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A STUDY ON DYNAMIC CHARACTERISTICS OF A NEW REMOTE TRANSFORMER CURRENT CONVERTER WITHOUT COMPENSATING CAPACITOR

Sulton Faizullaevich Amirov
Tashkent State Transport University, Address: 1, Temir yulchilar street, 1 st avenue 100167, Tashkent, Uzbekistan, E-mail: sulton.amirov@bk.ru, Mob.: +998904265341;, sulton.amirov@bk.ru

Nargisa Kamilovna Babanazarova
Bukhara Engineering-Technological Institute, Address: 15, K. Murtazaev street, 200100, Bukhara, Uzbekistan E-mail: nargisa2003@list.ru, Mob.: +998914060009;, nargisa2003@list.ru

Nurullo Rahmatullaevich Yuldashev
Tashkent State Transport University, Address: 1, Temir yulchilar street, 1 st avenue 100167, Tashkent, Uzbekistan, E-mail: yuldashev.n.r@mail.ru, Mob.: +998977726509., yuldashev.n.r@mail.ru

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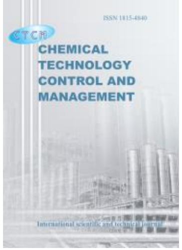

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A STUDY ON DYNAMIC CHARACTERISTICS OF A NEW REMOTE TRANSFORMER CURRENT CONVERTER WITHOUT COMPENSATING CAPACITOR

Amirov Sultan Faizullaevich[1], Babanazarova Nargisa Kamilovna[2],
Yuldashev Nurilla Rahmatullaevich[3]

[1]Tashkent State Transport University, Address: 1, Temir yulchilar street, 1 st avenue 100167, Tashkent, Uzbekistan,
E-mail: sulton.amirov@bk.ru, Mob.: +998904265341;
[2]Bukhara Engineering-Technological Institute, Address: 15, K. Murtazaev street, 200100, Bukhara, Uzbekistan
E-mail: nargisa2003@list.ru, Mob.: +998914060009;
[3]Tashkent State Transport University, Address: 1, Temir yulchilar street, 1 st avenue 100167, Tashkent, Uzbekistan,
E-mail: yuldashev.n.r@mail.ru, Mob.: +998977726509.

***Abstract**: In this research paper, analytical equations of the transient characteristics of a new remote transformer current converter without a compensating capacitor have been obtained when a stepwise, linearly increasing, sinusoidal and sinusoidal with a damped amplitude of effects was applied to their input. It has been shown that the developed current converter can be represented in the structural schemes of monitoring and control systems in the form of a series-connected real differentiating link without statism and inertial (aperiodic) link of the first order, and in the case of neglecting active losses in the magnetic circuit and when the converter is operating in idle mode, i.e in the form of ideal differentiating link. It has been established that the transient response of the developed current transducer has an aperiodic character when a surge primary current is fed to its input, and with a relatively very large value of the time constant of the secondary circuit compared to the time constant of the magnetic circuit, transient response approaches transient response of a real differentiating link.*

***Keywords:** remote current transformer, multi-turn core, compensating capacitor, parametric structural scheme, dynamic response, transient response, physical-technical effect, surge current, linearly increasing current, sinusoidal current, sinusoidal current with damped amplitude.*

***Аннотация:** Ишда киришларига импулсли, чизиқли ошиб борувчи, синусоидал ва сўнўвчи амплитудага эга синусоидал ташқи таъсирлар берилганда компенсацияловчи конденсатори бўлмаган янги масофавий трансформаторли ток ўзгартиргичи ўтиш характеристикаларининг аналитик тенгламалари олинган. Ишлаб чиқилган ток ўзгартиргичи назорат ва бошқарув тизимларининг структуравий схемаларида кетма-кет уланган статизмга эга бўлмаган реал дифференциал ва биринчи тартибли апериодик (инерцион) звенолар кўринишида, магнит ўрамидаги актив йўқотишларнинг ҳисобга олинмагани ва ўзгартгичнинг юкламасиз ишлаш режимида эса – идеал дифференциал звено кўринишида тасвирланиши мумкинлиги кўрсатилган. Ишлаб чиқилган ток ўзгартгичи киришига импулсли бирламчи ток берилганида ўтиш характеристикаси апериодик кўринишда эга бўлиши ва иккиламчи занжирнинг вақт доимийси қийматининг магнит занжирининг вақт доимийси қийматига нисбатан жуда катта бўлганида эса ўтиш характеристикаси реал дифференциал звенонинг ўтиш характеристикасига яқинлашиб бориши аниқланган.*

***Таянч сўзлар:** масофавий ток ўзгартгич, кўп ўрамли ўзак, компенсацияловчи конденсатор, параметрик структуравий схема, динамик характеристика, ўтиш характеристика, физик-техниккавий эффект, импулсли ўзгарувчи ток, чизиқли ошиб борувчи ток, синусоидал ток, сўнўвчи амплитудаси синусоидал ток.*

