

Analysis of instantaneous power components of electric circuit with a semiconductor element*

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Abstract: Both a classical instantaneous power method and a method based on equations of instantaneous power orthogonal components balance have been used to analyze power processes in electric circuits with semiconductor elements. Automated method of forming instantaneous power harmonic components was used to obtain analytical expressions and numerical values of instantaneous power components of analyzed electric circuits. A coefficient for estimation of a semiconductor converter nonlinearity degree has been offered.

Key words: semiconductor element, instantaneous power, equations of instantaneous power orthogonal components balance

1. Introduction

Nowadays semiconductor elements are an inseparable part of electric devices and systems. During the design and operation of semiconductor converters the determination of their energy indices is very important. Researchers often use the notion “apparent power” calculated by the product of current I_{RMS} and voltage U_{RMS} root-mean-square (RMS) values [1-2]:

$$S = I_{RMS}U_{RMS}. \quad (1)$$

According to the existing methods of the analysis of power processes in circuits with non-sinusoidal currents and voltages, apparent power S includes three components: active power P_0 , reactive power or shift power Q and distortion power D [2-8]:

$$S = \sqrt{P_0^2 + Q^2 + D^2}, \quad (2)$$

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$$S = \sqrt{\left(\sum_{k=0}^K P_{0k}\right)^2 + \left(\sum_{k=1}^K Q_k\right)^2} + D^2, \quad (3)$$

where:

$$\left(\sum_{k=0}^K P_{0k}\right) - \text{sum of active power components,}$$

$$\left(\sum_{k=1}^K Q_k\right) - \text{sum of reactive power components,}$$

D^2 – distortion power squared, k – power harmonic number, K – number of the analyzed power harmonics.

General notions and calculation expressions for apparent power and its components are shown in a number of papers [1-10].

Existing theories make it possible to estimate the values of active, reactive power, as well as distortion power. However, researchers still consider it expedient to pay attention to more precise analysis of the processes taking place in circuits with semiconductor converters, which are elements with explicit nonlinearity [11-16]. It is caused by the fact that the existing integral method [2-3] of power process analysis does not allow one to fully discover energy conversion regularities peculiar to systems with semiconductor elements.

2. Problem statement

The purpose is to refine the calculating method of the nonlinear electric circuits by taking into account the power components on the semiconductor elements.

3. Materials and research results

Analysis of an electric circuit with a diode

It was proposed in paper [14] to use instantaneous power (IP) method for the analysis of systems with semiconductor elements. In the present paper this approach was applied for the analysis of the balance of IP components of an electric circuit with an ideal diode connected in series with active resistance (Fig. 1).

Equations of balance of IP orthogonal components were formed by automated algorithm of IP components formation [17].

A polynomial function connecting diode output U_C and input U_S voltages was selected as an approximating function of an ideal diode nonlinear characteristics.

$$U_C(U_S) = a_0 + a_1 U_S + a_2 U_S^2 + \dots + a_n U_S^n, \quad (4)$$

where a_0, a_1, a_2, a_n – polynomial coefficients.

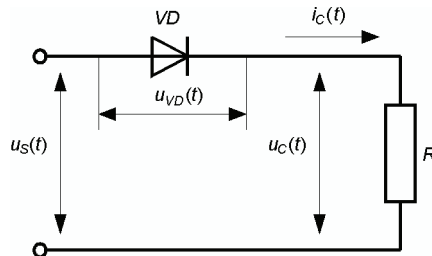


Fig. 1. Analyzed electric circuit with a diode

In the course of the research a number of polynomials of different degrees were analyzed (Fig. 3) and corresponding coefficients for the presented polynomials were obtained: for the third degree $a_0 = 1.054 \cdot 10^{-1}$, $a_1 = 5.757 \cdot 10^{-1}$, $a_2 = 4.252 \cdot 10^{-1}$, $a_3 = -1.225 \cdot 10^{-1}$; for the sixth degree $a_0 = 6.314 \cdot 10^{-2}$, $a_1 = 5.155 \cdot 10^{-1}$, $a_2 = 7.597 \cdot 10^{-1}$, $a_3 = -9.727 \cdot 10^{-2}$, $a_4 = -3.525 \cdot 10^{-1}$, $a_5 = 9.662 \cdot 10^{-2}$, $a_6 = 2.791 \cdot 10^{-2}$, and for the tenth degree $a_0 = 2.441 \cdot 10^{-2}$, $a_1 = 5.000 \cdot 10^{-1}$, $a_2 = 1.886$, $a_3 = -6.925 \cdot 10^{-12}$, $a_4 = -6.536$, $a_5 = 2.562 \cdot 10^{-11}$, $a_6 = 1.356 \cdot 10^1$, $a_7 = -3.482 \cdot 10^{-11}$, $a_8 = -1.322 \cdot 10^1$, $a_9 = 1.564 \cdot 10^{-11}$, $a_{10} = 4.789$.

