ISSN: 2350-0328
International Journal of Advanced Research in Science, Engineering and Technology
Vol. 3, Issue 7 , July 2016

Performance of Magnitemodulying Current Sensor

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ABSTRACT: The paper shows a linear dynamic model magnitomodulyatsionnye DC converter. In this article we make a revised calculation of the transition process in the model magnitomodulyatsionnye DC converter, without producing replacement of pulse-width modulation (PWM) on the analysis method of space (ILA).
Currently, there are a number of methods for studying nonlinear discrete systems. Systems with a pulse width modulation method most accurately describe the state space. It is the most common and fairly simple. The exact solution for the analysis of systems with pulse-width modulation is obtained in the form of recurrent condition that allows to find the desired value by means of turn-based computing. Other methods to find a closed form solution, either close or too complex.

KEYWORDS: DC converter, a mathematical model, the static characteristics, dynamic, active zone, filter, battery, pulse width modulation, the analysis method of space, nonlinear discrete-time systems, impulse.

I. INTRODUCTION

In the systems of monitoring and controlling (MCS) the process of recharging in self-contained power sources as the primary DC-DC converter magnitomodulyatsionnye current sensors (MMCS) are most often used [1], built on the basis of magnetic transistor multivibrators (MTM) with the transformation of the current pulse - duration, i.e., width- pulse modulation (PWM). Scheme of one of the developed MMCS is shown in Figure 1.

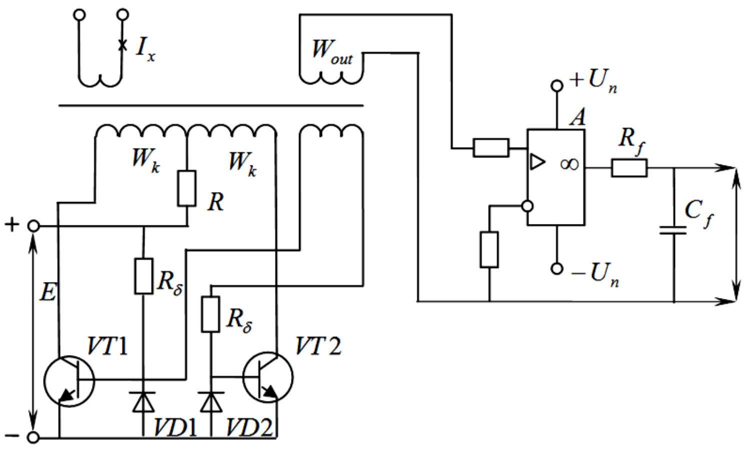

Fig.1 . Magnitomodulyatsionny sensor of DC

The operating principle of this sensor is as follows. In the absence of a controlled duration of current I_x durations of T_1 and T_2 half-periods of generated pulses, provided the symmetry of the circuit will be equal to each other. When a current I_x flows, due to the fact that one has a magnetizing current I_x half- steps, and in the other - demagnetizing, durations T_1 and T_2 become uneven. Consequently, the pulse duration T_1 and T_2 is a function of the controlled

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International Journal of Advanced Research in Science, Engineering and Technology
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current I_x. AC output MTM which carries information about the magnitude and direction of a DC controlled is removed from the output transformer W_{out}.

The voltage from the output winding W_{out} is lead to the input of the amplifier - limiter, which limits the voltage at the top and bottom. Duration of pulses T_1 and T_2 vary depending on the controlled current and volt - second area of positive and negative pulses on winding W_{out} are equal. After the bilateral restrictions there appear constant component, proportional of which is equal to the controlled current, and the sign depends on the direction of the current. The variable component is filtered using a low pass filter (LPF).

II. TEXT DETECTION

It should be noted that in the known circuits MMCS [2] it is necessary that the overall power wire downstream devices, such as amplifiers , would not be electrically connected to the source of MTM power, as for subsequent devices common wires is the output of one of the ballast resistors , which is not always convenient. In this case you need an additional source of MTM Power.

