when calculating its frequency characteristics, it is necessary to take into account the presence of internal resistance of the inductor and current leakage through the dielectric of the capacitor. In this paper, such a real circuit is investigated, for which exact, not known so far, formulas for the resonant frequency and the corresponding amplitude are found. This makes it possible to evaluate exactly the errors arising from the use of various approximate formulas widely used in practice.

Keywords—parallel RLC- circuit, current resonance, exact resonant frequency formula, approximate formulas for resonant frequency, amplitude resonance, phase resonance.

I. INTRODUCTION

Consider the parallel oscillating circuit shown in Fig. 1.

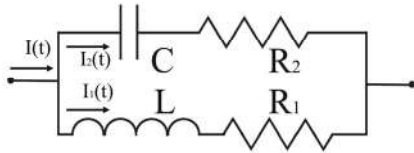


Fig. 1. Real parallel oscillating circuit

AC voltage $U = A \cdot \cos(\omega t + \varphi)$, where A is the amplitude, ω is the frequency, and φ is the phase, are applied to the input of this circuit. The current $I(t, \omega)$ through the circuit depends on the frequency ω .

There are several definitions of resonant frequency.

Definition 1: the frequency ω_0 at which the complex impedance of the circuit will be purely real: $\text{Im} Z = 0$, $|Z| = \text{Re} Z$. We call this phase resonance.

Definition 2: the frequency ω_1 at which the module of the complex impedance of the circuit $|Z|$ will acquire an extreme value. We call this amplitude resonance. For a circuit of a given type, the impedance modulus may, depending on the values of

the circuit parameters, have a maximum, minimum, or no extreme points.

For a series or parallel RLC - circuits, where the capacitor, inductor and resistor are connected either all in series or all in parallel, these two definitions coincide, yielding the classical formula for the resonant frequency $\omega_0 = \omega_1 = 1/\sqrt{LC}$ [2], [3] [4]. However, when R_1 or R_2 - are non-zero, these definitions lead to different frequencies [1], [13]. For small values of R_1 and R_2 frequencies ω_0 and ω_1 differ little from each other and therefore are used ω_0 instead of ω_1 in calculations (it is considered that $\omega_1 \approx \omega_0$). Until now, there was no exact formula for calculating the amplitude resonant frequency ω_1 . Several approximate formulas are given in textbooks and reference books [2], [3], [4], but the exact limits of their application and the errors that occur when the exact resonance frequency is replaced by an approximate value are not indicated. The exact formulas were known only in partial cases, when R_1 or R_2 are zero or $R_1 = R_2$ [1], [13]. A short version of the results of exact calculations of the amplitude resonance frequency of the circuit shown in Fig. 1 were stated without proof in [11]. This paper presents proofs of exact formulas that generalise all known partial results and allow us to evaluate the accuracy of all currently used approximate formulas for calculating the resonant frequency of the circuit under consideration. After finding such a frequency, the next step will be to find an amplitude to the current at this resonant frequency. The exact value of such amplitude will also be calculated. The discovery of exact formulas, which were previously unknown, makes it possible to identify errors arising from different approximate formulas. The study of other circuits was started in [8]-[10],

II. CALCULATION OF RESONANCE FREQUENCY

We introduce the notations of some quantities related to the

$$\text{circuit: } a = \frac{R_1^2 C}{L}, \quad b = \frac{R_2^2 C}{L}, \quad A = 1 + 2a + \sqrt{ab},$$

$$B = 1 + 2b + \sqrt{ab}, \quad D^2 = \frac{A}{B} = \frac{1 + 2a + \sqrt{ab}}{1 + 2b + \sqrt{ab}} \quad (1)$$

The quantities $Q_1 = \sqrt{a}$ and $Q_2 = \sqrt{b}$ are known as the Q-factors of parallel circuits $R_1 LC$ and $R_2 LC$, respectively ([3],

ch.21). For circuits that find practical application $a < 1$ and $b < 1$ (often significantly close to zero). The value D characterizes the asymmetry of the circuit.

