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Dynamic characteristics of new remote transformer current transducers with compensating capacitor

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ABSTRACT: in this article, analytical equations for the transient characteristics of a new remote transformer current transducer with a compensating capacitor when applying to its input an abrupt, linearly increasing, sinusoidal and sinusoidal with damped amplitude of influences have been obtained. It is shown that the developed current transducer can be represented in the structural diagrams of monitoring and control systems in the form of a series-connected ideal differentiating link, a real differentiating link without statism and a second-order inertial link, and in the case of neglecting active losses in the magnetic circuit, in the form of a series-connected ideal differentiating and vibrational links. It has been established that for the case of connecting the primary circuit of the current transducer to a sinusoidal current network with a damped amplitude, it shows that at $> \omega_0$ (where δ is the damping coefficient and $\omega_0$is the natural angular frequency of the secondary circuit), the transient current of the secondary circuit consists of the sum of two free aperiodic and forced damped sinusoidal components, at $\delta = \omega_0$ consists of one free aperiodic and forced damped sinusoidal components, and at $\delta < \omega_0$one free and one forced damped sinusoidal components, the degree of damping of which depends on the time constants of the secondary and primary circuits of the current transducer, respectively.

KEY WORDS: remote current transducer, multi-turn core, compensating capacitor, parametric structural diagram, dynamic characteristic, transient characteristic, physical-technical effect, hopping current, linearly increasing current, sinusoidal current, sinusoidal current with damped amplitude.

RELATED WORK: The article covers the dynamic characteristics of a new remote transformer current transducers, the magnetic circuit of which is made in the form of a multi-turn core, which leads to an increase in sensitivity, and using three identical current converters, remotely installed to measure currents of all three phases with connected measuring windings in an open delta circuit, expands the functional device capabilities.

Transducers of this type were first studied in detail in the work of V.E. Kazanskiy, namely current measuring transducers in relay protection. But transducers of this type had a number of disadvantages, such as low output power, low sensitivity, large dimensions and high cost. Author V.S. Kovzhenkin, in his work on the study of distance current transformers in relation to relay protection of 110-220 kV lines, proposed a new design of a remote transformer transducer having a higher measurement accuracy than previously known, but the author did not succeed in reducing the size, and therefore the cost of the transducer.

I.INTRODUCTION

In recent years, to measure large currents of high-voltage electrical equipment, in particular for converting currents in high-voltage power lines, remote transformer current transducers (RTCT) have begun to be widely used [1, 2, 3].

A new RTCT has been developed for measuring currents in the wires of a three-phase high-voltage line at Tashkent State Transport University, installation, the principle of operation and features of which is detailed described in [5, 6].

In this article, we research the dynamic characteristics of a new RTCT with a compensating capacitor (CC). As is known [7, 8], CC is used to increase the sensitivity and output power of the RTCT.

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Vol. 8, Issue 7 , July 2021

The dynamic characteristic of the RTCT, in the general case, is the relationship between the informative parameters of the output and input signals and the time or the dependence of the output signal on the input signal in a dynamic mode. It is appropriate to describe the dynamic characteristic of a RTCT, like any measuring transducer, by a differential equation, transfer or complex frequency functions [9].

II. MAIN PART

Analytical expressions of the dynamic characteristics of developed RTCT with CC in the form of operator equation can be relatively easily obtained using a parametric structural scheme (PSS), compiled for its dynamic mode [10].

Note that the PSS in terms of the methodology for their compilation, transformation and obtaining the corresponding equations from them do not fundamentally differ from the structural schemes 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 schemes 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 transducer, 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, till the elementary transformation, reflecting in the PSS the processes occurring in the transducer, and secondly, it allows revealing all possible influences of internal and external disturbances on the parameters and coefficients of intrachain and interchain PTEs, and thirdly, it allows relatively easily obtaining analytical expressions for studying the static, dynamic and metrological characteristics of the transducer [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 the investigated transducer [11, 12].

Since the sequence of compiling the PSS of the measuring transducers is detailed in the scientific works of prof. Zaripova M.F., in particular in [10], devoted to the energy-informational model of circuits of various nature and the apparatus of the PSS, then here we restrict ourselves to the presentation of the compiled PSS of the developed RTCT with CC to study its dynamic characteristics (Fig. 1). The following physical and technical interchain effects (PTE) and parameters are involved in the PSS of RTCT with CC under study:1) inter-circuit PTE between the being converted electric current $I_{э1}$and the magnetic voltage$U_{\mu1}$with the conversion coefficient $K_{I_{э1}U_{\mu1}} = w_1$, where$w_1 = 1$isthe number of turns of the primary winding of the RTCT (in our case, the bus with the converted current, $[-]$; 2) intra-circuit FTE for converting magnetic voltage $U_{\mu1C}$ into magnetic flux $Q_{\mu1}$ is the parameter of the magnetic capacitance $C_{\mu1\delta}$of the air gap on the path of the working magnetic flux $Q_{\mu1}$of the magnetic circuit, where$C_{\mu1\delta} = \frac{\delta}{\mu_0 S_\mu}, [H]$; S_μ, $\delta$are respectively the cross-sectional area and the length of the air gap in the path of the working magnetic flux, $[m^2]$; $[m]$; $\mu_0 = 4\pi \cdot 10^{-7}, \left[\frac{H}{m}\right]$ is magnetic constant; 3) in-chain PTE for converting magnetic flux$Q_{\mu1}$into magnetic voltage $U_{\mu1C}$is parameter of magnetic rigidity$W_{\mu ст}$of the steel part of the magnetic circuit on the path of the working magnetic flux$Q_{\mu1}$, where$W_{\mu ст} = \frac{l_{\mu ст.}}{\mu\mu_0 S_{\mu ст.}}, [1/H]$; $S_{ст.}$, $l_{\mu ст.}$arerespectively the cross-sectional area and length of the ferromagnetic multiturn core (FMC) in the path of the working magnetic flux$[m^2]$; $[m]$; 4) in-circuit PTE for converting magnetic current $I_\mu$into magnetic voltage $U_{\mu1R}$is parameter of active magnetic resistanceR_μFMCon the path of the working magnetic flux $Q_{\mu1}$, where$R_\mu = G_{э.вихр.}$, $G_{э.вихр.}$are the electrical conductivity of FMC on the way of eddy currents, $[S]$; 5) in-circuit PTE for converting the rate of change of the magnetic currentI'_μinto the magnetic voltage $U_{\mu1L}$isthe parameter of the magnetic inductance $L_\mu$of the steel part (FMC) of the magnetic circuit on the path of the working magnetic flux$Q_{\mu1}$, where$L_\mu = C_{э.вихр.}$, $C_{э.вихр.}$arethe electrical capacity of the MVS on the path of eddy currents, $[F]$; 6) inter-circuit PFC of ampere-turns between electric current $I_{э2}$and magnetic voltage$U_{\mu2}$of the secondary circuit of RTCT with conversion factor$K_{I_{э2}U_{\mu2}} = w_2$, where$w_2$is number of turns of the secondary measuring winding, $[-]$;

