«IGOR SIKORSKY KYIV POLYTECHNIC INSTITUTE»

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POWER ELECTRONICS
Electronics devices modelling in MATLAB Simulink

PRACTICUM

Recommended by the Methodical Council of the Igor Sikorsky Kyiv Polytechnik Institute as a tutorial for bachelor's degree programs for an educational program "Engineering of automated electrical engineering complexes"

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Electronic network educational edition

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POWER ELECTRONICS

Electronics devices modelling in MATLAB Simulink

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The presented manual outlines the main provisions for the computer workshops implementation, topics covered by sections of the course on the linear and nonlinear dynamic systems with power electronics devices study. The educational edition of the computer workshops contains the main theoretical information, the program of work, instructions for its implementation, the report content and control questions.

Existing methods of linear and nonlinear dynamic systems simulation based on the principles of visual-oriented programming using models in the form of component-blocks combinations, by means of which interconnection of devices and systems functional models are formed among themselves, are considered.

The educational edition is intended for graduates of the master's degree in specialty 141 "Power engineering, electrical engineering and electromechanics", educational program "Electrical supply systems".

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INTRODUCTION

The MATLAB system is a high-level programming language designed for engineering and scientific computing and the simulation tools creation for various devices and systems. It is based on matrix computing algorithms with operations on vectors groups, which is the main difference of this system from other known packages - Mathcad, Maple, Mathematika and others. Due to matrix and vector representation, developers have been able to significantly increase the speed of computing, effectively use the memory resources and ensure high accuracy of calculations.

MATLAB implemented a modular construction principle with a wide range of modifications and extensions, which confirms the composition of this product, namely: dozens of application packages and more than two hundred applications and extensions, the richest library of functions (over 800), and a huge amount of documentation that has tens of thousands of pages.

For easy use, the entire MATLAB system is divided into sections, executed in the form of software packages, the most common of which formed the core. Other packages are combined or exist individually in the form of so-called Toolboxes.

Among others, the Simulink package designed to simulate linear and nonlinear dynamic systems should be highlighted. It is based on the principles of visual-oriented programming using models in the form of component blocks combinations, through which interconnected devices and systems functional models. During this mathematical model describing the behavior of such a system, is formed and solved automatically. For the researcher, Simulink creates a lot of possibilities, ranging from the device functional representation and up to generating the codes used to program microprocessors.

The Simulink package, together with the Simpowersystems expansion pack (earlier versions - Power Systems Blockset), is the basis for studying and researching power electronics and electromechanical devices.

Simulink is a rather independent MATLAB tool, and when working with it, you do not need to know MATLAB itself and its other applications at all. On the other hand, access to MATLAB and its other tools remains open, they can be used in Simulink. Some of the MATLAB packages have tools that are embedded in Simulink (for example, the Lti-viewer of the Control System Toolbox, a package for developing control systems).

When working with Simulink, the user has the ability to upgrade library blocks, create their own, as well as create new library libraries.

In the case of modeling, the user can choose a method for solving differential equations, as well as a way to change the modeling time (with a fixed or variable step). During the simulation there is the ability to monitor the processes occurring in the system. To do this, use special surveillance devices that are part of the Simulink library. Modeling results can be presented as graphs or tables.

The advantage of Simulink is also that it allows you to replenish block libraries using subroutines written in MATLAB, in C + +, Fortran, and Ada languages.

The Simulink library contains blocks that are mainly focused on the specific devices simulation in the functional schemes form. It includes scaling signals sources, linear and nonlinear blocks, quantizers, integrators, differentiators, meters, etc. The library of Simpowersystems includes a set of blocks for electrical devices simulation in the form of passive and active electrical elements, power sources, electric motors, transformers, semiconductor elements. With Simulink and Simpowersystems you can simulate the devices work in the time domain, as well as perform analysis of their properties - to calculate the circuit resistance, to obtain amplitude and phase-frequency characteristics, to perform currents and voltages harmonic analysis.

The undoubted advantage of Simulink and Simpowersystems is the ability to build models of complex electrical systems based on simulation and functional modeling. So, for the semiconductor converter power part construction, Simpowersystems units simulating the elements and devices are used, and in its control system, the functional units of Simulink. They reflect the algorithm of its work without representation of the electric circuit. Due to this approach, unlike the well-known packages of circuit design such as Orcad, Pspice, Designlab, Workbench, etc., the model is simplified, the memory is stored, the speed of calculations and the performance of the PC are increased. It is important to note that after constructing a functional model, the complex stage of compiling and solving algebraic and differential equations is eliminated and the possibility of visual control of the generated model behavior processes that occur in it is provided.

When designing models using the Simpowersystems elements and blocks from the Simulink library, it is possible to attract the functions of the system MATLAB, which significantly expands the ability to simulate electrical systems and semiconductor devices. Despite the size of the Simpowersystems library, there are occasions when the required block, as such, is not present in the library. In these cases, the user can develop their own blocks using the existing library elements and using the created subsystem in Simulink.

All of the foregoing makes it possible to claim that Simpowersystems and Simulink are modern packages with extensive capabilities for simulating power electronics, electromechanical and continuously developing automation systems.

TOPIC #1: RESEARCH OF RECTIFIER OPERATION

Computer Practicum #1

Research of rectifiers work

The purpose of the work is to get acquainted with the simplest schemes of rectifiers, to construct models, and to simulate the prescribed rectifier circuits. Build and explore the main characteristics of rectifiers.

Basic theoretical information

Rectifiers - are electrical devices designed to convert the energy source of AC voltage into the DC voltage power.

The composition of the rectifier is shown on the generalized structural scheme, depicted in Fig.1.1.

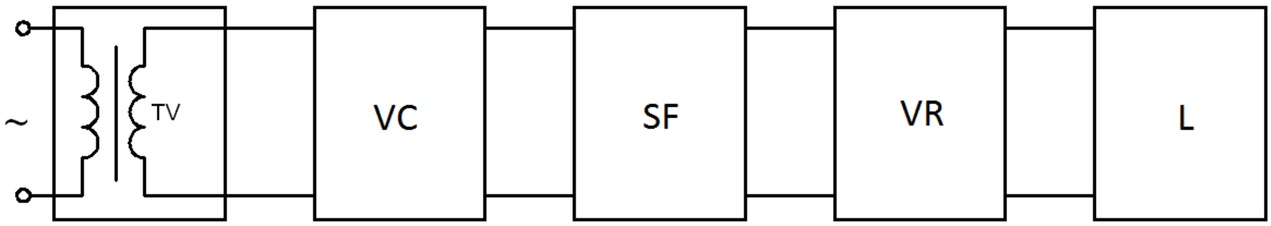


Fig. 1.1. Schematic diagram of rectifier:

TV — voltage transformer; VC — valve circuit; SF — smoothing filter;

VR — voltage regulator); L — load

Transformer is designed to convert the value of network voltage to the value required for the work of the rectifier. It also provides electrical (galvanic) network and load.

The valve circuit converts the alternating voltage into a rectified - pulsating unipolar. It can be executed on semiconductor keys.

The smoothing filter converts the rectified voltage to a constant. Filters are made on reactive elements, which have the property to accumulate electric energy: condensers, throttles. Such filters are called passive.

For powering electronic devices, active filters are often used based on transistors, operational amplifiers and reactive elements.

The voltage regulator supports voltage at the load and constant level in the event of a change in network voltage or load within specified limits.

In case of the need to adjust the voltage on the load according to the required law and within the specified limits, voltage regulators are used. Note that the stabilizer is also a kind of regulator, which provides automatic regulation on the basis of the constant value of voltage on the load.

The regulator (stabilizer) can be switched on and from the side of the voltage variable (to the transformer).

Parameters of rectifier nodes and their elements, their operating modes, must be coordinated with the given conditions of work load. Load is also considered an element rectifier, because the change in its resistance during operation affects the mode of operation of the entire device.

The smoothing filter, the stabilizer (regulator), and sometimes the transformer may not be part of the rectifier, in which it is not necessary.

In addition to the specified nodes, the rectifier may have nodes and elements of protection against short circuit, overload, and reduction of network voltage. These are the following elements and nodes: a fuse, an automatic circuit breaker, an electronic security device, elements and nodes indicating the presence and value of voltage and current, as well as units of diagnostics of efficiency.

Rectifiers are classified by the number of phases - single-phase and multiphase (the latter - most often three-phase). At power rectifiers there are low power (up to 100 W), medium (up to 10 kW) and large (more than 10 kW).

Rectifiers are unmanaged and controlled. The first ones are built on uncontrolled valves - diodes, and the latter are controlled by, for example, thyristors.

According to the principle of rectifiers are divided into one- and two-stroke.

Single-stroke called rectifiers, in which the current on the secondary winding current flows once during the voltage network and in only one direction.

An important parameter of the rectifier is the multiplicity of the pulsations of the rectified voltage m - the ratio of the frequency of the pulsations of the rectified voltage to the frequency of the network. In one-step rectifiers, it corresponds to the number of phases of the network.

Two-stroke (double-phase) rectifiers, in which the current on the secondary winding of the transformer, during the voltage of the network, flows twice and in different directions. The multiplicity of pulsations in two-stroke rectifiers equals the doubling of the number of phases.

The work of the rectifier actually consists in the fact that the load with the help of keys is switched on to the source of AC voltage energy so that for the duration of each half-period of its voltage (positive and negative) current in the load proceeded in one direction. Proceeding from this, the most important node of the rectifier is the valve circuit - the scheme of rectification.

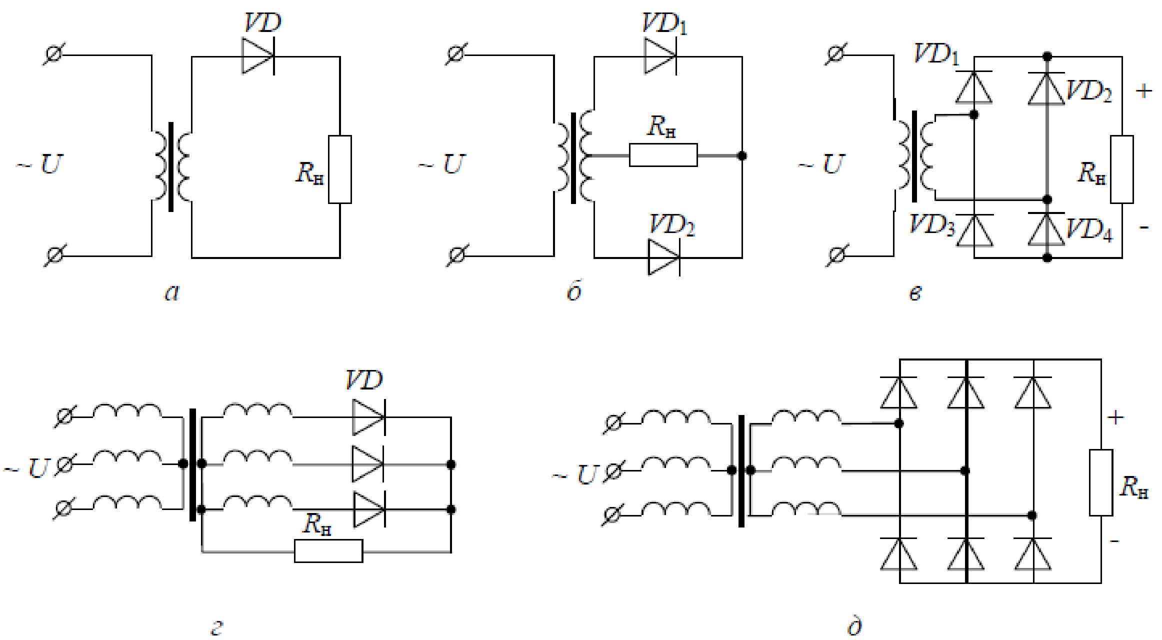


Fig. 1.2. rectifiers: *а* – single-phase monohalfperiod;

б – single-phase with zero output; *в* – single-phase bridge; *г* – three-phase zero;

д – three-phase bridge.

Tasks for work

Task 1.1. Construction of a one-step rectifier model with an RL-load.

Build a model and measure current and voltage on the diode and load.

Output data for simulation:

− U = 220 V;

− f = 50 Hz;

− R = 2 Ohm;

− $L = 5 \cdot 10^{-3}$ Hn.

Model construction:

Table 1.1 - Models and model parameters in the MATLAB / Simulink environment:

Library	Block	Parameters
SimPowerSystems/Electrical Source	AC Voltage Source	200+4·N
SimPowerSystems/Power Electronics	Diode	–
SimPowerSystems/Measurements	Current Measurement	–
SimPowerSystems/Measurements	Voltage Measurement	–
SimPowerSystems/Elements	Series RLC Branch	R = 2+2·N (Ohm), $L = (5+N) \cdot 10^{-3}$ (H)
Simulink/Sinks	Scope	–
SimPowerSystems/Elements	Ground	–
Simulink/Signal Routing	Demux	–
Simulation time		0,2 c
Solver		ode45

To construct the model, you need to open the SimPowerSystems tree in Simulink and activate the string of the Electrical Sources tree (source of power). The Electrical Sources section opens on the right side of the window. Use the left mouse button (LK) to drag the icon of the voltage source AC Voltage Source into the model window.

Similarly, in the window of the model, the serial icon of the Series RLC Branch of the Series RLC Branch from the Elements section, the Voltage Measurement voltmeter icons and the Current Measurement ammeter from the Measurements section (measuring and monitoring devices) are rotated alternately. From the Simulink library, there are icons of the Scope oscilloscope from the Sinks section and Demux from the Signal Routing section. The connection of the blocks to the circuit is carried out (Fig. 1.3), in which the oscilloscope Scope is connected to the encoder Scope through Demux demultiplexer, which distinguishes two separate signals from the general Vector Simulink signal that are output to the connected oscilloscope.

The oscilloscope has four inputs. The number of inputs is set after calling the Scope oscilloscope window (Fig. 1.4) with the Parameters button of another window named Parameters Scope and the General tab - the general parameters where the required number of axes Number axes is installed.

In the parameter setting blocks, settings are made of a supply voltage of 220 V, a frequency of 50 Hz (AC voltage source source window), a 2 Ohm resistor, an inductor of 5 mH and a capacitance inf (infinity) [the Series RLC Branch parameter window].

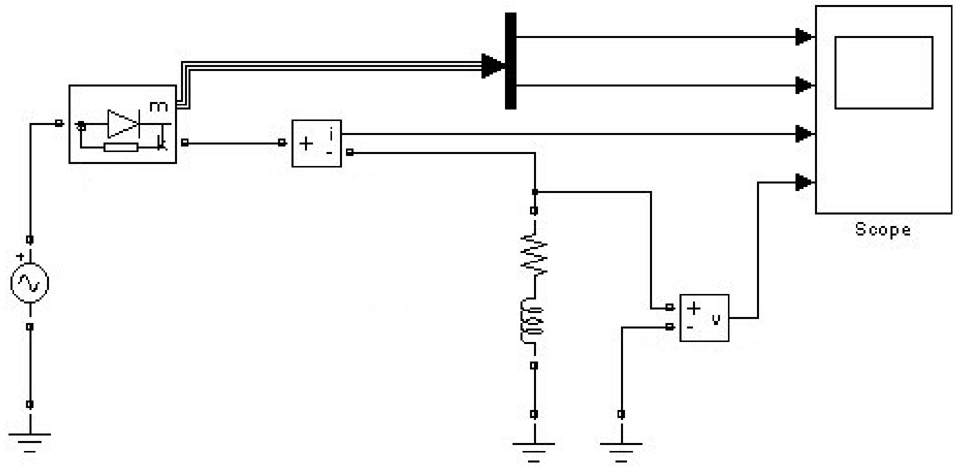


Fig. 1.3. Model of one-step rectifier with RL - load

The window of the parameters of the diode with the setup settings is shown in Fig. 1.4. If in the circuit, Snubber reduces the resistance of the resistor to a value of 10-20 Ohms, high-frequency oscillations may appear on the load current curve, indicating the need for careful attention to the choice of parameters of the elements in this circuit.

Less sensitive processes of switching the diode to the choice of capacity of this chain, but lowering it below 10-7 F can also cause the appearance of similar oscillations. Inductance Lon begins to affect the picture of processes in the case of values greater than 1 ... 5 mH.

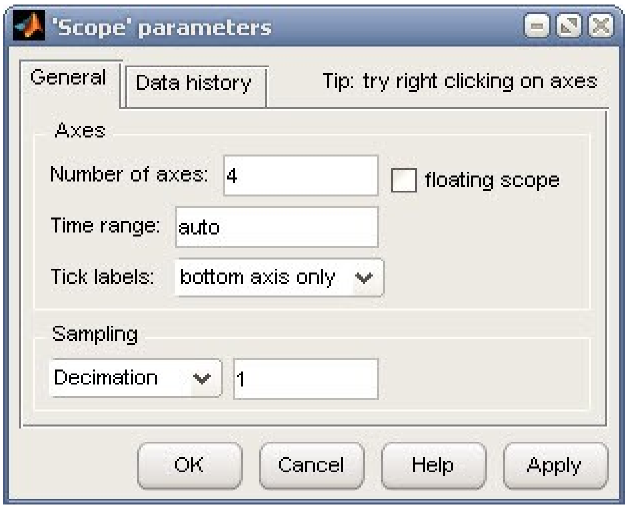


Fig. 1.4. Scope parameter setting window

It is allowed to choose the value of this parameter infinitely small or even zero. Time diagrams of current and voltage on the diode and current and voltage on the load are shown on oscillograms (Fig. 1.5).

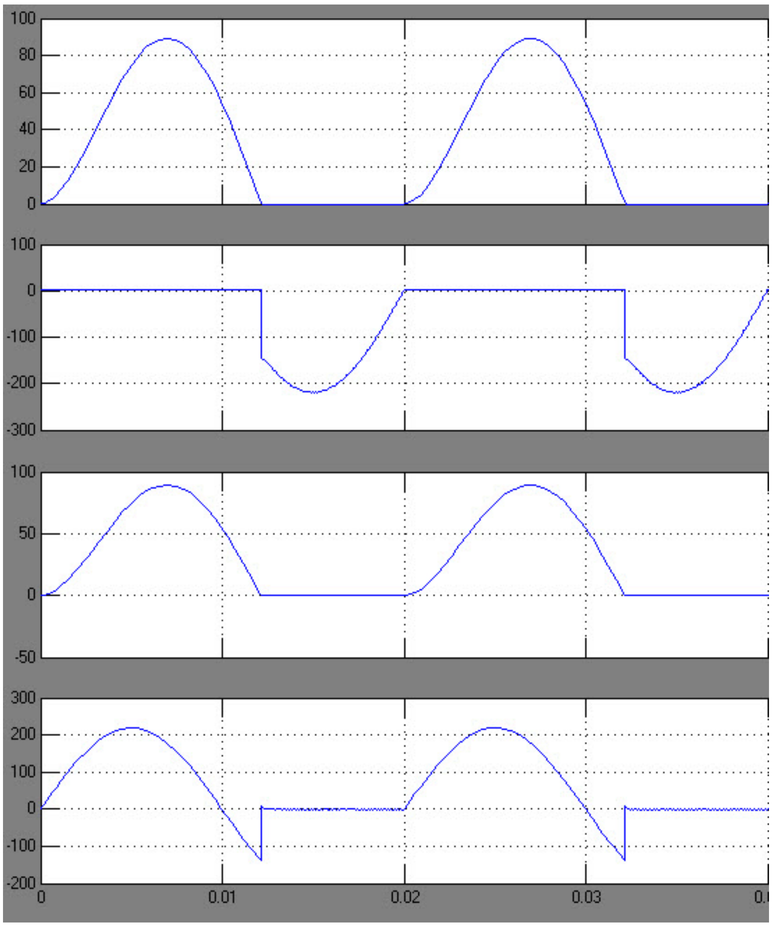


Fig. 1.5. Time charts of current and voltage

Task 1.2. Construction of the one-stage thyristor rectifier model with RL-load.

Construct a model and measure the voltage and current on the load.

Output data for simulation:

− U = 100 V;

− f = 50 Hz;

− R = 2 Ohm;

− L = 5 mH;

− angle of opening thyristor 90°.

Table 1.2 — Models and model parameters in the MATLAB / Simulink environment:

Library	**Block**	**Parameters**
SimPowerSystems/Electrical Source	AC Voltage Source	100+5·N

SimPowerSystems/Power Electronics	Thyristor	–
SimPowerSystems/Measurements	Current Measurement	–
SimPowerSystems/Measurements	Voltage Measurement	–
SimPowerSystems/Elements	Series RLC Branch	R = 2+2·N (Ohm), L = (5+N)·10^{-3} (H)
SimPowerSystems/Elements	Ground	–
Simulink/Sources	Pulse Generator	Period = 0.02, Pulse Width = 5%, Phase Delay = 0.02/4
Simulink/Sinks	Scope	–
Simulink/Sinks	Terminator	–
Simulation time		0,2 c
Solver		ode45

The collected schema of the rectifier model is shown in Fig. 1.6 and it is executed similarly to the scheme of the diode rectifier on Fig. 1.3.

Features of the considered scheme: unlocking the thyristor is carried out from the generator Pulse Generator, connected to the port g; Information port m of the thyristor is muted (connected Terminator block, located in the section of Sinks of the library Simulink). In the absence of the Terminator block, an error will be displayed in the command window.

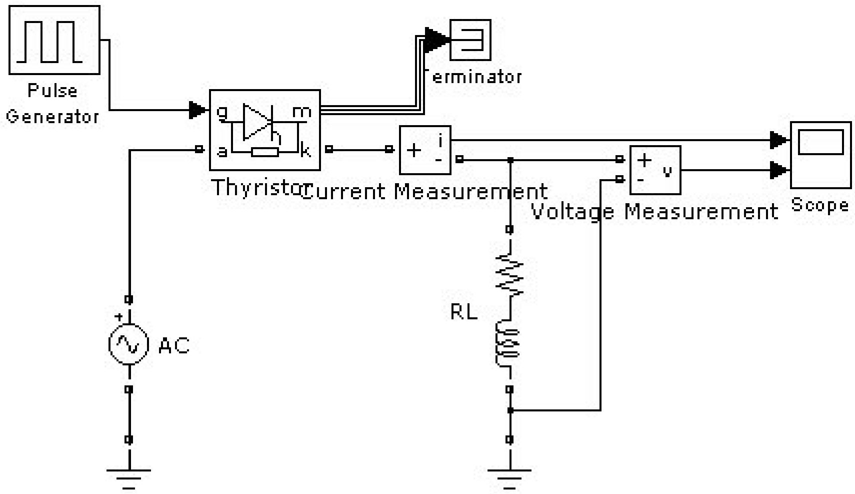


Fig. 1.6. Model of single-stage thyristor rectifier with RL – load

Parameters of the generator Pulse Generator are given in the window (Fig. 1.7.), from which it is seen that the period (Period) is 0.02 s, Pulse Width - 5% of the period, Phase Delay - 90 °). The window for adjusting the thyristor parameters is shown in Fig. 1.8.