When you use the above MMCS additional power supply is not needed.
In order to improve the characteristics of weight and size and unification of MMCS, and to avoid an interference in the monitored AC voltage circuit, a sensor input circuit is organized as follows. The core part is magnetized from the side of the controlled current flowing through a calibrated branch line from the main current-carrying wiring harness consisting of several wires located between the power connectors. For example, if the total number of wires between the power terminals is 10, one wire is passed, resulting in MTM loaded on the closed loop formed by a tap and harness in the core box. In order to not overload the MTM, the input circuit L_{ch} choke is put. Scheme of input circuit of MMCS is shown in Figure 2 .

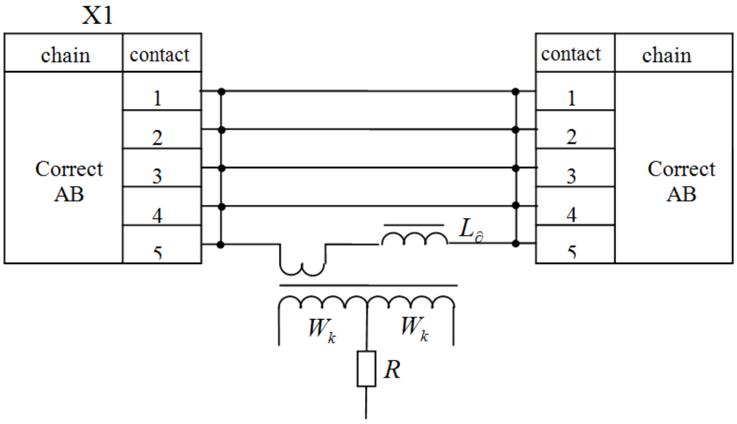

Fig.2 . Input circuit MMCS

Since the resistance of the branch line is small, even for small values of L_{ch} inductor the time constant of the choke input circuit is quite high, and the input circuit will have a significant effect on the static and dynamic characteristics of MMCS.

III.EXT INPAINTING

Since the considered sensor is the element of MCS, knowledge of its dynamic performance is important in the development and design of I & C, having in its composition MMCS. When analyzing the dynamics of MCS it is needed to know how dynamic link or set of links appears MMCS in the total structural diagram of MCS.
MMCS based on MTM with pulse-width modulation (PWM) as known [3], are discrete nonlinear elements. Moreover, there are two types of non-linearity: a) nonlinearity due view modulation (PWM); b) the non-linearity of the static characteristic MMCS [1].

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It is known [4] that the pulse system with PWM for small deviations of the pulse width can be represented as linear with pulse-amplitude modulation (PAM). This pulse exposure effect is not dependent on their shape and defined by their areas. In calculation the transient error process will depend not only on the depth of modulation, but also on the type of linear part decreasing with the decrease of the last bandwidth [3].
In the vast majority of MCS, operating portion of the static characteristic MMCS on which the system behavior are primarily interested for designers, is a linear plot. Therefore, when analyzing the dynamics MMCS its static characteristic $U_{out} = f(I_x)$ linear is accepted.
There are a number of linear pulse systems analyzing techniques [3,4]. However, here it is the most convenient method z - transform [5]. This method allows to analyze the dynamics of systems with less computing than with other methods.
Consider the transition process in MMCS, whose scheme is shown in Fig.1., When applied to its input current I_x of a single jump.
Imagine MMCS input circuit as a delay element of the first order with a transfer function:

$$W_{ent}(p) = \frac{R_r / R_0}{1+\tau_{ent} p} \qquad (1)$$

Where R_0, R_r - respectively, the total resistance of a tap and harness section resistance between connectors $X1$ and $X2$; $\tau_{ent} = \dfrac{L_{ch}}{R_0 + \dfrac{R}{W_k^2}}$ - the time constant of the input circuit

Linear pulse system represented in [3] in the form of a simple pulse element compound forming the δ - pulses and the present continuous portion containing a shaping element and a continuous part. Block diagram of an analog low-pass filter MMCS represented by a linear pulse link is shown in Figure 3.

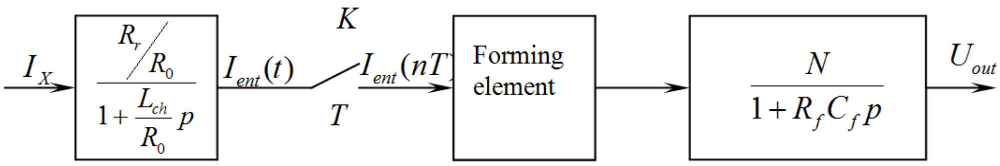

Fig. 3. The linear dynamic model MMCS with the low pass filter analogy.

