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RELIABILITY OF ELECTRIC MACHINES

VIBRATIONS AND NOISES OF ELECTRIC MOTORS

COMPUTER WORKSHOP

Recommended by the Methodical Council of the KPI named after I. Sikorsky as a tutorial for master's degree students according to the educational program "Electric Machines and Apparatus" on specialty 141 "Electric Power Engineering, Electrical Engineering and Electromechanics"

Kyiv
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VIBRATIONS AND NOISES OF ELECTRIC MOTORS

COMPUTER WORKSHOP

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This tutorial is intended for the “Reliability of electric machines: Vibrations and noises of electric machines” computer workshops subject for the specialty 141 "Electric Power Engineering, Electrical Engineering and Electromechanics" students, studying under the educational program "Electrical Machines and Apparatus". Computer workshops will teach professionally modeling, spectral processing and analysis of vibrational sensors signals in electric machines using modern software such as MatLab, National Instruments LabView and Comsol Multiphysics.

CONTENT

INTRODUCTION

The discipline "Reliability of Electric Machines: Vibrations and Noises of Electric Machines" is included in the curricula of educational-professional and educational-scientific programs of preparation of masters "Electrical Machines and Apparatuses" by specialty 141 "Electricity, Electrical Engineering and Electromechanics". The syllabus envisages the completion of 6 computer workshops in the discipline in the amount of 18 classroom hours.

The workshop reinforces the theoretical knowledge gained during the course of the lecture, in particular, on the study and processing of signals and signal spectra of vibration sensors based on the results of vibration measurement of an induction motor. Both original software developed by Beresta LLC and modern software products are used to model these processes: MatLab, National Instruments LabView and Comsol Multiphysics.

Each computer workshop contains a program of work and an algorithm for its implementation. The workshop consists of the specific mathematical model development of the object to be studied by the student and individual variants of tasks with appropriate object parameters.

Detailed information about vibrational diagnosis of electric machines can be found in references [1-6].

Computer Workshop №1

Processing and research of vibration sensors signals in induction motor in the program AUM

(2 hours)

Work objecive. Get the skills of working with the AUM program on an example of studying a stored signal by measuring the induction motor (IM) vibrations.

Work program.

1. Get acquainted with the coordination and measuring unit of the firm "Beresta".
2. Get acquainted with the specifics of work in the program **Aum**
   a. Signal distribution
   b. Signal amplification
   c. Spectra and its professional settings. Explaining the settings.
   d. Sonogram
3. Create a signal distribution and signal spectrum in the double-window panel.
4. Create Sonograms in single-window panels:
   a) Signal distribution
   b) Signal spectrum.
   c) Slow-acted spectrum.
5. Create a report on the implementation of a computer workshop.

Methodical instructions for the implementation of a computer workshop.

To 1st item:

The AUM (Adaptive Control Monitor) program allows pre-processing, visualization and storage of received vibration signals as project files. The **Aum** program (Fig. 1.1) allows you to visualize the received signals both as functions of time (primary signals) and in the form of their spectrograms.

To 2nd item:

In order to get acquainted with the basics of working in the **Aum** program, you need to listen to information from the teacher about the computer workshop or watch the video [12, 13].

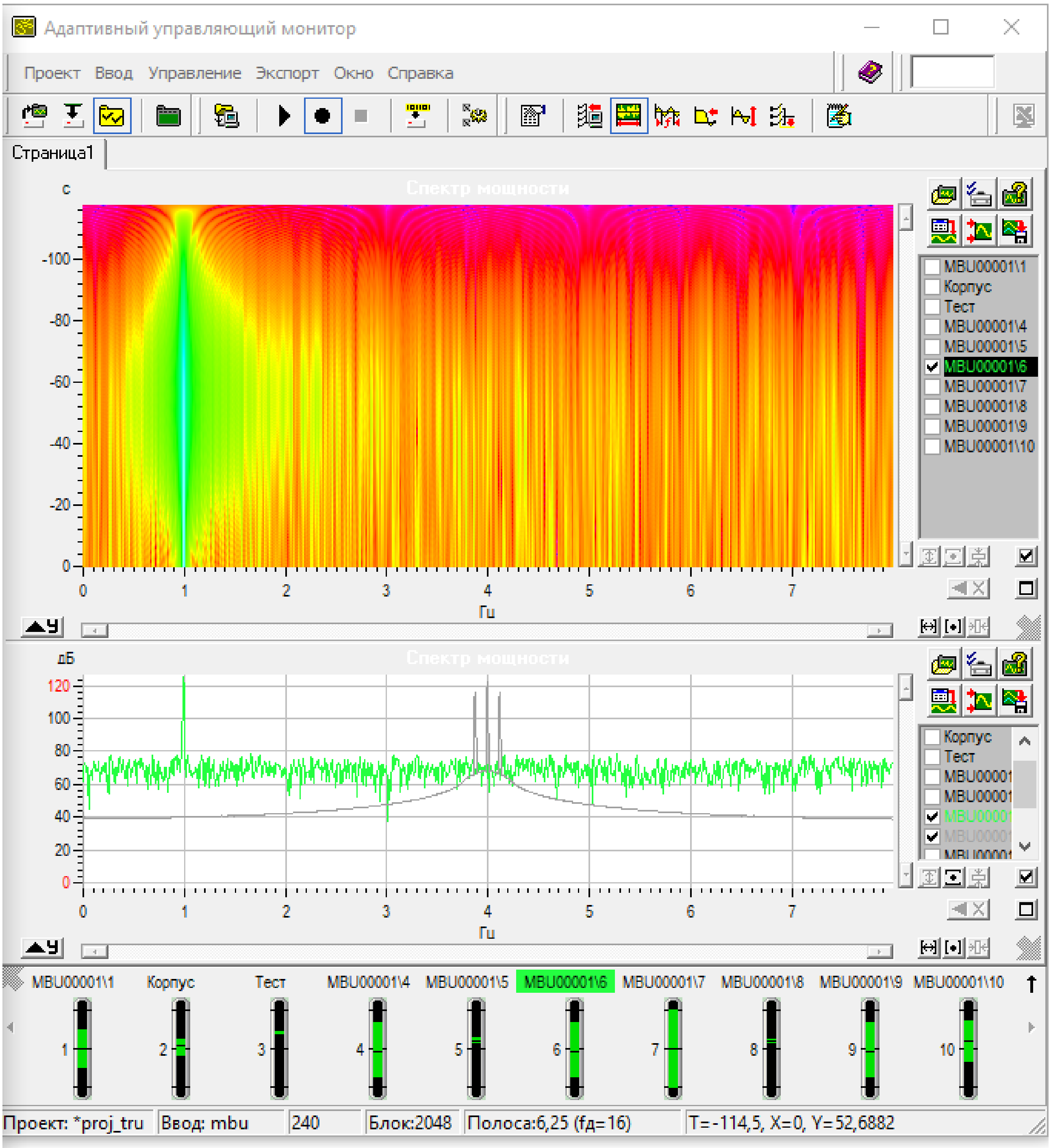


Fig. 1.1 – The "Adaptive Control Monitor" (**Aum**) program window

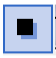
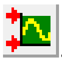
To 3rd item:

The order of creation of signal distribution and spectrum of the signal:

1. create 2 double-window processing pages;
2. click the Window tab - Collapse all;
3. adjust the panels according to the variant. Run panels;
4. achieve good visualization of the signal distribution and signal spectra graphs;
5. define max, min values and signal period;
6. save the project, copy the image to the protocol;
7. save the input (by limiting the time of entering the maximum value of the ordinates in the picture of the sonogram): Input - input to the disk.

To 4th item:

The algorithm for creating a sonogram with a slow-acting spectrum.

1. Install the Aum program and launch it.
2. Open the "Project" file, which is in the program folder using the "Project-Open" tab (Figure 1.2).
3. After opening the project, launch it by clicking on the button 
4. After the project has been launched, the power spectrum will appear in the "Adaptive Control Monitor" window. 
5. Once the process is stopped, you need to change the type of image from the "Graph" to "Sonogram" by clicking on the button . This all happens in the "Adaptive Control Monitor" window
6. Choose one of the signals (Fig. 1.3).
7. Then you need to select the sampling frequency by pressing the button , which is located in the top taskbar of the program, we agree with the condition by pressing "Yes" and choose the frequency 16.0
8. Run the program 
9. In the "Adaptive Control Monitor" window, you can see a picture of a signal in the form of a sonogram.

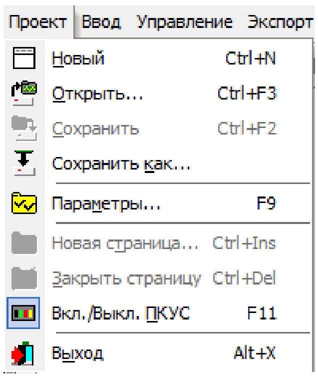


Fig . 1.2 – Project tab

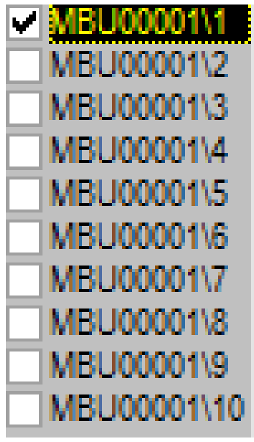


Fig. 1.3 – The choice of one of the researched signals

Task variants are presented in Table. 1

Since work in the program **Aum** is carried out in "Offline mode", when the real matching and measuring unit is not connected (which can be checked in the "MBU Driver Settings") and the user can work with 10 test signals, then you do not need to save the signal in the program **Aum**. If necessary, you can save only the project (files with the extension *.apf).

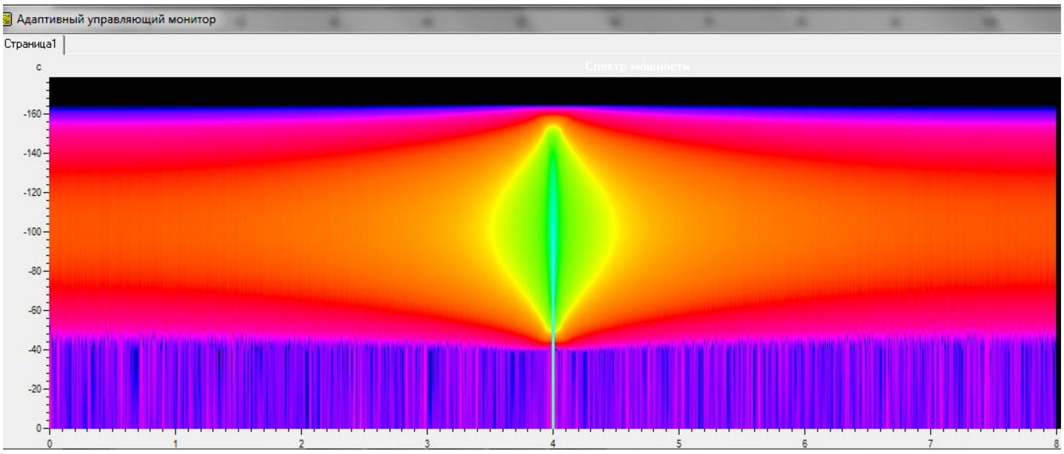


Fig. 1.4 – Spectrum sonogram, which is installed temporarily.

Table 1.1 Variants for a computer workshop 1

	Ctrl+G				F9		
Вар-т (Variant)	Канал (Channel)	Вход (Input)	Ус. (Amplifying)	Окно (Window)	Палитра сонограммы (Sonogram Palette)	Дополнительный метод обработки (Additional processing method) AUM	Дополнительный метод обработки (Additional processing method) DeepSea
1	5	U	0	Прямоугольное	Монотонная	Фаза взаимного спектра	Проходная функция
2	5	Uз	6	Прямоугольное	Радуга	Функция когерентности	Модуль взаимного сп.
3	4	Uс	12	Бартлетта	Морская	Передаточная функция H1	Действ. Взаимн. спектра
4	3	I	18	Бартлетта	DeepSea16	Передаточная функция H2	Мнимая взаимн. спектра
5	6	Q	24	Хэннинга	Морская	Диаграмма Найквиста ВС	Д. Найквиста (взаимного)
6	8	G	30	Хэннинга	Радуга	Диаграмма Найквиста ПФ	Фазовый спектр
7	4	T	36	Хэмминга	Монотонная	Фаза взаимного спектра	Передаточная ф-я H1
8	6	U	42	Хэмминга	Радуга	Функция когерентности	Передаточная ф-я H2
9	9	Uз	48	Натолла	Морская	Передаточная функция H1	Действ. передаточной H1
10	2	Uс	54	Натолла	DeepSea16	Передаточная функция H2	Мнимая передаточной H1
11	4	I	60	Гаусса	Морская	Диаграмма Найквиста ВС	Характерист. Конструкций
12	4	Q	66	Гаусса	Радуга	Диаграмма Найквиста ПФ	Д. Найквиста (передаточной)
13	5	G	72	Прямоугольное	Монотонная	Фаза взаимного спектра	Когерентность
14	3	T	66	Прямоугольное	Радуга	Функция когерентности	Гистограмма
15	6	U	60	Бартлетта	Морская	Передаточная функция H1	Огибающая Гильберта

Table 1.1 (continuation)

16	9	Uз	54	Бартлетта	DeepSea16	Передаточная функция H2	Модуль передаточной
17	6	Uc	48	Хэннинга	Морская	Диаграмма Найквиста ВС	Кепстр
18	6	I	42	Хэннинга	Радуга	Диаграмма Найквиста ПФ	Октавный спектр
19	8	Q	36	Хэмминга	Монотонная	Фаза взаимного спектра	Кепстр
20	6	G	30	Хэмминга	Радуга	Функция когерентности	Модуль передаточной
21	7	T	24	Натолла	Морская	Передаточная функция H1	Огибающая Гильберта
22	6	U	18	Натолла	DeepSea16	Передаточная функция H2	Гистограмма
23	8	Uз	12	Гаусса	Морская	Диаграмма Найквиста ВС	Когерентность
24	10	Uc	6	Гаусса	Радуга	Диаграмма Найквиста ПФ	Д. Найквиста (передаточной)
25	4	I	0	Прямоугольное	Монотонная	Фаза взаимного спектра	Характерист. Конструкций
26	8	Q	6	Прямоугольное	Радуга	Функция когерентности	Мнимая передаточной H1
27	10	G	12	Бартлетта	Морская	Передаточная функция H1	Действ. передаточной H1
28	1	T	18	Бартлетта	DeepSea16	Передаточная функция H2	Передаточная ф-я H2
29	10	U	24	Хэннинга	Морская	Диаграмма Найквиста ВС	Передаточная ф-я H1
30	4	Uз	30	Хэннинга	Радуга	Диаграмма Найквиста ПФ	Фазовый спектр

To 5th item:

It is necessary to create a report on the implementation of a computer workshop in which to present:

1. title page of the protocol;
2. purpose of work, work program;
3. show options for the variant;
4. show signal distribution and signal spectrum in one-sided or two-sided panels;
5. show sonograms in one-time panels:
   a) signal distribution;
   b) signal spectrum;
   c) slow-set spectrum;
6. show all program settings windows and sign them correctly;
7. write meaningful conclusions about the work. Explain why you got such results.

Computer workshop №2

Processing and research of vibration sensors signals in induction motor in the program DeepSea

(2 hours)

Work objective. Get DeepSea's skills on an example of studying a stored signal by results of measurement of the induction motor vibrations.

Work program.

1. Get acquainted with the coordination and measuring unit (CMU) of the firm "Beresta".
2. Get acquainted with the specifics of work in the program **DeepSea**
   e. Signal distribution
   f. Signal amplification
   g. Spectra and its professional settings. Explaining the settings.
   h. Sonogram
3. Create a signal distribution and signal spectrum in the double-window panel.
4. Create Sonograms in single-window panels:
   a) signal distribution
   b) signal spectrum.
   c) slow-acted spectrum.
5. Create a report on the implementation of a computer workshop.

Methodical instructions for the implementation of a computer workshop.

To 1st item:

The **DeepSea** program (Fig. 2.1) allows further detailed processing, analysis and research of the received signals stored in the **AUM** project files in the case of working with recorded real signals of vibration sensors. Since you work offline in **AUM,** you can work with any recorded signal in files **Cos5ch.dfd, NyqTst.dfd, Test200.dfd, Zoom3ch.dfd** located in the folder **C:\Program Files (x86)\DeepSea\Data.**

DeepSea program has a programmed number of special mathematical methods of signal processing that allow processing and presenting signals in the form of oscillograms, spectrograms, sonograms, histograms, calculate mutual functions (coherence function, transfer function, cepstra, etc.).

To 1st, 3rd, 4th items:

In order to get acquainted with the basics of working in DeepSea**,** you need to listen the information from teacher about the computer workshop or watch the video [14].

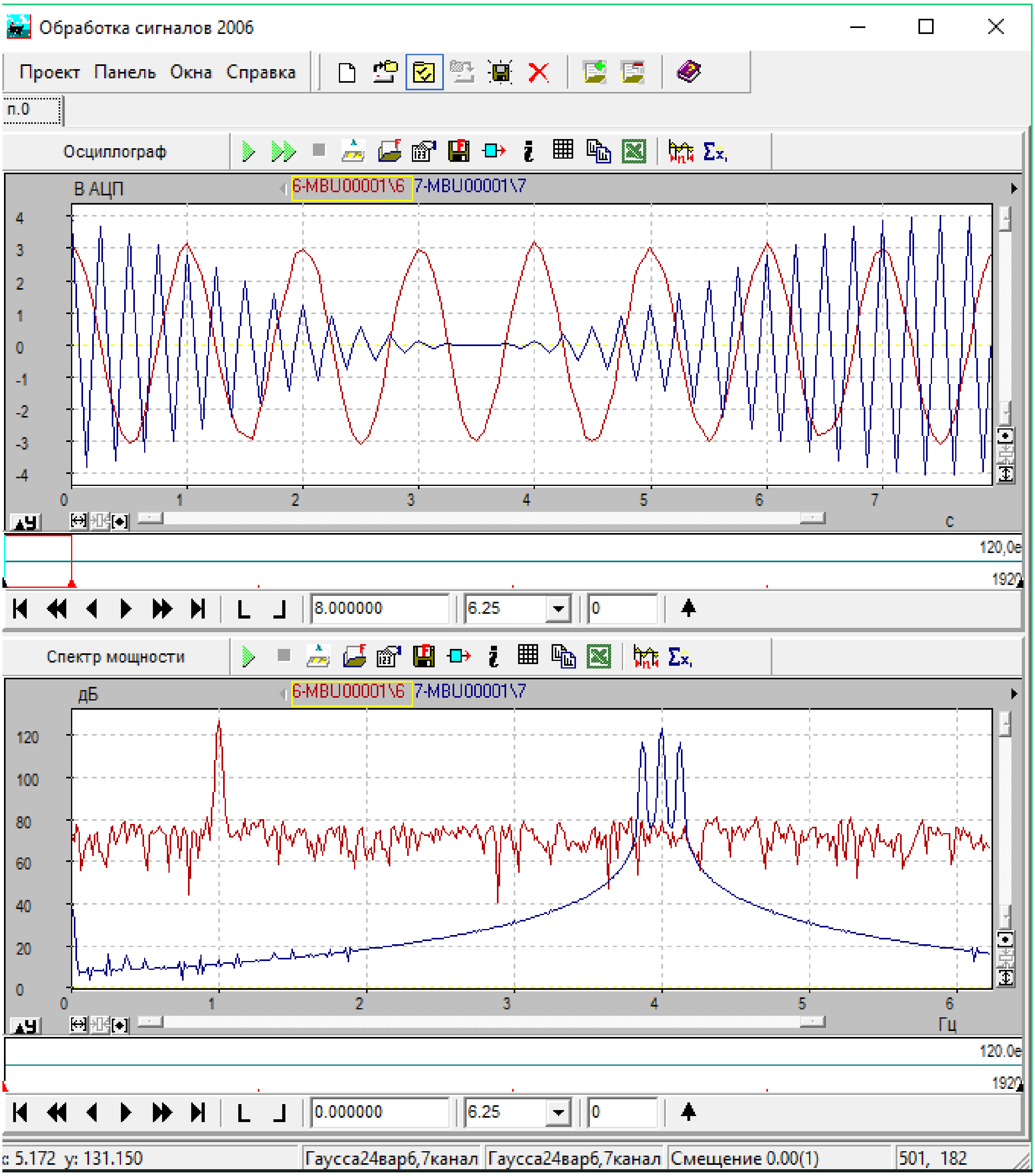


Fig. 2.1 - The **DeepSea** program window

To 3rd item:

The order of work execution in the program DeepSea:

1. you can add one of the panels:
    a. two-screen graphic panel;
    b. Sonogram panel;
    c. double-window graphic panel;
    d. single-window graphic panel;
2. open the AUM file in the data entry on all panels * .dfd;
3. select the processing method on the panels;
4. select a channel according to your variant;
5. configure the panels;
6. start the process of demonstrating of signals or spectra in the panel.

To 5th item:

It is necessary to create a report about the implementation of a computer workshop in which present:

1. title page of the protocol;
2. purpose of work, work program;
3. specify options of the variant;
4. give signal distribution and signal spectrum in one-sided or two-sided panels;
5. show sonograms in one-sided panels:
    a) signal distribution;
    b) signal spectrum;
    c) slow-set spectrum;
6. show all program settings of windows and sign them correctly;
7. write meaningful conclusions about the work. Explain why you got such results.

For protection of computer workshop №2:

1. know at a sufficiently professional level where and what vibration sensor signal processing parameters are in the **DeepSea** program;
2. create a report on the implementation of computer workshop;
3. know the concept: cepstrum, correlation, etc.

Basic information for working in computer workshop №2

Correlation is the interdependence of two or more random variables. Its essence lies in the fact that when changing the value of one variable there is a natural change (decrease or increase) of other variables. When calculating correlations, they try to determine if there is a statistically reliable relationship between two or more variables in one or more samples. The correlation connection only speaks of the interconnection of these parameters, and in this particular sample, in another sample, we can not observe the correlation obtained.

Correlation index (Fig. 2.2). The correlation coefficient (r) characterizes the magnitude, which reflects the degree of interconnection of the two variables among themselves. It can range from -1 (negative correlation) to +1 (positive correlation). If the correlation coefficient is 0, then this indicates that there is no correlation between the variables. Moreover, if the correlation coefficient is closer to 1 (or -1), they say a strong correlation, and if closer to 0, then a weak correlation.

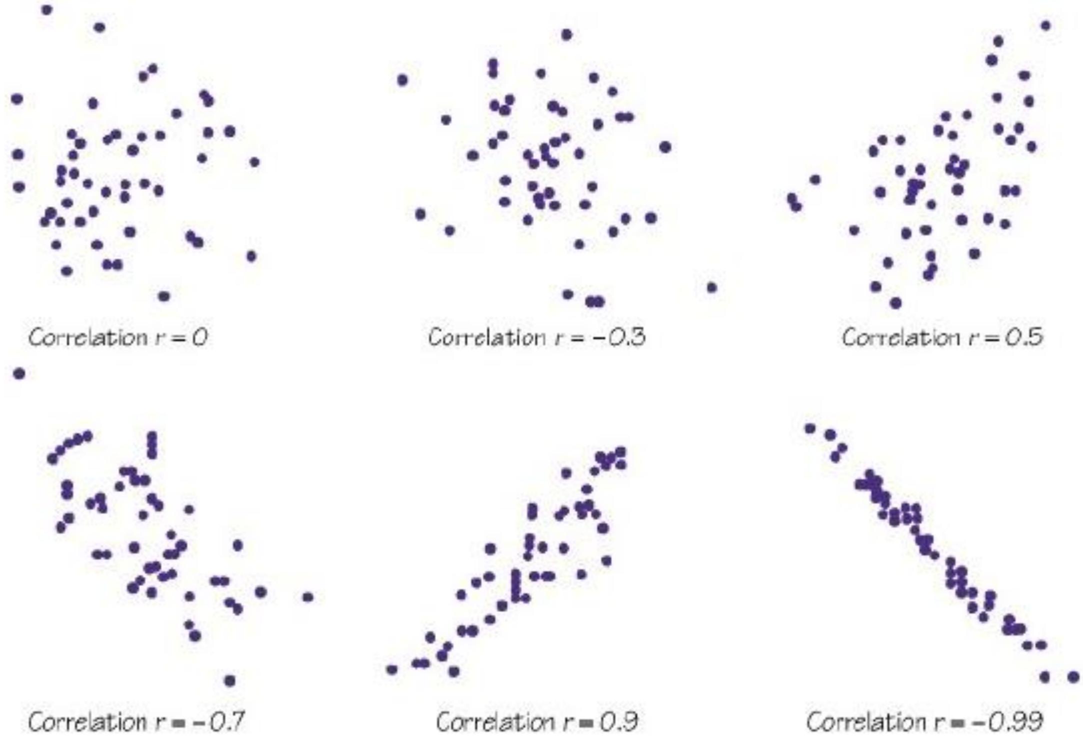


Fig. 2.2 – Different values of the correlation index

With a positive correlation, the increase (or decrease) of the values of one variable leads to a natural increase (or decrease) of another variable, i.e., the relationship of type increase-increase (decrease-decrease).

In the case of a negative correlation, the increase (or decrease) of the values of one variable leads to a regular decrease (or increase) of another variable, i.e., the relationship of type increase-decrease (decrease-increase).

Cepstrum – is the spectrum of the spectrum, the result of the application of the Fourier transform to the spectrum (or the logarithm of the spectrum) of the signal strength. Thus, it will be possible to present the output spectral information even more compactly, when each harmonic series of the initial spectrum will be represented by only one (ideally) component in the cepstrum (Fig. 2.3).

