Current Inverter as Actuator for Plasma Position Control Systems in Tokamaks

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***Abstract* — The mode of operation for single-phase thyristor current inverter (CI), allowing to control the current's value in an inductive load, is proposed. The control algorithm for the CI, forming the average (on a period of auto-oscillations) output voltage, proportional to the value of the input control signal at minimal voltage amplitude, is designed. The initial stage of the CI operation (current increasing through the inductive energy storage and the CI's launching into the auto-oscillation mode of operation) is proposed. The autonomous protection elements for the CI are presented. The experimental test done has demonstrated the reliability of the designed control algorithm and the declared quality of the CI's operation reaching.**

***Index Terms* — tokamak, plasma position control system, control system's actuator, current inverter, auto-oscillations.**

I. INTRODUCTION

Tokamaks [1] are the leaders in the present thermonuclear fusion race. High temperature plasma in tokamaks is confined by strong toroidal magnetic field together with plasma current field and poloidal magnetic fields created by a set of magnetic coils powered by controlled power supplies of various types: multiphase thyristor rectifiers [2], voltage [2-4] and current inverters [5,6]. For tokamak plasma shape and plasma current control [7] the response time of the controlled thyristor rectifier is sufficient. However, for plasma position control systems in tokamaks the actuators with faster response time are often needed. For example, IGBT voltage inverters are used on TCV (Switzerland) [3] and EAST (China) [4] tokamaks, CIs are exploited in Globus-M (Ioffe Institute, S-Petersburg, Russia) [5] and T-11M (TRINITI, Troitsk, Russia) tokamaks [6].

This paper represents the high-performance actuator of plasma position control systems on the base of single-phase thyristor CI with response time of the order of 200 μs. This actuator operates in four quadrants: positive-negative voltage, applied to a control coil, positive-negative current through a control coil.

The paper is organized by the following way. Section II describes the CI's mode of operation, which allows to control the current's value through an inductive load, and the CI's control goal statement. In Section III the CI's control algorithm is designed. The CI's initial stage of operation is described in Section IV. Autonomous protection elements of the CI are presented in Section V. The results of the CI's experimental test are shown in Section VI. Conclusion summarizes the basic achievements of this work.

II. CI'S MODE OF OPERATION

The schematic of single-phase bridge thyristor CI is shown in Fig. 1a. The voltage source U_0 together with the inductive energy storage L_S forms the current source I_S. The inductive load L of the CI in Fig. 1a denotes the appropriate equilibrium coil of a tokamak.

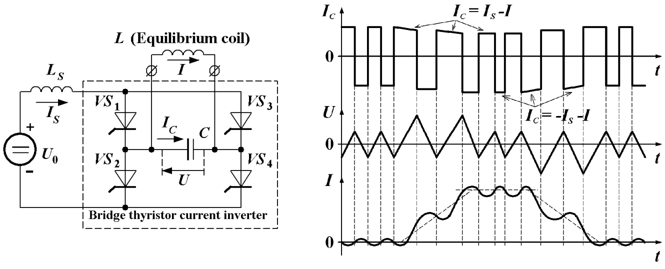

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Fig.1. a) Electrical circuit of single-phase bridge thyristor CI. b) Time diagrams of: the current I_C through the capacitor C, the CI's output voltage U and the current I through the equilibrium coil L.

The time diagrams in Fig. 1b explain the CI's operational mode, which allows to control the value of the current I through the equilibrium coil L. Suppose some current I_S flows already through the inductive energy storage L_S (Fig. 1a) and the thyristors VS_1, VS_4 are turned on. The capacitor C is charged by the current $I_C=I_S-I$. The voltage U on the capacitor C is increased and when it reaches some positive (in accordance with Fig. 1) value, the thyristors VS_2, VS_3 are switched on. Since reverse voltage of the capacitor C is now applied to the thyristors VS_1, VS_4, they are switched off and the capacitor C is further being recharged by the current $I_C=-(I_S+I)$. When the voltage U on the capacitor C reaches some negative value, the thyristors VS_1, VS_4 are switched on again. Now the reverse voltage is applied to the thyristors VS_2, VS_3. Further this process is repeated. Choosing properly the levels of the voltage U, at which CI's switching take place, it is possible to vary the average (on a period of auto-oscillations) voltage, applied to the coil L and therefore to control the current's value I through the equilibrium coil L.