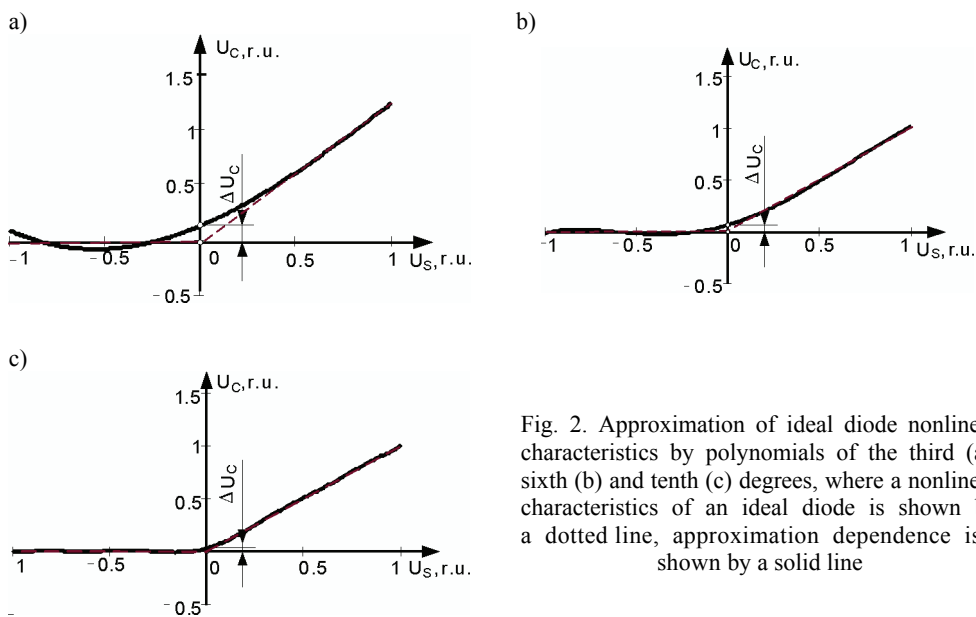


Fig. 2. Approximation of ideal diode nonlinear characteristics by polynomials of the third (a), sixth (b) and tenth (c) degrees, where a nonlinear characteristics of an ideal diode is shown by a dotted line, approximation dependence is shown by a solid line

To form a n -th power polynomial (4) and IP components at the diode output it is necessary to perform the following actions according to the algorithm of forming IP harmonic components on the diode (Fig. 3) [17]:

- arrays U_{Sa} and U_{Sb} of real and imaginary, respectively, orthogonal components of supply voltage are assigned;