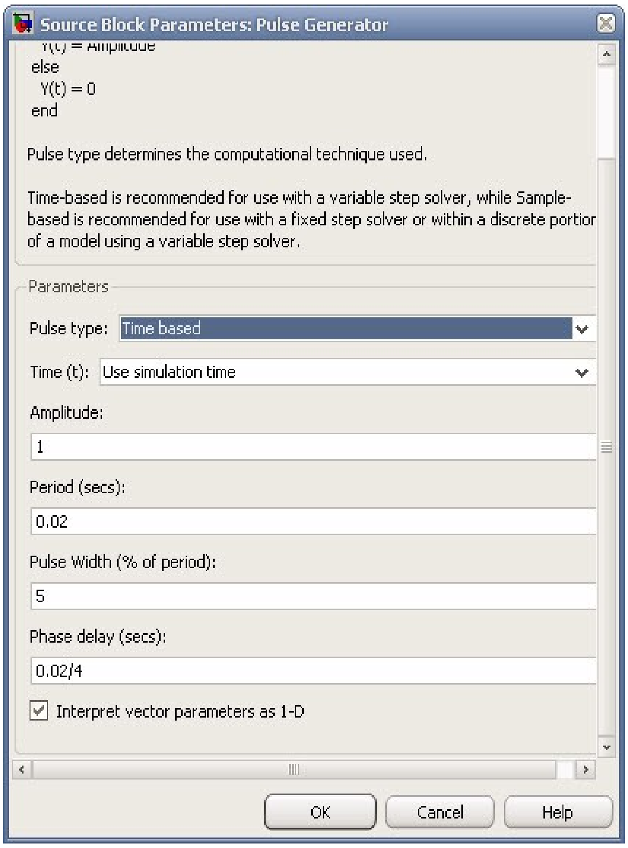


Fig. 1.7. Window for adjusting parameters Pulse Generator

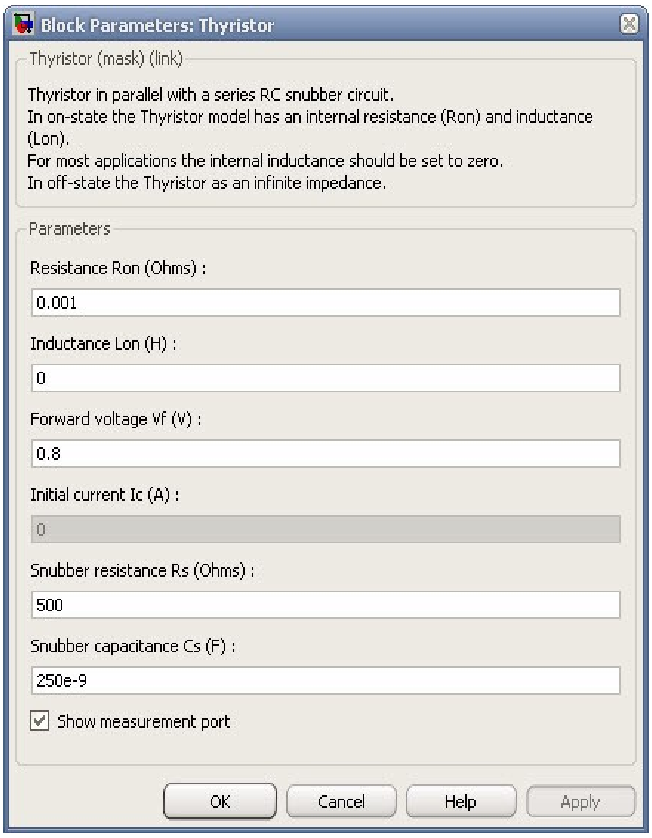


Fig. 1.8. Window for adjusting thyristor parameters

The simulation results are presented in the form of time diagrams of current through load and voltage on load on Fig. 1.9.

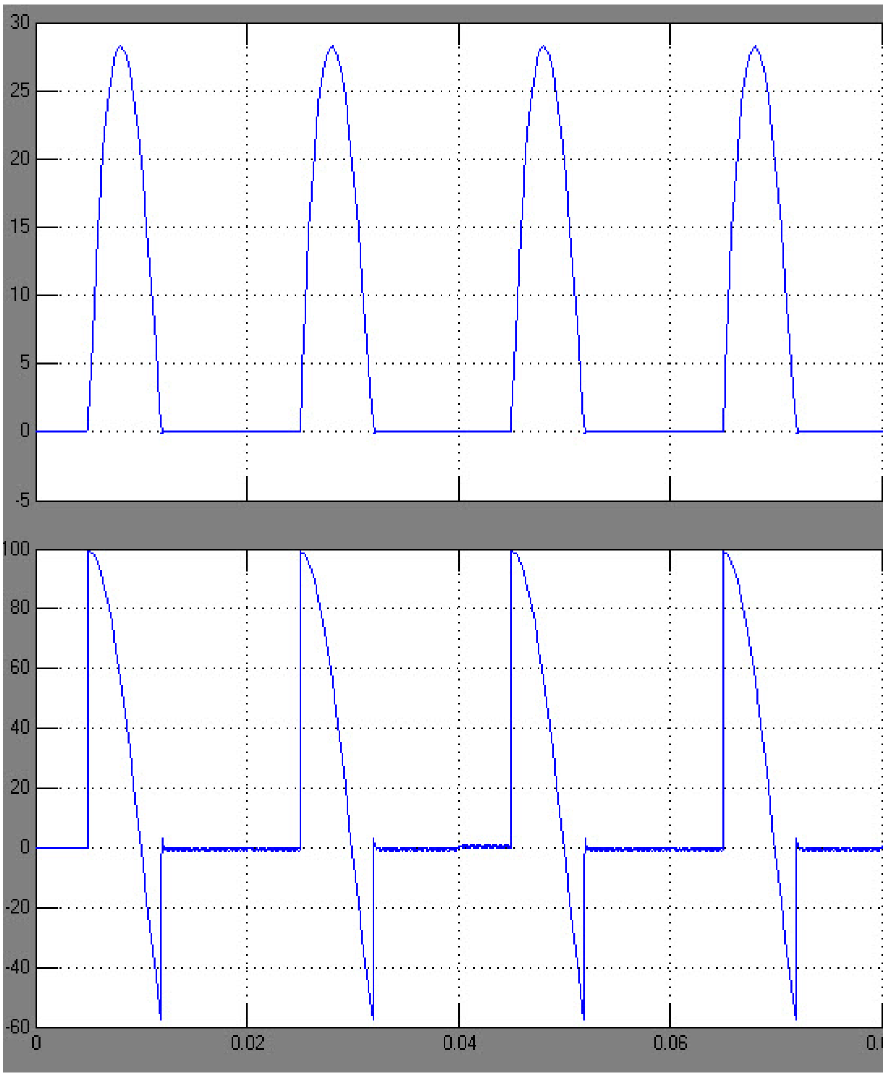


Fig. 1.9. Time diagram of current and voltage at the load

Task 1.3. Construction of the model of a three-phase rectifier with R-load.

The purpose of the work is to construct the model and to measure the stresses on the load.

Output data for simulation**:**

− U = 380 V;

− f = 50 Hz;

− phase delay 90°;

− R = 500 Ohm.

Table 1.3 — Blocks and model parameters in the MATLAB / Simulink environment:

Library	Block	Parameters
SimPowerSystems/Electrical Source	Three-Phase Source	380+5·N, Fig. 1.11
SimPowerSystems/Power Electronics	Universal Bridge	Number of bridge arms – 3 Power electronic device – Diodes
SimPowerSystems/Measurements	Current Measurement	–
SimPowerSystems/Measurements	Voltage Measurement	–
SimPowerSystems/Elements	Series RLC Branch	R = 500+5·N
SimPowerSystems/Elements	Ground	–
Simulink/Sources	Pulse Generator	
Simulation time		0,2 s
Solver		ode45

Schematic of the rectifier is shown in Fig. 1.10. It contains a three-phase power source, the 3-phase Source, the Universal Bridge Rectifier Bridge (Power Electronics), the R Series RLC Branch load (Elements section), the Voltage Measurement voltmeter (Measurement section), and the Scope oscilloscope (Sinks section).

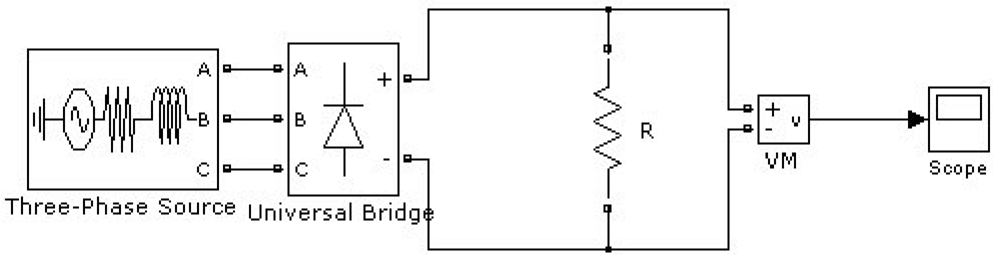


Fig. 1.10. Model of a three-phase rectifier with R-load

Some specificity of the tuning is to choose the parameters of the power supply unit and the rectifier bridge unit.

Here is a brief summary of the settings for the three-phase power supply.

Block settings settings window:

Phase-to-phase rms voltage (V) - current value of linear voltage;

Phase angle of phase A (deg) - initial phase of voltage in phase A (degrees);

Frequency (Hz) - frequency (Hz) of the variable voltage source;

Internal connection - phase connection of the source. The parameter value is selected from the list:

Y - star;

Yn - star with zero wire;

Yg is a star with a grounded neutral.

Specify impedance using short-circuit level - the problem of full resistance of the source using short circuit parameters. After setting this option, additional graphs appear in the dialog box for entering the short-circuit source parameters.

Source resistance (Ohms) - own source resistance (Ohm);

Source inductance (H) - own source inductance (H);

3-phase short-circuit level at base voltage (VA) is the short-circuit power at the base voltage;

Base voltage (Vrms ph-ph) is the active linear base voltage. The value of the linear baseline voltage of the source, based on which the power of short circuit is determined;

X / R ratio is the ratio of inductive and active resistance.

In the case of the impedance (complex resistance) of the source due to the short-circuit power (short circuit), the reactive resistance of the source is determined by the expression:

$$X = \frac{U_{кз}^2}{Q_{кз}} \tag{1.1}$$

$Q_{кз}$ – short circuit power; $U_{кз}$ – voltage source, during which the short circuit power is determined. The active resistance of the source is expressed by expression

$$R = \frac{X}{k} \quad (1.2)$$

де k – parameter X/R.

The installed source parameters are shown in Fig. 1.11.

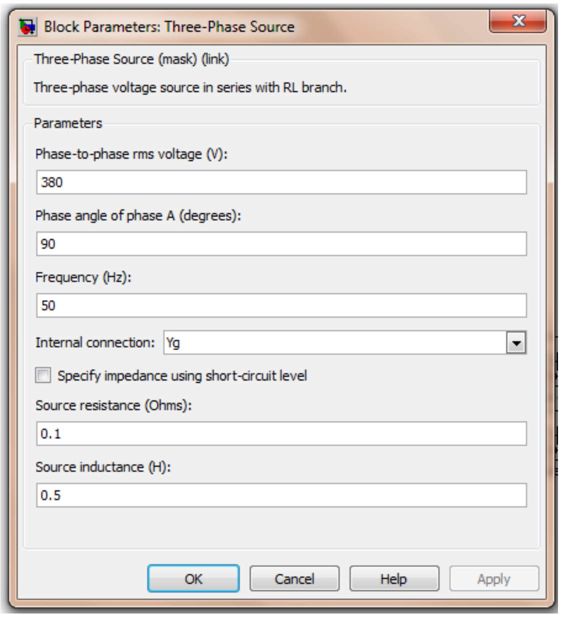


Fig. 1.11. Source options window

Similarly, the parameters of a universal bridge are shown in Fig. 1.12.

The output voltage of the model of a three-phase rectifier with an active load is shown in Fig. 1.13.

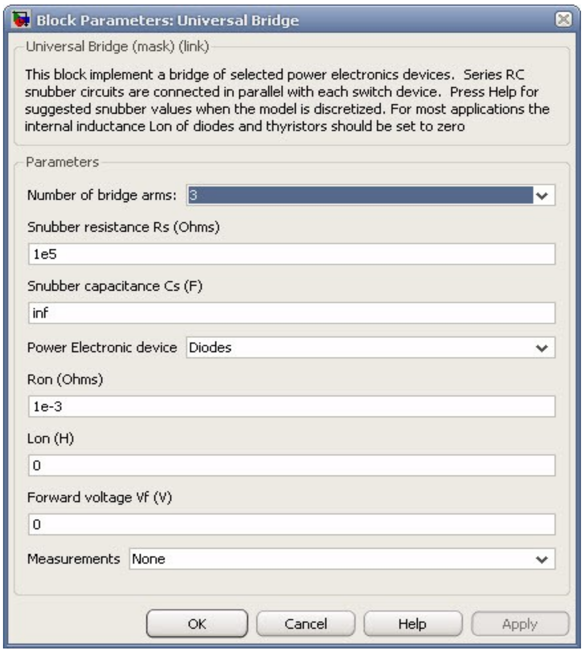


Fig. 1.12. Block options window Universal Bridge

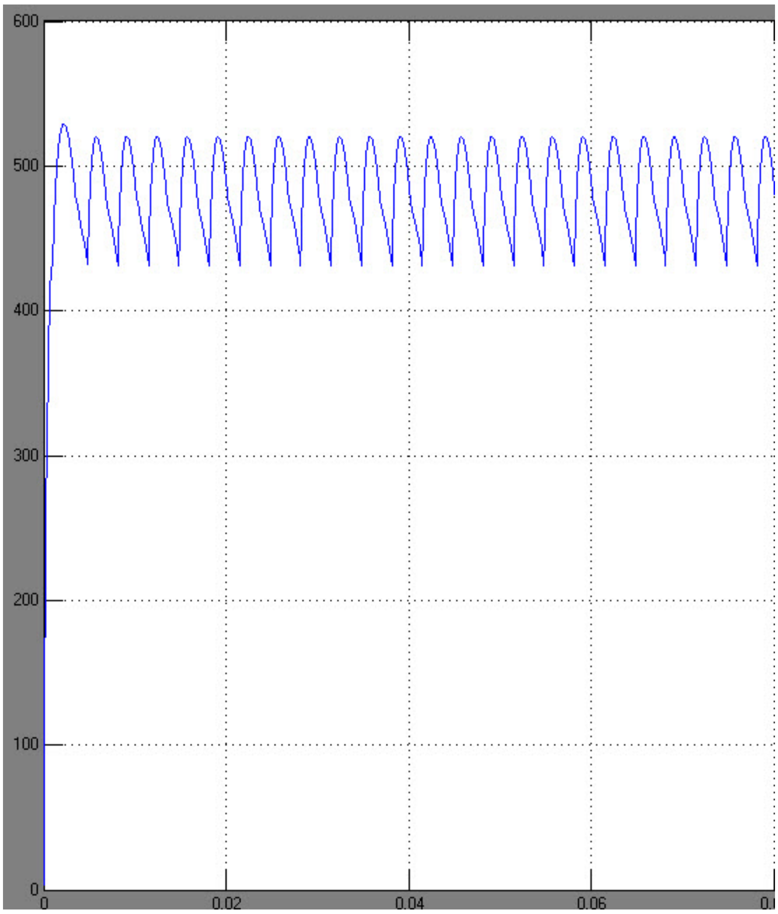


Fig. 1.13. Output voltage graph of the model of a three-phase rectifier

Task 1.4. Construction of the model of double-phase rectifier with a zero point of the transformer and a capacitive filter.

Measure voltage on load, current and voltage on diode.

Output data for simulation**:**

− U = 220 V;

− f = 50 Hz;

− $U_{вих}$ = 40-45 V;

− $R_{н}$ = 25 Ohm;

− amplitude of the variable voltage component on the load to 15% (7 V).

The rectifier model (Fig. 1.14) contains an AC Voltage power supply with a voltage of 220 V, a linear transformer Linear Transformer (the setting window for its parameters is shown in Fig. 1.14), two diode diode, a C filter, connected in parallel with the load R. For monitoring through the port m by the current and voltage on the diode Demux demultiplexer and the Scope1 oscilloscope with two inputs are used. Another Scope oscilloscope is used to obtain a timing diagram of the output voltage.

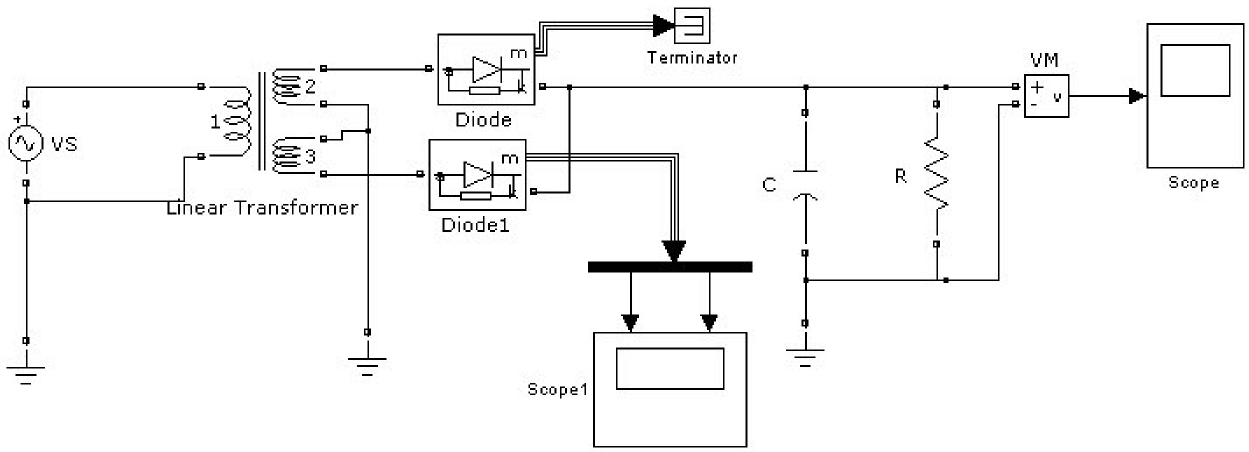


Fig. 1.14. Two-phase rectifier model with zero transformer point and capacitive filter

Table 1.4 — Blocks and model parameters in the MATLAB / Simulink environment:

Library	**Block**	**Parameters**
SimPowerSystems/Electrical	AC Voltage Source	220

Source		
SimPowerSystems/Power Electronics	Diode	–
SimPowerSystems/Measurements		–
SimPowerSystems/Measurements	Voltage Measurement	–
SimPowerSystems/Elements	Series RLC Branch	R = 20+5·N (Ohm)
SimPowerSystems/Elements	Series RLC Branch	$C = (1+N)\cdot 10^{-3}$ (F)
SimPowerSystems/Elements	Ground	–
Simulink/Sinks	Scope	–
Simulink/Signal Routing	Demux	–
Simulink/Sinks	Terminator	–
SimPowerSystems/Elements	Linear Transformer	
Simulation time		0,2 s
Solver		ode45

To adjust the model in the window parameters of the blocks, the value of 220 V and the frequency of 50 Hz of the supply voltage of the source of the AC Voltage, the parameters of the transformer (Fig. 1.15), the load resistance of 25 Ohms, the capacity of the filter 0,001 F. should be set. Note that the simulation time is given to 0,2 s .

Timing diagrams of the voltage on the filter, current and voltage on the diode are shown in Fig. 1.16 and 1.17 respectively.

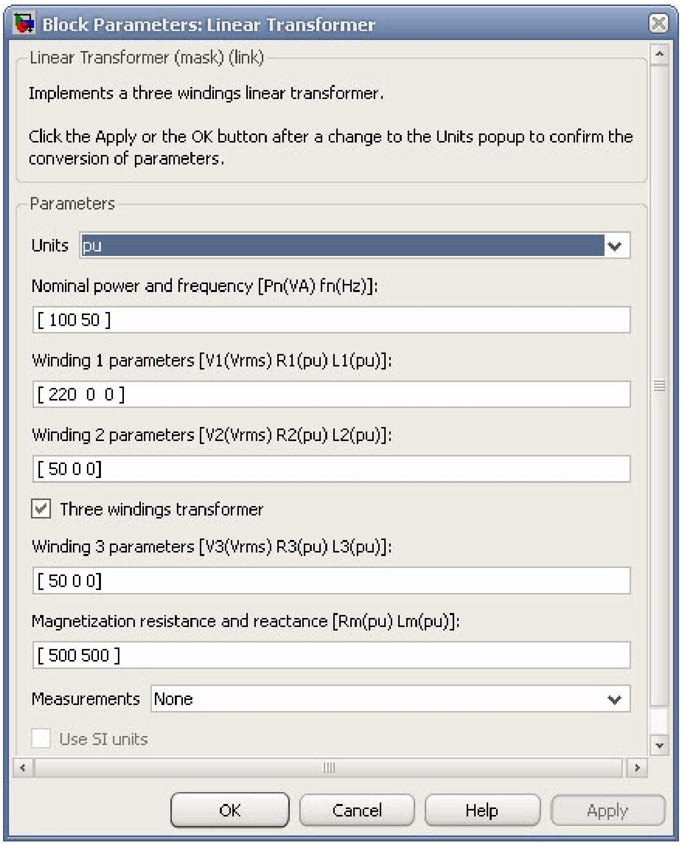


Fig. 1.15. Transformer parameters window

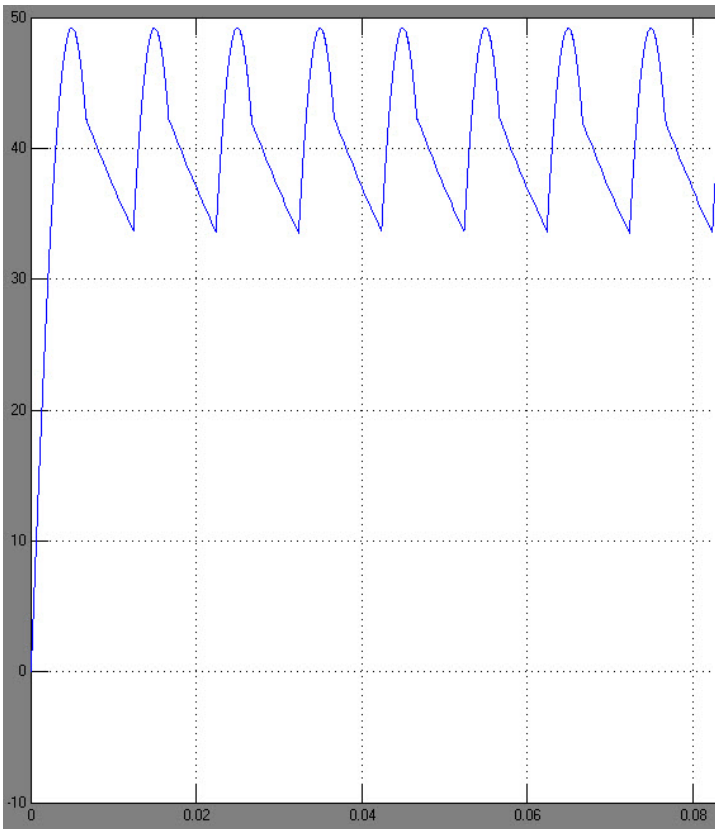


Fig. 1.16. Load voltage chart

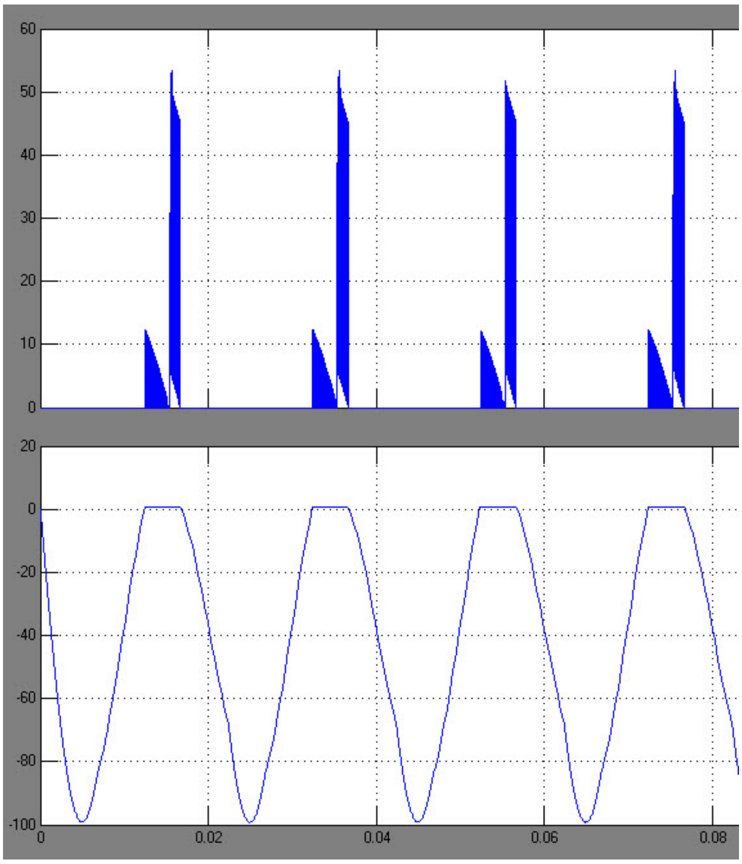


Fig. 1.17. Diode current and voltage chart

Control questions and tasks

1. Introduce the structural scheme of the rectifier.

2. Purpose of each component rectifier.

3. Introduce the blocks from which the model of a two-phase rectifier with a zero point of the transformer and a capacitive filter is made up.