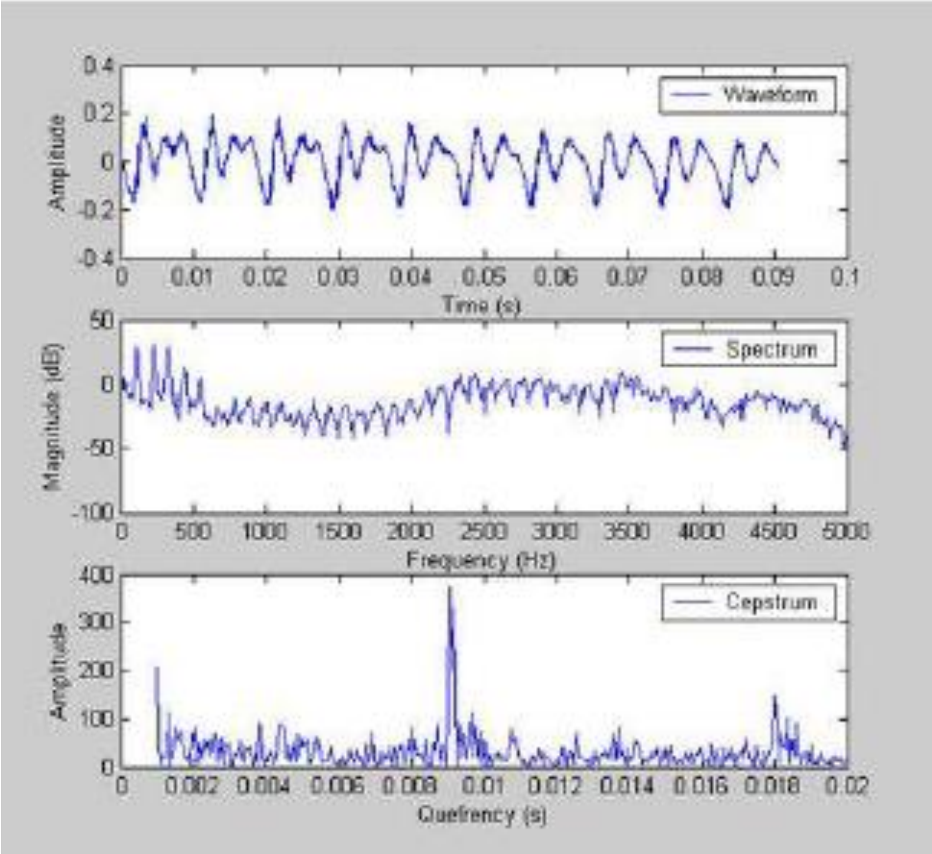


Fig. 2.3 – Signal, spectum, cepstrum

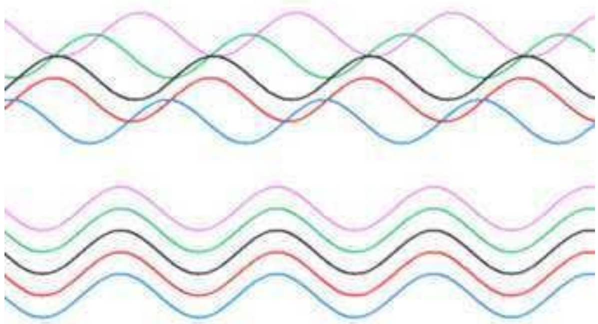


Fig. 2.4 – Coherence waves

Coherence - correlationment (consistency) of several oscillation or wave processes in time, which is manifested in their compilation. Oscillations are coherent (consistent), if the difference between their phases is constant in time, and oscillations of the same frequency are obtained during oscillation. An example is two sinusoidal oscillations of the same frequency. The coherence of the wave means that in different spatial points the oscillation waves occur synchronously, that is, the phase difference between the two points does not depend on time. Lack of coherence, therefore - a situation where the phase difference between two points is not constant, but changes over time. This situation can occur if the wave was generated by not just one emitter, but a set of identical, but independent (that is, uncorrelated) emitters.

Coherent ones are called waves with constant phase difference (Figure 2.4). This mathematical property manifests itself at interference - that is, when the waves "fold" at different points of space.

Computer Workshop №3

Modeling and processing of the induction motor vibration sensors signal using the main elements in the program National Instruments LabView

(2 hours)

Work objective. Simulate and process the signal of an induction motor vibration sensor using the main elements in the **National Instruments LabView** program.

Work program:

1. get acquainted with the basics of work in the program **National Instruments LabView,** in particular, work in **Block Diagram** and **Front Panel;**
2. create a scheme of basic elements;
3. set the signal parameters in **Block Diagram** in accordance with the variant;
4. simulate directly the signal with the specified parameters;
5. determine the parameters of the signal under study;
6. show the numerical results of the processing of the studied signals in the **Front Panel;**
7. show the distribution of the studying signal with the specified parameters in the **Front Panel;**
8. display and record a sound interpretation of the studying signal using **Play Waveform;**
9. create a report about the implementation of computer workshop.

Methodical instructions for the implementation of a computer workshop.

To 1st item:

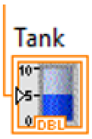
In order to get acquainted with the basics of work in the program National Instruments LabView, you need to listen an information from the teacher about the computer workshop or watch the video [15].

Besides of the main program file **National Instruments – NI Labview 2015 x32.exe you** also need to install 2 toolkits: **Toolkits. NI Sound & Vibration Toolkit.exe** and **Toolkits. NI-DAQmx Data Acquisition Driver Software for Windows.exe**

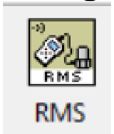
To 2nd-7th items:

In order to create a scheme of the main elements (for this part of the computer workshop, the student shows his creativity and can use any blocks), it is necessary:

1. set the signal parameters (amplitude, phase, frequency, etc.) in **Block Diagram** in accordance with the variant;
2. simulate directly signal with the specified parameters (sinusoidal, etc.);

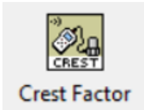
3. determine the parameters of the studying signal and output them in **Front Panel** using the **Tank** element 

through **the** following **Block Diagram** elements:

a) root mean square value (**Rms**) 

;

b) peak value (**Peak**); 

c) peak signal factor (**Crest factor**) 

;

d) value between the maximum and minimum of a signal (**Max-min**) 

.

Algorithm for creating a scheme of basic elements:

Click **Create Project** -> **Blank VI**.

It is necessary to create a scheme shown in Fig. 3.1 using the given elements.

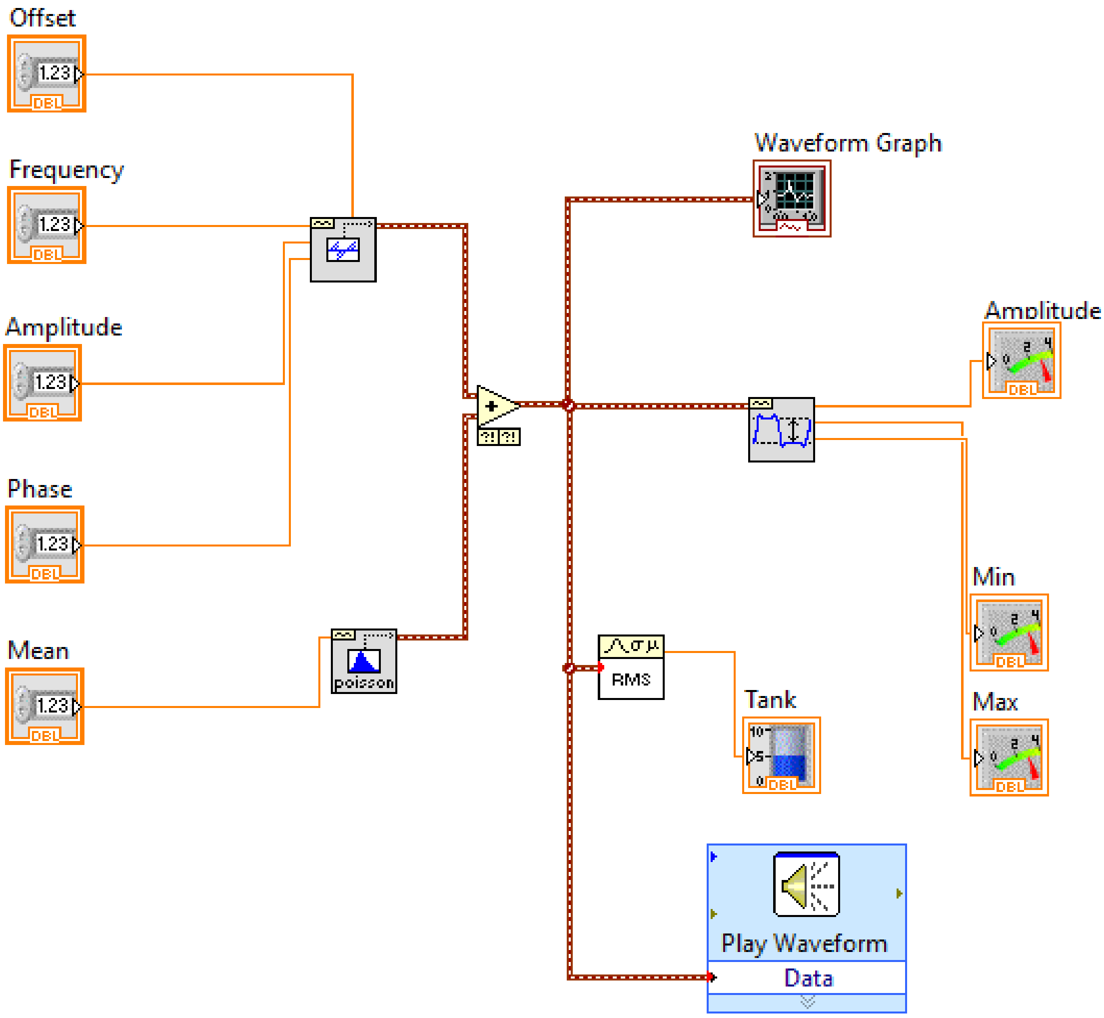


Fig. 3.1 – Scheme in **Block Diagram**

In **Block Diagram** function tree**,** which can be used, it is opens with the right mouse click on the white background and is called **Functions** (Fig. 3.2). In this functions tree, the interests are mainly the elements located in the **Sound and Vibration** tab (Fig 3.3 – 3.4). Moreover, some elements can be repeated in other tabs.

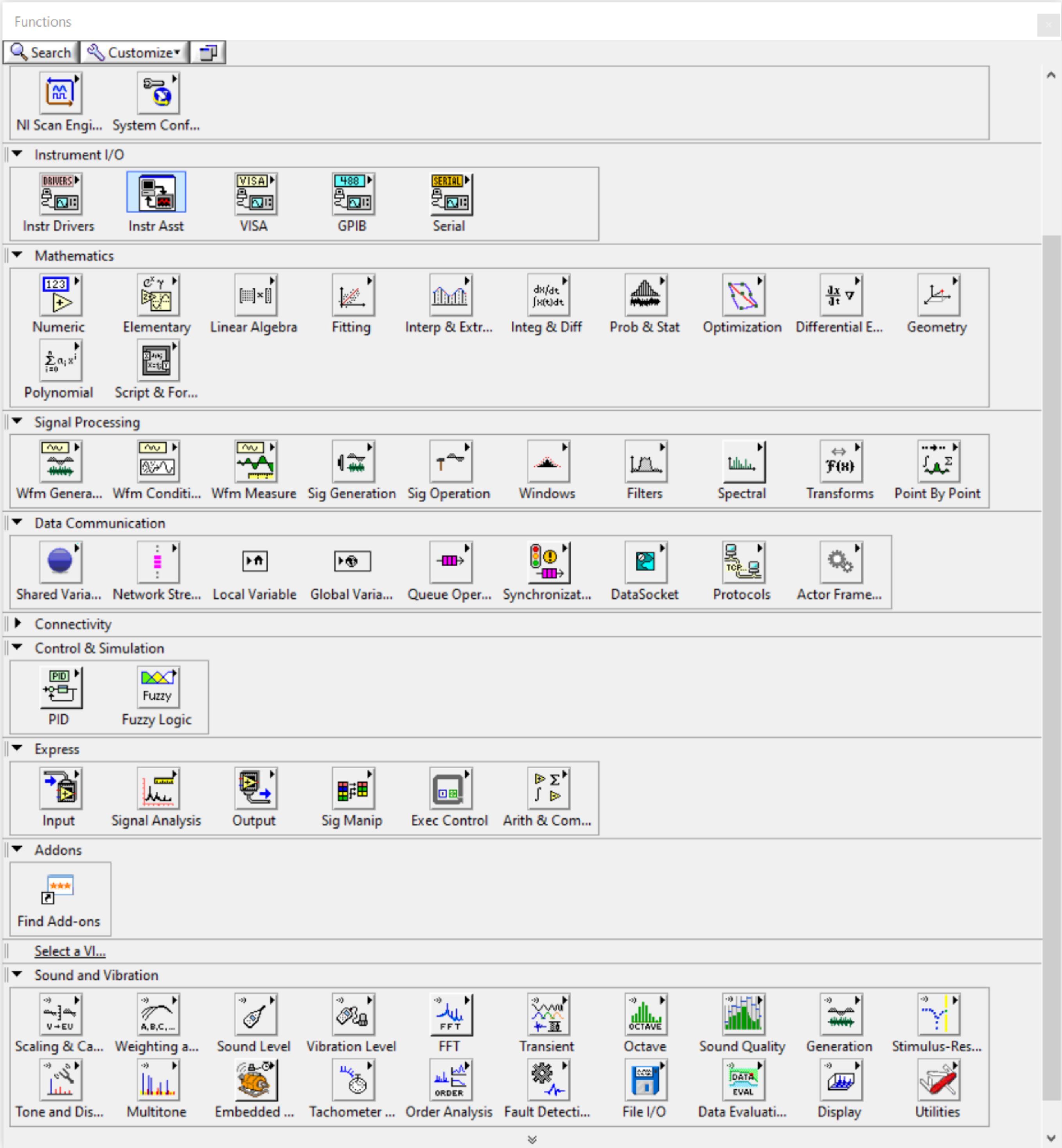


Fig. 3.2 – functions tree **Functions** in **Block Diagram**

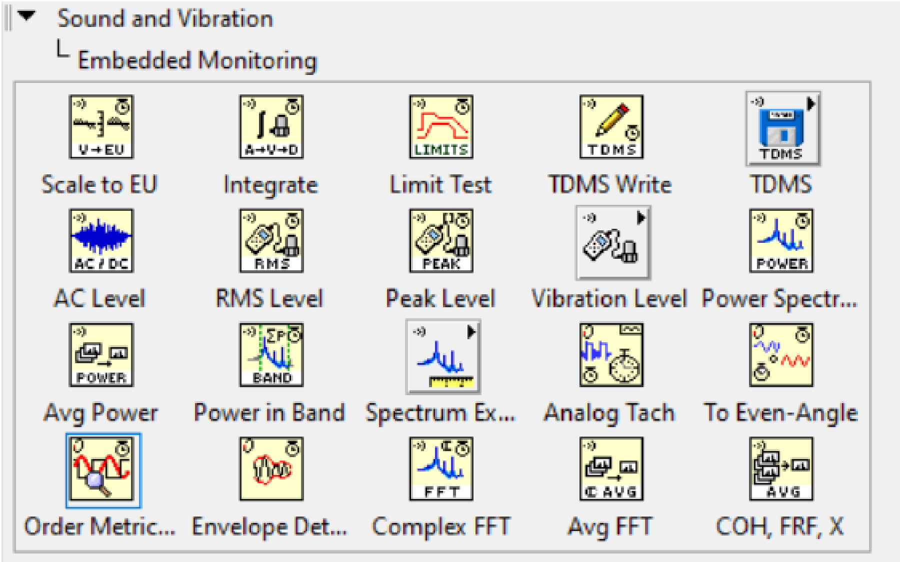


Fig. 3.3 – Elements in **Embedded Monitoring** in the **Sound and Vibration**

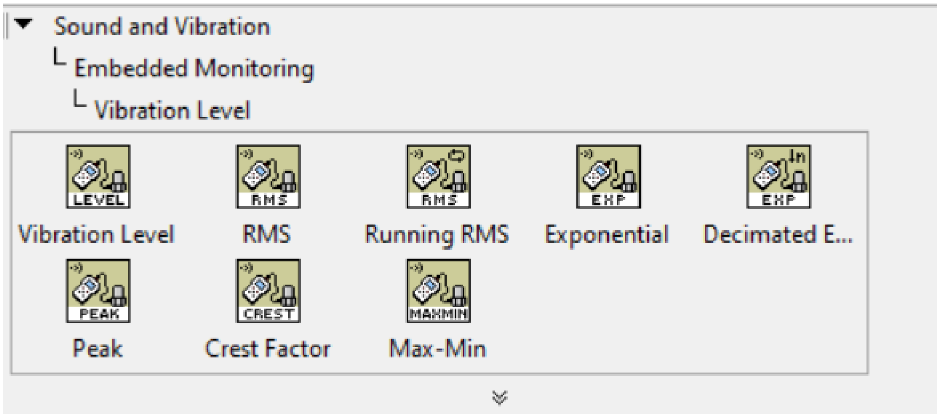


Fig. 3.4 – Elements in **Vibration Level** in the **Embedded** Monitoring tab

In the **Front Panel** control elements tree, that can be used, is opened by right-clicking on the gray background in the cell and is called **Controls** (Fig. 3.5). In this control elements tree, the interests are mainly the elements located in the **Classic -> Numeric** tab. Moreover, some elements can be repeated in other tabs.

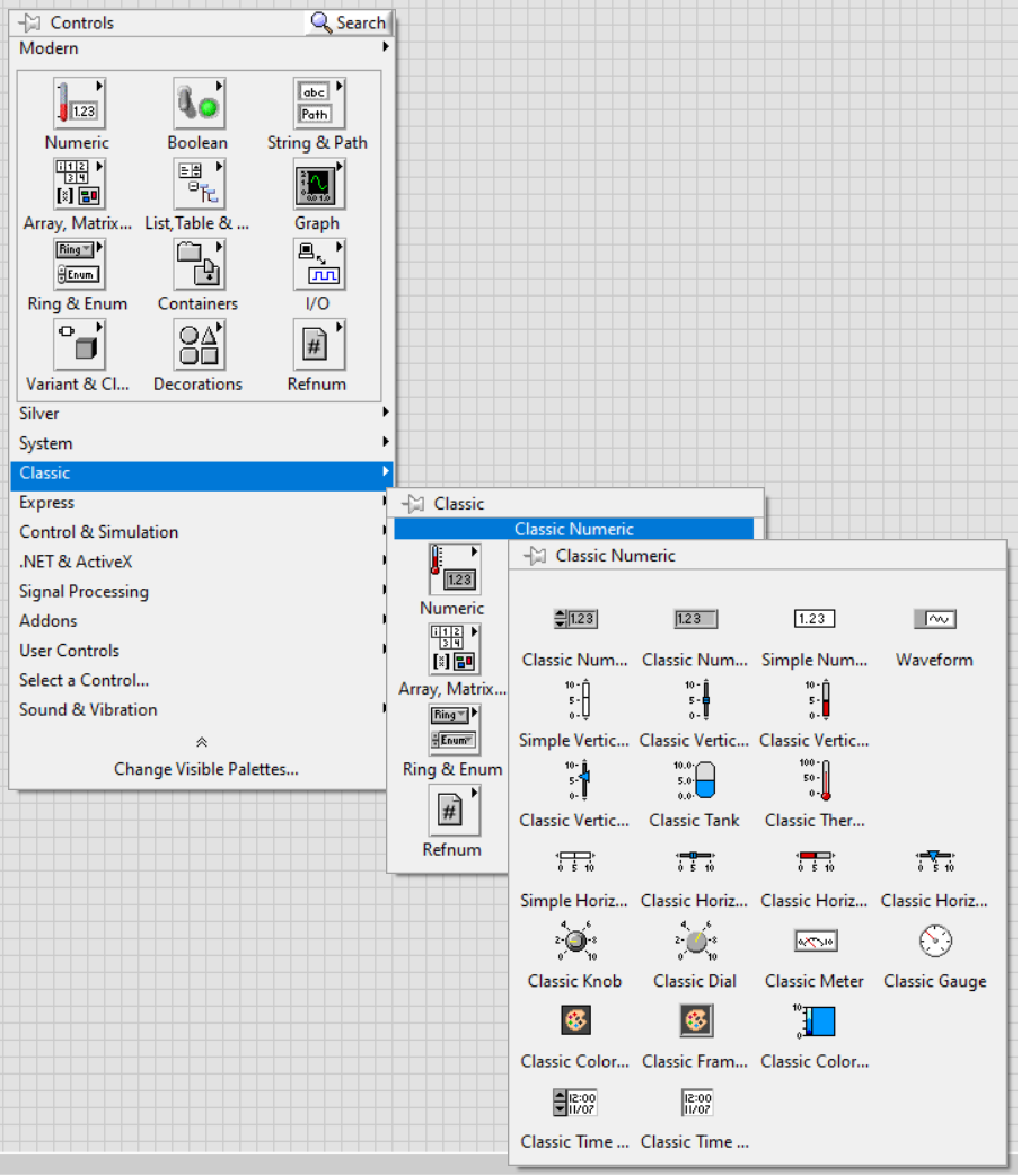
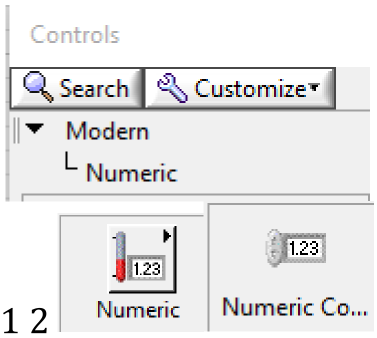


Fig. 3.5 – Control elements tree **in Front Panel**

Press right-click in **Front Panel**. Add five element **Numeric Control** in order to set signal parameters (amplitude, phase, frequency, etc.). Sign them, set values according to the variant, tune properties:



1 2
Fig. 3.6 – Elements selection

We sign them and set the values as follows:

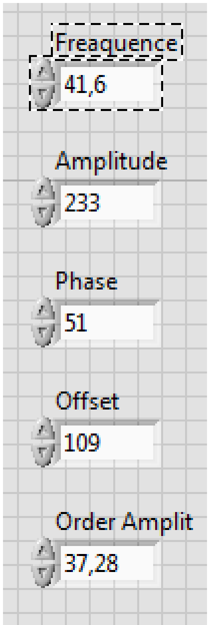


Fig. 3.7 – Setting the signal parameters according to the variant in **Front Panel**

In **Block Diagram,** we're adding five elements of **Numeric constant:**

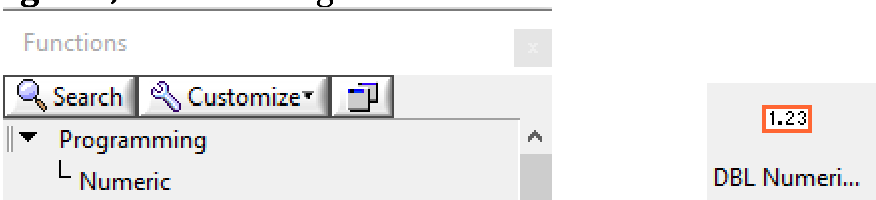


Fig. 3.8 – Elements adding

Right-clicking on the element and select point **Properties** and configure it as it is indicated in the following picture.

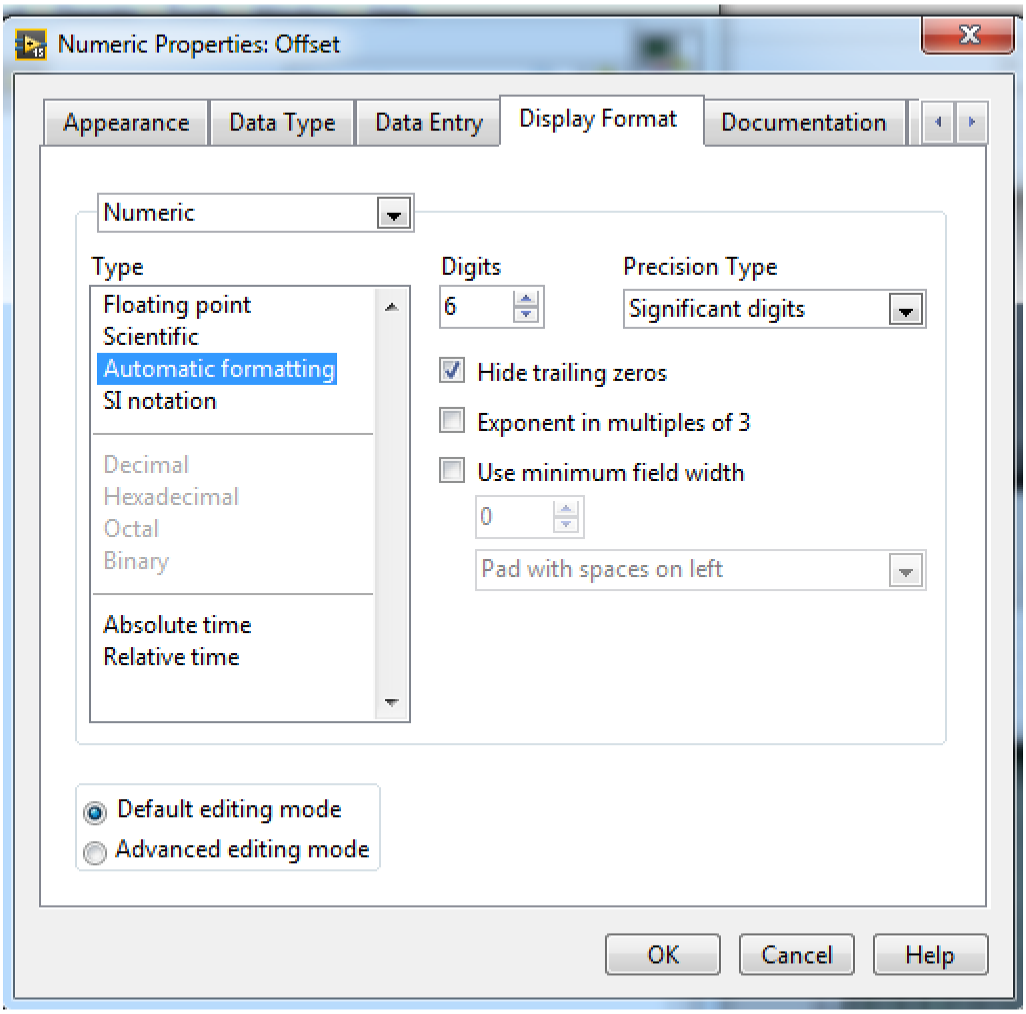


Fig. 3.9 – **Offset** block options

In **Block Diagram** we're adding element **Sawtooth Waveform:**

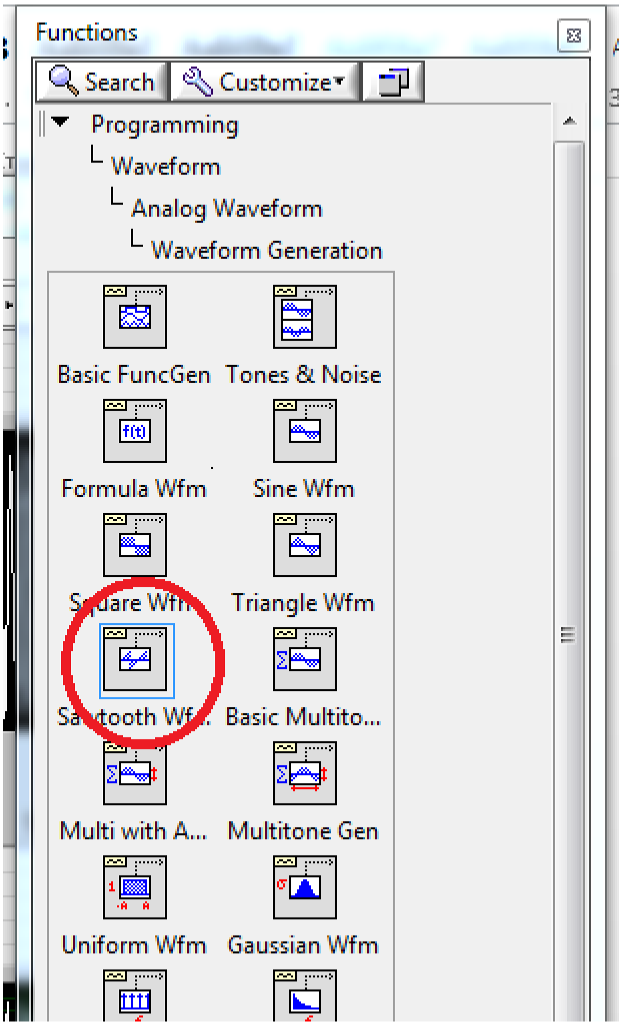


Fig. 3.10 – Adding an element **Sawtooth Waveform**

In **Block Diagram** we're adding element **Poisson Noise:**

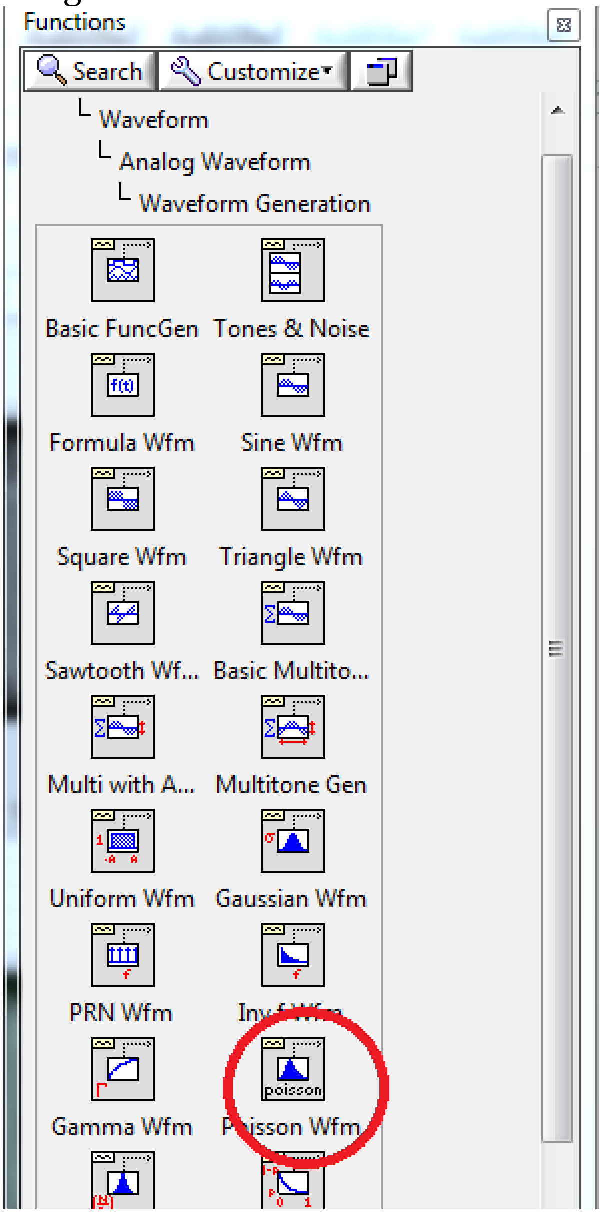


Fig. 3.11 – Adding an element **Poisson Noise**

In **Block Diagram** from toolkit **Sound and Vibration** and subtab **Vibration Level** adding elements **RMS, Peak, Max-Min, Crest Factor:**