In an entrance proceeds the current I_{ent} which is smaller in R_r/R_0 time than current I_x. The key K becomes isolated with the period of T and forms trellised function $I_{ent}(t)$ of continuous function $I_{ent}(nT)$. The forming element forms impulses of the set form, in this case – rectangular. Transfer function of the forming element is equal in our case [3]:

$$K_f(p) = \frac{1-e^{-\lambda pT}}{p}, \qquad (2)$$

Where $\lambda = \dfrac{\tau_u}{T}$, τ_u - respectively the relative duration and duration of the created impulse.
Thus, transfer function of the given continuous part for MMCS with analog LPF looks as follows:

$$W(p) = \frac{1-e^{-\lambda pT}}{p} \cdot \frac{N}{1+\tau_f p} \qquad (3)$$

Where $N = \dfrac{K_{const}}{\lambda}$ - coefficient of transfer of continuous part; $\tau_f = R_f C_f$ - LPF time constant; $K_{const} = \dfrac{dU_{out}}{dI_x}$ - static efficiency of transfer of MMCS. On condition of the static characteristic of the considered MMCS it has $K_{const} = const$.

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International Journal of Advanced Research in Science, Engineering and Technology

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We will make Z for finding the reaction of MMCS to a single jump of current – transformation of transfer function of the given continuous part of MMCS. It is known [4] that transfer function of pulse system with the shaper of a zero order is equal:

$$W(z) = W_1(z) - z^{-1} W_1(z, 1-\lambda), \tag{4}$$

Where $W_i(z) = Z\left\{\frac{W(p)}{p}\right\} - z$ - the transformed function from reaction of continuous part of the sensor to a single jump; Z - a symbol of z – transformations; $W_1(z,1-\lambda) = Z_\delta\left\{\frac{W(p)}{p}\right\}$ - the modified z – transformation from reaction of the given part of MMCS to a single jump; - a symbol of the modified z – transformation.

For finding the functions $W_1(z)$ and $W_1(z,1-\lambda)$ we will also use tables of z – transformations [5]:

$$W_1(z) = \frac{z(1-e^{-\frac{T}{\tau_f}})}{(z-e^{-\frac{T}{\tau_f}})(z-1)}, \tag{5}$$

$$W_1(z,1-\lambda) = \frac{z}{z-1} - \frac{z e^{-\frac{(T-T_u)}{\tau_f}}}{z-e^{-\frac{T}{\tau_f}}}. \tag{6}$$

Substituting (5) and (6) into (4) we receive:

$$W_1(z) = N\left[\frac{z(1-e^{-\frac{T}{\tau_f}})}{(z-1)(z-e^{-\frac{T}{\tau_f}})} - \frac{1}{z-1} + \frac{e^{-\frac{(T-T_u)}{\tau_f}}}{z-e^{-\frac{T}{\tau_f}}}\right] = N\frac{e^{-\frac{(T-T_u)}{\tau_f}} - e^{-\frac{T}{\tau_f}}}{z-e^{-\frac{T}{\tau_f}}}. \tag{7}$$

Output signal for the pulse system containing a key, the shaper and LPF is a reaction of an entrance chain of MMCS to a single jump of the current:

$$I_{ent}(t) = \frac{R_r}{R_0}(1-e^{-\frac{t}{\tau_{ent}}}). \tag{8}$$

[5]: Then its z – the image has the following appearance [5]:

$$I_{ent}(z) = \frac{R_r}{R_0}\frac{z(1-e^{-\frac{t}{\tau_{ent}}})}{(z-1)(z-e^{-\frac{t}{\tau_{ent}}})}. \tag{9}$$

Reaction of MMCS with the analog LPF in a single jump of current is registered with the expression:

$$U_{out}(z) = N\frac{R_r}{R_0}\frac{(e^{-\frac{T-\tau_u}{\tau_f}} - e^{-\frac{T}{\tau_\phi}})(1-e^{-\frac{T}{\tau_{ent}}})z}{(z-1)(z-e^{-\frac{T}{\tau_f}})(z-e^{-\frac{T}{\tau_{ent}}})} \tag{10}$$