4. Classification of rectifiers.

5. Classification of rectifiers by the principle of action.

6. Identify the main electrical circuits of the rectifiers.

TOPIC #2: RESEARCH OF AUTONOMOUS INVERTERS

Computer Practicum #2

Research of autonomous inverters

The purpose of the work is to get acquainted with models of autonomous inverters, to construct models and to simulate the schemes of autonomous inverters. Perform harmonic analysis for these inverter circuits.

Basic theoretical information

Stand-alone inverters are devices that operate on an autonomous load and are designed to convert DC voltage to an alternating current voltage of the induced or regulated frequency.

Autonomous inverters are used:

- in power supply systems for AC consumers, when the only source of power is a DC source (for example, a battery or solar battery);

- in systems of guaranteed power supply in case of power supply voltage disappearance (for example, for power plants personal needs - for power supply of control, measurement and protection devices);

- for feeding process equipment, the frequency of voltage differs from the industrial frequency of 50 Hz;

- for frequency regulation of the speed of asynchronous motors;

- for power supply of AC consumers from DC power supply lines;

- to convert a constant voltage of one level to a constant voltage of another level (voltage conversion).

The switching elements in the inverters are thyristors or power transistors.

Depending on the specifics of electromagnetic processes, current inverters and voltage inverters are distinguished.

Before constructing models of half-bridge and bridge inverters of current (hereinafter - Models) it is necessary to adjust the Simulink-model in this way:

- add to the model the powergui block of the SimPowerSystem library (Fig.2.1);

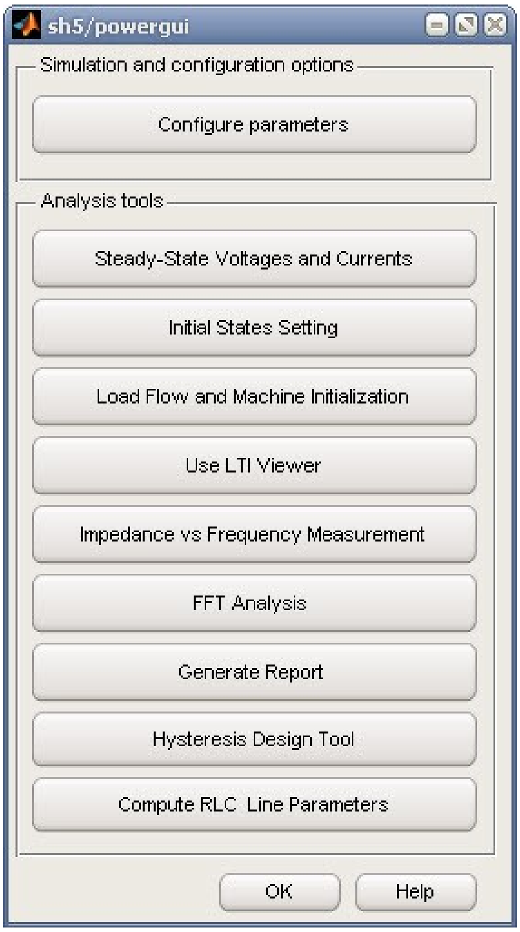


Fig. 2.1.Window powergui block

- adjust the block according to Fig. 2.2, where to go to the Configure parameters setting;

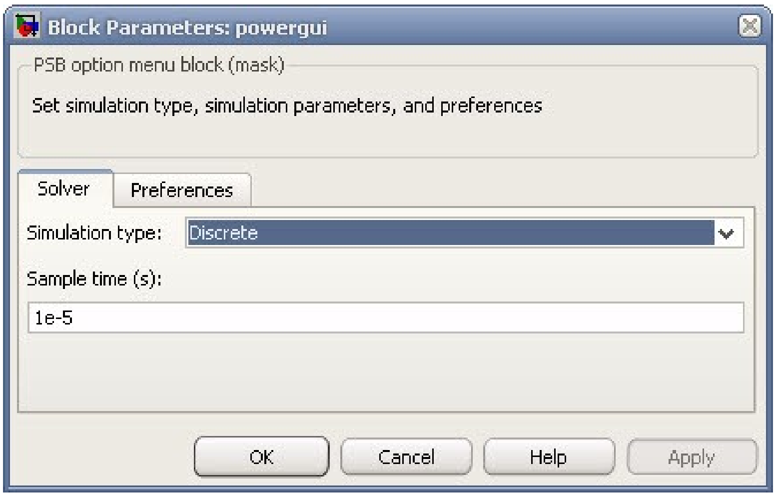


Fig. 2.2.Watch the powergui block

Parameters:

Simulation type: Discrete;

Sample time: 1e-5.

5. Building models must be executed in one model window.

6. The peculiarity of laboratory work is the use of the Multimeter block to build graphic dependencies. The setting of the Multimeter is shown in Fig. 2.3. The Plot selected measurements option must be enabled.

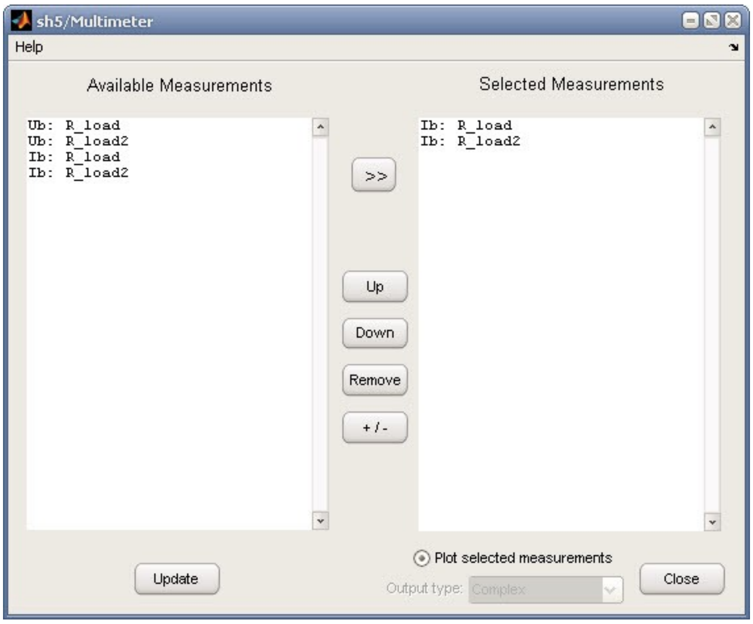


Fig. 2.3. The Multimeter block setting window

To use the Multimeter, you need to configure the parameters of the Series RLC Branch in accordance with Fig. 2.4.

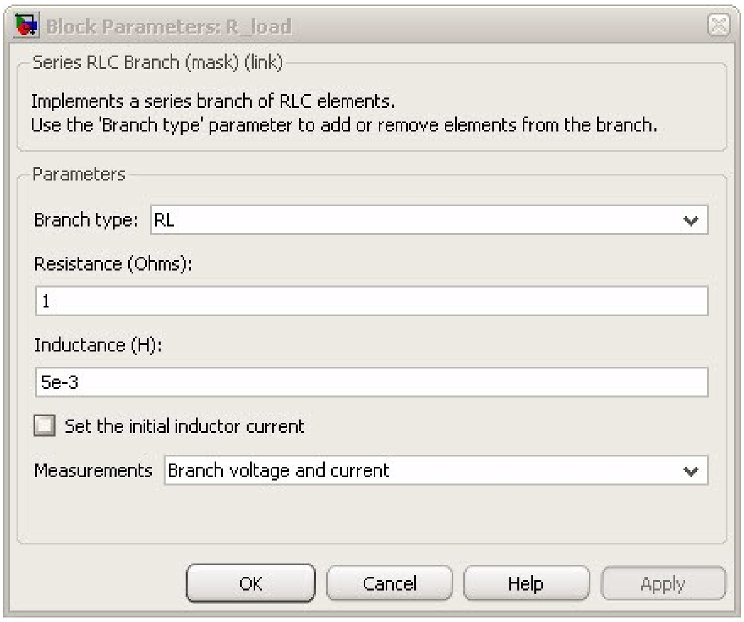


Fig. 2.4. Configure the Series RLC Branch

7. For analysis, the model should contain the To Workspace block (Fig. 2.5.) of the Simulink / Sinks library with the settings shown in Fig. 2.6.

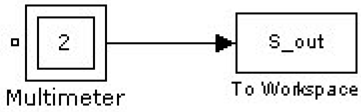


Fig. 2.5. To To Workspace Block

Setting up the To Workspace block:

Variable name: S_out;

Save format: Structure With Time.

8. To construct the spectral composition of the signal, FFT Analysis is used. Setting panel panels are shown in Fig. 2.6.

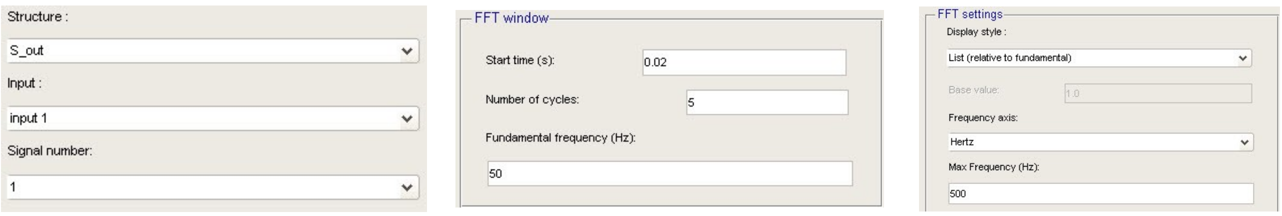


Fig. 2.6. Configure FFT Analysis

Parameters:

Structure: S_out;

Input: input 1;

Signal number: 1 or 2;

Start time: 0.02 s;

Number of cycles: 5;

Fundamental frequency: 50 Hz;

Max Frequency: 500 Hz.

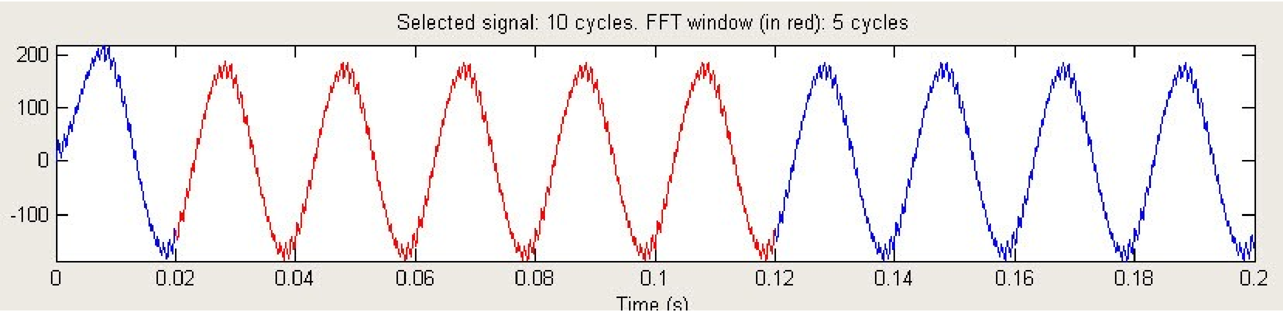


Fig. 2.7. FFT analysis window

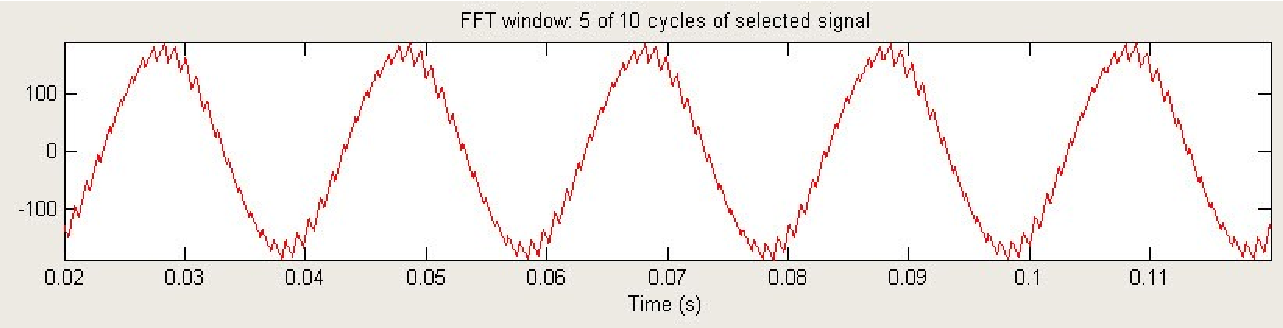
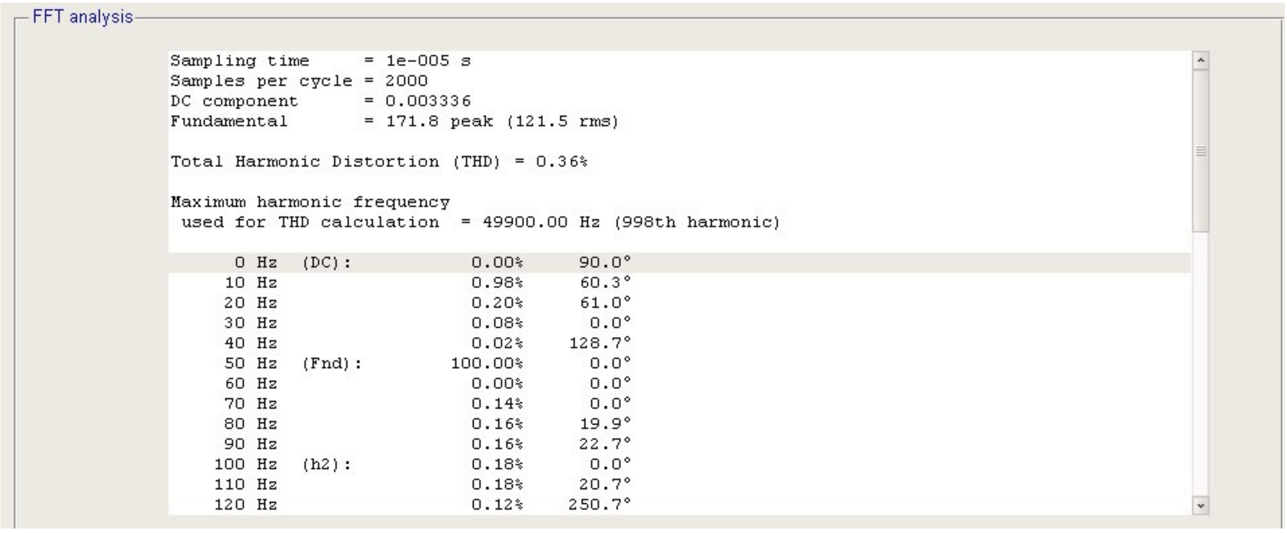


Fig. 2.8. FFT analysis window


FFT analysis

```
Sampling time      = 1e-005 s
Samples per cycle  = 2000
DC component       = 0.003336
Fundamental        = 171.8 peak (121.5 rms)

Total Harmonic Distortion (THD) = 0.36%

Maximum harmonic frequency
 used for THD calculation  = 49900.00 Hz (998th harmonic)

      0 Hz  (DC):          0.00%     90.0°
     10 Hz                 0.98%     60.3°
     20 Hz                 0.20%     61.0°
     30 Hz                 0.08%      0.0°
     40 Hz                 0.02%    128.7°
     50 Hz  (Fnd):       100.00%      0.0°
     60 Hz                 0.00%      0.0°
     70 Hz                 0.14%      0.0°
     80 Hz                 0.16%     19.9°
     90 Hz                 0.16%     22.7°
    100 Hz  (h2):          0.18%      0.0°
    110 Hz                 0.18%     20.7°
    120 Hz                 0.12%    250.7°
```

Fig. 2.9. FFT analysis window

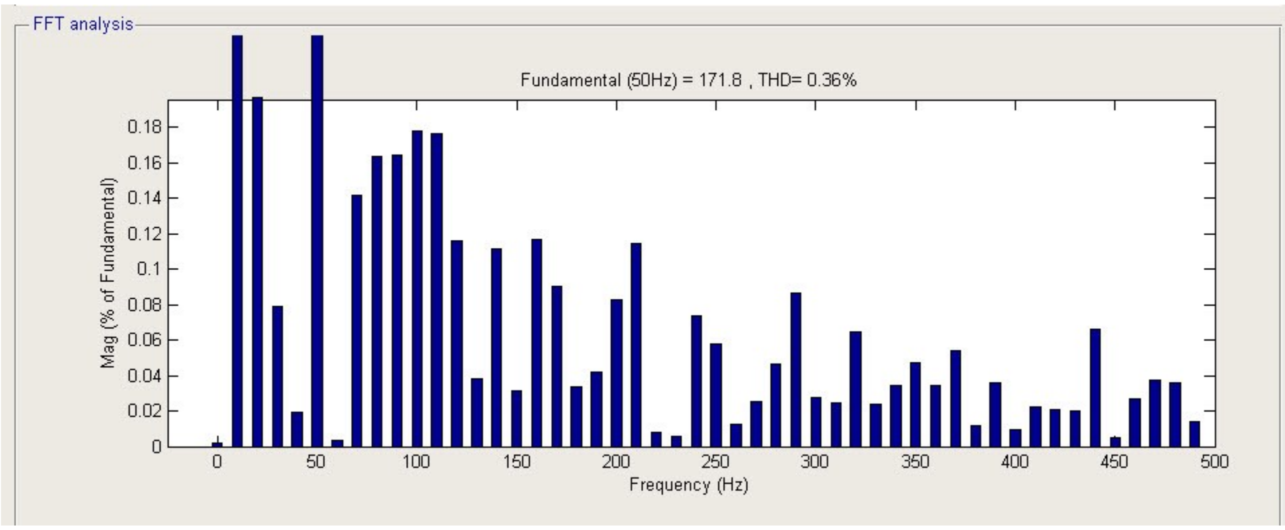


Fig. 2.10. FFT analysis window

Tasks for work

Task 2.1. Construction of a half-bridge current inverter model with a RL-load

Construct the model and conduct current measurement on the load.

Output data for simulation (see Table 2.1)**:**

− $U = 400$ V;

− $R = 1$ Ohm;

− $L = 5\cdot10^{-3}$ H.

Model construction:

Table 2.1 — Models and model parameters in the MATLAB / Simulink environment:

Library	**Block**	**Parameters**
SimPowerSystems/Electrical Source	DC Voltage Source	Amplitude: $200+4\cdot N$
SimPowerSystems/Power Electronics	Universal Bridge	Fig. 2.12.
SimPowerSystems/Elements	Series RLC Branch	Branch type: *RL* $R = 2+2\cdot\mathrm{N}$ (Ohm), $L = (5+\mathrm{N})\cdot10^{-3}$ (H)

		Measurements: Branch voltage and current
SimPowerSystems/Extra Library/Discrete Control Blocks	Discrete PWM Generator	Fig. 2.13, Ts=5e-6
Simulation time		0,2 s
Solver		ode45

The model of the half-bridge inverter is depicted in Fig. 2.11.

