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Selection of linear filter elements parameters for measuring of voltage and currents components of direct and inverse order

***Abstract**. In the paper is presented the review of control functions of linear filters of symmetric components, in the systems for measuring of symmetric components of voltages and currents in electric networks, composed of impedances with passive R, L, C parameters.*
The characteristics of process and procedure for determination of parameters of filters elements based on mathematical model of three-phase filter equivalent circuit have been emphasized. The results on behaviour of measuring system with linear filter behaviour obtained in the analysis with application of MATLAB simulation have also been presented.

***Streszczenie.** W artykule przedstawiono przegląd filtrów liniowych składowych symetrycznych, w zastosowaniu do systemów pomiarowych tych składowych prądu i napięcia sieci elektroenergetycznej, zbudowanych z elementów RLC. Opisano wynik działania pomiarów, wykonanych przez podany system, modelu symulacyjnym w programie Matlab. (**Dobór parametrów filtru liniowego do pomiaru składowej zgodnej i przeciwnej napięcia i prądu w sieci elektroenergetycznej**).*

Keywords: measuring, parameter, filter, symmetric components.
Słowa kluczowe: pomiary, parametry, filtr, składowe symetryczne

Introduction

Economic parameters and reliability of power networks exploitation depend on quality parameters of electric energy, and one of the most important and most influent quality parameters which influences the efficiency of three-phase power network is symmetry of network voltage.

In secondary circuits of power networks (measuring, protection and control) filters with two, three of more branches have been used. In determination of values and adjustment of filter parameters, filters have been mainly treated as independent electric circuits, because the values of source impedances are considered lesser in regard to impedances of filter elements [1, 2, 3, 4].

With this assumption, the calculations in this paper have been also performed – it is considered that parameters of filter electric branches elements, connected to appropriate linear voltage values, are independent.

Possible asymmetries mainly are determined, measured or calculated by approximate methods [1, 3, 5, 6]. In the case of measuring, the current or voltage filters, which phase values of voltages/currents convert to symmetric values of components of voltages/currents, are used. All approximate measuring methods include high measuring uncertainties and the biggest disturbance appears in the case of filters failure, which is usually derived as three-phase circuit.

The most used three-phase filter of symmetric components of direct and inverse orders is composed of three electric branches and has been presented on Fig. 1 [1, 2].

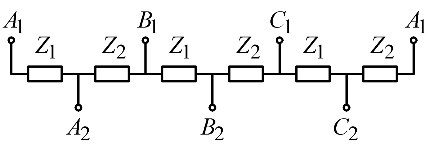

Fig.1. Three-phase filter of symmetric components of direct and inverse order

Disintegration of filter leads to impedance value discrepancy from nominal values. This can occur because errors during the manufacturing of filter elements as well as because of changes of impedances values due to changes of frequency, voltage or temperature.

Frequency change leads to changes of reactance value, since inductive reactance is directly and capacity reactance is inversely proportional to frequency.

Voltage discrepancies from nominal values cause changes of coils inductivity with ferromagnetic sheet metal in magnetic circuit. Temperature changes entail changes of active resistances and capacitances [7, 8, 9].

Determination of filter parameters values

Value changes of filter elements impedances are caused by discrepancy of parameters value R, f, L and C from nominal values. Inequality of impedances values and nominal values affects active as well as reactive part of filter impedance. Changed impedance value can be mathematically defined as a sum of nominal Z_n value and impedance change ΔZ, with expression:

(1) $$Z_h = Z_n + \Delta Z$$

where: nominal filter impedance Z_n is a sum of active and reactive part, and change of impedance value is included by introduction of coefficient h_*:

(2) $$Z_n = R_n + jX_n\,,\ \ \Delta Z = R_n \cdot h_{*R} + jx_n \cdot h_{*X}$$

Coefficients h_{*R} and h_{*X} of change of active and reactive impedance part are determined for each filter respectively, depending on its construction.