We will make the return z – transformation having used tables [5]:

$$U_{out}(t) = N\frac{R_r}{R_0}(a_1 + a_2 e^{-\frac{t}{\tau_f}} + a_3 e^{-\frac{t}{\tau_{ent}}}), \tag{11}$$

where $a_1 = \frac{e^{-\frac{T-\tau_u}{\tau_f}} - e^{-\frac{T}{\tau_f}}}{1-e^{-\frac{T}{\tau_f}}}$, $a_2 = \frac{(e^{-\frac{T-\tau_u}{\tau_f}} - e^{-\frac{T}{\tau_f}})(1-e^{-\frac{T}{\tau_{ent}}})}{(1-e^{-\frac{T}{\tau_f}})(e^{-\frac{T}{\tau_{ent}}} - e^{-\frac{T}{\tau_f}})}$, $a_3 = \frac{e^{-\frac{T-\tau_u}{\tau_f}} - e^{-\frac{T}{\tau_f}}}{e^{-\frac{T}{\tau_f}} - e^{-\frac{T}{\tau_{ent}}}}$.

As the considered MMCS is a pulse link that values of an output signal are defined in time points $t = nT$ and are average values for the period, as the expression (11) doesn't consider the scope of pulsations at LPF exit.

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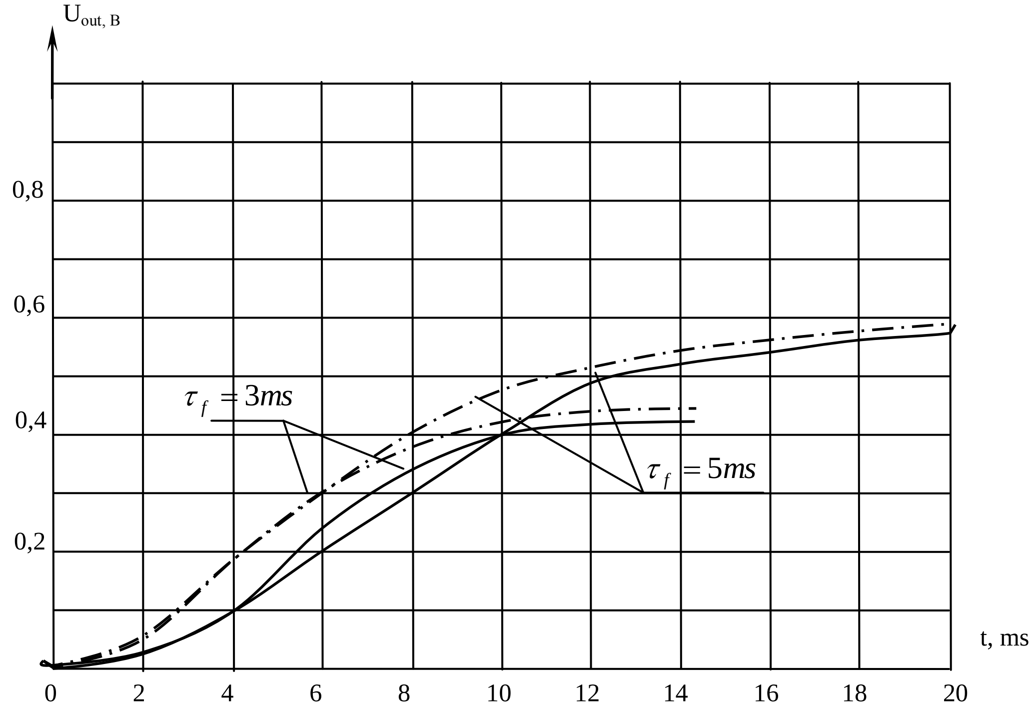

Fig. 4. Schedules of transition process at different values of τ_f : continuous – calculated ones; dotted – experimental.

