

ООО “Center of ultrasonic technologies”

Methods and algorithms for controlling ultrasonic devices

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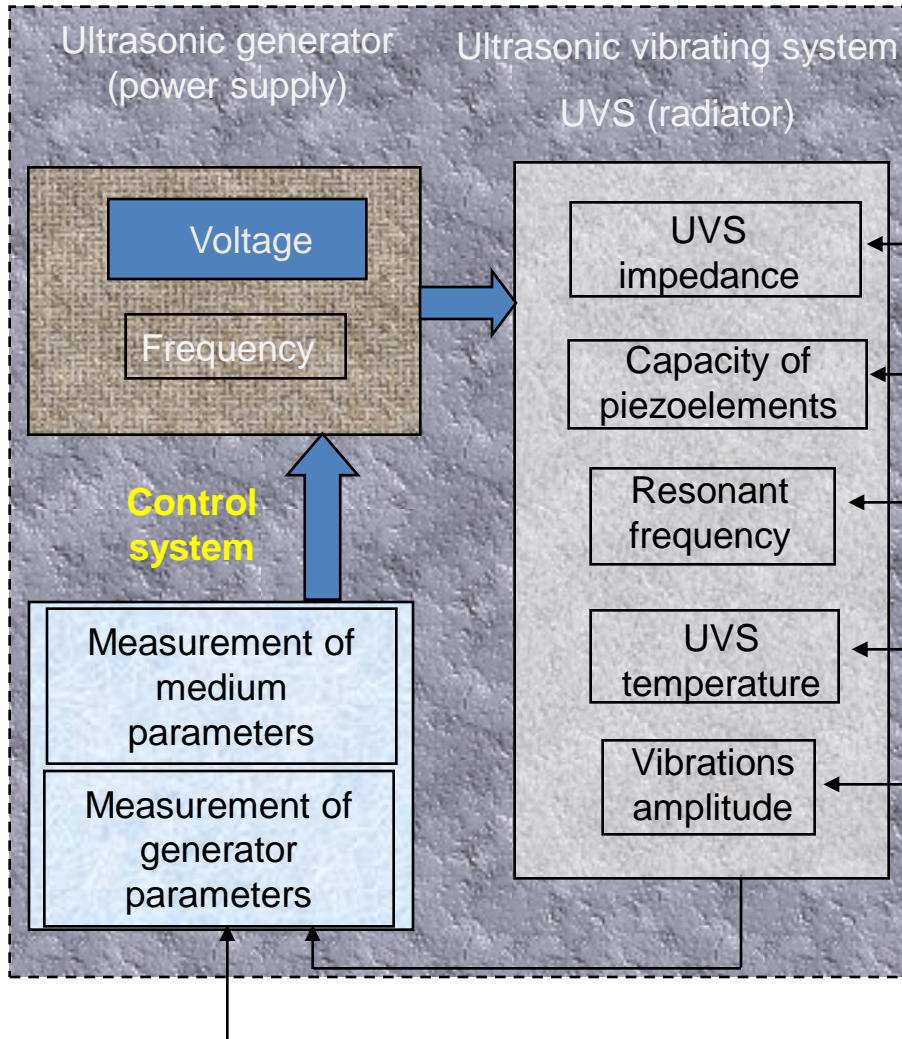
Doctor of Technical Sciences, Professor, Honored Inventor of the Russian Federation, Senior Member IEEE. Laureate of the Russian Government Award in the field of science and technology, author of more than 900 scientific publications (including more than 100 patents, more than 20 monographs and textbooks), Deputy Director for Scientific Work of the Biysk Technological Institute of the Altai State Technical University.

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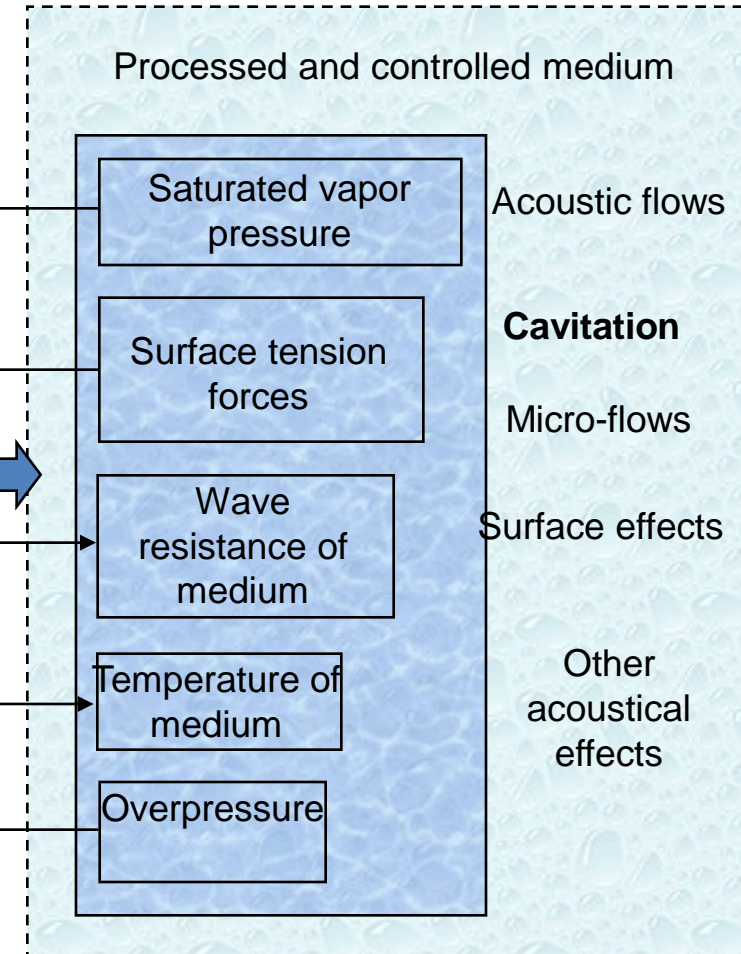
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Ultrasonic exposure

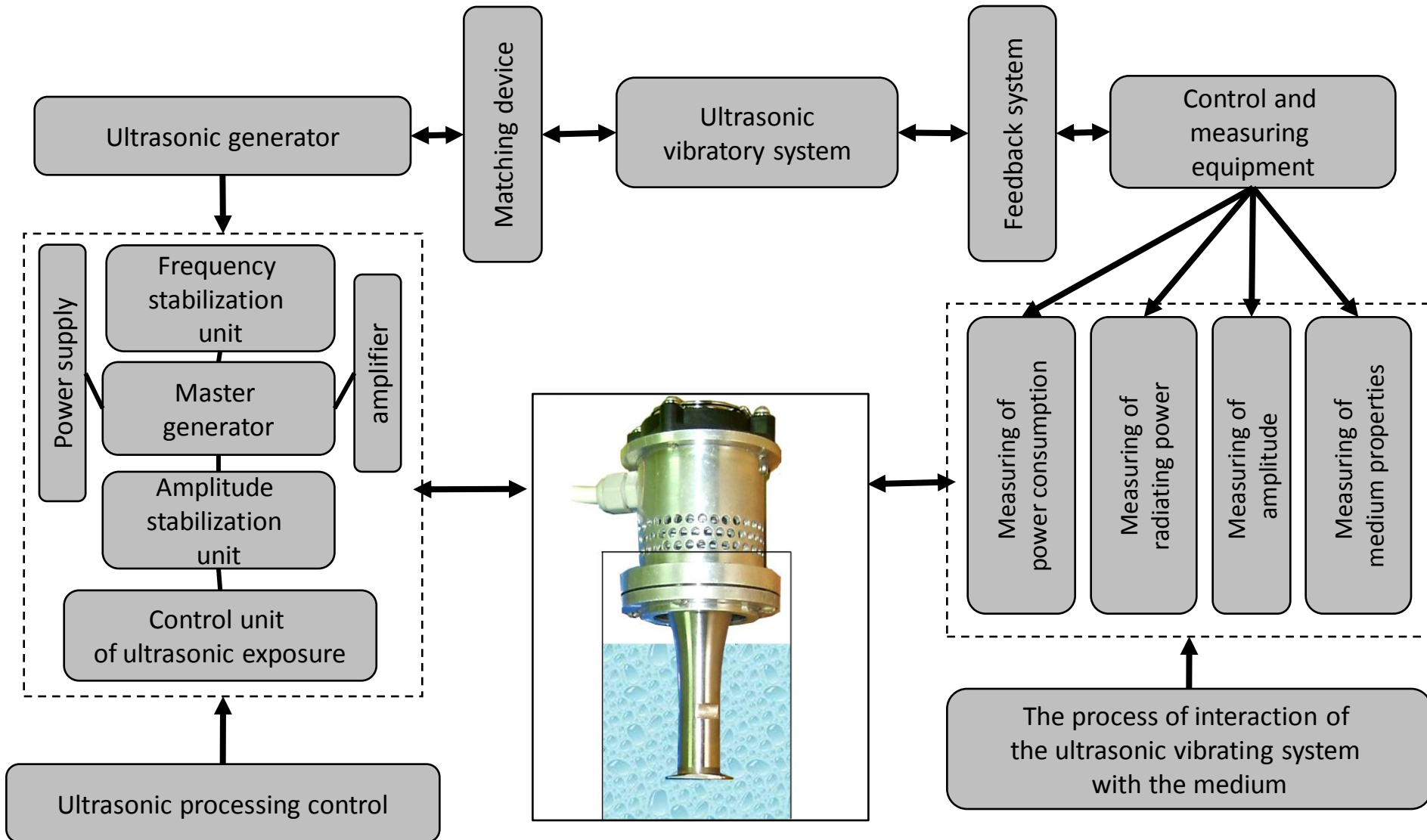
Ultrasonic industrial device



Technological process



Ultrasonic industrial device



Controlling parameters

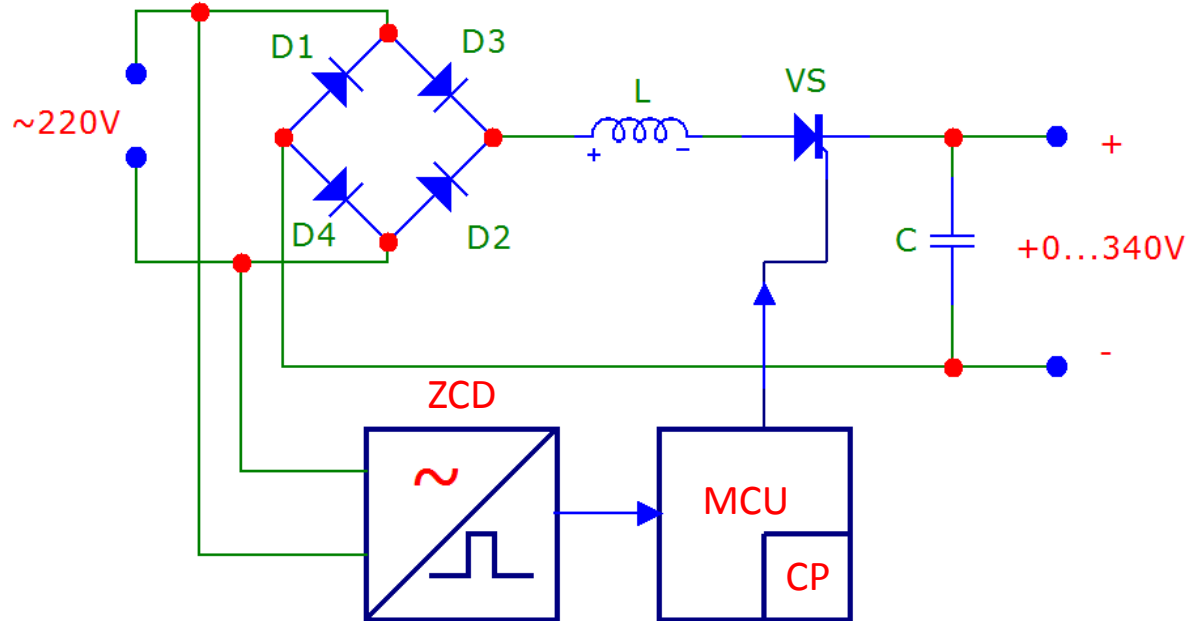
- 1. Power consumption: adjustment of amplitude and intensity of ultrasonic exposure.
- 2. Frequency of electric vibrations: ensuring compliance with the resonance frequency of the vibratory system under any conditions.
- 3. Operating modes of the generator: ensuring optimal exposure.

