Dynamic characteristics of a new remote transformer current converter with compensating capacitor

Babanazarova N.K.

ABSTRACT

In the paper analytical equations of transient characteristics of a new remote transformer current converter with a compensating capacitor are obtained when a jumping, linearly increasing, sinusoidal and sinusoidal with damped amplitude influences are applied to their input. It is shown that the developed current converter can be represented in structural schemes of control and management systems in the form of a series-connected ideal differentiating link, a real differentiating link without statism and an inertial link of the second order, and in the case of neglecting active losses in the magnetic core - in the form of a series-connected ideal differentiating and oscillating links. It is established, for the case of connection of the primary circuit of the current converter to the network of sinusoidal current with damped amplitude, that at $\delta>\omega_0$ (where δ is the damping coefficient and ω_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 $\delta=\omega_0$ - 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 depend on the time constants of the secondary and primary circuit of the current converter, respectively.

Keywords: Remote current converter, multifilament core, compensating capacitor, parametric structural scheme, dynamic characteristic, transient characteristic, physical-technical effect, jump current, linearly increasing current, sinusoidal current, sinusoidal current with damped amplitude

Introduction. In recent years, remote transformer current converters (RTCTs) have been widely used to measure large currents of high-voltage electrical equipment, in particular, to convert currents in high-voltage transmission lines [1, 2, 3].

In Tashkent State Transport University, a new DTPT for measuring currents in the wires of a three-phase high-voltage line has been developed, the device, principle of operation and features of which are detailed in [5,6].

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

The dynamic characteristic of DTPT, in general, is the dependence between the informative parameters of the output and input signals and time or the dependence of the output signal on the input signal in dynamic mode. The dynamic characteristic of DTPT, as any measuring transducer, is usually described by a differential equation, transfer or complex frequency functions [9].

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

It should be noted that the PSS by the methods of their compilation, transformation and obtaining the corresponding equations 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 features. Thus, if in the structural schemes the processes occurring in the automatic system are displayed in the form of a set of series, parallel and mixed connected typical links, then in the PCS of the converter a further decomposition of typical links to the parameters of resistance, inductance, capacitance and their corresponding inverse parameters of conductivity, deductivity and rigidity of circuits of different physical nature, as well as to the physical effects and phenomena (so-called physical-technical effects (PTE)) within a circuit of the same physical nature is made Such decomposition, firstly, allows to reflect in more detail, up to elementary transformation, the processes occurring in the converter, secondly, allows to reveal all possible influences of internal and external perturbations on the parameters and coefficients of intra-circuit and inter-circuit FTEs, and thirdly, allows to analyze the processes occurring in the converter, secondly, allows to reveal all possible influences of internal and external perturbations on the parameters and coefficients of intra-circuit and inter-circuit FTEs.