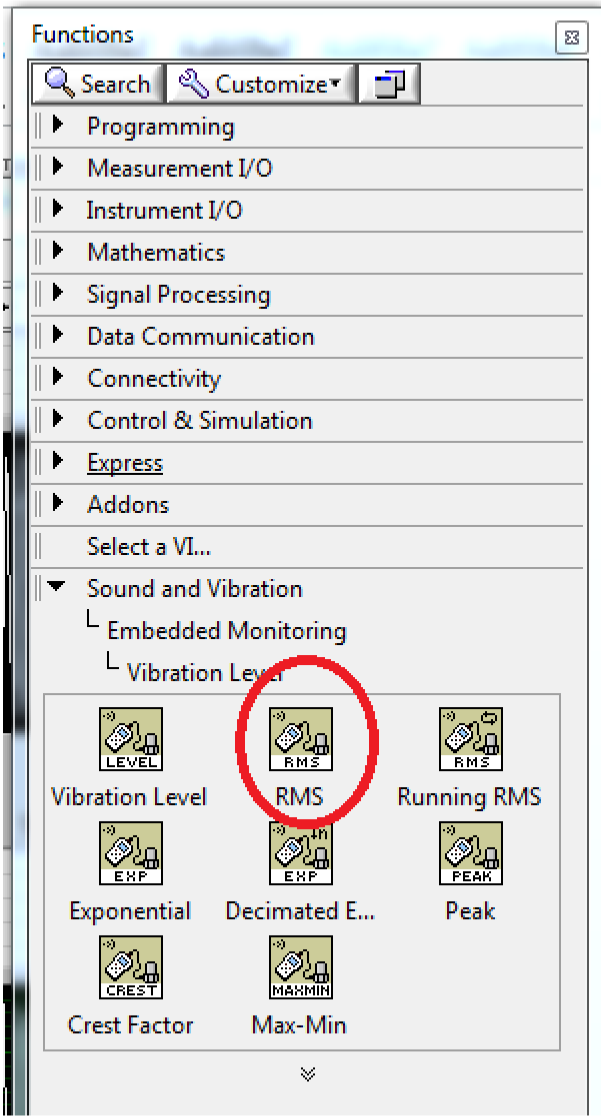


Fig. 3.12 – Element **RMS** adding

Go to the **Front Panel** and adding the following elements:

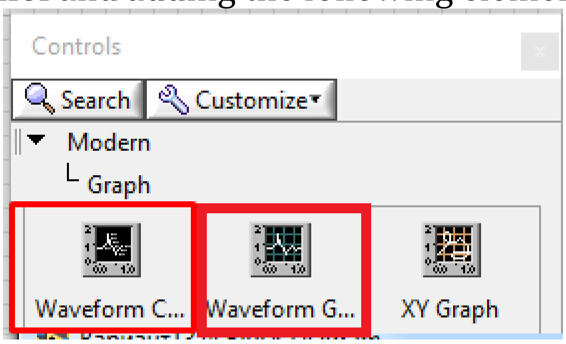


Fig. 3.13 – Other elements adding

Add 3 elements **Meter**; one **Waveform graph** and **Tank**, adjust their properties (Fig. 3.14).

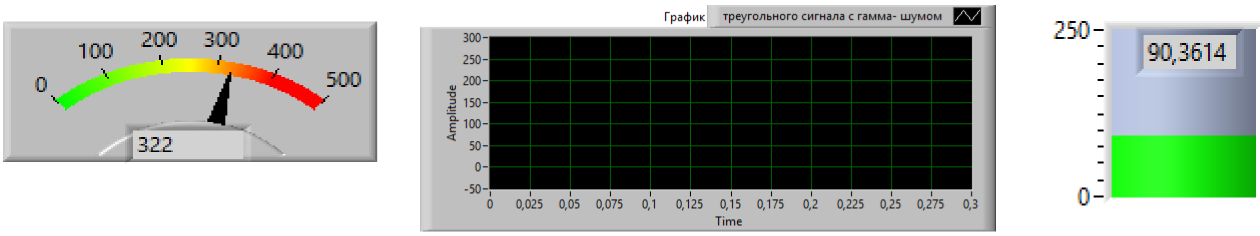
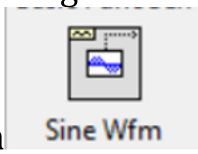


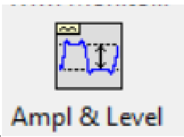
Fig. 3.14 – Elements **Meter, Waveform graph** and **Tank**

Right-click in **Block Diagram and** in **Search** find and add elements that determine the signal according to the variant (Fig. 3.15):

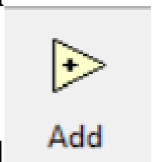
Sine Waveform 

or **Square Waveform** 

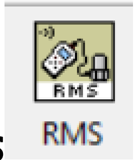
,

Amplitude and Level 

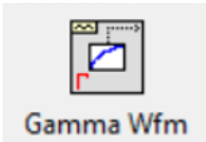
,

Add 

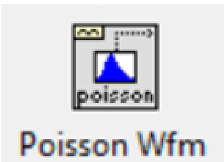
to summing up signals and noise,

RMS 

,

and noise block **Gamma Waveform** 

or **Poisson Waveform.**



The parameters of these elements must be adjusted according to the variant.

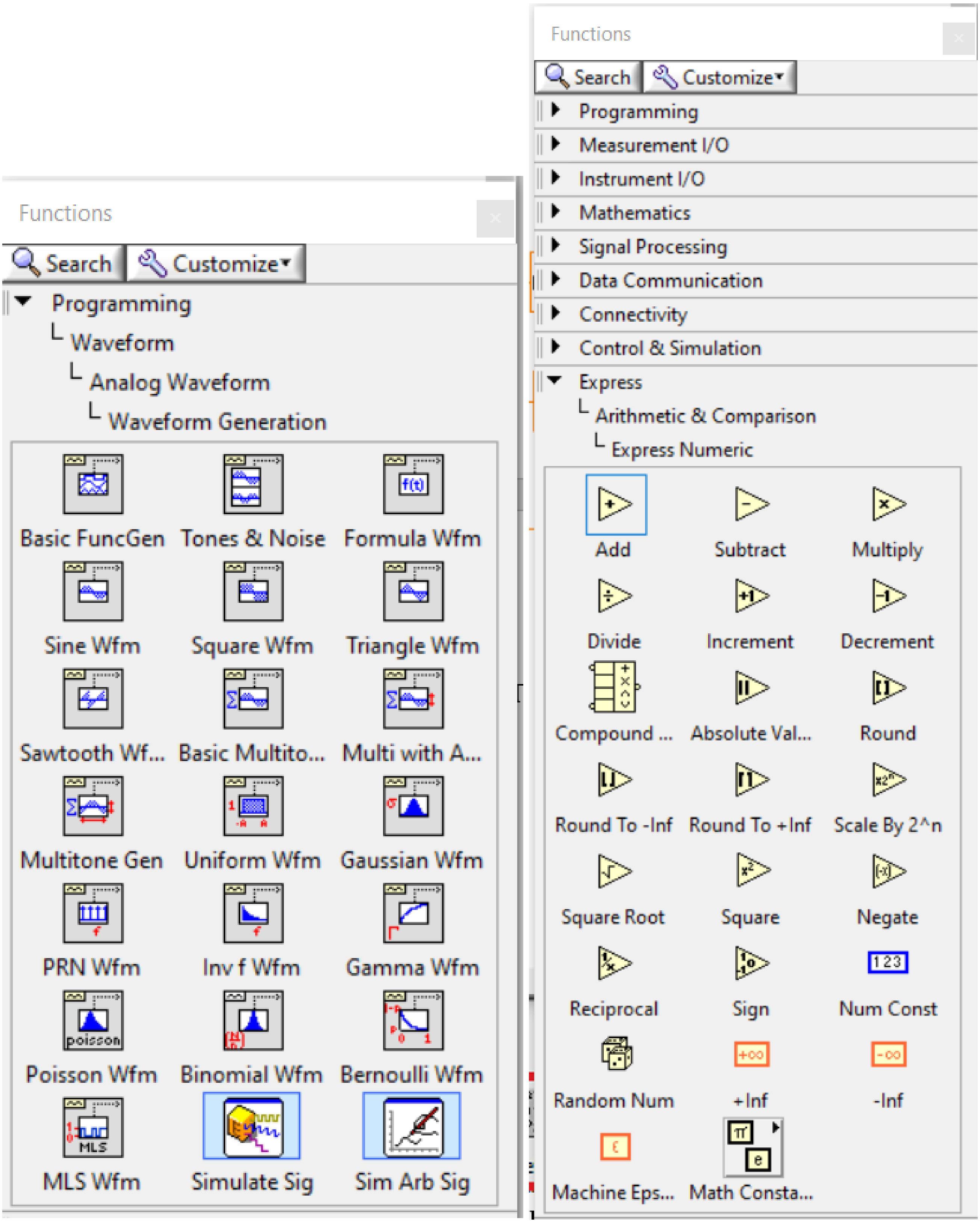


Fig. 3.15 – Other elements adding from functions tree **Functions** in **Block Diagram**

Connect elements, configure blocks for correct operation and run the scheme. It should be noted that each element has many color inputs and outputs for connecting different elements to each other. You must connect elements by using a connection line, connected to contacts of the same colour. 

In **Block Diagram**, we connect and subscribe all the added elements in such way as on a Fig. 3.1.

In **Front Panel** show the signal distribution and indications of other sensors. We're getting the result shown in Figure 3.16

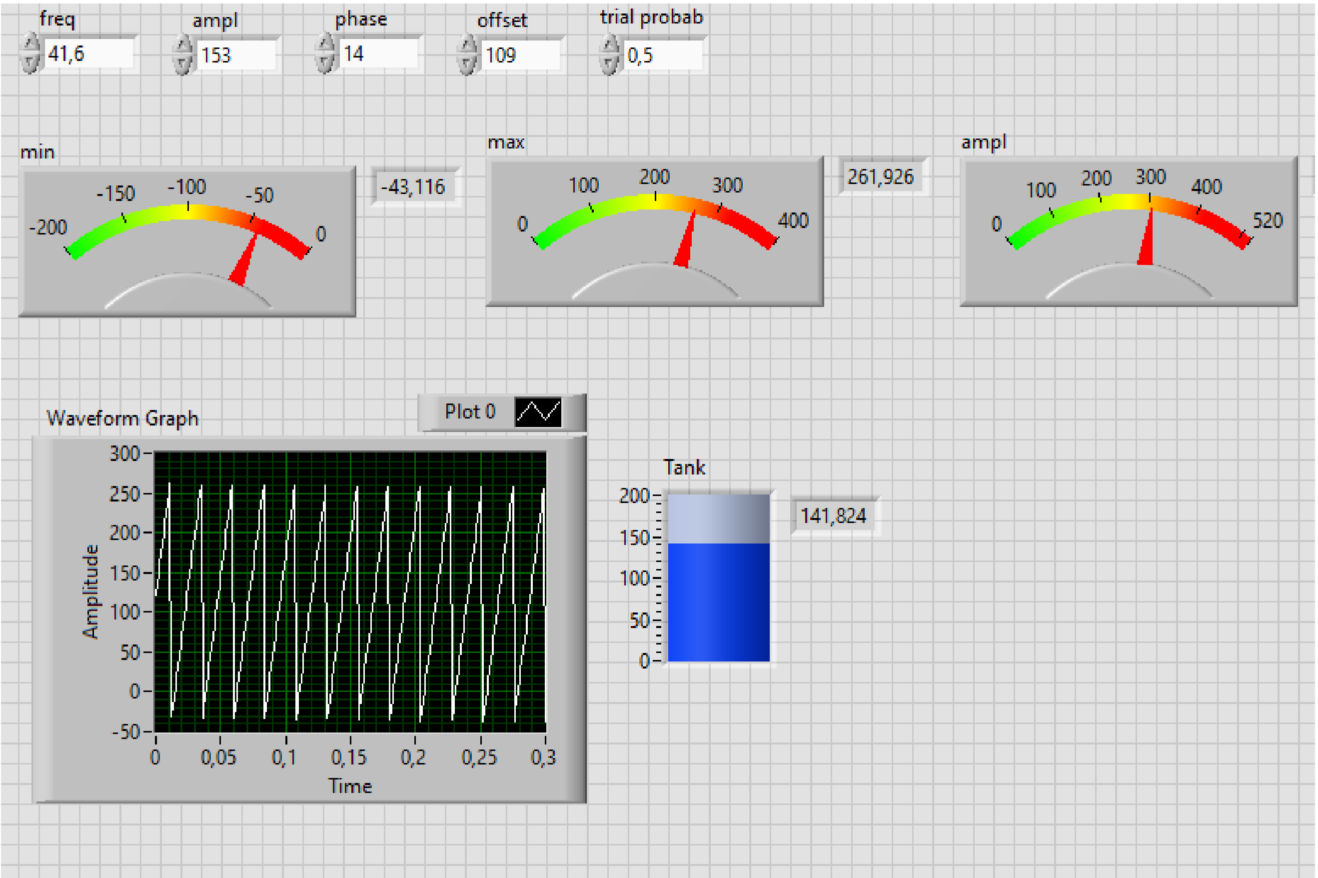
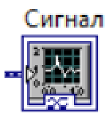


Fig. 3.16 – Working window in **Front Panel**

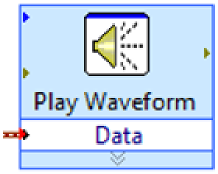
In order to display the signal distribution (Fig. 3.18, top) **in the Front Panel** it is necessary to add **Waveform Chart** from the **Controls** element library. 

As a result, **Waveform Graph** will be automatically added to **Block Diagram**, which must be connected directly to the signal source 

and renamed to "Signal".

Next, you need to copy the image to the protocol and save the project.

To 8th item:

Add **Play Waveform** 

for output the sound.

Variants for computer workshops tasks №3 and №4 are presented in Table. 3.1

Table 3.1 Variants for computer workshops tasks №3 and №4

Simulate Signal

Variant	Signal type	Frequency (Hz)	Amplitude	Phase (deg)	Offset	Add noise	Noise type	Noise amplitude	Additional parameters		
1	Triangle	31,1	233	44	95	+	Bernoulli Noise	Trial probability	0,3	Trials	75
2	Sawtooth	41,6	167	51	109	+	MLS Sequence	Trial probability	0,5	Trials	100
3	Sine	10,1	189	30	67	+	Inverse F Noise	Noise amplitude	0,6	Exponent	1
4	Square	20,6	211	37	81	+	Inverse F Noise	Noise amplitude	0,6	Exponent	2
5	Triangle	31,1	233	44	95	+	Inverse F Noise	Noise amplitude	0,6	Exponent	3
6	Sawtooth	41,6	167	51	109	+	Uniform White Noise	Noise amplitude	37,28		
7	Sine	10,1	189	30	67	+	Gaussian White Noise	Standard deviation	26,72		
8	Square	20,6	211	37	81	+	Periodic Random Noise	Spectral amplitude	30,24		
9	Triangle	31,1	233	44	95	+	Gamma Noise	Order	33,76		
10	Sawtooth	41,6	167	51	109	+	Poisson Noise	Mean	37,28		
11	Sine	10,1	233	30	67	+	Binomial Noise	Trial probability	0,4	Trials	135
12	Sawtooth	41,6	153	14	109	+	MLS Sequence	Trial probability	0,5	Trials	50
13	Square	20,6	199	37	81	+	Periodic Random Noise	Spectral amplitude	25		
14	Sawtooth	41,6	211	51	109	+	Gamma Noise	Order	19,9		
15	Triangle	31,1	233	44	95	+	Periodic Random Noise	Spectral amplitude	26,72		
16	Sawtooth	41,6	167	51	109	+	Gamma Noise	Order	30,24		

Table 3.1 (continuation)

17	Sine	10,1	189	30	67	+	Uniform White Noise	Noise amplitude	16,7		
18	Square	20,6	211	37	81	+	Gaussian White Noise	Standard deviation	18,9		
19	Triangle	31,1	233	44	95	+	Periodic Random Noise	Spectral amplitude	21,1		
20	Sawtooth	41,6	167	51	109	+	Gamma Noise	Order	23,3		
21	Sine	10,1	189	30	67	+	Poisson Noise	Mean	16,7		
22	Square	20,6	211	37	81	+	Binomial Noise	Trial probability	0,6	Trials	55
23	Square	10,1	233	51	109	+	Periodic Random Noise	Spectral amplitude	30,24		
24	Triangle	41,6	153	44	81	+	Gamma Noise	Order	33,76		
25	Sawtooth	20,6	199	37	109	+	Poisson Noise	Mean	37,28		
26	Sine	41,6	211	44	95	+	Binomial Noise	Trial probability	0,4	Trials	135
27	Sawtooth	31,1	233	51	81	+	MLS Sequence	Trial probability	0,5	Trials	50
28	Square	20,6	211	30	95	+	Periodic Random Noise	Spectral amplitude	25		
29	Sawtooth	31,1	233	14	109	+	Gamma Noise	Order	19,9		
30	Triangle	41,6	167	37	67	+	Periodic Random Noise	Spectral amplitude	26,72		

To 9th item:

It is necessary to create a report about the implementation of a computer workshop, in which present:

1. title sheet of the protocol;
2. purpose of work, work program;
3. show options for the variant;
4. show the scheme in **Block Diagram;**
5. show the scheme in **Front Panel;**
6. show the specified signal parameters (amplitude, phase, frequency, etc.);
7. show the results of signal simulation with the specified parameters (sinusoidal, etc.);
8. show the results of processing of this signal (determination of the root mean square value, determination of the peak signal factor, determination of the signal amplitude, determination of the Max-min value, etc.);
9. show numerical results of processing these signals in the **Front Panel;**
10. show the distribution of the signal with the specified parameters in the **Front Panel;**
11. write meaningful conclusions about the work. Explain why you got such results;
12. send to the the teacher a sound interpretation of the signal being recorded using **Play Waveform**.

Computer Workshop №4

Modeling and processing of the vibration sensors signal of induction motor using the elements of Simulate Signal and Spectral Measurements in the program National Instruments LabView

(2 hours)

Work objective. Simulate and implement the vibration sensor signal processing of induction motor by using **Simulate Signal** and **Spectral Measurements** in the **National Instruments LabView.**

Work program:

1. get acquainted with the basics of work in the program **National Instruments LabView**, in particular, work in **Block Diagram** and **Front Panel;**
2. create a scheme in **Block Diagram** with signal parameters using elements **Simulate Signal** and **Spectral Measurements;**
3. set the signal parameters according to the variant in the **Simulate Signal** element;
4. determine the signal parameters in the element **Spectral Measurements;**
5. display the numerical results of processing of the studied signals in **Front Panel;**
6. display the distribution of the signal with the specified parameters in **Front Panel;**
7. display the signal distribution spectrum with the specified parameters in **Front Panel;**
8. show a sound interpretation of the studying signal using **Play Waveform;**
9. create a report about the implementation of a computer workshop.

Methodical instructions for the implementation of a computer workshop.

To 1st item:

In order to get acquainted with the basics of work in the program **National Instruments LabView**, you need to listen the information from the teacher about the computer workshop or watch the video [15].

To 2nd-8th items:

Algorithm for creating a scheme with signal parameters using elements Simulate Signal and Spectral Measurements.

It is necessary to create a scheme shown in Fig. 4.1 or Fig. 4.2 using the following elements.

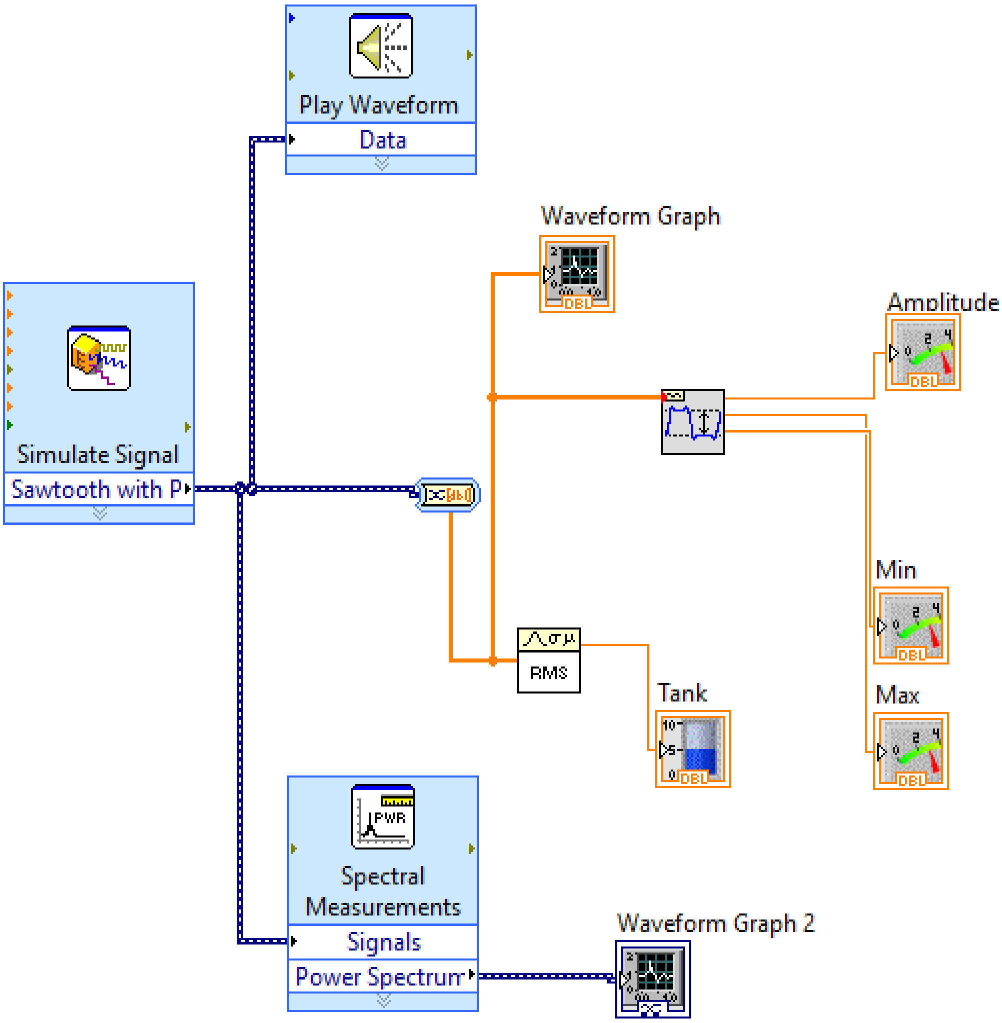


Fig. 4.1 – Scheme with signal parameters using elements **Simulate Signal** and **Spectral Measurements** (option 1)