Frequency changes the most often, and with the assumption that it changes for value Δf in regard to nominal value (f_n), $f = fn + \Delta f$ the value of complex impedance of ohm-inductive (RL) character also changes:

(3) $$Z_h = R_n + j2\pi\left(f_n + \Delta f\right)L = Z_n + jX_n \cdot h_{*X}$$

In the case of frequency change, the value of coefficient h_* for R,L circuit is:

(4) $$h_{*X} = \Delta f / f_n$$

Value of impedance of ohm-capacitive RC character is:

(5) $$Z_h = R_n - j\frac{1}{2\pi\left(f_n + \Delta f\right)C} = Z_n + jX_n \cdot h_{*X}$$

In the case of frequency change in the circuit RC the value of coefficient h_* is:

(6) $$h_{*X} = \Delta f / \left(f_n + \Delta f\right)$$

In changes of values of inductivity for ΔL regarding the nominal value, the following expression has been used (3),

$\Leftrightarrow\ h_{*X} = \dfrac{\Delta L}{L_n}$, and in discrepancy of capacitance values ΔC from nominal value, expression (5) $\Leftrightarrow\ h_{*X} = \dfrac{\Delta C}{C_n + \Delta C}$.

When the value of active component changes for ΔR regarding the given value

$$Z_n = R_n + \Delta R + jX_n = Z_n + R_n \cdot h_{*R}\ ,\ \Leftrightarrow\ h_{*R} = \frac{\Delta R}{R_n}\ ,$$

three-phase symmetric circuit of arbitrary selected filter can be equivalent to single-phase scheme of quadripole which equation is [1]:

(7) $\quad U_1 = Z_{11}I_1 + Z_{12}I_2\ ,\ U_2 = Z_{21}I_1 + Z_{22}I_2$

Expressions that connect parameters of single-phase equivalent scheme $Z_{11}^F = Z_{22}^F$ to values of impedances Z_1 and Z_2 on Fig. 1, are listed hereafter [1].

In feeding of the filter, which scheme is presented on Fig. 1, from the direct order voltage system, equations that connect values of those impedances are:

(8) $$Z_{11}^F = Z_{22}^F = \frac{Z_1 + Z_2}{3}\ ,\ Z_{12}^F = \frac{Z_1 + a^2 Z_1}{3}$$

$$Z_{21}^F = \frac{Z_2 + a^2 Z_1}{3}$$

In the case of filter feeding , with scheme on Fig. 1, from the inverse order voltage system, the following is obtained:

(9) $$Z_{11}^{(F)} = Z_{22}^{(F)} = \frac{Z_1 + Z_2}{3}\ ,\ Z_{12}^{(F)} = \frac{Z_2 + a^2 Z_1}{3}$$

$$Z_{21}^{(F)} = \frac{Z_2 + aZ_1}{3}$$

Complex operators a and a^2 have values $a=e^{j120}$, $a^2=e^{-j120}$.

Then, for filters fed from the direct order voltage system by expressions (1) and (8) at symmetric discrepancy of impedance values from nominal, the following relations are valid:

(10) $$Z_{11h}^{(F)} = Z_{22h}^{(F)} = \frac{Z_{1h} + Z_{2h}}{3} = Z_{11n}^{(F)} + \frac{\Delta Z_1}{3} + \frac{\Delta Z_2}{3}$$

(11) $$Z_{12h}^{(F)} = \frac{Z_{2h} + aZ_{1h}}{3} = Z_{12n}^{(F)} + \frac{\Delta Z_2}{3} + \frac{a\Delta Z_1}{3}$$

(12) $$Z_{21h}^{(F)} = \frac{Z_{2h} + a^2 Z_{1h}}{3} = Z_{21n}^{(F)} + \frac{\Delta Z_2}{3} + \frac{a^2 \Delta Z_1}{3}$$

For filters fed from the inverse order voltage system from (1) and (9) is:

(13) $$Z_{11h}^{(F)} = Z_{22h}^{(F)} = \frac{Z_{1h} + Z_{2h}}{3} = Z_{11n}^{(F)} + \frac{\Delta Z_1}{3} + \frac{\Delta Z_2}{3}$$

(14) $$Z_{12h}^{(F)} = \frac{Z_{2h} + a^2 Z_{1h}}{3} = Z_{12n}^{(F)} + \frac{\Delta Z_1}{3} + \frac{a^2 \Delta Z_2}{3}$$

(15) $$Z_{21h}^{(F)} = \frac{Z_{2h} + aZ_{1h}}{3} = Z_{21n}^{(F)} + \frac{\Delta Z_2}{3} + \frac{a\Delta Z_1}{3}$$

and values ΔZ_1 and ΔZ_2 are determined by relation (2).

Equivalent T schemes can be used as electric circuits of linear filters symmetric components of direct and inverse order. Equation (7) corresponds to two equivalent T schemes on Fig. 2.a and Fig. 2.b.