***Аннотация:** В работе получены аналитические уравнения переходных характеристик нового дистанционного трансформаторного преобразователя тока без компенсирующего конденсатора при подаче на их вход скачкообразного, линейно возрастающего, синусоидального и синусоидального с затухающей амплитудой воздействий. Показано, что разработанный преобразователь тока может представляться в структурных схемах систем контроля и управления в виде последовательно соединенного реального дифференцирующего звена без статизма и инерционного (апериодического) звеня первого порядка, а в случае пренебрежения активными* *потерями в магнитопроводе и при работе преобразователя в режиме холостого хода - в виде идеального дифференцирующего звена. Установлено, что переходная характеристика разработанного преобразователя тока при подачи на его вход скачкообразного первичного тока имеет апериодический характер и при сравнительно большом значении постоянной времени вторичной цепи по сравнению с постоянной времени магнитной цепи переходная характеристика приближается к переходной характеристики реального дифференцирующего звена.*

Ключевые слова: *дистанционный преобразователь тока, многовитковый сердечник, компенсирующий конденсатор, параметрическая структурная схема, динамическая характеристика, переходная характеристика, физико-технический эффект, скачкообразный ток, линейно возрастающий ток, синусоидальный ток, синусоидальный ток с затухающей амплитудой.*

Inroduction

Recently, remote transformer current converters (RTCC) have begun to be widely used to measure large currents of high-voltage electrical equipment, in particular in high-voltage power lines. [1, 2, 3].

RTCC are installed at a safe insulation distance from high-voltage equipment and have a fairly simple design [4].

At the Tashkent State Transport University, a new RTCC has been developed for measuring currents in the wires of a three-phase high-voltage line, a device, the principle of operation and features of which is described in detail in [5,6].

In this article, we research the dynamic characteristics of a new RTCC without a compensating capacitor. As is known [1], a compensating capacitor is used to increase the sensitivity and output power.

Research Methods and the Received Results

Dynamic characteristic of the DCDC, in the general case, is the dependence between the informative parameters of the output and input signals and the time or the dependence of the output signal on the input in the dynamic mode. It is customary to describe the dynamic characteristic of the DCDC, like any measuring transducer, by a differential equation, transfer or complex frequency functions [7].

Analytical expressions of the dynamic characteristics of the developed RTCC in the form of an operator equation can be relatively easily obtained using a parametric structural scheme (PSS), compiled for its dynamic mode [8].

It should be noted that PSS in terms of the methodology for their compilation, transformation and obtaining corresponding equations from them do not fundamentally differ from the structural diagrams widely used in the theory of automatic regulation and control for the analysis and synthesis of automatic systems, but at the same time it has some of its own characteristics. So, if in the structural diagrams the processes occurring in the automatic system are displayed in the form of a set of serially, parallel and mixed-connected standard links, then in the PSS of the converter, a further decomposition of the standard links is carried out to the parameters of resistance, inductance, capacitance and their corresponding inverse parameters of conductivity, deduction, and the rigidity of chains of different physical nature, as well as to physical effects and phenomena (the so-called physical and technical effects (PTE)) within a chain of one physical nature and between two chains of different physical nature. Such a decomposition, firstly, allows in more detail, before an elementary transformation, to reflect the processes occurring in the converter, in its PSS, and secondly, it allows revealing all possible influences of internal and external disturbances on the parameters and coefficients of intrachain and interchain PTEs, and in thirds, makes it relatively easy to obtain analytical expressions for the study of static, dynamic and metrological characteristics of the converter [8,9,10].

Therefore, a very important advantage of PSS in comparison with conventional structural schemes is their physical clarity, which gives a clearer, more detailed understanding of the processes occurring in converter under study [11].

Since the sequence of compiling the PSS of the measuring transducers is detailed in the scientific works of Zaripova M.F. [8], devoted to the energy-informational model of circuits of various nature and the apparatus of the PSS, we will here restrict ourselves to the presentation of the compiled PSS developed by the RTCC for the study of its dynamic characteristics (Fig. 1).

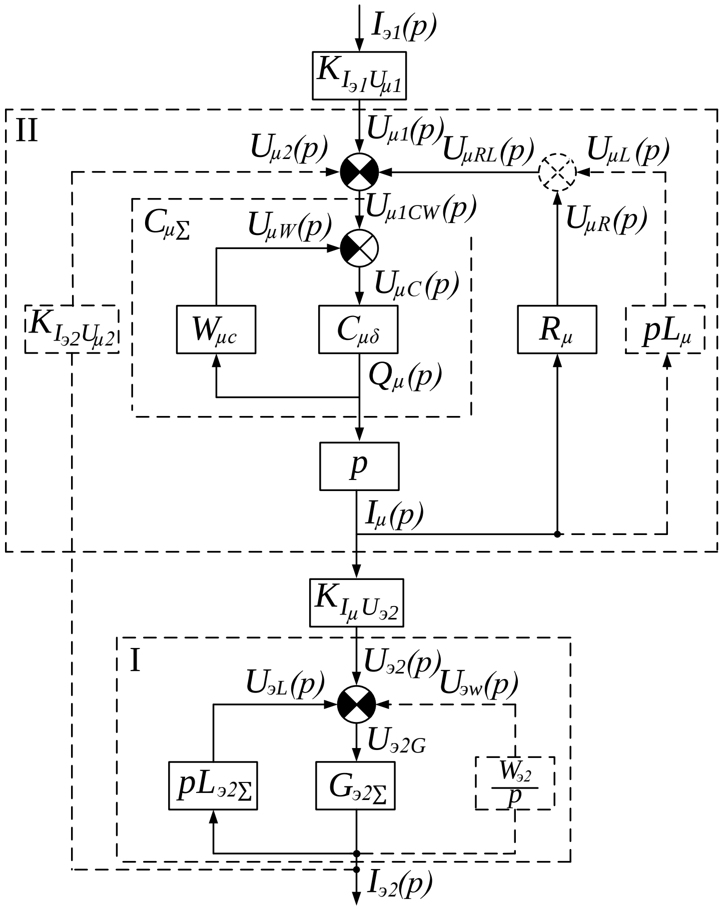


Fig. 1. ***Parametric structural scheme of the developed RTCC to determine its dynamic characteristics.***