The block diagram of the actuator on the base of the thyristor CI is presented in Fig. 2.

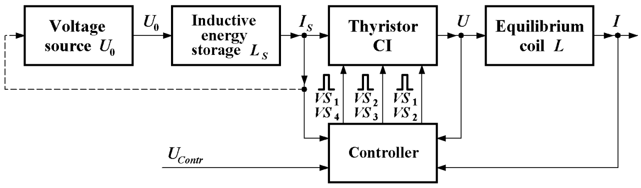

Fig. 2. Block diagram of the actuator on the base of CI.

The voltage source U_0 provides the current I_S flowing through the inductive energy storage L_S. The voltage source U_0 can be the controlled one: this case is denoted by the dotted line in Fig. 2 showing the feedback loop, which stabilizes the current I_S at the given value $I_S \approx$Const.

The control goal for the CI is formulated as follows. It is necessary to design the controller, which converts the input control signal U_{Contr} to firing pulses for corresponding thyristors of the CI (Fig. 2) in accordance with the demands:

- The controller must provide stable auto-oscillations of the CI at any values of currents I_S, I and at any value of the input control signal U_{Contr}.
- The average (on a period of auto-oscillations) voltage, applied to the equilibrium coil L, must be proportional to the value of the input control signal U_{Contr}: $\bar{U} = k \cdot U_{Contr}$.
- The amplitude of output voltage U must be close to minimum, available for the given CI's parameters and for any values of I_S, I, and U_{Contr}.

III. CI'S CONTROL ALGORITHM

In accordance with Fig. 1a the state equations for the CI are as follows.

The first state, VS_1, VS_4 are turned on $(\dot{U} > 0)$:

$$\dot{U} = (I_S - I)/C, \quad \dot{I} = U/L. \tag{1}$$

The second state, VS_2, VS_3 are turned on $(\dot{U} < 0)$:

$$\dot{U} = (-I_S - I)/C, \quad \dot{I} = U/L. \tag{2}$$

The control algorithm for the CI is based on the assumption that $\dot{U} \approx Const$ on time intervals between CI's switching.

The important parameter of the thyristors used is the turn off time τ_q. Introduce the parameter $\tau_{\min} \geq \tau_q$ (the guaranteed time for the thyristor's turn off).

Fig. 3a shows the detailed time diagram of the voltage $U(t)$ at the CI's state 1 $(\dot{U} > 0)$ and $U(0)=-U_0$ (the point A in Fig. 3a). The capacitor C is charged by the current $I_C=I_S-I$. To turn on the thyristors VS_2, VS_3 on the time interval AB is impossible because of the reverse voltage, applied to these thyristors. Firing the thyristors VS_2, VS_3 on the interval BC must be prohibited because of the time interval, during which the reverse voltage will be applied to the thyristors VS_1, VS_4, will be less, than $\tau_{\min}$.

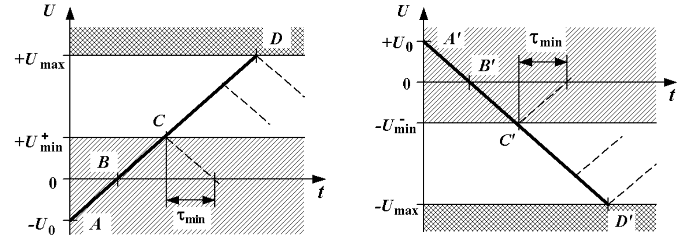

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Fig. 3. Time diagrams of the CI's output voltage $U(t)$ at the:
a) state 1 ($\dot{U} > 0$); b) state 2 ($\dot{U} < 0$).