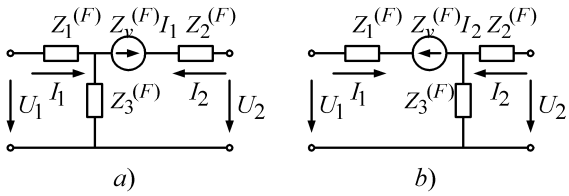

Fig.2. Equivalent schemes of symmetric components filter with passive elements

In feeding from the direct order voltage system, according to Fig. 2a, from expressions (10) – (12) is obtained:

(16) $$Z_{1h}^{(F)} = Z_{2h}^{(F)} = Z_{11h}^{(F)} - Z_{12h}^{(F)} = Z_{1n}^{(F)} + \frac{\Delta Z_1 (1-a)}{3}$$

(17) $$Z_{vh}^{(F)} = Z_{21h}^{(F)} - Z_{12h}^{(F)} = Z_{vn}^{(F)} + \frac{\Delta Z_1 \left(a^2 - a^3\right)}{3}$$

(18) $$Z_{3h}^{(F)} = Z_{12h}^{(F)} = Z_{12v}^{(F)} + \frac{\Delta Z_2}{3} + \frac{a\Delta Z_1}{a}$$

If scheme is fed from the inverse order voltage system, according to scheme on Fig. 2.a, from expressions (13) – (15) is obtained:

(19) $$Z_{1h}^{(F)} = Z_{2h}^{(F)} = Z_{11h}^{(F)} - Z_{12h}^{(F)} = Z_{1n}^{(F)} + \frac{\Delta Z_1 \left(1 - a^2\right)}{3}$$

(20) $$Z_{vh}^{(F)} = Z_{21h}^{(F)} - Z_{12h}^{(F)} = Z_{vn}^{(F)} + \frac{\Delta Z_1 \left(a - a^2\right)}{3}$$

(21) $$Z_{3h}^{(F)} = Z_{12h}^{(F)} = Z_{12n}^{(F)} + \frac{\Delta Z_2}{3} + \frac{a^2 \Delta Z_1}{a}$$

With analogous procedure for scheme on Fig. 2.b can also be obtained expressions similar to group of expressions (16) – (21).

Characteristics of filters symmetric components of direct and inverse order depend on filter type, that is, on the fact whether the filter is of direct FDR or inverse order FIR, and also on the fact whether scheme is fed from the voltage system or direct order U^d or voltage system of inverse order U^i and, finally, on whether the values are $Z_{12n}^{(F)} = 0$ or $Z_{21n}^{(F)} = 0$.

In order to have final expression with simpler form, in the case of $Z_{21n}^{(F)} = 0$, the parameters of equivalent scheme on Fig. 2.a can be used, and when $Z_{21n}^{(F)} = 0$ the parameters of equivalent scheme on Fig. 2.b should be used

Values determined according to this procedure for the filter fed from the inlet side are presented in Table 1. Similar expressions can be obtained if filter is fed from the discharge side.

If it possible for any filter impedance to determine discrepancies from nominal values, the real question is whether by regulating the parameters of other elements in a different way is possible to achieve better accuracy, that is, is the filter adjustment possible.

Better accuracy can be simply achieved if the condition that $Z_{3h}^{(F)} = 0$ is introduced (which can be seen of Fig. 2).

For direct order filter than is obtained:

(22) $$Z_{3h}^{(F)} = \frac{\Delta Z_2}{3} + \frac{a\Delta Z_1}{3} = 0$$

Table 1. Characteristic values of filter parameters of equivalent quadripole when fed from the inlet side

