SIMULATION OF CIRCUITS EXCITED BY PERIODIC SIGNALS IN MATLAB

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The paper deals with the proposal for simulation of dynamic circuits excited by periodic nonsinusoidal signals in MATLAB environment. The formulation of the circuit equations is done using sparse tableau analysis. The complete response is obtained using symbolic calculus that is one of significant advantages of MATLAB. The graphical representation of the complete response, transient part of complete response and steady-state part of complete response of the circuit are given.
Key words: circuit simulation, sparse tableau analysis, Laplace transform, MATLAB, complete response.

МОДЕЛЮВАННЯ ЕЛЕКТРИЧНИХ КІЛ ПРИ ЗБУДЖЕННІ ПЕРІОДИЧНИМИ СИГНАЛАМИ У СЕРЕДОВИЩІ MATLAB

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Запропоновано метод моделювання динамічних електричних кіл зі збудженням несинусоїдальними сигналами в середовищі MATLAB. Формування рівнянь балансу електричних кіл виконано за допомогою методу аналізу на основі розріджених таблиць. Отримано повні рівняння відгуку тестового збурення на основі символьних обчислень, які є однією з важливих переваг використання MATLAB. Наведено графічне надання функцій повного відгуку, неусталеної складової повного відгуку, а також усталеної складової функції повного відгуку електричного кола.
Ключові слова: моделювання електричних кіл, аналіз методом розріджених таблиць, перетворення Лапласа, MATLAB, повний відгук.

PROBLEM STATEMENT. Circuit simulation is an important area of research because is used in a wide spectrum of applications from microelectronic to electric power distribution networks.

Simulation of circuits excited by periodic nonsinusoidal signals can be done in the time domain or in the complex frequency domain, but in the both cases, it is time-consuming activity.

In the time domain, finding the complete response of such circuit means to solve a dynamic circuits that have not only resistors but also dynamic elements (inductors and/or capacitors). Simulation of these circuits is sometimes very demanding activity, because the equations for such type of circuits take the form of integrodifferential equations with the right-hand side having the form of the periodic function.

Another tool for the simulation of these circuits is to transform the circuit with its initial conditions directly into the complex frequency domain using the Laplace transform. After transforming of given circuit into the complex frequency domain, it can be dealt with it as if it consisted of sources and resistors only, because the passive elements have impedances, which can be regarded as generalized resistances.

In the complex frequency domain, the problem of finding the complete response of such circuits it could be done by applying the Laplace transform together with the sparse tableau analysis that enables to formulate the circuit equations in systematic and automatic way.

Combining this procedure together with the symbolic computation of MATLAB, there is no difficulty in simulating of dynamic circuits, because

formulation of the circuit equations, solving the obtained equations, and taking the inverse Laplace transform are executed in MATLAB environment.

MATLAB greatly reduces the effort demanded to solve the set of algebraic equations and to take the inverse Laplace transform made by a hand, thus there is no difficulty in simulating of the circuits excited by periodic input signals.

The MATLAB environment is very user-friendly with powerful built-in routines that enable to solve a very wide variety of computations. Its great advantage is the fact that the user has not to spend time in learning software but he can spend time in learning the principles of s problem.

EXPERIMENTAL PART AND RESULTS OBTAINED.

Simulation of electric circuits. Simulation of the electric circuits is defined as the process where a computer is used to evaluate a model of the circuit [1–7]. Model of the circuit is a mathematical description of the circuit. The model is described by the input and output relationships that for analog circuits form a set of algebraic and differential equations.

The set of these equations consists of the equations depend on the topology of the circuit and the equations depend on the type of the circuit elements.

The equations, depending on the topology of the circuit, represent how the circuit elements are connected to one another in the circuit. These equations are called the connection equations.

The equations, which depend on the type of the circuit element, describe the voltage-current relationship and they are called the element equations or branch

equations.

There exist many techniques for the mathematical description of the circuits there, e.g. mesh current analysis, nodal voltage analysis, direct using of the Kirchhoff's laws [1–4]. Better ones are those techniques, which enable to formulate equations in systematic and automatic way, e.g. modified nodal analysis and sparse tableau analysis [1, 8, 9].