In the PSS of the investigated RTCC, the following PTEs and parameters are involved: 1) inter-circuit PTE between the converted electric current $I_{э1}$ and the magnetic voltage $U_{\mu 1}$ with the conversion coefficient $K_{I_{э1}U_{\mu 1}} = w_1$, where $w_1 = 1$ is the number of turns of the primary winding (in our case, the bus with the convertible current), [-]; 2) in-circuit PTE for converting the magnetic voltage $U_{\mu 1C}$ into the magnetic flux $Q_{\mu 1}$ – the parameter of the magnetic capacity $C_{\mu 1\delta}$ of the air gap on the path of the working magnetic flux $Q_{\mu 1}$ of the magnetic circuit, where $C_{\mu 1\delta} = \frac{\delta}{\mu_0 S_\mu}, [H]$; S_μ, δ are respectively the cross-sectional area and the length of the air gap in the path of the working magnetic flux, $[m^2]$; $[m]$; $\mu_0 = 4\pi \cdot 10^{-7}\ \frac{H}{m}$ is magnetic constant; 3) in-chain PTE for converting magnetic flux $Q_{\mu 1}$ into magnetic voltage $U_{\mu 1C}$ is parameter of magnetic rigidity of $W_{\mu\text{ст}}$ steel part of the magnetic circuit on the path of the working magnetic flux $Q_{\mu 1}$, where $W_{\mu\text{ст}} = \frac{l_{\mu\text{ст.}}}{\mu\mu_0 S_{\mu\text{ст.}}}, [1/H]$; $S_{\mu\text{ст.}}$, $l_{\mu\text{ст.}}$ are respectively the cross-sectional area and the length of the steel part (multi-turn core) of the magnetic circuit in the path of the working magnetic flux, $[m^2]$; $[m]$; 4) intrachain PTE for converting magnetic current I_μ into magnetic voltage $U_{\mu 1R}$ is parameter of active magnetic resistance R_μ of the steel part (multi-turn core) of the magnetic circuit on the path of the working magnetic flux $Q_{\mu 1}$, where $R_\mu = G_{\text{э.вихр.}}$, $G_{\text{э.вихр.}}$ are electrical conductivity of the steel part of the magnetic circuit in the path of eddy currents, $[S]$; 5) in-circuit PTE for converting the rate of change of the magnetic current тока I'_μ into the magnetic voltage $U_{\mu 1L}$ is the parameter of the magnetic inductance L_μ of the steel part (multi-turn core) of the magnetic circuit on the path of the working magnetic flux $Q_{\mu 1}$, where $L_{\mu} = C_{\text{э.вихр.}}$, $C_{\text{э.вихр.}}$ is electrical capacity of the multi-turn core on the path of eddy currents, $[F]$; 6) inter-circuit PFC of ampere turns between the electric current $I_{\text{э}2}$ and the magnetic voltage $U_{\mu 2}$ of the RTCC secondary circuit with the conversion coefficient $K_{I_{\text{э}2}U_{\mu 2}} = w_2$, where w_2 is the number of turns of the secondary measuring winding, [-]; 7) intra-circuit PTE for converting electric voltage $U_{\text{э}2G}$ into electric current $I_{\text{э}2}$ of the secondary circuit RTCC – parameter of electrical conductivity $G_{\text{э}2\sum}$, where $G_{\text{э}2\sum}$ is the total electrical conductivity of the secondary circuit (secondary winding and load), $[S]$; 8) intra-circuit PTE for converting the rate of change of electric current $I'_{\text{э}2}$ into electric voltage $U_{\text{э}2L}$ – parameter of electrical inductance $L_{\text{э}2}$, where $L_{\text{э}2\sum} = (L_{\text{э}2} + L_{\text{э}2\text{н}})$, $L_{\text{э}2}$, $L_{\text{э}2\text{н}}$ is electric inductance, respectively, of the secondary circuit, measuring winding and RTCC loads, $[H]$; $C_{\mu 2\sum}$ is total magnetic capacity of the secondary magnetic circuit, $[H]$; 9) parameter of electrical rigidity $W_{\text{э}2}$, $[F^{-1}]$, where $W_{\text{э}2}$ is interturn electric rigidity of the measuring winding; p is a complex variable (operator).

Let us write a system of equations according to the PSS that describes the dynamic mode of operation of the developed RTCC. To facilitate the compilation of equations for the PSS of the converter, we will divide it into two (I-II) sections. In order to simplify the study of the dynamic characteristics of RTCC in the first approximation, we can neglect the magnetic inductance (electrical capacitance in the path of eddy currents in the magnetic circuit) L_{μ} of the magnetic circuit, the interturn electrical rigidity $W_{\text{э}2}$ and the demagnetizing effect of the secondary magnetic field on the magnetic field of the converted RTCC current due to their smallness. values (in the PSS, these branches with the PTE coefficient and parameters are shown by dashed lines) [12, 13].