Principles of power regulation of ultrasonic generators

Changing the supply voltage of the high-frequency converter of the ultrasonic generator using:

1. a single-phase thyristor regulator.
2. a 3-phase thyristor voltage regulator.
3. a switch-mode step-down power regulator.

Circuit of a single-phase thyristor power regulator



ZCD – zero-cross detector;
MCU – microcontroller unit;
CP – control program;
VS – power thyristor key.

Ranges of phase change of the control pulses of the power key of the regulator

The range of the phase change of the control pulses:

$$\varphi = 90 \dots 180; \varphi = 270 \dots 360$$

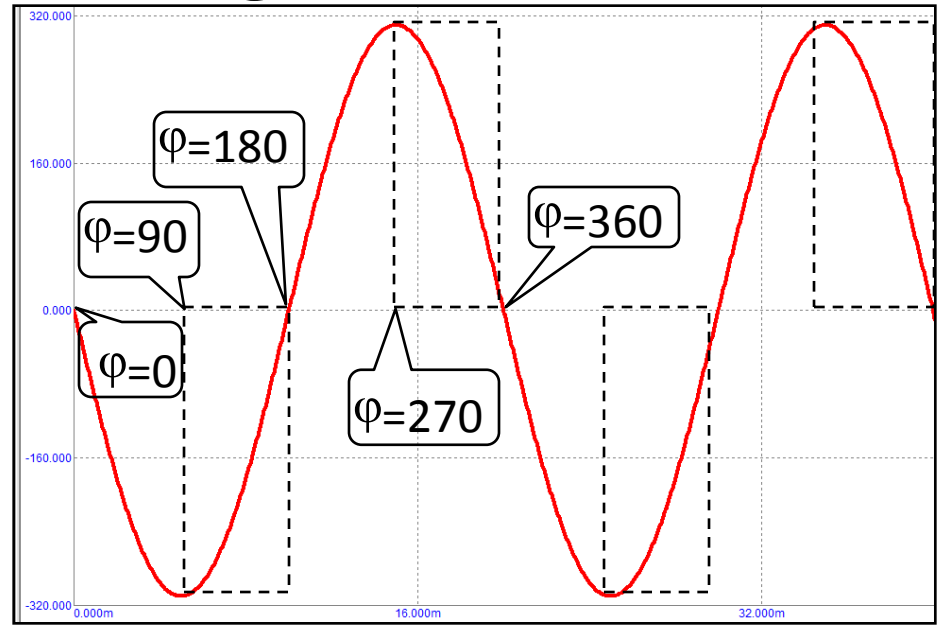


Figure 1 – The form of the supply network voltage with operation zones of the thyristor regulator

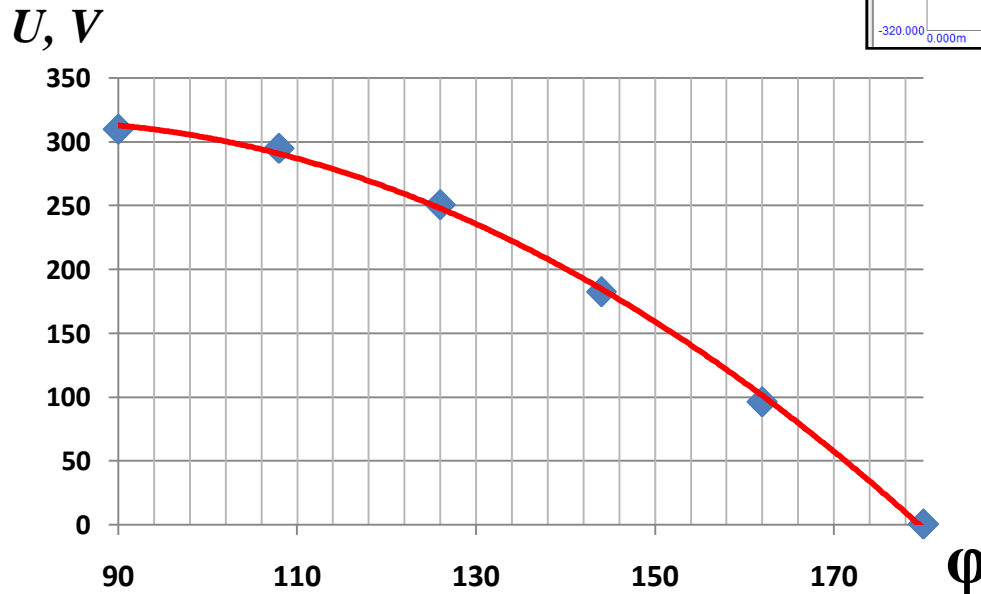
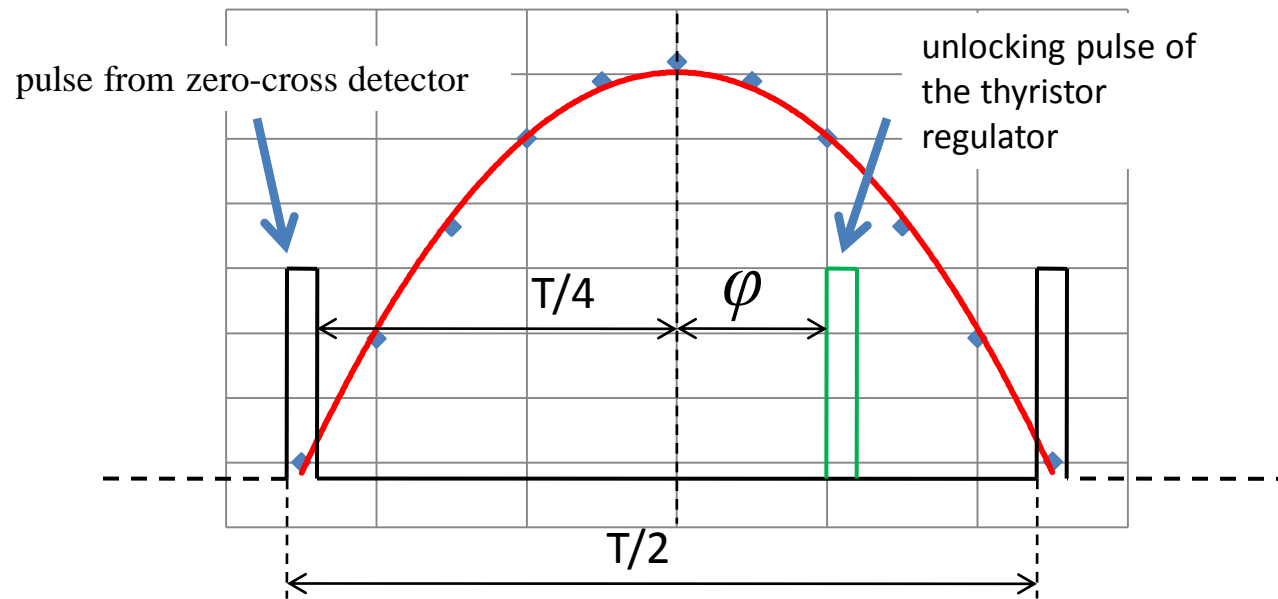


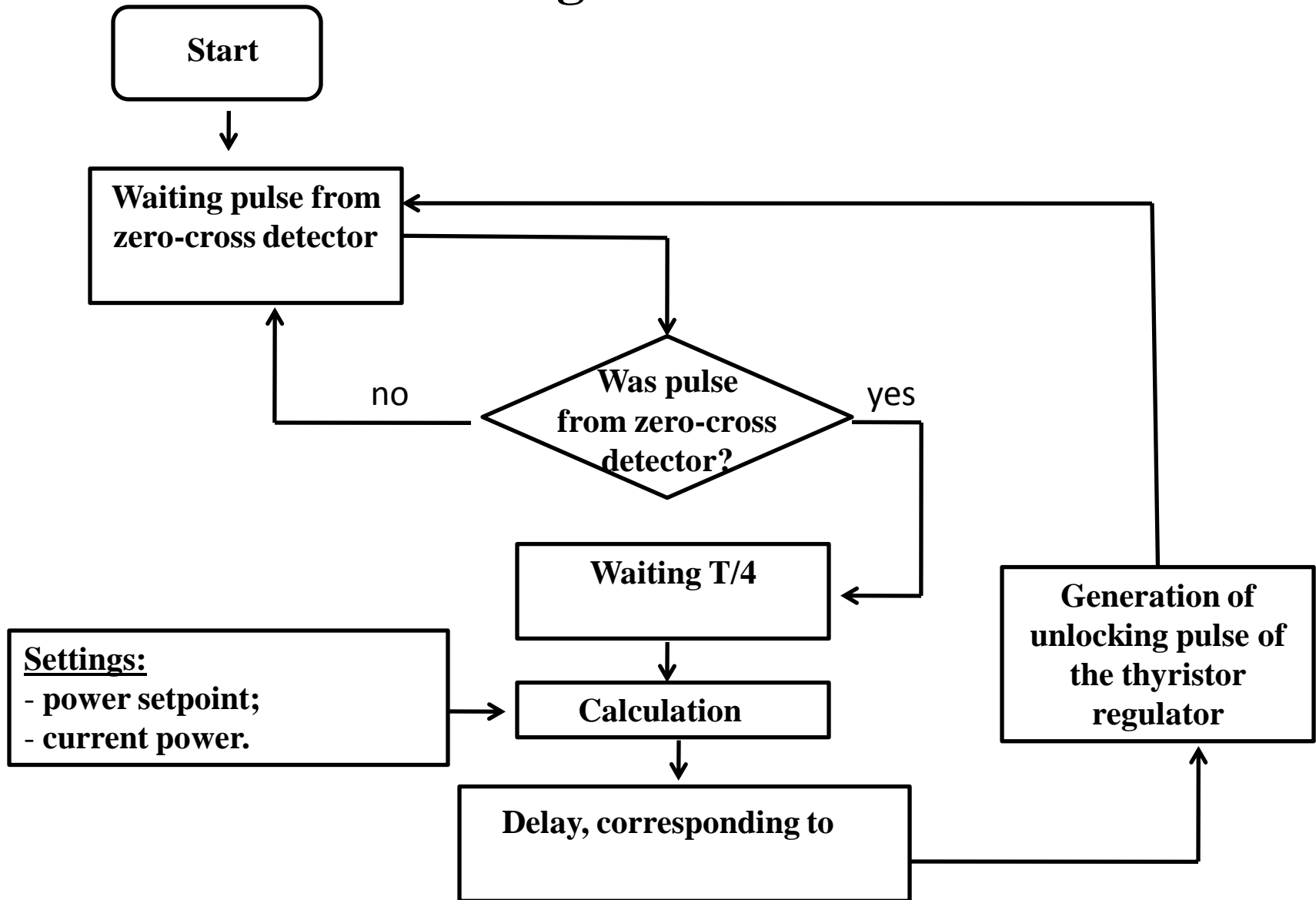
Figure 2 - Dependence of the regulator output voltage from the unlocking pulse phase of the thyristor key