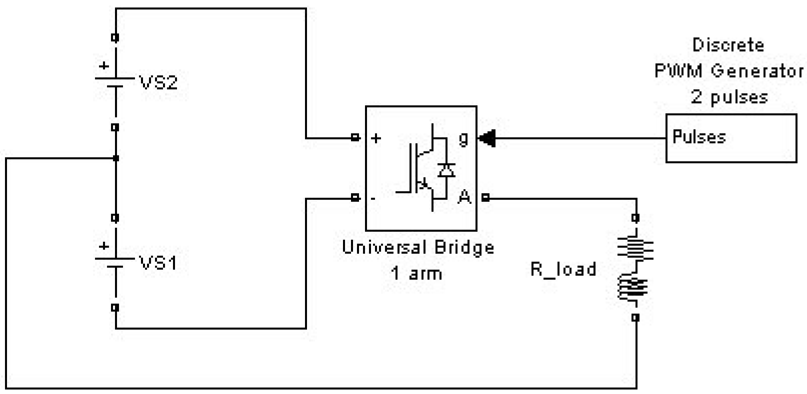


Fig. 2.11. Model of half-bridge current inverter with RL - load

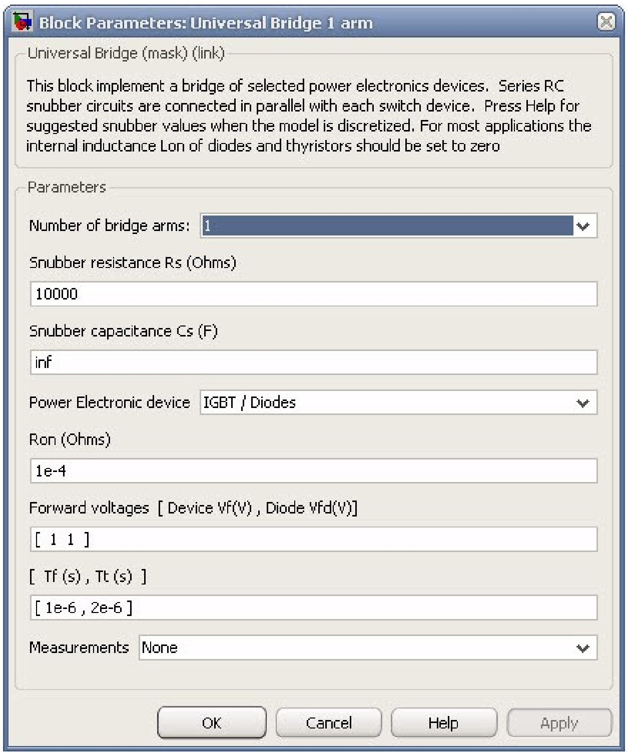


Fig. 2.12. Block configuration window Universal Bridge

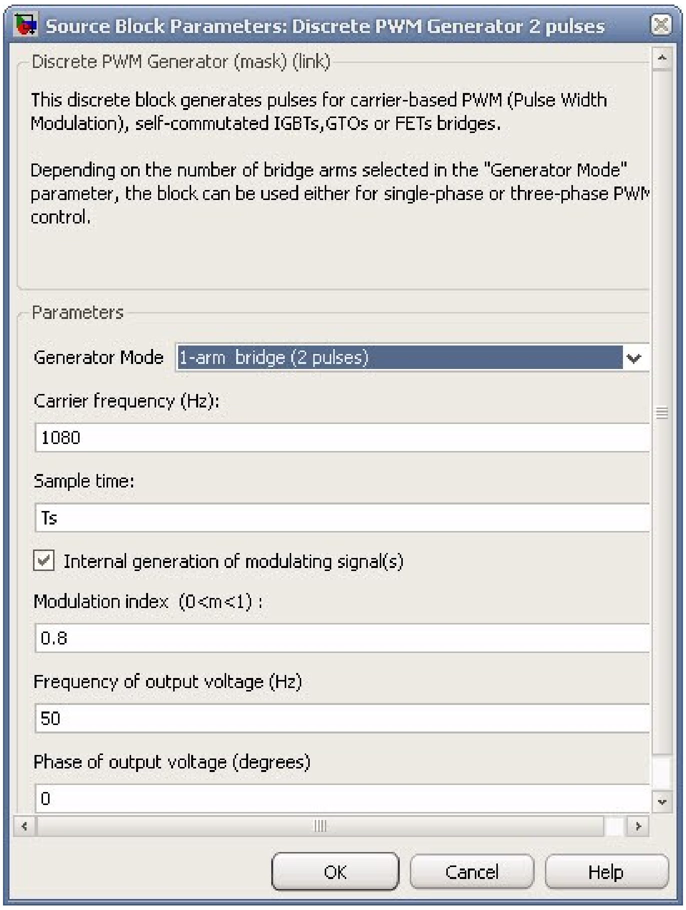


Fig. 2.13. Setting the Discrete PWM Generator

Task 2.2. Construction of the model of bridge inverter current with RL - load

Construct the model and carry out measurement of current and voltage on the load.

Output data for simulation**:**

− $U = 400$ V;

− $R = 1$ Ohm;

− $L = 5 \cdot 10^{-3}$ H.

Model construction:

Table 2.2 — Blocks and model parameters in the MATLAB / Simulink environment:

Library	Block	Parameters
SimPowerSystems/Electrical	DC Voltage Source	400+4·N

Source		
SimPowerSystems/Power Electronics	Universal Bridge	Fig. 2.15
SimPowerSystems/Measurements	Current Measurement	–
SimPowerSystems/Measurements	Voltage Measurement	–
SimPowerSystems/Elements	Series RLC Branch	R = 2+2·N (Ohm), L = (5+N)·10^{-3} (H)
Simulink/Sinks	Scope	–
SimPowerSystems/Elements	Ground	–
SimPowerSystems/Extra Library/Discrete Control Blocks	Discrete PWM Generator	Fig. 2.16
Simulation time		0,2 s
Solver		ode45

The model of the bridge inverter is depicted in Fig. 2.14.

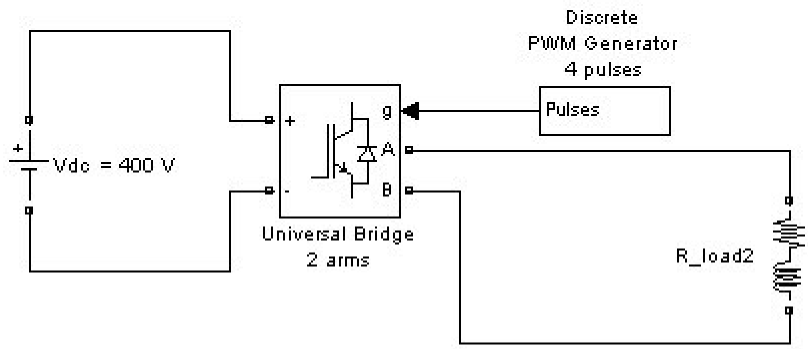


Fig. 2.14. The model of the bridge inverter

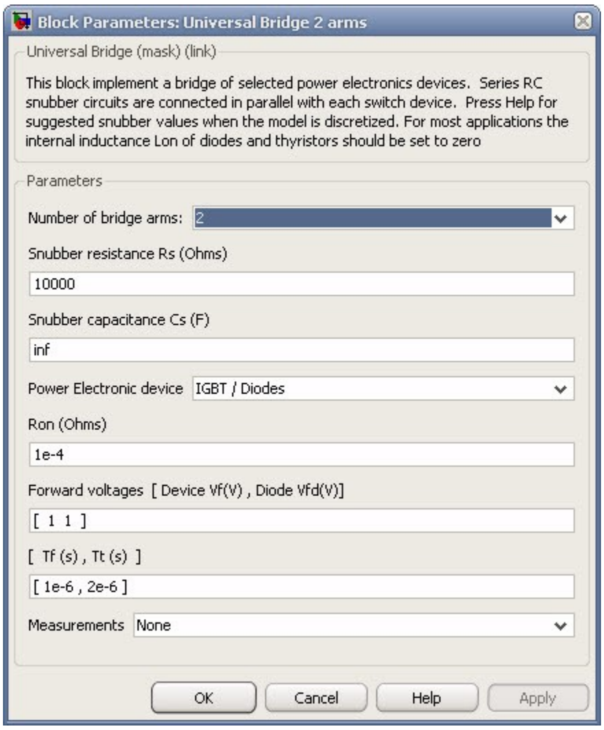


Fig. 2.15. Block setting window Universal Bridge

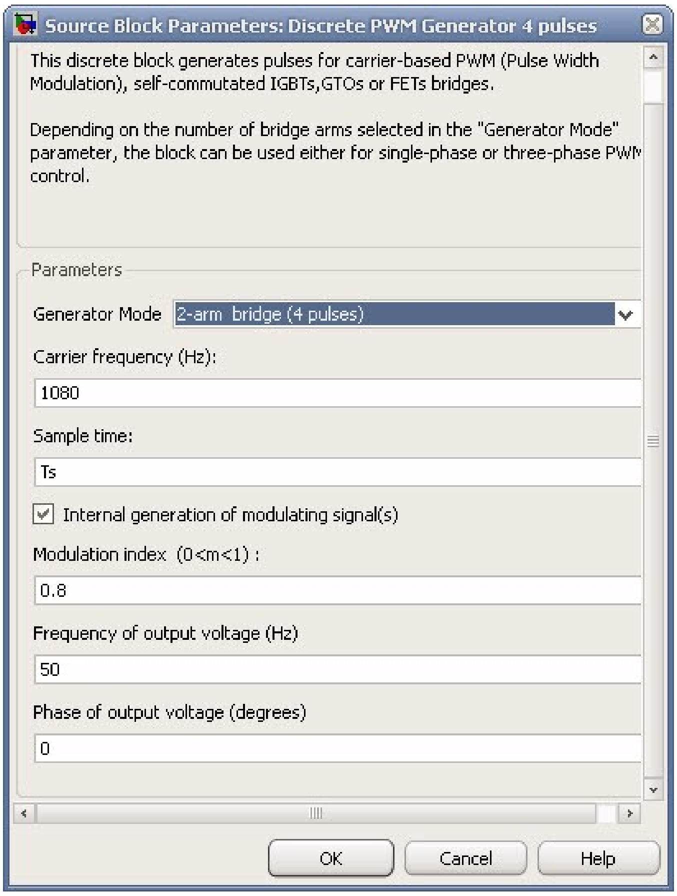


Fig. 2.16. Configure Diskrete PWM Generator

The graphs of the current load of the half-bridge and bridge inverters are shown in Fig. 2.17.

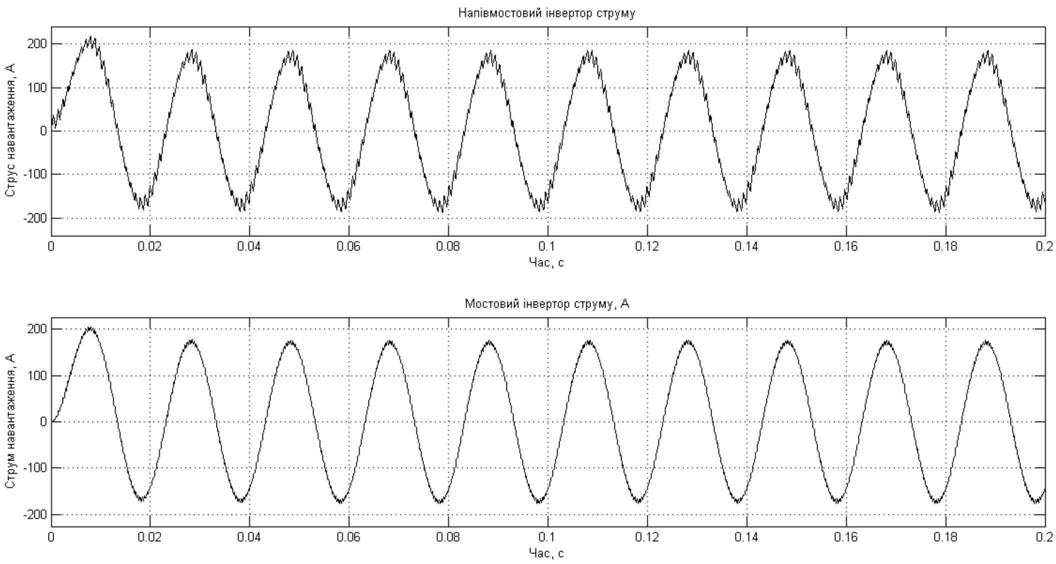


Fig. 2.17. Load current charts

Harmonic analysis is necessary for both variants of circuit inverters. The results of harmonic analysis are presented in Fig. 2.7 ... 2.10. It is necessary to estimate the THD for both circuits and make the appropriate conclusions.

Control questions and tasks

1. Purpose of autonomous inverters.
2. Application of autonomous inverters.
3. Disclose the essence and explain the principle of FFT analysis.
4. THD coefficient.
5. To name and explain the adjustment of the main measuring blocks used in this work.
6. Principle of operation of the measuring part of the laboratory circuits.

Computer Practicum #3

Research of the autonomous voltage inverter characteristics

The purpose of the work is to get acquainted with the models and operating modes of the autonomous voltage inverter. To study and construct the quasi-static and static characteristics of the autonomous voltage inverter.

Basic theoretical information

Semiconductor converters convert electrical energy with parameters into electrical energy with parameters under the influence of control signals. In addition to the power semiconductor elements in the semiconductor converter, as a rule, include other elements, to them, in the first place, include:

- reactive elements - capacitors, coils of inductance, chokes;
- electromagnetic transforming elements - power and measuring transformers;
- a control system, which in the general case is a complex electronic device implemented on elements of integrated circuits or on a microcontroller;
- alarm and alarm system of emergency modes.

Properties of power electronics systems are studied based on their main characteristics, which can be divided into static, quasi-static and dynamic.

Quasi-established characteristics:

- instantaneous electromagnetic processes in the load, in the power source and power semiconductor elements in the steady state operation of the semiconductor converter;
- spectral characteristics - voltage and current spectra in the supply chain and in the load of the converter.

Static characteristics establish a connection between the average, effective (effective) or amplitude values of state variables, which include:

- load (external) characteristics, which are dependencies of the output voltage from the load current;

- electromagnetic characteristics, representing the dependences of the amplitude, operating (average) currents (voltages) in the power circuit and the semiconductor elements of the converter from the load current;

- power characteristics - dependencies of power in the power supply of the converter, as well as losses of power in the semiconductor elements of the converter from the power in the load.

Time is an independent variable in case of simulation. Therefore, quasi-established and transient characteristics are the result of simulation and can be easily obtained through simulation.

Independent variables during the construction of static characteristics are the active or average values of state variables in steady state. Therefore, obtaining static characteristics requires a special modeling experiment, during which it is necessary to change the independent variable and determine the necessary dependencies in the steady state.

Let's consider the methods for obtaining the above characteristics and dependencies on the example of a three-phase autonomous voltage inverter (AIN) with sinusoidal pulse width modulation (PWM) at the carrier frequency.

At present, stand-alone inverters are increasingly used in electromechanical systems for controlling AC motors, power supply systems as active rectifiers, active filters, reactive power compensators, and others. In all of these devices, the inverter is connected to the alternating voltage source on the one hand, and on the other hand to the DC source.

The coefficient of modulation in the inverter is the ratio of the amplitude of the simulating voltage to the amplitude of the pollen voltage:

$$M = \frac{U_m\text{мод}}{U_m\text{нес}}. \tag{3.1}$$

In the range of modulation coefficient 0 <m <1, the inverter is in the linear zone.

In the three-phase AIN, the simulating voltage control of the keys of each shoulder of the inverter is shifted by 120 degrees. These signals are compared to the saw-like carrier voltage and generate control signals for each shoulder. According to the transistor control signals, voltage is generated at each phase of the load.

Tasks for work

Model description

Various models are used to obtain the basic characteristics of the inverter, differing mainly in measuring blocks and recording the measurement results in the working space of MATLAB. During this, the inverter itself, its power supply, control and load remain unchanged, they are presented in Fig. 1. The parameters of the model are shown in the table. 1. Block Subsystem is presented in Fig. 2. The Sample time parameter (if set) must be 1e-4.

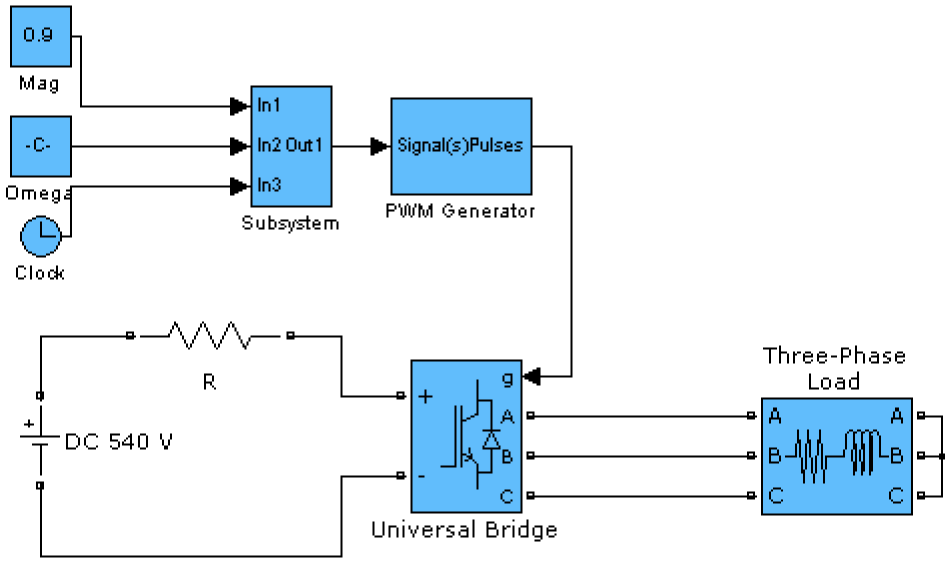
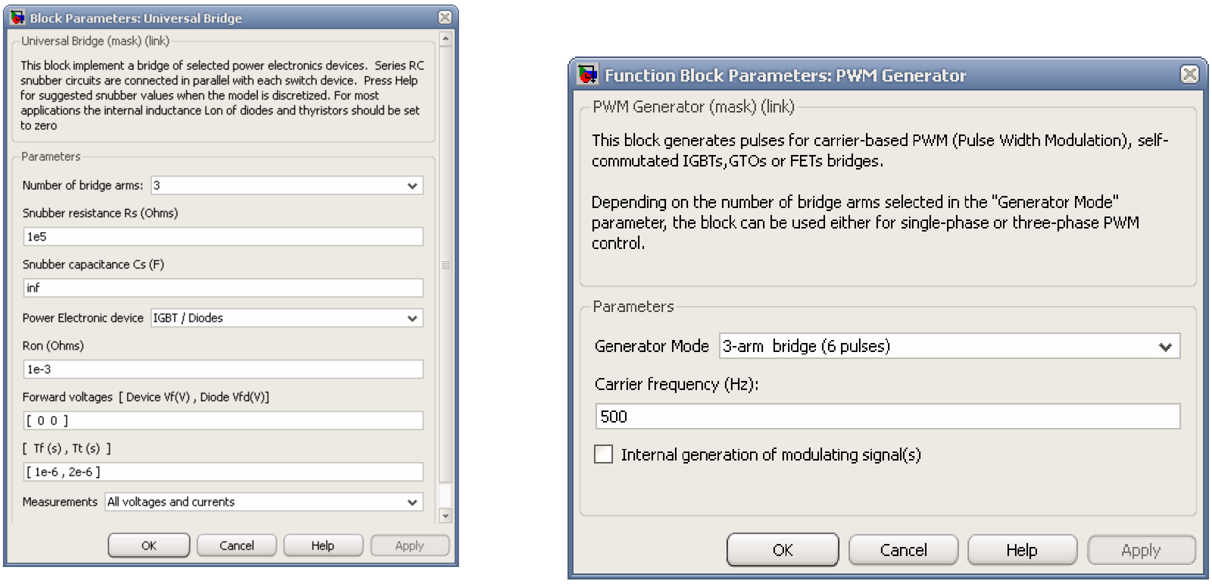


Fig. 1. Inverter model

Table 3.1. — Blocks and model parameters in the MATLAB / Simulink environment

Library	Block	Parameters
SimPowerSystems/Electrical Source	DC Voltage Source	Amplitude: 500+4·N
SimPowerSystems/Power Electronics	Universal Bridge	Fig. 3.2

SimPowerSystems/Elements	Three-Phase Series RLC Branch	Branch type: *RL* R = 2+2·N (Ohm), $L = (5+N)\cdot 10^{-3}$ (H) Measurements: Branch voltage and current
Simulink/Sources	Clock	–
Simulink/Sources	Constant **(Mag)**	Constant value: 0.9
Simulink/Sources	Constant **(Omega)**	Constant value: 2*pi*25
SimPowerSystems/Extra Library/ Control Blocks	PWM Generator	Fig. 2*б*
Simulation time		0,2 s
Solver		ode45



а б

Fig. 3.2. Window configuration options block

The parameters of the blocks necessary for building the Subsystem subsystem are given in Table. 3.2.

Table 3.2. — Blocks and subsystem subsystem parameters

Library	**Block**	**Parameters**
Simulink/Signal routing	Mux	Number of inputs: 3
Simulink/User-Defined Functions	Fcn	According to the formulas (3)…(5) and Fig. 3.3

The subsystem is generated by collecting schematics in the model window (Fig. 3.3a) without the input and output ports (In and Out, respectively) and the combination of Ctrl + G.

The blocks Fcn, Fcn1, Fcn2 compute the modulating control signals of the transistors in the shoulders A, B, C of the inverter, according to the formulas (3.3) - (3.5):

$$u(1) * \sin(u(2) * u(3)); \tag{3.3}$$

$$u(1) * \sin(u(2) * u(3) - 2 * pi / 3); \tag{3.4}$$

$$u(1) * \sin(u(2) * u(3) + 2 * pi / 3). \tag{3.5}$$

In Fig. 3b shows the setting window for the Fcn block.

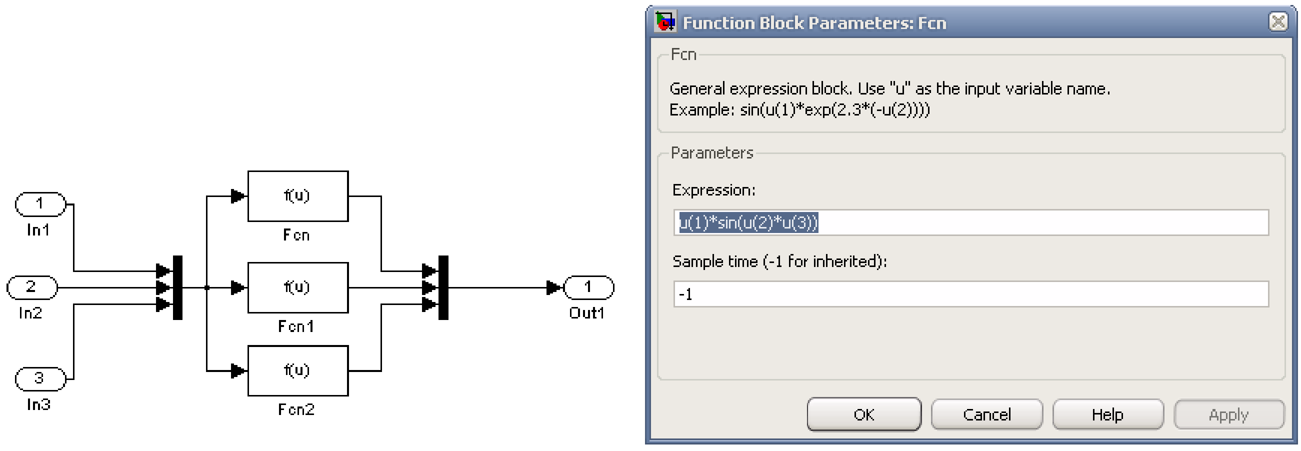
The pollen voltage of the bearing frequency generated by the Control System block has an amplitude of 1 V. Therefore, the value of the signal of the Meg block is equal to the modulation factor of the inverter [see. (1)]. The subsystem block input (Fig. 3.1) contains three signals:

- u (1) - amplitude of modeling voltage (block Mag);

- u (2) is the angular frequency of the modulating voltage $\omega = 2\pi f$, where f = 25 Hz (block Omega);

− u(3) − time (block Clock).