Sparse tableau analysis. Sparse tableau analysis is a very useful method for systematic and automatic formulation of the circuit equations for every circuit as well as for dynamic circuits.

In general, circuit equations take form of a set of simultaneous nonlinear first-order differential equations. For purely resistive and linear circuit the circuit equations take form of a set of simultaneous linear algebraic equations.

The connection equations are obtained by applying Kirchhoff's laws to the circuit, which leads to the two sets of linear algebraic equations in terms of the branch currents and the branch voltages. The set of connection equations must be linearly independent.

The first set of the connection equations can be expressed [1]:

$$\mathbf{A}\,\mathbf{i} = \mathbf{0}\,, \qquad (1)$$

where $\mathbf{i}$ is a matrix of branch currents, $\mathbf{A}$ being the node versus branch reduced-incidence matrix, having the coefficients $+1, -1, 0$.

The second set of the connection equations can be expressed in terms of the branch voltages using the fundamental loop versus branch incidence matrix. The better way is to write this set of the equations in terms of the branch voltages and the node voltages as [1]

$$\mathbf{u} = \mathbf{A}^{\mathrm{T}}\mathbf{v}\,, \qquad (2)$$

where $\mathbf{A}^{\mathrm{t}}$ is the transposed matrix $\mathbf{A}$, $\mathbf{u}$ being the branch voltage vector, $\mathbf{v}$ being the node voltage vector.

The element equations are related according to the voltage-current characteristics of the elements. For linear circuits containing all the basic elements the element equations can be expressed [1]

$$\mathbf{K}_{\mathrm{u}}\mathbf{u} + \mathbf{K}_{\mathrm{i}}\mathbf{i} = \mathbf{s}\,, \qquad (3)$$

where $\mathbf{K}_{\mathrm{u}}, \mathbf{K}_{\mathrm{i}}$ are the matrices containing the coefficients that define the linear voltage-current relationships for the circuit elements uniquely, $\mathbf{s}$ being the vector containing the parameters of the independent voltage and current sources.

Assembling the equations (1), (2), and (3), the sparse tableau equations are constituted. It is convenient to rewrite the sparse tableau equations as a single matrix equation [1]:

$$\mathbf{T}\,\mathbf{x} = \mathbf{w}\,, \qquad (4)$$

where $\mathbf{T}$ is the square tableau matrix, $\mathbf{x}$ being the vector of unknown variables, $\mathbf{w}$ being the vector containing zero vectors of appropriate dimensions and the vector $\mathbf{s}$.

The tableau matrix has many zeros and is said to be sparse. Sparse systems consist of very large systems of equations and they always have to be solved by special routines. Sparse matrix solver is also available as MATLAB built-in routine [10–16].

Sparse tableau analysis is most general formulation of the equations describing the circuit because the solution provides the currents through all elements, the voltages across all elements and all nodal voltages simultaneously. It offers a systematic and automatic approach for assembling and solving the circuit equations [1].

The Laplace transform and the inverse Laplace transform. The Laplace transform for a time-domain function $f(t)$ (must be zero for $t < 0$) of a real variable t is [2–6]:

$$\hat{f}(p) = \mathscr{L}\{f(t)\} = \int_{0}^{\infty} f(t)e^{-pt}\,dt\,, \qquad (5)$$

where p is a complex variable (meaning the complex frequency, $p = \sigma + \mathrm{j}\omega$), and $\hat{f}(p)$ is a complex frequency function.

The inverse Laplace transform is defined by the integral [2–6]:

$$f(t) = \frac{1}{2\pi\mathrm{j}} \int_{\sigma-\mathrm{j}\infty}^{\sigma+\mathrm{j}\infty} \hat{f}(p)e^{pt}\,dp\,, \qquad (6)$$

where $\mathrm{j} = \sqrt{-1}$ is an imaginary unit.

Complex frequency-domain repre-sentation of basic circuit elements. The complex frequency-domain representation of basic circuit elements is obtained by taking the Laplace transform of their voltage-current relationships.