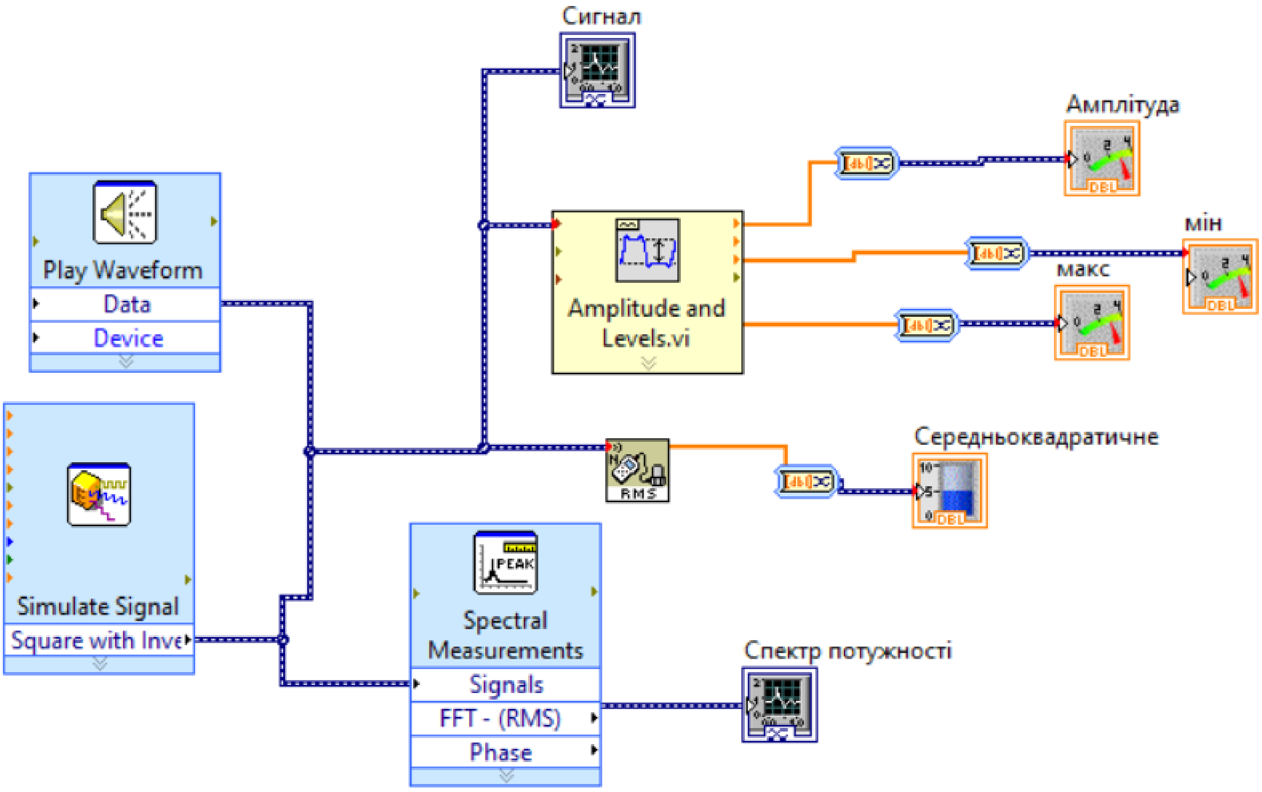


Fig. 4.2 – Scheme with signal parameters using elements **Simulate Signal** and **Spectral Measurements** (option 2)

When creating the scheme shown in Fig. 4.2, it is necessary to use the **Convert to Dynamic Data** element (Fig. 4.3) to be able to combine elements with different types of contacts), which can be added from the functions tree **Functions** in **Block Diagram** (Fig. 4.4). This element must be configured in accordance with the parameters shown in Fig. 4.5

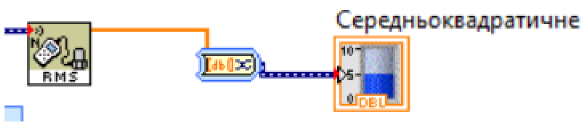


Fig. 4.3 – In the center - element **Convert to Dynamic Data**

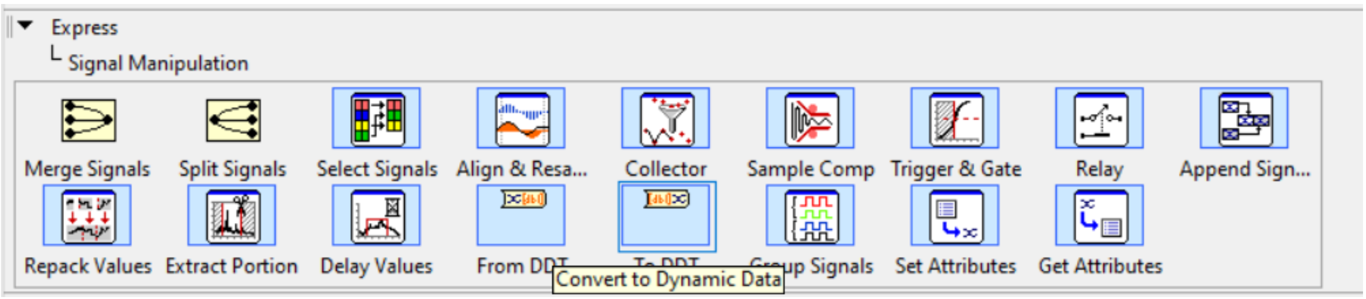


Fig. 4.4 – Element **Convert to Dynamic Data** from functions tree **Functions** in **Block Diagram**

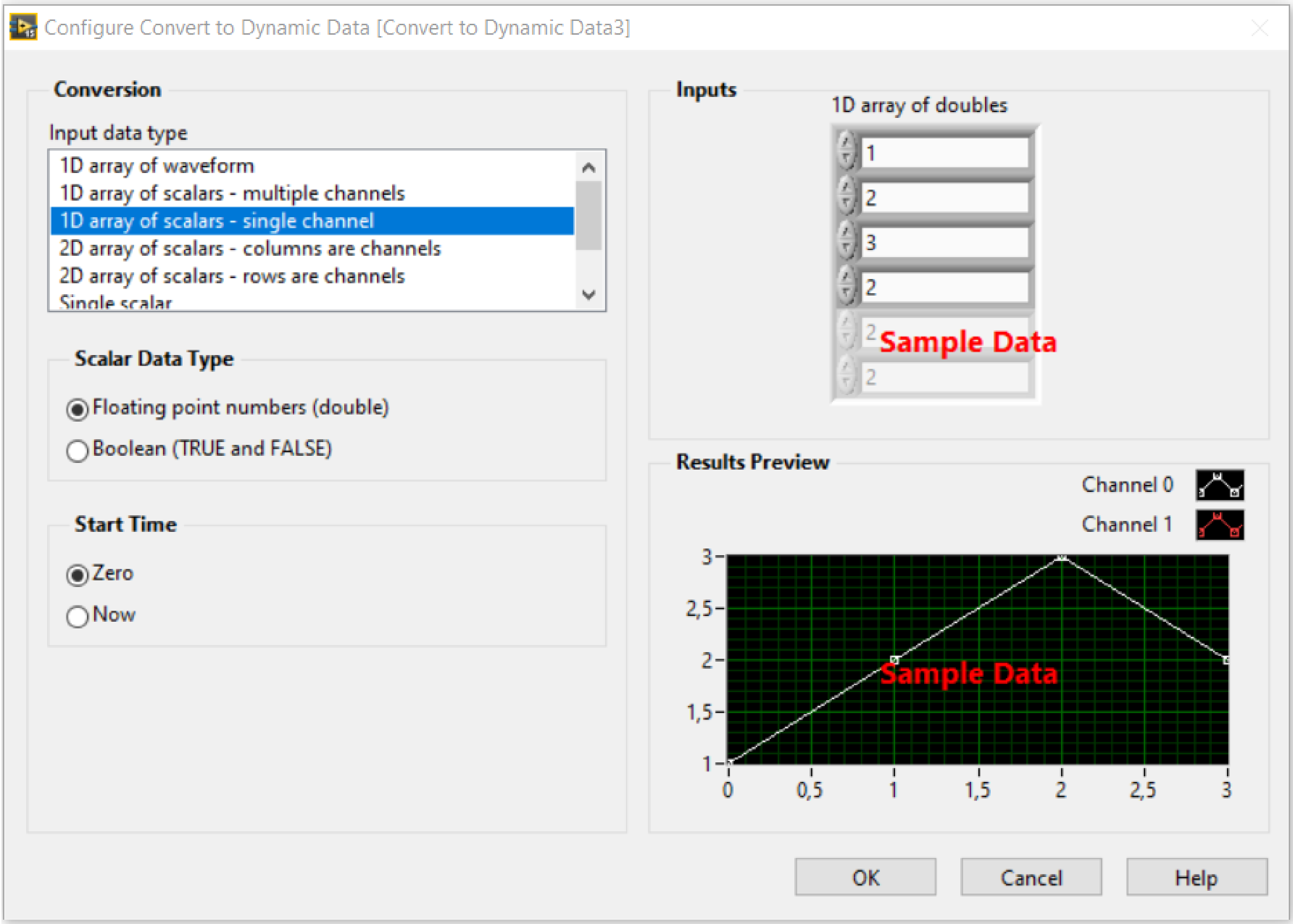


Fig. 4.5 – Parameters of element **Convert to Dynamic Data**

In the **Front Panel**, remove five elements from the previous computer workshop. Add **Waveform graph**.

In **Block Diagram** add **Simulate Signal**, **Spectral Measurments**, **Play Waveform**, set their parameters (Fig. 4.6).

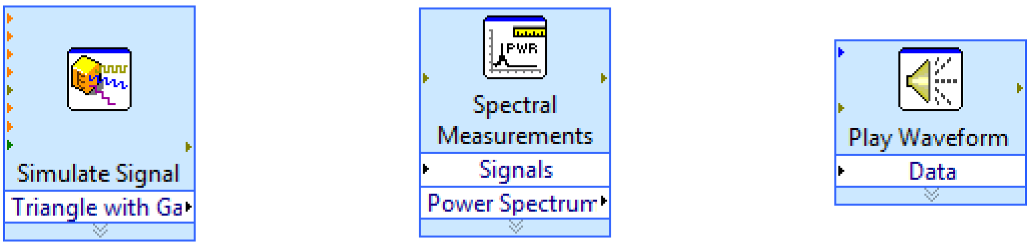


Fig. 4.6 – Adding elements

Start the scheme, copy the image, save the project under a different name.

Set the given signal parameters according to the variant in the element **Simulate Signal** (Fig. 4.7).

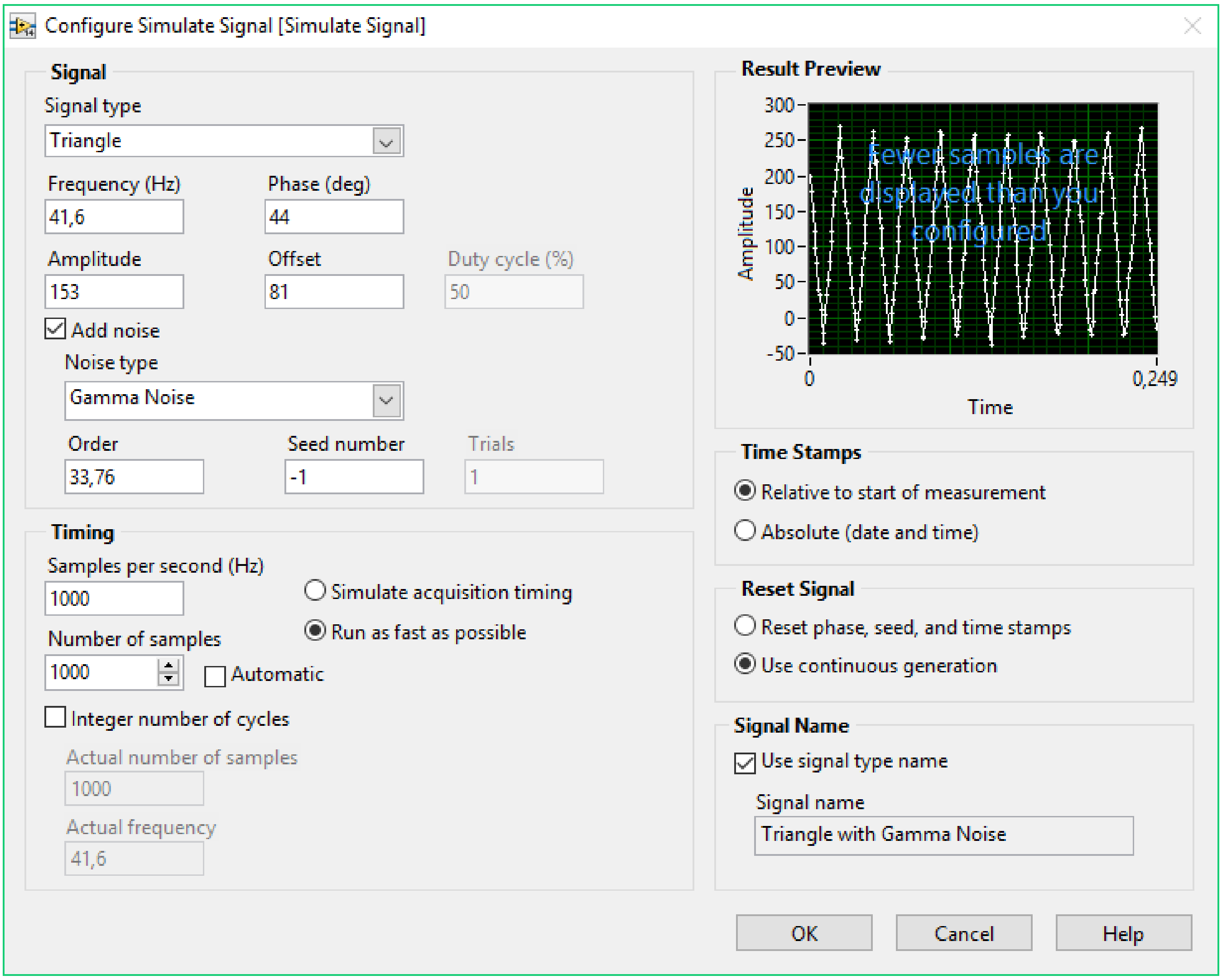


Fig. 4.7 – **Simulate Signal** unit options

When constructing these schemes, it is necessary that in the blocks that specify signals (**Triangle Waveform** and **Simulate Signal**) in addition to equally set parameters of the amplitude, phase, frequency and offset should coincide the values **sample info (Fs** and **#s)** with values **Samples per second (Hz)** and **Number of samples,** otherwise it will be the different signals (for this variant these values are equal to 1000).

To check the signals, we eliminate noise from the schemes and get the same signal parameters: A=306; max=234; min=-72; RMS=120,196; which indicates the correctness of the schemes. When noise is connected, the above-mentioned signal parameters fluctuate in a small range, the signal waveform looks asymmetric horizontally – the signal quality deteriorates. Further determination of the signal parameters is reduced to its instantaneous or approximately averaged values, only the period (inversed to frequency) T = 0,0227 s of the signal remains unchanged.

Next, you need to set the signal parameters in the element **Spectral Measurements** in accordance with the variant (Fig. 4.8).

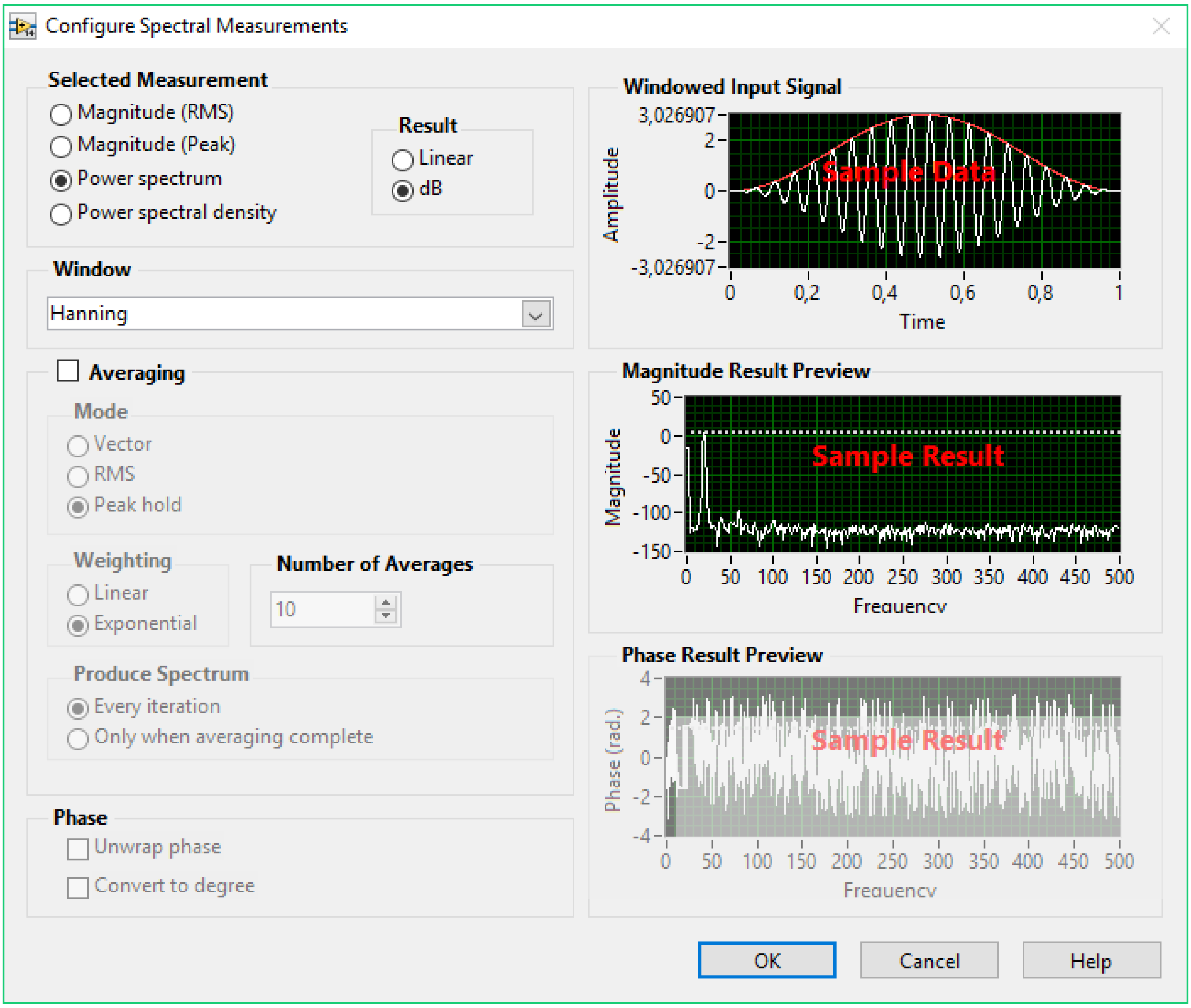
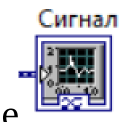


Fig. 4.8 – **Spectral Measurments** block parameters

Connect elements, configure blocks for correct operation and run the scheme. The calculation results are shown in Figures 4.9-4.15.

In order to display the distribution of the signal (Figures 4.9-4.11, top) in **Front Panel** you need to add from the elements library **Waveform Chart** 

.

As a result, **Waveform Graph** will be automatically added to **Block Diagram,** which must be connected directly to the signal source 

and renamed to "Signal".

In order to display the signal spectrum (Figures 4.9-4.11, bottom) in **Front Panel** you need to add from the elements library **Waveform Chart** 

. As a result, **Waveform Graph** will be automatically added to **Block Diagram,** which must be connected directly to **Spectral Measurements** 

and renamed to "Power Density Signal Spectrum".

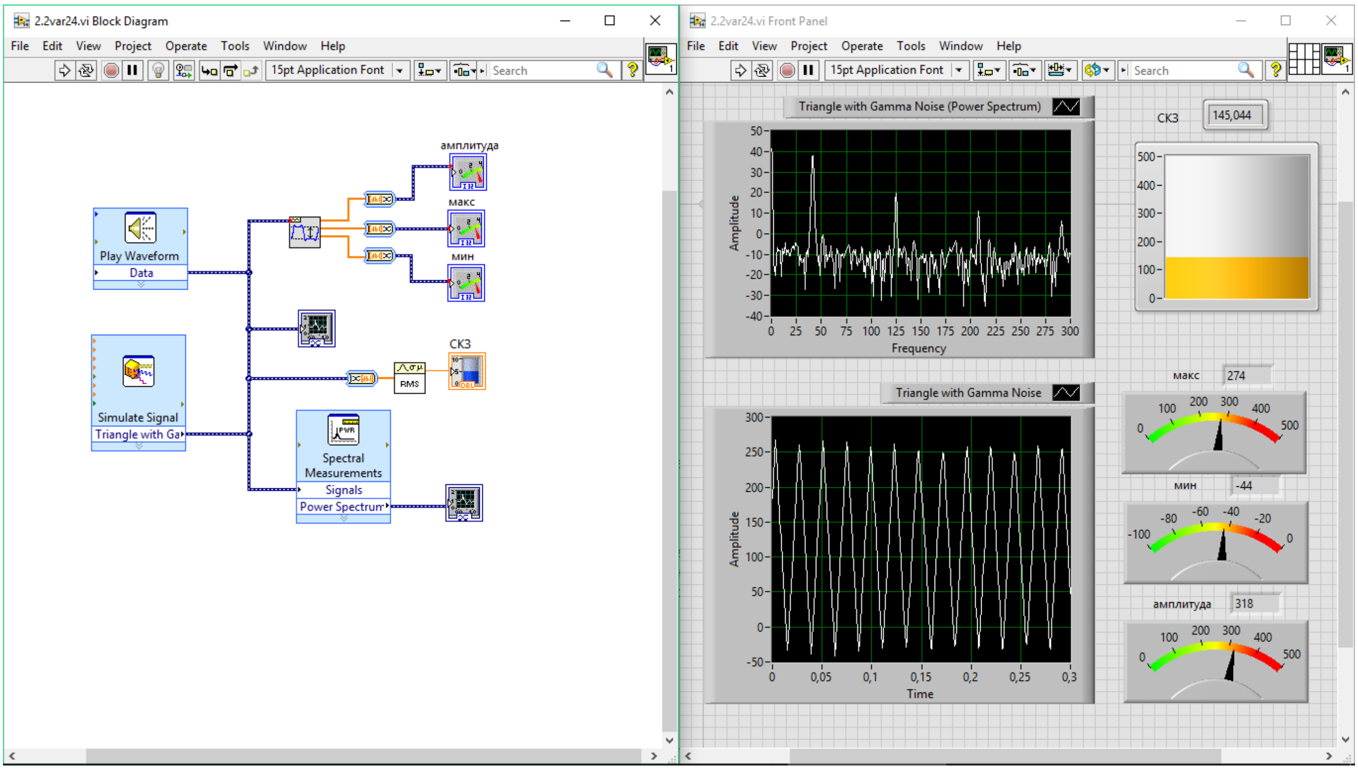


Fig. 4.9 – LabWiev working windows – **Block Diagram** and **Front Panel**

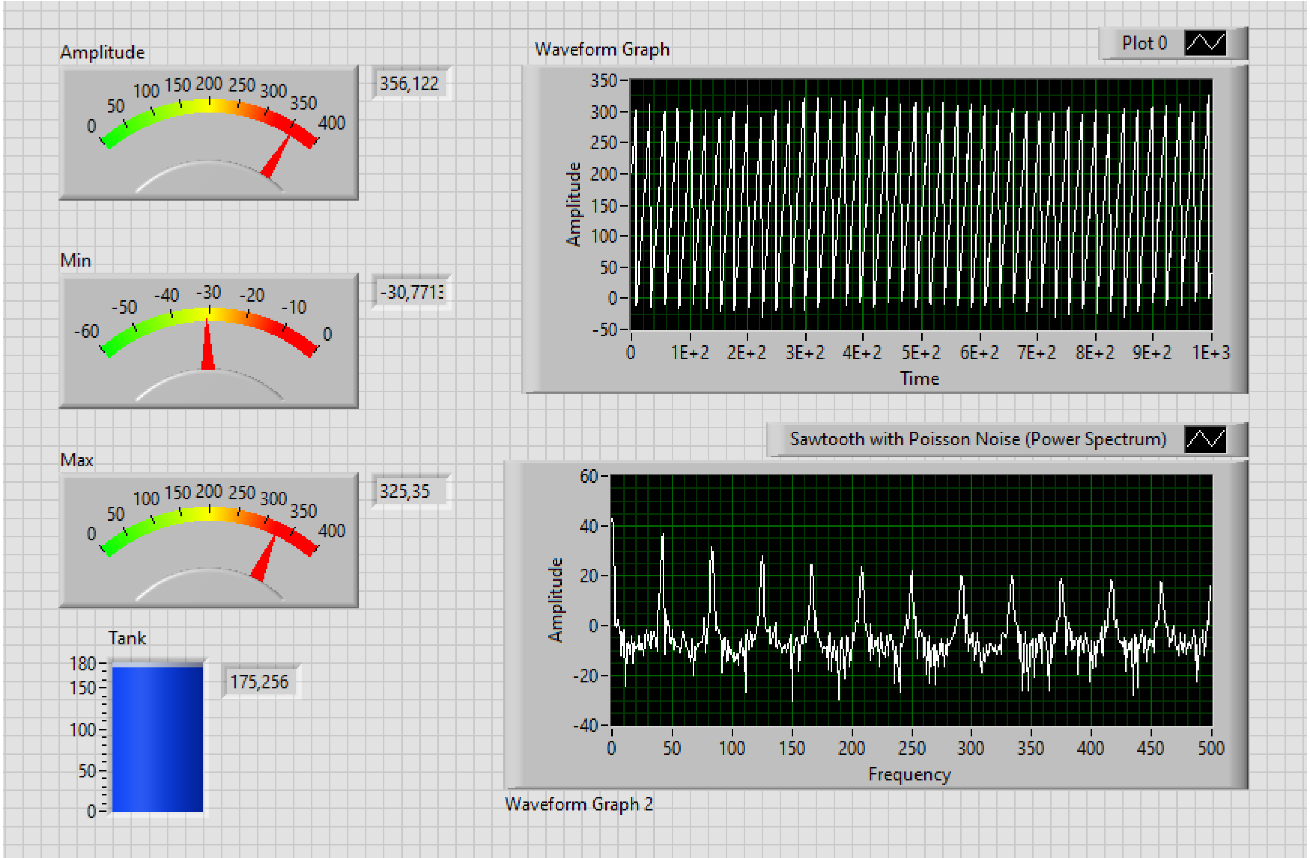


Fig. 4.10 – Working window in **Front Panel** with signal distribution and signal distribution spectrum.

