International Journal on "Technical and Physical Problems of Engineering" (IJTPE)
Published by International Organization of IOTPE
ISSN 2077-3528
IJTPE Journal
www.iotpe.com
ijtpe@iotpe.com
September 2024 | Issue 60 | Volume 16 | Number 3 | Pages 120-126

ANALYSIS OF METHOD OF CALCULATING CONVERSION CIRCUIT BASED ON GENERALIZED FUNCTIONS

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Abstract- The article analyzes the piecewise linear approximation method for electrical semiconductor circuits. An approximation is considered that makes it possible to represent a semiconductor device in the form of a replacement circuit consisting of an ideal semiconductor device and linear elements, which makes it possible to represent an electrical circuit with a semiconductor device in the form of a four-pole. Taking into account the fact that discontinuous functions cannot be differentiated in the usual way, the introduction of generalized functions that allow the differentiation operation is discussed. At the same time, functions acting on a certain space of basic functions are also taken into account, which must have continuous derivatives of all orders and be finite, that is, disappear beyond some limited domain. The classical solution method is analyzed, which is described by high-order differential equations, which is explained by the complexity of determining the integration constants and the complexity of the period equations, and the method for obtaining reliable periodic solutions is based on finding a solution and the form of a complete Fourier series. Discontinuous functions that cannot be differentiated in the usual way are investigated. The introduction of generalized functions that allow performing the differentiation operation is considered. In the mathematical analysis of the transient process, each period of alternating voltage supplied to the circuit is considered separately, taking into account the sequence of periodic processes corresponding to a given period. From a mathematical point of view, this formally means the periodic continuation of current or voltage pulses of the converter on the time axis. Thus, these pulses are described as a harmonic series. Using a Simulink model of a rectifier circuit with switching to a sinusoidal voltage, the transient process for an electrical circuit is analyzed. Models of the generalized Simulink function and FFT analysis are being compiled, which allow us to study transients.

Keywords: Linear Approximation Method, Electrical Semiconductor Circuit, Simulink Model, FFT Analysis, Four-Pole, Linear Section.

1. INTRODUCTION

Semiconductor devices in converter technology, automation, electronics, and radio engineering require continuous improvement of methods for calculating steady-state and transient processes in semiconductor device circuits. The significantly asymmetric shape of the volt-ampere characteristics of the semiconductor devices leads to the widespread use of methods that develop the basic provisions of the stocking method and are based on piecewise linear approximations. One of the most important stages of the calculation is determining the moments of transition from one linear section of the characteristic to another. The practical applicability of the methods is mainly determined by how simple this task is solved. The article is devoted to a method based on the use of generalized functions. The use of such functions to solve differential equations makes it possible to obtain finite expressions in closed form or in the form of a Fourier series without determining the roots of the characteristic equation and the integration constants [1, 4, 8, 10].

Three approximation methods are usually used in the analysis and calculation of circuits with semiconductor devices:

a) nonlinear analytical function (integral approximation);
b) straight line segments (piecewise linear approximation);
c) combination of a nonlinear function with a linear approximation

Piecewise linear approximation makes it possible to move from nonlinear differential equations to linear equations describing processes in individual sections. In these cases, the direct form of the real characteristic allows approximation by only two straight segments.

When using nonlinear elements in various AC electrical circuits, complex problems arise that are not acceptable in linear electrical circuits. Each nonlinear element has the ability to transform the range of acting periodic EMF (voltage or current sources). If a nonlinear alternating current electrical circuit contains elements that are thermally inertia less, then the currents and voltages in them are more or less non-sinusoidal. Currents and voltages are assumed to be sinusoidal in nonlinear circuits containing only inertial nonlinear elements. The piecewise linear approximation method is one of the main engineering methods for calculating nonlinear

Registered: 231107 Article Info: 1838 Accepted: 240823
Reserved: 240316 Available: 240930

circuits and is based on piecewise linear approximation of the characteristics of a nonlinear element. A graphical and analytical solution is possible.

Firstly, the real voltage characteristic is replaced by a piecewise linear one (segments of straight lines). The current or voltage curve is constructed using the three-projection method. The analytical solution consists in substituting linear equations into nonlinear equations, while at each site the problem is solved as linear. For convenience, replacement circuits are drawn on each section of the volt-ampere characteristic. It is necessary to pair the solution in one section of linearity with the solution in another section, calculate the coordinates of the transition points from one linear section to another.