Admittance of the circuit shown in Fig. 1 can be written in the form:

$$Y = \frac{1}{Z} = \frac{1}{Z_c} + \frac{1}{Z_L} = \frac{1}{R_2 + \frac{1}{pC}} + \frac{1}{R_1 + pL} \quad (2)$$

Let us substitute here $p = j\omega$ and make a change of variable $x = \omega^2 CL$. Then:

$$Y(\omega) = \frac{j\omega C}{1 + j\omega CR_2} + \frac{1}{R_1 + j\omega L} = \sqrt{\frac{C}{L}} \cdot \frac{j\omega\sqrt{CL}}{1 + j\omega\sqrt{CL} \cdot R_2\sqrt{\frac{C}{L}}} + \sqrt{\frac{C}{L}} \cdot \frac{1}{R_2\sqrt{\frac{C}{L}} + j\omega\sqrt{CL}} \quad (3)$$

$$Y(\omega) = \sqrt{\frac{C}{L}} \cdot \left(\frac{j\sqrt{x}}{1 + j\sqrt{bx}} + \frac{1}{\sqrt{a} + j\sqrt{x}} \right) = \sqrt{\frac{C}{L}} \cdot Y_{ab}(x) \quad (4)$$

The first term in this formula corresponds to the current I_2 , and the second corresponds to the current I_1 . This substitution allows us to move from analysing the function of four parameters C, L, R_1, R_2 to studying the function of only two parameters a, b . Constant factor $\sqrt{C/L}$ does not depend on frequency ω . The quantity $\rho = \sqrt{L/C}$ is known as the characteristic impedance of the circuit.

To find the frequency of phase resonance we need to equate to zero the imaginary part of the admittance $Y(\omega)$:

$$\text{Im} Y(\omega) = \sqrt{\frac{C}{L}} \left(\frac{\sqrt{x}}{1 + bx} - \frac{\sqrt{x}}{x + a} \right) = 0 \quad (5)$$

In this way, we obtain the frequency of phase resonance x_φ :

$$x_\varphi = \frac{1-a}{1-b}, \text{ see e.g. [2], p. 313.} \quad (6)$$

The amplitude of current $I(t) = I_1(t) + I_2(t)$ depends on the modulus of admittance $|Y(\omega)|$, so our task is to study the function $y(x) = |Y_{ab}(x)|^2$. Calculating the square of the modulus, we get:

$$y(x) = \frac{(1-x)^2 + x(\sqrt{a} + \sqrt{b})^2}{(1+bx) \cdot (a+x)} \quad (7)$$

Fig. 2 shows graphs of the function $1/y(x)$ for some values of a and b for $a < 1$ and $b < 1$. The value $x=1$ corresponds to the frequency $\omega_0 = 1/\sqrt{LC}$. The maximum of the function $1/y(x)$ corresponds to the minimum value of the current amplitude $I(t, \omega)$ - it occurs at the resonance frequency ω_1 . The graphs clearly show the difference between frequency ω_1 and frequency ω_0 .

To make it convenient to differentiate this function, let us decompose it into simple fractions. We will find the coefficients

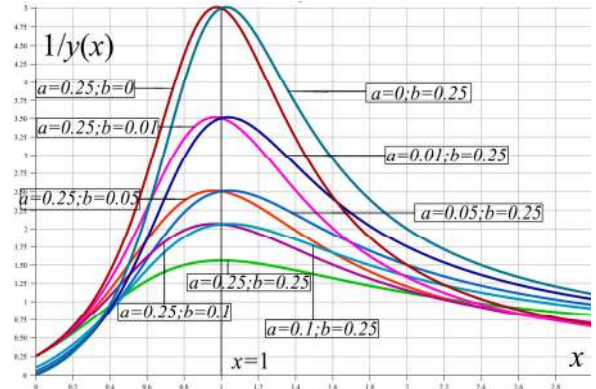


Fig. 2. Impedance modulus square without frequency-independent factor. On the x-axis - reduced frequency.