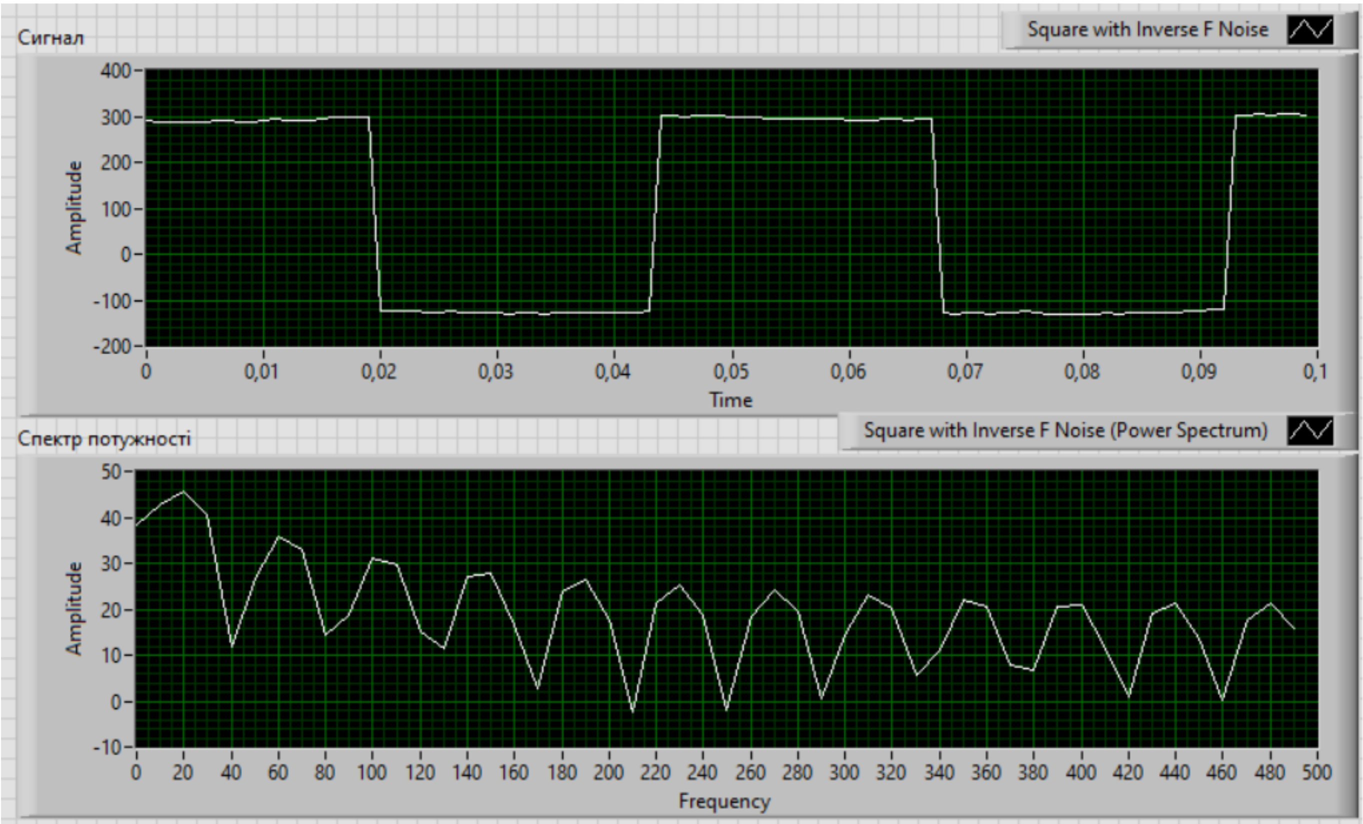


Fig. 4.11 – Signal distribution and signal spectrum with specified parameters in **Front Panel**

Next, in **Front Panel,** you need to display the signal parameters (Fig. 4.12), signal distribution (Fig. 4.13) and the signal distribution spectrum (Figures 4.14, 4.15) with the specified parameters in accordance with the task variant.

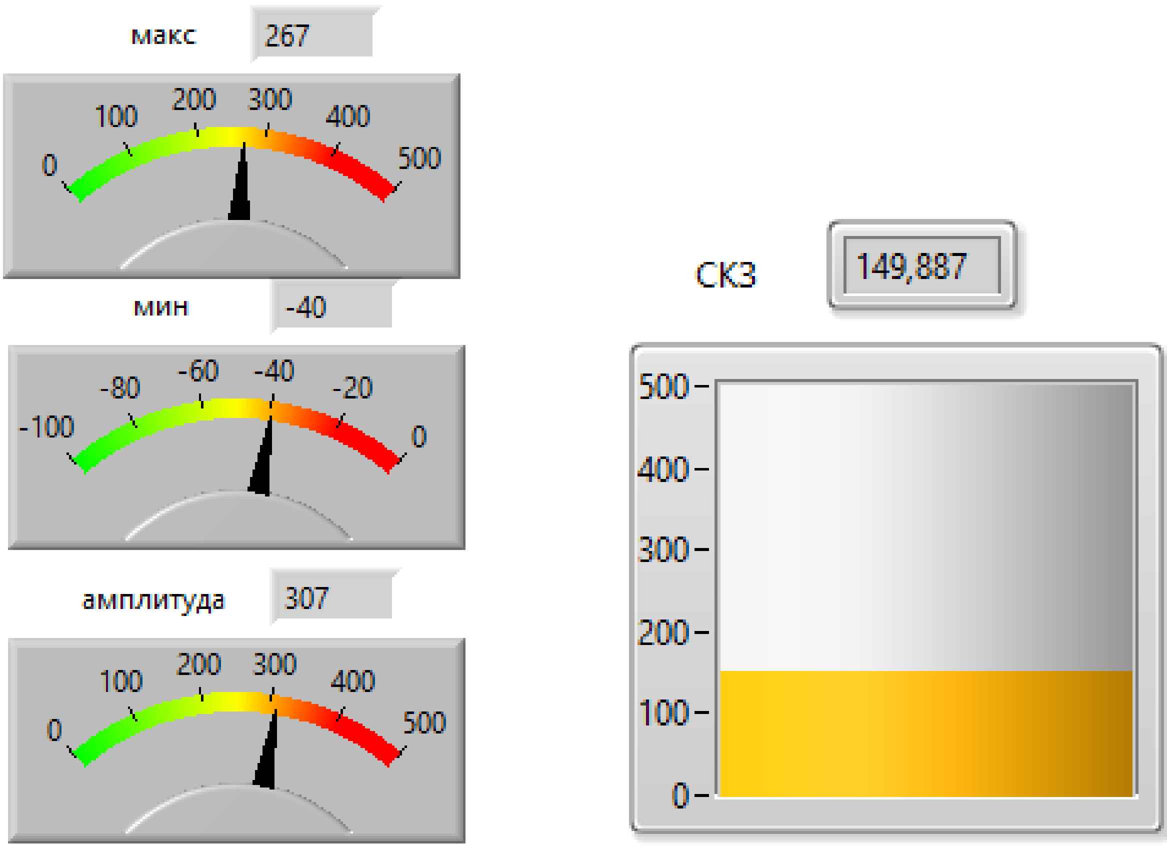


Fig. 4.12 – Signal settings in **Front Panel**

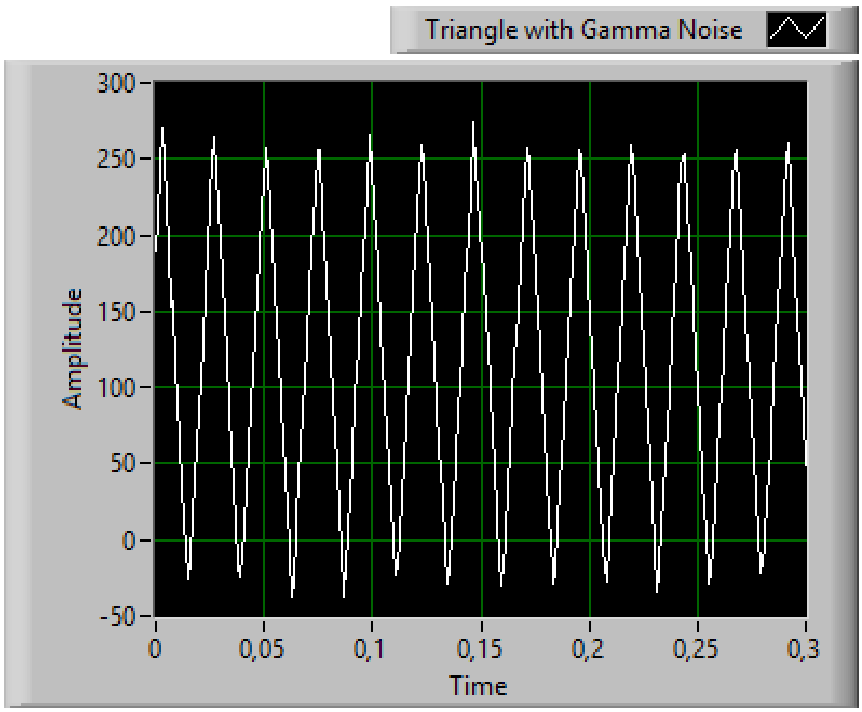


Fig. 4.13 – Signal distribution with the specified parameters in **Front Panel**

The construction of the power density spectrum without noises and with noises is shown on Figures 4.14, 4.15.

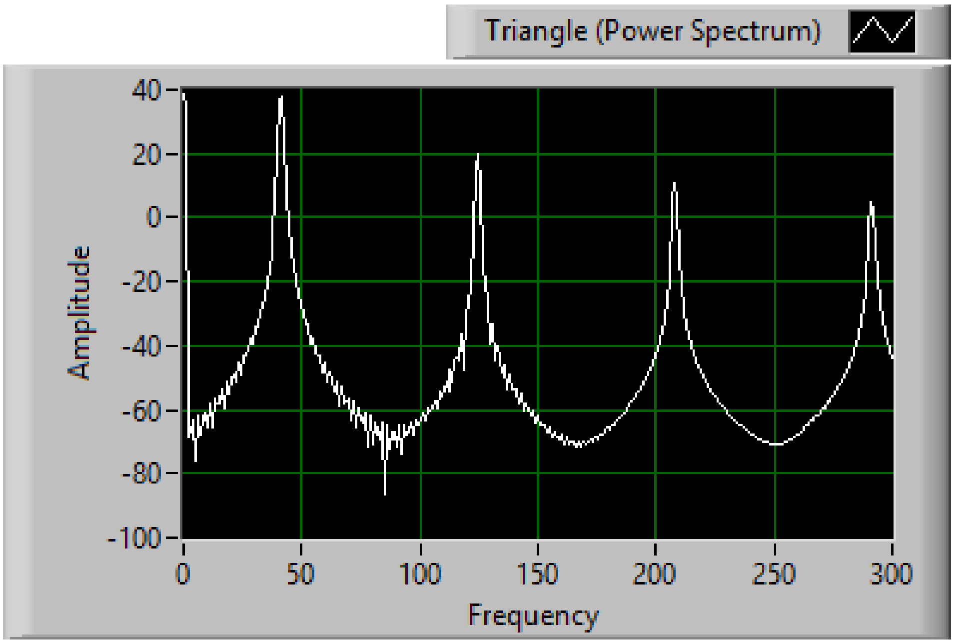


Fig. 4.14 – Construction of power density signal without noises

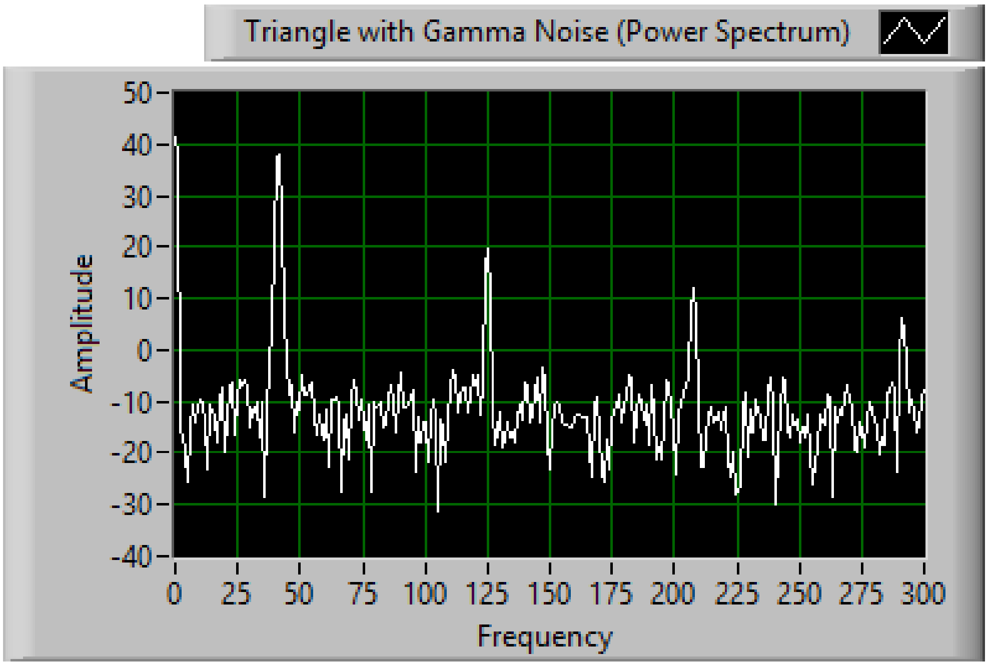


Fig. 4.15 – Construction of power density signal with noises

Copy image to protocol, save project.

To 9th item:

It is necessary to create a report about the implementation of a computer workshop in which to present:

1. title page of the protocol;
2. purpose of work, work program;
3. show options for the variant;
4. show the scheme in **Block Diagram** with signal parameters using **Simulate Signal** and **Spectral Measurements;**
5. show the scheme in **the Front Panel;**
6. show the specified signal parameters (amplitude, phase, frequency, etc.) in **Simulate Signal** and **Spectral Measurements;**
7. show the results of signal simulation with the specified parameters (sinusoidal, etc.);
8. show the results of processing this signal (determination of the root mean square value, determination of the peak signal factor, determination of the signal amplitude, determination of the Max-min value, etc.);
9. show numerical results of processing these signals in the **Front Panel;**
10. show the signal distribution with the specified parameters in **Front Panel;**
11. write meaningful conclusions about the work. Explain why you got such results;
12. send a recorded audible interpretation of the signal being studied using **Play Waveform**.

Computer workshop №5

Spectral processing of electromagnetic vibroperturbing forces signals in an induction motor: intact and in the presence of damages of rotor rods in programs Comsol Multiphysics and MatLab

(4 hours)

Work objective. Analyze changes in the signals spectra of the electromagnetic vibroperturbing forces in an induction motor with the rotor rods damage appearing in programs **MatLab** and **Comsol Multiphysics**.

Work program:

1. create a model of intact induction motor (IM) in the program **Comsol Multiphysics**;
2. simulate single variant of rotor rods damage in IM;
3. get schedules for the distribution of the magnetic tension tensor normal component along the surface of the IM's rotor (or line through the middle of the air gap) for intact IM and IM which has damaged rotor rods;
4. write formulas and calculate frequencies of harmonics for intact IM and IM which has damaged rotor rods;
5. obtain distributions and spectra of the magnetic tension tensor for intact IM and IM which has damaged rotor rods in the program **MatLab**;
6. create the distribution and spectrum of the difference sigal for the studied IM, which has damaged rotor rods;
7. numerically analyze the change in amplitudes of harmonics in the spectra of vibroperturbing forces for intact IM and IM which has damaged rotor rods;
8. compare the spectra of damaged IM: vibrational acceleration, vibrational velocity, vibrational displacement;
9. create a report on the implementation of a computer workshop. Protect your computer workshop.

Methodical instructions for the implementation of a computer workshop.

To 1st point:

Skills in the program **Comsol Multiphysics** were received by students in the discipline "Mathematical modeling of electromechanical energy converters".

In order to get acquainted with the working in this computer workshop, you must listen the information from the teacher about the computer workshop or watch the video [16].

To perform a computer workshop, you must use the following algorithm for constructing a model of the studied IM. The variants for the tasks are given in Table 5.1.

Also, the study of the signals of vibroperturbing forces can be carried out on the version of the IM model that was created in the computer workshop №6 of the discipline "Mathematical modeling of electromechanical energy converters" [8], or the student can choose the IM to be used in the diploma design, having previously agreed with the lecturer.

Abbreviated algorithm for constructing an induction motor model

1. Create the correct mathematical model of the induction motor:
   - draw a transverse section of the induction motor active part in the program **Autocad**;
   - import the induction motor geometry into the program **Comsol**;
   - set the parameters of the induction motor elements;
   - set time-dependent task parameters;
   - set parameters for outputting calculation results.
2. Calculate and visualize the electromagnetic field of a short-circuit induction motor.

Features of the simulation process:

1. Construction of the cross-section of the researched IM active zone is realized by drawing its elements: external and internal diameters of the stator and rotor, the slots of the stator and the rotor, the shaft.
2. The IM model must be centered so that the centers of the circles are located in the coordinates (0; 0) (Fig. 5.1). You can center it in Autocad or shift it in Comsol (which is inconvenient).
3. For further research in programs **Autocad** or **Comsol Multiphysics** (redefining the parameters of the model is necessary) it is necessary to create a circle passing through the middle of the air gap to calculate the spatial distribution of the magnetic tension tensor or magnetic induction.
4. It is necessary that all sections of the lines in the drawing are executed with maximum precision, since the gap between them leads to the impossibility of constructing a grid of finite elements in the program **Comsol Multiphysics**.
5. After constructing the model in **Autocad** the file must be saved in the *.dxf extension. Files with this extension are intended to be integrated into other software products.
6. Choose a single-layer winding.
7. The student selects the geometric sizes of stator and rotor slots independently.
8. The stator winding material must be set as air. This is due to the fact that the winding of the stator is made of a large set of conductors, and not from the massive volume of copper. Therefore, an alternating magnetic field does not induce vortex currents in the winding.
9. The material of the rotor windings is copper.
10. There is no need to set the current density in the winding of the rotor. The current density in the rotor winding is created as a result of the induction of the EMF.

11. Calculation of the mathematical model is carried out for the nominal load regime.
12. Grooves in the IM stator should be open or semi-open. However, in the IM should be drawn 3 lines passing: on the surface of the stator, on the surface of the rotor, in the middle of the air gap. These lines will determine the distributions of magnetic tension tenor and magnetic induction.
13. When assigning the grooves of the stator belonging to a particular phase zone, you should pay attention to the number of grooves that are assigned to it. It must be equal to q, which will manifest itself in the correct correspondence of the distribution of the magnetic field in the IM of its pole quantity.
14. Criteria for the correctness of worksop implementation in **Comsol**:
    a. Induction - adequate values (as in all electric machines: B_δ=0,8 T, B_z=2,3 T);
    b. The width of the teeth of the stator and the rotor must be approximately the same.

Features of the construction of vibration sensors signals based on the results of vibroperturbing forces calculations in the induction motor.

Tensor of magnetic tension is the superficial strength of force, that is, the force acting on the rotor of the IM and is applied to the unit of the surface of the rotor.

The signal of the vibration sensor in mathematical modeling can be obtained in two ways:

1) Placing the vibration sensor at the point of the sensor conditional arrangement on the surface of the stator's tooth and conduct a simulation of the IM with the rotor, which will make one rotation for 100-400 points (calculations). In this case, the rotor's rods will pass through the point of the sensor conditional arrangement and a signal will be formed in the sensor, which according to certain assumptions will correspond with the high accuracy to the vibration sensor signal. Such a simulation process is very costly both in terms of calculation time and in the calculated capabilities of computers.

2) A simpler but less precise way is the following. It is assumed that according to the definition of a traveling wave, with a certain accuracy, the spatial distribution of the magnetic tension tensor (vibroperturbing forces), calculated on the surface of the stator, is similar to the vibration sensor signal located at the point of the sensor conditional arrangement, since, in rotation of the rotor, the spatial distribution of the magnetic tension tensor will pass the conditional location of the vibration sensor and repeat the same vibroperturbing forces. Such a simulation process is much less costly both in terms of calculation time and in the calculated capabilities of computers.

Table 5.1 – Variants for a computer workshop №5.

Variant	m	p	Z1	q	Z2	D1_ext	D1_int	3*	δ, mm	D2_ext	5*	k_arm	D_shft	J 1, ×10⁶ A/m²	μ Fe
1	3	1	54	9	33	260	119,6	156,0	2	115,6	69	0,6	28	4,00	800
2	3	1	18	3	51	230	105,8	149,5	0,8	104,2	68	0,65	27	4,15	900
3	3	1	24	4	15	200	92,0	140,0	1	90,0	63	0,7	25	4,30	1000
4	3	1	30	5	21	500	230,0	375,0	1,2	227,6	171	0,75	68	4,45	1100
5	3	2	36	3	28	470	216,2	376,0	1,5	213,2	171	0,8	68	4,60	1200
6	3	2	24	2	33	440	202,4	264,0	1,7	199,0	119	0,6	48	4,75	1300
7	3	2	36	3	23	410	188,6	266,5	2	184,6	120	0,65	48	4,90	1400
8	3	4	48	2	34	380	174,8	266,0	0,8	173,2	121	0,7	48	5,05	1500
9	3	3	36	2	46	350	161,0	262,5	1	159,0	119	0,75	48	5,20	1600
10	3	1	54	9	35	320	147,2	256,0	1,2	144,8	116	0,8	46	5,35	800
11	3	1	18	3	51	290	133,4	174,0	1,5	130,4	78	0,6	31	5,50	900
12	3	1	24	4	16	260	119,6	169,0	1,7	116,2	76	0,65	30	5,65	1000
13	3	1	30	5	21	230	105,8	161,0	2	101,8	71	0,7	29	5,80	1100
14	3	3	18	1	27	200	92,0	150,0	0,8	90,4	68	0,75	27	5,95	1200
15	3	2	24	2	15	500	230,0	400,0	1	228,0	182	0,8	73	6,10	1300
16	3	5	30	1	23	470	216,2	282,0	1,2	213,8	128	0,6	51	6,25	1400
17	3	3	36	2	29	440	202,4	286,0	1,5	199,4	130	0,65	52	6,40	1500
18	3	4	24	1	33	410	188,6	287,0	1,7	185,2	130	0,7	52	6,55	1600
19	3	1	36	6	22	380	174,8	285,0	2	170,8	128	0,75	51	4,00	800
20	3	1	48	8	33	350	161,0	280,0	0,8	159,4	128	0,8	51	4,15	900
21	3	1	36	6	47	320	147,2	192,0	1	145,2	87	0,6	35	4,30	1000
22	3	1	54	9	34	290	133,4	188,5	1,2	131,0	85	0,65	34	4,45	1100
23	3	3	18	1	53	500	230,0	350,0	1,5	227,0	159	0,7	64	4,60	1200
24	3	2	24	2	15	470	216,2	352,5	1,7	212,8	160	0,75	64	4,75	1300
25	3	5	30	1	22	440	202,4	352,0	2	198,4	159	0,8	63	4,90	1400
26	3	3	36	2	27	410	188,6	246,0	0,8	187,0	112	0,6	45	5,05	1500
27	3	4	24	1	33	380	174,8	247,0	1	172,8	112	0,65	45	5,20	1600
28	3	1	36	6	23	350	161,0	245,0	1,2	158,6	111	0,7	44	5,35	800
29	3	1	48	8	34	320	147,2	240,0	1,5	144,2	108	0,75	43	5,50	900
30	3	1	36	6	45	290	133,4	232,0	1,7	130,0	104	0,8	42	5,20	1600

Marking:	
	m - number of phases; p - number of pairs of poles; Z1- number of stator slots; q - the number of slots per pole and phase; J1 - current density in stator winding; μ - stator magnetic flux permeability. **Dimensions in Table 4 are in mm.**
	D1_arm_int = k_arm*D1_ext
	D2_arm_ext = k_arm*D2_ext
1*	External diameter of the stator magnetic core(D1_ext);
2*	Internal diameter of stator cutting (D1_int);
3*	The diameter defining the depth of the stator slots (**D1_arm_int**);
4*	Extenal rotor diameter (D2_ext);
5*	The diameter defining the depth of the rotor slots (**D2_arm_ext**);
6*	Thickness of the air gap δ, mm;
7*	Diameter of the rotor shaft (D_shft);

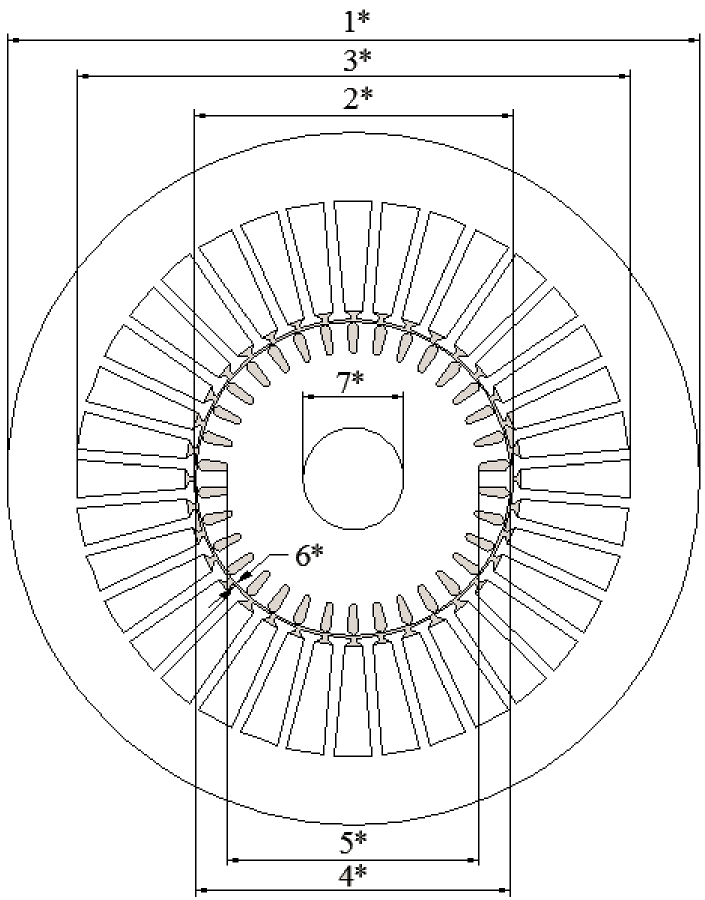


Fig. 5.1 – Sketch of induction motor

Table 5.1 (continuation)

Variant	The number of IM's damaged winding rods	Rotor winding material	slip, s, %
1	2	Al	3,2
2	3	Cu	3,5
3	4	Fe	3,8
4	5	Au	4,1
5	2	Pt	4,4
6	3	Ti	4,7
7	4	bronze	5
8	5	brass	5,3
9	2	W	5,6
10	3	Ag	5,9
11	4	Ni	6,2
12	5	Al	3,2
13	2	Cu	3,5
14	3	Fe	3,8
15	4	Au	4,1
16	5	Pt	4,4
17	2	Ti	4,7
18	3	bronze	5
19	4	brass	5,3
20	5	W	5,6
21	2	Ag	5,9
22	3	Ni	6,2
23	4	Al	3,2
24	5	Cu	3,5
25	2	Fe	3,8
26	3	Au	4,1
27	4	Pt	4,4
28	5	Ti	4,7
29	2	bronze	5
30	3	brass	5,3

Extended algorithm for constructing an induction motor model:

1. Construction begins with the choice of 2D geometry (do not choose axisymmetric):

Open **Comsol Multiphysics** (create new *.mph file)

File→New→Model Wizard 

→2D 

2. Choose physics **Magnetic fields (mf)** in the tab AC/DC, add (**add**) choosed physics and push **Done.**

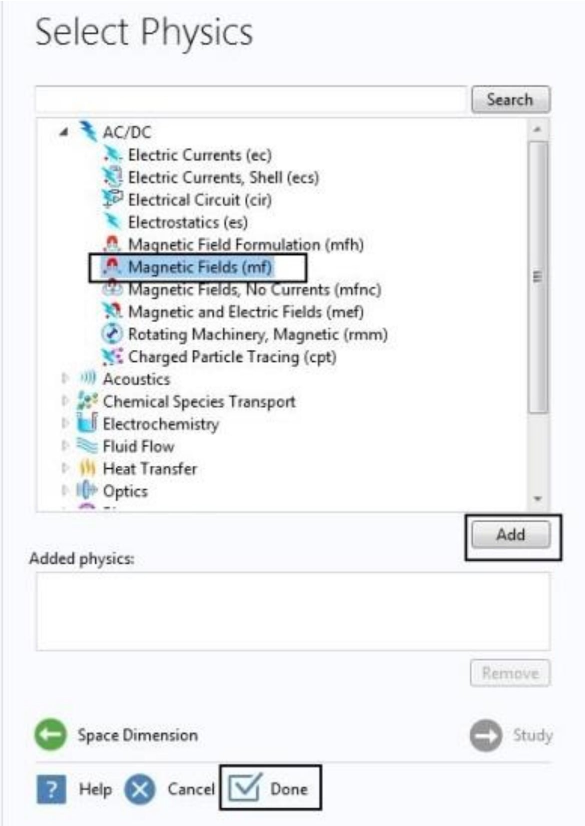


Fig. 5.2 – The choice of mathematical model physics

3. For the further convenient model creation in the **Comsol** program, you should place the center of the shaft in the center of the coordinates in the **Autocad** model. It is also necessary to set the meter unit in the settings. And to build a given version of the drawing in meters.