Typical time intervals of the thyristor regulator







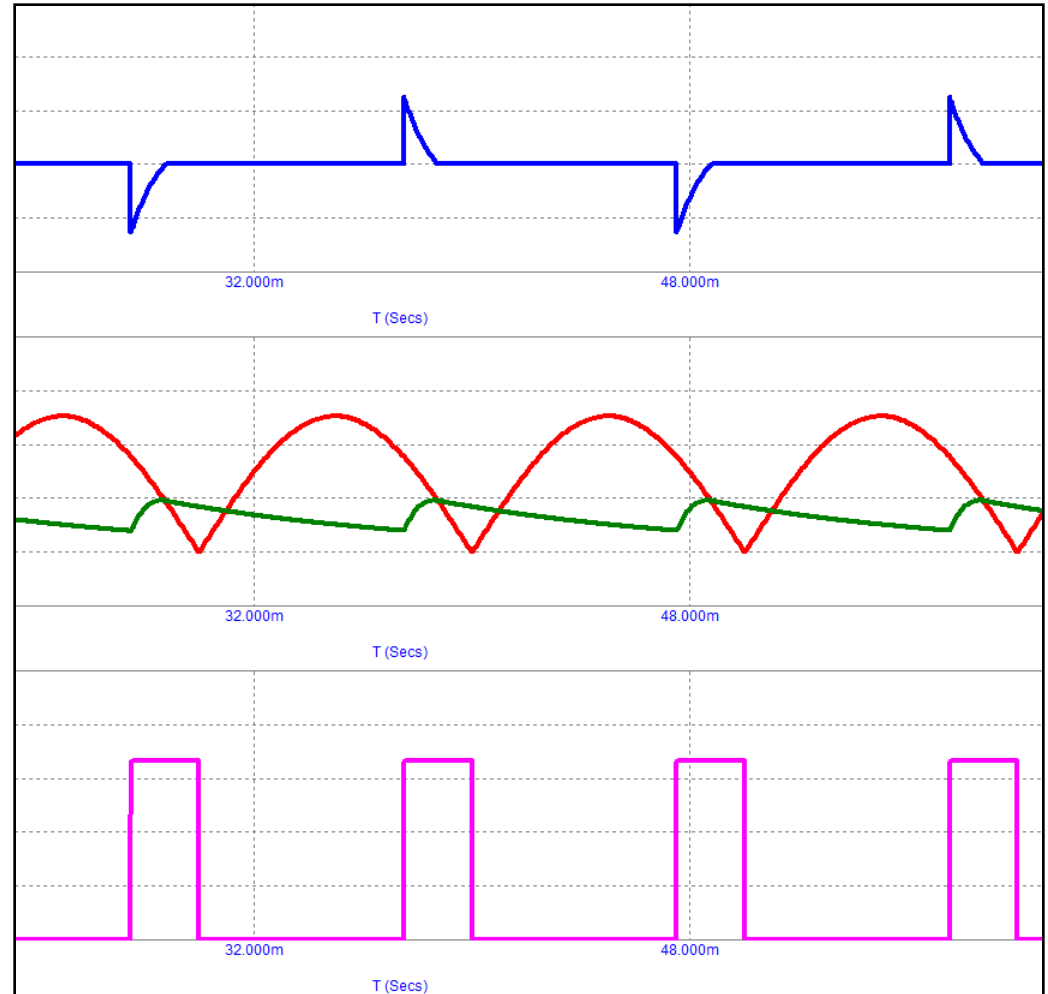
T – period of AC supply voltage

Algorithm for controlling a single-phase thyristor regulator

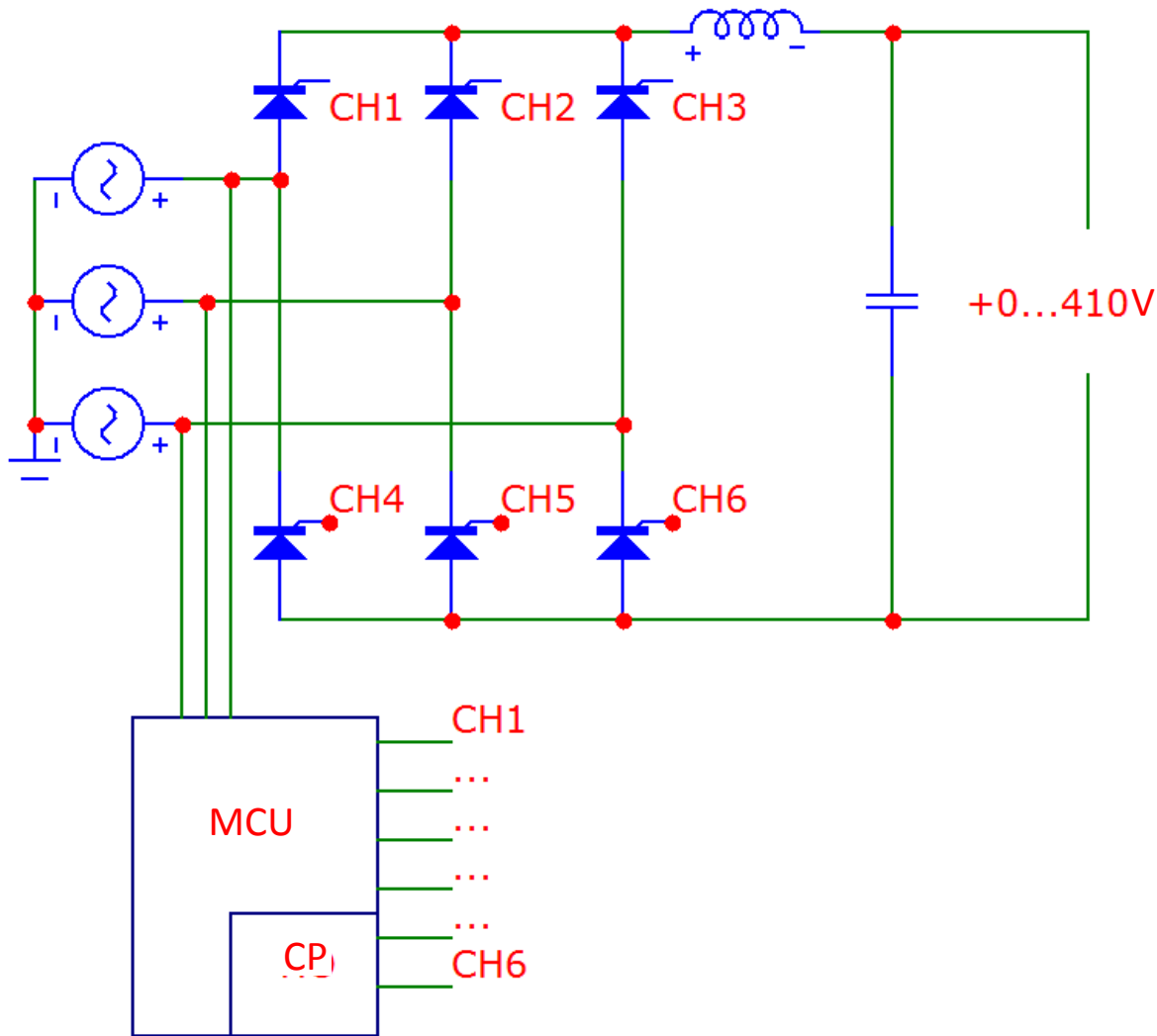


Diagrams of voltages, currents and control signals of a single-phase thyristor regulator

-  The current form from power supply line
-  The voltage form after the diode bridge
-  The voltage form from regulator
-  Unlocking pulse of the thyristor



Circuit of a three-phase thyristor power regulator

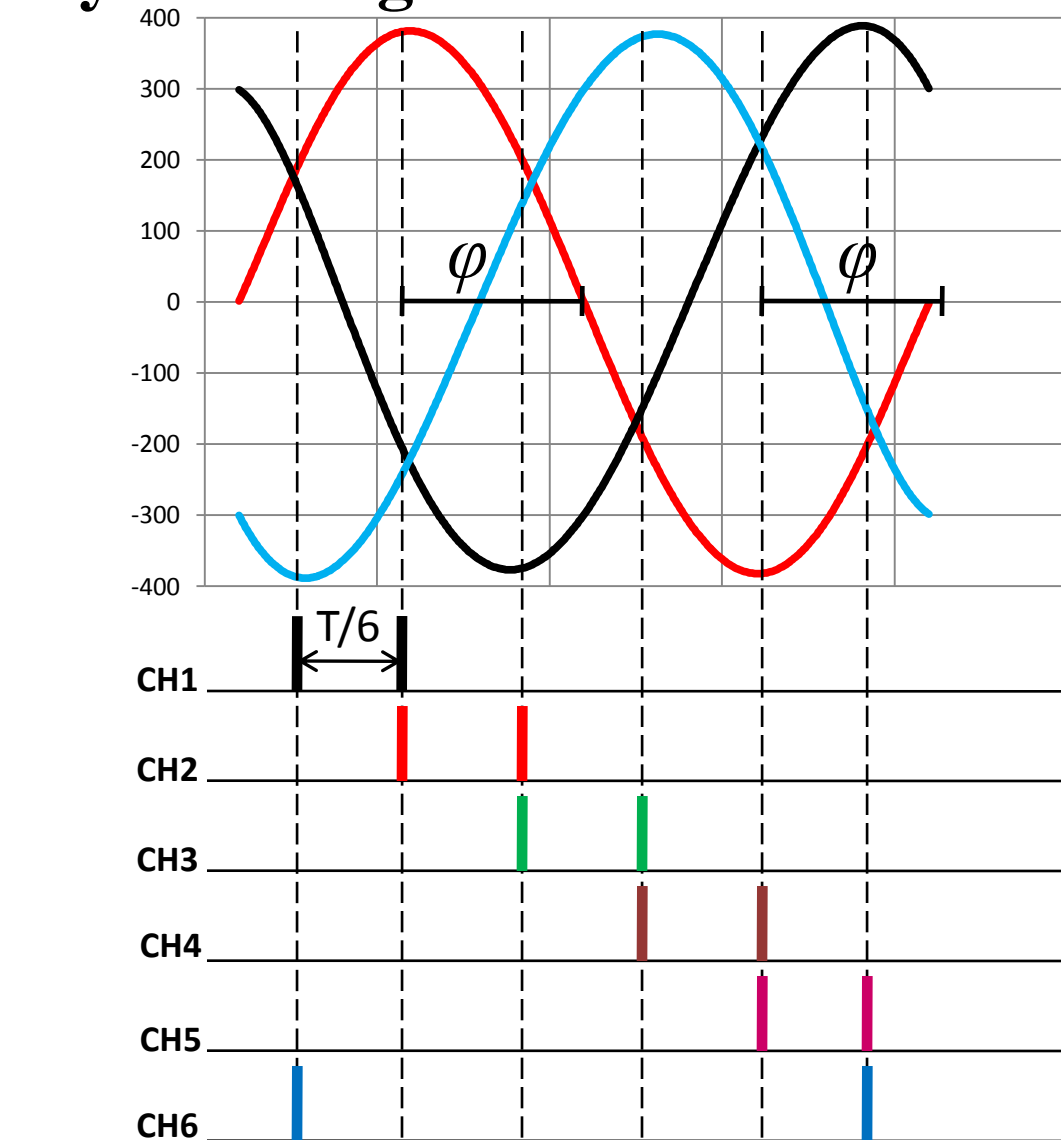


CH1...CH6 – control channels of thyristors;
MCU – microcontroller unit;
CP – control program;

Typical time intervals of the three-phase thyristor regulator

The range of the change of the control pulse phases:

$$\varphi = 90 \dots 180; \varphi = 270 \dots 360$$



T – period of AC mains voltage

Diagrams of voltages, currents and control signals of a three-phase thyristor regulator



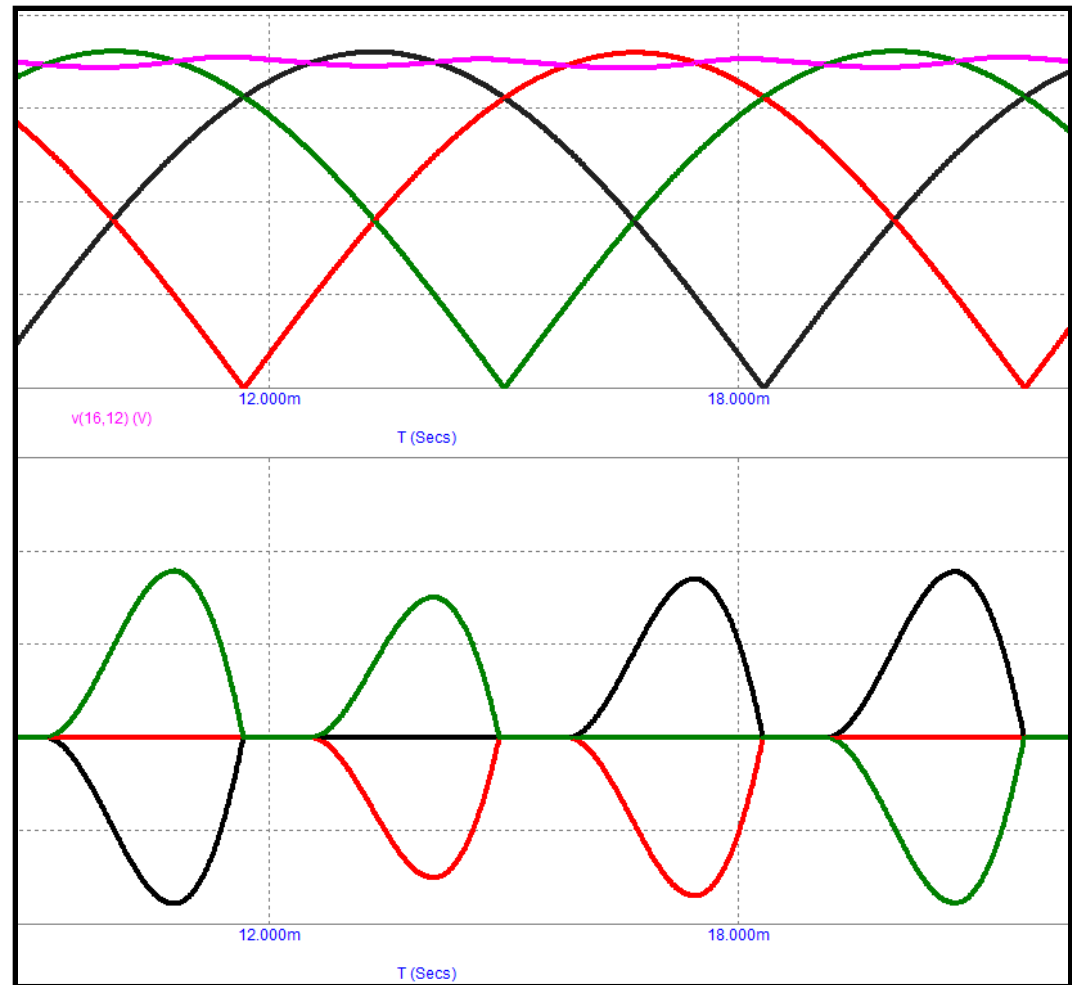
Diagrams of rectified voltage by ABC phases.