Filter Type	Order of phases of feeding voltage	Equivalent scheme on Fig. 2	$Z_{1h}^{(F)}=Z_{2h}^{(F)}$	$Z_{3h}^{(F)}$	$Z_{vh}^{(F)}$
FDR	U^d	a	$Z_{11n}^{(F)}+\frac{\Delta Z_1(1-a)}{3}$	$\frac{\Delta Z_2}{3}+\frac{a\Delta Z_1}{3}$	$Z_{21n}^{(F)}+\frac{\Delta Z_1(a^2-a)}{3}$
	U^i	a	$Z_{11n}^{(F)}+\frac{\Delta Z_1(1-a)}{3}$	$\frac{\Delta Z_2}{3}+\frac{a\Delta Z_1}{3}$	$Z_{12n}^{(F)}+\frac{\Delta Z_1(a^2-a)}{3}$
FIR	U^d	a	$Z_{11n}^{(F)}+\frac{\Delta Z_1(1-a^2)}{3}$	$\frac{\Delta Z_2}{3}+\frac{a^2\Delta Z_1}{3}$	$Z_{12n}^{(F)}+\frac{\Delta Z_1(a-a^2)}{3}$
	U^i	b	$Z_{11n}^{(F)}+\frac{\Delta Z_1(1-a^2)}{3}$	$\frac{\Delta Z_2}{3}+\frac{a^2\Delta Z_1}{3}$	$Z_{21n}^{(F)}+\frac{\Delta Z_1(a-a^2)}{3}$
where: $\Delta Z_1=R_{n1}h_{*R1}+jX_{n1}h_{*X1}$, $\Delta Z_2=R_{n2}h_{*R2}+jX_{n2}h_{*X2}$					

And for inverse order filter:

$$Z_{3h}^{(F)}=\frac{\Delta Z_2}{3}+\frac{a^2\Delta Z_1}{3}=0 \tag{23}$$

Left-hand parts of expressions (22) and (23) contain complex values, so each of those equations divides into two equations. In one of them is real value equal to zero, and in other imaginary.

If expressions (2) are considered, for direct order filter the condition for accuracy of filter adjustment is obtained in the form:

$$\begin{gathered} R_{n2}\,h_{*R2}-\frac{R_{n1}h_{*R1}}{2}-\frac{\sqrt{3}X_{n1}h_{*X1}}{2}=0 \\ \frac{\sqrt{3}R_{n1}h_{*R1}}{2}+X_{n2}h_{*X2}-\frac{X_{n1}h_{*X1}}{2}=0 \end{gathered} \tag{24}$$

and for inverse order filter (*FIR*):

$$\begin{gathered} R_{n2}h_{*R2}-\frac{R_{n1}h_{*R1}}{2}+\frac{\sqrt{3}X_{n1}h_{*X1}}{2}=0 \\ -\frac{\sqrt{3}R_{n1}h_{*R1}}{3}+X_{n2}h_{*X2}-\frac{X_{n1}h_{*X1}}{2}=0 \end{gathered} \tag{25}$$

Analysis of performance of filter linear circuit with RLC parameters

Simulation scheme of measurement of voltage and current symmetric components and influence of changes of linear filter impedances due to frequency changes has been obtained from the equation (2):

$$\left|\hat{Z}(f)\right| \Leftrightarrow Z(s)=\frac{V(s)}{I_z(s)} \tag{26}$$

Filter impedance in Laplacian domain is:

$$Z(s)=\frac{V(s)}{I(s)}=\frac{LCs^2+RCs+1}{Cs} \tag{27}$$

If from the scheme on Fig. 3 resistance, inductivity or capacitance is excluded, values must be alternative 0, 0, infinity (inf). Diagram for Z and argument Z (for ex.) on Fig. 4 relates to measuring values of voltage and current of elementary test for determination of Z for frequency f=300Hz. For obtaining of frequent characteristic of impedance it is necessary to establish ($A\ B\ C\ D$ matrix) a space model of system condition. At the input is one voltage source and at the output measuring current block system. Function $Z(s)$ can be transformed form the matrix of space condition and Bode function as follows:

```
[A,B,C,D] = power2sys('psbseriesbranch');
freq = logspace(1,4,500);
w = 2 *freq;
[Ymag,Yphase
] = bode(A,B,C,D,1,w);
% invert Y(s) to get Z(s)
Zmag = 1./Ymag;
Zphase = -Yphase;
subplot(2,1,1)
loglog(freq,Zphase)
grid
title('1,3,5 th harmonic filter')
xlabel('Frequency, Hz')
ylabel('Impedance Zmag')
subplot(2,1,2)
semilogx(freq,Zphase)
xlabel('Frequency, Hz')
ylabel('phase Z')
grid
```