After this – save the file in *.dxf

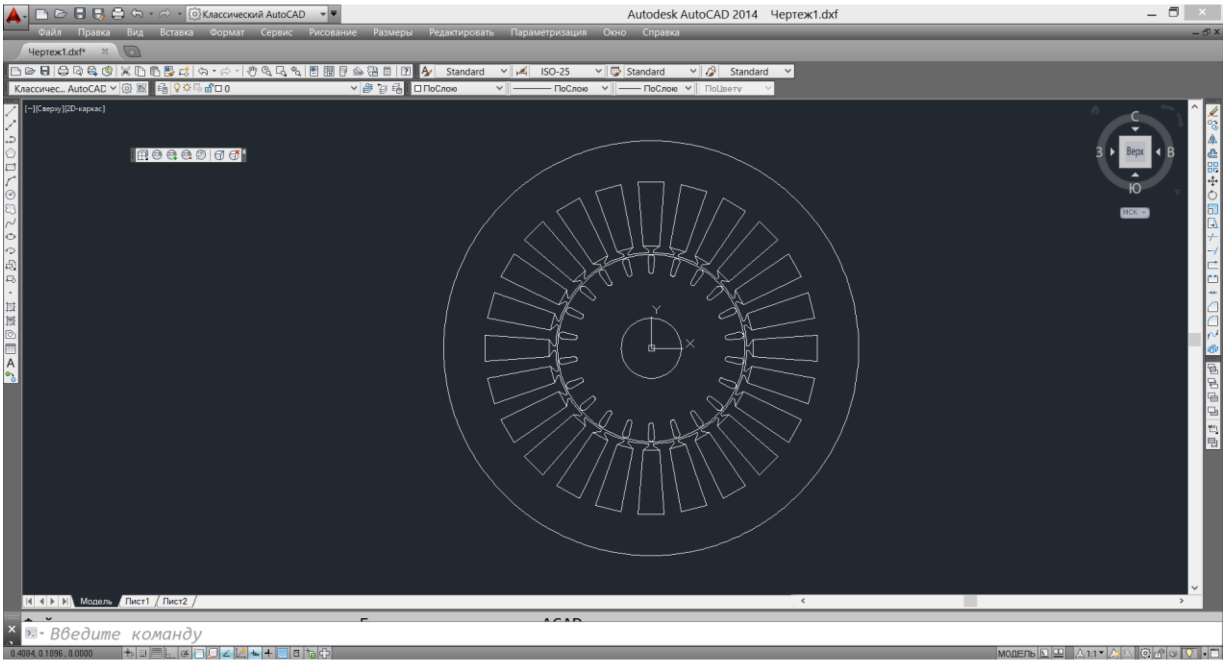


Fig. 5.3 – Drawings of IM in the program **Autocad**

4. In the tab **Model Builder** right mouse button select **Global Definition** and add **Variables.**

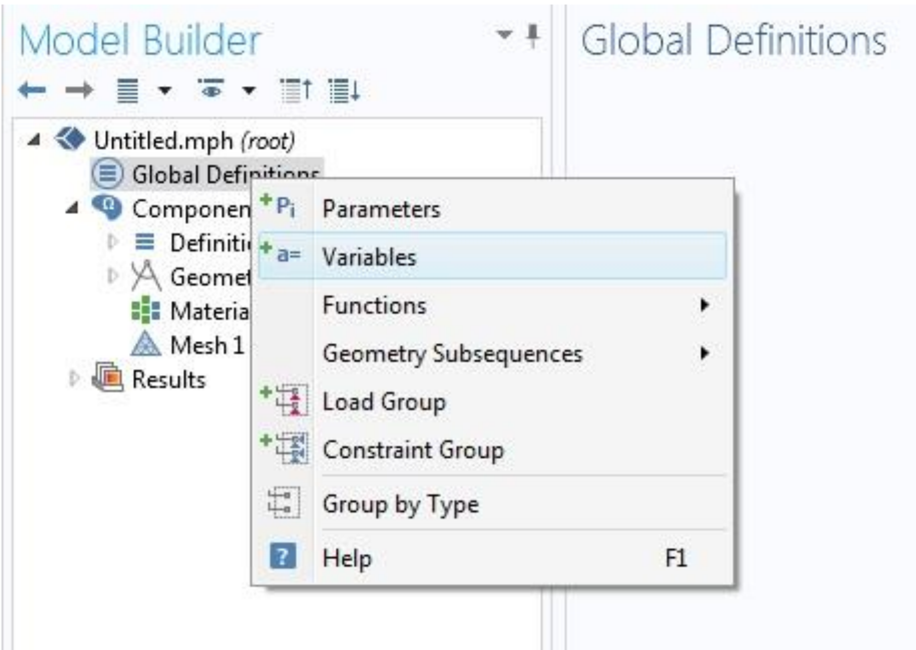


Fig. 5.4 – Addition **Variables** in the tab **Model Builder**

5. To create a rotating three-phase current system, you need to add the following variables:

Name	Expression	Unit	Description
Ja	J1*cos(w*t)	A/m^2	
Jb	J1*cos(w*t+2*pi/3)	A/m^2	
Jc	J1*cos(w*t-2*pi/3)	A/m^2	
J1	6e6[A/m^2]	A/m^2	
t	1[s]	s	
f	50[Hz]	Hz	
w	2*pi*f*skovz	1/s	
skovz	0.045		

Fig. 5.5 – Setting currents in the tab **Variables**

6. In the tab **Geometry1** add **Import:**

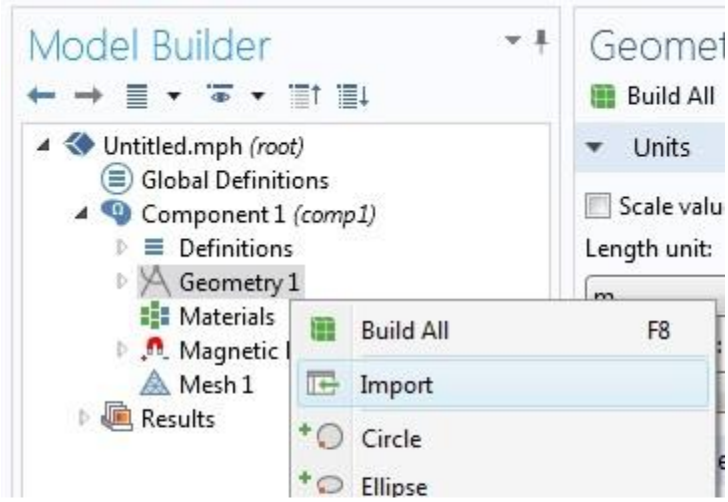


Fig. 5.6 – Addition the tab **Import**

7. Open a file created earlier in the CAD program:

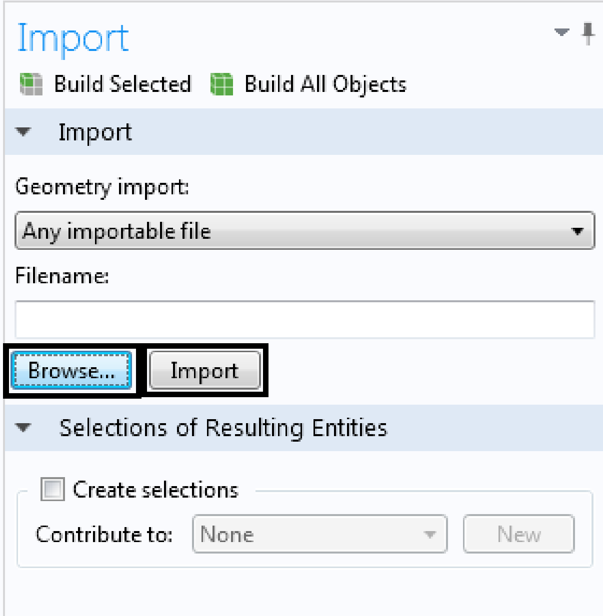
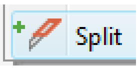


Fig. 5.7 – Import the geometry from the file

And import it by clicking the button **Import**

8. Split drawings into individual elements using the added tab

Geometry1→Conversions → 

And activate the button **ON** 

in tab **Split**

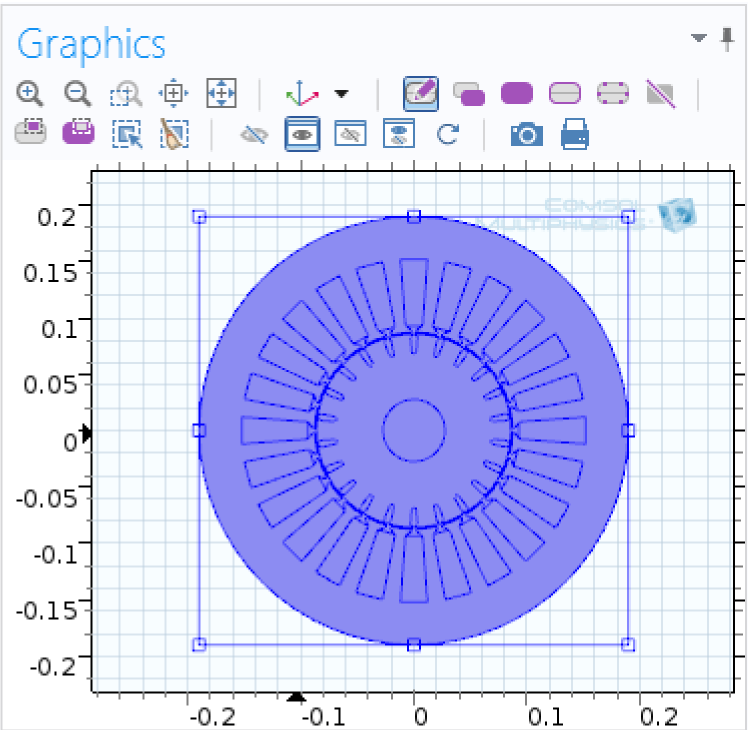


Fig. 5.8 – Imported geometry from file

Then click on the drawing layout in the **Graphics** field to add it to the **Input** tab.

Left-click on the **Geometry1** tab and click on the Geometry - **Build All** (or F8)

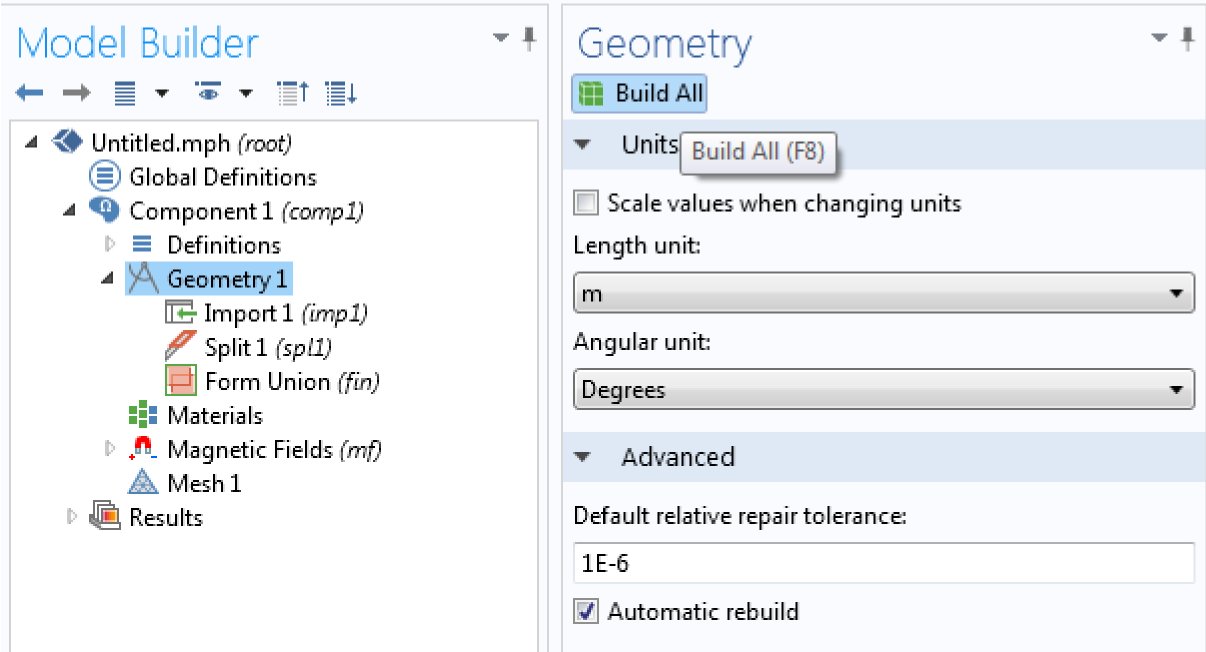
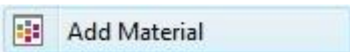


Fig. 5.9 – Build all items in the tab **Geometry1**

6. Using **Materials library** in the **Materials** tab add materials: air, iron and copper for rotor windings. Copper in the stator windings is not necessary, because in this task windings serve as sources of the field and in them do not research eddy currents.

To do this in the tab 

choose 

And in a new window add (**Add to Component 1**) **Soft iron (without losses)** and **Air**:

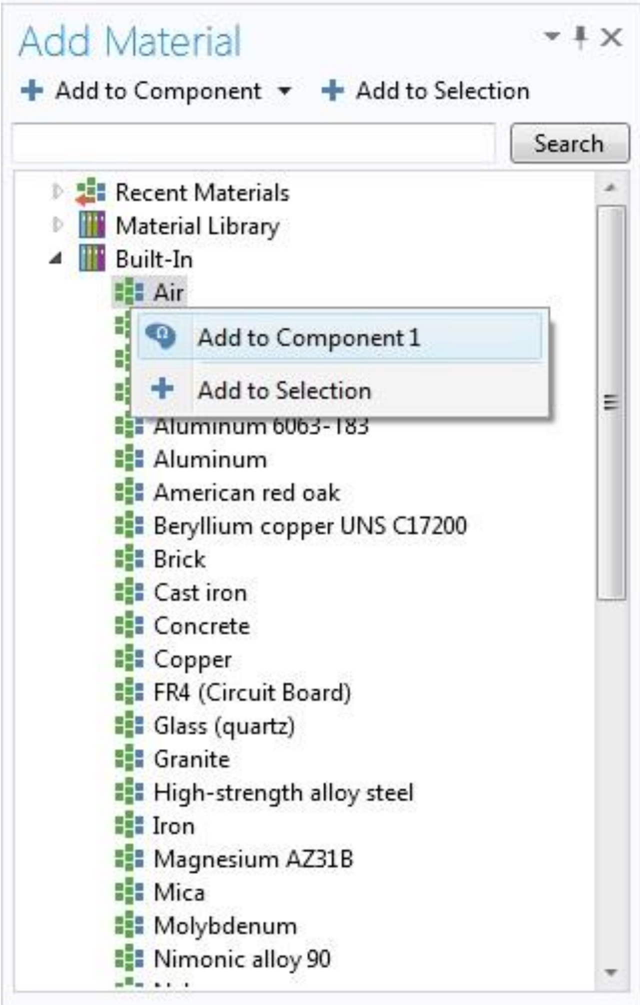


Fig. 5.10 – Add materials from the library of materials

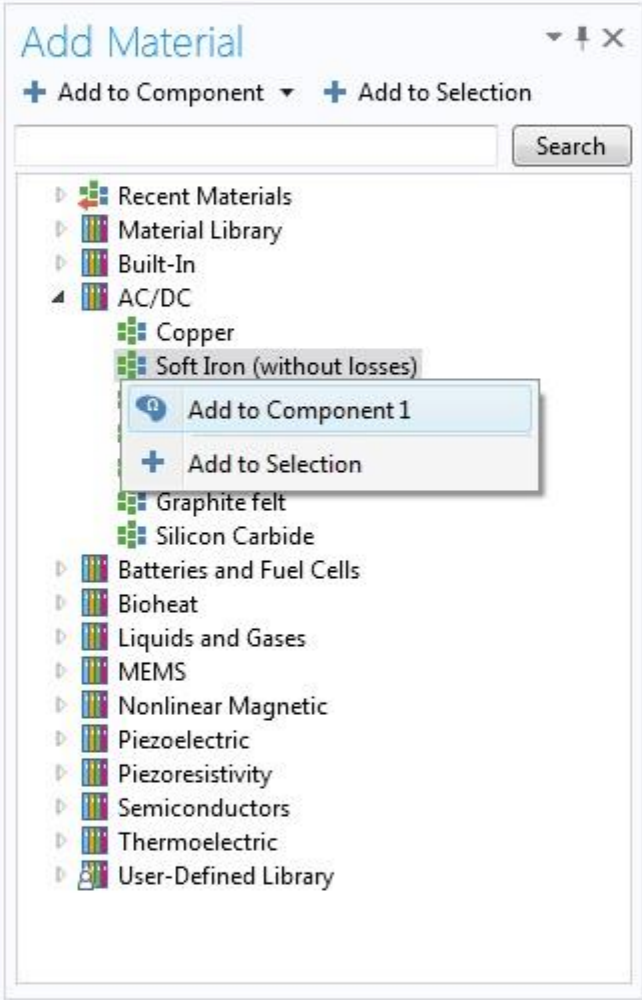
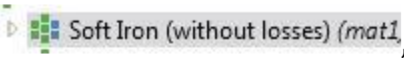


Fig. 5.11 – Add materials from the library of materials

7. Specify the magnetic permeability of iron, μ=1000, clicked on

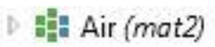
Materials→ 

, and choose in the tab **Material** appropriate parameter

Property	Name	Value
Relative permeability	mur	1000

Fig. 5.12 – Specifying the material's permeability μ

After that, in the Graphics window, select the blocks corresponding to the induction motor's magnetic core.

Click on the tab 

, select blocks corresponding to the area with magnetic permeability of air (including winding):

8. Set the three-phase system of currents.

To do this, in the **Model Builder** window, select **External Current Density**

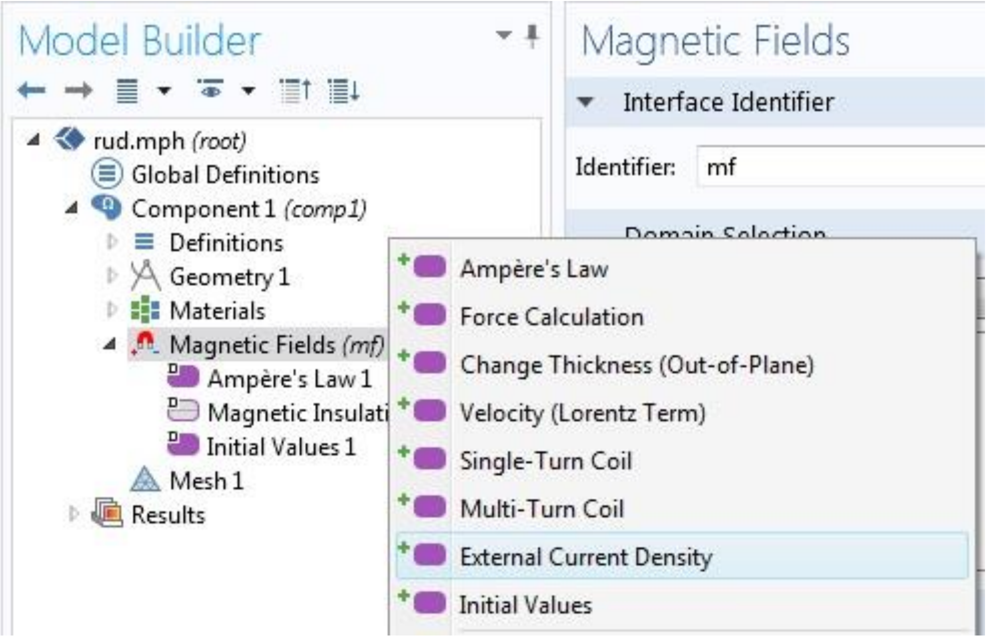


Fig. 5.13 – Setting external sources of current densities

And create a parameter for windings of each phase **External Current Density** (6 pcs.), by selecting the appropriate area in the window **Graphics**.

Select the desired surface and prescribe the density of the currents along the Z axis, and watch the sign, as for phase A it is taken with a plus sign, and for X, we choose the same current density for phase A, but with a minus.

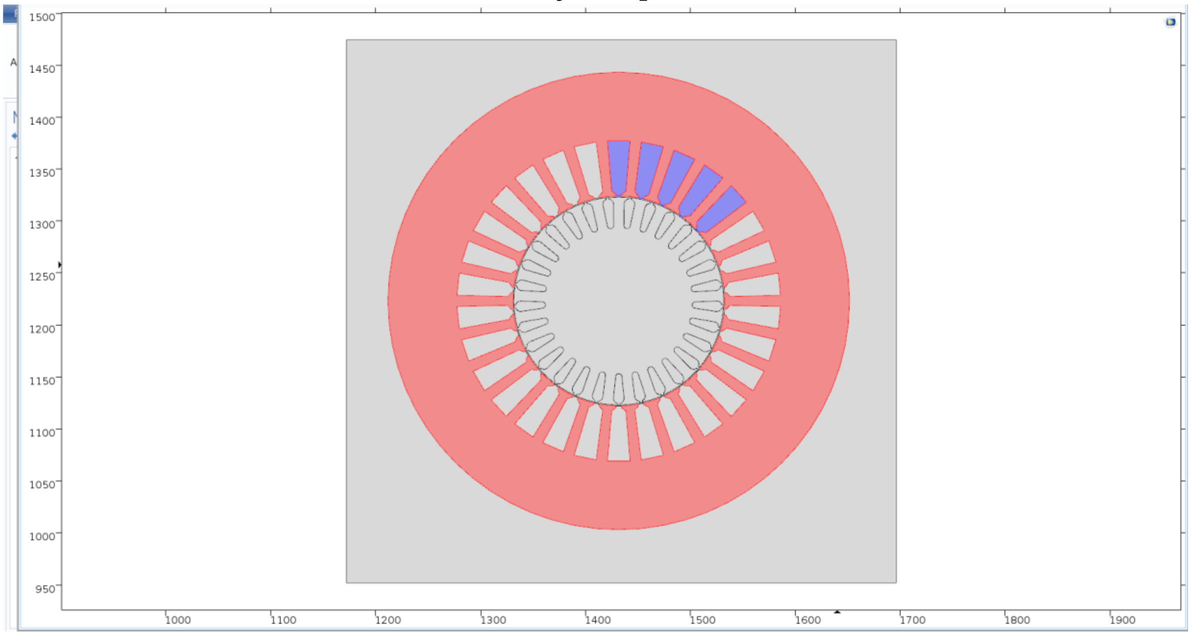


Fig. 5.14 – Setting external sources of current densities

in the phase zones of the stator winding

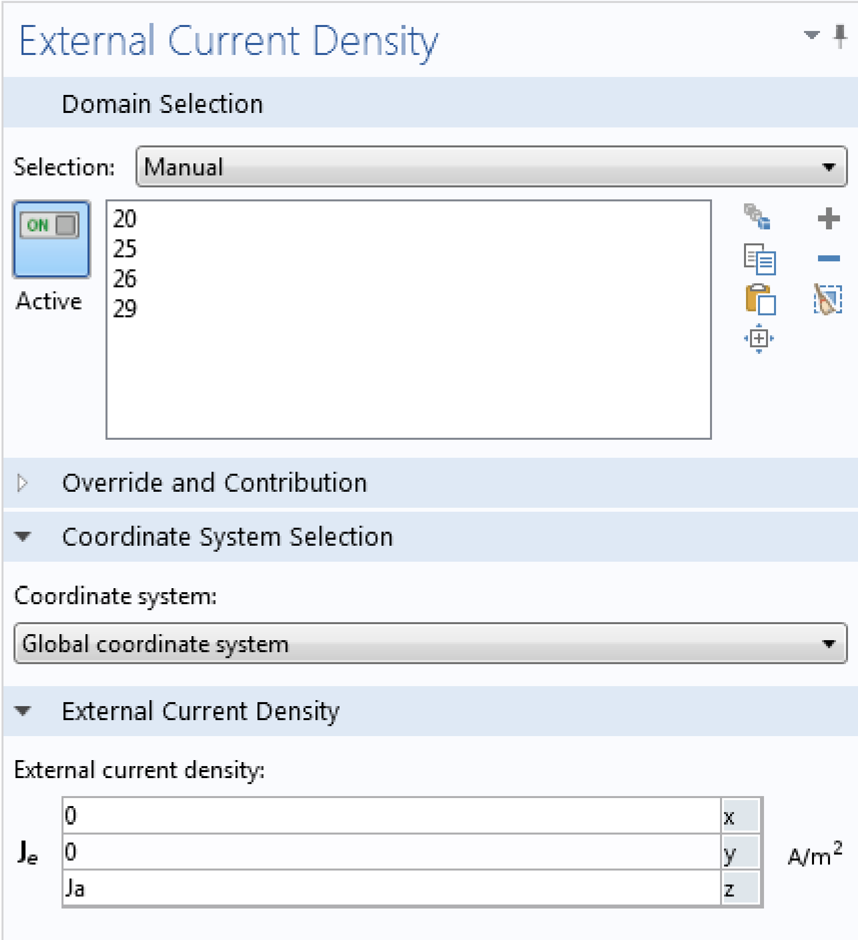


Fig. 5.15 – Setting external sources of current densities

in the phase zones of the stator winding

9. Specify the material of rotor windings - according to the variant (table 5.1 (continued)) (hereinafter, as an example – **Copper**)