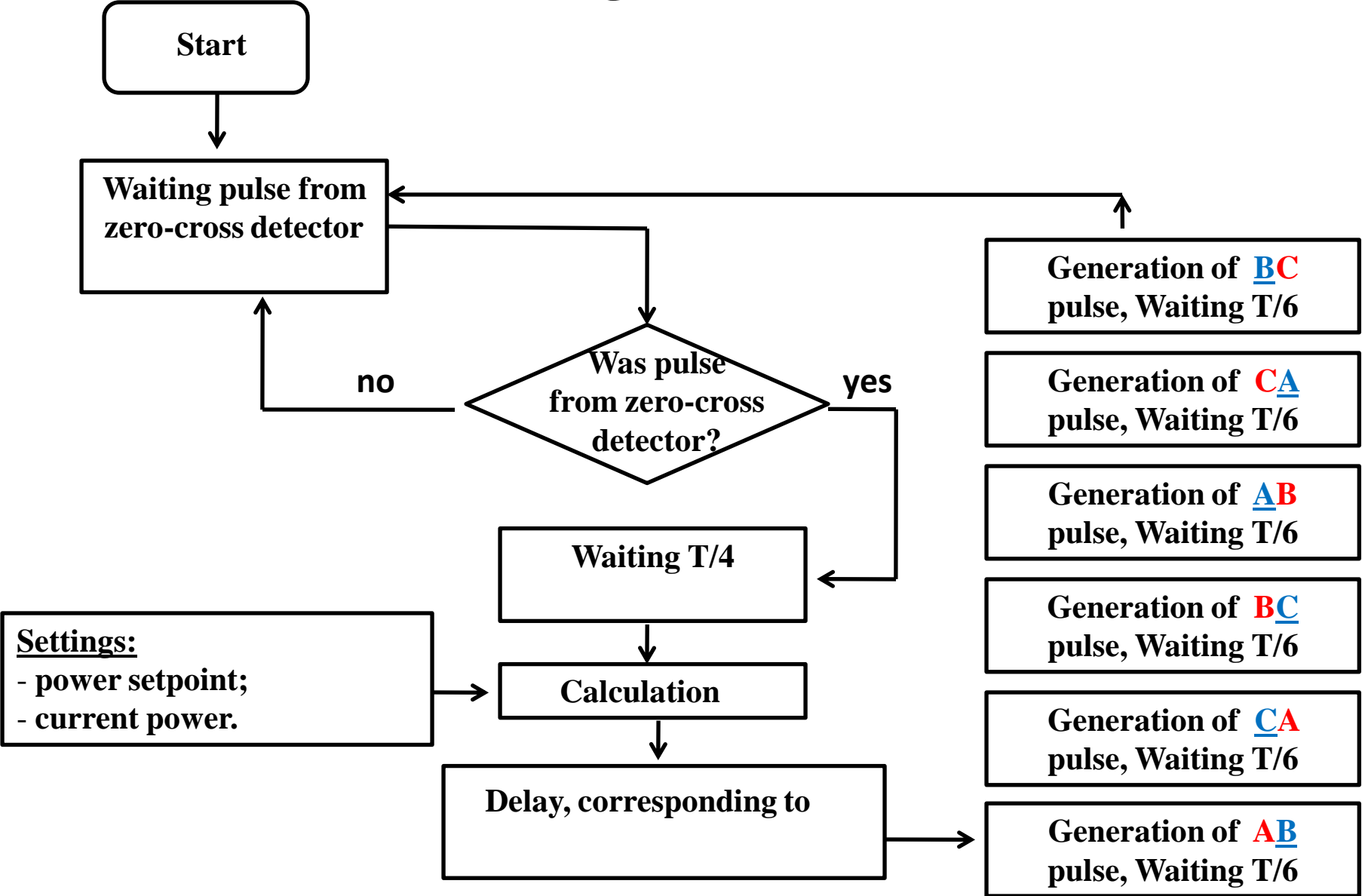
Voltage on load



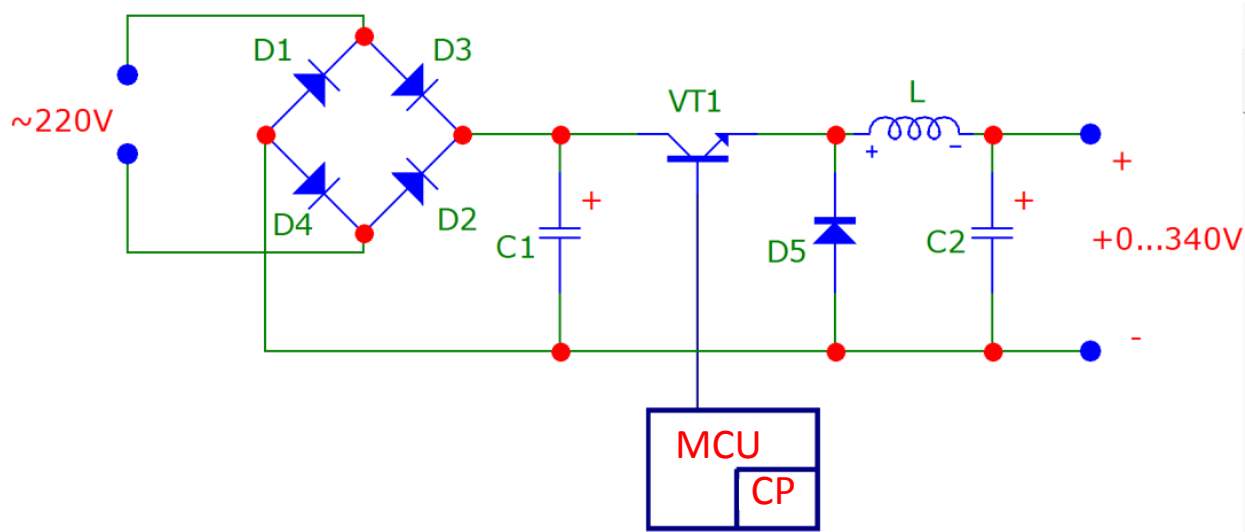
Current consumption by ABC phases



Algorithm for controlling a three-phase thyristor regulator

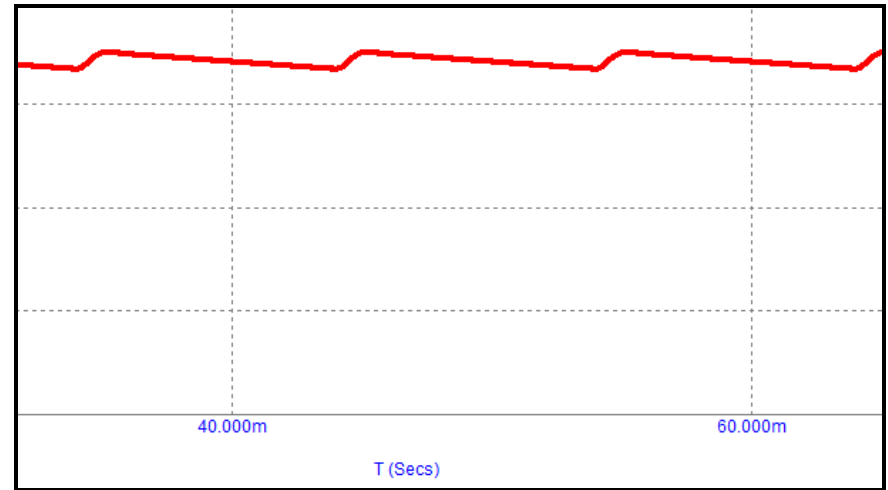
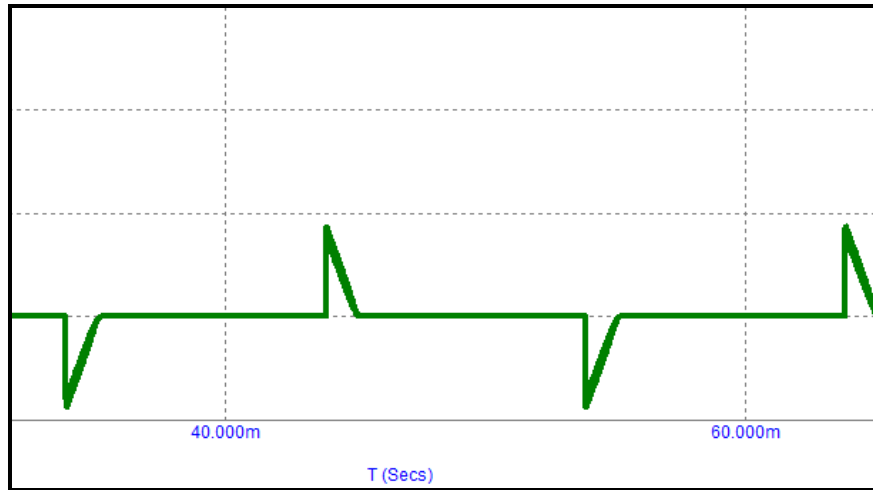





Circuit of a switch-mode step-down power regulator

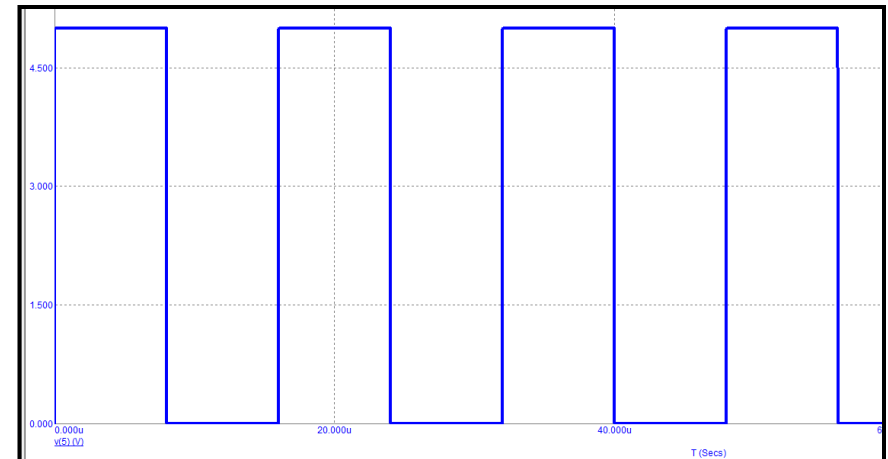


MCU – microcontroller unit;
CP – control program;