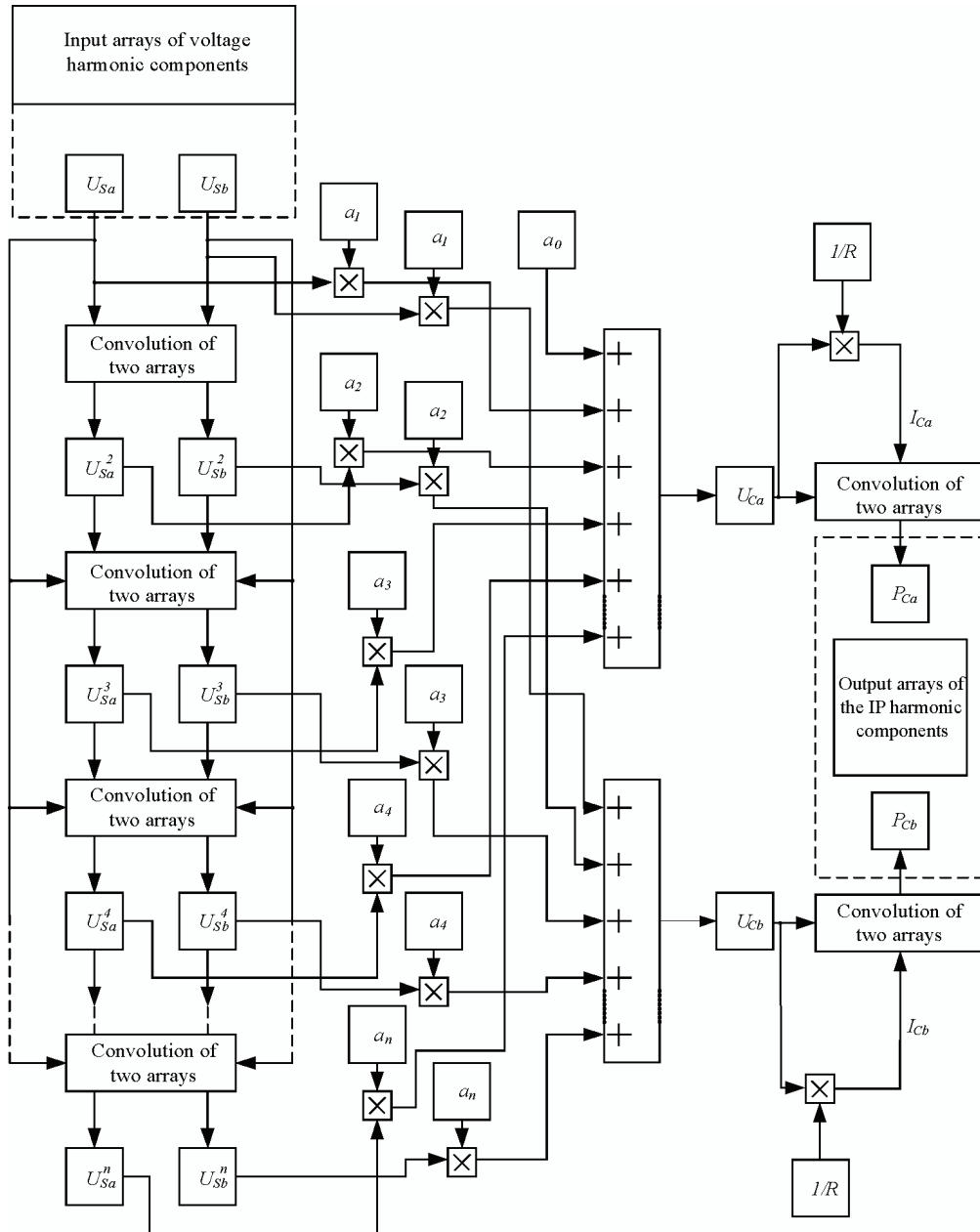


Fig. 3. Algorithm of forming harmonic components of IP of the analyzed electric circuit with a diode

- approximation polynomial degree is assigned and on the basis of the assigned above arrays of input voltage U_S their n -th degrees arrays are formed using the discrete convolution algorithm;

- the obtained arrays of input voltage U_S n -th degrees are multiplied by polynomial corresponding coefficients and U_{Ca} and U_{Cb} – real and imaginary, respectively, voltage harmonic components at diode output are determined;
- current harmonic components I_{Ca} , I_{Cb} are found by multiplying corresponding voltage components U_{Ca} , U_{Cb} at diode output by $1/R$;
- IP imaginary components of a nonlinear circuit with a diode are determined by multiplying the obtained arrays U_{Ca} , U_{Cb} and I_{Ca} , I_{Cb} , respectively.

Analysis of IP components of the considered circuit is shown as an example. To make the analytical expressions shorter the third degree of polynomial (4) was accepted, and input voltage was presented by a real component of the first harmonic $U_S = U_{Sa1}$ (Tab. 1). Diode reverse voltage was calculated as: $U_{VDa} = U_{Sa1} - U_{Ca}$.

Table 1. Harmonic composition of voltages and current in the analyzed circuit with a diode