ISSN: 2350-0328
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Vol. 8, Issue 7 , July 2021

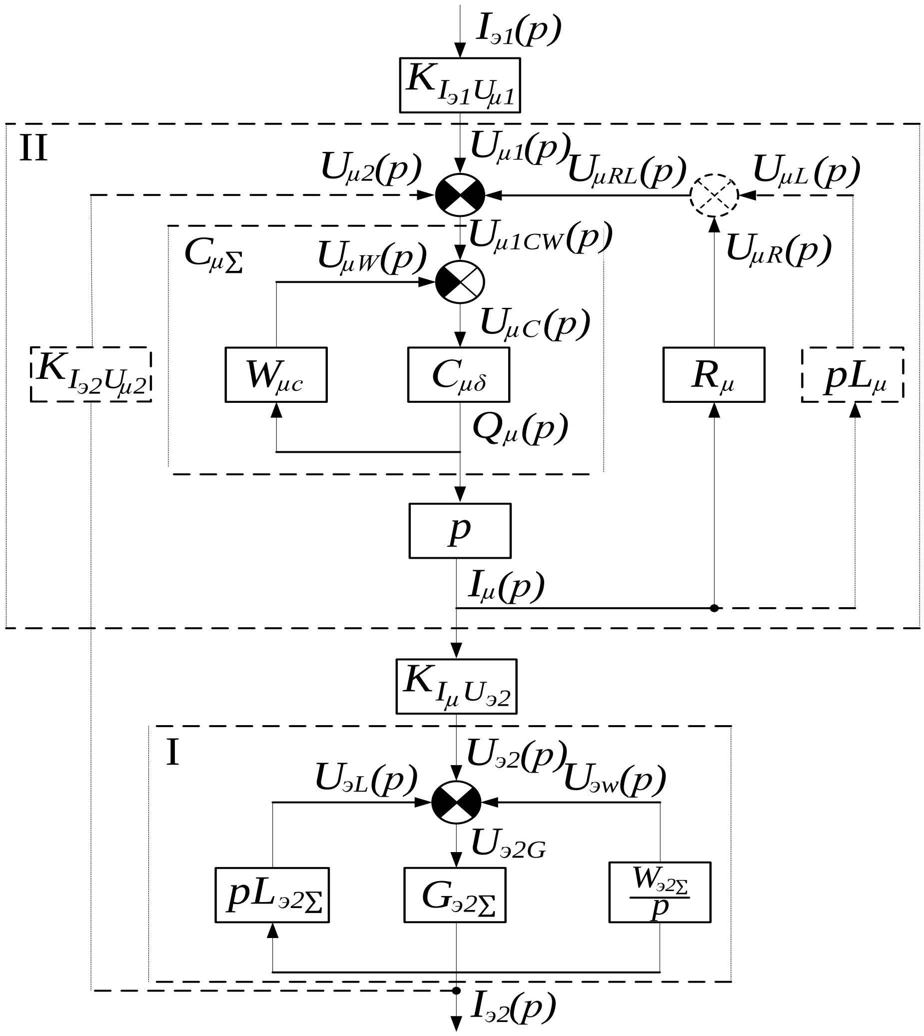

Fig. 1. Parametric structural scheme of the developed RTCT to determine its dynamic characteristics