The voltage-current relationship for a linear resistor having resistance R in the complex frequency domain [2, 4]

$$\hat{u}(p) = R\hat{i}(p)\,, \qquad (7)$$

where $\hat{u}(p)$ is the Laplace transform of voltage $u(t)$ across the resistor, and $\hat{i}(p)$ is the Laplace transform of current through the resistor.

The voltage-current relationship for a linear inductor having inductance L in the complex frequency domain [2, 4]:

$$\hat{u}(p) = pL\hat{i}(p) - Li(0)\,, \qquad (8)$$

where $\hat{u}(p)$ is the Laplace transform of voltage $u(t)$ across the inductor, $\hat{i}(p)$ is the Laplace transform of current through the inductor, and $i(0)$ is the initial condition.

The equation (8) is used to represent the linear inductor in the complex frequency domain as the series connection of two circuit elements that corresponds to the sum of voltages on the right-hand side of (8).

The voltage-current relationship for the coupled inductors having self-inductances L_1, L_2 and mutual inductance M in the complex frequency domain [2, 4]:

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$$\begin{bmatrix} \hat{u}_1(p) \\ \hat{u}_2(p) \end{bmatrix} = \begin{bmatrix} pL_1, & \pm pM \\ \pm pM, & pL_2 \end{bmatrix} \begin{bmatrix} \hat{i}_1(p) \\ \hat{i}_2(p) \end{bmatrix} - \\ - \begin{bmatrix} L_1, & \pm M \\ \pm M, & L_2 \end{bmatrix} \begin{bmatrix} i_1(0) \\ i_2(0) \end{bmatrix}, \quad (9)$$

where $\hat{u}_1(p), \hat{u}_2(p)$ is the Laplace transform of voltages $u_1(t), u_2(t)$ across the inductors L_1, L_2 respectively, $\hat{i}_1(p), \hat{i}_2(p)$ is the Laplace transform of currents through the inductors L_1, L_2 respectively, and $i_1(0), i_2(0)$ are the initial conditions.

The voltage-current relationship for a linear capacitor having capacitance C in the complex frequency domain [2, 4]

$$\hat{u}(p) = \frac{1}{pC}\hat{i}(p) + \frac{u(0)}{p}, \quad (10)$$

where $\hat{u}(p)$ is the Laplace transform of voltage $u(t)$ across the capacitor, $\hat{i}(p)$ is the Laplace transform of current through the capacitor, and $u(0)$ is the initial condition.

The equation (10) is used to represent the linear capacitor in the complex frequency domain as the series connection of two circuit elements that corresponds to the sum of voltages on the right-hand side of (10).

Independent voltage and current sources are represented by the Laplace transform of their voltages and currents.

Dependent voltage and current sources are represented by the Laplace transform of their controlled voltages and currents, and controlling voltages and currents.

The ideal operational amplifier operates the same way in the complex frequency domain as it does in the time domain, thus the Laplace transform of its operating conditions is applied in the complex frequency domain [2].

Complex frequency-domain representation of sparse tableau equations. Applying the Laplace transform to the equations (1)–(3), and (4) the following equations are obtained:

$$\mathbf{A}\hat{\mathbf{i}} = \mathbf{0}, \quad (11)$$

where $\hat{\mathbf{i}}$ is a vector of the complex frequency-domain representation of branch currents of the circuit,

$$\hat{\mathbf{u}} = \mathbf{A}^T \hat{\mathbf{v}}, \quad (12)$$

where $\hat{\mathbf{u}}$ is a vector of the complex frequency-domain representation of branch voltages of the circuit, $\hat{\mathbf{v}}$ being a vector of the complex frequency domain of node voltages of the circuit,

$$\hat{\mathbf{K}}_u \hat{\mathbf{u}} + \hat{\mathbf{K}}_i \hat{\mathbf{i}} = \hat{\mathbf{s}}, \quad (13)$$

where $\hat{\mathbf{K}}_u, \hat{\mathbf{K}}_i$ are the matrices containing the coefficients that define the complex frequency domain linear voltage-current relationships for the circuit elements uniquely, $\hat{\mathbf{s}}$ being the vector containing the complex frequency-domain parameters of the independent voltage and current sources and the initial conditions.