Since the sequence of compiling the SAR of measuring transducers is described in detail in the scientific works of Prof. M.F. Zaripov, in particular in [10], devoted to the energy-information model of circuits of different nature and the SAR apparatus, we will limit ourselves here to presenting the compiled SAR of the developed DTPT with QC for the study of its dynamic characteristics (Fig. 1). The following physical and technical inter-chain effects (FTEs) and parameters are involved in the SAR of the investigated DTPT with QC: 1) inter-chain FTE between the converted electric current I_{e1} and magnetic voltage $U_{\mu1}$ with conversion coefficient $K_{(I_{e1} U_{\mu1})}=w_1$, where $w_1=1$ is the number of turns of the DTPT primary winding (in our case the busbar with the converted current, [-]; 2) intra-chain FTE of conversion of magnetic voltage $U_{\mu1C}$ into magnetic flux $Q_{\mu1}$ is the parameter of magnetic capacitance $C_{\mu1\delta}$ of the air gap on the path of working magnetic flux $Q_{\mu1}$ of the magnetic circuit, where $C_{\mu1\delta}=\delta/(\mu_0 S_\mu)$,[H]; S_μ, δ are, respectively, the cross-sectional area and length of the air gap on the path of working magnetic flux, [m^2]; [m]; $\mu_0=4\pi\cdot10^{-7}$,[H/m] - magnetic constant; 3) intra-chain FTE of conversion of magnetic flux $Q_{\mu1}$ into magnetic voltage $U_{\mu1C}$ - magnetic stiffness parameter $W_{\mu st}$ of the steel part of the magnetic circuit on the path of the working magnetic flux $Q_{\mu1}$, where $W_{\mu st}=l_{(\mu st.)}/(\mu\mu\mu_0 S_{(\mu st.)})$,[1/H]; $S_{(\mu st.)}$, $l_{(\mu st.)}$, [m^2]; [m]; 4) intra-chain FTE of conversion of magnetic flux $Q_{\mu1}$ into magnetic voltage $U_{\mu1C}$ - cross-sectional area and length of the ferromagnetic multifilament core (MBC), respectively.) - respectively cross-sectional area and length of the ferromagnetic multifilament core (MFC) on the path of the working magnetic flux, [m^2]; [m]; 4) intrachain FTE of conversion of magnetic current I_μ into magnetic voltage $U_{\mu1R}$ - parameter of active magnetic resistance R_μ of the MFC on the path of the working magnetic flux $Q_{\mu1}$, where $R_\mu=G_{(e. vortex)}$, $G_{(e.vortex)}$ - electrical conductivity of the MBS on the path of eddy currents, [S]; 5) intra-chain FTE of conversion of the rate of change of magnetic current I_μ' into magnetic voltage $U_{\mu1L}$ - parameter of magnetic inductance L_μ of the steel part (MBS) of the magnetic circuit on the path of working magnetic flux $Q_{\mu1}$, where $L_\mu=C_{(e. vortex)}$, $C_\mu=C_{(e. eddy)}$, $C_{(e.eddy)}$ - electric capacitance of the MBC on the path of eddy currents, [F]; 6) interchain FTE of ampervites between electric current I_{e2} and magnetic voltage $U_{\mu2}$ of the secondary circuit of DTPT with conversion coefficient K_(I_e2

$U_{\mu 2}$)=w_2, where w_2 - - number of turns of the secondary measuring winding, [-]; 6) inter-chain FTE of electromagnetic induction between magnetic current I_μ and electric voltage of the secondary circuit of DTPT U_{e2} with conversion coefficient $K_{(I_\mu U_{e2})}=w_2$, where w_2 is the number of turns of the secondary measuring winding, [-]; 7) intra-chain FTE of conversion of electric voltage U_{e2G} into electric current I_{e2} of the secondary circuit of DTPT - the parameter of electric conductivity $G_{(e2\sum)}$, where $G_{(e2\sum)}$ is the total electric conductivity of the secondary circuit (secondary winding and load), [S]; 8) in-circuit FTE of conversion of the rate of change of electric current $I_{e2}^{'}$ into electric voltage U_{e2L} - the parameter of electric inductance L_{e2}, where $L_{(e2\sum)}=$ 〖(L〗 $_{e2}+L_{e2n}$), L_{e2}, L_{e2n} - electric inductance of the secondary circuit, measuring winding and load of DTPT, respectively, [H]; $C_{(\mu 2\sum)}$ - total magnetic capacitance of the secondary magnetic circuit, [H]; 9) in-circuit FTE of conversion of electric charge Q_{e2} into electric voltage U_{e2W} - electric stiffness parameter $W_{(e2\sum)}=W_{e2}+W_{e2k}$,[F^{-1}], where W_{e2} is the intercurrent electric stiffness of the measuring winding, $W_{e2k}=1/C_{e2k}$ is the electric stiffness of the CC connected to the secondary circuit to increase the output power of DTPT; p is a complex variable (operator).