As an example transitional characteristics on linear model of the considered MMCS with the amplifier limiter for the following parameters have been calculated $W_k = 150$; $W_б = 50$; $W_д = 4$; $R_0 = 0{,}0169$ $Ом$. The constant of time of LPF changed with a step of 0,5 ms from 1 ms to 5 ms. By means of linear model average value of output tension paid for the period. The inductance size $L_{ch} = \frac{L_{ch}(0) + L_{ch}(I_{x\max})}{2}$, where $I_{x\max}$ - the maximum value of current in tap I paid off at each step of calculations anew as she depends on current I_{ent} size.

In fig. 4. settlement schedules of transition processes in MMCS for an average during tension at the exit at $\tau_f = 3$ ms and $\tau_f = 5$ ms are shown. In the same place for comparison are brought bending around experimentally removed oscillograms of transition process. The divergence between settlement and experimental data doesn't exceed 11-15%. And at increase in a constant of time of LPF τ_f it is a divergence decreases, for example, at (τ_f / T)=8 the divergence makes $\delta = 15\%$, and at $\frac{\tau_f}{T} = 12$ and 16 – respectively 7% and 1,5%.

Now we will consider the MMCS nonlinear dynamic model. In it to article we will make the specified calculation transitional process in MMCS, without making at the same time replacement of PWM by AMS.

Now there is a number of methods of researches of nonlinear discrete systems [6]. Systems with modulation of width of an impulse are most precisely described by the method of space states [7]. It is the most general and quite simple. The exact decision in the analysis of system with PWM turns out in the form of the recurrent state allowing to find required sizes by means of step-by-step calculations. Other methods allowing to find a solution in an analytical look either are brought closer or are too difficult.

Management of a state discrete systems register in a matrix form [7]:

$$\frac{dV(x)}{dx} = AV(x) , \quad (12)$$

Where $x = t - nT$; T – impulse period; $V(x)$– a vector – the column representing at the same time output variables and variable states; A - a square matrix of coefficients.

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The solution of the equation (12) has the following appearance [7] $V(x)=F_0(x)V(0^+)$:
where $F_0(x)$- an expanded matrix of transition of system for an interval $0<x\le\tau_U$; τ_U - impulse duration; $V(0^+)$ - entry conditions at the moment $x=0^+$, i.e. on the right.
For an interval $\tau_U \le x \le T$ the solution of the equation (12) has an appearance: $V(x)=F_1(x)V(\tau_u^+)$
Where $F_1(x)$ - an expanded matrix of transition for this interval; $V(\tau_u^+)$- entry conditions at the moment $x(\tau_u^+)$.
For drawing up the equations of a condition of MMCS with PWM it is necessary to make previously the block diagram of the sensor for a method of space of states a constant of integrators and adders [6].
As an example of calculation of transition process we will take MMCS with the amplifier limiter at an impact of the only jump of the measured current I_x . For drawing up the block diagram of MMCS we will transform transfer function of an output chain as follows:

$$W_{out}(p)=\frac{I_{ent}(p)}{I_x(p)}=\frac{1}{1+p\tau_{ent}}=\frac{p^{-1}}{p^{-1}+\tau_{ent}},$$

Where τ_{ent} - a constant of time of an output chain. From here the current, magnifying the core, will be in equal to:

$$I_{ent}(p)=I_x(p)\frac{p^{-1}}{p^{-1}+\tau_{ent}} \quad (13)$$

We will designate $E_1=\frac{1}{(p^{-1}+\tau_{ent})}$ and after simple transformations we receive:

$$E_1(p)=\frac{1}{\tau_{ent}}-\frac{E_1(p)}{\tau_{ent}}p^{-1} \quad (14)$$

Similarly we will transform the LPF transfer function

$$U_{out}(p)=U_m(p)p^{-1}E_2p^{-1} \quad (15)$$

where

$$E_2(p)=\frac{1}{\tau_f}-\frac{E_2(p)}{\tau_f}p^{-1} \quad (16)$$

$U_m(p)$ – tension at the exit of the pulse-width modulator being leaving for LPF; E_1 and E_2 – signals on entrances of the corresponding integrators in the block diagram of MMCS.
Using ratios (13) – (16) we build the block diagram of MMCS for its analysis by the method of spatial states (fig. 5.). Variables currents are I_x , I_{ent} and tensions are U_m and U_{out} .