And only at the point C (Fig 3a), for which the time of the positive voltage U decreasing to zero will be equal to $\tau_{\min}$, switching to the state 2 is possible without disruption of CI's auto-oscillations. Assuming, that current $I_C=-(I_S+I)$ is changed insignificantly during the time interval $\tau_{\min}$, it is possible to write the next expression for voltage U at the point C (Fig. 3a):

$$U = U^{+}_{\min} = (I_S + I) \cdot \tau_{\min} / C . \tag{3}$$

Introduce Boolean variables x_0, x_1 in accordance with the conditions:

$$\begin{cases} x_0 = 1, \text{ if } \dot{U} > 0; \\ x_0 = 0, \text{ if } \dot{U} < 0. \end{cases} \qquad \begin{cases} x_1 = 1, \text{ if } U \geq U^{+}_{\min}; \\ x_1 = 0, \text{ if } U < U^{+}_{\min}. \end{cases}$$

Also, consider auxiliary Boolean control signals u_1 and u_2. Agree, that $u_1=1$ is the command for CI's switching from state 1 to state 2, and $u_2=1$ is the command for CI's switching from state 2 to state 1.

Boolean variables y_1, y_2 denote the output Boolean signals of the controller: $y_1=1$ corresponds to the firing pulses for the thyristors VS_2, VS_3 (CI's switching from state 1 to state 2), and $y_2=1$ corresponds to the firing pulses for the thyristors VS_1, VS_4.

Thus, for the CI's switching from state 1 to state 2 without disruption of auto-oscillations, it is necessary to provide:

$$y_1 = u_1 \wedge x_0 \wedge x_1 , \tag{4}$$

where the symbol " $\wedge$ " is the sign of the logical "AND".

If there was no switching of the CI to state 2 on the interval CD (Fig. 3a) due to Boolean control signal u_1, then at the point D, at which the voltage U reaches the value $U_{\max}$ (the maximum voltage for the thyristors used), forced CI's switching to state 2 must be done independently on other conditions.

Introduce Boolean variable x_2 in accordance with the conditions:

$$x_2 = 1,\ \text{if}\ U \geq U_{\max}; \qquad x_2 = 0,\ \text{if}\ U < U_{\max}.$$

The equation (4) is transformed to the next one:

$$y_1 = (u_1 \wedge x_0 \wedge x_1) \vee x_2, \tag{5}$$

where the symbol "$\vee$" is the sign of the logical "OR".

In addition, introduce two Boolean blocking signals b_1 and b_2. If b_1=0 or b_2=0 then y_1=y_2=0=*Const* independently on other conditions (that is, no CI's switching is possible). The difference between the signals b_1 and b_2 is that b_1 is the ''external'' blocking signal, needed for organization of the initial stage of CI's operation, while b_2=0 is the output signal of the timer, started at the moments of CI's switching. Thus, the next change of the CI's state is possible only after the time interval (from previous switching) becomes greater, than timer's pulse duration (τ~50 μs). It is necessary to prevent false firing pulses for the thyristors VS_1-VS_4 during transients in the CI, when essential switching interferences arise. Thus, the final form of the equation (5) is:

$$y_1 = b_1 \wedge b_2 \wedge [(u_1 \wedge x_0 \wedge x_1) \vee x_2]. \tag{6}$$

Analogous areas for the CI's state 2 ($\dot{U} < 0$) are shown in Fig. 3b. The voltage U at the point C' is determined by the expression:

$$U = -U^{-}_{\min} = -(I_S - I) \cdot \tau_{\min} / C, \tag{7}$$

and the condition $U \leq -U_{\max}$ is verified at the point D'.