Input voltage U_{Sa} in the circuit	U_{Sa}^2	U_{Sa}^3
$\begin{pmatrix} 0 \\ U_{a1} \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \end{pmatrix}$	$\begin{pmatrix} \frac{1}{2}U_{a1}^2 \\ 0 \\ \frac{1}{2}U_{a1}^2 \\ 0 \\ 0 \\ 0 \\ 0 \end{pmatrix}$	$\begin{pmatrix} 0 \\ \frac{1}{2}U_{a1}^2 \\ 0 \\ \frac{1}{4}U_{a1}^3 \\ 0 \\ 0 \\ 0 \end{pmatrix}$
Voltage U_{Ca} at diode output (consumer's voltage)	Consumer's current I_{Ca}	Diode voltage $U_{VDa} = U_{Sa} - U_{Ca}$
$\begin{pmatrix} a_0 + \frac{1}{2}a_2U_{a1}^2 \\ a_0U_{a1} + \frac{1}{2}a_3U_{a1}^3 \\ \frac{1}{2}a_2U_{a1}^2 \\ \frac{1}{4}a_3U_{a1}^3 \\ 0 \\ 0 \\ 0 \end{pmatrix}$	$\begin{pmatrix} a_0 + \frac{1}{2}a_2U_{a1}^2 \\ a_0U_{a1} + \frac{1}{2}a_3U_{a1}^3 \\ \frac{1}{2}a_2U_{a1}^2 \\ \frac{1}{4}a_3U_{a1}^3 \\ 0 \\ 0 \\ 0 \end{pmatrix} \frac{1}{R}$	$\begin{pmatrix} -a_0 - \frac{1}{2}a_2U_{a1}^2 \\ U_{a1} - a_0U_{a1} - \frac{1}{2}a_3U_{a1}^3 \\ -\frac{1}{2}a_2U_{a1}^2 \\ -\frac{1}{4}a_3U_{a1}^3 \\ 0 \\ 0 \\ 0 \end{pmatrix}$

Composition of IP elements of the considered electric circuit with a diode was determined analytically in accordance with the given data (Tab. 1):

$$p_{VDa}(t) = p_{Sa}(t) - p_{Ca}(t), \quad (5)$$

$$\begin{pmatrix}
 -\frac{1}{4}a_0^2 - \frac{1}{4}a_0a_2U_{al}^2 - \frac{3}{16}a_2^2U_{al}^4 + \frac{1}{2}a_1U_{al}^2 - \frac{1}{2}a_1^2U_{al}^2 - \frac{1}{2}a_1a_3U_{al}^4 + \frac{1}{4}a_3U_{al}^4 - \frac{5}{32}a_3^2U_{al}^6 \\
 \frac{1}{2}a_0U_{al} - a_0a_1U_{al} - \frac{1}{2}a_0a_3U_{al}^3 + \frac{1}{2}a_2U_{al}^3 - a_1a_2U_{al}^3 - \frac{5}{8}a_2a_3U_{al}^5 \\
 -\frac{1}{2}a_0a_2U_{al}^3 - \frac{1}{4}a_2^2U_{al}^4 + \frac{1}{2}a_1U_{al}^2 - \frac{1}{2}a_1^2U_{al}^2 - \frac{3}{4}a_1a_3U_{al}^4 + \frac{3}{8}a_3U_{al}^4 - \frac{1}{4}a_3^2U_{al}^6 \\
 -\frac{1}{4}a_0a_3U_{al}^3 - \frac{3}{8}a_2a_3U_{al}^5 - \frac{1}{2}a_1a_2U_{al}^3 + \frac{1}{4}a_2U_{al}^3 \\
 -\frac{1}{4}a_1a_3U_{al}^4 - \frac{1}{8}a_3^2U_{al}^6 - \frac{1}{8}a_2^2U_{al}^4 + \frac{1}{8}a_3U_{al}^4 \\
 -\frac{1}{8}a_2a_3U_{al}^5 \\
 \frac{1}{32}a_3^2U_{al}^6
 \end{pmatrix} \frac{1}{R} =$$

$$\begin{pmatrix}
 \frac{1}{4}U_{al}^2(2a_1 + a_3U_{al}^2) \\
 \frac{1}{2}U_{al}(a_0 + a_2U_{al}^2) \\
 \frac{1}{8}U_{al}^2(4a_1 + 3a_3U_{al}^2) \\
 \frac{1}{4}a_2U_{al}^2 \\
 \frac{1}{8}a_3U_{al}^4 \\
 0 \\
 0
 \end{pmatrix} \frac{1}{R} -$$