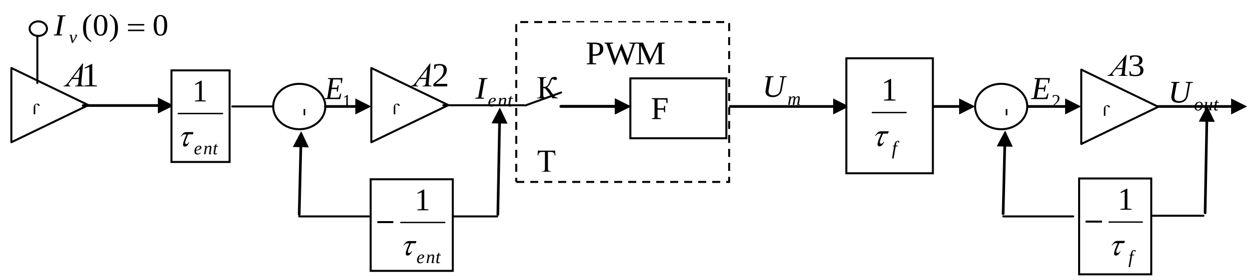

Fig. 5. the block diagram of MMCS for the analysis by the method space of states.

PWM on the block diagram is shown in the form of the key K, forming δ - impulses with method T and amplitude $I_{out}(nT)$ and the nonlinear shaper F forming positive rectangular impulses amplitude U_m on a piece $0\le x\le T_1$ and negative impulses with the same amplitude on a piece $T\le x\le_1 T$.
We will work out the equations of a condition of MMCS from the analysis of his block diagram. Its name is the differential equations of the first order for the variables I_x , I_{ent} , U_x , U_{out} :

ISSN: 2350-0328
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$$\begin{cases} \frac{dI_x}{d_x} = 0, \\ \frac{dU_x}{d_x} = 0, \\ \frac{dI_{ent}}{d_x} = \frac{I_x}{\tau_{ent}} - \frac{I_{ent}}{\tau_{ent}}, \\ \frac{dU_{ent}}{d_x} = \frac{U_m}{\tau_f} - \frac{I_{out}}{\tau_f} \end{cases} \tag{17}$$

Writing down system of the equations (6) in a matrix form, we will receive matrixes of variables and coefficients:

$$V(x) = \begin{bmatrix} I_x \\ I_{ent} \\ U_m \\ U_{out} \end{bmatrix}, \quad A = \begin{bmatrix} 0 & 0 & 0 & 0 \\ \frac{1}{\tau_{ent}} & -\frac{1}{\tau_{ent}} & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & \frac{1}{\tau_f} & -\frac{1}{\tau_f} \end{bmatrix}$$

The equations characterizing a condition of system at the time of switching is registered as follows:

$$\begin{cases} I_x(nT^+) = I_x(nT) \\ I_{ent}(nT^+) = I_{ent}(nT) \\ U_m(nT^+) = -U_m(nT) \\ U_{out}(nT^+) = U_{out}(nT) \end{cases} \tag{18}$$

Apparent from (18), at the moments of switching only the output signal of the pulse-width modulator changes a sign. For system of the equations (18) we will write down a matrix of switching:

$$B = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & -1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

The main objective in the analysis of systems by method of space of states is finding a transitional matrix. It is known [7] that the transitional matrix is equal:

$$F(t) = L^{-1}\{[pI - A]^{-1}\},$$

where I - a single matrix.
The matrix $[pI - A]$ is equal in our case:

$$[pI - A] = \begin{bmatrix} 1 & 0 & 0 & 0 \\ -\frac{1}{\tau_{ent}} & p + \frac{1}{\tau_{ent}} & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & -\frac{1}{\tau_f} & p + \frac{1}{\tau_f} \end{bmatrix}$$

We will write down the image according to Laplace of a transition matrix:

$$F(p) = [pI - A]^{-1} = \frac{1}{\det[pI - A]} \begin{bmatrix} A_{11} & A_{21} & A_{23} & A_{41} \\ A_{12} & A_{22} & A_{32} & A_{42} \\ A_{13} & A_{23} & A_{33} & A_{43} \\ A_{14} & A_{24} & A_{34} & A_{44} \end{bmatrix}$$