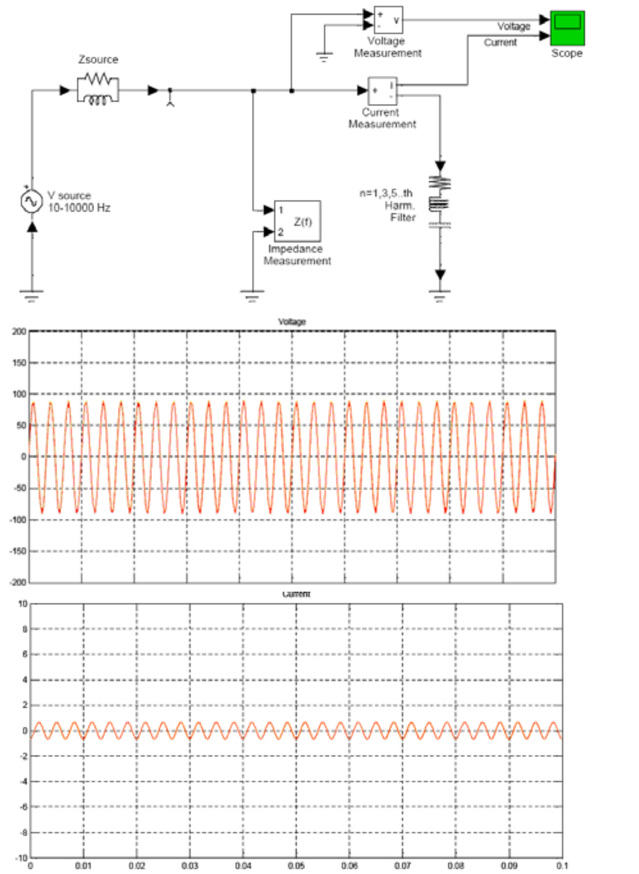

Fig.3. Measuring scheme with voltage source whose parameters are: ideal sinusoidal AC voltage, amplitude 100V; phase position (0):0; frequency (Hz):10-104; initial time:0 source impedance $Zsour$ parallel link Rll$L$, R((Ω)=10; L(H)=10e-03, RLC – parameters filter: resistance R(Ω)=1; inductivity L(H)=1e-03, capacitance C(F)=1e-06

Next, the block impedance $Z(f)$ can be measured, and drawn diagram of impedance as the frequency function. Requirement of impedance measurement is to disconnect current source from the measuring scheme, Fig. 3. In addition are presented two diagrams: first with the values of impedance module: $\left|\hat{Z}(f)\right|$ and second with phase values, that is, $arg\,\hat{Z}(f)$ impedance.

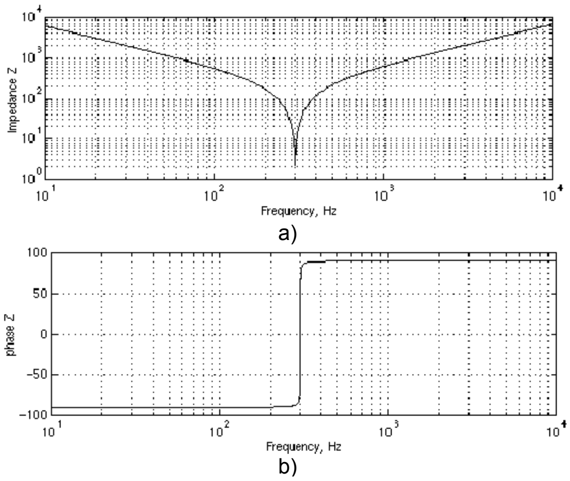

Fig.4. Diagram for: a) Z and b) argument (Z) relates to determination of parameters Z by measurement of voltage and current values

Example: Source parameters: ideal AC voltage source, amplitude 100V, phase position (deg): 0; elementary frequencies (Hz):50; initial time 0; frequency adjustment [f = (10 – 10000) Hz]; source impedance – parallel link RIIL, $R(\Omega)$=10; $L(H)$=10e-03.

Standard measuring impedance: $Z(f)$ and multiplication factor 1. Sample parameters of liner filter RLC [resitance $R(\Omega)$=1; inductivity (H)=100e-03; capacitance $C(F)$=10e-06] and variants: a) full RLC, b) serial RL c) serial RC.

a) Measurement of basic harmonic of voltage and current with application of linear filter with RLC impedance [$R(\Omega)$=1; $L(H)$=100e-03; $C(F)$=10e-06], scheme and diagrams: voltage ordinate ±200V, current ordinate ±10A, f=50Hz.

Measuring scheme on Fig. 3, by which the following diagrams are obtained, has been used.