Let us obtain the operator equation for the secondary circuit current for the case when there is no compensating capacitor and the load has an active-inductive character.

For the I section of the PSS, the following equations are valid:

$$I_{\text{э}2}(p) = G_{\text{э}2\sum}\ U_{\text{э}2G}(p), \tag{1}$$

$$U_{\text{э}2G}(p) = U_{\text{э}2}(p) - U_{\text{э}2L}(p), \tag{2}$$

$$U_{\text{э}2L}(p) = pL_{\text{э}2\sum} I_{\text{э}2}(p), \tag{3}$$

Substituting (3) into (2), and then (2) into (1), after simple transformations we have the following expression:

$$I_{\text{э}2}(p) = \frac{G_{\text{э}2\sum} U_{\text{э}2}(p)}{1 + G_{\text{э}2\sum} L_{\text{э}2\sum} p}. \tag{4}$$

According to the PSS for the electric voltage at the ends of the measuring (secondary) winding of the RTCC, we have the following equation:

$$U_{\text{э}2}(p) = K_{I_{\mu}U_{\text{э}2}} I_{\mu}(p). \tag{5}$$

According to the II section of the PSS, the following equations can be written:

$$I_{\mu}(p) = pQ_{\mu 1}(p), \tag{6}$$

$$Q_{\mu 1}(p) = pC_{\mu 1\delta} U_{\mu 1C}(p), \tag{7}$$

$$U_{\mu 1C}(p) = U_{\mu 1CW}(p) - U_{\mu 1W}(p), \tag{8}$$

$$U_{\mu 1W}(p) = W_{\mu\text{ст}} Q_{\mu 1}(p), \tag{9}$$

$$U_{\mu 1CW}(p) = U_{\mu 1}(p) - U_{\mu R}(p), \tag{10}$$

$$U_{\mu R}(p) = R_{\mu} I_{\mu}(p). \tag{11}$$

Substituting equation (9) into (8), and then (8) into equation (7), we obtain the following equation:

$$Q_{\mu 1}(p) = \frac{C_{\mu 1\delta}}{1 + W_{\mu\text{ст}} C_{\mu 1\delta}} U_{\mu 1CW}(p) = C_{\mu 1\sum} U_{\mu 1CW}(p), \tag{12}$$

where $C_{\mu 1\sum} = \frac{C_{\mu 1\delta}}{1 + W_{\mu\text{ст}} C_{\mu 1\delta}}$.

Taking into account equations (10), (11), and (12), equation (6) takes the following form:

$$I_{\mu}(p) = \frac{pC_{\mu 1\Sigma}}{1+R_{\mu}C_{\mu 1\Sigma}p}U_{\mu 1}(p). \tag{13}$$

From the PSS we have the following:

$$U_{\mu 1}(p) = K_{I_{\text{э}1}U_{\mu 1}}I_{\text{э}1}(p). \tag{14}$$

Substituting (14) into (13), the resulting equation into (5), and the result into equation (4), we finally have:

$$I_{\text{э}2}(p) = \frac{pG_{\text{э}2\Sigma}C_{\mu 1\Sigma}K_{I_{\text{э}1}U_{\mu 1}}K_{I_{\mu}U_{\text{э}2}}}{(1+G_{\text{э}2\Sigma}L_{\text{э}2\Sigma}p)(1+R_{\mu}C_{\mu 1\Sigma}p)}I_{\text{э}1}(p). \tag{15}$$

Expression (15) is a mathematical model of the dynamic mode developed by the RTCC with a load, but without a compensating capacitor.

Let us rewrite (15) in the following, more convenient for analysis, form:

$$I_{\text{э}2}(p) = \frac{pT_{\text{э}12}}{(1+T_{\text{э}2}p)(1+T_{\mu}p)}I_{\text{э}1}(p) = W_1(p)I_{\text{э}1}(p), \tag{16}$$

where $W_1(p) = \frac{pT_{\text{э}12}}{(1+T_{\text{э}2}p)(1+T_{\mu}p)}$ is transfer function RTCC without compensating capacitor, $[-]$; $T_{\text{э}12} = G_{\text{э}2\Sigma}C_{\mu 1\Sigma}K_{I_{\text{э}1}U_{\mu 1}}K_{I_{\mu}U_{\text{э}2}}$ is time constant of the magnetizing circuit, $[s]$; $M_{\text{э}12} = C_{\mu 1\Sigma}K_{I_{\text{э}1}U_{\mu 1}}K_{I_{\mu}U_{\text{э}2}}$ is mutual inductance between primary and secondary circuits, $[H]$; $T_{\text{э}2} = G_{\text{э}2\Sigma}L_{\text{э}2\Sigma}$ time constant of the RTCC secondary electrical circuit, $[s]$; $T_{\mu} = R_{\mu}C_{\mu 1\Sigma}$ is time constant of the RTCC magnetic circuit, $[s]$.

An analysis of the compiled PSS of RTCC and the form of its transfer function shows that the developed RTCC without a compensating capacitor can be represented in the structural scheme of monitoring and control systems in the form of a series-connected real differentiating link without statism and an inertial (aperiodic) link of the first order. It should be noted that in the case of neglect of active losses in the magnetic circuit ($R_{\mu} = 0$) and when the RTCC operates in no-load mode, the current converter can be represented in structural diagrams in the form of an ideal differentiating link.