All models have a sampling step (Max Step Size = le-4).



а *б*

Fig. 3.3. A window (b) of the simulator signal calculation unit

1. Quasi-established characteristics

Quasi-established processes are the basis for studying physical phenomena in the inverter for the implementation of spectral analysis and, finally, obtaining the basic analytical relations for calculating the above static characteristics.

A model for obtaining electromagnetic quasi-stationary processes and spectral analysis is presented in Fig. 3.4. The parameters of the measurement units of the model, highlighted in yellow, are shown in the Table. 3.3. Time of modeling - 0,2 s.

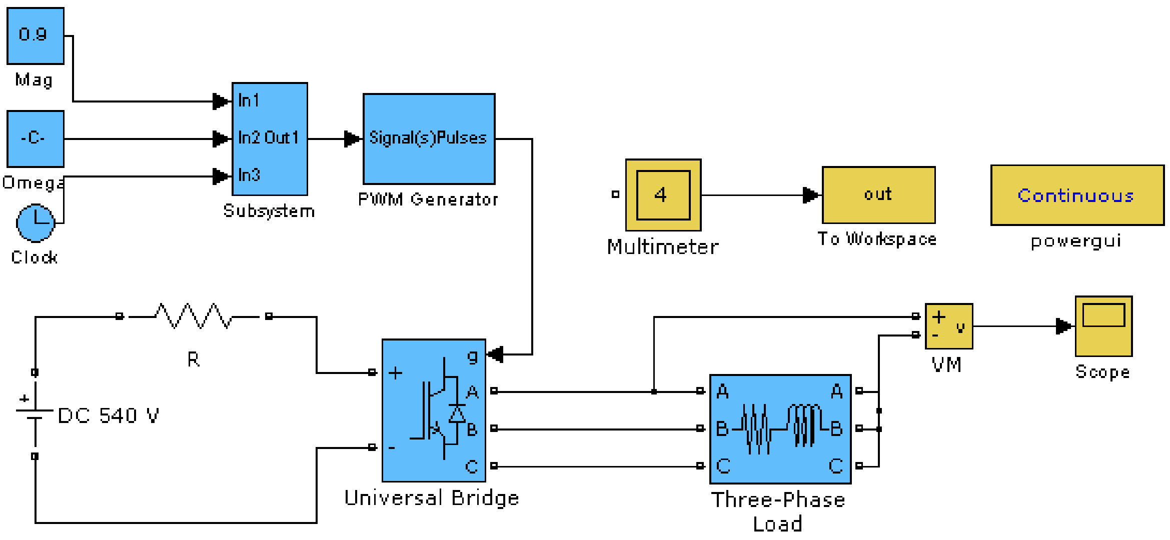


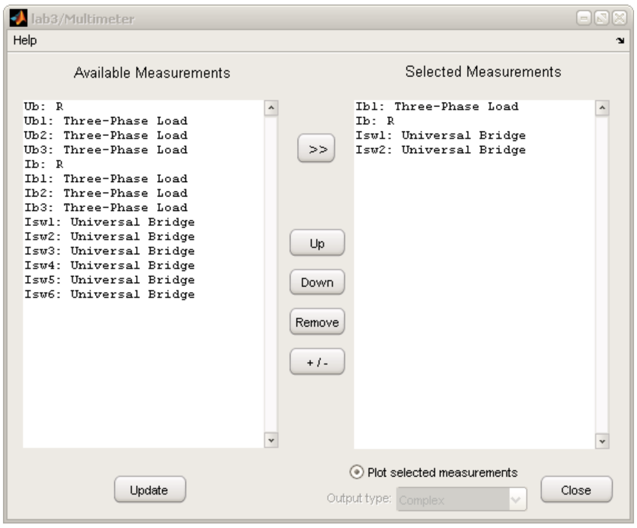
Fig. 3.4. Model for obtaining characteristics of electromagnetic quasi-stationary processes

The voltage in phase A of the load and its spectrum obtained during the adjustment of the oscilloscope using the Powergui block are shown in Fig. 3.5.

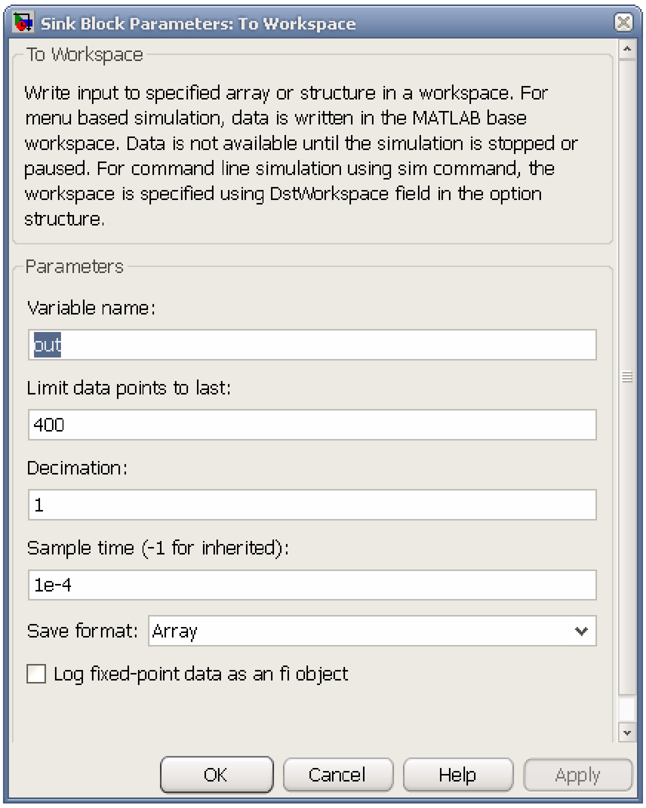
Table 3.3. — Parameters of measurement blocks

Library	**Library**	**Parameters**
Simulink/Sinks	Scope	Fig. 3.6
SimPowerSystems/Measurements	Multimeter	Fig. 3.5*a*
SimPowerSystems/Measurements	Voltage Measurement	–
SimPowerSystems/Elements	Series RLC Branch	Branch type: *R* *R* = 0.1 Measurements: Branch current
Simulink/Sinks	To Workspace	Fig. 3.5*б*

The width of the pulse varies according to the sinusoidal law at a frequency of 25 Hz, the modulation coefficient m = 0.9. The resistance (r = 0.1 Ohm), included in the power supply circle, simulates the source's internal impedance and allows measuring the source current with the Multimeter. This unit sequentially measures the load current, current in semiconductor SWl, SW2 of the inverter's shoulder A and current in the supply chain.

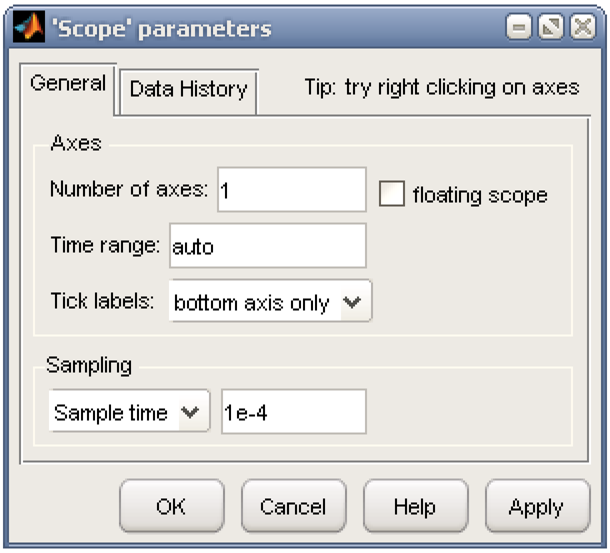


а

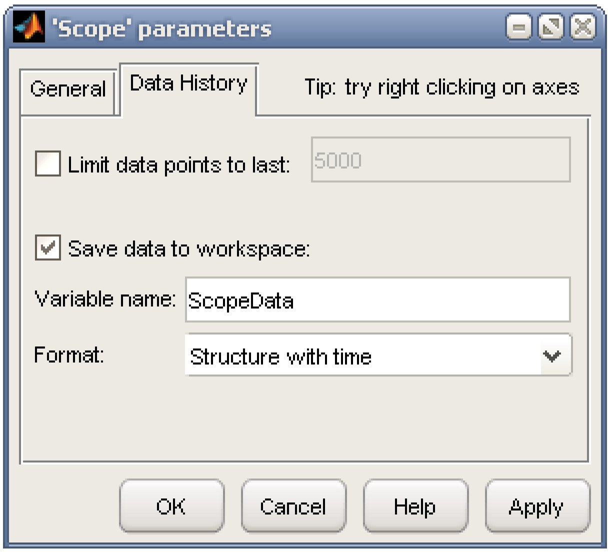


б

Fig. 3.5. Multimeter blocks setting windows (5 *а*) and To Workspace (5 *б*)



а



б

Fig. 3.6. Configure the Scope

Harmonic component of the phase voltage at the output of the inverter is shown in Fig. 3.7. Corresponding FFT Analysis settings are shown in Fig. 3.8.

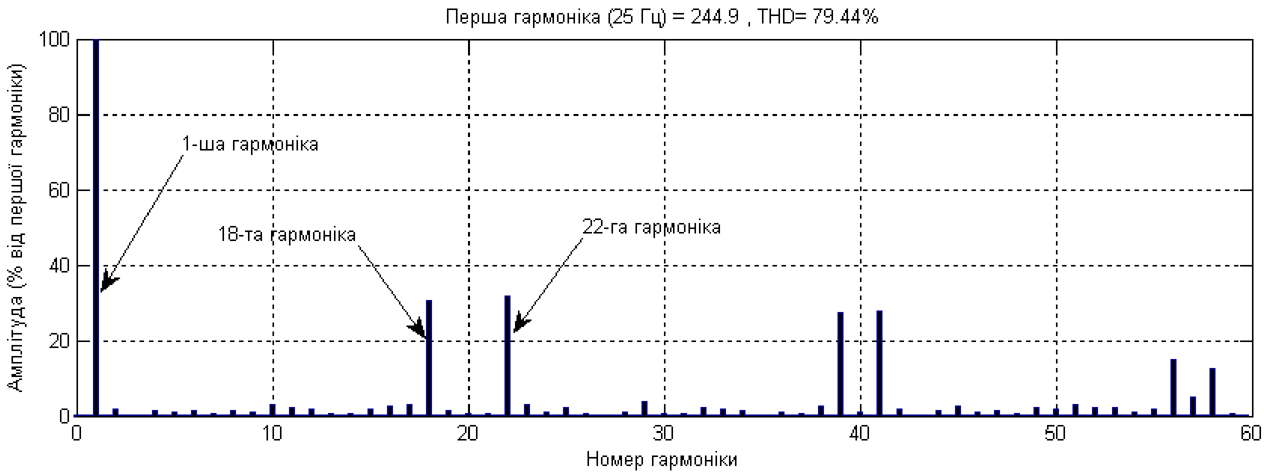
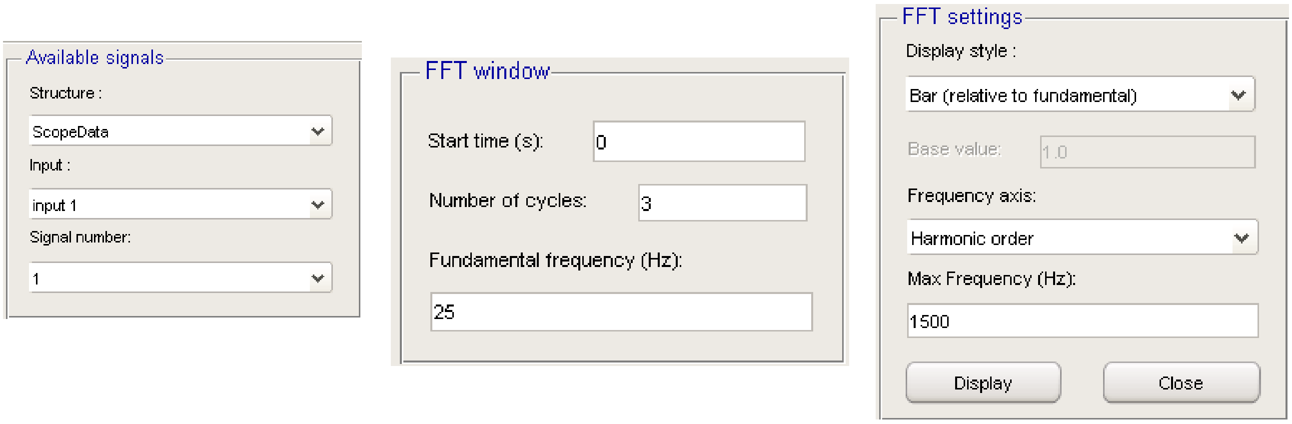


Fig. 3.7. Harmonic components of the phase voltage at the output of the inverter



а *б* *в*

Fig. 3.8. Setting FFT Analysis

From Fig. 3.7 it follows that the voltage spectrum contains the fundamental modulation frequency (25 Hz) and the side frequencies located to the right and left of the harmonics, multiples of the carrier frequency (500 Hz in our case) to the modulation frequency.

The simulation results are written to the Workspace block in the workspace, quasistal currents are constructed while executing the program presented in Listing 3.1.

Task 3.1

Listing 3.1

```
t=0:1e-4:399*1e-4;  % Set the time
i_Load=out(:,1);  % Create a load current variable
```

```
i_dc=out(:,2);      % Create a power supply variable
i_SW1=out(:,3);  % Create a current variable SW1
i_SW2=out(:,4);  % Create a current variable SW2
% Construction of load current and power graphics
Subplot (2,1,1);
Plot (t,i_Load, t,i_dc);
Ylabel ('Current, A');
Xlabel ('Time, s');
grid on;
legend ('Current of phase A load, A', 'Current circle generator, A',      'Location',
'Best');
% Construction of current charts in semiconductor keys
Subplot (2,1,2);
Plot (t,i_SW1,t,i_SW2);
Ylabel ('Current, A');
Xlabel ('Time, s');
grid on;
legend('Curret through SW1, A','Current through SW2, A', 'Location', 'Best');
```

To create a program whose code is shown in Listing 3.1, you must enter the edit list1 in the Matlab window, the program prompts you to create a file named list1, and then the Editor window to insert the code from Listing 3.1. The execution of the program leads to the construction graphs of quasi-stationary processes shown in Fig. 3.9.

From the consideration of electromagnetic processes, it follows that the load current is equal to the algebraic sum of the currents of the SWl, SW2 keys. During this semi-period, when the modulating voltage is positive, the current flows through VT1, and if it is locked due to the presence of inductance in the load, the current is switched to the diode D2. Similarly, during a negative modulating voltage current VT2 and D1 are carried out. The load current contains the first harmonic and a pulsating component whose magnitude depends on the frequency of the carrier signal and the constant load time. The amplitude of the first harmonic is determined from the expression

$$I_m(1) = \frac{U_m(1)}{\sqrt{R^2 + (\omega L)^2}}, \tag{3.6}$$

where $U_m(1)$, $I_m(1)$ − amplitude values of the first harmonics of phase voltage and load current.

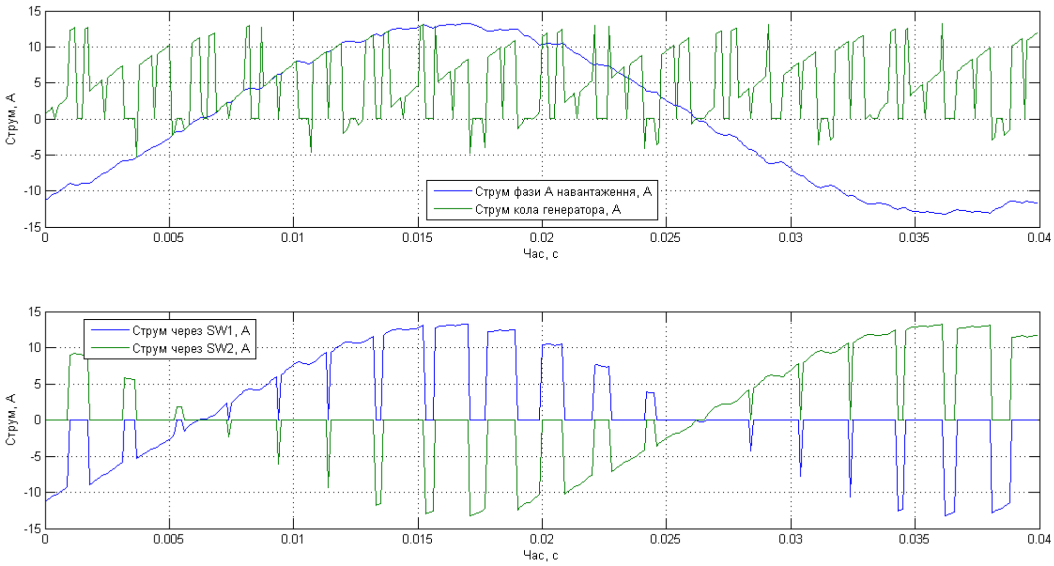


Fig. 3.9. Charts of quasi-tuned processes in an autonomous voltage inverter

The amplitude of the pulsating component can be determined by the approximate formula, taking into account, in this case, that it is determined by the harmonics, which are closest to the first one. In this case, it is the 18th and 22nd harmonics. Since the amplitudes of harmonic voltages on these harmonics are approximately equal, we have

$$\Delta I_m = \sqrt{\left(\frac{U_m}{\sqrt{R^2 + (18\omega L)^2}}\right) + \left(\frac{U_m(22)}{\sqrt{R^2 + (22\omega L)^2}}\right)} + \frac{\sqrt{2}U_m(18)}{\sqrt{R^2 + (18\omega L)^2}} = I_m\sqrt{2}. \tag{3.7}$$

where Um (18) Um (22) is the amplitude of the voltage on the 18th and 22nd harmonics.

In the calculation of losses in the semiconductor elements of the inverter, it should be borne in mind that the constructive inverter (or at least the inverter's shoulder), as a rule, is an integral modular design in which heat losses are distributed evenly. Therefore, such losses should be counted on the entire shoulder. Since the direct voltage drop and the direct resistance of the open transistor and the diode are almost identical, the losses in the shoulder of the inverter in quasi-stationary mode can be calculated by the formula

$$P_{SW} = \frac{R_{on}(I_m^2(1) + \Delta I_m^2)}{2} + \frac{2U_f I_m(1)}{\pi} = \\ = R_{on}(I^2(1) + I_m^2(18)) + \frac{2U_f I_m(1)}{\pi}. \qquad (3.8)$$

where P_{SW} − the power loss in the shoulder of the inverter R_{on} − the resistance of the open semiconductor key; U_f − voltage drop on open key; $I(1) = \frac{I_m(1)}{\sqrt{2}}$ − current of the first harmonic.

The total and active power in a load are determined by expressions

$$S_{load} = \frac{3U_m(1)I_m(1)}{2}; \\ P_{load} = \frac{3U_m(1)I_m(1)}{2}\cos\varphi. \qquad (3.9)$$

Power of supply source

$$S_{source} = U_{dc}I_{dc}. \qquad (10)$$

2. Static characteristics of the three-phase inverter

Static characteristics of the inverter can be obtained in different ways. Let's consider three of them, which use MATLAB software and MATLAB connection from MS Office. Each of the methods is considered on a concrete example of obtaining a certain static characteristic.

2.1 Calculation and construction of the regulatory characteristic

The receipt of the control characteristic is carried out on the model presented in Fig. 3.10. Parameters of the units for measuring the amplitude of the first harmonic of the output voltage are given in Table. 3.4.

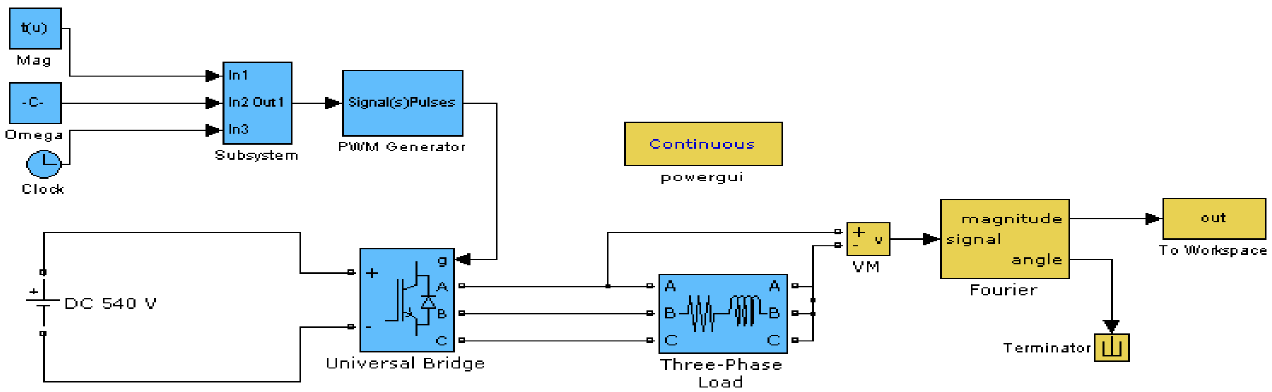


Fig. 3.10. Model for obtaining a control characteristic

Table 3.4. — Parameters of measurement blocks

Library	**Block**	**Parameters**
Simulink/Sinks	To Workspace	Variable name: out; Limit data to last: 1; Sample time: 1e-4.
SimPowerSystems/Extra library/Measurements	Fourier	Fundamental frequency: 25; Harmonic n: 1.
SimPowerSystems/Measurements	Voltage Measurement	–
Simulink/Sinks	Terminator	–

The regulatory characteristic can be obtained by executing Listing 3.2 (similar to Listing 3.1 operations).

Task 3.2

Listing 3.2

```
clear all;
t=0:0.1:2; %Set the time
```

```
%Open the file lab3_2.mdl, which contains a model for construction
% regulatory characteristics AIH
open('lab3_2.mdl');
for u=1:21,
set_param('lab3_2/Mag','Value','t(u)');% Set Mag block parameters
sim('lab3_2'); % Run the model
f(u)=out;% Create an array where the value of the output variable out is written
end
% Carry out the construction of the regulatory characteristic AIH
plot(t,f);
title('Regulatory characteristic AIH')
ylabel('Output Voltage, V');
xlabel('Input Voltage, V');
grid on;
```

Based on the results of the Listing 3.2 program, a regulatory characteristic is constructed (Figure 3.11).