6) inter-circuit PFC of electromagnetic induction between the magnetic current I_μ nd the electric voltage of the secondary circuit of RTCT $U_{\text{э}2}$ with the conversion coefficient $K_{I_\mu U_{\text{э}2}} = w_2$, where w_2 is the number of turns of the secondary measuring winding, $[-]$; 7) in-circuit PTE for converting electric voltage $U_{\text{э}2G}$ into electric current $I_{\text{э}2}$ of the secondary circuit RTCT – the parameter of electrical conductivity $G_{\text{э}2\Sigma}$, where $G_{\text{э}2\Sigma}$ 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 $U_{\text{э}2L}$ is parameter of electrical inductance $L_{\text{э}2}$, where $L_{\text{э}2\Sigma} = (L_{\text{э}2} + L_{\text{э}2\text{н}})$, $L_{\text{э}2}$, $L_{\text{э}2\text{н}}$ are electric inductance, respectively, of the secondary circuit, measuring winding and RTCT loads, $[H]$; $C_{\mu 2\Sigma}$ is the total magnetic capacity of the secondary magnetic circuit, $[H]$; 9) intrachain PTE for converting electric charge $Q_{\text{э}2}$ into electric voltage $U_{\text{э}2W}$ is parameter of electrical rigidity $W_{\text{э}2\Sigma} = W_{\text{э}2} + W_{\text{э}2\text{к}}$, $[F^{-1}]$, where $W_{\text{э}2}$ is the turn-to-turn electric rigidity of the measuring winding, $W_{\text{э}2\text{к}} = \frac{1}{C_{\text{э}2\text{к}}}$ is electric inductance, respectively, of the secondary circuit, measuring winding and RTCT loads; p is a complex variable (operator).

Let us write a system of equations according to the PSS, which describes the dynamic mode of operation of the developed RTCT with CC. To facilitate the drawing up of equations for the PSS of the transducer, we will divide it into two (I-II) sections. In order to simplify the study of the dynamic characteristics of RTCT with CC, in the first approximation, we can neglect the magnetic inductance (electrical capacitance on the path of eddy currents in the magnetic circuit) L_μ of the magnetic circuit, the interturn electric rigidity $W_{\text{э}2}$ and the demagnetizing effect of the

ISSN: 2350-0328
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Vol. 8, Issue 7 , July 2021

secondary magnetic field on the magnetic field of the converted current RTCT with CC from - due to the smallness of their values (in the PSS, these branches with the PTE coefficient and parameters are shown by dashed lines) [13].

Let us obtain the operator equation for the secondary circuit current for the case when the CC is connected in series with the load in the secondary circuit.

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

$$I_{э2}(p) = G_{э2\sum} U_{э2G}(p), \tag{1}$$
$$U_{э2G}(p) = U_{э2}(p) - U_{э2L}(p) - U_{э2W}(p), \tag{2}$$
$$U_{э2L}(p) = pL_{э2\sum} I_{э2}(p), \tag{3}$$
$$U_{э2W}(p) = \frac{W_{э2к}}{p} I_{э2}(p). \tag{4}$$

Substituting (3) and (4) in (2), and then (2) in (1), after simple transformations, we have the following expression:

$$I_{э2}(p) = \frac{pC_{э2\sum} U_{э2}(p)}{(L_{э2\sum} C_{э2\sum} p^2 + R_{э2\sum} C_{э2\sum} p + 1)}. \tag{5}$$

According to the PSS for the electric voltage at the ends of the measuring (secondary) winding of the RTCT, we have the following equation [14]:

$$U_{э2}(p) = K_{I_\mu U_{э2}} I_\mu(p). \tag{6}$$

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

$$I_\mu(p) = pQ_{\mu 1}(p), \tag{7}$$
$$Q_{\mu 1}(p) = pC_{\mu 1\delta} U_{\mu 1C}(p), \tag{8}$$
$$U_{\mu 1C}(p) = U_{\mu 1CW}(p) - U_{\mu 1W}(p), \tag{9}$$
$$U_{\mu 1W}(p) = W_{\mu ст} Q_{\mu 1}(p), \tag{10}$$
$$U_{\mu 1CW}(p) = U_{\mu 1}(p) - U_{\mu R}(p), \tag{11}$$
$$U_{\mu R}(p) = R_\mu I_\mu(p). \tag{12}$$

Substituting equation (10) into (9), and then (9) into equation (8), we obtain the following equation:

$$Q_{\mu 1}(p) = \frac{C_{\mu 1\delta}}{1 + W_{\mu ст} C_{\mu 1\delta}} U_{\mu 1CW}(p) = C_{\mu 1\sum} U_{\mu 1CW}(p), \tag{13}$$

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

Taking into account equations (11), (12) and (13), equation (7) takes the following form:

$$I_\mu(p) = \frac{pC_{\mu 1\sum}}{1+R_\mu C_{\mu 1\sum} p} U_{\mu 1}(p). \tag{14}$$

From PSS we have the following:

$$U_{\mu 1}(p) = K_{I_{э1} U_{\mu 1}} I_{э1}(p). \tag{15}$$

Substituting (15) into (14), the resulting equation into (6), and the result into equation (5), we have:

$$I_{э2}(p) = \frac{p^2 K}{(L_{э2\sum} C_{э2\sum} p^2 + R_{э2\sum} C_{э2\sum} p + 1)(1 + R_\mu C_{\mu 1\sum} p)} I_{э1}(p) = W_2(p) I_{э1}(p). \tag{16}$$

here $W_2(p)$, $[-]$ is transfer function RTCT with CC; $K = C_{э2\sum} M_{э12}, [s^2]$.

Expression (16) is a mathematical model of the dynamic mode of the developed RTCT with a series connection of a compensating capacitor with a load.

Analysis of the compiled RTCT with CC and its transfer function shows that the developed RTCT with CC can be represented in the structural schemes of monitoring and control systems in the form of a series-connected one ideal differentiating link, one real differentiating link without statism and a second-order inertial link. It should be noted that in the case of neglecting active losses in the magnetic circuit ($R_\mu = 0$), the current transducer can be represented in structural schemes in the form of a series-connected ideal differentiating and oscillatory links.

An analysis of the operation of the developed RTCT with CC shows that the time constant of the magnetic circuit $T_\mu = R_\mu C_{\mu 1\sum}$ is approximately two to three orders of magnitude less than the time constant of the secondary circuit of the RTCT with CC. Therefore, the time constant T_μ in the first approximation can be neglected.