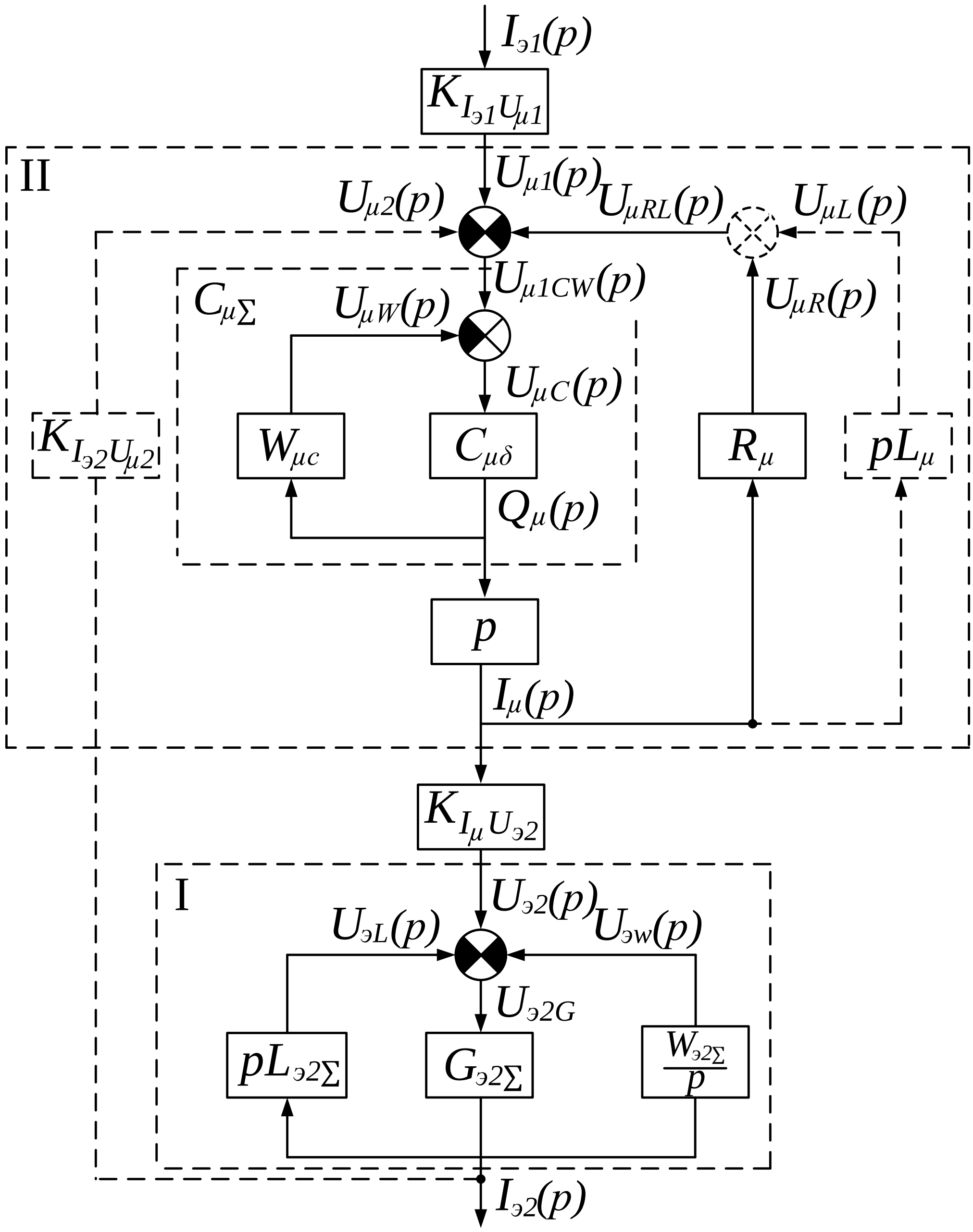


Fig. 1. Parametric structural diagram of the developed DTPT to determine its dynamic characteristics

Let's write the system of equations by SAR describing the dynamic mode of operation of the developed DTPT with CC. In order to simplify the formulation of equations on the SAR of the converter, we will divide it into two (I-II) sections. In order to simplify the study of the dynamic characteristics of DTPT with QC in the first approximation we can neglect the magnetic inductance (electrical capacitance on the path of eddy currents in the magnetic core) L_μ of the magnetic circuit, the interscrew electrical stiffness W_e2 and the demagnetizing effect of the magnetic field of the secondary current on the magnetic field of the transformed current of DTPT with QC because of the smallness of their values (in the PCA these branches with the FTE coefficient and parameters are shown by dashed lines) [13].