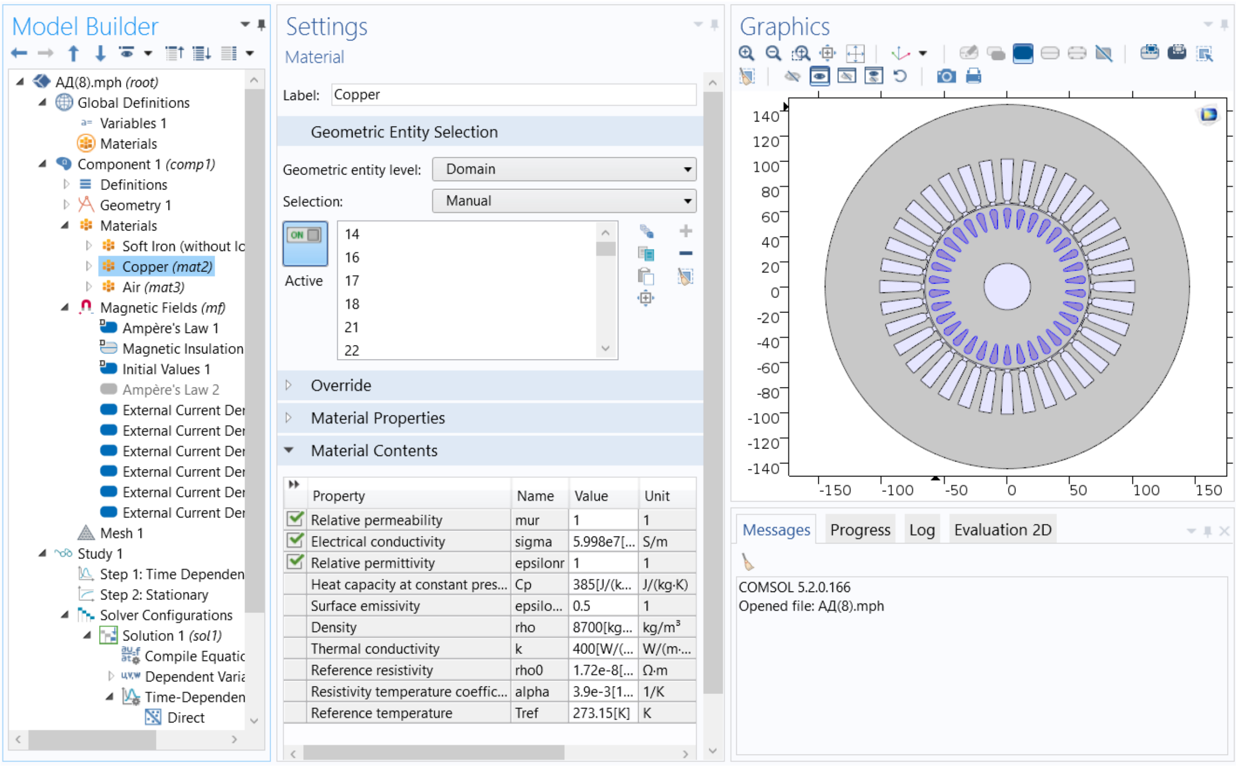


Fig 5.16 – Specify the material of rotor windings - Copper

10. **To take into account the saturation effect in the magnetic conductor, you must:**

In the **Magnetic Fields (mf)** tab duplicate existing **Ampere's Law** tab or add a new **Ampere's Law** tab and rename it **Ampere's Law Iron:**

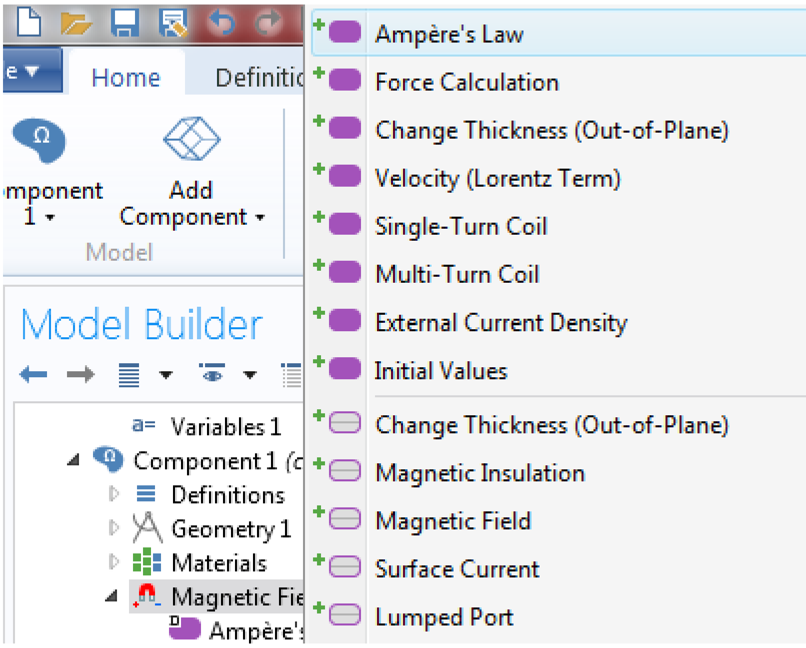


Fig. 5.17 – Adding **Ampere's Law** physical properties tab

11. By clicking on **Ampere's Law** tab, select the magnetic conductor (iron):

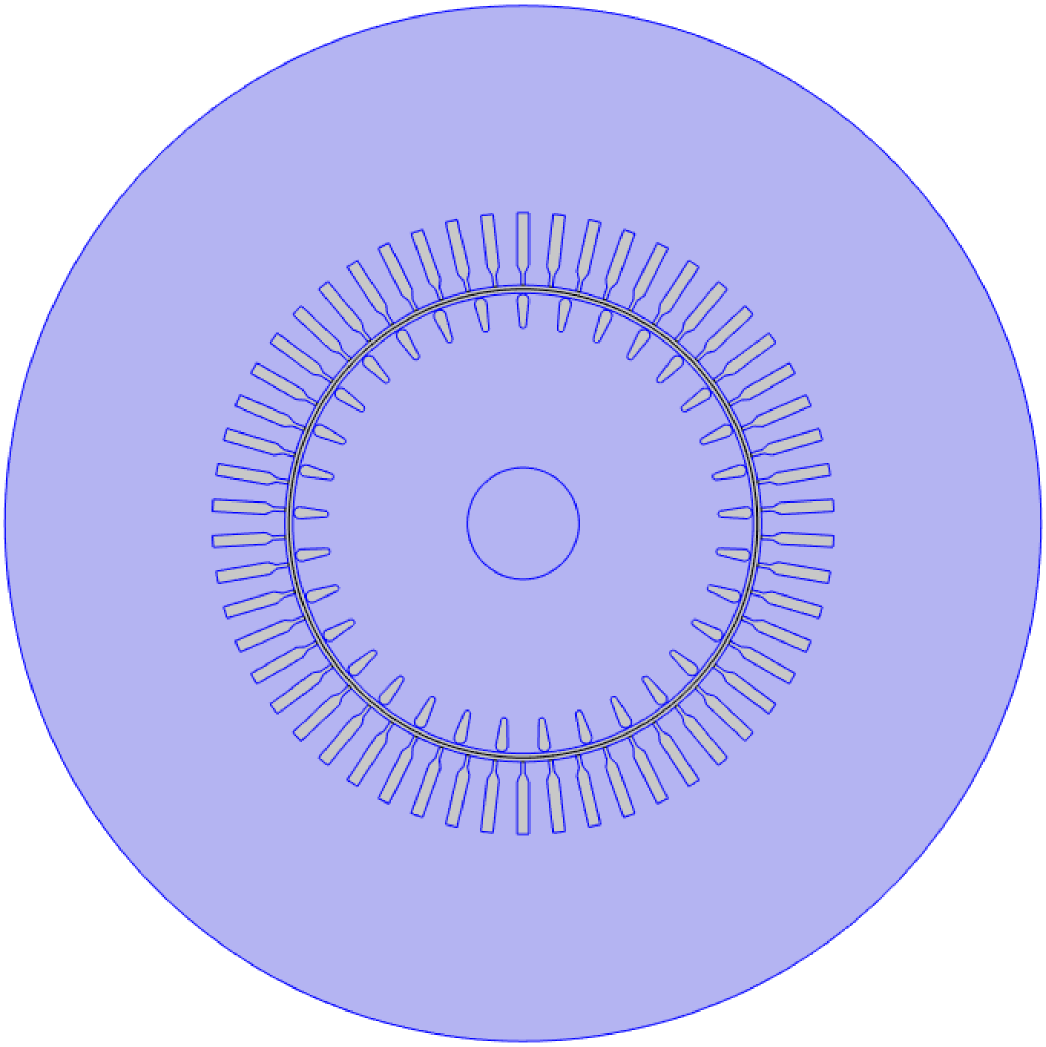


Fig. 5.18 – Iron selecting to adding physical properties to **Ampere'sLaw**

12. Change at the bottom of this **Ampere's Law** in **Magnetic Field** window to **HB curve:**

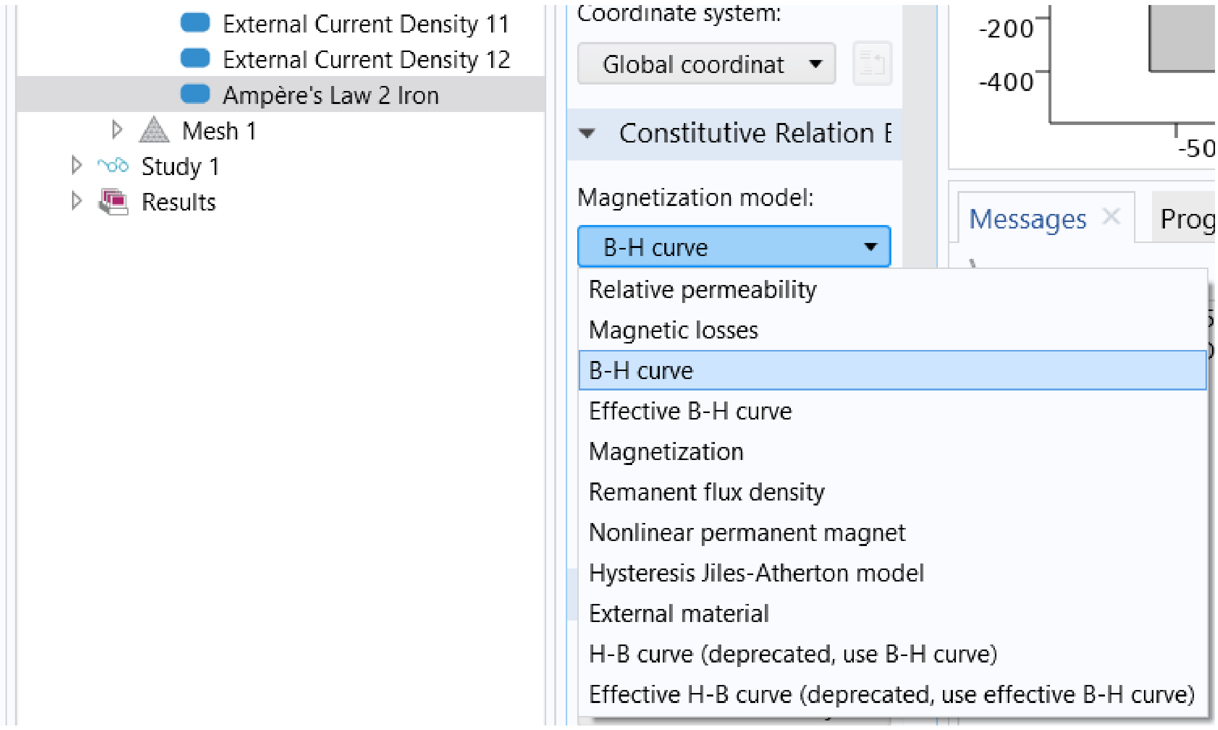


Fig. 5.19 – Change settings in **Ampere's Law tab**

Also in the **Study** you need to set the following parameters in **Fully Coupled:**

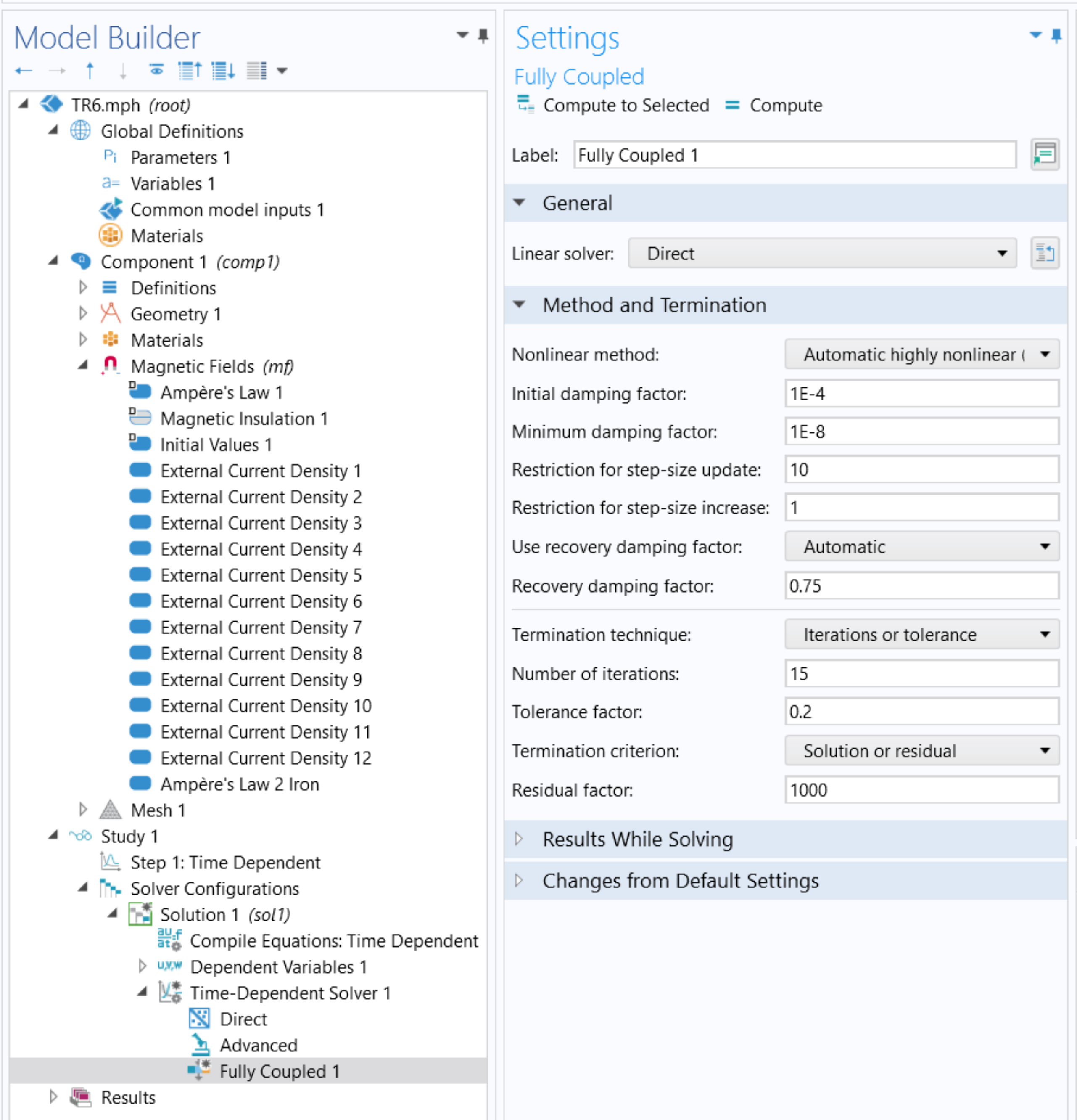


Fig. 5.20 – Changing parameters in **Study** in **Fully Cupled**

The number of iterations must be set at least 15-25.

13. Add **Free Triangular** in the tab **Mesh**:

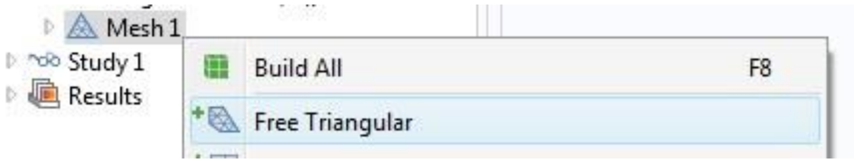


Fig. 5.21 – Add grid parameters **Free Triangular** in the tab **Mesh**

And set the following mesh parameters in **Size**:

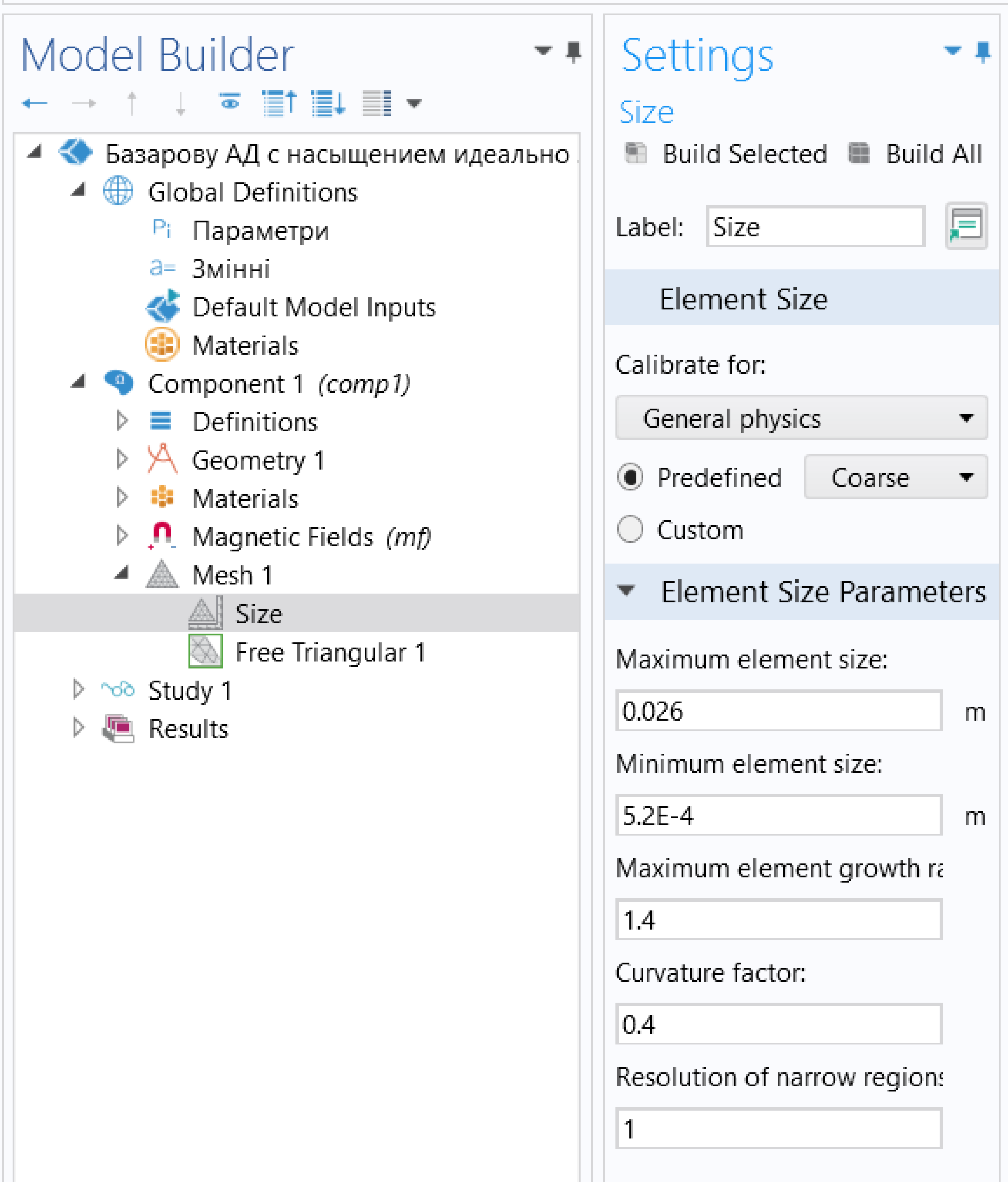


Fig. 5.22 – Mesh settings in **Size**

Mesh quality can be adjusted within any limits, although it is recommended – from **Coarser** to **Finer**.

14. Add parameters **Time Dependent** in the tab **Study1**, having previously added **Study1** on the toolbar:

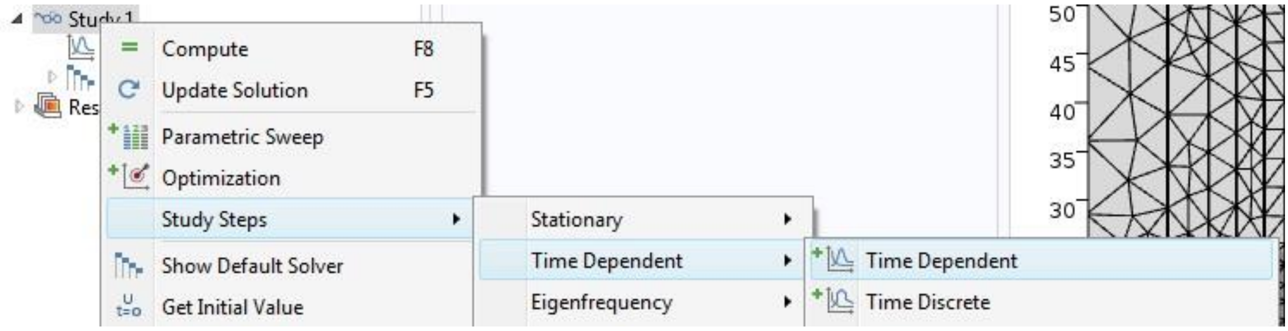


Fig. 5.23 – Adding task **Time Dependent** in the tab **Study1**

Also - set the required parameters for Time Dependent in the corresponding window.

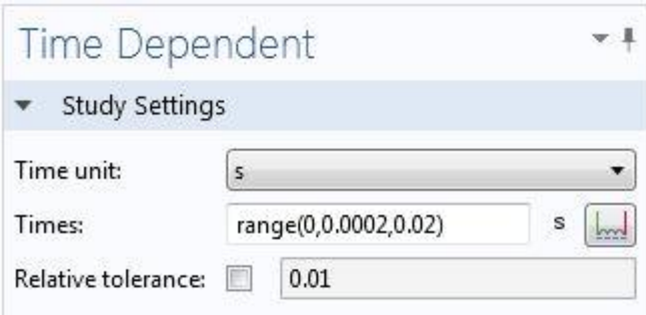


Fig. 5.24 – Setting options **Time Dependent** in the tab **Study1**

15. In the toolbar, calculate the process by choosing «**Compute**» 

16. After the calculations in the window **Model Builder** add **Contour1**, by right clicking on the mouse **Magnetic flux density**:

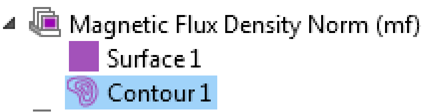


Fig. 5.25 – Adding the tab **Contour1** in the tab **Magnetic flux density**

Write in the **Surface** tab to reproduce the magnetic streams:

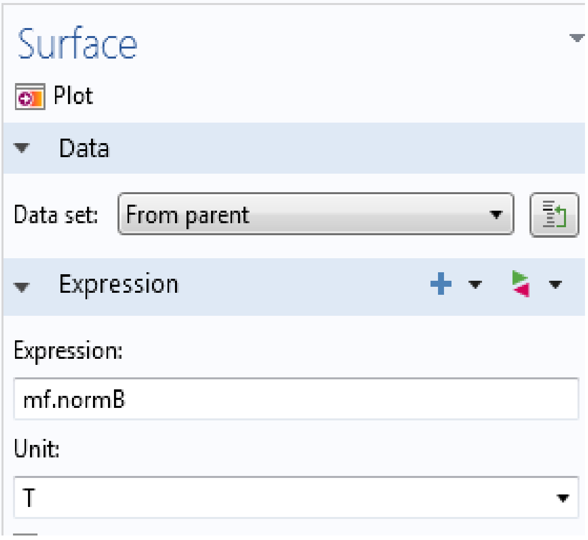


Fig. 5.26 – Setting the options in the tab **Surface**

And in the tab **Contour** write:

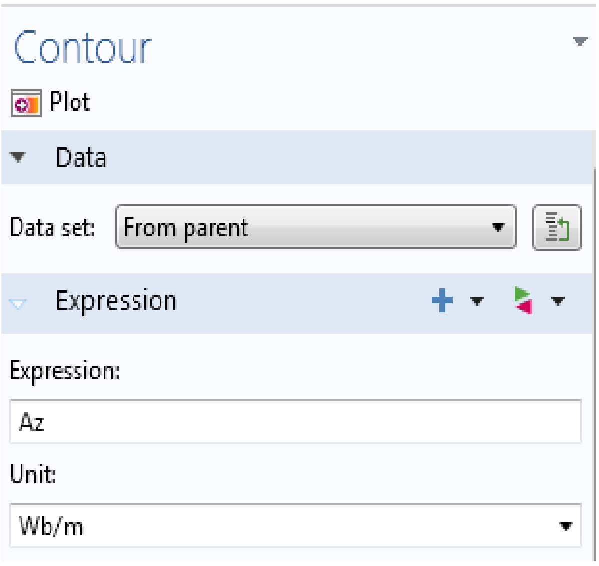


Fig. 5.27 – Setting the options in the tab **Contour**

To output results, add the necessary parameters, as shown in the example and click **Plot**.