$$\begin{pmatrix}
 \frac{1}{4}a_0^2 + \frac{1}{4}a_0a_2U_{al}^2 + \frac{3}{16}a_2^2U_{al}^4 + \frac{1}{2}a_1^2U_{al}^2 + \frac{1}{2}a_1a_3U_{al}^4 + \frac{5}{32}a_3^2U_{al}^6 \\
 a_0a_1U_{al} + \frac{1}{2}a_0a_3U_{al}^3 + a_1a_2U_{al}^3 + \frac{5}{8}a_2a_3U_{al}^5 \\
 \frac{1}{2}a_0a_2U_{al}^2 + \frac{1}{4}a_2^2U_{al}^4 + \frac{1}{2}a_2^2U_{al}^2 + \frac{3}{4}a_1a_3U_{al}^4 + \frac{1}{4}a_3^2U_{al}^6 \\
 \frac{1}{4}a_0a_3U_{al}^3 + \frac{3}{8}a_2a_3U_{al}^5 + \frac{1}{2}a_1a_2U_{al}^3 \\
 \frac{1}{4}a_1a_3U_{al}^4 + \frac{1}{8}a_3^2U_{al}^6 + \frac{1}{8}a_2^2U_{al}^4 \\
 \frac{1}{8}a_2a_3U_{al}^5 \\
 \frac{1}{32}a_3^2U_{al}^6
 \end{pmatrix} \frac{1}{R},$$

where $p_{Vd}(t)$, $p_{Sa}(t)$, $p_{Ca}(t)$, – IP at diode, power supply and load, respectively.

The above mentioned analytical expressions for the balance of IP orthogonal components of the analyzed electric circuit with a diode show that it is necessary to take into account IP components, even at an ideal diode, when IP balance equations are formed. When the spectral analysis of voltage and current is performed, current and voltage harmonic components, including constant component, will occur at the ideal diode. It results in the presence of IP corresponding components during the analytical analysis of the equations.

The calculated parameters of the analyzed circuit (Fig. 1) were compared with the values obtained by calculation of a mathematical model created in Matlab environment. In this case values of active resistance $R = 1$ Ohm and input voltage $U_{Sa1} = 1$ V were accepted.

Root-mean-square values Δi_{RMS} and Δp_{RMS} of current and power signal errors, respectively, as well as comparison of the degree of coinciding the curves obtained using the Matlab model and calculated ones (Fig. 4), as to determination coefficient R^2 and root-mean-square deviation (RSD), were accepted as the criteria for estimating the accuracy of calculation of the electric circuit with a diode (Tab. 2).

In Figure 4 dotted lines present the curves created according to the obtained by analytical expressions (Tab. 1) and (5); solid lines present the curves created by the values, obtained as a result of mathematical modeling of the analyzed electric circuit in Matlab.

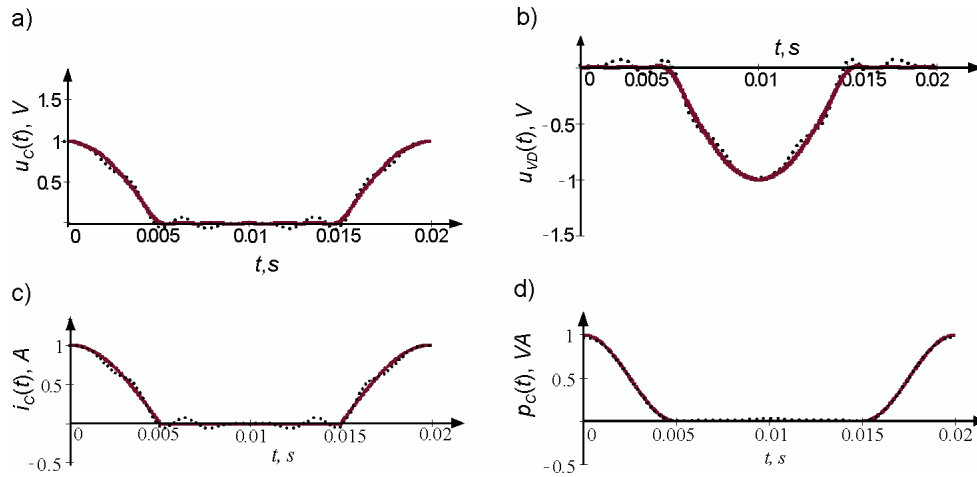


Fig. 4. Curves of diode input voltage (a), diode reverse voltage (b), circuit current (c), load power (d) when diode nonlinear characteristics is presented by a polynomial of the tenth degree

It is evident from Table 2 that as approximation accuracy improves the degree of coinciding of the curves created according to the results of mathematical modeling of the analyzed electric circuit in Matlab and the proposed analytical method increases.