The sparse tableau equations expressed as the single matrix equation in the complex frequency domain using the Laplace transform is

$$\hat{\mathbf{T}}\hat{\mathbf{x}} = \hat{\mathbf{w}}, \quad (14)$$

where $\hat{\mathbf{T}}$ is the square tableau matrix expressed in the complex frequency domain, $\hat{\mathbf{x}}$ being the vector of unknown variables in the complex frequency domain, $\hat{\mathbf{w}}$ being the vector containing zero vectors of appropriate dimensions and the vector $\mathbf{s}$ in the complex frequency domain.

Periodic signal and its description in the time domain and the complex frequency domain. Periodic signal $f_{\text{signal}}(t)$ is a signal that for every value of time t satisfies the relationship [4]:

$$f_{\text{signal}}(t) = f_{\text{signal}}(t + n.T_{\text{period}}), \quad (15)$$

where T_{period} is the fundamental period, n is the whole number, i.e. $n = \pm 1, \pm 2, ...$ When periodic signal $f_{\text{signal}}(t)$ is zero for $t < 0$ and has a finite number of discontinuities within the period T_{period}, it can be represented in another form as the sum of infinite time-shifted finite pulses. Let $f_{\text{signal\_}T}(t)$ is a pulse having duration T_{period}, which is identical to the signal $f_{\text{signal}}(t)$ at the interval $\langle 0, T_{\text{period}} \rangle$, and zero out of the interval. When the pulse $f_{\text{signal\_}T}(t)$ is repeated periodically, the signal $f_{\text{signal}}(t)$ is created [2, 4]:

$$f_{\text{signal}}(t) = \sum_{n=0}^{\infty} f_{\text{signal\_}T}(t - n.T_{\text{period}}). \\ .1(t - n.T_{\text{period}}), \quad (16)$$

where $1(t)$ is a unit step function.

The Laplace transform of the periodic signal $f_{\text{signal}}(t)$ is given [2, 4]:

$$\hat{f}_{\text{signal}}(p) = \frac{\hat{f}_{\text{signal\_}T}(p)}{1 - e^{-pT_{\text{period}}}}, \quad (17)$$

where $\hat{f}_{\text{signal\_}T}(p)$ is the Laplace transform of the pulse $f_{\text{signal\_}T}(t)$, working on the presumption that $f_{\text{signal\_}T}(t)$ is zero for all $t < 0$.

Procedure of finding the complete response of the circuits to periodic input signal. Finding the complete response of the circuit to periodic input signal implies [5]:

– to find the complex frequency-domain representation of the input periodic signal;

– to find the complex frequency-domain representation of the circuit elements using the Laplace transform;

– to determine the transient part of the complete response for $t > 0$ at first in the complex frequency domain and next to take the inverse Laplace transform of it in order to obtain the time-domain representation

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the transient part of the complete response for $t > 0$;

– to determine the complete response over the interval $(0, T_{\text{period}})$ at first in the complex frequency domain and next to take the inverse Laplace transform of it in order to obtain the time-domain representation the complete response over the interval $(0, T_{\text{period}})$;

– to determine the steady-state response over the interval $(0, T_{\text{period}})$ at first in the complex frequency domain and next to take the inverse Laplace transform of it in order to obtain the time-domain representation the steady-state response over the interval $(0, T_{\text{period}})$;

– to find the steady-state response for $t > 0$ in the time domain;

– finally, to find the time-domain representation of the complete response of the circuit for $t > 0$.

All the steps for finding the complete response of dynamic circuit given above can be easily executed using MATLAB environment.

In next text, the proposed procedure for circuit simulation in MATLAB environment is applied to two representative circuits and the graphical representation of obtained circuit responses is given for both of them.

The examples comprise two circuits excited by periodic input signals. The first one is the first-order circuit and the second one the second-order circuit.

The Example A. The circuit of this example is *RL* circuit (Fig. 1 – left) excited by periodic saw waveform shown in Fig. 1 (right), which is applied at time $t = 0$. It is suppose that all the initial conditions are equal zero.
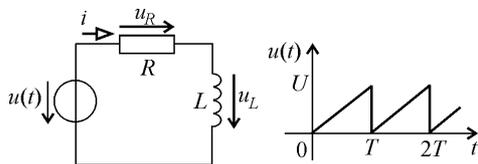

Figure 1 – The *RL* circuit (left) excited by a periodic saw wave (right)

The given signal has the following parameters: the amplitude U and the period T . The aim is to find the complete response of the circuit to given input using the proposed procedure in MATLAB environment.