2. SOLVING DIFFERENTIAL EQUATIONS BASED ON GENERALIZED FUNCTIONS

The accepted approximation makes it possible to represent the semiconductor device as a replacement circuit consisting of an ideal semiconductor device and linear elements (Figure 1). This allows to imagine an electric circuit with a semiconductor device in the form of a four-pole, at the output of which an ideal semiconductor device is turned on (Figure 2). For the current and voltage at the output of a four-pole, a differential equation can be written [1, 2, 7].

$$\begin{cases} A(s)u(\vartheta)+B(s)i(\vartheta)=K(s)j(\vartheta) \\ \vartheta=\omega t \end{cases} \quad (1)$$

where, $A(s), B(s), K(s)$ are the polynomials of the operator p of degree n (if the degrees of one of the two polynomials are less, then part of the higher coefficients in them is zero differentiation operator), and $s=\dfrac{d}{dt}$ is the differentiation operator.

If the characteristic of the semiconductor device is assumed to be piecewise linear, then Equation (1) is valid for all points, except for the transition from one linear section of the characteristic to another breakpoints), since at these points the current and voltage derivatives may have discontinuities [1, 3, 9]. The classical method of solving such a problem is the method of stocking. The method is very clear, but in practice, it is difficult to apply it to the calculation of circuits, the processes that are described by high-order differential equations, which is explained by the difficulty of determining the integration constants and the complexity of the period equations.

Other methods for determining periodic solutions are based on finding the solution and the shape of the complete Fourier series. These methods make it possible to create period equations without having to integrate the corresponding linear equations. However, when using such methods, Equations (1) must be supplemented with jump conditions that take into account the discontinuities of the functions i and u and their derivatives, or generalized derivatives must be introduced.

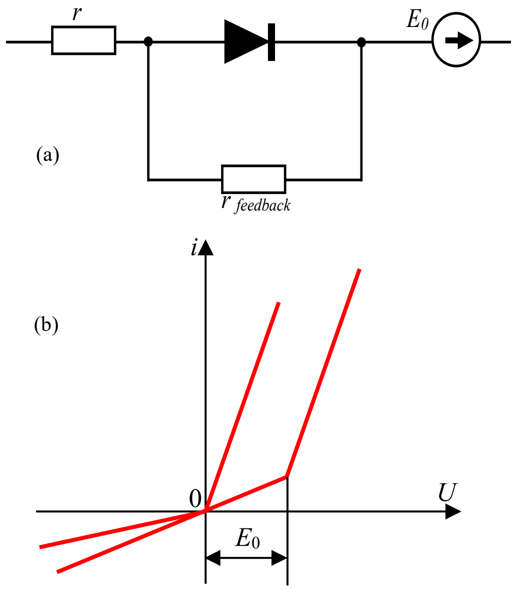


Figure 1. Replacement circuit consisting of an ideal semiconductor device and linear elements (a) and characteristics (b)

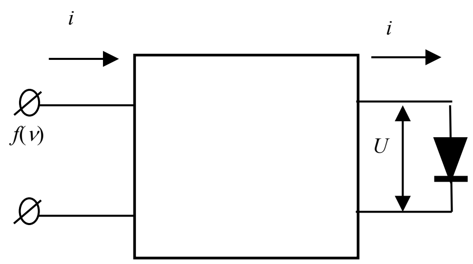


Figure 2. An electric circuit with a semiconductor device in the form of a four-pole

In both cases, the solution of the equations leads to a system of $2n+l$ equations (l is the number of linear sections of the characteristic traversed during the period; n is the order of the differential equation). These equations are linear concerning $2n$ unknowns, which are the values of the discontinuity of the functions i and u and their derivatives, and are transcendental concerning l unknowns is t_1 of time corresponding to the moments of discontinuities [1, 4, 5, 9].

As it is known, discontinuous functions cannot be differentiated in the usual way. The introduction of generalized functions allows the differentiation operation to always be carried out. The concept of a generalized function is related to the concept of a function that acts on a certain space K of the basic functions. These basic functions $f(x)$ must have continuous derivatives of all orders and be finite, that is, vanish outside some bounded domain. Then any ordinary function $f(x)$ is associated with a functional that puts a certain number of influences by this function and the main function $\varphi(x)$.

$$(f,\varphi)=\int f(x)\varphi(x)dx \quad (2)$$

Thus, a generalized function is a continuous linear functional defined on the space of K basic functions. If the function $f(x)$ is continuous and smooth, then the generalized function is the same as the usual one [1, 6, 7].