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

The following equations are valid for the I-th section of the PSS:

$$I_{э2}(p) = G_{э2\Sigma}\ U_{э2G}(p), \qquad (1)$$

$$U_{э2G}(p) = U_{э2}(p) - U_{э2L}(p) - U_{э2W}(p), \quad (2)$$

$$U_{э2L}(p) = pL_{э2\sum}I_{э2}(p), \quad (3)$$

$$U_{э2W}(p) = \frac{W_{э2к}}{p}I_{э2}(p). \quad (4)$$

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

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

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

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

The following equations can be written for the II- oth sections of the SAR:

$$I_\mu(p) = pQ_{\mu1}(p), \quad (7)$$

$$Q_{\mu1}(p) = pC_{\mu1\delta}U_{\mu1C}(p), \quad (8)$$

$$U_{\mu1C}(p) = U_{\mu1CW}(p) - U_{\mu1W}(p), \quad (9)$$

$$U_{\mu1W}(p) = W_{\mu ст}Q_{\mu1}(p), \quad (10)$$

$$U_{\mu1CW}(p) = U_{\mu1}(p) - U_{\mu R}(p), \quad (11)$$

$$U_{\mu R}(p) = R_\mu I_\mu(p). \quad (12)$$

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

$$Q_{\mu1}(p) = \frac{C_{\mu1\delta}}{1 + W_{\mu ст}C_{\mu1\delta}}U_{\mu1CW}(p) = C_{\mu1\sum}U_{\mu1CW}(p), \quad (13)$$

Where $C_{\mu1\sum} = \frac{C_{\mu1\delta}}{1+W_{\mu ст}C_{\mu1\delta}}$.

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

$$I_\mu(p) = \frac{pC_{\mu1\sum}}{1+R_\mu C_{\mu1\sum}p}U_{\mu1}(p). \quad (14)$$

From the SAR we have the following:

$$U_{\mu1}(p) = K_{I_{э1}U_{\mu1}}I_{э1}(p). \quad (15)$$

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

$$I_{э2}(p) = \frac{p^2K}{(L_{э2\sum}C_{э2\sum}p^2+R_{э2\sum}C_{э2\sum}p+1)(1+R_\mu C_{\mu1\sum}p)}I_{э1}(p) = W_2(p)I_{э1}(p). \quad (16)$$

here W_2 (p), [-] is the transfer function of DTPT with KK; 〖K=C〗 _(e2∑) M_e12,[s^2].

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

Results. The analysis of the compiled SAR of the CTDT with a compensating capacitor and its transfer function shows that the developed CTDT with a compensating capacitor can be represented in the structural schemes of control and management systems in the form of a series connected one ideal differentiating link, one real differentiating link without statism and an inertial link of the second order. It should be noted that in case of neglecting the active losses in the magnet core (R_μ=0) the current converter can be represented in the structural schemes as a series connected ideal differentiating and oscillating links.

The analysis of the operation of the developed DTPT with CC shows that the time constant of the magnetic circuit T_μ 〖=R〗 _μ C_(μ1∑) is approximately two or three orders of magnitude less than the time constant of the secondary circuit of DTPT with CC. Therefore, the time constant T_μ can be neglected in the first approximation.

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

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

Thus, using the PCA method, the operator equation for investigating the dynamic properties of the developed DTPT with QC connected to the secondary circuit is obtained. It is necessary to obtain transient, impulse transient, frequency and amplitude-phase frequency characteristics of the developed DTPT with QC.