As is known [14], in order to study the dynamic properties of elements (links) of control and management systems, the reaction of elements is determined when a step, impulse, linearly increasing and harmonic action is applied to their input. In addition, it should be noted that in the design of RTCC intended for operation in transient modes of high-voltage electrical equipment, it is important to study the RTCC response to sinusoidal current with damped amplitude. In practice, this case occurs very often when a bus with a converted current is broken or disconnected from the network [15]. In connection with the above, in order to study the dynamic properties of the developed RTCC, let us determine its reactions under the above input influences.

1. Connecting the RTCC primary circuit to DC power supply $i_{\text{э}1} = I_{\text{э}10} = const$. Substituting the operator image of the direct current supplied to the primary circuit $I_{\text{э}1}(p) = \frac{I_{\text{э}10}}{p}$ into equation (16), we obtain the following operator equation:

$$I_{\text{э}2}(p) = \frac{T_{\text{э}12}I_{\text{э}10}}{(1+T_{\text{э}2}p)(1+T_{\mu}p)}, \tag{17}$$

The original secondary current found using the inverse Laplace transform [16] has the following form:

$$i_{\text{э}2}(t) = \frac{T_{\text{э}12}I_{\text{э}10}}{T_{\text{э}2}-T_{\mu}}\left(e^{-\frac{t}{T_{\text{э}2}}} - e^{-\frac{t}{T_{\mu}}}\right), \tag{18}$$

Examination of function (18) for an extremum showed that for

$$t_{max} = \frac{T_{\text{э}2}T_{\mu}}{T_{\mu}-T_{\text{э}2}}ln\frac{T_{\text{э}2}}{T_{\mu}} \tag{19}$$

transient current has a maximum value (Fig. 2).

Analysis of the curves of the transient response of the developed RTCC with MVS when a stepwise primary current is supplied to its input, built based on equation (18) (Fig. 2), shows that at $T_{\text{э}2} \gg T_{\mu}$ (in practice, this condition is often fulfilled), the transient response of the RTCC approaches the transient characteristic of a real differentiating link.

2. Connecting the primary circuit of the RTCC to the impulse current source (delta function δ (t)). From the course «Theory of automatic control» it is known [14] that the expression of the impulse transient (weight) characteristic $w(t)$ can be defined as a derivative of the transient characteristic $h(t)$, i.e. $w(t) = h'(t)$. Therefore, there is no need to separately searching the response of the developed RTCC to impulse action.

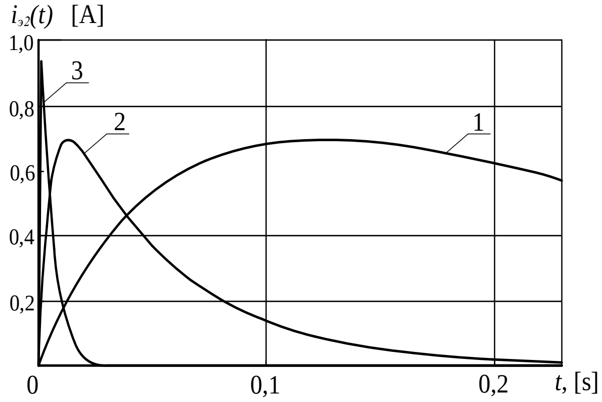


Fig. 2. ***The curves of the transient characteristics of the developed RTCC when a surge current is applied to its input:*** *1 - at* $T_{э2} = 0{,}5\ s$, $T_\mu = 0{,}05\ s$; *2 -* $T_{э2} = 0{,}05\ s$, $T_\mu = 0{,}005\ s$; *3 -* $T_{э2} = 0{,}05\ s$, $T_\mu = 5 \cdot 10^{-5}\ s$.

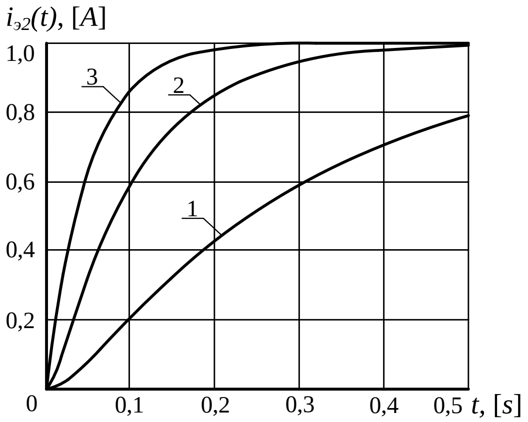


Fig. 3. ***The curves of the transient characteristics of the developed RTCC when a linearly increasing current is applied to its input:*** *at* $T_{э2} = 0{,}05\ s$, $T_\mu = 5 \cdot 10^{-5}\ s$; $T_{э12} = 0{,}004\ s$.

3. Connecting the RTCC primary to a ramp current source $i_{э1} = k_I t$, where k_I *is* aspect coefficient, $[A/s]$.

Substituting the operator image of the linearly increasing current supplied to the primary circuit $I_{э1}(p) = \frac{k_I}{p^2}$. into equation (16), we obtain the following operator equation

$$I_{э2}(p) = \frac{T_{э12}\, k_I}{p(1+T_{э2}p)(1+T_\mu p)}, \tag{20}$$

The original of the last equation found using the decomposition theorem [10] has the following form:

$$i_{э2}(t) = I_{э10}\left[1 + \frac{1}{T_\mu - T_{э2}}\left(T_{э2}e^{-\frac{t}{T_{э2}}} - T_\mu e^{-\frac{t}{T_\mu}}\right)\right], \tag{21}$$

where $I_{э10} = T_{э12}\, k_I$.