From Fig. 3.8 it is seen that the inverter is a linear link in the range of modulation coefficient change 0 <m <1. For m> 1, the control characteristic becomes nonlinear. By regulation characteristic is determined by the gain of the inverter as a link in the control system.

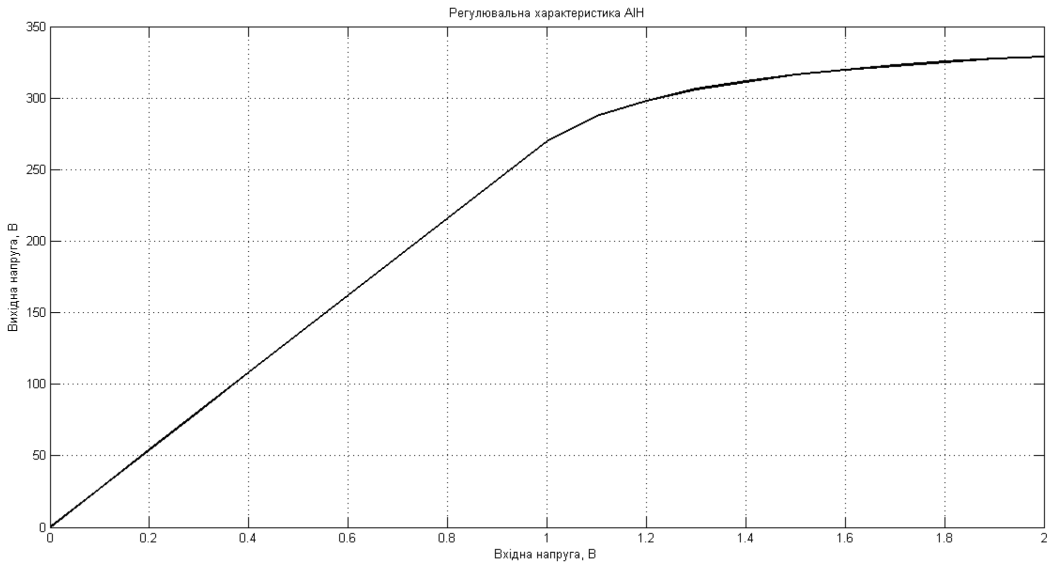


Fig. 3.11. Regulatory characteristic of AIN

Control questions and tasks

1. Purpose of a stand-alone inverter.
2. Component elements of semiconductor converters.
3. Quasi-established characteristics of AIN.
4. Static characteristics of AIN.
5. Definition and assignment of the modulation factor in the inverter.
6. Purpose and function of the main elements of the model schemes.
7. Principle of the basic schemes of laboratory work.
8. Appointment of the main elements of the working schemes of laboratory work.

Computer Practicum #4

Research of the autonomous voltage inverter characteristics

Calculation and construction of external (load), electromagnetic and power characteristics of the inverter.

The purpose is to get acquainted with the models and operating modes of the autonomous voltage inverter. To study and construct the external (load), electromagnetic and energy characteristics of the autonomous voltage inverter.

Basic theoretical information

1. Calculation and construction of external (load), electromagnetic and power characteristics of the inverter

In the model experiment under consideration (CP #3), the load current during the simulation period varies due to a change in the EDF at such a rate, during which it is possible to neglect the voltage drop on the load inductance:

$$L\frac{di}{dt} << R \tag{4.1}$$

Model of a three-phase inverter with variable load.

The simulation time is 1.0 s, the sampling step (Max Step Size = 1e-4), the modulation coefficient m = 0.9.

Block Multimeter is consistently measured values of load current, voltage and current in the power supply circle inverter.

Programmable source whose configuration window is shown in Fig. 4.1, designed to change the load of the inverter during simulation time.

The measuring part of the model contains four blocks. The contents of the Subsystem block are shown in Fig. 4.2. It sequentially defines:

- Amplitude of the first harmonic of the load current (block Fourier);
- Phase of the first harmonic of load current (block Fourier);
- Amplitude of the first harmonic of the linear load voltage (block Fourier 1);
- Average power supply of the inverter (block Fourier 2);
- Effective current in the semiconductor shoulder of the inverter (block RMS);

- Instantaneous current and load voltage.

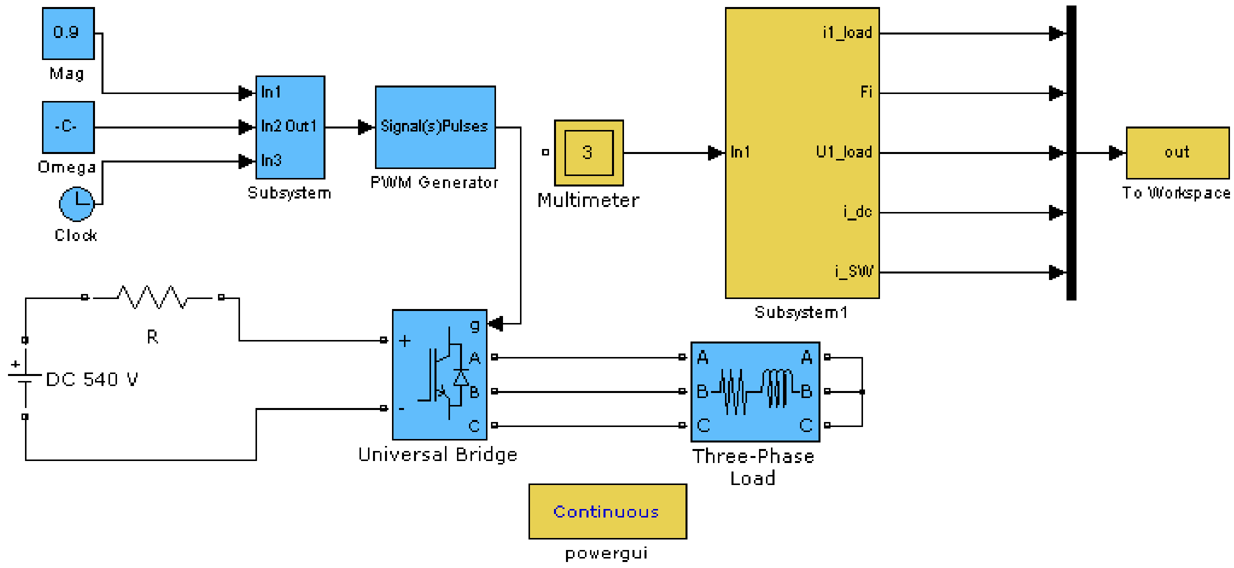


Fig. 5.1. Model of a three-phase inverter with variable load

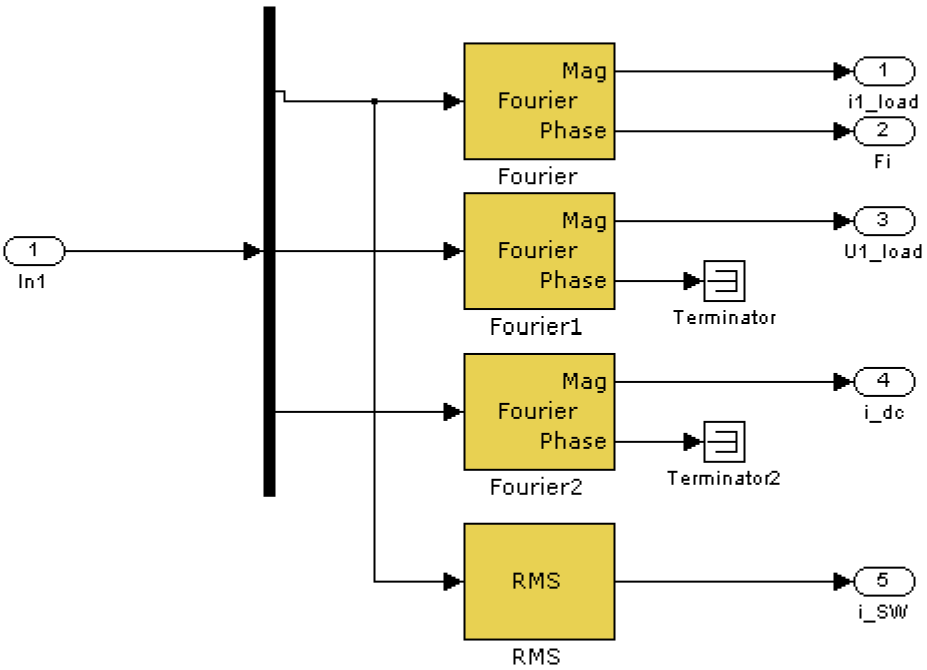


Fig. 5.2. Measuring part of the model

The To Workspace block is used to write to the working space of MATLAB values measured by the Subsystem block. When the checkbox is checked, in the Limit data points to last field, the number of fields in the field of final measurements is written to the working space (the initial measurements are deleted). During this time, the recording is equal to the product of the number of measurements for the maximum sampling step. In our case, t = 8000 · 10-4 = 0.8 s. This assumption allows you to exclude data from the transient process in the schema.

The parameters of blocks for constructing models (Fig. 4.1 and 4.2 of CP #4) are given in Table. 4.1.

Table 4.1. — Block parameters

Library	**Block**	**Parameters**
Simulink/Sinks	To Workspace	Variable name: out; Limit data to last: 1; Decimation: 1; Sample time: 1e-4. Array
SimPowerSystems/Extra library/Discrete Measurements	Discrete Fourier	Fundamental frequency: 25; Harmonic n: 1.
SimPowerSystems/Extra library/Measurements	RMS	Fundamental frequency: 25;
SimPowerSystems/Measurements	Multimeter	Load current (R); Load voltage (R); Current (Ib1 Three-Phase Load).
SimPowerSystems/Elements	Three-Phase Series RLC Branch	Branch type: *RL* *R* = R1 (Ohm), *L* = L1 (H) Measurements: Branch voltage and current

Simulink/Sinks	Terminator	–
Simulation time		0,2 s
Solver		ode45

For the construction of static characteristics is the program, presented in Listing 4.1. Load and electromagnetic characteristics, calculated and built by the program, are shown in Fig. 4.3.

The program, represented by Listing 4.1, also calculates the power in the load and in the supply chain, which enables to construct the energy characteristics of the inverter. To execute it in accordance with the number of the variant in the list to accept R1=10+2·N; L1=(5+2·N)·10^{-3}.

Task 4.1

Listing 4.11

```
clear all;
%Open the file lab4_1.mdl
open('lab4_1.mdl');
R1=20;
L1=0.1;
for u=1:10,
R1=R1-1;
sim('lab4_1'); % Run the model
for m=1:5;
f(u,m)=out(m);% Create an array where the value of the output variable out is written
end
end
for k=1:10
I1_Load(k)=f(k,1); % Amplitude of the 1st harmonic of load current
Fi(k)=f(k,2);% Load current phase
```

```
U1_Load(k)=f(k,3);% Amplitude of the 1st harmonic of linear load voltage
I_dc(k)=f(k,4);% Average value of power supply current
I_SW(k)=f(k,5);% The current value of current in the inverter branch
I0_SW(k)=2*I1_Load(k)/pi; % Average value of current in the inverter branch
end
P_dc=540.*I_dc;% Power supply power
S_Load=(sqrt(3)*U1_Load.*I1_Load)/2;% Full load power
P_Load=S_Load.*cos(0-Fi*pi/180);% Active load power
subplot(2,1,1);
plot(I1_Load, U1_Load);
title('Load characteristic');
ylabel('Load voltage (phase A), V');
xlabel('Load current (phase A), A');
grid on;
% Construction of current charts in semiconductor keys
subplot(2,1,2);
plot(I1_Load,I_dc,I1_Load,I_SW,I1_Load,I0_SW);
ylabel('Current, A');
xlabel('Load current (phase A), A');
grid on;
legend('Current circle generator, A', 'The current of the inverter branch, A', 'Average
value of the current of the inverter branch, A', 'Location', 'Best');
% Construction of current charts in semiconductor keys
figure;
subplot(2,1,1);
plot(P_load,P_dc);
title('Power characteristic of the inverter');
ylabel('Power of power circle, W');
xlabel('Active power load, W');
grid on;
```

```
subplot(2,1,2);
plot(S_Load,P_dc);
title('Power characteristic of the inverter');
ylabel('Power of power circle, W');
xlabel('Load capacity, VA');
grid on;
```

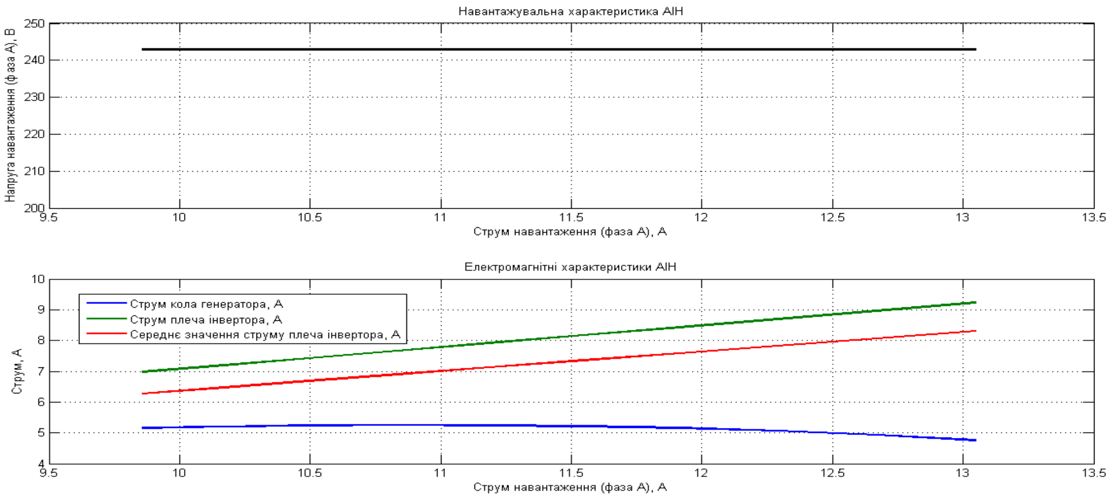


Fig. 4.3. Loading and electromagnetic characteristics

3. Dynamic characteristics of the three-phase inverter

Dynamic characteristics include:

- transient electromagnetic processes in the load and power sources with a spin-like change in the value of the input signal;

- transient electromagnetic processes in the load at a jump-free change in the power supply parameters;

- Transient electromagnetic processes in the power source when a jump-like change in load parameters;

- Transient electromagnetic processes in the semiconductor elements of the converter at their switching.

An autonomous inverter voltage in the control system is a nonlinear link with discretely variable parameters. This non-linearity is manifested in the fact that the delay of the output voltage in the transient process relative to the input signal depends on the moment of change of the input signal relative to the saw-like carrier voltage and the magnitude of the change of the input signal. The frequency of the carrier-like saw-tension voltage in modern systems far exceeds the bandwidth of the system. Therefore, most often AIN is considered as without an inertial link. If the output value is considered as the current load current, then the dynamics of the AIN is determined by the dynamic load properties. Sometimes the inverter is replaced by a linear aperiodic link, the constant time of which is taken equal to the period of the carrier-like saw-tension voltage.

The model study of the dynamics of the inverter allows us to construct a functional model that reflects the physics of its operation. It is constructed in a rotating coordinate system using the method of the resulting vector. During this change of state in the model the results correspond to their amplitude value. Such a model is depicted in Fig. 4.4.

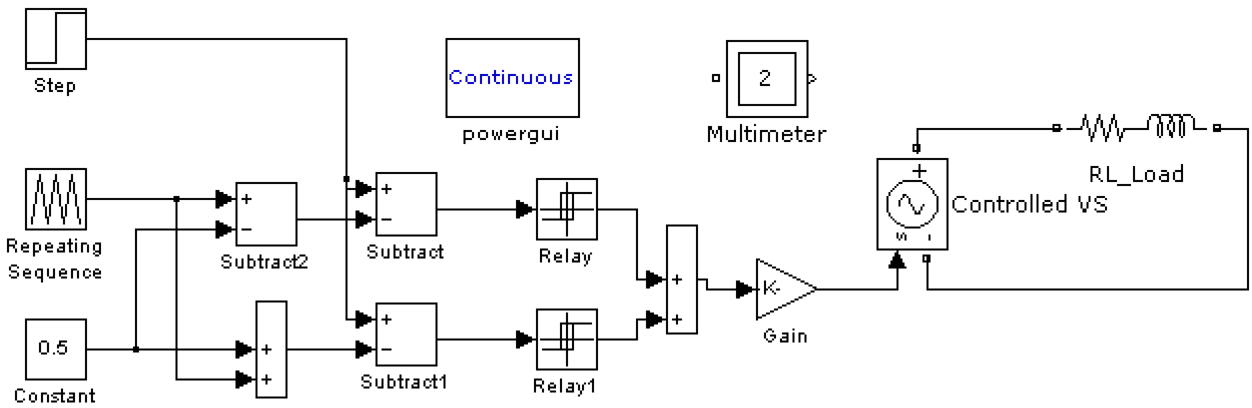


Fig. 4.4. Model for the study of dynamic characteristics

The functional model of the inverter is implemented using the blocks of the main library of Simulink. The active-inductive load of the inverter is implemented using the blocks of the SimPowerSystem library. Parameters of blocks not included in the previous models are listed in the Table. 4.1. The simulation time is 0.08 s, the sampling step is 1E-4. The transition process in the model is shown in Fig. 4.5.

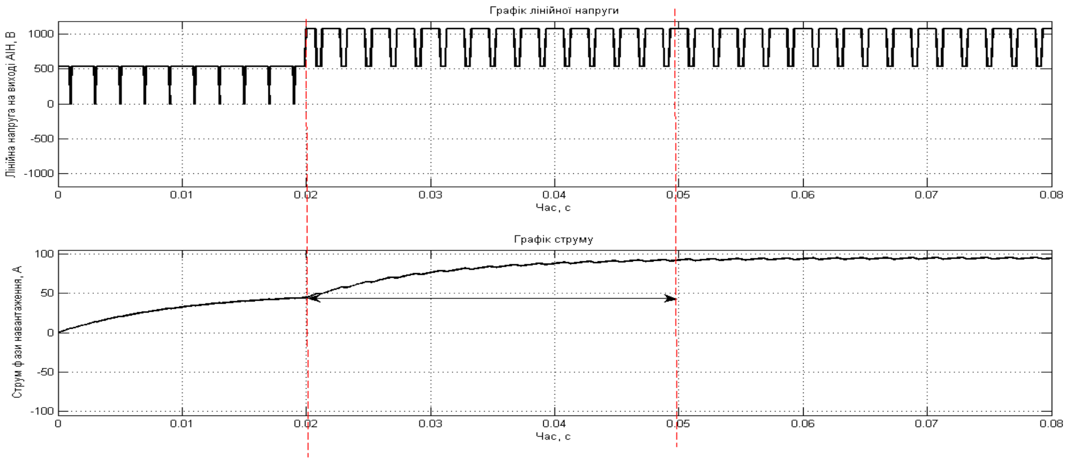


Fig. 4.5. Graph of the transition process

The upper oscillogram shows the linear voltage at the AIN output during the jump of the input signal, on the bottom - the current in the load phase. The delay of the voltage response here is 2.5 ms, and practically does not affect the nature of the transient process by current, which confirms the possibility of representing the inverter without an inertial link.

Parameters of blocks for constructing are presented in Table. 4.2.

Table 4.2. — Block parameters

Library	**Block**	**Parameters**
Simulink/Source	Step	Step time: 0.02; Initial value: 0; Output: 0.8; Sample time: 1e-4.
Simulink/Source	Repeating Sequence	Time values: 0 1e-3 1e-3 2e-3; Output values: - 0.5 0.5 0.5 - 0.5
Simulink/Source	Constant	Constant value: 0.5
Simulink/Math Operation	Sum	-; Sample time: 1e-4.

Simulink/Math Operation	Substract	-; Sample time: 1e-4.
Simulink/Math Operation	Gain	Gain 540; Sample time 1e-4.
Simulink/Discontinuities	Relay 1, 2	Switch on point: 0.001; Switch off point: 0.001; Output when on 1; Output when off:0; Sample time: 1e-4;
SimPowerSystem/Electrical Sources	Controled Voltage Source	Source type DC, Initial amplitude 0
Simulation time		0,08 s
Solver		ode45

The Universal bridge does not make it possible to simulate the transient processes when switching the inverter semiconductor keys, since only the delay time during switch-off is taken into account in its parameters.

Control questions and tasks

1. Basic static characteristics of the inverter.
2. The main dynamic characteristics of the inverter.
3. Principle of the model used in the work for the study of static characteristics.
4. Assignment of model elements used in the work for the study of static characteristics.
5. Principle of the model used in the work for the study of dynamic characteristics.
6. Appointment of the model elements used in the work to study the dynamic characteristics.

TOPIC #3: RESEARCH OF IMPULSE LOWERING REGULATOR OF DC VOLTAGE

Computer Practicum #5

Research of impulse lowering regulator of DC voltage

The purpose of the work: to build a model and to simulate the given scheme of the system. Build and explore system features.

Basic theoretical information

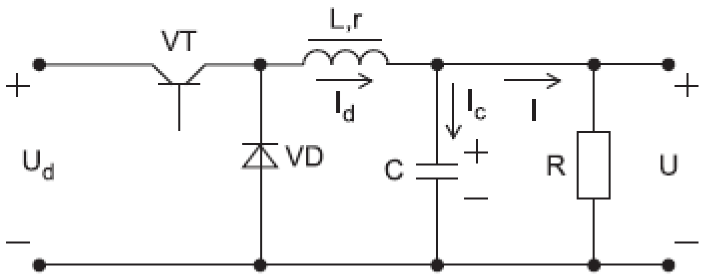
In technical devices, there are many primary sources of electricity that produce it in the form of constant voltage. These include solar cells operating on the basis of the photoelectric effect, thermoelectric generators and magnetohydrodynamic (MHD) generators, fuel cells that use the energy of chemical reactions, accumulators as sources of stored electricity, electric power generators of constant voltage, etc. To bring the constant voltages of these sources to the required level, its stabilization or (i) regulation requires constant voltage converters in constant. The power of such converters can reach tens or even hundreds of kilowatts. In the case of such capacities it is advisable to use one-cascade transducers.