Since the input of the circuit is the signal specified graphically by the plot first it is necessary to express the time domain representation of the saw pulse during the period T . The equation of the saw pulse is

$$u_T(t) = \frac{U}{T}t.1(t) - \frac{U}{T}(t-T).1(t-T) - $$
$$-U.1(t-T). \tag{18}$$

The Laplace transform of (18) is

$$\hat{u}_T(p) = \frac{U}{p^2 T}\left(1 - e^{-pT}\right) - \frac{U}{p}.e^{-pT} . \tag{19}$$

The complex frequency-domain representation of the input signal using the Laplace transform is

$$\hat{u}(p) = \frac{\hat{u}_T(p)}{1 - e^{-pT}} . \tag{20}$$

The transient response $i^{(\text{trans})}(t)$ for $t > 0$ of the current $i(t)$ is

$$i^{(\text{trans})}(t) = \frac{U}{R}\left(\frac{L}{RT} - \frac{1}{1 - e^{-\frac{RT}{L}}}\right)e^{-\frac{R}{L}t}.1(t). \tag{21}$$

The complete response $i_T(t)$ of the current $i(t)$ for $0 < t < T$ is

$$i_T(t) = \frac{U}{RT}\left[t - \frac{L}{R}\left(1 - e^{-\frac{R}{L}t}\right)\right]. \tag{22}$$

The steady-state response $i_T^{(\text{steady})}(t)$ of the current $i(t)$ for $0 < t < T$ is

$$i_T^{(\text{steady})}(t) = \frac{U}{R}\left[\frac{1}{T}t - \frac{L}{RT} + \frac{e^{-\frac{R}{L}t}}{1 - e^{-\frac{R}{L}T}}\right]. \tag{23}$$

The steady-state response $i^{(\text{steady})}(t)$ of the current $i(t)$ for $t > 0$:

$$i^{(\text{steady})}(t) = \sum_{n=0}^{\infty} i_T^{(\text{steady})}(t-nT).1(t-nT) . \tag{24}$$

The complete response of the current $i(t)$ for $t > 0$ is

$$i(t) = i^{(\text{steady})}(t) - i^{(\text{trans})}(t) . \tag{25}$$

The voltage across the resistor $u_R(t)$ and the voltage across the inductor $u_L(t)$ are found as the result of the sparse tableau analysis that comprises the voltage-current relationships for the resistor and the inductor.
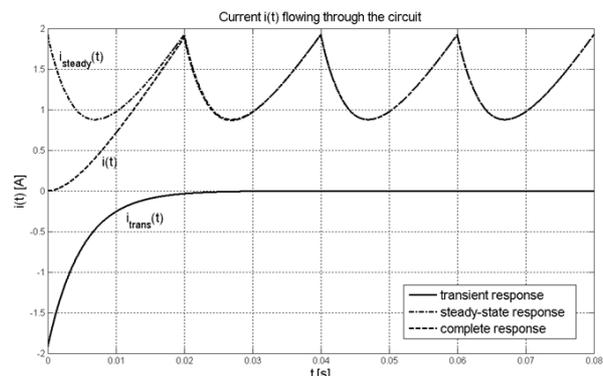

Figure 2 – MATLAB plot of the current, $i(t)$, for the circuit shown in Fig. 1

After running the program composed in MATLAB environment, the simulation results of *Example A* are obtained.