Table 2. Estimation of the accuracy of calculating current components in the circuit and IP where diode nonlinear characteristics is presented by a polynomial of the third, sixth and tenth degrees

Polynomial of the third degree			
$\Delta i_{RMS}, \%$		$\Delta p_{RMS}, \%$	
15.575		16.635	
RMD	R^2	RMD	R^2
55.068	0.815	49.036	0.803
Polynomial of the sixth degree			
$\Delta i_{RMS}, \%$		$\Delta p_{RMS}, \%$	
15.226		2.304	
RMD	R^2	RMD	R^2
29.307	0.901	0.915	0.996
Polynomial of the tenth degree			
$\Delta i_{RMS}, \%$		$\Delta p_{RMS}, \%$	
1.678		2.079	
RMD	R^2	RMD	R^2
3.461	0.988	0.426	0.998

To estimate the values of diode IP harmonic components at different degrees of approximating function (third, sixth and tenth) they were correlated with power supply IP value that

was accepted as the basic one. During the research IP constant components P_{0VD} , P_{0S} and their root-mean-square values

$$\sqrt{\sum_{k=0}^{10} P_{kVD}^2}, \sqrt{\sum_{k=0}^{10} P_{kS}^2}$$

on the diode and power supply, respectively, were analyzed (Tab. 3).

Table 3 illustrates that constant component is the most ponderous diode IP component. This fact can be explained by the following. The biggest errors of approximation can be seen in the domain of small values of input voltage (Fig. 2). Due to this error, even at zero value of input voltage $u_C(t)$, initial voltage will be equal to ΔU_C . This value decreases as the order of approximating function grows as in the case with the values of diode IP constant component (Tab. 2).

Table 3. Numerical evaluation of IP components on the diode

The degree of approximating polynomial function	P_{0VD}/P_{0S}	$\sqrt{\sum_{k=0}^{10} P_{kVD}^2} / \sqrt{\sum_{k=0}^{10} P_{kS}^2}$
The third degree	0.571	0.443
The sixth degree	0.077	0.066
The tenth degree	0.046	0.039

Thus, the higher the degree of approximating function of diode nonlinear characteristics is the smaller the numerical value of the calculated harmonic components of IP at an ideal diode is.

Analysis of electric power with thyristors

Numerical evaluation of apparent power components of an elementary circuit consisting of an idealized thyristor active resistance connected in series was also done. This circuit is shown below (Fig. 5). It was assumed that the circuit is supplied by a sinusoidal voltage source. Under such conditions, in case when control angle $\alpha = 0$, the thyristor can be regarded as a diode.

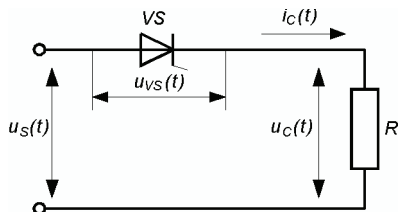


Fig. 5. Analyzed electric circuit with a thyristor

As thyristor nonlinear characteristics is difficult to approximate even if the value of control angle is fixed, the way of analysis of the numerical modeling results was chosen for this re-

search. Only ponderous voltage and current harmonics of the analyzed circuit were taken into account. These harmonics were obtained through computation of the given electric circuit mathematical model in Matlab environment.

Automated method of forming IP harmonic components [17] was used to obtain analytical expressions and numerical values of IP components at power supply, thyristor and active resistance. Balance equations for orthogonal components of IP of the analyzed circuit were formed and numerical values of power characteristics at different angles of thyristor control were analyzed. The obtained data are shown in Tables 4-6.

Table 4. Values of parameters obtained at the power supply

Parameter name	Parameter values at different control angles α			
	30°	70°	90°	130°
P_0	0.375	0.279	0.198	0.047
S	0.537	0.457	0.383	0.18
Q	-0.028	-0.106	-0.122	-0.072
D	0.383	0.346	0.304	0.158
S^2	0.288	0.209	0.146	0.032
P_0^2 / S^2	0.488	0.371	0.268	0.067
Q_2^2 / S^2	0.278	0.054	0.101	0.16
D^2 / S^2	0.509	0.575	0.631	0.773
P_{RMS}	0.666	0.575	0.454	0.14
P_{RMS}^2	0.444	0.331	0.206	0.02
P_0^2 / P_{RMS}^2	0.317	0.235	0.191	0.112
P_a^2 / P_{RMS}^2	0.681	0.649	0.394	0.397
P_b^2 / P_{RMS}^2	$1.87 \cdot 10^{-3}$	0.115	0.416	0.491

The following designations are used in Tables 4-6: P_0 – active power; S – apparent power; Q – reactive power; D – distortion power; P_{RMS} – IP RMS value; P_a – IP real component; P_b – IP imaginary component.