Then the operator equation (3.36) takes the following form:

ISSN: 2350-0328

International Journal of Advanced Research in Science, Engineering and Technology

Vol. 8, Issue 7 , July 2021

$$I_{э2}(p) = \frac{p^2 K}{(L_{э2\sum} C_{э2\sum} p^2 + R_{э2\sum} C_{э2\sum} p + 1)} I_{э1}(p). \qquad (17)$$

Thereby, using the PSS method, an operator equation was obtained for investigating the dynamic properties of the developed RTCT with a CC connected to the secondary circuit. It is necessary to obtain transient, pulse transient, frequency and amplitude-phase frequency characteristics of the developed RTCT with CC.

As is known [12], in order to study the dynamic properties of elements (links) of control and management systems, their response is determined when stepped, impulse, linearly increasing and harmonic influences are applied to their input. In addition, it should be noted that when designing RTCTs intended for operation in transient modes of high-voltage electrical equipment, it is important to study the RTCT response to a sinusoidal current with damped amplitude [15]. In order to study the dynamic properties of the developed RTCT with CC, let us determine its reactions under the above input influences.

1. Connection of the RTCT primary circuit to the DC power source $i_{э1} = I_{э10} = const$. Taking into account $I_{э1}(p) = \frac{I_{э10}}{p}$, operator equation (17) takes the following form:

$$I_{э2}(p) = \frac{pKI_{э10}}{(L_{э2\sum} C_{э2\sum} p^2 + R_{э2\sum} C_{э2\sum} p + 1)} = \frac{pK\omega_0^2 I_{э10}}{p^2 + 2\delta p + \omega_0^2} = \frac{F_1(p)}{F_2(p)}, \qquad (18)$$

here $2\delta = \frac{R_{э2\sum}}{L_{э2\sum}}, [s^{-1}]$; $\omega_0^2 = \frac{1}{L_{э2\sum} C_{э2\sum}}, [s^{-2}]$.

The characteristic equation $F_2(p) = p^2 + 2\delta p + \omega_0^2 = 0$, as is known [16], has the following roots:

$$p_{1,2} = -\delta \pm \sqrt{\delta^2 - \omega_0^2}, \qquad (19)$$

The nature of the transient processes will be significantly different depending on whether the roots (19) are real and complex, which are determined by the following different relations between δ and ω_0: 1) $\delta > \omega_0$; 2) $\delta = \omega_0$; 3) $\delta < \omega_0$ [16].

Let us examine these three cases.

a) let $\delta > \omega_0$, i.e. the roots of the characteristic equation are real and unequal to each other.

The original of the operator transient current according to (18), found using the expansion theorem [16], has the following form:

$$i_{э2}(t) = \frac{KI_{э10}\omega_0^2}{2\sqrt{\delta^2 - \omega_0^2}} \left[\left(\sqrt{\delta^2 - \omega_0^2} - \delta \right) e^{-\left(\delta - \sqrt{\delta^2 - \omega_0^2}\right)t} + \right.$$
$$\left. + \left(\sqrt{\delta^2 - \omega_0^2} + \delta \right) e^{-\left(\delta + \sqrt{\delta^2 - \omega_0^2}\right)t} \right]. \qquad (20)$$

From the transient current characteristic (Fig. 2, a), built based on (20), it can be seen that the transient process has an aperiodic character and, at a certain time value, the transient current graph has a maximum value.

Examining the current function $i_{э2}(t)$ according to (20) for an extremum, we find the following time value at which the current has a maximum value:

$$t_{max} = \frac{1}{2\sqrt{\delta^2 - \omega_0^2}} ln \frac{\delta - \sqrt{\delta^2 - \omega_0^2}}{\delta + \sqrt{\delta^2 - \omega_0^2}}. \qquad (21)$$

b) let $\delta = \omega_0$, i.e. the roots of the characteristic equation are real and equal to each other. As is known [16], for this case the expression of the original of the transient current becomes undefined due to the equality of both the numerator and the denominator to zero. Using L'Hôpital's rule [17], we obtain the following expression for the original transient current

$$i_{э2}(t) = KI_{э10}\omega_0^2(1 - \delta t)e^{-\delta t}. \qquad (22)$$

The nature of the transient processes in this case does not qualitatively differ from the case when $\delta > \omega_0$. However, unlike the previous case, the moment the current reaches its maximum value is reduced and is determined by the following expression:

$$t_{max} = \frac{2}{\delta}. \qquad (23)$$

c) now, let $\delta < \omega_0$, i.e. the roots of the characteristic equation are complex and conjugate: $p_{1,2} = -\delta \pm j\omega'_{св}$, where $\omega'_{св} = \sqrt{\omega_0^2 - \delta^2}$ is the angular frequency of free or natural oscillations in the secondary circuit of RTCT with CC, $[s^{-1}]$ [16].

Application of the decomposition theorem allows obtaining the following expression for the original secondary current:

ISSN: 2350-0328
International Journal of Advanced Research in Science, Engineering and Technology
Vol. 8, Issue 7 , July 2021

$$i_{э2}(t) = -\frac{KI_{э10}\omega_0^3}{\omega'_{св}} e^{-\delta t} sin(\omega'_{св}t - \varphi_1), \quad (24)$$

$\varphi_1 = arctg(\omega'_{св}/\delta)$ is the phase angle between voltage and current of the RTCT secondary circuit, $[degri]$.