A and B (1) in the expansion using the method of uncertain coefficients, substituting the values $x = -a$ $x = -1/b$. Thus:

$$y(x) = \frac{1}{1 + \sqrt{ab}} \left(\frac{A}{x+a} + \frac{Bx}{1+bx} - 2 \right) \quad (8)$$

To find the extremal point $x_0 = \omega_1^2 CL$ of the function $y(x)$, we differentiate the last formula and look for the root of the derivative:

$$\frac{dy}{dx} = \frac{1}{1 + \sqrt{ab}} \left(\frac{-A}{(x+a)^2} + \frac{B}{(1+bx)^2} \right) = 0 \quad (9)$$

$$\frac{x+a}{1+bx} = D = \sqrt{\frac{A}{B}} \quad (10)$$

$$x_0 = \frac{\sqrt{A} - a\sqrt{B}}{\sqrt{B} - b\sqrt{A}} = \frac{\sqrt{1+2a+\sqrt{ab}} - a \cdot \sqrt{1+2b+\sqrt{ab}}}{\sqrt{1+2b+\sqrt{ab}} - b \cdot \sqrt{1+2a+\sqrt{ab}}} = \frac{D-a}{1-Db} \quad (11)$$

This formula was first given in [11].

Let us consider some special cases of the resulting formula.

- If $a = b = 0$ (ideal contour: $R_1 = R_2 = 0$), then

$A = B = 1$, $x_0 = 1$ and we get the classic formula:

$$\omega_1 = \omega_0 = 1/\sqrt{CL} \quad (12)$$

- If $a = 0$ ($R_1 = 0$) or $b = 0$ ($R_2 = 0$), then we get the already known formulas for the resonant frequency [13]:

$$x_0 = \sqrt{1+2a} - a \text{ or } x_0 = \frac{1}{\sqrt{1+2b} - b} \quad (13)$$

$$\omega_1^2 = \frac{1}{CL} \cdot (\sqrt{1+2a} - a), \text{ or } \omega_1^2 = \frac{1}{CL} \cdot \frac{1}{\sqrt{1+2b} - b} \quad (14)$$

- If $a = b \neq 1$ (balanced oscillatory circuit: $R_1 = R_2$) then $x_0 = 1$ and we will get the formula $\omega_1 = \omega_0 = 1/\sqrt{CL}$. In this case, we also have zero phase shift of voltage relative to current at the resonant frequency: $\text{Im} Y(\omega_0) = 0$. The discussion of the extreme case $a = b = 1$ will be done in the final part of the paper when analysing the derived formulas.

Note that at present, numerous textbooks and reference books provide several approximate formulas for calculating the resonant frequency. They are based on the assumption that the

phase shift is equal to zero or on the assumption that the resistances R_1 and R_2 is small and at some point in the calculation it can be neglected. However, it is impossible to estimate the error that arises when using such approximate formulas. The exact formula found for the resonant frequency makes it possible to estimate the errors in calculations using such approximate formulas. For this estimation, we will use the series decomposition of $x_0 = (D-a)/(1-Db)$ (11) in powers of a and b , under the assumption of $a < 1$ and $b < 1$. Such assumptions are often fulfilled in practical applications. All further decompositions of the resulting exact formula into power series, in order to use them for approximate calculations, will assume that: $a < 1$, $b < 1$. The first two terms of the expansion give a good enough approximation under the condition $a, b < 0.3$:

$$x_0 = 1 - \frac{1}{2}(a-b)(\sqrt{a} + \sqrt{b})^2(1-a-b) + \dots \quad (15)$$

The remaining term in this decomposition has degree ≥ 4 with respect to the parameters a and b .