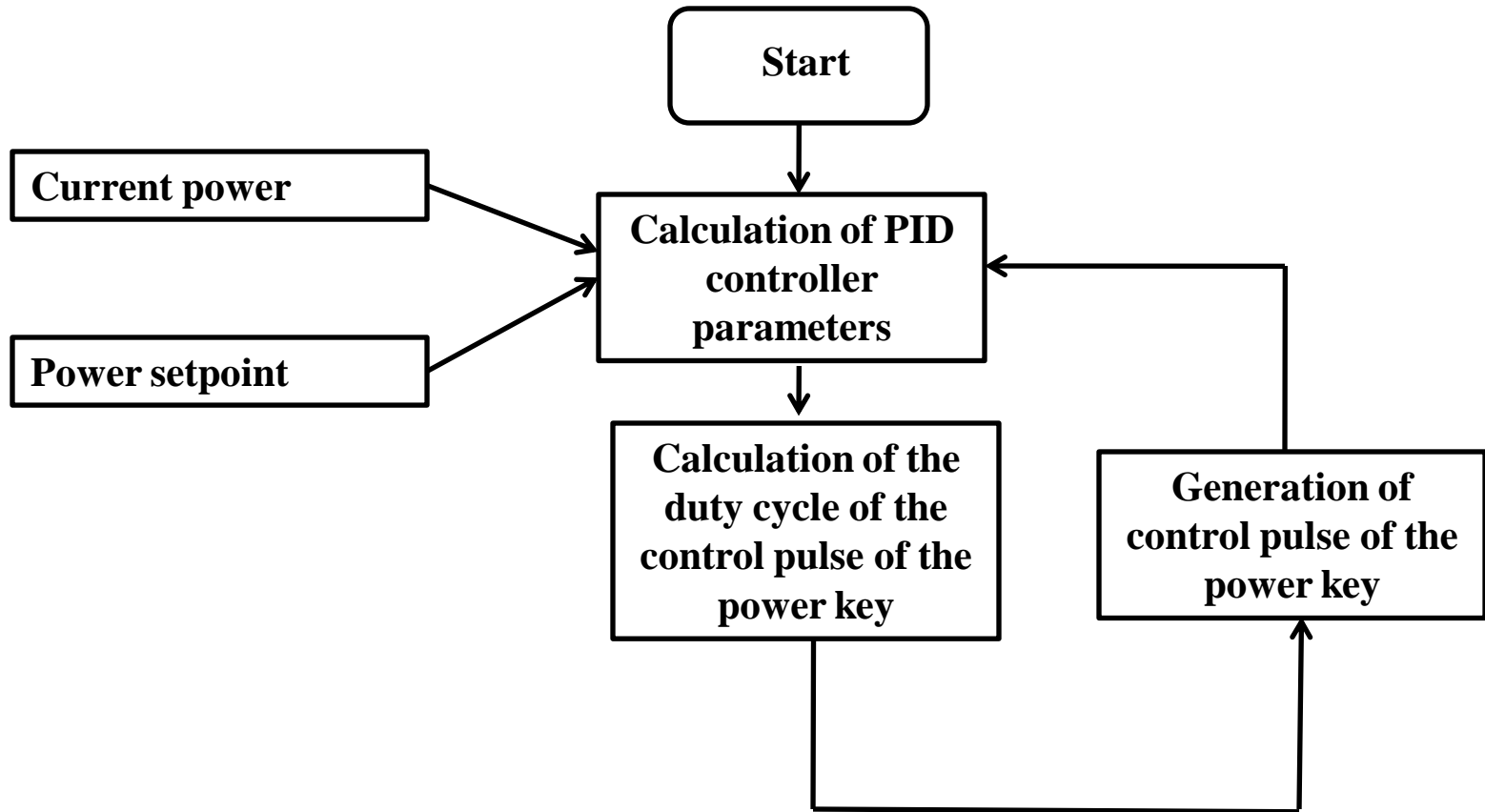
Diagrams of voltages, currents and control signals of a switch-mode step-down power regulator



-  - the current form from power supply line (pulsation 50 Hz);
-  - the voltage on load (pulsation 50 Hz);
-  - power key control pulses of a switch-mode step-down regulator (~60 kHz).



Algorithm for controlling a switch-mode step-down regulator

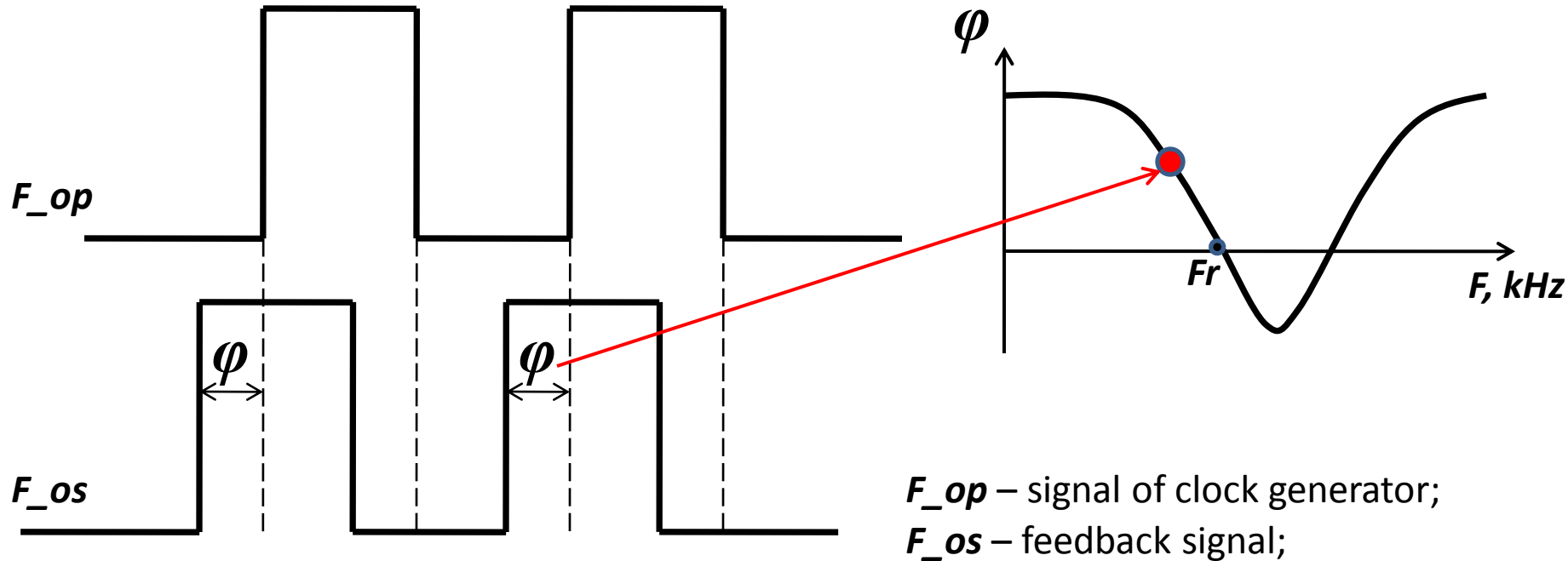


Frequency control of ultrasonic generators

Principle: automatic phase-locked loop (PLL) of the electronic generator.

The criterion for adjustment to resonance: the equality to zero (or a certain value) of the phase shift between the signal of the clock generator F_{op} and the feedback signal F_{os} (current through the piezoelectric transducer of the ultrasonic vibratory system).

Phases of feedback signals and clock generator during operation of the PLL



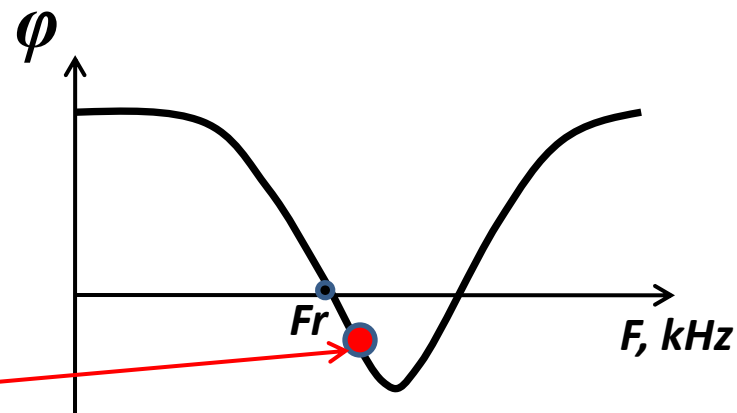
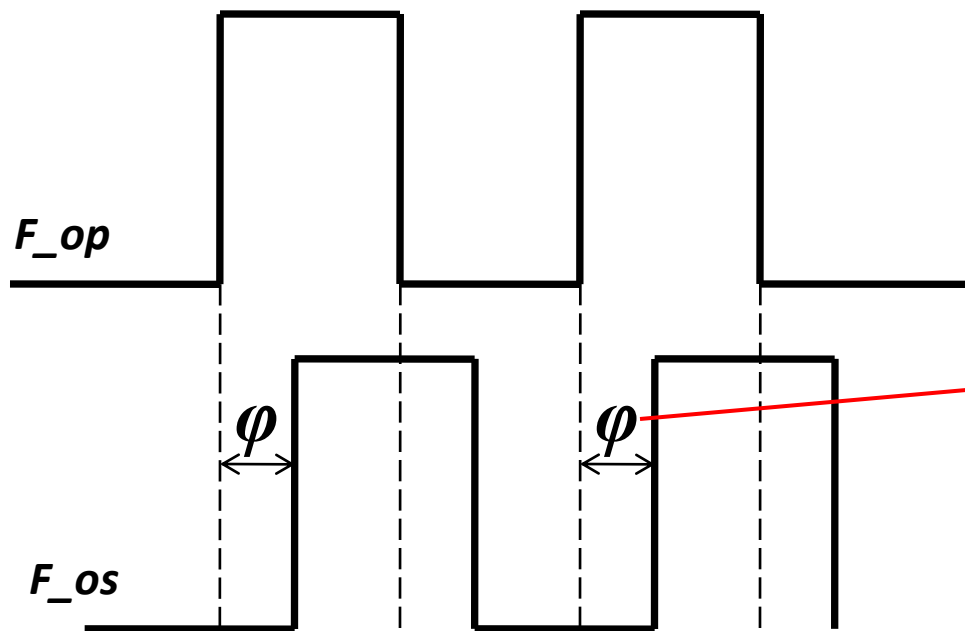
Frequency of clock generator is **lower** of resonance frequency of vibratory system.

F_{op} – signal of clock generator;
 F_{os} – feedback signal;

Fr – resonance frequency;

φ – the phase shift between the signal of the clock generator and the feedback signal

Phases of feedback signals and clock generator during operation of the PLL



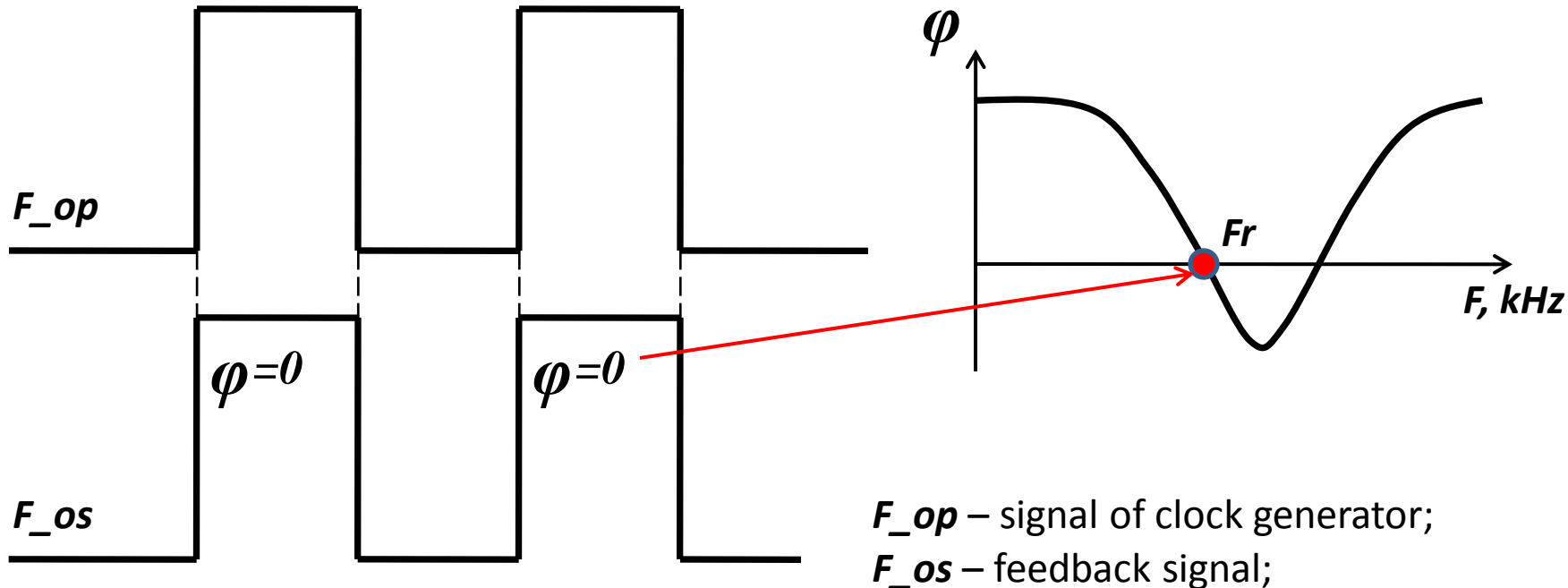
F_{op} – signal of clock generator;
 F_{os} – feedback signal;

Fr – resonance frequency;

φ – the phase shift between the signal of the clock generator and the feedback signal

Frequency of clock generator is **higher** of resonance frequency of vibratory system.