Introduce Boolean variables x_3, x_4 in accordance with the conditions:

$$\begin{cases} x_3 = 1,\ \text{if}\ U \leq -U^{-}_{\min}; \\ x_3 = 0,\ \text{if}\ U > -U^{-}_{\min}. \end{cases} \qquad \begin{cases} x_4 = 1,\ \text{if}\ U \leq -U_{\max}; \\ x_4 = 0,\ \text{if}\ U > -U_{\max}. \end{cases}$$

Correspondingly, the expression for the output signal y_2 is:

$$y_2 = b_1 \wedge b_2 \wedge [(u_2 \wedge \overline{x}_0 \wedge x_3) \vee x_4], \tag{8}$$

where the symbol "$\overline{*}$" is the sign of the logical negation.

Suppose, that some positive average (on a period of auto-oscillations) value $\overline{U}$ of the output voltage U is fixed. It is obviously that for the requirement of minimum U amplitude executing (the third part of the control goal) it is necessary to fix the negative voltages U (at which the CI's switching from state 2 to state 1 arises) at the level $U = -U^{-}_{\min}$. Then: $\overline{U} = (U^{+} - U^{-}_{\min})/2$, where U^{+} - are the levels of the positive voltages U, at which the CI's switching from state 1 to state 2 must be done. Thus:

$$U^{+} = 2 \cdot \overline{U} + U^{-}_{\min} = 2 \cdot \overline{U} + (I_S - I) \cdot \tau_{\min} / C. \tag{9}$$

Analogously, for the case of the given negative average value $\overline{U}$ of the output voltage U, the CI's switching from state 1 to state 2 should be done at the levels $U = +U^{+}_{\min}$ and the negative voltages U^{-}, at which the CI's switching from state 2 to state 1 should be done, are determined by the equation:

$$U^{-} = 2 \cdot \overline{U} - U^{+}_{\min} = 2 \cdot \overline{U} - (I_S + I) \cdot \tau_{\min} / C. \tag{10}$$

According to the second part of the control goal: $\overline{U} = k \cdot U_{Contr}$. Thus:

$$U^{+} = 2 \cdot k \cdot U_{Contr} + (I_S - I) \cdot \tau_{\min} / C, \tag{11}$$

$$U^{-} = 2 \cdot k \cdot U_{Contr} - (I_S + I) \cdot \tau_{\min} / C. \tag{12}$$

To satisfy the second part of the control goal it is necessary to impose the following conditions on auxiliary Boolean control signals u_1 and u_2:

$$u_1 = 1\ \text{if}\ U \geq U^{+}; \quad u_1 = 0\ \text{if}\ U < U^{+}. \tag{13}$$

$$u_2 = 1\ \text{if}\ U \leq U^{-}; \quad u_2 = 0\ \text{if}\ U > U^{-}. \tag{14}$$

In conclusion it is necessary to limit the absolute value of the current I through the equilibrium coil L in accordance with the relation: $|I| < I_{\max} < I_S$. The current I limitation should preferably be provided on the analog level by the restrictions on the input control signal U_{Contr}: before the input control signal U_{Contr} using in (11), (12), it is necessary to process it the unit, choosing the average value of the three signals: $U^{+}_{Contr} = K \cdot (I_{\max} - I)$, $U^{-}_{Contr} = K \cdot (-I_{\max} - I)$, and U_{Contr}, where the U^{+}_{Contr} and the U^{-}_{Contr} are the control algorithms, stabilizing the value of the current I at the levels ($+I_{\max}$) and ($-I_{\max}$) correspondingly.

One of the possible controller's structure, realizing the CI's control algorithm (6), (8), (11-14), is presented in Fig. 4.

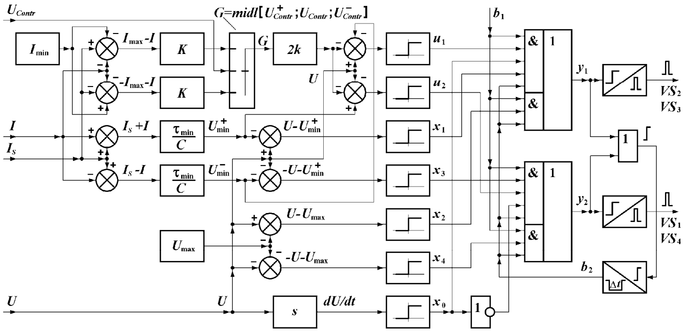

Fig. 4. Block diagram of the CI's controller.