Alternatively, in standard notation:

$$\omega_1^2 = \frac{1}{LC} \left(1 - \frac{1}{2} \left(\frac{C}{L} \right)^2 (R_1^2 - R_2^2)(R_1 + R_2)^2 \left(1 - \frac{C}{L} (R_1^2 + R_2^2) \right) + \dots \right) \quad (16)$$

From this expansion it follows that when approximating ω_1 using ω_0 , the error has a degree two relative a and b :

$$|x_0 - 1| = \frac{1}{2}|a-b|(\sqrt{a} + \sqrt{b})^2|1-a-b| + \dots \quad (17)$$

The second well-known and widely used approximate formula for calculating the resonant frequency is the formula:

$$x_0 \approx \frac{1-a}{1-b} \quad (18)$$

It is obtained from the assumption that the phase shift is equal to zero $\text{Im} Y(\omega_0) = 0$ (frequency of phase resonance). With this approximation, the error will be of degree one relative to a and b :

$$x_0 - \frac{1-a}{1-b} = (a-b) \left[1 - \frac{1}{2}(a-b+2\sqrt{ab}) + \dots \right] \quad (19)$$

The third known approximate formula for calculating the resonant frequency is the formula:

$$x_0 \approx \frac{\sqrt{1+2a}-a}{\sqrt{1+2b}-b} = x_1 \quad (20)$$

which is obtained by multiplying the corresponding formulas for the cases $a = 0$ ($R_1 = 0$) and $b = 0$ ($R_2 = 0$). In this case:

$$x_0 - \frac{\sqrt{1+2a}-a}{\sqrt{1+2b}-b} = \sqrt{ab}(b-a) \left[1 - a - b - \frac{1}{2}\sqrt{ab} + \dots \right] \quad (21)$$

The error has an degree two relative a and b .

Fig. 3 shows the difference between the frequencies of phase and amplitude resonance and their approximations. Point M_1 is the phase resonance frequency calculated by (6), point M_2 is the amplitude resonance frequency calculated by (11), point M_3 is an approximation of the amplitude resonance frequency calculated by (20), and point M_4 corresponds to the frequency $\omega_0 = 1/\sqrt{CL}$.

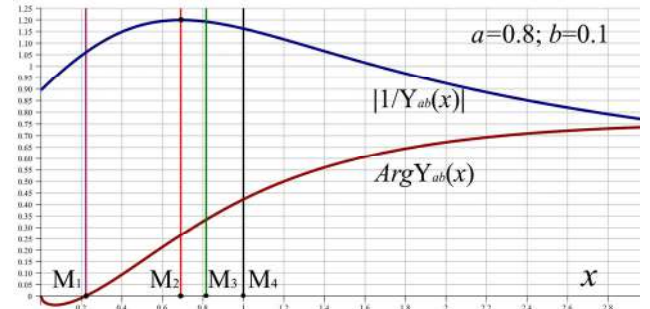


Fig. 3. Typical example of amplitude-frequency and phase-frequency response plot with phase and amplitude resonance points and their approximation.

III. CONDITIONS FOR THE EXISTENCE OF PHASE AND AMPLITUDE RESONANCE

After obtaining the exact formulas for the resonant frequencies, one can easily get an answer to the question when phase and amplitude resonance exists. That is, in which conditions the imaginary part of the admittance can refer to zero, and in which conditions the modulus of the admittance can have an extreme point. These conditions for amplitude resonance were first published in [12]. In order to get a complete understanding of the circuit under consideration, we discuss the main results below. Formula (6) gives a value for the reduced frequency of phase resonance, which must be positive. From the condition of positivity of the reduced frequency, we obtain the conditions for the existence of phase resonance: $a > 1$ and $b > 1$ or $a < 1$ and $b < 1$. Fig. 4 shows the regions on the plane of variable parameters a and b , in which the phase resonance exists.

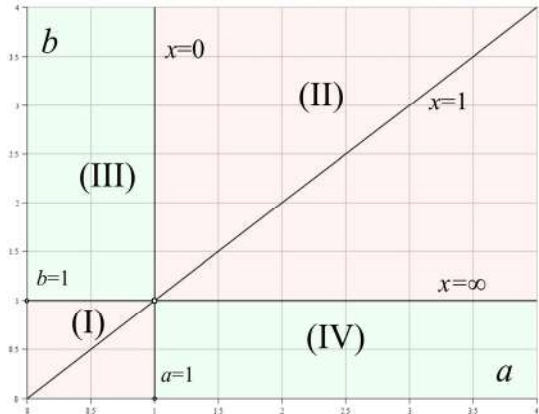


Fig. 4. Existence and non-existence areas of phase resonance.