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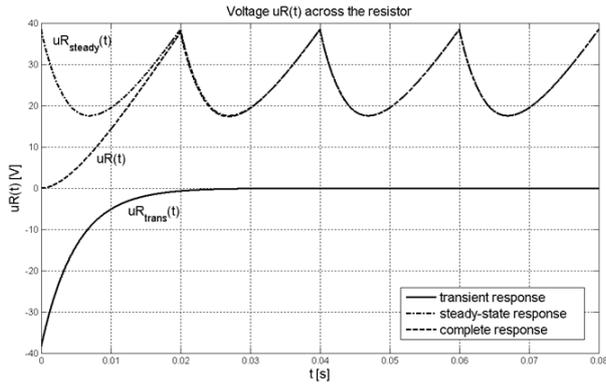
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Figure 3 – MATLAB plot of the of the voltage across the resistor, $u_R(t)$, for the circuit shown in Fig. 1

The corresponding graphical representations of all the responses of the circuit are given the following values of the circuit parameters: $R = 20\ \Omega$, $L = 0.1$ H, $T = 0.02$ s, $U = 50$ V, and they are depicted in the figures Fig. 2, Fig. 3, and Fig. 4.

In Fig. 2, the current $i(t)$ flowing through the circuit shown in Fig. 1 is shown. The plot indicates that steady-state values of the current $i(t)$ are obtained after the first period T.

It can be observed that waveform of the voltage across the resistor (Fig. 3) and the voltage across the inductor (Fig. 4) also obtain their steady-state values after the first period T.
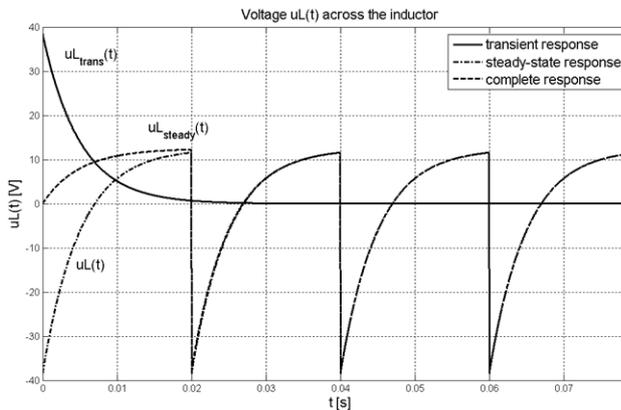
Figure 4 – MATLAB plot of the of the voltage across the inductor, $u_L(t)$, for the circuit shown in Fig. 1

The Example B. The circuit of this example is *RLC* circuit shown in Fig. 5 (left). It is clear that the circuit is a second-order one. The voltage, $u(t)$, of the voltage source is the periodic square wave shown in Fig. 5 (right). The circuit is at steady state before the input voltage $u(t)$ is applied at time $t = 0$. The aim is to find all the element currents and voltages for $t > 0$ if all the initial conditions are equal zero.
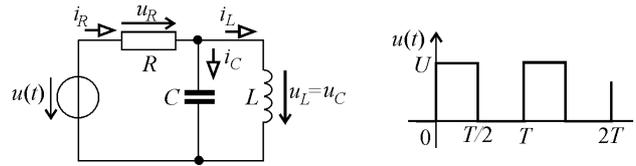

Figure 5 – The *RLC* circuit (left) excited by a periodic square wave (right)

Since the input of the circuit is the signal specified graphically by the plot, at first it is necessary to express the time domain representation of the square wave pulse during the period T. The equation for the square pulse is

$$u_T(t) = U.1(t) - U.1(t - \frac{T}{2}).\qquad(26)$$

The Laplace transform of (26) is

$$\hat{u}_T(p) = \frac{U}{p}\left(1 - e^{-p\frac{T}{2}}\right).\qquad(27)$$

The complex frequency-domain representation of the input signal using the Laplace transform is

$$\hat{u}(p) = \frac{\hat{u}_T(p)}{1 - e^{-pT}}.\qquad(28)$$

The results for the problem given in the *Example B* were obtained by simulating the circuit in MATLAB environment.

The corresponding graphical representations of all the element current and voltage responses are given for the following values of the circuit parameters: $R = 100\ \Omega$, $L = 0.012$ H, $C = 2\ \mu$F, $T = 0.008$ s, $U = 25$ V [2]. They are shown in figures Fig. 6 to Fig. 10.