Analysis of the obtained transient response equation and its RTCC curves without a compensating capacitor when connected to a linearly increasing current source showed (Fig. 3) that the transient response is aperiodic, and the transient time is mainly determined by the RTCC secondary circuit time constant.

4. Connect the primary circuit of the RTCC to a sinusoidal current source. For this dynamic regime, operator equation (16) takes the following form:

$$I_{э2}(p) = \frac{pT_{э12}\omega I_{э1m}}{(1+T_{э2}p)(1+T_\mu p)(p^2+\omega^2)} = \frac{F_1(p)}{F_2(p)}. \tag{22}$$

The characteristic equation $F_2(p) = 0$ has the following roots: $p_1 = -\frac{1}{T_{э2}}$; $p_1 = -\frac{1}{T_\mu}$; $p_{3,4} = \pm j\ \omega$.

Substituting these roots into the expansion formula [10], we find the original function $I_{э2}(p)$:

$$i_{э2}(t) = \frac{F_1(-\frac{1}{T_{э2}})}{F_2'(-\frac{1}{T_{э2}})} e^{-\frac{t}{T_{э2}}} + \frac{F_1(-\frac{1}{T_\mu})}{F_2'(-\frac{1}{T_\mu})} e^{-\frac{t}{T_\mu}} + \frac{F_1(j\ \omega)}{F_2'(j\ \omega)} e^{j\ \omega t} + \frac{F_1(-j\ \omega)}{F_2'(-j\ \omega)} e^{-j\ \omega t} =$$

$$= a_1(t) + a_2(t) + a_3(t) + a_4(t), \tag{23}$$

$$a_1(t) = -\frac{T_{\text{э}2}T_{\text{э}12}\omega I_{\text{э}1m}}{(T_{\text{э}2}-T_\mu)\left(1+\omega^2T_{\text{э}2}^2\right)}e^{-\frac{t}{T_{\text{э}2}}}, \tag{24}$$

$$a_2(t) = -\frac{T_\mu T_{\text{э}12}\omega I_{\text{э}1m}}{(T_{\text{э}2}-T_\mu)\left(1+\omega^2T_\mu^2\right)}e^{-\frac{t}{T_\mu}}, \tag{25}$$

$$a_3(t) = \frac{T_{\text{э}12}\omega I_{\text{э}1m}}{2\sqrt{\left(1+\omega^2T_{\text{э}2}^2\right)\left(1+\omega^2T_\mu^2\right)}}e^{j(\omega t-\varphi_1)}, \tag{26}$$

$$a_4(t) = \frac{T_{\text{э}12}\omega I_{\text{э}1m}}{2\sqrt{\left(1+\omega^2T_{\text{э}2}^2\right)\left(1+\omega^2T_\mu^2\right)}}e^{-j(\omega t-\varphi_1)}, \tag{27}$$

where $\varphi_1 = arctg(\omega T_{\text{э}2}) + arctg(\omega T_\mu)$.

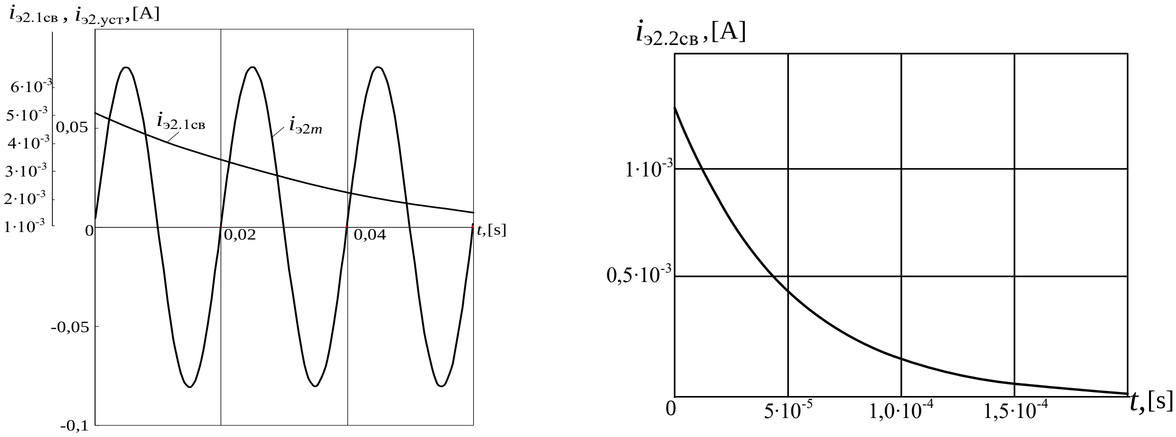
Substituting (24) - (27) into equation (23), after some simple transformations, we finally obtain the following expression of the RTCC transient response in the form of a secondary current:

$$i_{\text{э}2}(t) = \frac{T_{\text{э}12}\omega I_{\text{э}1m}T_{\text{э}2}}{(T_{\text{э}2}-T_\mu)\left(1+\omega^2T_{\text{э}2}^2\right)}e^{-\frac{t}{T_{\text{э}2}}} - \frac{T_{\text{э}12}\omega I_{\text{э}1m}T_\mu}{(T_{\text{э}2}-T_\mu)\left(1+\omega^2T_\mu^2\right)}e^{-\frac{t}{T_\mu}} +$$