Phases of feedback signals and clock generator during operation of the PLL



Frequency of clock generator is **equal** of resonance frequency of vibratory system.

F_{op} – signal of clock generator;
 F_{os} – feedback signal;

Fr – resonance frequency;
 φ – the phase shift between the signal of the clock generator and the feedback signal

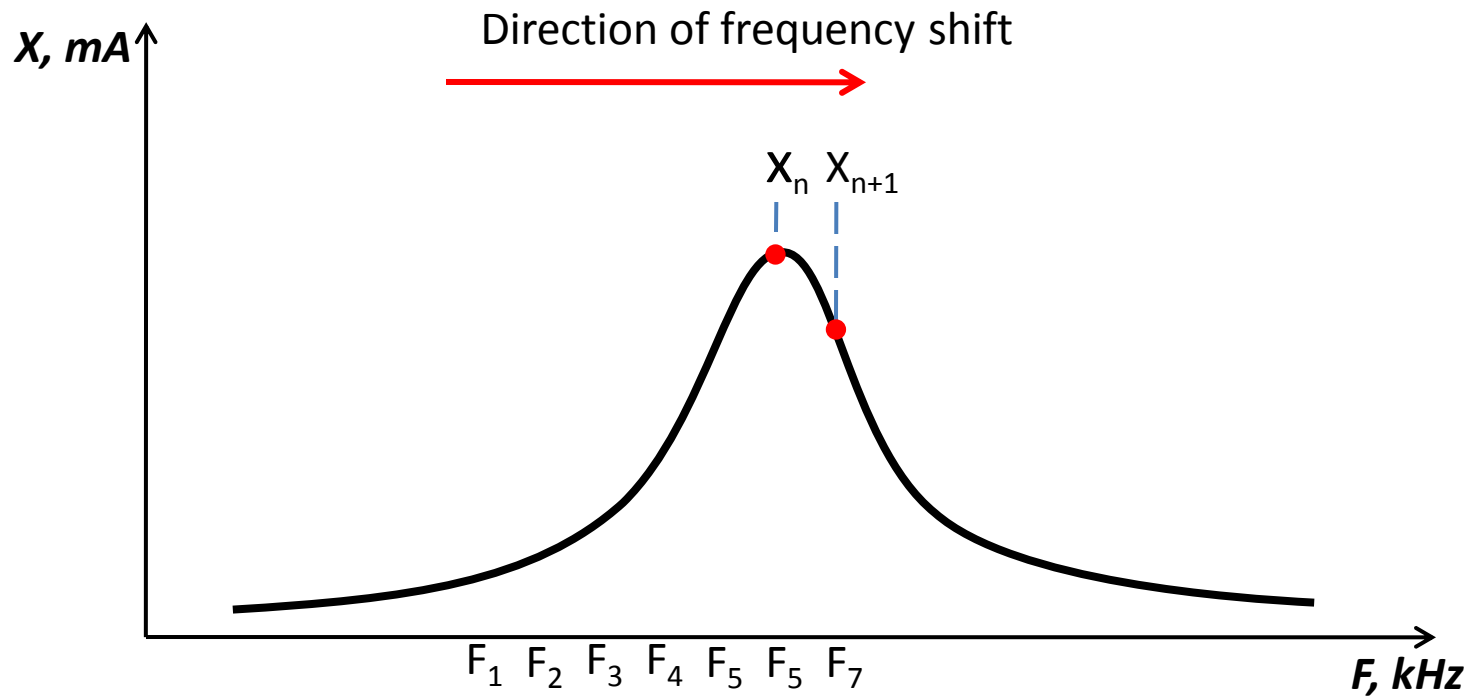
Ensuring optimal operating modes of the generator

- 1. Search for the resonant frequency of the ultrasonic vibratory system for optimal exposure
- 2. Restoration of the resonant operating mode. Reconfigurations and restarts
- 3. Generation of signals for monitoring the operation of devices.

Searching of the resonant frequency of the ultrasonic vibratory system

- The **maximum value** of the amplitude-frequency characteristic of the ultrasonic vibratory system.
- The **maximum** amplitude-frequency characteristic of the ultrasonic vibratory system.

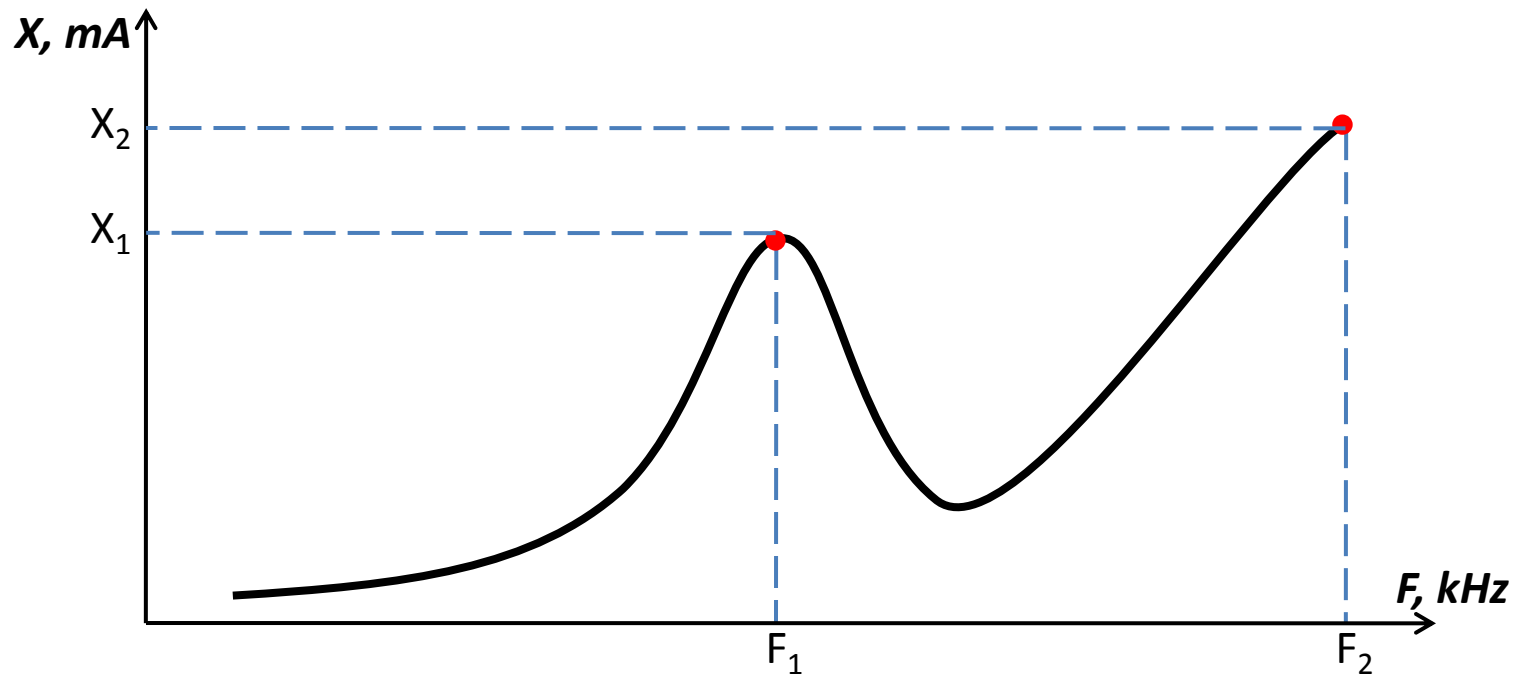
Search algorithm for the resonant frequency of the ultrasonic vibratory system (search for the maximum value)



Step of frequency shift: $dF = F_{n+1} - F_n$

The condition for finding the resonance: $X_{n+1} < X_n$

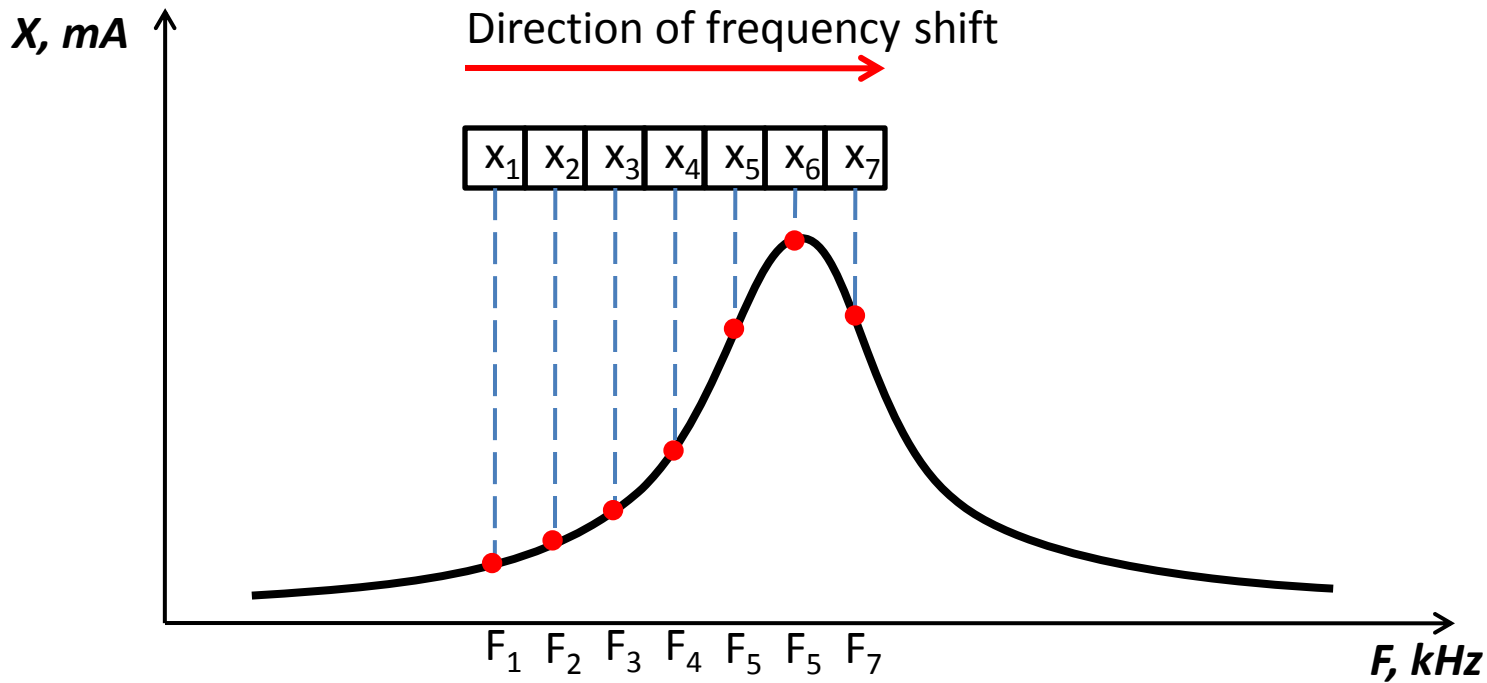
Disadvantages of search algorithm for the resonant frequency of the ultrasonic vibratory system by the maximum value of amplitude-frequency response



F_1 - the frequency of the maximum of the function (resonant frequency);

F_2 - the frequency of the maximum value of the function.