In the region (I) of the parameter space (a, b) the argument of admittance changes sign from negative to positive as it passes through zero, indicating the point of phase resonance. In the region (II) vice versa, from positive to negative. In regions (III) and (IV) there is no phase resonance.

From (11) for the reduced frequency of the amplitude resonance, which must also be positive, we find the conditions for the existence of the amplitude resonance. The corresponding area is represented in Fig. 5. In region (I), the function $y(x)$ has a minimum, i.e. there is a current resonance (minimum of

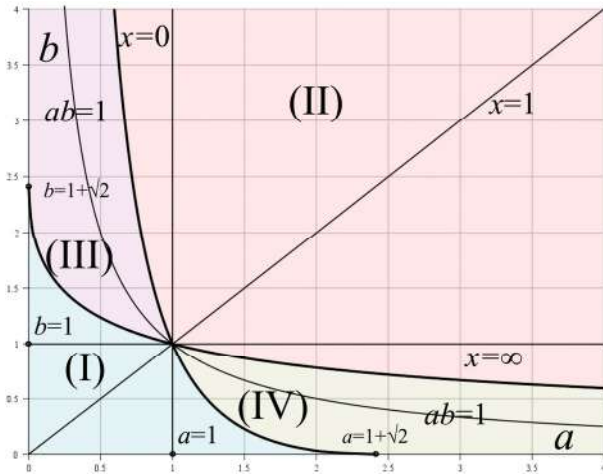


Fig. 5. Existence and non-existence areas of amplitude resonance.

admittance). In area (II), the function $y(x)$ has a maximum, that is, voltage resonance (admittance maximum) takes place. In area (III) and (IV) there is no amplitude resonance, the admittance modulus has no extreme points.

Moreover, in area (III), the admittance modulus is monotonically decreasing, and in area (IV), the admittance modulus is monotonically increasing. Comparison of Fig. 4 and 5 shows that there are such values of the parameters a and b , at which there is amplitude resonance, but there is no phase resonance. The boundaries of areas (I)-(IV) are sixth order curves, which are obtained from the equations:

$$\sqrt{1+2a+\sqrt{ab}} - a \cdot \sqrt{1+2b+\sqrt{ab}} = 0 \quad (22)$$

$$\sqrt{1+2b+\sqrt{ab}} - b \cdot \sqrt{1+2a+\sqrt{ab}} = 0 \quad (23)$$

Let us give the equation of one of these curves (the second one will be symmetric):

$$\begin{aligned} & -x^5 y + 4x^4 y^2 + 4x^4 y + x^4 - 6x^3 y - \\ & -4x^3 - 4x^2 y + 2x^2 - xy + 4x + 1 = 0 \end{aligned} \quad (24)$$

These curves intersect the coordinate axes at points $1+\sqrt{2}$. These points appeared in the study of circuits consisting of only three elements RLC [13] as boundary points that separate the intervals of existence and non-existence of amplitude resonance. Similar regions for some other circuits were studied in [5], [7].

IV. CALCULATING THE AMPLITUDE VALUE AT THE RESONANT FREQUENCIES

After finding the resonant frequencies, the next task is to find the value of the amplitude of the current passing through the circuit at the resonant frequencies. This task is reduced to calculating the value of the admittance modulus at the found frequencies. We will calculate the value of the function

$y(x) = |Y_{ab}(x)|^2$ at the points that are of most interest. These are the points of phase resonance x_ϕ , amplitude resonance x_0 and the point $x=1$. First, we substitute into (7) the value $x=1$, which is frequency $\omega = 1/\sqrt{CL}$, often used for the first

approximation of the frequency of both phase and amplitude resonance.