Each generalized function has derivatives of any order:

$$\left[\bar{f}(x)+\bar{g}(x)\right]^{(m)}=\bar{f}(x)^{(m)}+\bar{g}(x)^{(m)};$$

$$\left[\lambda\bar{f}(x)\right]^{(m)}=\lambda\bar{f}(x)^{(m)};\ \left[\bar{f}(x)+\bar{g}(x)\right]^{(s)}=\bar{f}^{(m+1)}(x).$$

Every periodic generalized function $\bar{f}(x)$ is the sum of a trigonometric series [1, 6]:

$$\bar{f}(x)=\frac{a_0}{2}+\sum_{v=1}^{\infty}\left(a_v\cos vx+b_v\sin vx\right) \tag{3}$$

where,

$$a_v=\frac{1}{pi}\int_{-pi}^{pi}f(x)\cos vxdx$$

$$b_v=\frac{1}{pi}\int_{-pi}^{pi}f(x)\sin vxdx$$

The a_v and b_v values can be determined using the capabilities of the Workspace command window of the MATLAB program. To do this, an algorithm is written for these values as follows:

>> f_1=int(f(x)cos(v*x)), x, -pi, pi;
>>f_2=int(f(x)sin(v*x)), x, -pi, pi;
>>av=1./pi×f_1;
>>bv=1./pi×f_2

The convolution of generalized functions is the expression:

$$\bar{f}(x)\times\bar{g}(x)=\int\bar{f}(x-y)\bar{g}(y)dy \tag{4}$$

To solve a differential equation using generalized functions:

$$L(s)\bar{f}(x)=\bar{h}(x) \tag{5}$$

It is necessary at the beginning to find a generalized function $\bar{g}(x)$, that is a solution to the differential equation

$$L(s)\bar{g}(x)=\delta(x) \tag{6}$$

where, $\delta(x)$ is Dirac delta function.

The function $\bar{g}(x)$ is called the fundamental solution (5). The desired solution of this expression is defined as a convolution of the fundamental solution $\bar{g}(x)$ and the right-hand side (5) $\bar{h}(x)$, i.e.: $\bar{f}(x)=\bar{g}(x)\bar{h}(x)$.

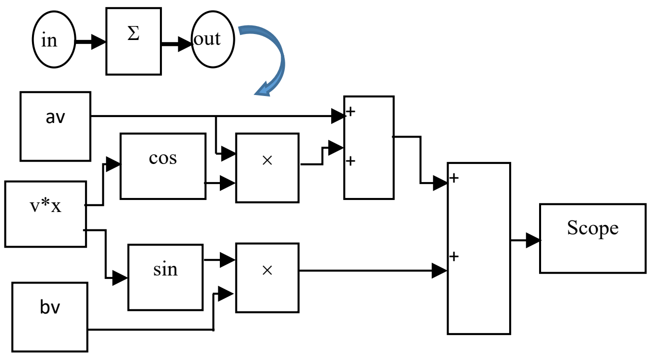


Figure 3. Simulink model of Equation (3)

To solve the differential equation, we write Equation (1) using generalized functions [1]:

$$A(s)u(\vartheta)+B(s)\bar{i}(\vartheta)=K(s)f(\vartheta) \tag{8}$$

Suppose that a periodic voltage with no jumps is applied at the input of the four-pole, that is, the function $\bar{f}(\vartheta)$ is smooth. In this case, the generalized function $\bar{f}(\vartheta)$ and $f(\vartheta)$ the function coincides with each other. We also assume that the image point passes the inflection point twice during the period.