In this paper we consider the basic circuits of converters, which carry out direct (single-cascade) transformation of a constant voltage into a constant without using any intermediate transformation, for example, a constant voltage in the variable with the subsequent transformation of the voltage constant into a constant. The study and research of these converters is carried out using virtual laboratory facilities. They allow you to get the basic characteristics of these converters in two ways:

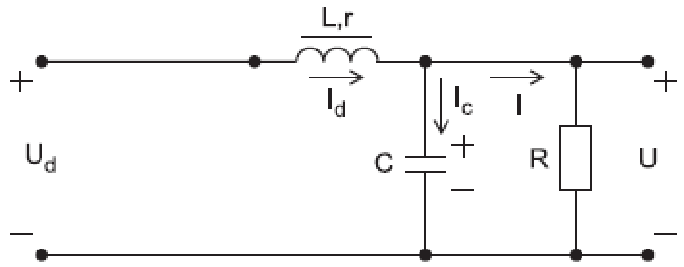
• "normal", changing the selected parameter and registering the values of the studied values during each simulation with the subsequent construction of the required characteristics;

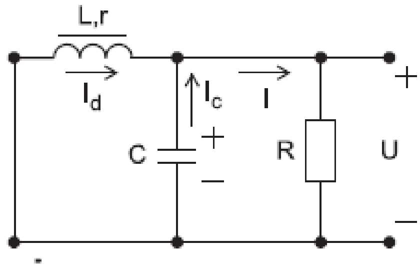
• software, in which the removal and construction of the main characteristics occurs automatically.

The circuit of the pulse reducing regulator of the constant voltage is shown in Fig. 5.1 a. calculation circuits for replacing the regulator at switching intervals are shown in Fig. 5.1 b, c. During the carrier frequency period (T), two switching intervals are sequentially formed.



a





б *в*

Fig. 5.1 Calculation scheme of the lowering regulator (a) and its substitution scheme (b, c) at switching intervals

In the first interval, when the transistor VT is turned on (Fig. 5.1b), the Ud voltage source is connected to the load through the collecting throttle L. During this, the energy is taken from the source and stored in the throttle L and in the capacitor C and is consumed in the load bearing R.

In the case of the off VT transistor in the second interval (Fig. 5.1 in), the current of the throttle L through the diode VD and the current of the capacitor C flow to the output of the converter through the load R.

Virtual laboratory installation and its characteristics

A virtual laboratory unit for investigating a pulse dampening regulator of constant voltage is shown in Fig. 5.2

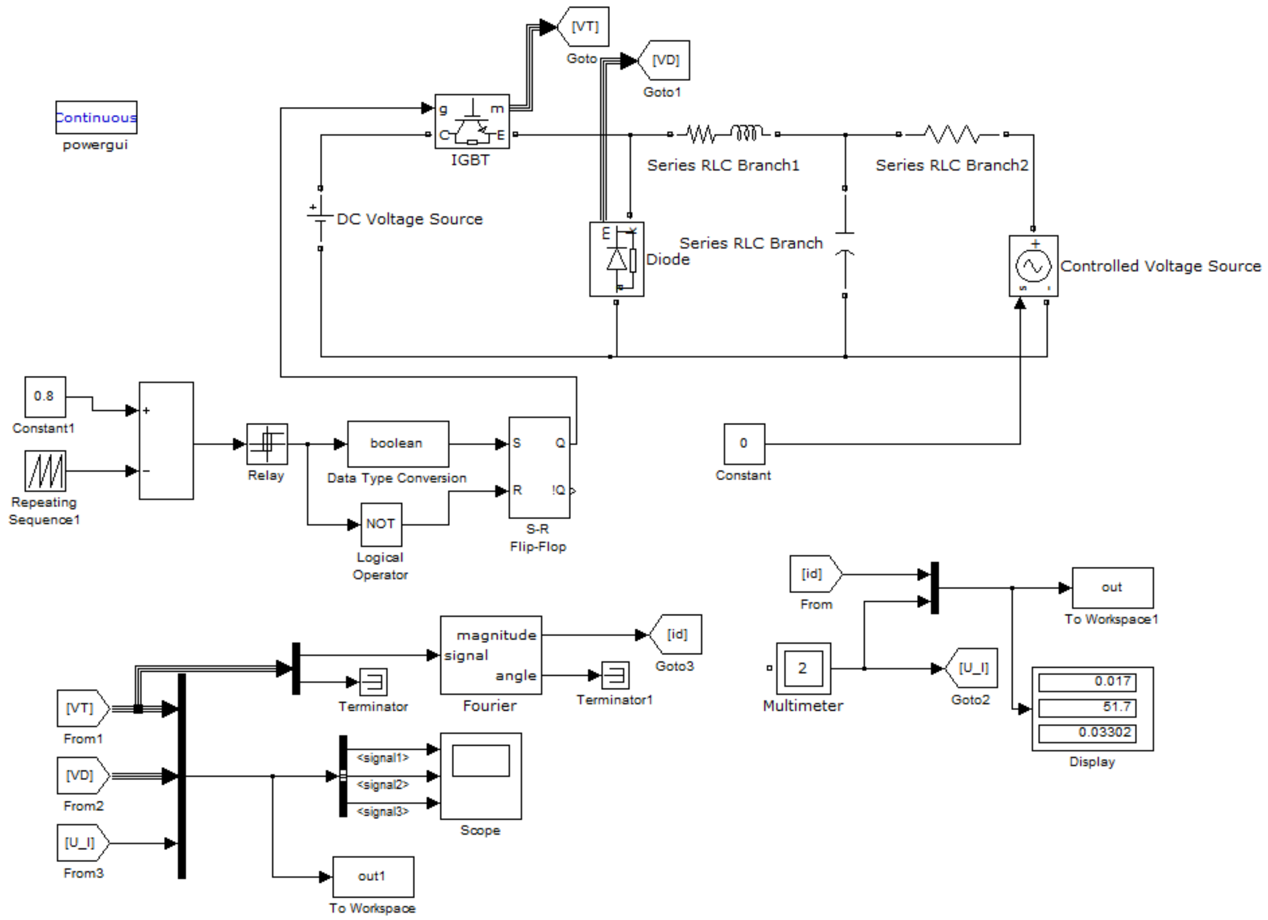


Fig. 5.2 Model of pulse reducing regulator of constant voltage

The development of a controller model with independent control was carried out using structurally-functional (Simulink package) and virtual (Sim Power System expansion pack) models. Presentation of simulation results is realized by software and instrumental media of MATLAB Simulink environment.

The pulse reduction regulator model contains a power, control and measuring part. Each block of the model has a window for adjusting the main parameters. The libraries and icon of the blocks, their assignment in the model, as well as the parameters of the blocks, components of the model are given in Table. 5.1. Time of simulation (Stop time) - 0.7 s, sampling step (Max Step Size) - 10-5.

Table 5.1 — Libraries, titles, icons and block parameters

Library	Block	Parameters
SimPowerSystems\ Power Electronics	Diode	Resistance Ron (Ohm) — 0,1, Inductance Lon (H) — 0, Forward voltage Vf (V) — 1, Initial current Ic (A) — 0, Snubber resistance Rs(Ohm)-1e5, Snubber capacitance Cs-inf
SimPowerSystems\ Power Electronics	IGBT	Resistance Ron (Ohm) — 0,1, Inductance Lon (H) — 0, Forward voltage Vf (V) — 1, Current 10% nail time Tf(s)-1e-6, Current nail time Tf(s)-2e-6, Initial current Ic (A) — 0, Snubber resistance Rs(Ohm) — 1e5, Snubber capacitance Cs-inf
SimPowerSystems\ Elements	Series RLC Branch	Branch type — R L, Resistance (Ohm) — 0,3+Ne-2 Inductance (H) — (1+N)e3, Measurements — Branch current
SimPowerSystems\ Electrical Sources	DC Voltage source	Amplitude (V) — 150+N, Measurements — None
SimPowerSystems\ Elements	Series RLC Branch	C-Branch type — C, Capacitance C(F) — 1e-4, Measurements — Branch voltage. R-Branch type — R, Resistance (Ohm) —– 10, Measurements — Branch current
SimPowerSystems\ Electrical Sources	Controlled Voltage source	Source type — DC, Initial amplitude — 0, Measurements — None
Simulink\ Sources	Constant	0
Simulink\ Measurement	Multimeter	Available Measurements — Ub: C, Ib: R. Selected Measurements — Ub: C, Ib: R.
Sim Power Systems \ Extras Library\ Measurement	Fourier	Fundamental frequency f(Hz) — 2000, Harmonic n — 0.
Simulink\ Sinks	To Workspace	Variable name — out, Limit data points to last — 5000,

		Decimation — 10, Sample time — 1e-5, Save format — Array. Variable name — out1, Limit data points to last — 20, Decimation — 1, Sample time— 1e-5, Save format — Array.
Simulink\ Signal Routing	Goto, From	–
Simulink\ Sinks	Display	–
Simulink\ Signal Routing	Mux	–
Simulink\ Signal Routing	Bus Selector	Number of inputs 3.
Simulink\ Sinks	Scope	Scope parameters: General-Number of axes-3, Time range-0.002, Sample time-1e-5. Data history: Variable name — out1. Format — structure with time.
Simulink\ Source	Repeating sequence	Time values — [0; 0,0001], Output values — [0; 1].
Simulink\ Math Operation	Summ	+-
Simulink\ Dicontinuous	Relay	Switch on point — 0,01; Switch off point— –0,01; Output when on — 1; Output when off — 0.
Simulink\ Logic and Bit Operation	Data type conversion	Output date type mode — boolean
Simulink\ Logic and Bit Operation	Logical operator	Operator — NOT
Simulink/Simulink Extras/Flip Flops	S-R Flip-Flop	Initial condition (state of Q) — 0.
Simulation time		0,7 s
Solver		ode45

Instantaneous values of the current and voltage on the transistor and the diode, voltage and load current can be observed on the screen of the oscilloscope (Fig. 5.2).

The same values in relative units as well as instantaneous relative power losses in the transistor and diode are constructed after simulation in the execution of the program presented in Listing 5.1.

Task 5.1

Listing 5.1:

```
Ub=150; r=0.4;
Ib=Ub/r;
t=0:1e-5:19e-5;
IVT1=out1(:,1);
IVT=IVT1/Ib;
UVT1=out1(:,2);
UVT=UVT1/Ub;
IVD1=out1(:,3);
IVD=IVD1/Ib;
UVD1=out1(:,4);
UVD=UVD1/Ub;
U1=out1(:,5);
U=U1./Ub;
I1=out1(:,6);
I=I1./Ib;
PVD=UVD.*IVD;
PVT=UVT.*IVT;
subplot(3,1,1);
plot(t,IVT,t,IVD);
grid on;
ylabel('IVT(p.u) IVD(p.u)');
legend('IVT', 'IVD','Location','Best');
subplot(3,1,2);
plot(t,UVT,t,UVD);
```

```
ylabel('UVT(p.u) UVD(p.u)');
legend('UVT','UVD','Location','Best');
grid on;
subplot(3,1,3);
plot(t,PVT,t,PVD);
grid on;
xlabel('time');
ylabel('PVT(p.u) PVD(p.u)');
legend('PVT','PVD','Location','Best');
```

In Fig. 5.3 shows graphs of electromagnetic processes in relative values for E = 0 B and γ = 0.8 * (* In all calculations, the basic values of the variables are: Ub = Ud = 150 V; Ib = Ub / r = 375 A. The relative values of the variables are calculated by dividing the absolute values of these variables into baseline values.).

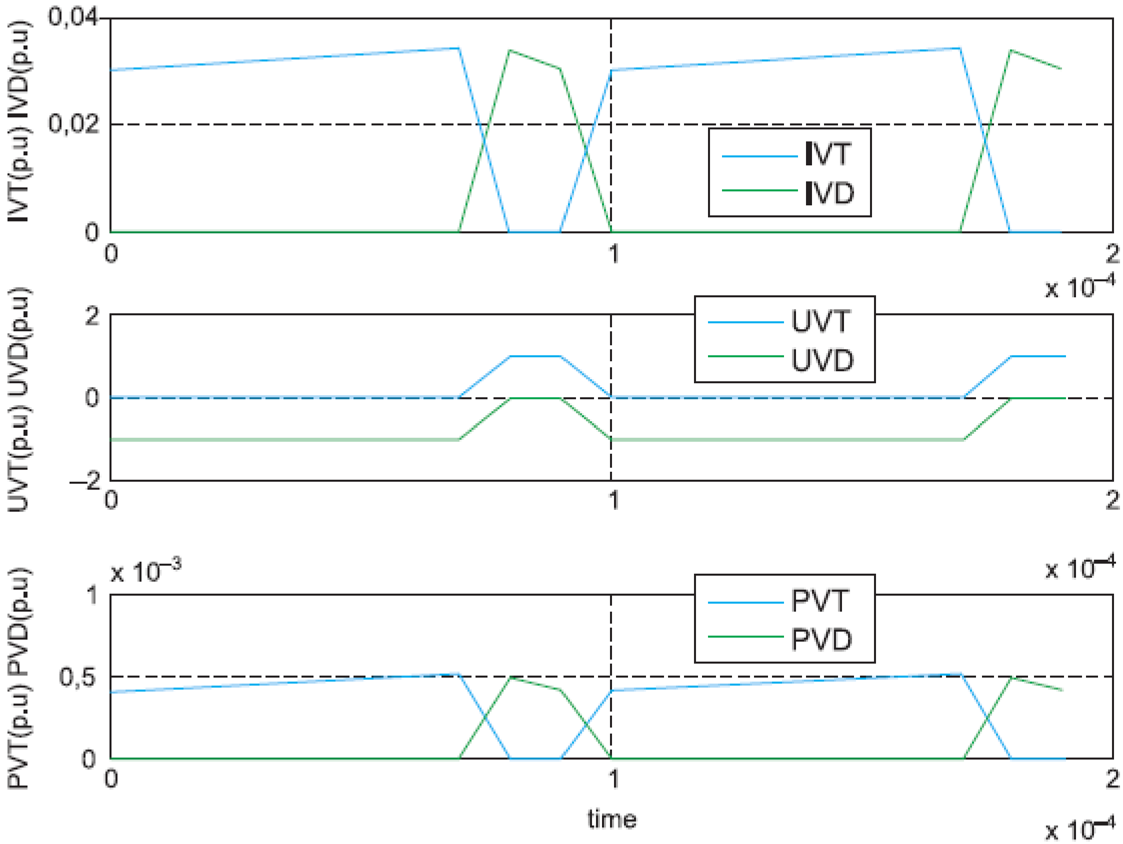


Fig. 5.3 Graphics of electromagnetic processes

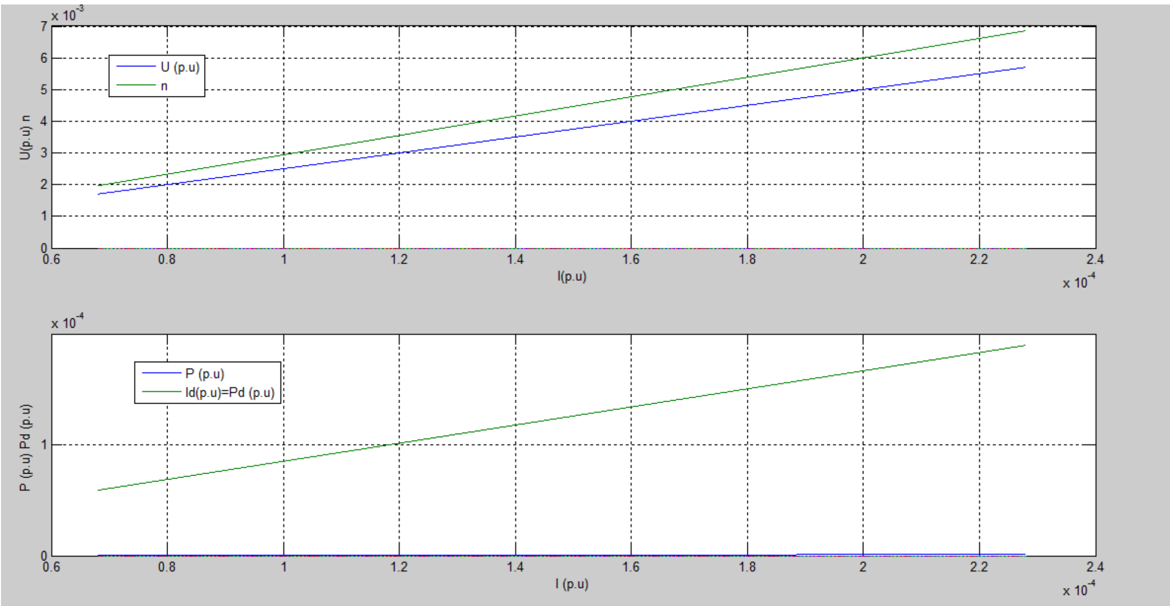


Fig. 5.4 Electromagnetic and energy characteristics of the regulator

The electromagnetic and energy characteristics of the regulator can be constructed using the program shown in Listing 5.2:

Task 5.2

Listing 5.2:

```
Ub=150; r=0.4; Ib=Ub/r;%Regulator parameters
Id1=out(:,1);
Id=Id1./Ib;
U1=out(:,2);
U=U1./Ub;
I1=out(:,3;
I=I1./Ib;
P=U.*I;
Pd=Id.*1;
n=P./Pd;
subplot(2,1,1);
plot(I,U,I,n,I,0);
grid on;
xlabel('I(p.u)');
```

```
ylabel('U(p.u) n');
legend('U (p.u)','n','Location','Best');
subplot(2,1,2);
plot(I,P,I,Pd,I,0);
grid on;
xlabel('I (p.u)');
ylabel('P (p.u) Pd (p.u) ');
legend('P (p.u)','Id(p.u)=Pd (p.u)','Location','Best');
```

Control questions and tasks

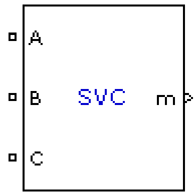
1. The main fields of application of reducing regulator of constant voltage.
2. Describe and characterize the principle of operation of the calculation scheme of the downregulator.
3. Describe the principle of action and disclose the designation of each control system item.
4. Describe the principle of operation and disclose the purpose of each element of the power part of the system model.
5. Describe the principle of operation and disclose the designation of each element of the measuring part of the system model.

TOPIC #4: RESEARCH OF REACTIVE POWER STATIC COMPENSATORS

Computer Practicum #6

The purpose is to get acquainted with the operating modes of static compensators of reactive power. Build a model and simulate a given circuit with a static compensator. Build and explore the main features of the system.

Basic theoretical information



The Static Var Compensator is designed to simulate a three-phase static reactive power compensator. The schematic of the compensator model is depicted in Fig. 6.1.

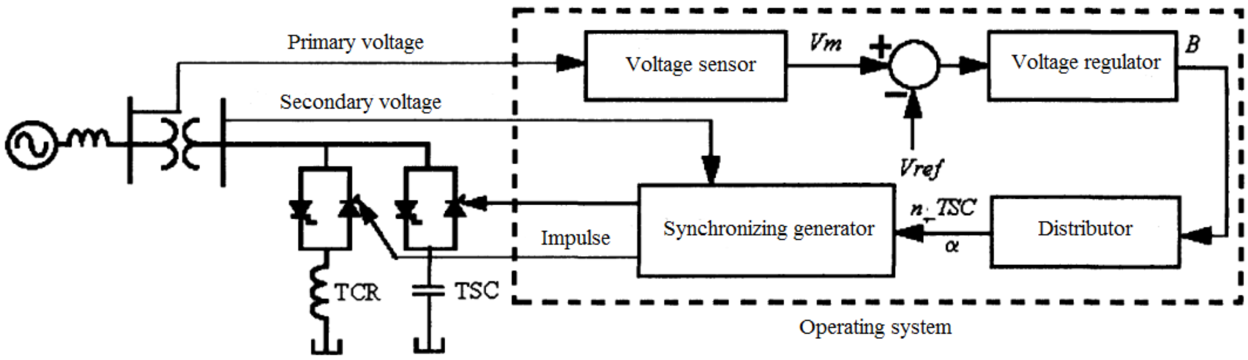


Fig. 6.1. Schematic model of the static compass

The management system includes:

- A voltage sensor that measures the voltage of the direct sequence to be controlled;

- A voltage regulator that uses the voltage error (the difference between measured and reference voltages) to determine the reactive conductivity of the TSC system required to maintain a constant linear voltage value;
- A distributor that determines which group of thyristors must receive pulses of control, as well as the angle of thyristor control;
- A synchronizing generator that generates pulses of thyristor control.

This block is used to calculate circuits using a vector method. The choice of the vector method of calculation is carried out using the powergui block. The model of the static compensator can be used to calculate three-phase power systems containing synchronous generators, motors and dynamic loads to determine the dynamic stability and the effect of a static compensator on electromechanical oscillations in the system, as well as on the capacity of the transmission line. Such a block contains simplified models of its constituent systems, which are represented by relatively simple transfer functions and delay elements, which give the correct result on the main frequency of the network.

Static reactive power compensator can operate in two modes:

- Voltage regulation;
- Reactive power management mode.

Volt-ampere characteristic of the compensator in the mode of voltage regulation is shown in Fig. 2.

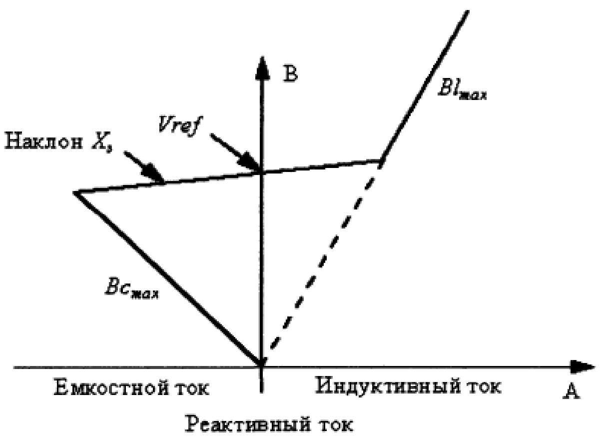


Fig. 6.2. Volt-ampere characteristic of the reactive power compensator

While the reactive conductivity of the compensator B does not exceed the limits of Bcmax and Blmax, which are determined by the values of reactive capacities of capacitors and reactors, the value of the voltage is determined by the value of the reference voltage. During this, as a rule, there is a voltage drop, as shown in Fig. 6.2.

Volt-ampere characteristic of the compensator in this mode is described by three equations:

$$V = V_{ref} + V_S * I - regulation\ mode;$$

$$V = \frac{I}{B_{C\max}} - mode\ of\ generating\ maximum\ capacitive\ power;$$

$$V = \frac{I}{B_{l\max}} - mode\ of\ generating\ maximum\ inductive\ power.$$

where V is the voltage of the direct sequence (v.o.); I - reactive current (V / Rbase). The value of I> 0 indicates the inductive nature of the current; XS - jet resistance in the recession (v / Rbase); Blmax - maximum inductive conductivity (V / Rbase); Pbase - base power (total for three phases).