$$y(1) = \frac{(\sqrt{a} + \sqrt{b})^2}{(1+a)(1+b)} \quad (25)$$

Let us substitute into (8) the value x_ϕ from (6) to obtain the value of the square of the admittance modulus at the phase resonance frequency:

$$y(x_\phi) = \frac{(\sqrt{a} + \sqrt{b})^2}{(1 + \sqrt{ab})^2} \quad (26)$$

Finally, we substitute into (8) the value calculated in (11). After some simple but cumbersome calculations, we obtain the following formula for the value of the square of the modulus $|Y_{ab}(x)|^2$ at the extreme point:

$$y_0 = y(x_0) = \left(\frac{\sqrt{a} + \sqrt{b}}{1 + \sqrt{ab}} \right)^2 - \frac{1}{1 - \sqrt{ab}} \cdot \left(\frac{\sqrt{a} - \sqrt{b}}{1 + \sqrt{ab}} \right)^2 \quad (27)$$

The first summand in this formula is the value of the $y(x_\phi)$ of the square of the modulus of the function $|Y_{ab}(x)|^2$ at the point of phase resonance. The second summand will be positive or negative depending on the sign of the expression $(1 - ab)$. Under the condition $ab < 1$, the function $|Y_{ab}(x)|^2$ will have a minimum and the additional summand in (27) will be negative and shows how much the minimum amplitude value at the point of amplitude resonance will be smaller than the amplitude value at the point of phase resonance. This happens in the parameter area (I) shown in Fig. 4. An additional curve in Fig. 5 with the equation $ab=1$ separates the areas (I) and (II). In the area (II) in Fig. 4, the second summand in (27) will be positive and shows how much the maximum amplitude value is greater than the amplitude value at the phase resonance point.

For small values of the parameters $a, b < 1$, it is also possible to construct a series decomposition of the value of the amplitude square over the parameters, which can be used in approximate calculations:

$$y_0 = y(x_0) = (\sqrt{a} + \sqrt{b})^2 [1 - (a+b) + (a^2 + ab + b^2) + \dots] \quad (28)$$

Let us consider some special cases of the resulting (27).

1. If $a = b = 0$ (ideal contour: $R_1 = R_2 = 0$), then $A = B = 1$, $x_0 = 1$ and we get $y_0 = 0$, $I(\omega) = 0$. This is the only option when no current passes through the circuit; the circuit has infinite resistance - classic current resonance.
2. If $b = 0$ ($R_2 = 0$), then we get the formula from [13]:

$$y_0 = a - (\sqrt{1+2a} - 1)^2 = 2(\sqrt{1+2a} - 1) - a \quad (29)$$

$$y_0 = a - a^2 + a^3 - \frac{5}{4}a^4 + \dots \quad (30)$$

3. If $a = 0$ ($R_1 = 0$) then we get the formula from [13]:

$$y_0 = b - (\sqrt{1+2b} - 1)^2 = 2(\sqrt{1+2b} - 1) - b \quad (31)$$

4. If $a = b \neq 1$ (balanced oscillatory circuit: $R_1 = R_2$) then $x_0 = 1$ and we also get the formula:

$$y(x_0) = \left(\frac{2\sqrt{a}}{1+a} \right)^2 = 4a(1-2a+3a^2-4a^3+\dots) \quad (32)$$

V. ERRORS IN APPLYING APPROXIMATE FORMULAE

After obtaining exact and approximate formulas for calculating some value, the question naturally arises about the applicability of approximate formulas and the error that arises when replacing the exact value with an approximate one. The circuit under consideration is widely used in various fields of electrical engineering, electronics and radio engineering. Practical needs have initiated a detailed study of such a circuit. Several approximate formulas for calculating the frequency of amplitude resonance of the circuit under consideration are applied, which were obtained under some simplifying assumptions in the process of calculations. However, it is impossible to evaluate the applicability, moreover, the error of such formulas without having an exact formula. Such exact formulas were unknown until now. Obtaining exact formulas in the present work allows us to answer questions about the applicability and error of all existing formulas. In addition, we propose our own approximate formulas, which in their simplicity give a sufficiently small error and an explicitly specified limit of applicability.