Write Equation (8) for linear sections of the characteristic. When the valve is open, the voltage on it is zero. Therefore, we get;

$$B(s)\bar{i}(\vartheta)=\bar{\psi}(\vartheta);\quad \bar{\psi}(\vartheta)=K(s)\bar{f}(\vartheta) \tag{9}$$

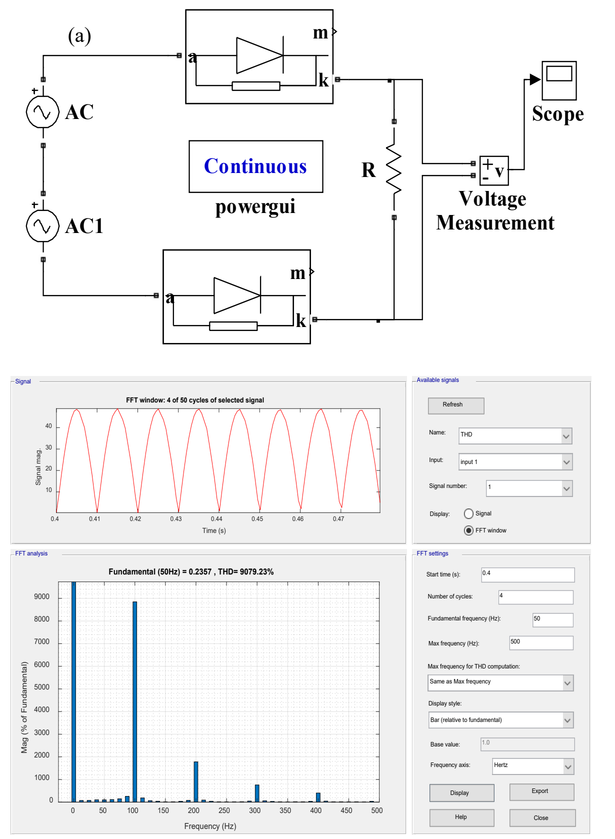
In the interval when the valve is locked, there is no current in the circuit and we get [1],

$$A(s)\bar{u}(\vartheta)=\psi(\vartheta) \tag{10}$$

Find a solution to each of the expressions (9) and (10). To do this, it is necessary first, as indicated above, to determine the fundamental solution of the equations. To find a fundamental solution to Equation (9), Equation (11) should be solved.

$$B(s)\bar{g}(\vartheta)=\delta(\vartheta) \tag{11}$$

As it is known, FFT analysis can be used for clear and fast analysis and obtaining results. To do this, a rectifier circuit is used, as shown in Figure 4a. The obtained characteristics are shown in the Figure 4b [1, 8, 9, 10].



(b)

Figure 4. Simulink model of the rectifier circuit (a) and FFT analysis (b)

Using Simulink model, it is possible to determine the ripple of the output current. Single full period of the output voltage can be analyzed, in addition, the result will be less influenced by unsteady mode and random interference in the voltage of the rectifier circuit. The values of the current and voltage on of the rectifier elements are generated in the oscilloscope. The input of the oscilloscope receives a vector consisting of 2 values: voltage on the rectifier element and the current flowing through it.

3. MATHEMATICAL ANALYSIS OF THE TRANSITION PROCESS

In transient processes, the current and voltage of an ideal converter (Figure 1) has the form of pulses, the shape of which gradually approaches the shape of periodic pulses of steady-state processes. Considering the process separately in each period of alternating voltage applied to the circuit, it is possible to imagine the entire process consisting of a sequence of periodic processes corresponding to a given period. From a mathematical point of view, this means a formal - periodic continuation of the current or voltage pulses of the converter on the time axis. It becomes possible to describe these impulses in harmonic series, i.e. [1, 2, 5].

$$\begin{cases} i_k = \sum_{v=-\infty}^{\infty} I_{vk} e^{jv\vartheta} \\ u_k = \sum_{v=-\infty}^{\infty} U_{vk} e^{jv\vartheta} \end{cases} \tag{12}$$

where, the index k denotes the name of the period of voltage applied to the circuit from the beginning of the transient process. This representation of the current and voltage of the converter recalls the form of recording the desired values in the method of sequential intervals, where the period of voltage applied to the circuit is selected for the time interval, and not a mediocre value is approximated by a harmonic series.