It is obviously, that other variants of the controller's structure are possible (including, for example, the use of microcontrollers).

IV. INITIAL STAGE OF THE CI'S OPERATION

Here one of the possible scenario for the initial CI's operation (current I_S increasing through the inductive energy storage L_S and the CI's launching into the auto-oscillation mode of operation) is presented.

In comparison with the CI's electrical circuit in Fig. 1a the electrical circuit in Fig. 5 is added by the starting capacitor C_0 and the thyristor VS_0.

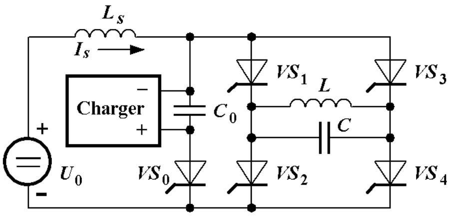

Fig. 5. Electrical circuit of the CI with the starting elements.

Before the operation cycle beginning the capacitor C_0 is charged to some voltage U_{C0} in the polarity given in Fig. 5.

The operation cycle of the actuator starts with the voltage source U_0 switching on and simultaneously the thyristors VS_1, VS_2 turning on (see Fig. 2). The current I_S is increased and when it reaches some threshold level $I_{S\,\min}$, the thyristor VS_0 is turned on. Now the reverse voltage of the charged capacitor C_0 is applied to the thyristors VS_1, VS_2, and these thyristors are switched off. The current I_S recharges now the capacitor C_0 and when the positive voltage U_{C0} (on the upper electrode of the capacitor C_0 in Fig. 5 relatively to the bottom electrode) exceeds some value $+U_{C0\,\min}$ the thyristor's pair VS_1, VS_4 (or VS_2, VS_3) are turned on. The thyristor VS_0 is switched off by the reverse voltage of the capacitor C_0 and remains off up to the operation cycle finish. With some delay the blocking signal b_1 is switched to logical "1" and further the CI operates in the auto-oscillation mode.

The CI's operation cycle is terminated when the current I_S is decreased below some critical level, at which one of the thyristors VS_1-VS_4 does not have enough time to turn off and disruption of auto-oscillation occurs.

V. AUTONOMOUS PROTECTION ELEMENTS

Each thyristor module VS_x (VS_0-VS_4 in Fig. 5) contains (except the thyristor itself) the protection elements:

- powerful varistor VR_{VSx} in parallel with the thyristor VS_x, which limits the voltage applied to the thyristor at the level $U_{VR}<U_{DRM}$ (and $U_{VR}<U_{RRM}$);
- inductor L_{VSx} in series with the thyristor for the (dI/dt) limitation at a thyristor's turning on ($(dI/dt)<(dI/dt)_{crit}$).

The value of the parameter $U_{\max}$ in the CI's control algorithm is chosen less then stabilization voltage U_{VR}.

The fact that the CI is powered by the current source I_S is, on the one hand, the positive factor in the case of the CI's auto-oscillations disruption, when one of the thyristors VS_1-VS_4 does not have enough time to turn off and throughout switching of the thyristors VS_1, VS_2 (or the thyristors VS_3, VS_4) occurs. The nominal current I_S flows throughout the thyristors VS_1, VS_2 (or the thyristors VS_3, VS_4) in this case and these thyristors don't fail. After the current I_S termination the CI is ready for operation again. Namely this feature of the CI allows to choose the value of the parameter $\tau_{\min}$ in the CI's control algorithm being close to the turn off time τ_q of the thyristors used.

On the other hand, the current source I_S is a very dangerous energy source because of any fault of the CI's control algorithm or the electrical connections breaking lead to the fault of the power supply circuit: the stored in the coil L_S energy must be applied to some element of the power supply circuit.