Where $\det[pI-A]=p^2\left(p+\frac{1}{\tau_{ent}}\right)\left(p+\frac{1}{\tau_f}\right)$ - determine the matrix of $[pI-A]$;

$$A_{11}=p\left(p+\frac{1}{\tau_{ent}}\right)\left(p+\frac{1}{\tau_f}\right);\ A_{21}=0;\ A_{31}=0;\ A_{41}=0;$$

$$A_{12}=\frac{p}{\tau_{ent}}\left(p+\frac{1}{\tau_f}\right);\ A_{22}=p^2\left(p+\frac{1}{\tau_f}\right);\ A_{32}=0;\ A_{42}=0;$$

$$A_{13}=0;\ A_{23}=0;\ A_{33}=p\left(p+\frac{1}{\tau_{ent}}\right)\left(p+\frac{1}{\tau_f}\right);\ A_{43}=0;$$

$$A_{14}=0;\ A_{24}=0;\ A_{34}=\frac{p}{\tau_{ent}}\left(p+\frac{1}{\tau_f}\right);\ A_{44}=p^2\left(p+\frac{1}{\tau_f}\right);$$

Having made the return transformation of Laplace of each element of a matrix $F(p)$, and substituting into it x instead of the values T_1 and T_2, we receive originals of a matrix of transition for the corresponding intervals of time.

For time interval $0<x\leq T_1$

$$F(T_1)=\begin{bmatrix} 0 & 0 & 0 & 0 \\ \left(1-e^{-\frac{T_1}{\tau_{ent}}}\right) & e^{-\frac{T_1}{\tau_{ent}}} & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & \left(1-e^{-\frac{T_1}{\tau_{ent}}}\right) & e^{-\frac{T_1}{\tau_{ent}}} \end{bmatrix}$$

For an interval $T_1<x\leq T$

$$F(T_2)=\begin{bmatrix} 0 & 0 & 0 & 0 \\ \left(1-e^{-\frac{T_2}{\tau_{ent}}}\right) & e^{-\frac{T_2}{\tau_{ent}}} & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & \left(1-e^{-\frac{T_2}{\tau_{ent}}}\right) & e^{-\frac{T_2}{\tau_{ent}}} \end{bmatrix}$$

The solution of the equation of a state (12) according to [7] has the following appearance:

$$V(x)=F(x)BV(0)$$

Here the entry conditions do not need to be defined at each step of calculations as the matrix B considers a change of conditions of variables at the switching moments.

We will designate $(T_1)=F(T_1)B$ and $(T_2)=F(T_2)B$.

The vector of entry conditions in a zero-time point has an appearance:

$$V=\begin{bmatrix} 1 \\ 0 \\ U_m \\ \Delta U_n \end{bmatrix}$$

where ΔU_n - amplitude of a pulsation of output tension.

For MMCS with the amplifier limiter a signal U_m is tension at the exit of the amplifier limiter. When using as the amplifier limiter of the integrated OU having supply voltage $\pm 12V$, amplitude of output tension will be near to $10V$.

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Amplitude of pulsations is found by means of one of a classical method of the analysis of linear chains. Having set entry conditions, we receive the solution of the matrix equation (12) in a look:

$$\begin{cases} V_n(T+T_1) = H(T_1)V_n(T) \\ V_{n+1}(T) = H(T_2)V_n(T+T_1) \end{cases}$$

Values T_1 and T_2, depending on current I_{ent} in the corresponding time points are on the expressions received in (8) if to substitute into them instead of the results of this expression $\frac{I_{ent}}{W_k}$.

IV. EXPERIMENTAL RESULTS

As an example transitional characteristics of output tension of MMTDC and average value of this tension for the period on the received MMPPT nonlinear model with the amplifier limiter for the following parameters have been calculated: $E = 20V$; $R = 200Om$; $R_b = 300\,Om$; $W_k = 150$; $W_k = 50$; $W_\partial = 4$; $r_0 = 0{,}0169\,Om$.

The constant of time of LPF changed with a step $0{,}5ms$ from $1ms$ to $5ms$.