To find a solution for this period, we present a differential equation describing the processes in the chain as a system [1, 10]:

$$A(s)\overline{u}_k + B(s)\overline{i}_k = \overline{\psi}_k(\vartheta) \tag{13}$$

where, k= 1, 2, ..., n. The solution of each of the Equations (13) due to the periodization has the same form as in the case of the wildest breakthrough:

$$u_k = \sum_{v=-\infty}^{\infty} \frac{a_{vk}}{A(jv)} e^{jv\vartheta} \tag{14}$$

$$i_k = \sum_{v=-\infty}^{\infty} \frac{b_{vk}}{A(jv)} e^{jv\vartheta} \tag{15}$$

where, the amplitudes a_{vk} and b_{vk} are determined by expressions:

$$b_{vk} = \frac{1}{2pi}\int_{\theta_1}^{\theta_2} \psi(x) e^{-jvx} dx; \quad a_{vk} = \frac{1}{2pi}\int_{\theta_1}^{\theta_2+2pi} \psi(x) e^{-jvx} dx$$

if they are replaced, respectively, θ_1 by $\theta_1^{(k)}$, θ_2 by $\theta_2^{k}(i_k)$ and θ_1, by $\theta_1^{(k+1)}$, θ_2 by $\theta_2^{k}(u_k)$.

In the case of a circuit with an ideal converter, it is possible to write equations concerning $\theta_1^{(k+1)}$, $\theta_2^{(k)}$ and $\theta_2^{(k+1)}$ in integral form, since they fully take into account the boundary values of the current and voltage of the converter [1, 2, 3, 6].

Indeed, the current of the converter turns to zero at the moment of its locking and remains equal to it until the moment of opening, and the voltage of the converter turns to zero at the moment of opening the valve and remains equal to it until the moment of locking. Thus, to calculate the transients, we have the Equations (16) and (17) [1]:

$$\begin{cases} \mathrm{ctg}\left(\frac{\delta}{2} + \gamma\right) = \Phi_1\left(\frac{\lambda}{2}\right) \\ \mathrm{ctg}\left(\frac{\delta}{2} + \gamma\right) = \Phi_2\left(\frac{\lambda}{2}\right) \end{cases} \tag{16}$$

The sequential solution of Equation (16) makes it possible to determine the opening and locking moments of the converter for each voltage period. In the case of transients, we present Equation (17) in a more convenient form for solving [1, 8, 10]:

$$\begin{cases} \mathrm{ctg}\left(\frac{\delta}{2}\lambda + \gamma + \theta_1^{(k)}\right) = \Phi_1\left(\frac{\lambda}{2}\right) \\ \mathrm{ctg}\left(\frac{\delta}{2}\lambda - \gamma - \theta_1^{(k)}\right) = \Phi_2\left(\frac{\lambda}{2}\right) \end{cases} \tag{17}$$

In these expressions $\theta_1^{(k)}$ and $\theta_2^{(k)}$ are the only values that depends on the number of the period of alternating voltage in transients. Because of this, each new solution is obtained as a result of one operation - shifting the $\mathrm{ctg}\frac{1}{2}\lambda$ graph by a certain angle $\left(\gamma + \theta_1^{(k)}\right)$ or $-\left(\gamma + \theta_1^{(k)}\right)$.

Determining the currents and voltages of converters in the form of Fourier series has a number of disadvantages. The main one is that the behavior of a series at a given point, according to the principle of localization, depends on the behavior of a series only in an infinitesimal neighborhood of this point. In other words, to find out, for example, the maximum current value for a given period, you need to sum up the harmonics for the entire interval $\left(\theta_1^{(k)} < \vartheta < \theta_2^{(k)}\right)$. Additionally, a significant number of harmonics will give a fairly accurate idea of curve shape.

This difficulty can be circumvented by requiring only an approximate solution to the problem. for example, the flow of current in the converter can be approximately judged by the value of the constant component and the time of the conductive state of the converter, if the shape of the current is considered to be known - triangular, trapezoidal or truncated sinusoid. The actual current curve is best approximated by a truncated sine wave. To build such a sine wave, you need to determine its amplitude. To do this, we have [1]:

$$2\pi I_0^{(k)} = I_m^{(k)} \int_{\theta_1^{(k)}}^{\theta_2^{(k)}} \left(\sin\vartheta - \cos\frac{1}{2}\lambda\right) d\vartheta;$$

$$I_m^{(k)} = \frac{\pi I_0^{(k)}}{\sin\frac{\delta}{2}\sin\frac{\lambda}{2} - \frac{1}{2}\lambda\cos\frac{\lambda}{2}}.$$

Figure 5 shows the switching of the circuit to a sinusoidal voltage.