$$+\frac{T_{\text{э}12}\omega I_{\text{э}1m}cos(\omega t-\varphi_1)}{\sqrt{\left(1+\omega^2T_{\text{э}2}^2\right)\left(1+\omega^2T_\mu^2\right)}} = I_{\text{э}2.1\text{св.}}e^{-\frac{t}{T_{\text{э}2}}} - I_{\text{э}2.2\text{св.}}e^{-\frac{t}{T_\mu}} + I_{\text{э}2m}cos(\omega t-\varphi_1) =$$

$$= i_{\text{э}2.1\text{св.}}(t) + i_{\text{э}2.2\text{св.}}(t) + i_{\text{э}2.\text{уст.}}(t). \tag{28}$$

Analysis of equation (28) and the curves constructed based on this equation (Fig. 4) shows that when the primary circuit of the RTCC is connected to a sinusoidal current network, the transient current consists of the sum of two free aperiodic, the decrease in the value of which in time is determined by the values of the time constants, respectively, of the secondary and magnetic circuits, and the forced sinusoidal steady-state components.



a) ***b)***

Fig. 4. ***Curves of free with a time constant $T_{\text{э}2}$, steady-state (a) and free with a time constant T_μ (b) components of the transient response of the developed RTCC when a sinusoidal current is applied to its input:*** *at $T_{\text{э}2} = 0,05\ s$, $T_\mu = 5\cdot10^{-5}\ s$; $T_{\text{э}12} = 0,004\ s$.*

5) Connection of the RTCC primary circuit to a sinusoidal current network with damped amplitude $i_{\text{э}1} = I_{\text{э}1}e^{-\frac{t}{T_{\text{э}1}}}sin\omega t$. For this dynamic regime, operator equation (16) takes the following form:

$$I_{\text{э}2}(p) = \frac{pT_{\text{э}12}\omega I_{\text{э}1m}}{(1+T_{\text{э}2}p)(1+T_\mu p)\left[\left(p+\frac{1}{T_{\text{э}1}}\right)^2+\omega^2\right]} = \frac{F_3(p)}{F_4(p)}. \tag{29}$$

The characteristic equation $F_4(p) = 0$ has the following roots: $p_1 = -\frac{1}{T_{\text{э}2}}$; $p_1 = -\frac{1}{T_\mu}$; $p_{3,4} = -\frac{1}{T_{\text{э}1}} \pm j\ \omega$.

Substituting these roots into the expansion formula [16], we find the original function $I_{\text{э}2}(p)$ in the following form:

$$i_{\text{э}2}(t)=\frac{F_3(-\frac{1}{T_{\text{э}2}})}{F_4'(-\frac{1}{T_{\text{э}2}})}e^{-\frac{t}{T_{\text{э}2}}}+\frac{F_3(-\frac{1}{T_\mu})}{F_4'(-\frac{1}{T_\mu})}e^{-\frac{t}{T_\mu}}+$$

$$+\frac{F_3(-\frac{1}{T_{\text{э}1}}+j\,\omega)}{F_4'(-\frac{1}{T_{\text{э}1}}+j\,\omega)}e^{\left(-\frac{1}{T_{\text{э}1}}+j\,\omega\right)t}+\frac{F_3(-\frac{1}{T_{\text{э}1}}-j\,\omega)}{F_4'(-\frac{1}{T_{\text{э}1}}-j\,\omega)}e^{\left(-\frac{1}{T_{\text{э}1}}-j\,\omega\right)t}=$$

$$=b_1(t)+b_2(t)+b_3(t)+b_4(t), \tag{30}$$

$$b_1(t)=-\frac{T_{\text{э}1}^2T_{\text{э}12}T_{\text{э}2}\omega I_{\text{э}1m}}{(T_{\text{э}2}-T_\mu)\left[(T_{\text{э}1}-T_{\text{э}2})^2+\omega^2T_{\text{э}1}^2T_{\text{э}2}^2\right]}e^{-\frac{t}{T_{\text{э}2}}}, \tag{31}$$

$$b_2(t)=\frac{T_{\text{э}1}^2T_\mu T_{\text{э}12}\omega I_{\text{э}1m}}{(T_{\text{э}2}-T_\mu)\left[\left(T_{\text{э}1}-T_\mu\right)^2+\omega^2T_{\text{э}1}^2T_\mu^2\right]}e^{-\frac{t}{T_\mu}}, \tag{32}$$

$$b_3(t)=\frac{T_{\text{э}12}I_{\text{э}1m}T_{\text{э}1}\sqrt{\left(1+\omega^2T_{\text{э}1}^2\right)e^{-\frac{t}{T_{\text{э}1}}}}}{2\sqrt{M^2+N^2}}e^{j[\omega t+90^0+\varphi_2(\omega)]}, \tag{33}$$

$$b_4(t)=\frac{T_{\text{э}12}I_{\text{э}1m}T_{\text{э}1}\sqrt{\left(1+\omega^2T_{\text{э}1}^2\right)e^{-\frac{t}{T_{\text{э}1}}}}}{2\sqrt{M^2+N^2}}e^{-j[\omega t+90^0+\varphi_2(\omega)]}, \tag{34}$$

where $M=T_{\text{э}1}^2\left(1-\omega^2T_{\text{э}2}T_\mu\right)-T_{\text{э}1}\left(T_{\text{э}2}+T_\mu\right)+T_{\text{э}2}T_\mu,[s^2];$ $N=\omega\left[T_{\text{э}1}^2\left(T_{\text{э}2}+T_\mu\right)\right]-$ $-2T_{\text{э}1}T_{\text{э}2}T_\mu,[s^2];$ $\varphi_2=arctg(N/M)-arctg(\omega T_{\text{э}1}),[degri].$