When the compensator operates in voltage stabilization mode, the response rate to the voltage changes in the system depends on the parameters of the voltage regulator, the reactance resistance X and the stability of the power system. For an integrating voltage regulator (Kr = 0), if the constant component of the measurement system time T and the value of the delay of the thyristor system can be neglected, then a closed control system consisting of a reactive power compensator and an energy system can be approximated by the system of the first order with the value of the time constant of the closed contour equals:

$$T_C = \frac{1}{K_i * (X_S + X_n)};$$

where TS - time constant of the closed circuit; Kr - coefficient of amplification of the proportional part of the voltage regulator; Ki - coefficient of amplification of the integrating part of the voltage regulator; XS - jet resistance in the recession; Xn - equivalent reactance of the power system.

Tasks for work

Task 6.1. Build a model and investigate the volt-ampere characteristics of the jet power compensator.

Output data for simulation (see Table 6.1):

– U = 200 kV;

– f = 50 Hz;

– S=3000 MVA;

– - capacity of the capacitor of the static compensator 300;

– - reactor power 200.

Model construction:

Table 6.1. — Blocks and model parameters in the MATLAB / Simulink environment

Library	Block	Parameters
SimPowerSystems/Electrical Source	Three-Phase Programmable Voltage Source	Peak amplitude: (500+4·*N*)e3, Phase: 0, Frequency: 50 (Hz).
SimPowerSystems/Elements	Three-Phase Series RLC Branch	Branch type: RL R= (500+4·*N*)e3^2/3000e6/10 L= (500+4·*N*)e3^2/3000e6/(2*pi*50)
SimPowerSystems/Elements	Three-Phase Series RLC Load	Nominal phase-to-phase voltage: (500+4·*N*)e3
SimPowerSystems/ Measurement	Three-Phase V-I Measurement	Base voltage: (500+4·*N*)e3
SimPowerSystems/ Application libraries/ FACTS library/ Power-	Static Var Compensator (Phasor Type)	Display: Control Parameters Mode of operation: Voltage regulation

Electronics based FACTS		Vref=1.0 Droop Xs=0.03 Voltage regulator [0 300]
Simulink/Signal Routing	Bus Selector	According to fig. 6.
Simulink/Signal Routing	Mux	–
Simulink/Math Operations	Gain	Gain: 2 Sample time: -1
Simulink/Signal Routing	From	Goto Tag: B1; Icon Display: Tag; Goto Tag: V1; Icon Display: Tag
SimPowerSystems/Elements	Ground	–
Simulink/Sinks	Scope	Number of axes: 2 Data history: Limit data points to last – disable option
SimPowerSystems	Powergui	Configure parameters: Simulation type: Phasor 50 Hz
Simulation time		1,0 s
Solver		Ode23tb

Adjustment of the Three-Phase Programmable Voltage Source is carried out in accordance with the table of options and Fig. 6.3.

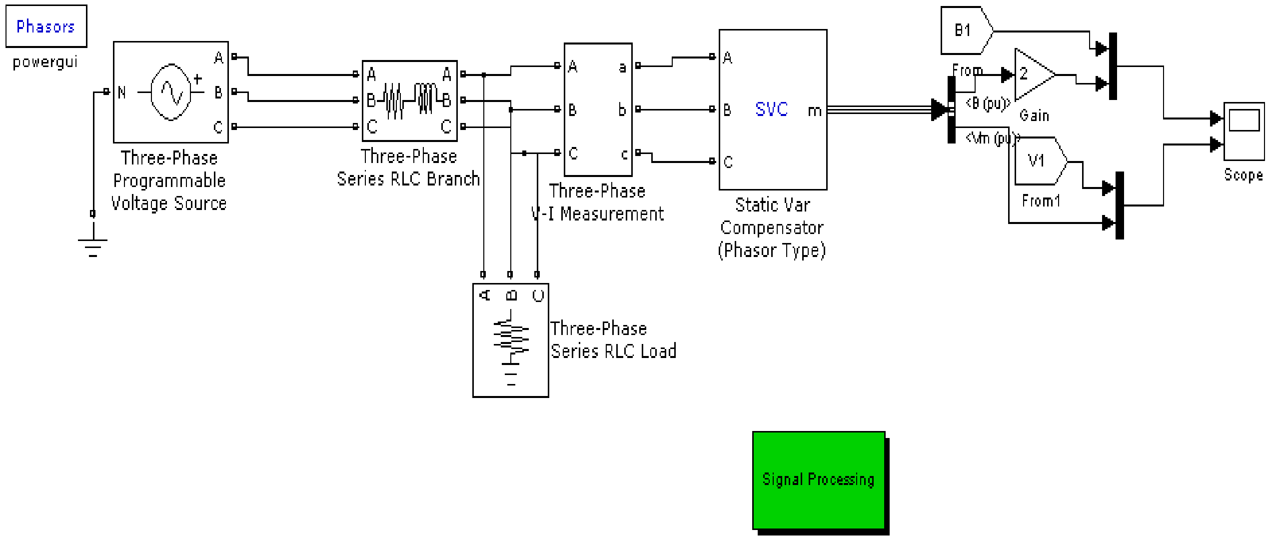


Fig. 6.2. Network scheme with static reactive power compensator

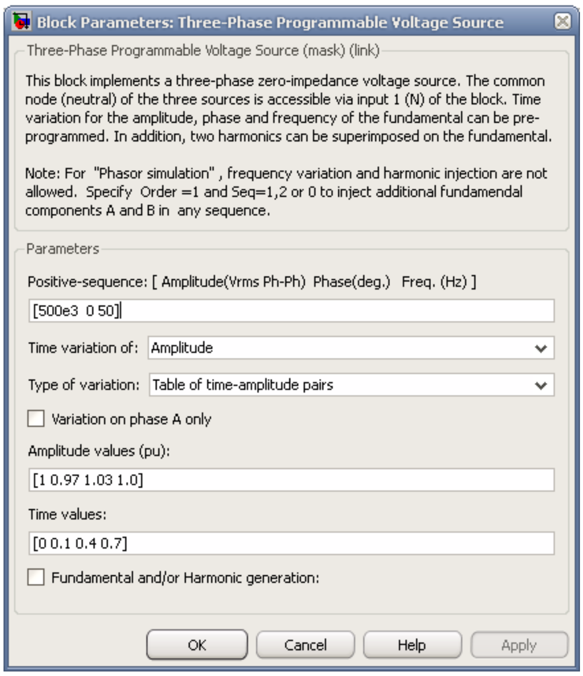


Fig. 6.3. Block setting window Three-Phase Programmable Voltage Source

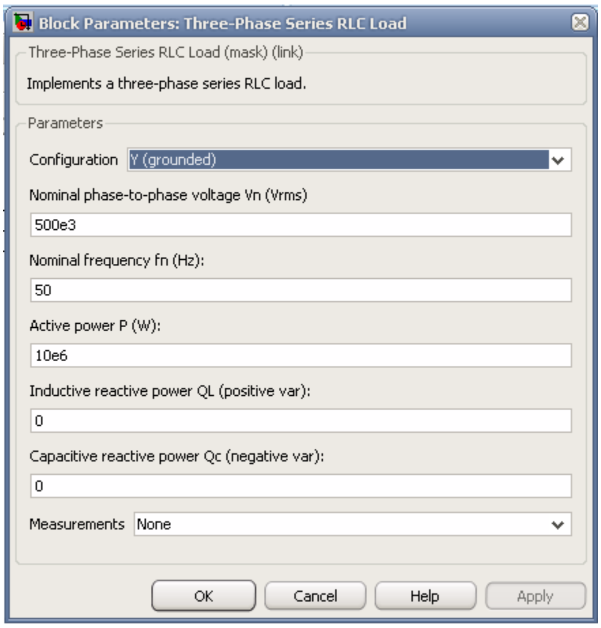


Fig. 6.4. Block Window Three-Phase Series RLC Load

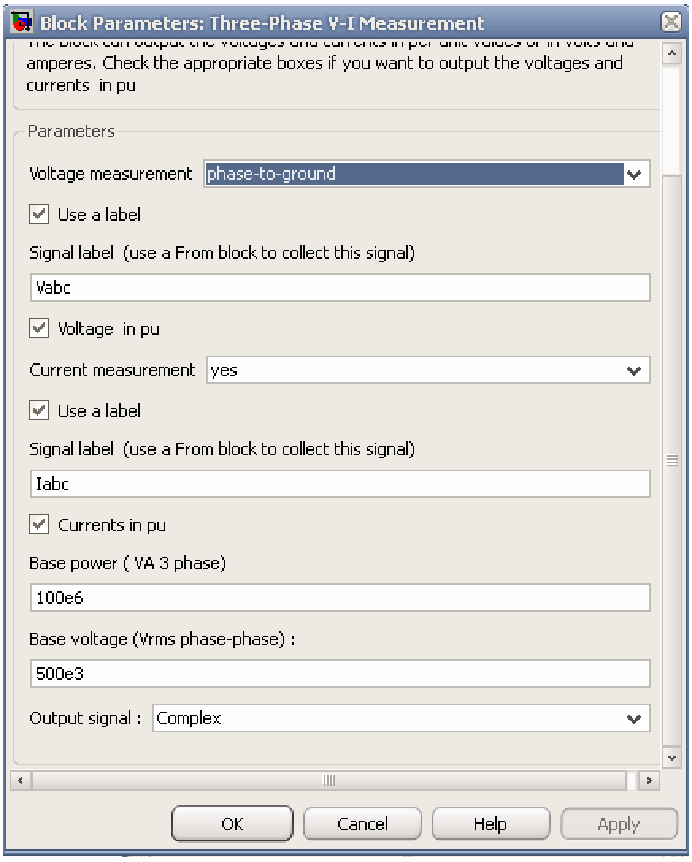


Fig. 6.5. Block window Three-Phase V-I Measurement

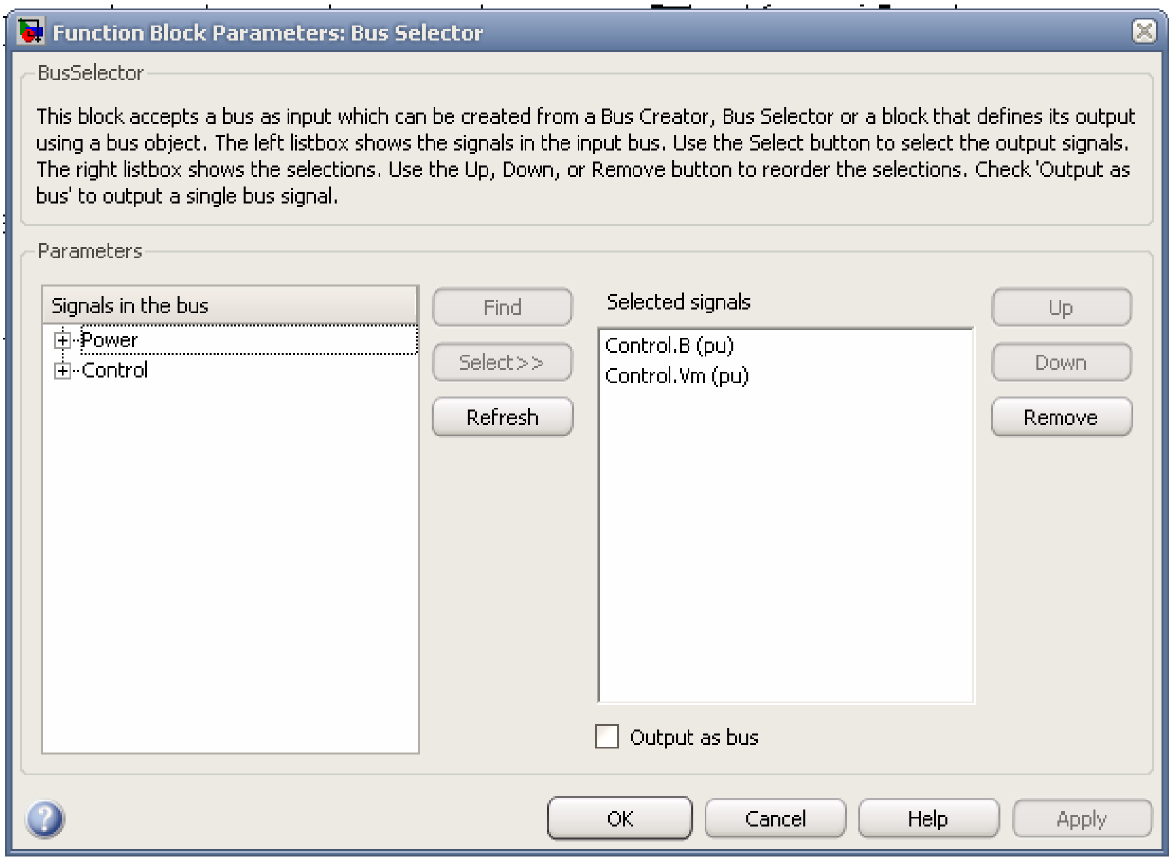


Fig. 6.6. Block configuration window Bus Selector

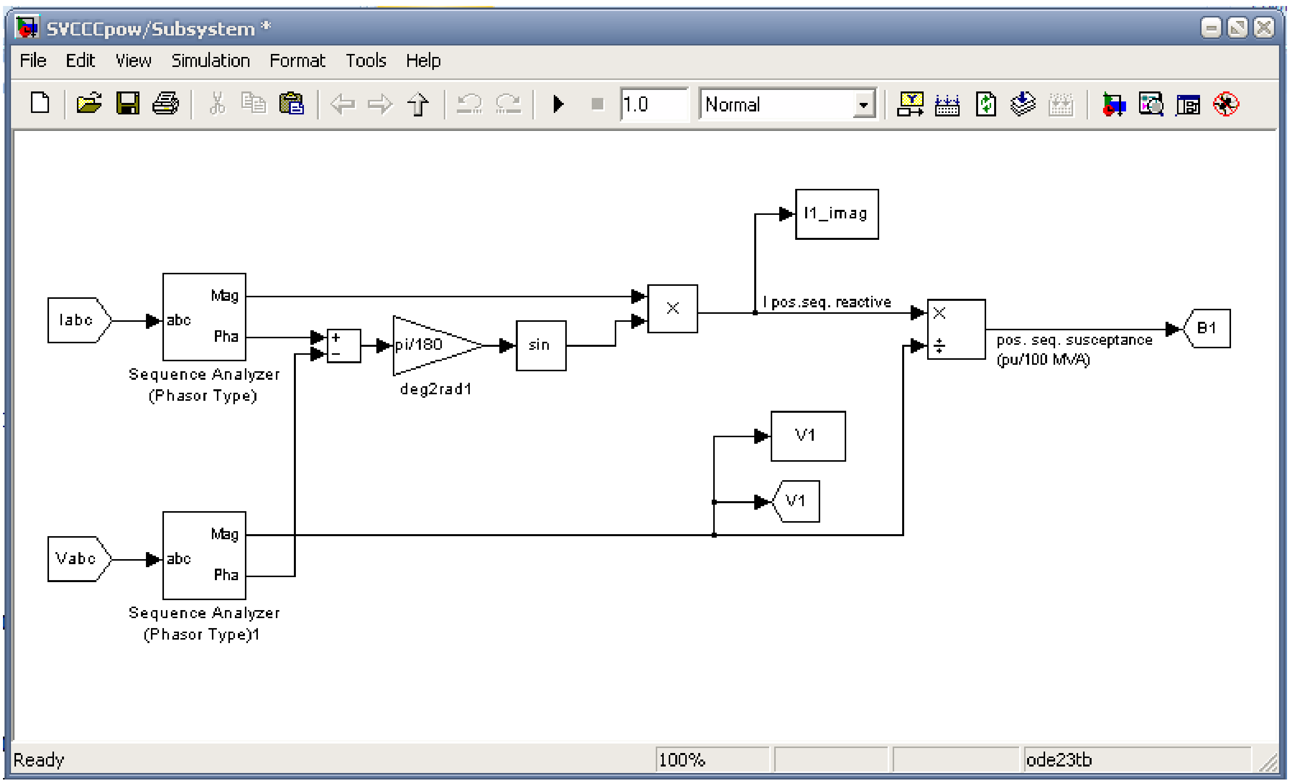


Fig. 6.7. A model of the subsystem for signal processing on the compensator

To construct a signal processing subsystem, you need to use a task table:

Table 6.2. — Blocks and model parameters in the MATLAB / Simulink environment

Library	**Block**	**Parameters**
Simulink/Signal Routing	From	Fig 6.8.
Simulink/ Math operations	Sum	Icon shape: regulator List of signs:+- Sample time:-1
Simulink/ Math operations	Gain	Gain: pi/180 Sample time:-1
Simulink/Math operations	Trigonometric function	Function: sin
Simulink/Math operations	Product	Number of inputs: ** Multiplication: Element-wise(.*) Sample time:-1
Simulink/Sincs	To workspace	Variable name: I1_imag; Limit Data points to last: inf; Decimation:1 Sample time:-1
Simulink/Math operations	Product	Number of inputs: */ Multiplication: Element-wise(.*) Sample time:-1
Simulink/Signal routing	Goto	Goto tag: B1; Tag visibility: Global
Simulink/Sincs	To workspace	Variable name: V1; Limit Data points to last: inf; Decimation:1

		Sample time:-1
Simulink/Signal routing	Goto	Goto tag: V1; Tag visibility: Global
Simpowersystems/Extra library/Phasor Library	Sequence Analyzer (Phasor Type)	–

During the work, remove and investigate the actual values of the reactive conductivity of the straight sequence B1 and the signal of the reactive conductivity control of the voltage regulator (Fig. 6.9).

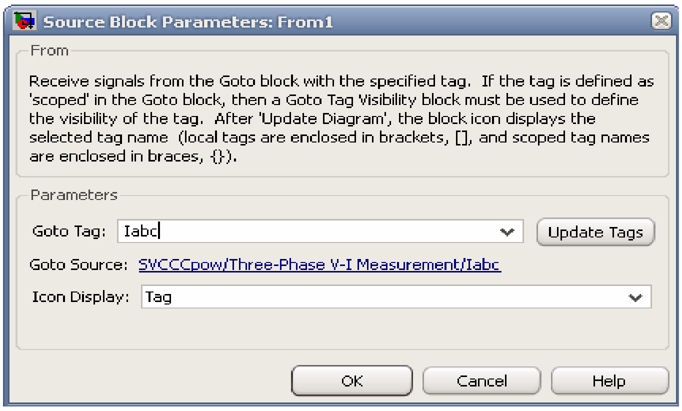


Fig. 6.8. An example window for setting the block From

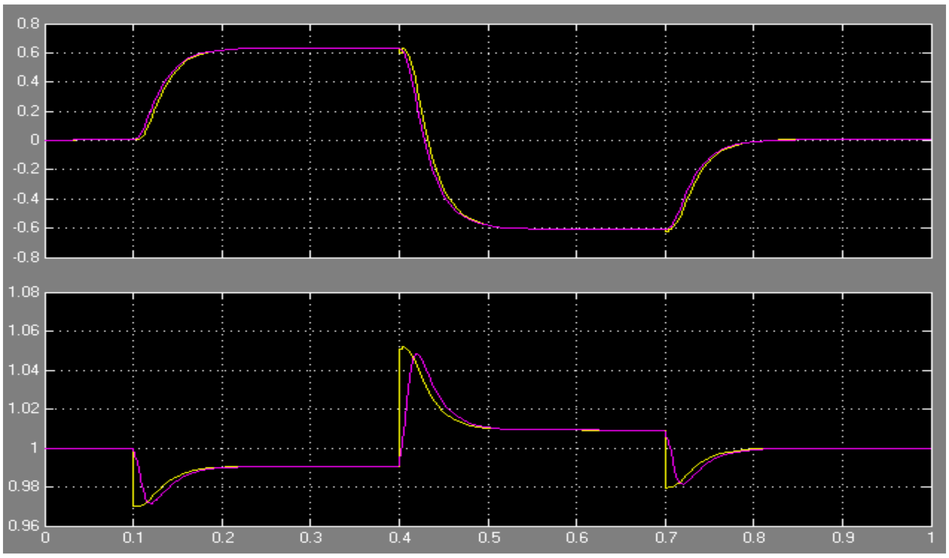


Fig. 6.9. System characteristics in steady state

Take down system characteristics when it is unstable (when S=600 MVA).

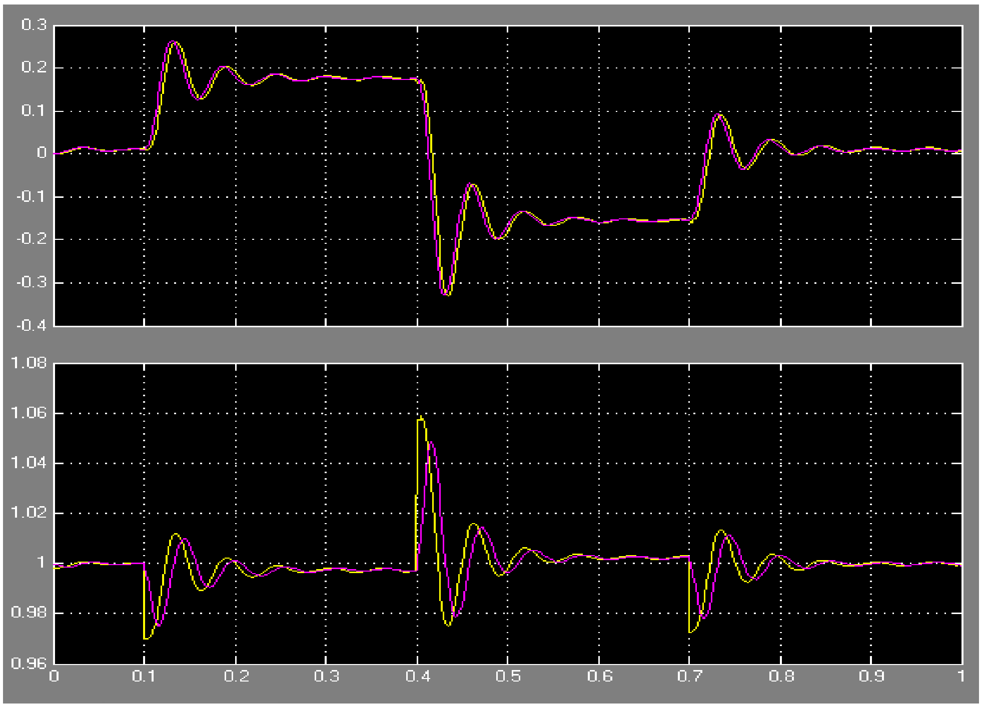


Fig. 6.10 Characteristics of the system in the mode of violation of stability

Control questions and tasks

1. The block diagram and components of the control system.
2. The purpose of the voltage sensor.
3. Purpose of the voltage regulator.
4. Appointment of the distributor.
5. The purpose of the synchronizing generator.
6. To give the voltage-ampere characteristics of the compensator in the mode of voltage regulation.
7. Operating modes of the static compensator.