Analysis of the obtained expressions for the secondary transient current of RTCT with CC$i_{э2}(t)$ (20), (22), (24) and time characteristics (Fig. 2, a), built on the basis of these expressions, showed that when the primary circuit of RTCT is connected with CC to the direct current source and when the condition$\delta > \omega_0$and$\delta = \omega_0$is satisfied, the transient current RTCT has an aperiodic character, at a certain value of time it has a maximum, and as the difference between the damping coefficient (δ) and the natural angular frequency (ω_0) of the secondary circuit tends to zero ($\delta - \omega_0 \geq 0$)the time for the current to reach its maximum value is reduced, and when $\delta < \omega_0$he transient current RTCT has an oscillatory character. In addition, another feature of connecting the primary RTCT circuit with CC to a DC source is that in the moment of switching ($t = 0$) the secondary current has a certain final value $i_{э2}(0)$.

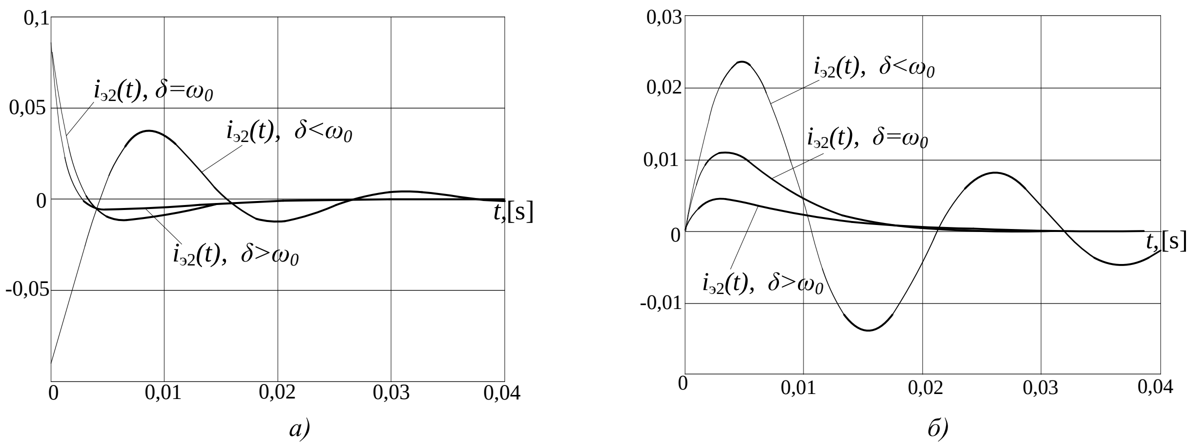


Fig. 2. Curves of the transient response of the developed RTCT with CC when supplying to its input a stepwise constant (a) and linearly increasing (b) currents at $T_{э2} = 0.05\ s$, $T_{э12} = 0.004\ s$.

2. Connecting the primary RTCT circuit to a source of linearly increasing current $i_{э1} = k_I t$, where k_I is the proportionality coefficient, $[A/s]$.Taking into account$I_{э1}(p) = \frac{k_I}{p^2}$operator equation (17) takes the following form:

$$I_{э2}(p) = \frac{Kk_I}{(L_{э2\sum}C_{э2\sum}p^2 + R_{э2\sum}C_{э2\sum}p + 1)} = \frac{Kk_I\omega_0^2}{(p^2 + 2\delta p + \omega_0^2)}. \quad (25)$$

The transition of the last operator expression to its original for the above three types of roots of the characteristic equation and the features of their temporal characteristics are detailed in the textbooks of Theoretical Foundations of Electrics [16]. Therefore, here we restrict ourselves to presenting the expressions of the original of the current in the secondary circuit, its temporal characteristics and the results of a comparative analysis to the case when a stepwise direct current, considered above, is fed to the input of the RTCT with CC.

a) for the case when $\delta > \omega_0$:

$$i_{э2}(t) = \frac{Kk_I\omega_0^2}{2\sqrt{\delta^2 - \omega_0^2}} e^{-\delta t} sh\sqrt{\delta^2 - \omega_0^2}t, \quad (26)$$

$$t_{max} = \frac{1}{\sqrt{\delta^2 - \omega_0^2}} arch\frac{\delta}{\sqrt{\delta^2 - \omega_0^2}}. \quad (27)$$

b) for the case when$\delta = \omega_0$:

$$i_{э2}(t) = Kk_I\omega_0^2 te^{-\delta t}, \quad (28)$$

$$t_{max} = \frac{1}{\delta}. (29)$$

c) for the case when $\delta < \omega_0$:

$$i_{э2}(t) = \frac{Kk_I\omega_0^2}{\omega'_{св}} e^{-\delta t} sin\omega'_{св}t. \quad (30)$$

Comparative analysis of the obtained expressions for the secondary transient current and their curves for the cases of connecting the primary RTCT circuit with a compensating capacitor to the sources of direct current, respectively (expressions (20), (22), (24) and Fig. 2, a) and linearly increasing current (expressions (26), (28), (30) and Fig. 2, b) shows that in both cases, with the corresponding ratios of the damping coefficient (δ) and the natural angular

ISSN: 2350-0328
International Journal of Advanced Research in Science, Engineering and Technology
Vol. 8, Issue 7 , July 2021

frequency (ω_0) of the secondary circuit, the nature of the transient process does not change, but at linear increasing current at $t = 0$, the transient secondary current will be zero, and the time for the current to reach its maximum value will be shorter.