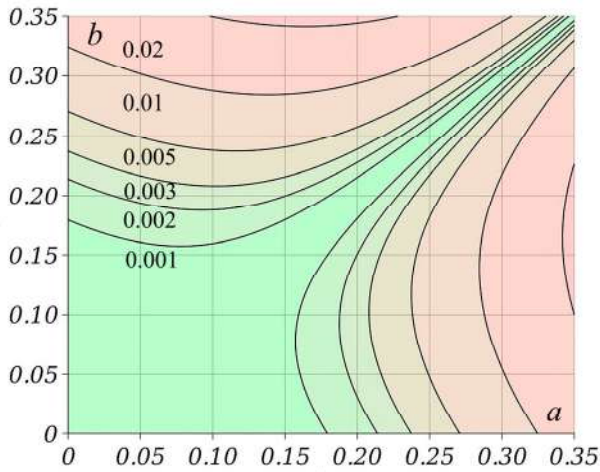


Fig. 6. Areas of parameters a, b with indication of the maximum absolute error when replacing the exact formula of the amplitude resonance frequency with its approximate value.

Fig. 6 illustrates the regions in the (a, b) parameter space where the absolute error between the exact value of the amplitude resonance frequency by (11), and its approximation does not exceed the specified precision $|x_0 - x_{0\text{approx}}| < \varepsilon$:

$$x_{0\text{approx}} = 1 - \frac{1}{2}(a-b)(\sqrt{a} + \sqrt{b})^2(1-a-b) \quad (33)$$

Fig. 7 shows the regions on the plane of parameters a and b , in which the absolute error between the exact value of the amplitude at the frequency of amplitude resonance (27) and its approximation (34) does not more than the specified precision $|y(x_0) - y(x_0)_{\text{approx}}| < \varepsilon$:

$$y(x_0)_{\text{approx}} = (\sqrt{a} + \sqrt{b})^2 [1 - (a+b) + (a^2 + ab + b^2)] \quad (34)$$

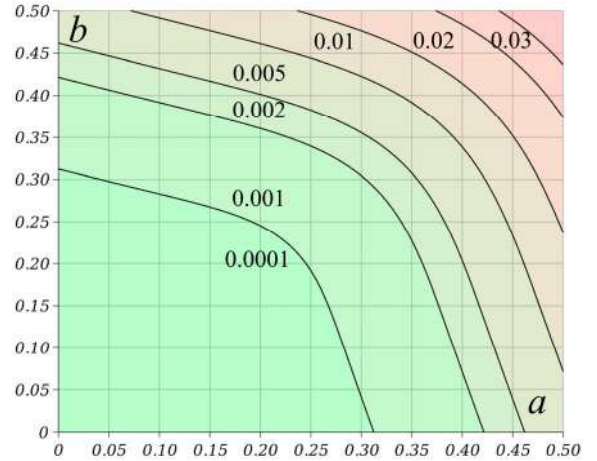


Fig. 7. The areas of the parameters a, b with indication of the maximum absolute error when replacing the exact formula of the amplitude value at the frequency of the amplitude resonance with its approximate value.

VI. CONCLUSION. PRACTICAL APPLICATIONS AND DISCUSSION OF THE RESULTS OBTAINED.

This work is primarily theoretical, grounded in the theory of linear electrical circuits. Therefore, the obtained results can find practical applications only in the context of mathematical models, which are based on standard assumptions used in the theory of linear circuits. The main of these assumptions are: the volt-ampere characteristic of all considered elements is linear; all electrical characteristics of the considered circuit elements are independent of time, temperature, pressure and other external factors; there is no reciprocal external parasitic electromagnetic influence of one element on another.