In Fig. 6, the current, $i_L(t)$, flowing through the inductor is depicted. The plot shows that steady-state values of the inductor current are 0 A and about 0.25 A. It is evident that the transient response of the current obtains very small values. Thus the steady-state response is equal to the complete response of the inductor current because of that.
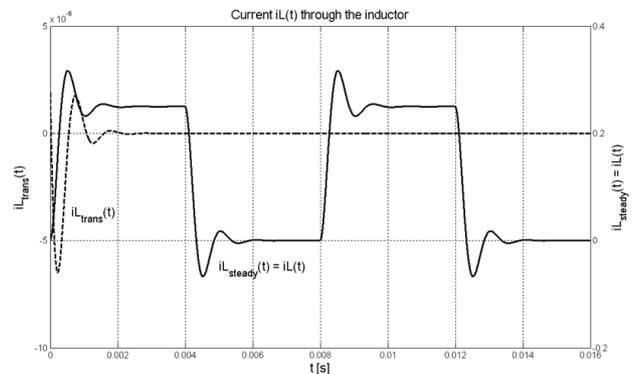

Figure 6 – MATLAB plot of the inductor current, $i_L(t)$, for the circuit shown in Fig. 5

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In Fig. 7, the voltage, $u_L(t)$, across the inductor is drawn. The plot shows that steady-state value of the inductor voltage is 0 A (at steady state the inductor acts as a short circuit). This graph is the same for the capacitor voltage, $u_C(t)$, because the inductor and capacitor are connected in parallel.
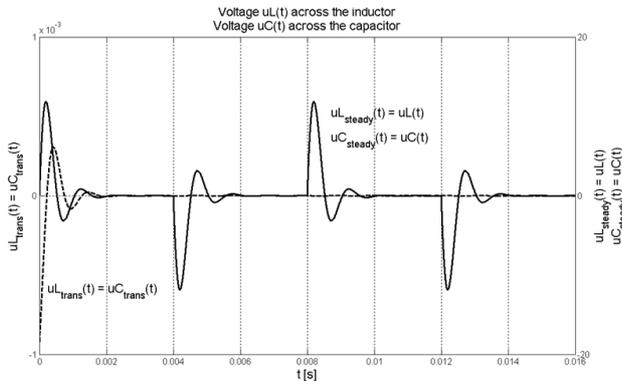

Figure 7 – MATLAB plot of the inductor voltage, $u_L(t)$, and capacitor voltage, $u_C(t)$, for the circuit shown in Fig. 5

In Fig. 8, the current, $i_C(t)$, flowing through the capacitor is depicted. The plot shows that steady-state value of the capacitor current is 0 A (at steady state the capacitor acts as an open circuit).

In Fig. 9, the current, $i_R(t)$, flowing through the resistor is drawn. The plot shows that steady-state values of the resistor current is 0 A and about 0.25 A (at steady state the inductor acts as a short circuit, the capacitor acts as an open circuit, thus the same current flows through the resistor and inductor).

In Fig. 10, the voltage, $u_R(t)$, across the resistor is depicted. Its plot is identical to the graph of the current, $i_R(t)$, flowing through the resistor (due to the voltage-current relationship for the resistor).
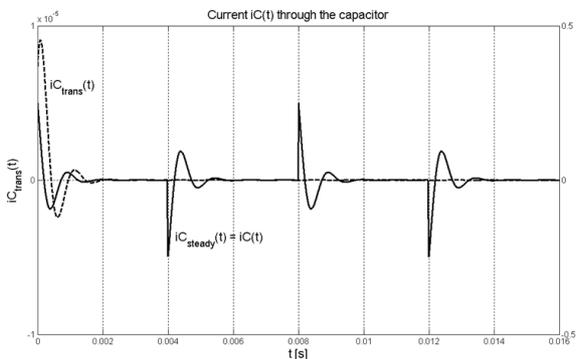

Figure 8 – MATLAB plot of the capacitor current, $i_C(t)$, for the circuit shown in Fig. 5