The controller's failure (the firing pulses loss for one of the thyristor's pairs VS_1, VS_4 or VS_2, VS_3) leads to the CI's direct current (DC) bus voltage U_{AB} (see Fig 6b) increasing up to the stabilization voltage U_{VR} of the protective varistors VR_{VSx} (the dotted line in Fig. 6a). These means, that the current I_S now flows through the protective varistors VR_{VSx} of the closed (at this time) thyristor's pair VS_1, VS_4 or VS_2, VS_3.

The varistors VR_{VSx} are protected the CI's thyristors from overvoltage but are usually destroyed themselves.

Not better situation occurs when, due to the firing pulses loss the voltage U_{AB} reaches the stabilization voltage U_{VR} of the protective varistors VR_{VSx}, and, nevertheless the firing pulses are formed further. The inductance of the thyristor VS_x – varistor VR_{VSx} loop is negligible and the current I_S, now flowing through the varistor VR_{VSx}, is switched to opening thyristor very fast that leads to the thyristor's fault due to the $(dI/dt)_{crit}$ overshooting.

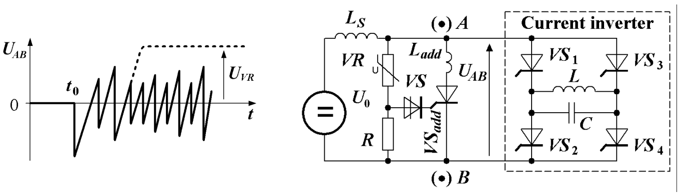

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Fig. 6. a) CI's input voltage U_{AB} diagram. b) CI's electrical circuit with the protection elements.

To avoid the described above damage events it is necessary to prevent the current I_S flowing through the protective varistors VR_{VSx}. One of the possible protection variant consists of the CI's DC bus (U_{AB}) shorting, when the voltage U_{AB} overshoots some threshold level U_{thresh}: $U_{\max}<U_{thresh}<U_{VR}$. Fig. 6b represents the CI's protection circuit with additional thyristor VS_{add}, shorting the CI's DC bus in case of the voltage U_{thresh} overshooting.

When the voltage U_{AB} exceeds the stabilization voltage U_{thresh} of the varistor VR (Fig. 6b) the current begins to flow through the varistor VR, creating the voltage drop on the resistor R. When this voltage exceeds the threshold level for the dinistor VS turning on, the firing pulse for the thyristor VS_{add} is formed. The thyristor VS_{add} is turned on, shorting the CI's DC bus. The current I_S now flows through the thyristor VS_{add} up to the current I_S termination.

The inductor L_{add} in series with the thyristor VS_{add} restricts (dI/dt) at the thyristor's VS_{add} turning on.

The specificity of the actuator's operation in tokamak is the strong magnetic coupling of the equilibrium coil with other poloidal coils of tokamak and the plasma itself. The most significant disturbances of the equilibrium coil's current occur at the plasma current disruption. To prevent the inductive disturbances influence on the CI's control algorithm it is useful to add the ballast coil L_{ball} (with inductance of the order of $0{,}1 \cdot L$) in series with the equilibrium coil L.

VI. EXPERIMENTAL TEST

In this Section the results of the experimental test for the actuator of the horizontal plasma position control system in the T-11M tokamak (Troitsk Institute for Innovation & Fusion Research, Troitsk, Russia) are presented.

The actuator of the above system on the base of CI is built with use of the thyristors TB173-2000 (U_{DRM}=U_{RRM}=2 kV, I_{TAV}=2 kA, $\tau_q \approx 80$ µs). The value of the parameter $\tau_{\min}$ in the CI's control algorithm is chosen equal (with some gap) to $\tau_{\min}$=100 µs. The value of the parameter $U_{\max}$ is equal to 1.5 kV (slightly less than the stabilization voltage U_{VR}=1.8 kV of the protective varistors VR_{VSx} used). The capacitor (C=420 µF) consists of three capacitors IM140-5 (140 µF, 5 kV) in parallel. The inductance of the equilibrium coil L of the above system (with the safety ballast coil $L_{ball} \approx 300$ µH) is about 3 mH.