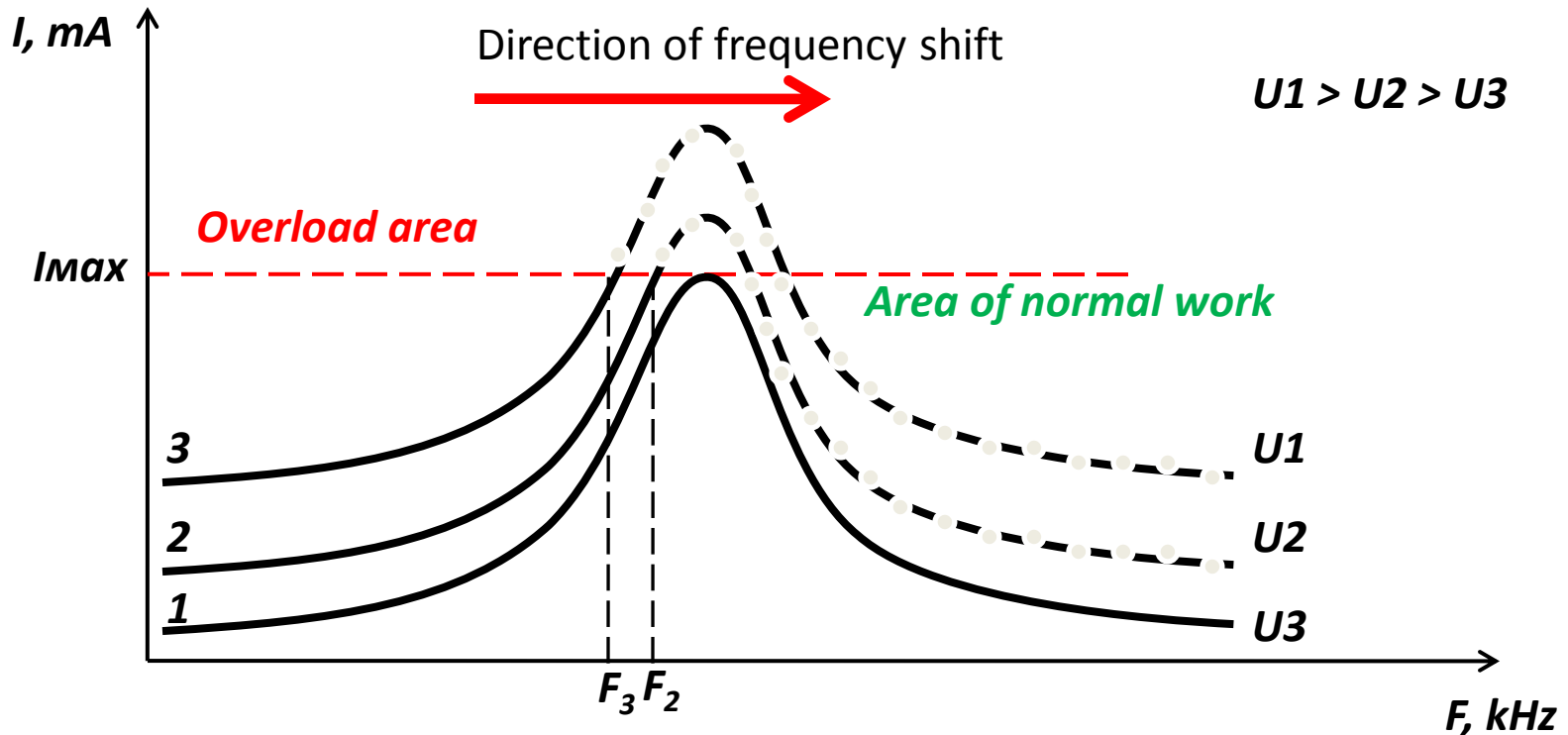
Search algorithm for the resonant frequency of the ultrasonic vibratory system (search for the maximum)



Step of frequency shift : $dF = F_{n+1} - F_n$

The condition for finding the resonance : $x_1 < x_2 < x_3 < x_4 > x_5 > x_6 > x_7$

Features of reception of amplitude-frequency response of the ultrasonic vibratory system for searching the resonant frequency



1 – Amplitude-frequency response without «overload»;

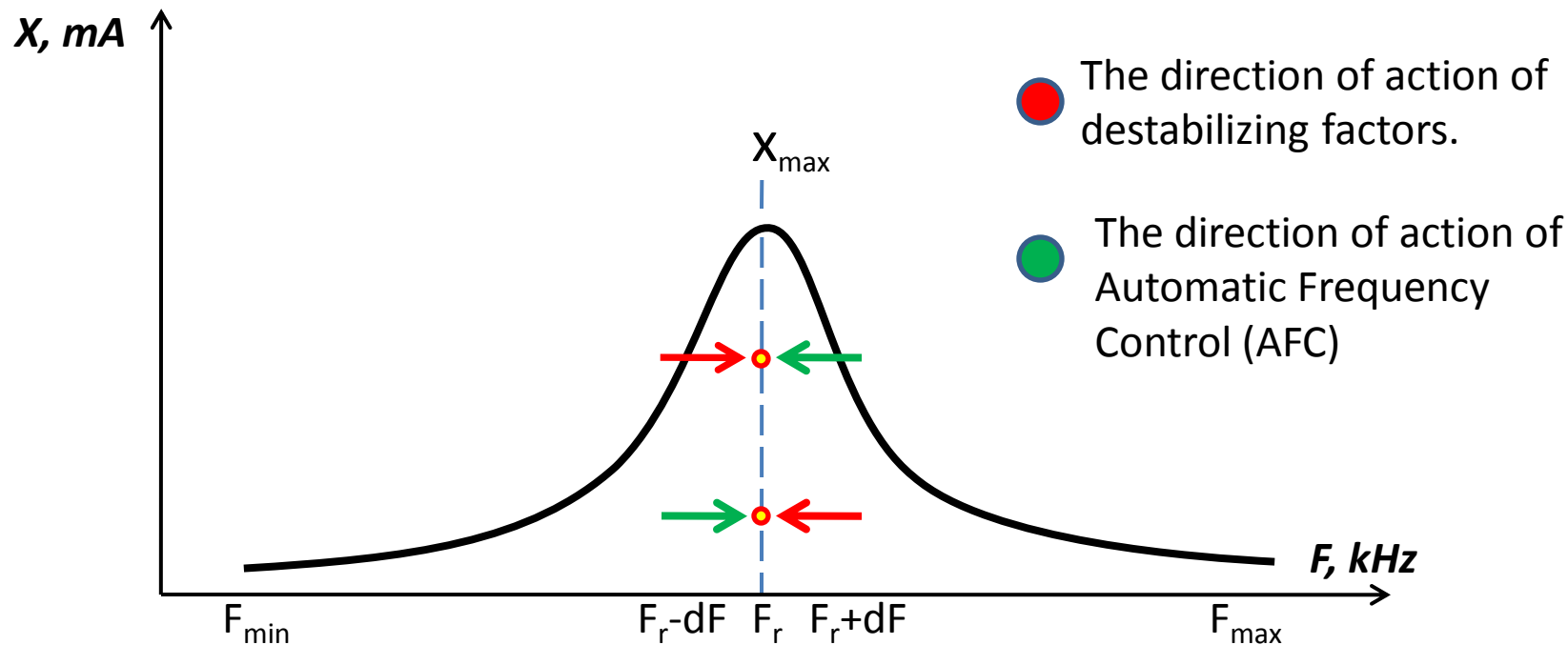
2,3 – Amplitude-frequency response with «overload»;

F_2 , F_3 – frequencies of termination of reception of amplitude-frequency responses #2 and #3;

U_1 , U_2 , U_3 – the voltages of amplitude-frequency responses #1, #2 and #3 receptions, respectively.

The principles of determining the “failure“ of the resonant operation mode of the ultrasonic vibratory system. Features of the ”restart“ of the electronic generator at “failure“ of the resonant operation mode of the ultrasonic vibratory system.

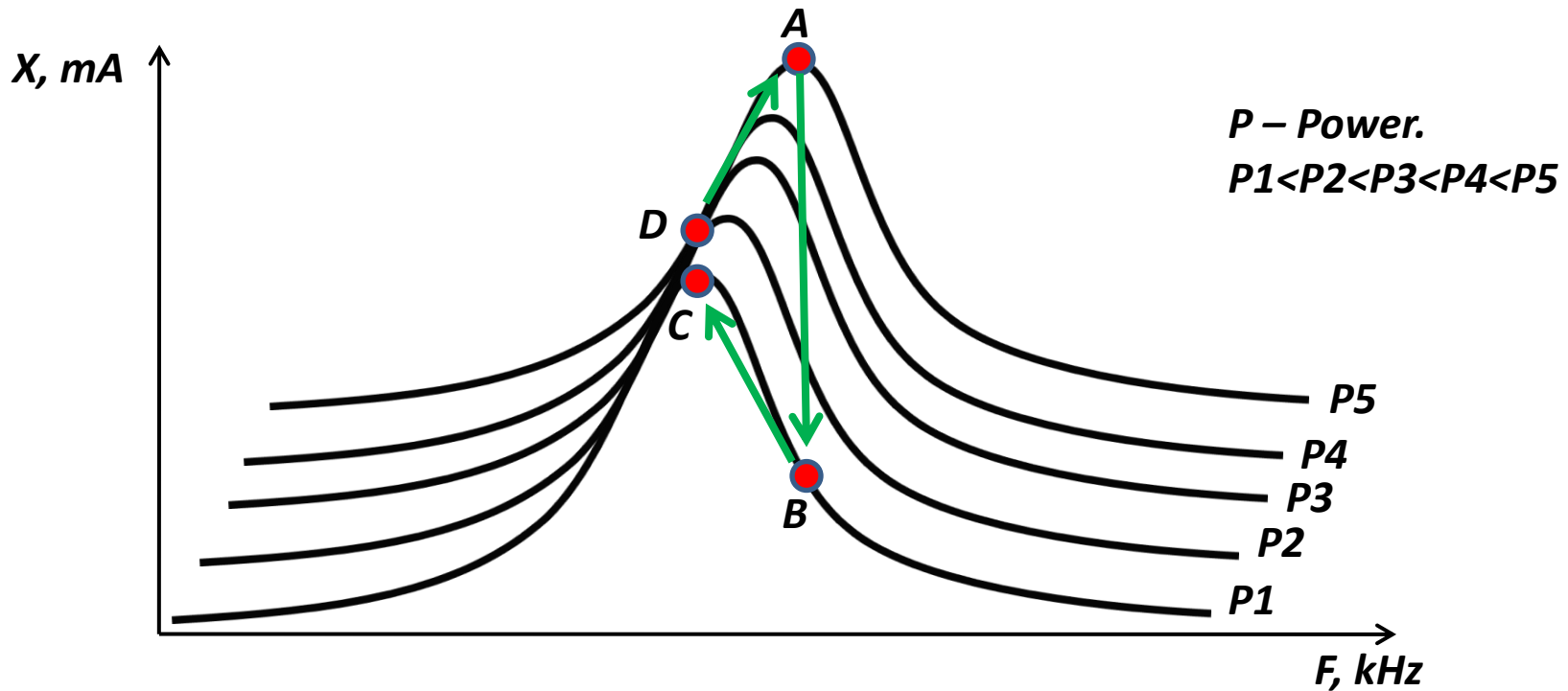
Determining of “failure” of the resonant operation mode of the ultrasonic vibratory system.