It is evident that all the responses of the circuit given in *Example* B are oscillatory-type responses with decreasing magnitude and the oscillation frequency that depends on the damped resonant frequency.
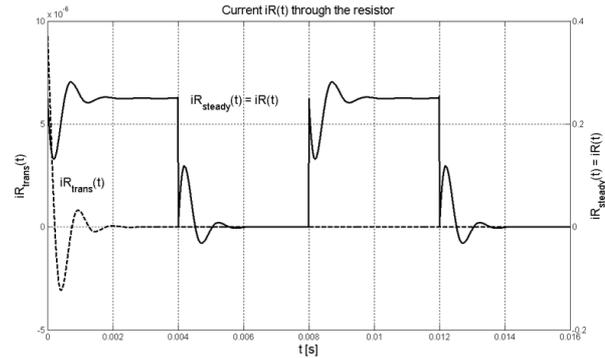

Figure 9 – MATLAB plot of the resistor current, $i_R(t)$, for the circuit shown in Fig. 5

Obtained results are in accordance with the fact that the simulated circuit of *Example B* is the second-order circuit. The characteristic equation of the second-order circuit can have two distinct real roots, two equal real roots, or two complex conjugate roots. If the characteristic equation has complex conjugate roots, the circuit is characterized as an underdumped circuit. The time responses of the underdumped circuit take form of oscillatory-type ones.
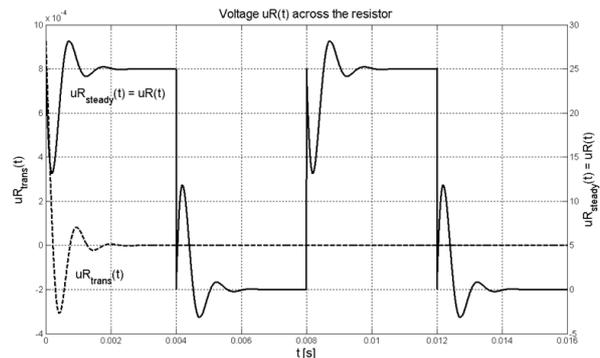

Figure 10 – MATLAB plot of the resistor voltage, $u_R(t)$, for the circuit shown in Fig. 5

In solved problem, given in *Example B*, the values of the transient responses are from the range 10^{-3} to 10^{-6} and the complete and steady-state responses from the range 10^{-1} to 10^{+2}. Due to this, all the plots shown in figures Fig. 6 to Fig. 10 are created with y-axes on both left and right side of the graphs. The two y-axes enable to display both sets of data on one graph even though relative values of the data belong to quite different value ranges.

CONCLUSIONS. The circuit simulation and graphical representation of the complete, transient, and steady-state responses for two linear circuits excited by the periodic input signal are found by solving the problem in MATLAB environment.

The program composed in MATLAB environment has many advantages over the calculus made by hand. It saves a lot of time, effort and provides the very simple visualization of the obtained results.

The elapsed time that represents the processing and

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execution of the instructions in the composed MATLAB program for given representative examples of the circuit analysis takes very short time. For the MATLAB program of *Example A*, the elapsed time is 129.922 seconds, and for the MATLAB program of *Example B*, the elapsed time is 156.422 seconds for step 10^{-6} and 1182.422 seconds for step 10^{-7} of MATLAB plots.

It is evident that the effort demanded to solve such type of problems is greatly reduced because it is not necessary to solve the set of algebraic equations and to take the direct and inverse Laplace transform.

Since the MATLAB environment is very user-friendly, the user has not to spend time in learning software but he can spend time in learning the fundamental principles of a solved problem.

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МОДЕЛИРОВАНИЕ ЭЛЕКТРИЧЕСКИХ ЦЕПЕЙ ПРИ ВОЗБУЖДЕНИИ ПЕРИОДИЧЕСКИХ СИГНАЛОВ В СРЕДЕ MATLAB

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Предложен метод моделирования динамических цепей с возбуждением несинусоидальными сигналами в среде MATLAB. Формирование уравнений баланса электрических цепей выполнено с помощью метода анализа на основе разреженных таблиц. Получены полные уравнения отклика тестового возмущения на основе символьных вычислений, которые являются одним из важных преимуществ использования MATLAB. Приведено графическое представление функций полного отклика неустойчивой составляющей полного отклика, а также устойчивой составляющей функции полного отклика цепи.

Ключевые слова: моделирование электрических цепей, анализ методом разреженных таблиц, превращение Лапласа, MATLAB, полный отклик.