Experimental studies indicate that these conditions are frequently not met across the entire frequency range. Nevertheless, for some frequency levels it can be stated that with a sufficient degree of accuracy the electrical parameters of passive elements will obey a linear law. The standard method consists in first experimentally examining the volt-ampere characteristics of circuit elements under assumed conditions of actual functioning and real working frequency range. Then subranges within the ranges under consideration are selected, in which the behaviour of all electronic elements can be considered linear with a sufficient degree of accuracy. Under these additional restrictions, the mathematical models of the linear circuit theory come into action. The following study of the circuit is reduced to the study of the behaviour of the transfer functions of the circuit. The mathematical problems arising in this case are related to the fact that such functions depend on a large number of parameters - each circuit element has its own parameter. The resulting functions are fractionally linear. If we are interested in amplitude characteristics, square roots arise, which makes the study of such functions extremely difficult in a general way. However, having exact solutions, as opposed to approximate formulas or exact numerical calculations of a particular circuit, has obvious advantages. One of these advantages is the possibility to make a qualitative analysis of the considered circuit and to make conclusions about the behaviour of the circuit when its parameters are changed. Here is one example of such a qualitative analysis

arising from the previously unknown formulas for resonant frequencies (11) that we obtained.

Bifurcation point of the resonant frequency. A careful consideration of (11) and Fig. 5 shows that the point (1, 1) in the region of parameters a and b is a special point - point of function discontinuity, which determines the value of the reduced frequency of the amplitude (also phase) resonance. This point is characterised by the fact that when the point (a, b) on the plane of variables tends to the point (1, 1), the limit of the function will be different depending on the path along which the point tends to its limit value. Fig. 5 shows three curves, as we tend towards the point (1,1) we obtain different limiting values of the resonant: 0, 1, ∞ . At the point (1, 1) itself, the admittance is a constant function independent of frequency. Obviously, there are no extreme points in this case. In the neighbourhood of such a bifurcation point, even small changes in the circuit parameters cause essential changes in the resonance frequency. Fig. 8 is a theoretical verification of the rule that has long been used in radio engineering: if you want to obtain stable resonance characteristics of a circuit, choose parameters (a, b) closer to the good point (0, 0) and away from the bad point (1, 1) [16], [17].

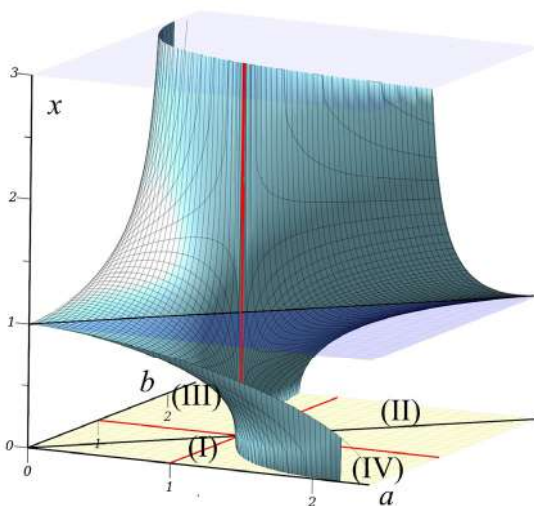


Fig. 8. Surface of the amplitude resonant frequency over the parameter plane (a, b) with the indicated bifurcation point (1,1). Where x is the reduced frequency x_0 from (11).

Another area of application of the results obtained is power electronics [14], [15]. While in radio engineering work in the neighbourhood of the point (0,0), with small values of resistances R_1 and R_2 , in some other cases the resistances R_1 and R_2 may be load resistances that take large values (at least one of them). In this case we get into region (II), (III) or (IV) in Fig. 5. Unlike area (I), no one has studied the resonance phenomena in these areas. This paper can be useful in analysing resonance phenomena when the current flows through the load resistance.

The obtained exact formulas can be used for fine-tuning wireless passive LC resonant sensors [6].

Fig. 8 shows that there is another area of stability of the resonant frequency. This is area (II), above which the resonance surface approaches the horizontal plane. The further away from the bifurcation point (1, 1) and closer to the line $a = b$ in area

(II), the less influence small changes of circuit parameters have on the change of the amplitude resonant frequency. In this area, it is recommended to work in circuits with large load resistance if it is necessary to control the resonant frequency.

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