IP components numerical calculation using automated algorithm [17] demonstrated that the difference of the corresponding components and integral characteristics of IP at the power supply (Tab. 4) and the load (Tab. 5) can be explained by the presence of IP components at the thyristor (Tab. 6). It should be noted that in this case the quadratic-value balances of RMS power, apparent power and distortion power, correspondingly, coincide.

Table 5. Values of parameters obtained at the load

Parameter name	Parameter values at different control angles α			
	30°	70°	90°	130°
P_0	0.372	0.265	0.183	0.038
S	0.374	0.272	0.192	0.042
Q	0	0	0	0
D	0.039	0.059	0.053	0.019
S^2	0.14	0.074	0.036	$1.77 \cdot 10^{-3}$
P_0^2 / S^2	0.989	0.952	0.923	0.801
Q_2^2 / S^2	0	0	0	0
D^2 / S^2	0.011	0.048	0.077	0.199
P_{RMS}	0.669	0.568	0.441	0.107
P_{RMS}^2	0.448	0.323	0.195	0.011
P_0^2 / P_{RMS}^2	0.31	0.218	0.172	0.124
P_a^2 / P_{RMS}^2	0.685	0.606	0.355	0.383
P_b^2 / P_{RMS}^2	$5.598 \cdot 10^{-3}$	0.176	0.473	0.493

Table 6. Values of parameters obtained at the thyristor

Parameter name	Parameter values at different control angles α			
	30°	70°	90°	130°
P_0	$2.44 \cdot 10^{-3}$	0.013	0.015	$9.02 \cdot 10^{-3}$
S	0.383	0.363	0.328	0.174
Q	-0.028	-0.106	-0.122	-0.072
D	0.382	0.347	0.304	0.158
S^2	0.147	0.131	0.107	0.03
P_0^2 / S^2	$4.06 \cdot 10^{-5}$	$1.35 \cdot 10^{-3}$	$2.07 \cdot 10^{-3}$	$2.69 \cdot 10^{-3}$
Q_2^2 / S^2	$5.43 \cdot 10^{-3}$	0.085	0.138	0.178
D^2 / S^2	0.995	0.913	0.86	0.826
P_{RMS}	0.035	0.099	0.108	0.068
P_{RMS}^2	$1.23 \cdot 10^{-3}$	$9.87 \cdot 10^{-3}$	0.012	$4.6 \cdot 10^{-3}$
P_0^2 / P_{RMS}^2	$4.85 \cdot 10^{-3}$	0.018	0.019	0.018
P_a^2 / P_{RMS}^2	0.409	0.43	0.821	0.618
P_b^2 / P_{RMS}^2	0.587	0.055	0.16	0.365

Each value is given for the source (S), load (C) and thyristor (VS):

$$P_{RMSS}^2 = P_{RMSC}^2 + P_{RMSVS}^2, \quad (6)$$

$$S_S^2 = S_C^2 + S_{VS}^2, \quad (7)$$

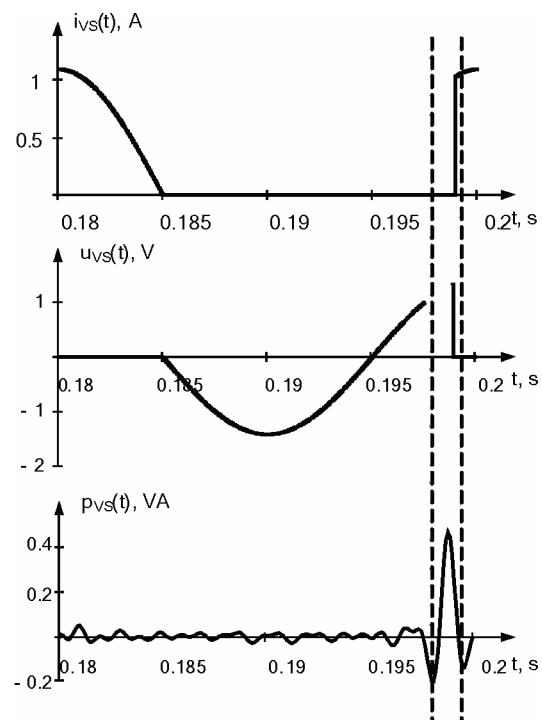
$$D_S^2 = D_C^2 + D_{VS}^2, \quad (8)$$

Reactive power balance also coincides:

$$Q_S = Q_C + Q_{VS}. \quad (9)$$

As the accuracy of numerical calculation improves, the values of semiconductor element active power tend to zero. Any improvement of computation accuracy does not result in zero values of IP orthogonal components.