The current source I_S consists of the pre-charged capacitive energy storage (C_S=36 mF, $U_0 \approx 2.5$ kV) (Fig. 1a) with the controlled thyristor switch, stabilizing the current I_S at the level $I_S \approx 2$ кA. The experimental test of the actuator was made in the regime of the current's $I(t)$ tracking for the "program" $I_{ref}(t)$ using the proportional control algorithm: $U_{Contr}=K \cdot [I_{ref}(t)-I(t)]$. The "program" $I_{ref}(t)$ is presented by the sine wave: $I_{ref}(t)=0.75 \cdot \mathrm{Sin}(2\pi \cdot 15 \cdot t)$ [kA] (the sine wave with the frequency 15 Hz at the amplitude 0.75 kA). The experimental results of the actuator test are presented in Fig. 7, showing the current $I(t)$ tracking for the "program" $I_{ref}(t)$ with sufficient accuracy.

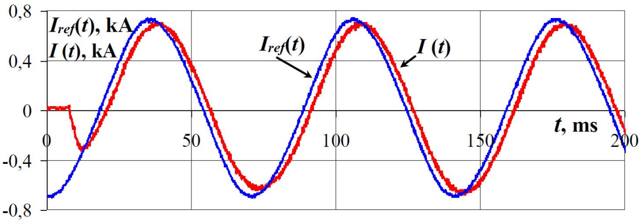

Fig. 7. Waveforms of the $I_{ref}(t)$ $I(t)$ ($I_{ref}(t)=0.75 \cdot \mathrm{Sin}(2\pi \cdot 15 \cdot t)$ [кA]).

The waveforms in Fig. 7 were made by the signals $I_{ref}(t)$ and $I(t)$ sampling with sampling period 100 µs. In parallel the signal of the CI's output voltage $U(t)$ were sampled with the same period 100 µs. Fig. 8 presents the fragment of the $U(t)$ waveform in the neighborhood of the 86th ms of the waveforms of Fig. 7 (the stage of the current $I(t)$ increasing).

The $U(t)$ samples in Fig. 8 are marked by the rhombus symbols with the sampling period 100 µs. The $U(t)$ waveform is restored by the linear approximation of the $U(t)$ signal on the time intervals between the CI's switching.

The restored $U(t)$ waveform (see Fig. 8) shows, that the time intervals from the moments of the CI's switching from state 2 ($\dot{U} < 0$) to the moments of the $U(t)$ zero crossing, are approximately equal to 100 µs (that is, $\tau_{\min}$). This means, that the actuator on the base of the CI operates at the switching frequencies, close to the maximum possible.

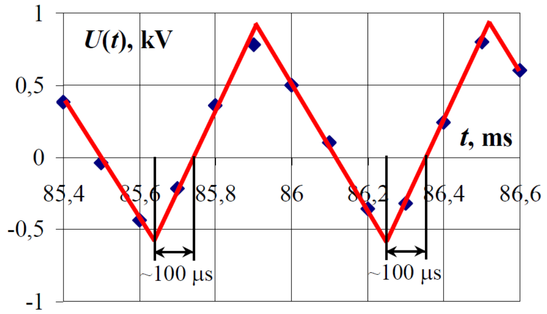

Fig. 8. Fragment of the CI's output voltage U waveform.

CONCLUSION

The described above actuators on the base of the thyristor CI operates effectively in such present tokamaks, as Globus-M (Ioffe Institute, S-Petersburg, Russia, 3 actuators) and T-11M, (Troitsk Institute for Innovation & Fusion Research, Troitsk, Russia, 2 actuators). Plasma position control systems of these tokamaks are provided their operations and the research programs carrying out in the fields of plasma physics and controlled thermonuclear fusion.

The described in this paper actuator can be also used in other applications, where the control of the current's value in an inductive load is needed with high performance and high accuracy.

ACKNOWLEDGMENT

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