3. Connecting the primary circuit of RTCT to a sinusoidal current source.For this case, taking into account $I_{э1}(p) = \frac{\omega I_{э1m}}{(p^2+\omega^2)}$operator equation (32) takes the following form:

$$I_{э2}(p) = \frac{p^2 K\omega\omega_0^2 I_{э1m}}{(p^2+2\delta p+\omega_0^2)(p^2+\omega^2)} = \frac{F_3(p)}{F_4(p)}. \quad (33)$$

The characteristic equation $F_4(p) = 0$has the following roots:$p_{1,2} = -\delta \pm \sqrt{\delta^2 - \omega_0^2}andp_{3,4} = \pm j\omega$.

The originals (33) found using the decomposition theorem [16] have the following form:

a) for the case when $\delta > \omega_0$:

$$i_{э2}(t) = I_{э2.1св.}e^{-\left(\delta-\sqrt{\delta^2-\omega_0^2}\right)t} - I_{э2.2св.}e^{-\left(\delta+\sqrt{\delta^2-\omega_0^2}\right)t} + I_{э2m}cos(\omega t - \varphi_2), \quad (34)$$

where$I_{э2.1св.} = \frac{\left(\delta-\sqrt{\delta^2-\omega_0^2}\right)^2 K\omega\omega_0^2 I_{э1m}}{2\sqrt{\delta^2-\omega_0^2}\left[\left(\delta-\sqrt{\delta^2-\omega_0^2}\right)^2-\omega^2\right]}, [A],$ (35)

$$I_{э2.2св.} = \frac{\left(\delta+\sqrt{\delta^2-\omega_0^2}\right)^2 K\omega\omega_0^2 I_{э1m}}{2\sqrt{\delta^2-\omega_0^2}\left[\left(\delta+\sqrt{\delta^2-\omega_0^2}\right)^2-\omega^2\right]}, [A], \quad (36)$$

$$I_{э2m} = \frac{K\omega^2\omega_0^2 I_{э1m}}{\sqrt{4\delta^2\omega^2+(\omega^2-\omega_0^2)^2}}, [A], \quad (37)$$

$$\varphi_2 = arctg\frac{\omega^2-\omega_0^2}{2\delta\omega}, [degri]. \quad (38)$$

b) for the case when $\delta = \omega_0$:

$$i_{э2}(t) = I_{э2св.}(2 - \delta t)e^{-\delta t} + I_{э2m}cos(\omega t - \varphi_2), \quad (39)$$

$$\text{where} I_{э2св.} = \frac{K\delta\omega\omega_0^2 I_{э1m}}{\delta^2+\omega^2}, [A]. \quad (40)$$

c) for the case when $\delta < \omega_0$:

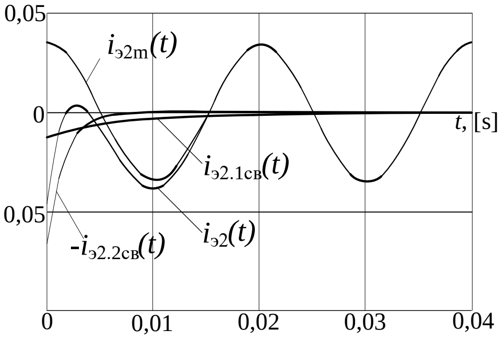
$$i_{э2}(t) = I_{э2св.}e^{-\delta t}cos(\omega'_{св} t - \varphi_3) + I_{э2m}cos(\omega t - \varphi_2), \quad (41)$$

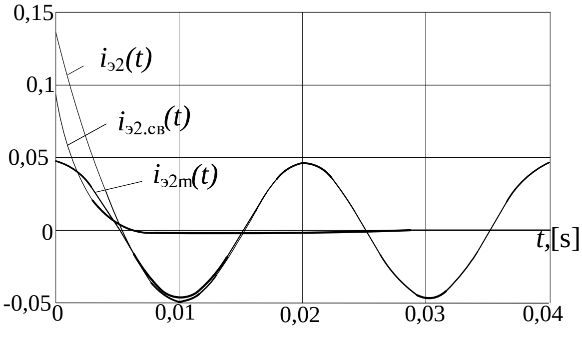
where$I_{э2св.} = \frac{K\omega\omega_0^4 I_{э1m}}{\omega'_{св}\sqrt{4\delta^2{\omega'_{св}}^2+\left[\delta^2-\left({\omega'_{св}}^2-\omega^2\right)\right]^2}}, [A],$ (42)

$$\varphi_3 = 2arctg\frac{\omega'_{св}}{\delta} + arctg\frac{2\delta^2-\left({\omega'_{св}}^2-\omega^2\right)}{2\delta\omega'_{св}}. [degri]. \quad (43)$$

Expressions (34), (39) and (41) are the transient characteristics of an RTCT with a compensating capacitor for the non-resonant mode of the secondary circuit. It should be noted that in most cases the RTCT secondary circuit is tuned to resonance voltages to obtain maximum output power. To obtain the transient characteristics of the RTCT with CC in the resonant mode in the secondary circuit of the RTCT in expressions (35) - (38) and (42), (43), it will be necessary to take into account the condition $\omega_0 = \omega$.

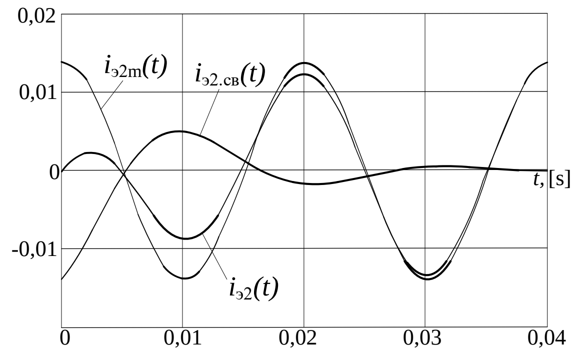
The analysis of the obtained expressions of the transient characteristics and their curves (Fig. 3) for the case of connecting the primary RTCT circuit with CC to a sinusoidal current source showed that at $\delta > \omega_0$ and $\delta = \omega_0$the free components of the transient current are aperiodic, and at $\delta < \omega_0$ are vibrational.