Fig. 6. Thyristor current, voltage and IP curves when control angle equals 70°



Restoration of IP curve $p_{vs}(t)$ on the semiconductor element (Fig. 6) in the time domain reflects a considerable burst corresponding to steep edge of current $i_{vs}(t)$ and voltage $u_{vs}(t)$ during thyristor switching. When the number of the analyzed current and voltage harmonics is increased, IP at nonlinear element approaches its true form – zero value during the whole period. I.e. IP orthogonal components are mutually compensated at the nonlinear element in time domain.

When integral estimation of IP on nonlinear element is made using power components RMS values, there is no mutual compensation.

Thyristor voltage-current characteristics will have a different form at different control angles. So, when a control angle is changed, the degree of thyristor nonlinearity also changes. Active power balance equation can be used to estimate the nonlinearity degree:

$$P_{0S1} = \sum_{k=0}^K P_{0Ck}, \quad (10)$$

where P_{0S1} – power supply active power; P_{0Ck} – k -th components of load active power.

If balance equations are presented through voltage and current orthogonal components, the following expression is obtained:

$$(U_{aS1}I_{a1} + U_{bS1}I_{b1})/2 = U_0I_0 + \left[U_{aC1}I_{a1} + U_{bC1}I_{b1} + \sum_{k=2}^K (U_{aCk}I_{ak} + U_{bCk}I_{bk}) \right] / 2, \quad (11)$$

or

$$[(U_{aS1} - U_{aC1})I_{a1} + (U_{bS1} - U_{bC1})I_{b1}] / 2 = U_0I_0 + \sum_{k=2}^K (U_{aCk}I_{ak} + U_{bCk}I_{bk}) / 2. \quad (12)$$

This expression can be interpreted in the following way: the level of active power components from voltage and current non-fundamental harmonic depends on distortion of voltage fundamental harmonic at semiconductor element output. Harmonic, the number of which coincides with the number of ideal supply circuit voltage harmonic, is a fundamental harmonic. So, the relation of the active component of load fundamental harmonic to active power component of this harmonic on the power supply can be used as a coefficient of semiconductor converter nonlinearity:

$$k_{nl} = P_{0C1} / P_{0S1}. \quad (13)$$

For linear element $k_{nl} = 1$, for an absolutely nonlinear one $k_{nl} = 0$. A semiconductor converter with no output mains-frequency current or voltage components is understood to be an absolutely nonlinear element.

Calculation k_{nl} for a circuit with a thyristor (Fig. 5) is shown in Table 7.

Table 7. Nonlinear coefficient value at different control angles

Control angle α	0°	30°	70°	90°	130°
k_{nl}	0.5	0.491	0.414	0.355	0.205

For control angle $\alpha = 0$, which corresponds to the circuit with a diode the $k = 0.5$ (Fig. 1), where one half-cycle of supply mains voltage at diode output is cut off.

4. Conclusion

- 1) It is proved, that the balance of the instantaneous power components for the circuit with the semiconductor element coincides only if instantaneous power components on this element are taken into account, even if this element represented as an ideal one. It gives the opportunity to investigate active, reactive, apparent powers and distortion power formation mechanism in the circuits with semiconductor elements.
- 2) It is shown, that when nonlinear element apparent power components are taken into consideration, balance on active and reactive powers coincides. Balance on the values of apparent power and distortion power, as well as root-mean-square values of instantaneous power components, coincides on quadratic values. It allows to realize electric circuit analysis using the analytical equations of the instantaneous power components balances and active, reactive, apparent powers and distortion power balances.
- 3) The authors offered to evaluate the degree of semiconductor converter's nonlinearity according to the relation of active components of load fundamental harmonic power to active power of the same harmonic of power supply. The offered nonlinearity coefficient allows to numerically evaluate in the simple and efficient way the degree of nonlinearity introduced by the semiconductor device in the electric circuit.

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