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

1. Connecting the primary circuit of DTPT to the source of direct current i_e1=I_e10=const. Taking into account I_e1 (p)=I_e10/p, the operator equation (17) takes the following form:

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

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+2δp+ω_0^2=0, as it is known [16], has the following roots:

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

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

Let us investigate these three cases.

(a) Let δ>ω_0, i.e., the roots of the characteristic equation are real and unequal to each other.

The original operator transient current by (18), found using the decomposition theorem [16], is as follows:

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

From the transient current characteristic (Fig. 2, a), plotted on the basis of (20), we can see that the transient process has an aperiodic character and at a certain value of time the transient current graph has a maximum value.

Examining the current function i_e2 (t) according to (20) for extremum, we find the following value of time, at which the current has the maximum value:

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

b) let δ=ω_0, i.e., the roots of the characteristic equation are real and equal to each other. As it is known [16], for this case the expression of the original transient current becomes undefined due to the equality of both numerator and denominator to zero. Using Lopital's rule [17], we obtain the following expression for the original transient current:

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

The character of transients in this case does not qualitatively differ from the case when δ>ω_0. But unlike the previous case, the moment of current reaching its maximum value is shortened and is determined by the following expression

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

c) now let δ<ω_0, i.e., the roots of the characteristic equation are complex and conjugate: p_1,2=-δ±jω_sv^', where ω_sv^'=√(ω_0^2-δ^2) is the angular frequency of free or natural oscillations in the secondary circuit of DTPT with CC, [s^(-1)] [16].

Application of the decomposition theorem allows us to obtain the following expression of the original secondary current:

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

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

The analysis of the obtained expressions of the secondary transient current of DTPT with CC i_e2 (t) (20), (22), (24) and time characteristics (Fig. 2.), a), constructed on the basis of these expressions showed that at connection of the primary circuit of DTPT with CC to the source of direct current and under fulfillment of the condition δ>ω_0 and δ=ω_0 the transient current of DTPT has aperiodic character, at a certain value of time has a maximum, and as the difference between the attenuation coefficient (δ) and natural angular frequency (ω_0) of the secondary circuit tends to zero (δ-ω_0≥0), the time to reach its maximum value decreases, and at δ<ω_0 the transient current of DTPT has an oscillatory character. Besides, one more peculiarity of connection of the primary circuit of DTPT with CC to the source of direct current is that at the moment of switching (t=0) the secondary current has some finite value i_e2 (0).