In fig. 6. settlement schedules of transition processes of MMCS for the average during the tension in an exit at $\tau_f = 3ms$ and $\tau_f = 5ms$ are given. And for comparison the bending-around oscillograms, and also curves constructed on linear model are provided (fig. 4).

The comparative analysis of curve transition processes shows that the nonlinear model describes transition processes in MMCS more precisely, however, at an increase τ_f the mistake which is turning out when replacing PWM by AIM decreases. It is expedient to take a difference of duration of a transition process in the linear and nonlinear models measured at $U_{out} = 0{,}9U_{out,inst}$

$$\delta = \frac{T_H - T_L}{T_H} \cdot 100\,\%,$$

where T_H, T_L - settlement duration of transition process in nonlinear and linear models respectively.

In fig. 6. dependence $\delta = f\left(\frac{\tau_f}{T}\right)$ is given. From the schedule it is visible that at $\frac{\tau_f}{T} = 16$, $\delta < 2\%$ it is already quite sufficient for the analysis of MMCS loudspeakers by means of linear model especially as for effective suppression of pulsations of output tension it is necessary to choose considerably big sizes of τ_f.

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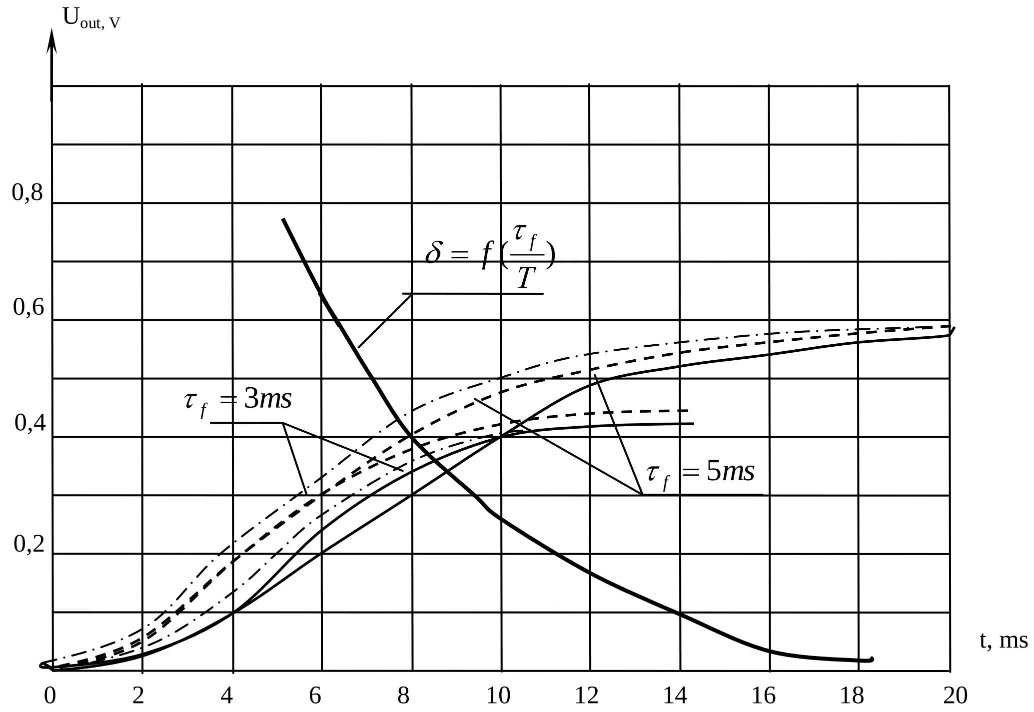

Fig. 6. Schedules of transitional processes at different values of τ_f and dependences of a mistake when calculating duration of transition process in MMCS by means of linear model from size $\frac{\tau_f}{T}$: continuous – on linear model; dash-dotted – on nonlinear model; dotted – experiment.

V. CONCLUSION

Thus, in this article the MMCS nonlinear dynamic model is developed. It is shown that at big constants of time of LPF $\left(\left(\frac{\tau_f}{T}\right) \geq 16\right)$ it is reasonable to represent MMCS in the block diagram of automatic control system in the form of a linear pulse link with PWM.

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