Condition of «failure» of the resonant operation mode:

1. $F < F_{\min}$ or $F > F_{\max}$.
2. The clock generator adjusts the frequency either up or down during a certain time interval

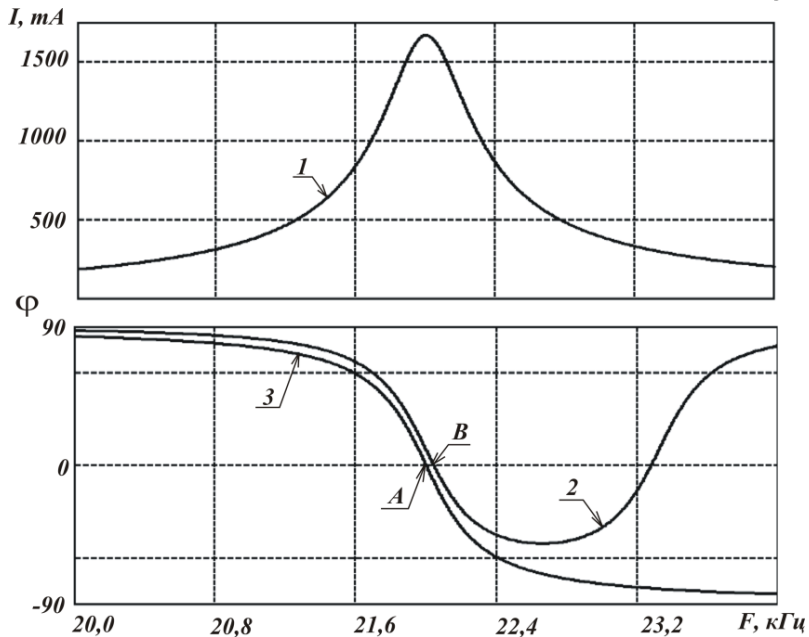
Features of “restart” after the ”failure“ of the resonant mode of operation



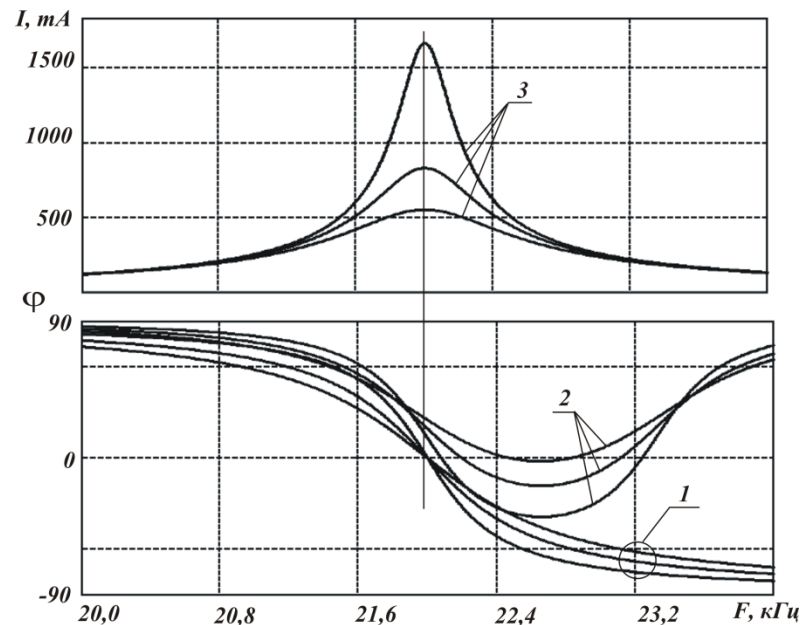
The amplitude-frequency characteristics obtained at various output power.

The principle of forming feedback signals for the power (amplitude) control systems and automatic phase-locked loop

Frequency responses of the ultrasonic vibratory system



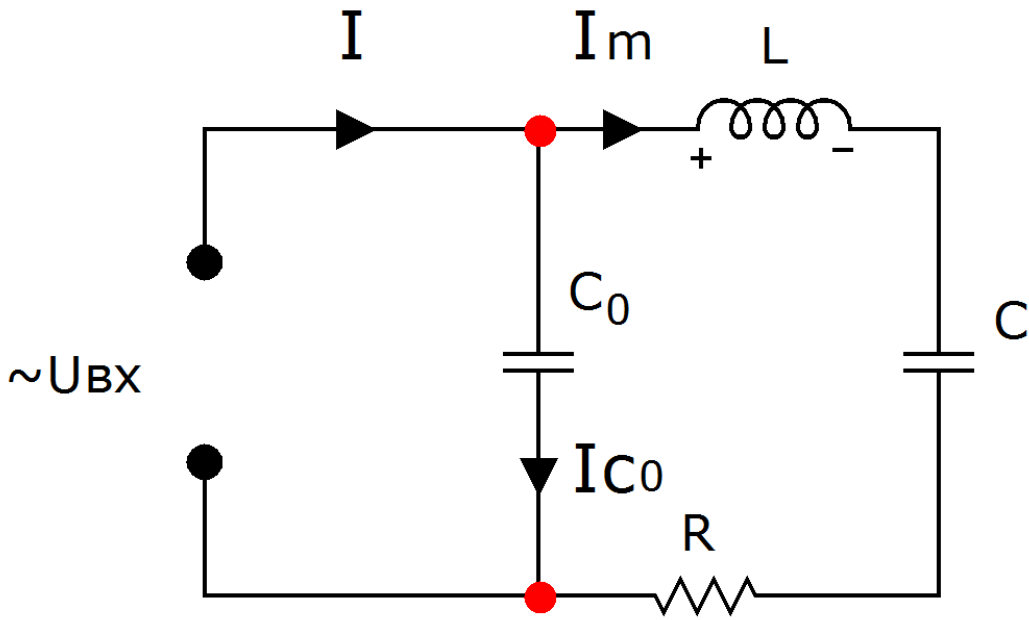
- 1 – amplitude-frequency response of the current of the mechanical branch of the vibratory system;
- 2 – phase-frequency response of the current consumed from the generator;
- 3 – phase-frequency response of the current of the mechanical branch of the vibratory system;
- A is the point of transition through the zero phase of the current of the mechanical branch of the vibratory system;
- B is the point of transition through the zero phase of the current of the vibratory system;



Amplitude-frequency and phase-frequency responses depending on the acoustic load

- 1 – phase-frequency response of the current of the mechanical branch of the vibratory system;
- 2 – phase-frequency response of the current consumed from the generator;
- 3 – amplitude-frequency response of the current in the mechanical branch.

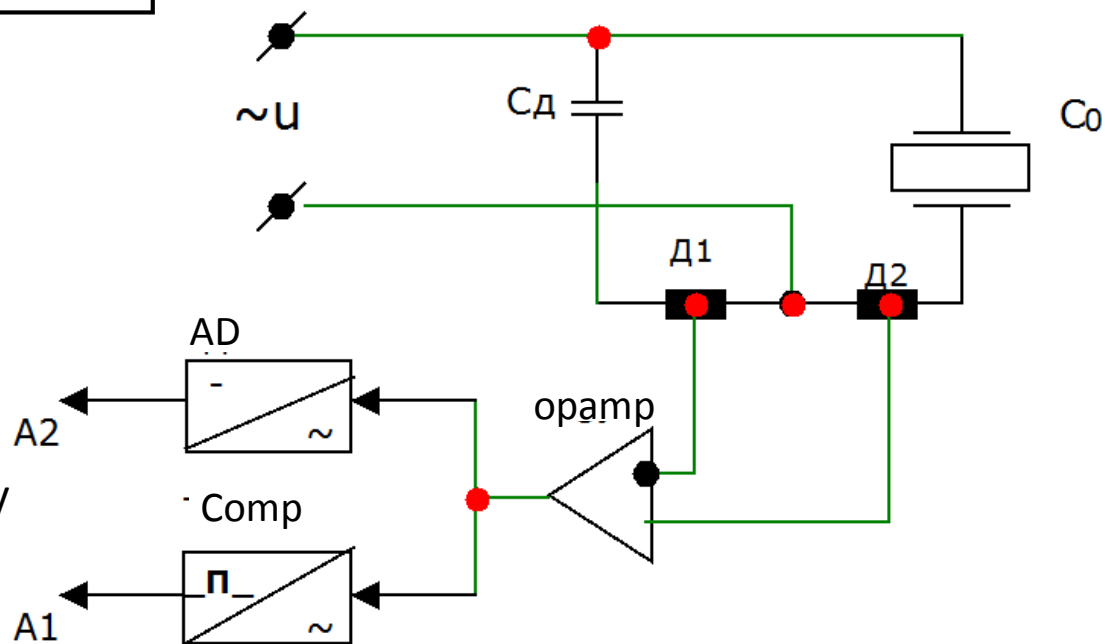
Mechanical branch current allocation circuit



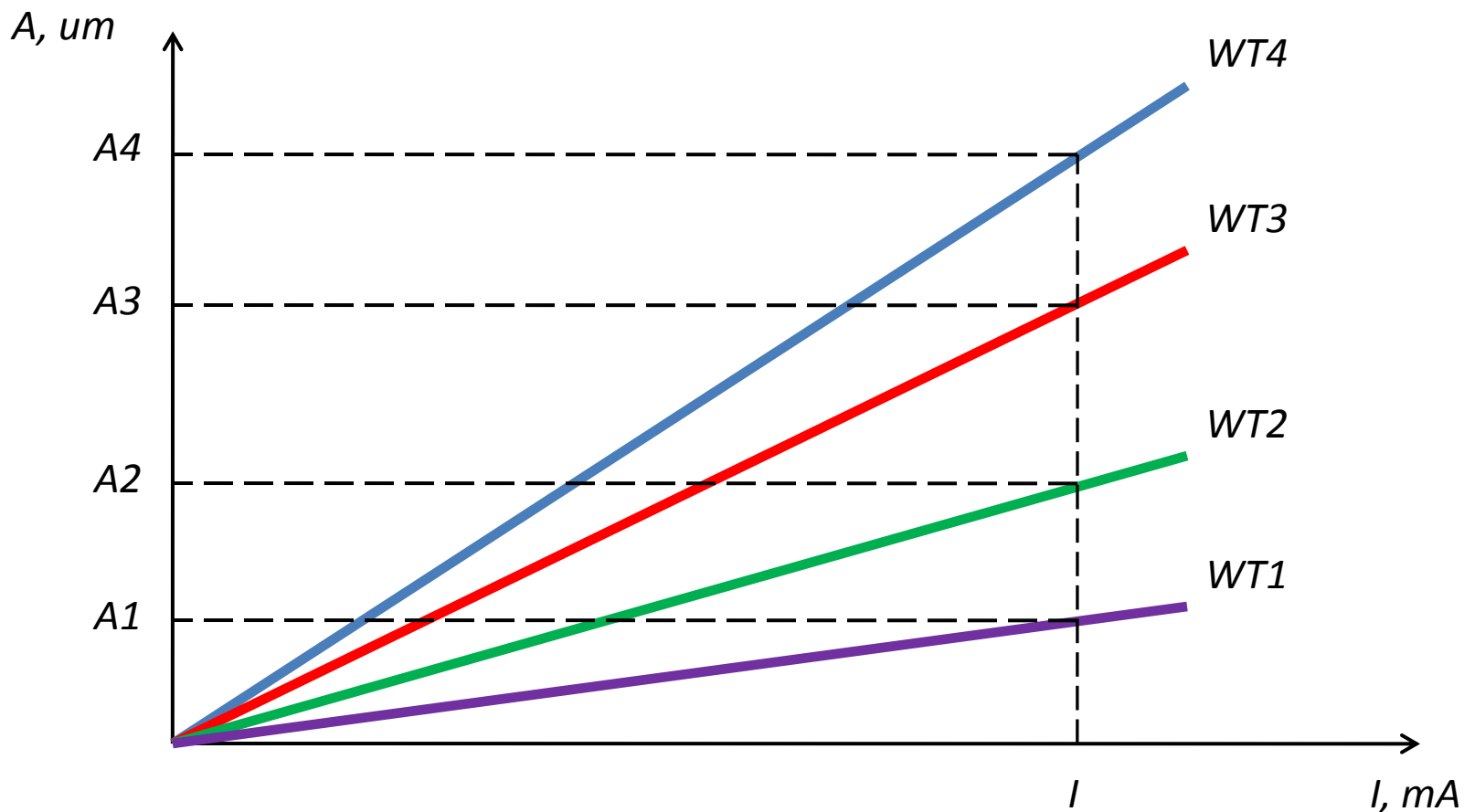
I – the total current consumed by the ultrasonic vibratory system;
 I_m – mechanical branch current ;
 I_{C_0} – capacitive current.

AD - block for allocating the amplitude value of the current of the mechanical branch;

Comp is a block for allocating a rectangular signal whose frequency and phase correspond to the frequency and phase of the current of the mechanical branch



The influence of replaceable working tools on the relationship of the current of the mechanical branch with the amplitude of mechanical vibrations



A – the amplitude of mechanical vibrations;
 I – current of the mechanical branch of the vibratory system;
WT – a replaceable working tool.