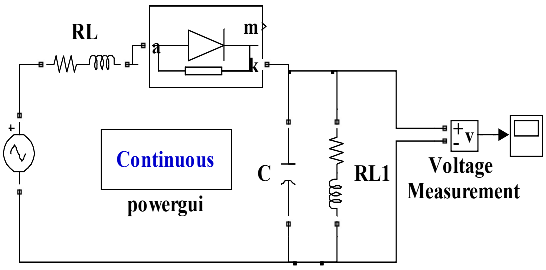


Figure 5. Simulink model of the of the rectifier circuit with switching to a sinusoidal voltage

It should be noted that Equation (17), due to the periodization of the process, take into account the initial conditions of the requirement that switching occur at moments or determined by the previous periodic process. This circumstance can lead to a significant distortion of processes that last for several periods. In the case of longer processes, the requirement of switching at moments or practically imposes no restrictions and can only lead to distortions in the first period from the beginning of the transition process. The Figure 6 shows FFT analysis of the rectifier circuit shown in Figure 5.

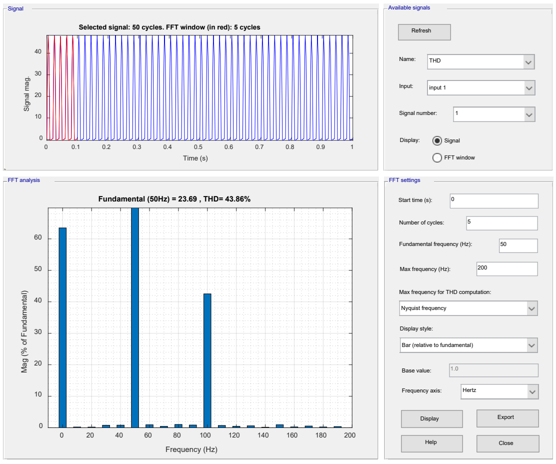


Figure 6. FFT analysis of the rectifier circuit shown in Figure 5

The differential equations describing electromagnetic processes in the converter (Figure 5) have the form [1, 10]:

$$\begin{aligned}&[s^3\omega^3 LL_1C + s^2\omega^2\left(LR_1 + L_1R\right) + \\ &+ s\omega\left(L + L_1 + CR_1R\right) + \\ &+ R + R_1]i + \left(s^2\omega^2 L_1C + s\omega r_1C + 1\right)u = U_m \sin\vartheta\end{aligned} \quad (18)$$

Using the Simulink model of the Equation (18), it is possible to analyze the transient process for the electrical circuit shown in Figure 7. To analyze the transient process, consider an example of a solution, where, R=105 Ohm; R_1=20 Ohm; L=0.030 Hn; L_1=0.150 Hn; C=170 mkF. The initial conditions are zero, the converter is ideal. The moment of switching on $\vartheta_1^{(1)} = 0$ [1, 7, 10].

The moment of locking the converter in the first period of alternating voltage from the beginning of the transient process is determined by the intersection point $ctg\frac{\lambda}{2}$ and the magnetic flux Φ_1 (Figure 8). The obtained graphs after simulating $\frac{1}{2}\lambda_2^{(1)} = 140°$ the model shown in Figure 7 are obtained from where $\vartheta_2^{(1)} = \lambda_2^{(1)} + \vartheta_1^{(1)} = 280°$. To determine the moment of opening of the transducer in the second period, it is shifted $\text{ctg}\frac{\lambda}{2}$ to the right by an angle $\vartheta_2^{(1)} = 280° - 180°$ and the $\frac{\lambda}{2}$ intersection point with the magnetic flux is Φ_2 curve is located. Then, $\frac{1}{2}\lambda_1^{(2)} = 107°$; $\vartheta_1^{(2)} = \vartheta_2^{(1)} - \lambda_1^{(2)} = 66^0$ (Figure 8).

It follows from the calculation results that the duration of the transient process is approximately five periods of applied voltage or, given that f = 50 Hz, the transition time t = 0.1 s is spent.