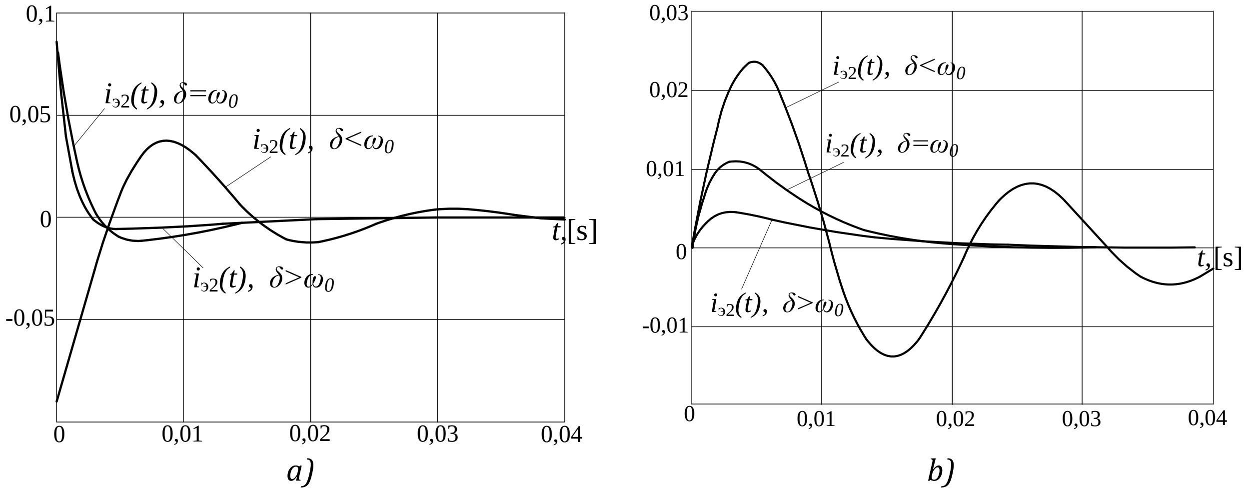


Fig. 2. Transient response curves of the developed DTPT with QC when a jumping constant (a) and linearly increasing (b) currents are applied to its input at T_e2=0.05 s, T_e12=0.004 s.

2. Connecting the primary circuit of DTPT to the source of linearly increasing current i_e1=k_I t, where k_I is the proportionality coefficient, [A/s]. Taking into account I_e1 (p)=k_I/p^2, the 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 into its original for the above three types of roots of the characteristic equation and the features of their time characteristics are described in detail in TOE textbooks [16]. Therefore, we will limit ourselves here to giving the expressions of the original of the current in the secondary circuit, its time characteristics and the results of comparative analysis of the case when a jump direct current, considered above, is applied to the input of DTPT with CC.

a) in the case where $\delta > \omega_0$:

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

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

b) in the case where $\delta = \omega_0$:

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

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

c) in the case where$\delta < \omega_0$:

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

The comparative analysis of the obtained expressions of the secondary transient current and their curves for cases of connection of the primary circuit of DTPT with a compensating capacitor to the sources of direct current (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 at the corresponding ratios of the attenuation coefficient (δ) and natural angular frequency (ω_0) of the secondary circuit the character of the transient process does not change, but at linearly increasing current at t=0 the transient secondary current will be equal to zero, and the time of current reaching its maximum value will be less.

3. Connecting the primary circuit of DTPT 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:

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

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

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

а) in the case where $\delta > \omega_0$:

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

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)

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

(36)

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

(37)

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

(38)

б) in the case where $\delta = \omega_0$:

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

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

в) in the case where $\delta < \omega_0$:

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

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

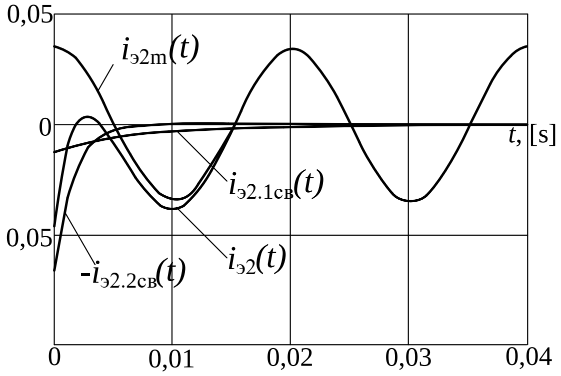
(42)

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

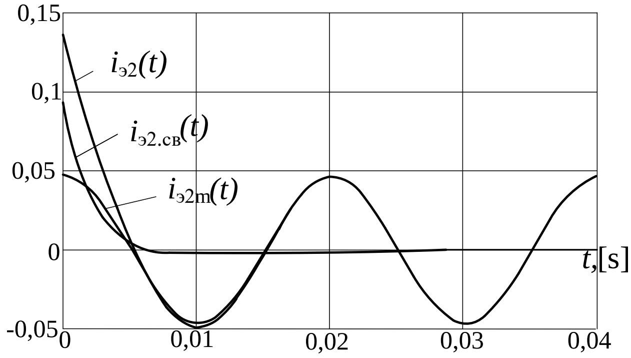
Expressions (34), (39) and (41) are the transient characteristics of DTPT with a compensating capacitor for the non-resonant mode of the secondary circuit. It should be noted that in most cases, to obtain the maximum output power, the secondary circuit of DTPT with a compensating capacitor is tuned to the voltage resonance. To obtain the transient characteristics of DTPT with CC at resonance mode in the secondary circuit of DTPT in expressions (35)-(38) and (42), (43) it will be necessary to take into account the condition ω_0=ω.