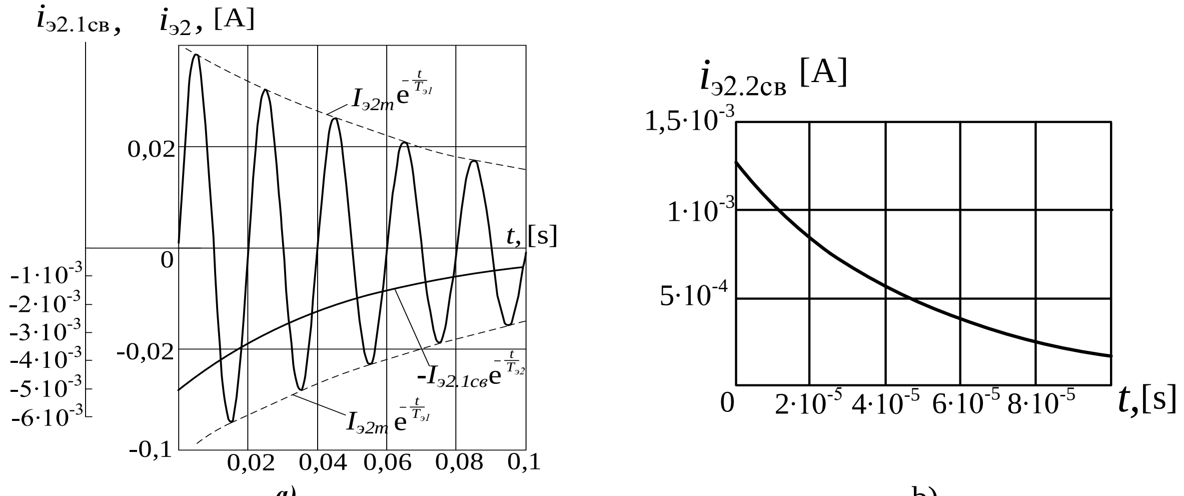
Substituting (31) - (34) into equation (30), after some simple transformations, we finally obtain the following expression of the RTCC transient response in the form of a secondary current:

$$i_{\text{э}2}(t)=-I_{\text{э}2.1\text{св.}}e^{-\frac{t}{T_{\text{э}2}}}+I_{\text{э}2.2\text{св.}}e^{-\frac{t}{T_\mu}}+I_{\text{э}2m.}e^{-\frac{t}{T_{\text{э}1}}}sin(\omega t+\varphi_2)=$$

$$=i_{\text{э}2.1\text{св.}}(t)+i_{\text{э}2.2\text{св.}}(t)+i_{\text{э}2}(t) \tag{35}$$

$$I_{\text{э}2.1\text{св.}}=\frac{T_{\text{э}1}^2T_{\text{э}2}T_{\text{э}12}\omega I_{\text{э}1m}}{(T_{\text{э}2}-T_\mu)\left[(T_{\text{э}1}-T_{\text{э}2})^2+\omega^2T_{\text{э}1}^2T_{\text{э}2}^2\right]},[A];\; I_{\text{э}2.2\text{св.}}=\frac{T_{\text{э}1}^2T_\mu T_{\text{э}12}\omega I_{\text{э}1m}}{(T_{\text{э}2}-T_\mu)\left[\left(T_{\text{э}1}-T_\mu\right)^2+\omega^2T_{\text{э}1}^2T_\mu^2\right]},[A];$$

$$I_{\text{э}2m.}=\frac{T_{\text{э}12}I_{\text{э}1m}T_{\text{э}1}\sqrt{\left(1+\omega^2T_{\text{э}1}^2\right)}}{2\sqrt{M^2(\omega)+N^2(\omega)}},[A].$$



a) b)

Fig. 5. ***Curves of the components of the transient response of the developed RTCC when a sinusoidal current with time constants is applied to its input $T_{\text{э}2}$, $T_{\text{э}1}$ (a) and T_μ (b):***

at $T_{\text{э}1}=0{,}1\ s$; $T_{\text{э}2}=0{,}05\ s$, $T_\mu=5\cdot10^{-5}\ s$; $T_{\text{э}12}=0{,}004\ s$.

Analysis of equation (36) and curves constructed on its basis (Fig. 5), shows that when the primary circuit of the RTCC is connected to a sinusoidal current network with damped amplitude, the transient current consists of the sum of two free aperiodic components and one forced sinusoidal damped component.

Conclusion

Therefore, in the article, analytical equations of the transient characteristics of a new remote transformer current converter without a compensating capacitor are obtained when applying to their input a stepped, linearly increasing, sinusoidal and sinusoidal with a damped amplitude of influences. It is shown that the developed current converter can be represented in the structural schemes of monitoring and control systems in the form of a series-connected real differentiating link without statism and inertial (aperiodic) link of the first order, and in the case of neglecting active losses in the magnetic circuit and when the converter is operating in idle mode as an ideal differentiating link

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