ISSN: 2350-0328
International Journal of Advanced Research in Science, Engineering and Technology
Vol. 8, Issue 7 , July 2021

a) ($at\ \delta>\omega_0$) b) ($at\ \delta$=ω_0)



c) ($at\ \delta<\omega_0$)

Fig. 3. Curves of the transient response of the developed RTCT when a sinusoidal current is applied to its input at $T_{э2}=0.05\ s$; $T_{э12}=0.004\ s$.

4) Connecting the primary circuit of an RTCT with a compensating capacitor to a sinusoidal current network with a damped amplitude $i_{э1}=I_{э1}e^{-\frac{t}{T_{э1}}}sin\omega t$. For this case, the secondary current in operator form is as follows:

$$I_{э2}(p)=\frac{p^2K\omega\omega_0^2I_{э1m}}{(p^2+2\delta p+\omega_0^2)\left[\left(p+\frac{1}{T_{э1}}\right)^2+\omega^2\right]}. \quad (44)$$

The characteristic equation $F_4(p)=0$has the following roots:$p_{1,2}=-\delta\pm\sqrt{\delta^2-\omega_0^2}andp_{3,4}=-\frac{1}{T_{э1}}\pm j\omega$.

The original of this current for three cases is as follows:

a) for the case when $\delta>\omega_0$:

$$i_{э2}(t)=I_{э2.1св.}e^{-\left(\delta-\sqrt{\delta^2-\omega_0^2}\right)t}-I_{э2.2св.}e^{-\left(\delta+\sqrt{\delta^2-\omega_0^2}\right)t}+I_{э2m}e^{-\frac{t}{T_{э1}}}cos(\omega t+\varphi_4), \quad (45)$$

where
$$I_{э2.1св.}=\frac{\left(\delta-\sqrt{\delta^2-\omega_0^2}\right)^2K\omega\omega_0^2T_{э1}^2I_{э1m}}{2\sqrt{\delta^2-\omega_0^2}\left\{\left[\left(\delta-\sqrt{\delta^2-\omega_0^2}\right)T_{э1}-1\right]^2+\omega^2T_{э1}^2\right\}}, [A] \quad (46)$$

$$I_{э2.2св.}=\frac{\left(\delta+\sqrt{\delta^2-\omega_0^2}\right)^2K\omega\omega_0^2T_{э1}^2I_{э1m}}{2\sqrt{\delta^2-\omega_0^2}\left\{\left[\left(\delta+\sqrt{\delta^2-\omega_0^2}\right)T_{э1}-1\right]^2+\omega^2T_{э1}^2\right\}}, [A] \quad (47)$$

$$I_{э2m}=\frac{K\omega_0^2I_{э1m}}{\sqrt{4\omega^2T_{э1}^2(1-\delta T_{э1})^2+[1-2\delta T_{э1}+(\omega_0^2-\omega^2)T_{э1}^2]^2}},, [A] \quad (48)$$

$$\varphi_4=-2arctg\omega T_{э1}+arctg\frac{1-2\delta T_{э1}+(\omega_0^2-\omega^2)T_{э1}^2}{2\omega T_{э1}(1-\delta T_{э1})}, [degri] \quad (49)$$

b) for the case when $\delta=\omega_0$:

$$i_{э2}(t)=I_{э2св.}(2-\delta t)e^{-\delta t}+I_{э2m}e^{-\frac{t}{T_{э1}}}cos(\omega t+\varphi_4), \quad (50)$$

where$I_{э2св.}=\frac{K\delta\omega\omega_0^2T_{э1}^2I_{э1m}}{2[(1-\delta T_{э1})^2+\omega^2T_{э1}^2]}$, $[A]$. (51)

c) for the case when$\delta<\omega_0$:

$$i_{э2}(t)=I_{э2.св.}e^{-\delta t}cos(\omega'_{св}t-\varphi_5)-I_{э2m}e^{-\frac{t}{T_{э1}}}cos(\omega t+\varphi_4), \quad (52)$$

$$I_{э2.св.}=\frac{K\omega\omega_0^4T_{э1}^2I_{э1m}}{\omega'_{св}\sqrt{4\omega'^2_{св}T_{э1}^2(\delta T_{э1}-1)^2+\left[1+\left(\delta^2-\omega'^2_{св}+\omega^2\right)T_{э1}^2\right]^2}}, [A] \quad (53)$$

$$\varphi_5=arctg\frac{1+\left(\delta^2-\omega'^2_{св}+\omega^2\right)T_{э1}^2}{2\omega'_{св}T_{э1}(\delta T_{э1}-1)}+2arctg\frac{\omega'_{св}}{\delta}, [degri] \quad (54)$$