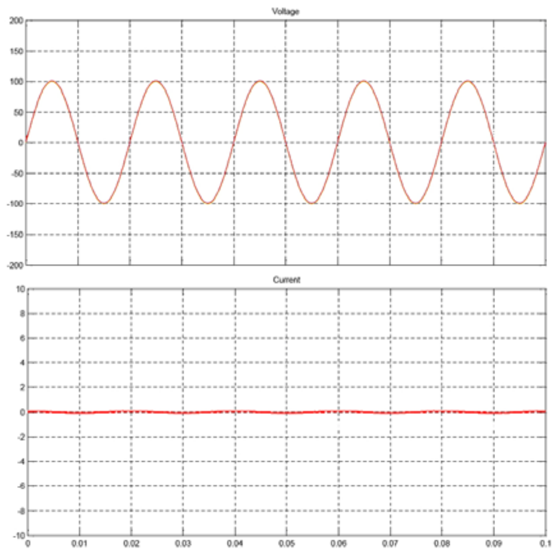

Fig.5. Time flow Diagrams of measured voltages and currents

b) Measurement of basic harmonic of voltage and current by linear filter with serial RL impedance [$R(\Omega)$=1; $L(H)$=100e-03], scheme and diagrams: voltage ordinate ±200V, current ordinate ±10A, f=50Hz.

Corrected scheme on Fig. 3 with excluded capacitance C [3, 7] is used.

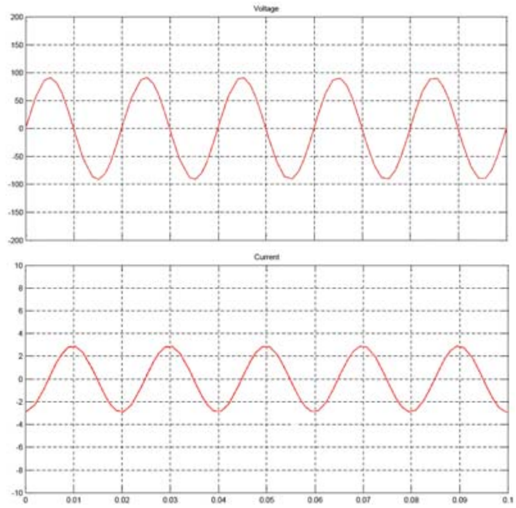

Fig.6. Basic harmonic of voltage and current measured by linear filter with serial RL impedance $R(\Omega)$=1; $L(H)$=100e-03], diagrams: voltage ordinate ±200V, current ordinate ±10A, f=50Hz

c) Measurement of basic harmonic of voltage and current by linear filter with serial RC impedance [$R(\Omega)$: 1;$C(F)$: 10e-06], scheme and diagrams: voltage ordinate ±200V, current ordinate ±10A, f=50Hz.

Corrected scheme on Fig. 3 with excluded inductivity L [3, 7] is used.

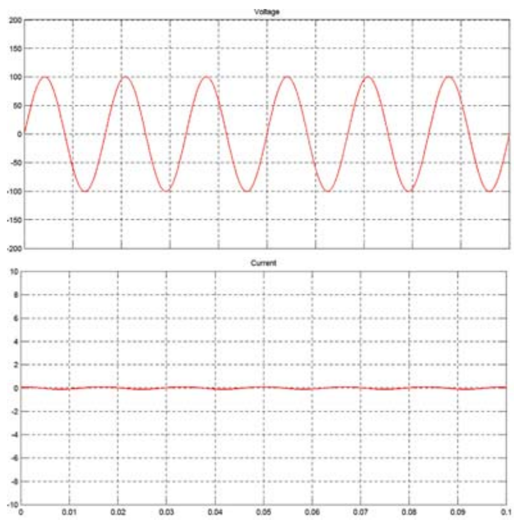

Fig.7. Basic harmonic of voltage and current measured by linear filter with serial RC impedance [$R(\Omega)$:1; $C(F)$:10e-06], ans diagrams: voltage ordinate ±200V, current ordinate ±10A, f=50Hz

Conclusion

As it can b seen from equations (24) and (25) for adjustment of filter accuracy there must be two elements, and appropriate filter adjustment is possible only in the case if obtained discrepancies form given values are not present in more than two or four independent filter parameters.

From obtained diagrams in tests, on Fig. 4-7, it can be seen that basic current harmonic in measurement follows basic voltage harmonic. Diagrams on Fig. 4.a and 4.b confirm that values of module and argument Z depend on developed harmonics and that this is necessary to be taken into consideration in projection of filter through constructive correction of elements parameters values given in Table 1.

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