Analysis of the obtained expressions of transient characteristics and their curves (Fig. 3) for the case of connection of the primary circuit of DTPT with CC to the expressions (34), (39) and (41) are the transient characteristics of DTPT with a compensating capacitor for the non-resonant mode of the secondary circuit. It should be noted that in most cases, to obtain the maximum output power, the secondary circuit of DTPT with a compensating capacitor is tuned to the voltage resonance. In order to obtain the transient characteristics of DTPT with CC at the resonant mode in the secondary circuit of DTPT in expressions (35)-(38) and (42), (43), it will be necessary to take into account the following condition $\omega_0 = \omega$.

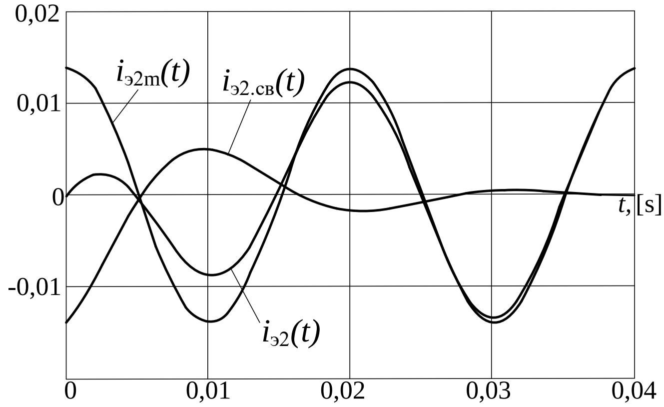
Analysis of the obtained expressions of transient characteristics and their curves (Fig.3) for the case of connection of the primary circuit of DTPT with CC to to a sinusoidal current source showed that at δ>ω_0 and δ=ω_0 the free components of the transient current have aperiodic character, and at δ<ω_0 - oscillatory.



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



b) ($at\ \delta = \omega_0$)



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

Fig. 3. Transient response curves of the developed DTPT when sinusoidal current is applied to its input at T_e2=0.05 s; T_e12=0.004 s.

4) Connection of the primary circuit of DTPT with a compensating capacitor to a sinusoidal current network with damped amplitude

$i_{э1} = I_{э1}e^{-\frac{t}{T_{э1}}}sin\omega t$. *For this case the secondary current in operator form has the following form:*

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

Характеристическое уравнение$F_4(p) = 0$ have the following roots: $p_{1,2} = -\delta \pm \sqrt{\delta^2 - \omega_0^2}$ и $p_{3,4} = -\frac{1}{T_{э1}} \pm j\omega$.

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

a) in the case where$\delta > \omega_0$:

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

where $I_{э2.1св.} =$

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

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

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

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

b) in the case where $\delta = \omega_0$:

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

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

c) in the case where$\delta < \omega_0$:

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

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

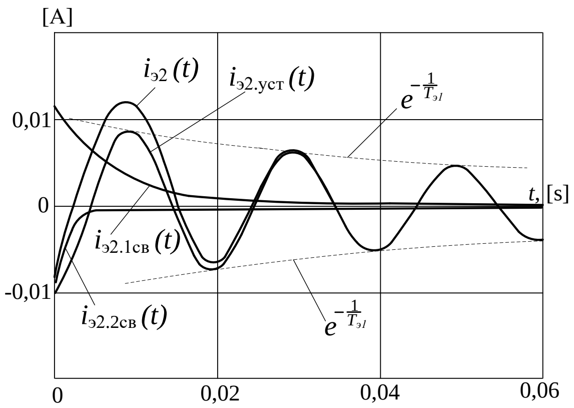
$$\varphi_5 = arctg\frac{1+\left(\delta^2-{\omega'_{св}}^2+\omega^2\right)T_{э1}^2}{2\omega'_{св}T_{э1}(\delta T_{э1}-1)} + 2arctg\frac{\omega'_{св}}{\delta}, [degri] \quad (54)$$

The analysis of the obtained expressions of transient characteristics (45), (50), (52) and their curves (Fig.4) for the case of connection of the primary circuit of DTPT with CC to the network of sinusoidal current with damped amplitude shows that at δ>ω_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 δ=ω_0 - one free aperiodic and forced damped sinusoidal components (Fig. 4, b), and at δ<ω_0 - one free and one forced damped sinusoidal components (Fig. 4, c), the degree of damping of which depend on the time constants of the secondary and primary circuits of DTPT with CC, respectively.