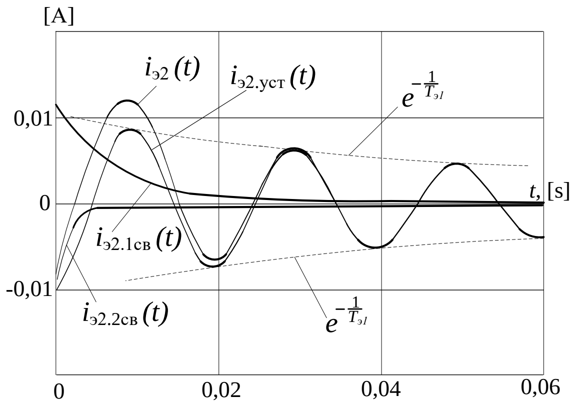
The analysis of the obtained expressions of the transient characteristics (45), (50), (52) and their curves (Fig. 4) for the case of connecting the primary RTCT circuit with CC to the sinusoidal current network with damped amplitude shows that at $\delta>\omega_0$the transient current of the secondary circuit consists of the sum of two free aperiodic and forced damped sinusoidal components (Fig. 4, a), at $\delta=\omega_0$is one free aperiodic and forced damped sinusoidal components

ISSN: 2350-0328
International Journal of Advanced Research in Science, Engineering and Technology
Vol. 8, Issue 7 , July 2021

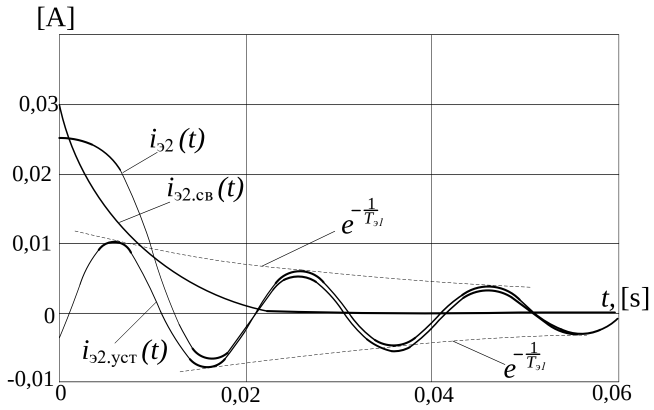
(Fig. 4, b), and at $\delta < \omega_0$ is one free and one forced damped sinusoidal components (Fig. 4, c), the degree of damping of which depends on the time constants of the secondary and primary circuits of the RTCT with CC, respectively.

III. CONCLUSION

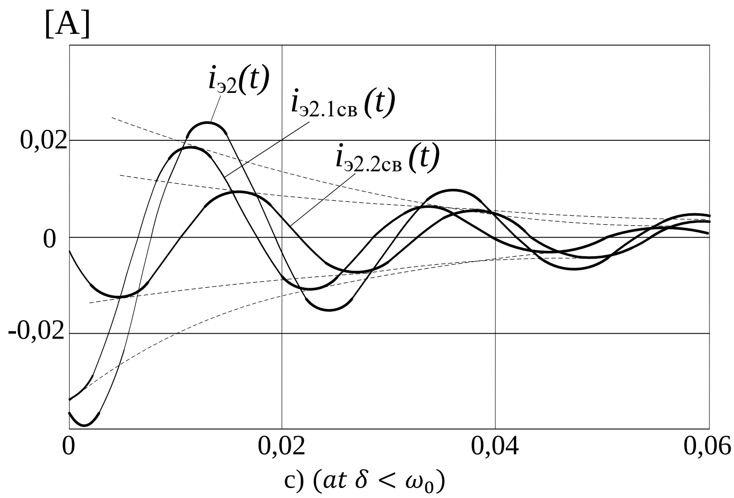
1. It is shown that the developed remote transformer current transducer with a compensating capacitor can be represented in the structural schemes of monitoring and control systems in the form of a series-connected ideal differentiating link, a real differentiating link without statism and a second-order inertial link, and in the case of neglecting active losses in the magnetic circuit is in the form of a series-connected ideal differentiating and oscillating links.



a) ($at\ \delta > \omega_0$)



c) ($at\ \delta{=}\omega_0$)



c) ($at\ \delta < \omega_0$)

Fig. 4. Curves of the transient response of the developed RTCT when a sinusoidal current with a damped amplitude is applied to its input at $T_{э2} = 0.05\ s; T_{э12} = 0.004\ s$.

2. It has been established that when the developed remote transformer current transducer with a compensating DC step capacitor is supplied to the primary circuit and at $\delta > \omega_0$ and $\delta = \omega_0$ (where δ is the damping coefficient and ω_0 is the natural angular frequency of the secondary circuit), the transient current has an aperiodic character, at a certain value of time has a maximum, and as the difference $(\delta - \omega_0)$ tends to zero, the time for the current to reach its maximum value is reduced, and at $\delta < \omega_0$ the transient current has an oscillatory character.

3. It is shown that for the cases of connecting the primary circuit of the developed remote transformer current converter with a compensating capacitor to the sources of constant and linearly increasing currents, respectively, with the corresponding ratios of the damping coefficient (δ) and natural angular frequency (ω_0) of the secondary circuit, i.e. at $\delta > \omega_0$ and $\delta = \omega_0$ the transient current is aperiodic, and at $\delta < \omega_0$ is oscillatory.

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Vol. 8, Issue 7 , July 2021

4. It has been established that for the case of connecting the primary circuit of the developed remote transformer current transducer with a compensating capacitor to a sinusoidal current network with a damped amplitude, it shows that at $\delta > \omega_0$ the transient current of the secondary circuit consists of the sum of two free aperiodic and forced damped sinusoidal components, at $\delta = \omega_0$ of one free aperiodic and forced damped sinusoidal components, and at $\delta < \omega_0$ of one free and one forced damped sinusoidal components, the degree of damping of which depends on the time constants of the secondary and primary circuits of the current transducer, respectively.

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