4. CONCLUSION

1. The paper analyzes the piecewise linear approximation method for electrical semiconductor circuits. An approximation was considered that allows us to represent a semiconductor device in the form of a replacement circuit consisting of an ideal semiconductor device and linear elements, which allows us to represent an electrical circuit with a semiconductor device in the form of a four-pole, at the output of which there is an ideal semiconductor device.
2. The classical solution method is analyzed, which is described by high-order differential equations, which is explained by the complexity of determining the integration constants and the complexity of the period equations, and the method for determining periodic solutions is based on finding a solution and the form of a complete Fourier series.
3. Due to the periodization of the process, the initial conditions of the requirement were taken into account, so that the switches occurred at moments or were determined by the previous periodic process.
4. This circumstance can lead to a significant distortion of processes that last for several periods. In the case of longer processes, the requirement to switch at certain points in time imposes practically no restrictions and can only lead to distortions in the first period from the beginning of the transition process.
5. Using mathematical calculations and simulation, the duration of the transient process, which is approximately five periods of applied voltage, was analyzed and the time of the transient process was determined.

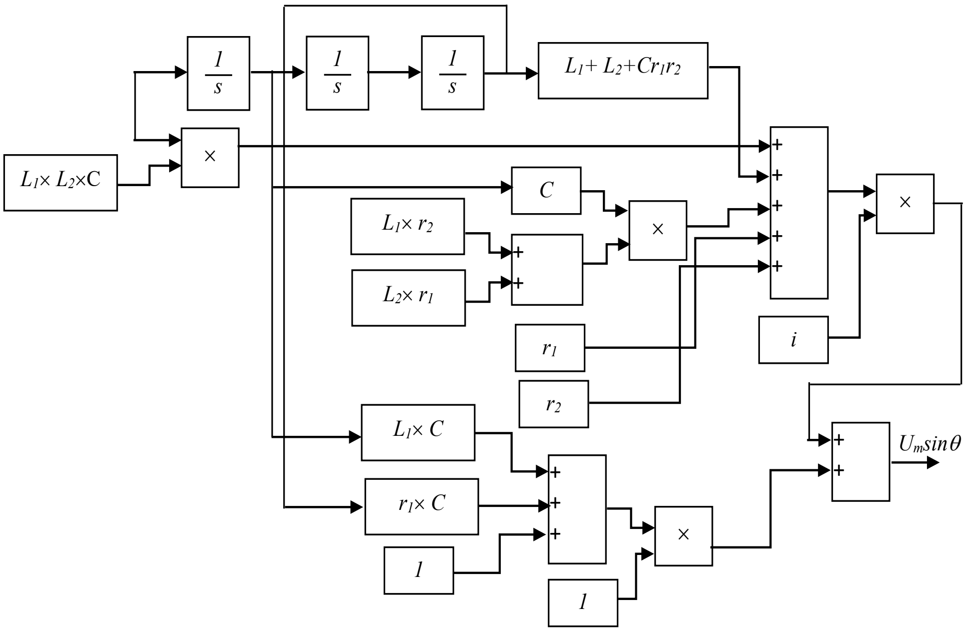


Figure 7. Simulink model for transient analysis according to Equation (18)

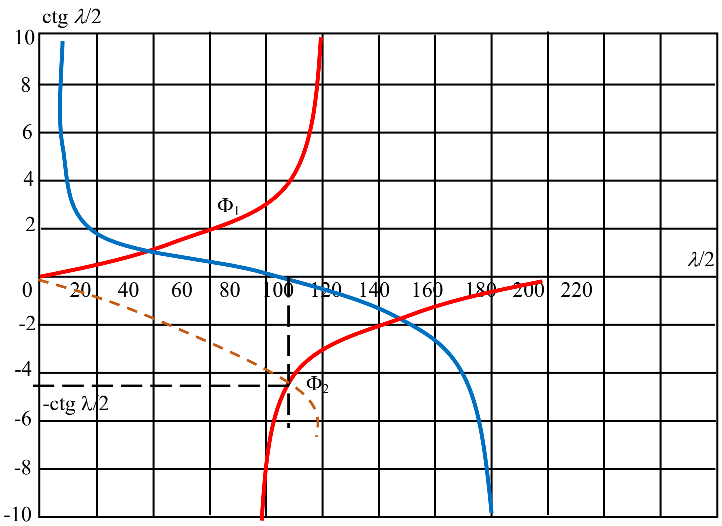


Figure 8. Dependences of changes in magnetic fluxes (Φ_1 and -Φ_2) during transients

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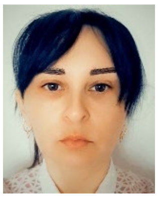

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