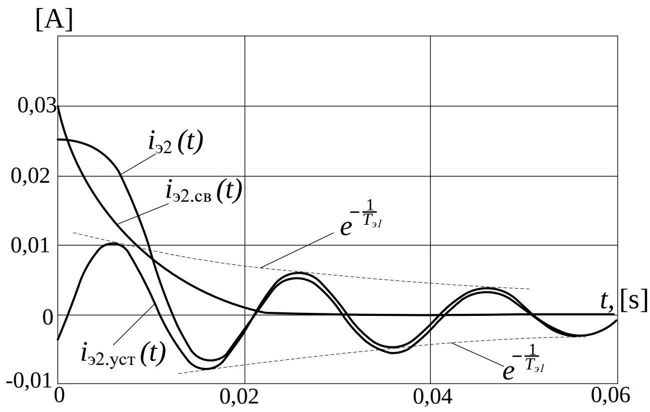
Conclusion

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

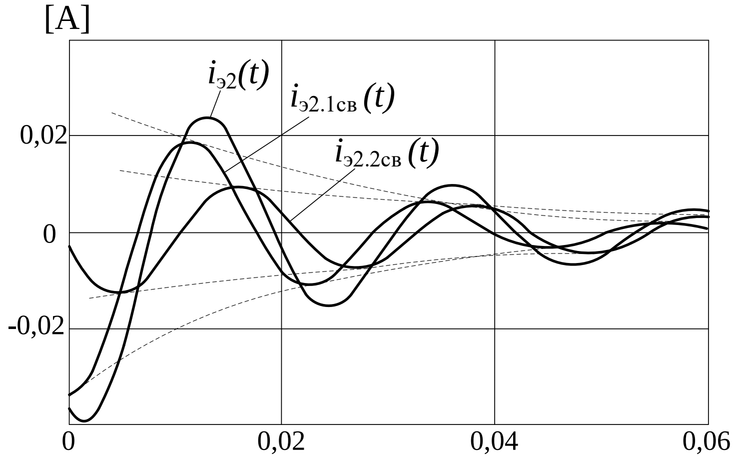
It is shown that the developed remote transformer current converter with compensating capacitor can be represented in the structural schemes of control and management systems in the form of a series-connected ideal differentiating link, real differentiating link without statism and inertial link of the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



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



b) ($at\ \delta$=ω_0)



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

Fig. 4. Transient response curves of the developed DTPT when a sinusoidal current with damped amplitude is applied to its input at T_e2=0.05 s; T_e12=0.004 s.

2. It is established, at supplying to the primary circuit of the developed remote transformer current converter with a compensating capacitor of jump-shaped direct current and at δ>ω_0 and δ=ω_0 (where δ - damping coefficients and ω_0 - 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 (δ-ω_0) tends to zero, the time to reach its maximum value decreases, and at δ<ω_0 transient current has an oscillatory character.

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

4. It is established, for the case of connection of the primary circuit of the developed remote transformer current converter with compensating capacitor to the network of sinusoidal current with damped amplitude shows that at δ>ω_0 the transient current of the secondary circuit consists of the sum of two free aperiodic and forced damped sinusoidal components, at δ=ω_0 - one free aperiodic and forced damped sinusoidal components, and at δ<ω_0 - one free and one forced damped sinusoidal components, the degree of damping which depend on the time constants of the secondary and primary circuits of the current converter, respectively.

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