17. To add currents to the results **(Current density, z component(mf.Jz))** it is neccessary:

Copy the tab **Magnetic Flux Density Norm** by clicking the tab **Duplicate:**

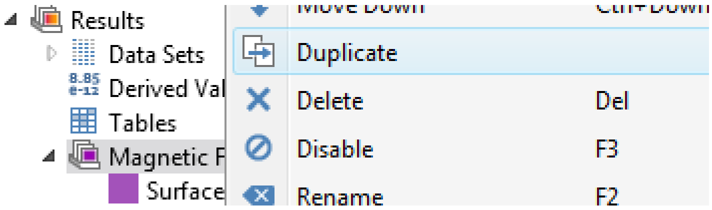


Fig. 5.28 – Duplicate tab **Current density, z component (mf.Jz)**

In the window **Surface** on the right **Expression** add **Current density, z component(mf.Jz):**

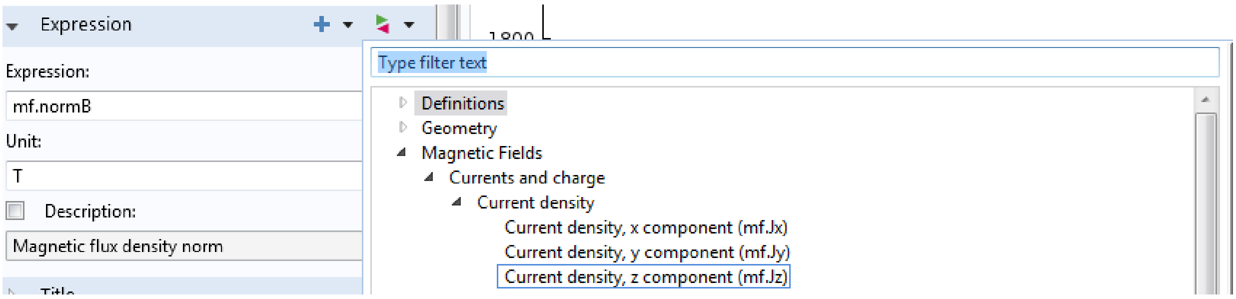


Fig. 5.29 – Specifying the formula **Current density, z component (mf.Jz)**

18. To add to the results the mapping of the distribution of lines of vector magnetic potential is necessary:

Copy the tab **Current density, z component** by clicking **Duplicate**:

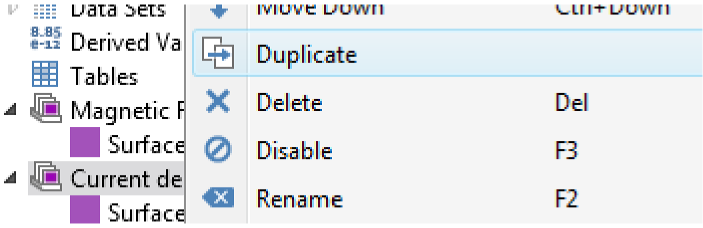


Fig. 5.30 – Duplicating the tab **Current density, z component (mf.Jz)**

Clicking **Magnetic flux density** choose **Contour:**

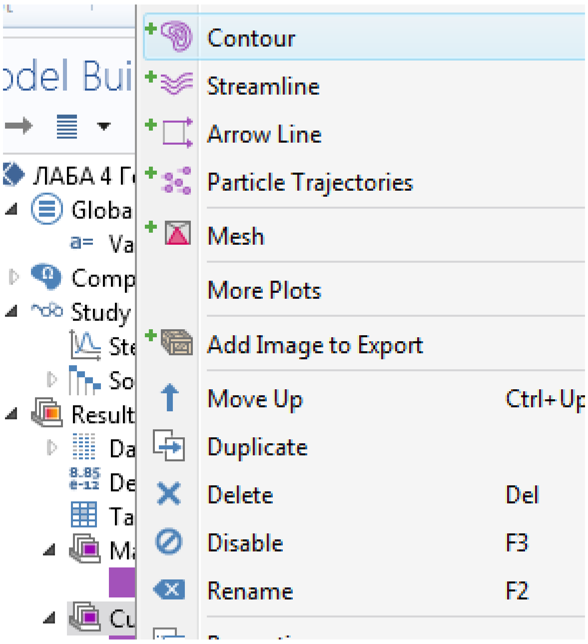


Fig. 5.31 – Adding the tab **Contour**

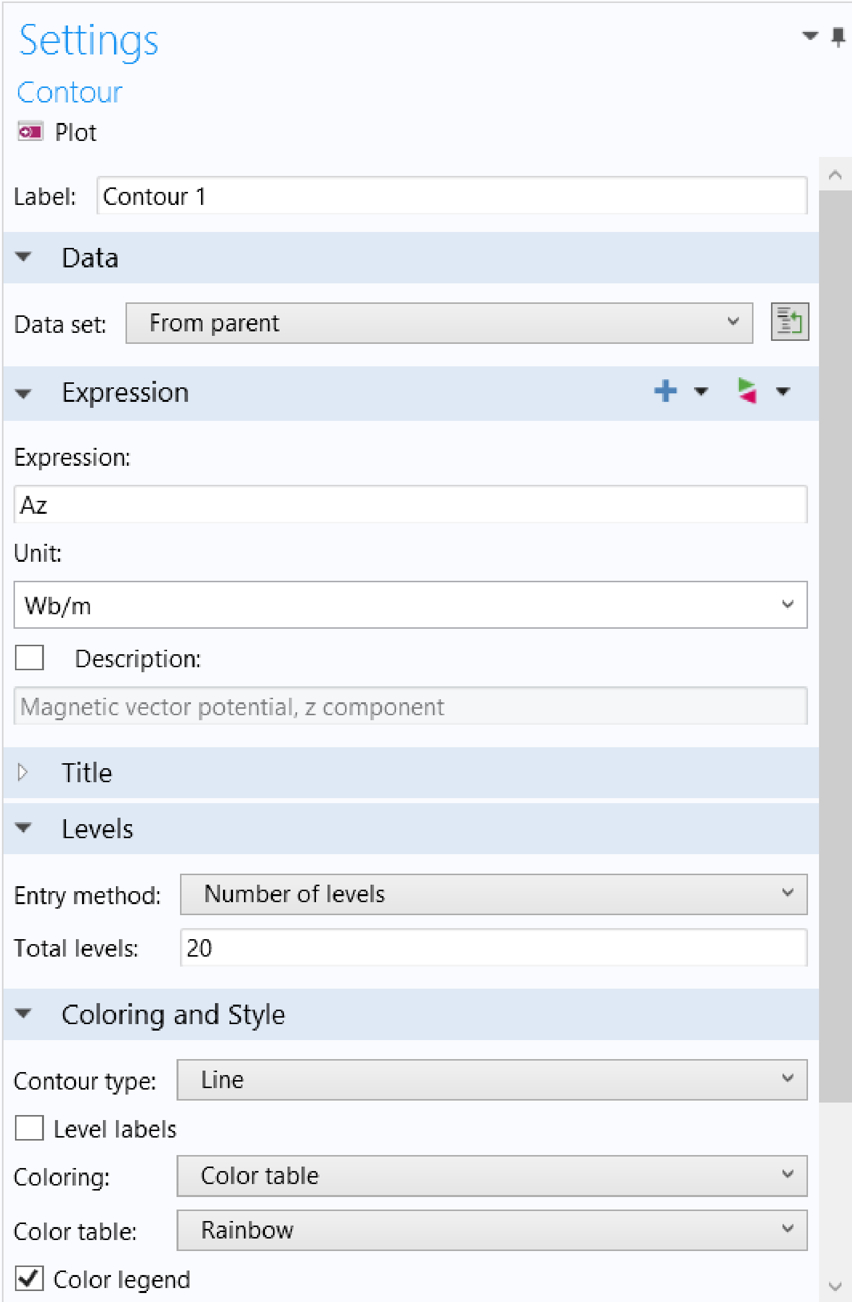


Fig. 5.32 – Setting the options in the tab **Contour**

In the window **Contour** on the right click **Expression** and add the **Magnetic vector potential, z component (Az):**

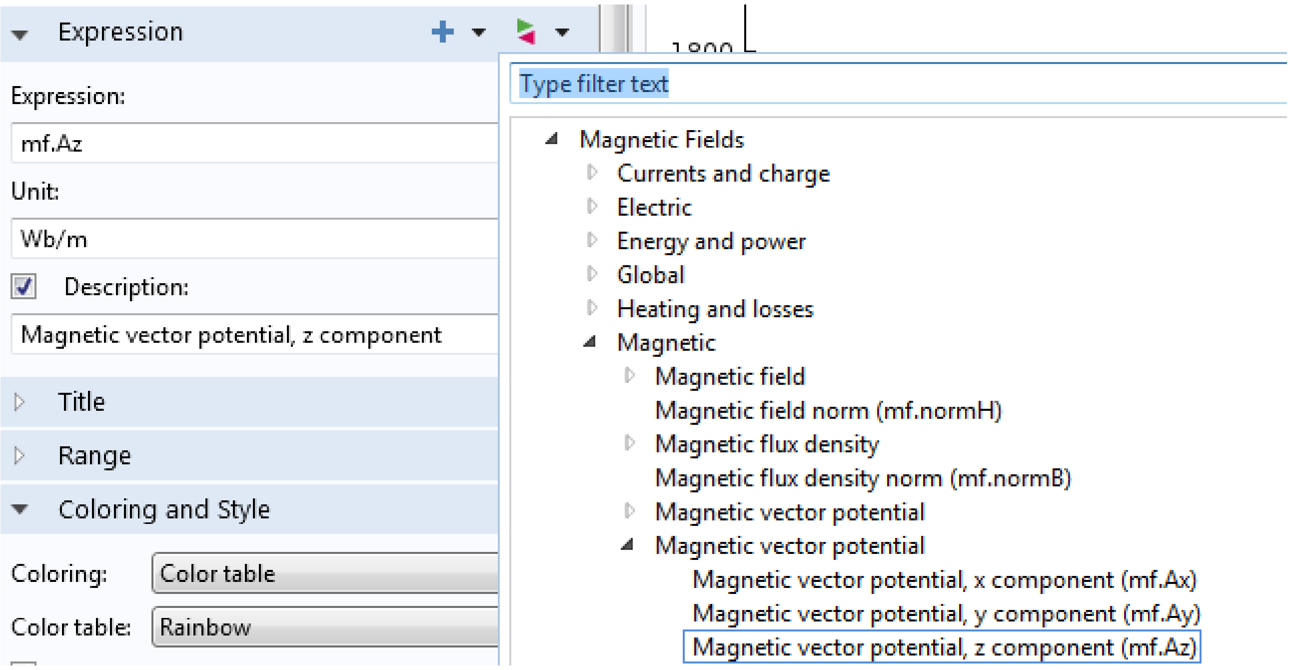


Fig. 5.33 – Specifiyng the formula **Magnetic vector potential, z component (Az)**

Change the name **Magnetic flux density** to **Magnetic vector potential, z component** by placing the cursor on **Description.**

19. Click on the toolbar to calculate the model **Compute** 

20. Criteria for the correctness of a computer workshop:

    1) Strength lines of the magnetic field correspond to the polarity of the IM.

    2) Maximum values of induction within limits 2-2.5 T (may vary depending on the option, but not more than 3 T).

    3) The currents in the rotor are distributed across the transverse section of the rotor slot evenly.

21. If, after calculation, the currents in the IM's rotor or stator are not displayed, and the maximum values of the currents on the figure scale have magnitudes of the order of 10^{10}, moreover currents in the stator was set about the value 10^6, then it is necessary to change the range of currents displayed on the screen, changing the order of the currents reflection on about 10^6 ... 10^7 in the parameter **Range**.

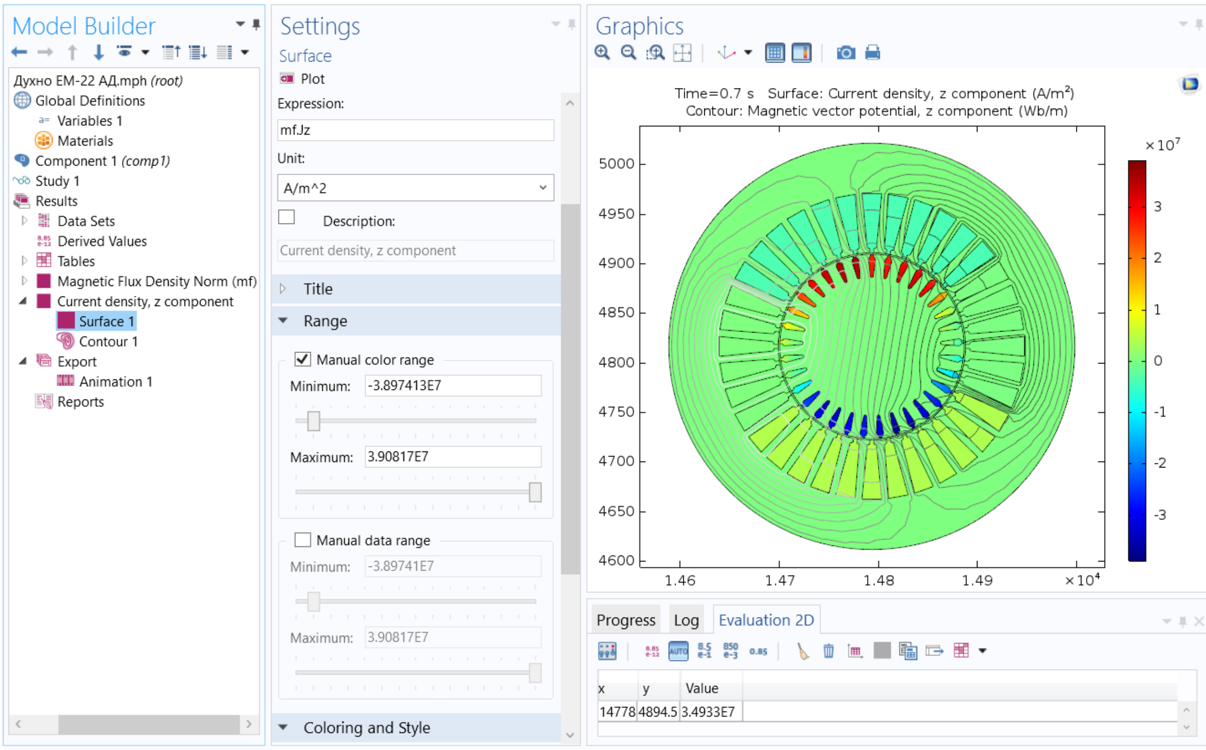


Fig. 5.34 – Setting the currents in the parameter **Range**

To 2nd point:

Simulation of rotor rods damage in IM is carried out by specifying the electrical conductivity σ = 0 only in rotor's damaged rods, in which the greatest currents are observed.

To 3rd point:

It is necessary to obtain schedules for the distribution of the normal component of the tensor of magnetic tension (**Maxwell's stress tensor**) along the surface of the IM rotor (or line through the middle of the IM air gap) for intact IM and IM, which has damaged rotor rods.

An important element of this mathematical model is a model of electromagnetic vibroperturbing forces, which are determined using the Maxwell's magnetic tension tensor, which characterizes the density of the electromagnetic force applied to the stator's cutting surface.

The components of the magnetic induction vector in the Cartesian coordinate system are determined by the formulas:

$$\dot{B}x = \frac{\partial \dot{A}_Z}{\partial y}; \dot{B}y = -\frac{\partial \dot{A}_Z}{\partial x},$$

According to the known projections $\dot{B}_x$, $\dot{B}_y$ it is easy to find on the stator's inner surface $\dot{B}_n$ – normal (directed along the vector normal to the surface of the rotor) and $\dot{B}_\tau$ – tangential (directed along the tangent to the surface of the rotor) components of the projection of the magnetic induction vector at a given point with coordinates x,y:

$$\dot{B}_n = \left(y\dot{B}_y + x\dot{B}_x \right) / R_\delta,$$

$$\dot{B}_\tau = \left(y\dot{B}_x - x\dot{B}_y \right) / R_\delta,$$

where R_δ – radius of stator cutting.

The normal component of the magnetic tension tensor $\vec{T}_n$ (directed along the vector normal to the surface) characterizes the action of radial vibroperturbing forces on the stator core, and the tangential component is the oscillation of the torque. In a normal-tangential coordinate system, the vector of the tensor of the magnetic tension is decomposed into a normal one T_n, and tangential T_τ components:

$$\vec{T} = \vec{n}T_n + \vec{\tau}T_\tau,$$

The relationship between the normal and tangential components of the magnetic induction vectors $\vec{B}$ and the magnetic tension tensor $\vec{T}$, whose direction in space does not coincide in the general case, is determined by the equations [9]:

$$T_n = \left| \frac{1}{2\mu_0} \cdot \left(\dot{B}_n^2 - \dot{B}_\tau^2 \right) \right|,$$

$$T_\tau = \left| \frac{\dot{B}_n \cdot \dot{B}_\tau}{\mu_0} \right|.$$

The components of a tensor in a normal-tangential coordinate system with known projections in the Cartesian coordinate system are determined by the following expressions (Fig. 5.35):

$$T_\tau = T_x \cos\alpha - T_y \sin\alpha = T_x \frac{y}{R_\delta} - T_y \frac{x}{R_\delta},$$

$$T_n = T_y \cos\alpha + T_x \sin\alpha = T_y \frac{y}{R_\delta} + T_x \frac{x}{R_\delta},$$

where α – angle between the abscissa and the tangential component of the magnetic tension tensor within one period of functions change $0 \le \alpha \le 2\pi / p$, p - the number of pole pairs of the IM. In further, stator radial vibrations of IM, will be considered as a normal component of the magnetic tension tensor

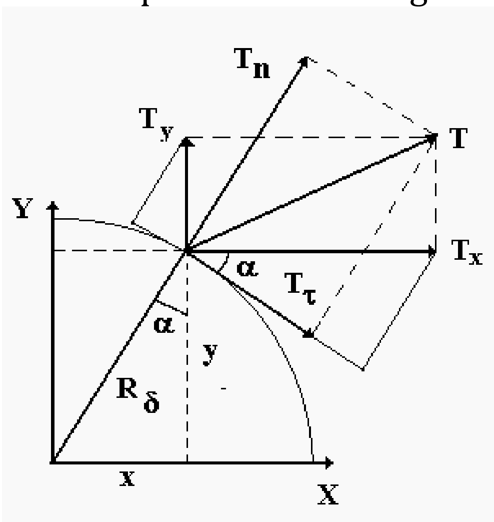


Fig. 5.35 – Components of the magnetic tension tensor in different coordinate systems

Construction of the distribution graph of the normal component of the magnetic tensor along the length of the air gap.

For further analysis of the vibroperturbing forces in the IM is necessary to find the distribution of the magnetic tension tensor normal component along the air gap.

To do this, after calculating the model is necessary:

1) In the tree **Model Builder→Component 1** Component 1 *(comp1)*→ **Definitions** Definitions →**Explicit 1** Explicit 1 choose **Boundary** and select all curved sections on the line passing through the middle of the air gap, either on the stator surface, or on the surface of the rotor.

2) In the tree **Model Builder→Component 1** Component 1 *(comp1)*→ →**Results** Results →**1D Plot Group** 1D Plot Group add **Line Graph** Line Graph.

3) In the parameters **Line Graph** (Fig. 5.36, b) in the options **Data Select** choose **From parent**, in the **Selection** choose **Explicit 1**. In the options **y-Axis Data** in the field **Expression** insert an expression for the normal component of the magnetic tension tensor vector:

(y*mf.dnTy+x*mf.dnTx)/R_rot

In general, it is necessary to create such graphs for distributing parameters on the stator cutting surface in the Comsol Multiphysics program:

1. **the normal component of the magnetic tension tensor vector (y*mf.dnTy+x*mf.dnTx)/R**, where R – rotor radius.
2. the tangential component of the magnetic tension tensor vector **(y*mf.dnTx-x*mf.dnTy)/R**, where R – rotor radius.
3. **the normal component of the magnetic induction vector (y*mf.By+x*mf.Bx)/R**
4. the tangential component of the magnetic induction vector **(y*mf.Bx-x*mf.By)/R**

In general, **Comsol Multiphysics** can solve the harmonic Stationary task (when the currents in the stator and rotor conductors are harmonic functions, and the results of the calculations are such that they are reflected at a certain time) and the time-dependent problem **Time-Dependent.** In second case, when constructing graphs, you must select a specific time point: **Time Selection → From list** (Figure 5.36).

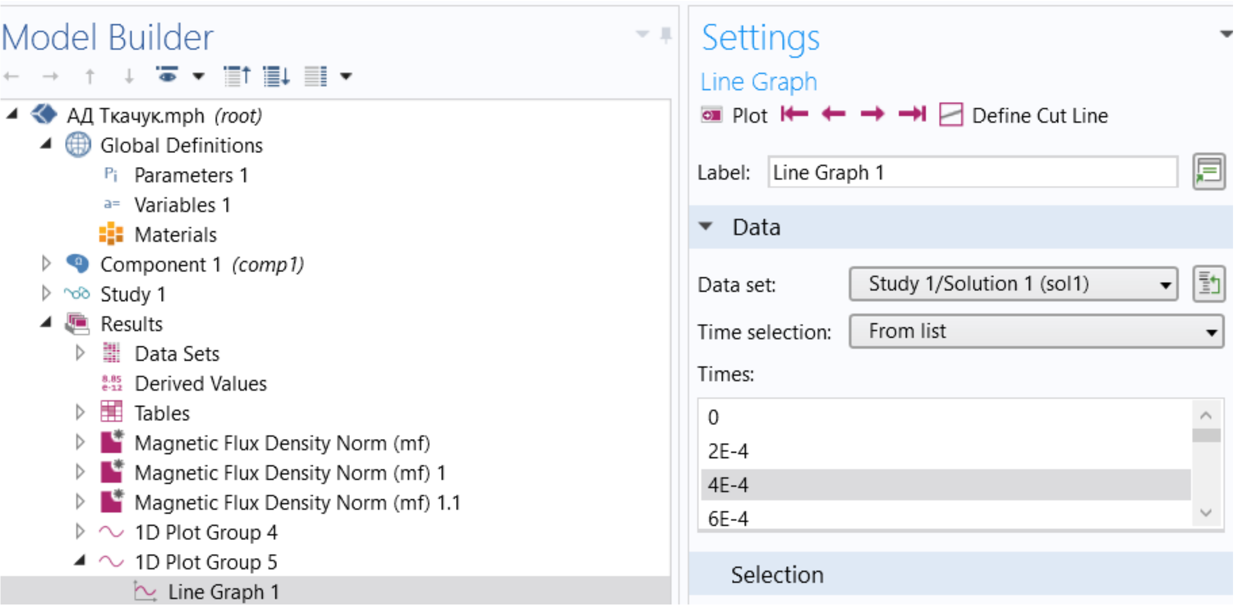


Fig. 5.36 – Parameters **Line Graph**

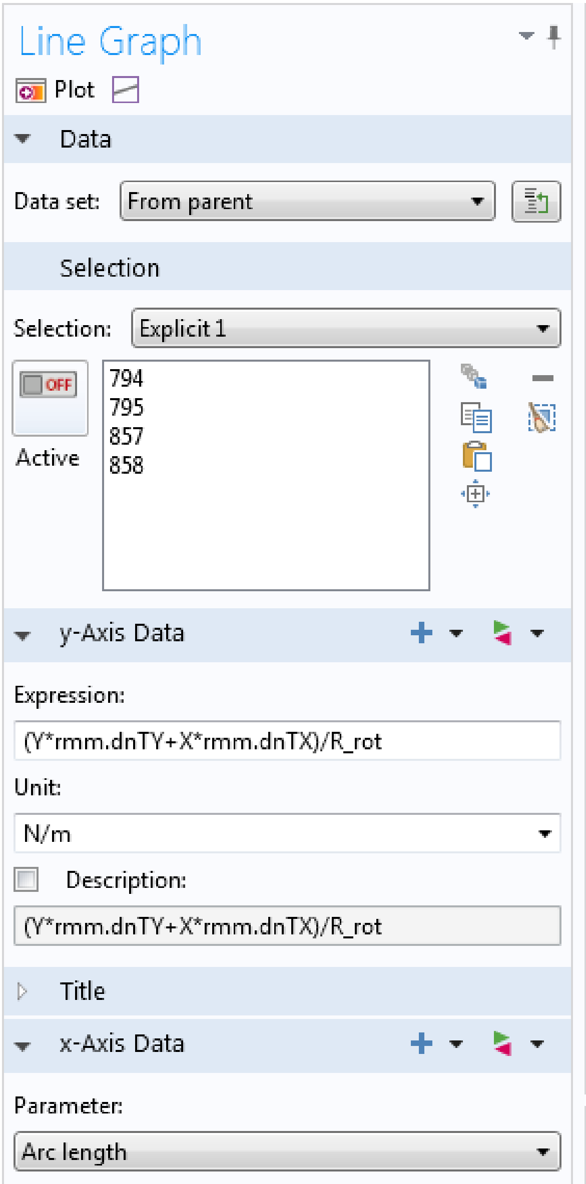


Fig. 5.37 – Parameters **Line Graph**

To avoid problems while working in **Matlab** should be set the correct parameters of the quality of the plotting (Fig. 5.38).

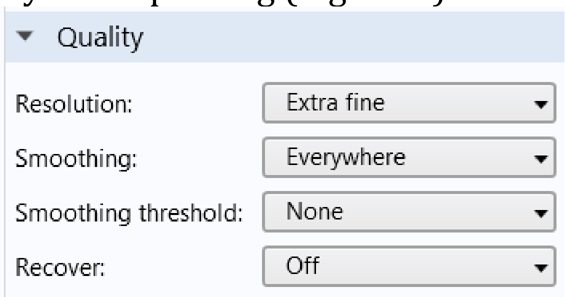


Fig. 5.38 – Parameters **Line Graph**

Moreover, if time-dependent task **Time-Dependent** is solved, in the results when displaying the graph on the screen it is necessary to put only one time point, and not to display all the graphs simultaneously (Fig. 5.36).

4) In the **x-Axis Data** parameters, select **Arc Length**. Press the **Plot** button, and then begins the construction of the magnetic tension tensor graph (Fig. 5.39, 5.40).

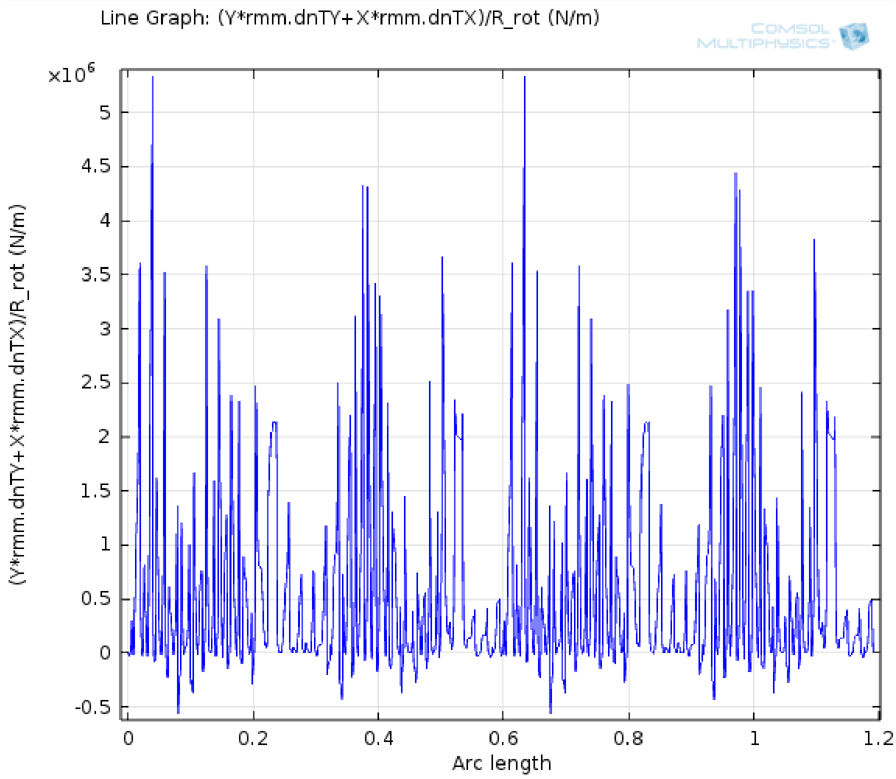


Fig. 5.39 – Distribution of the magnetic tension tensor in the intact IM

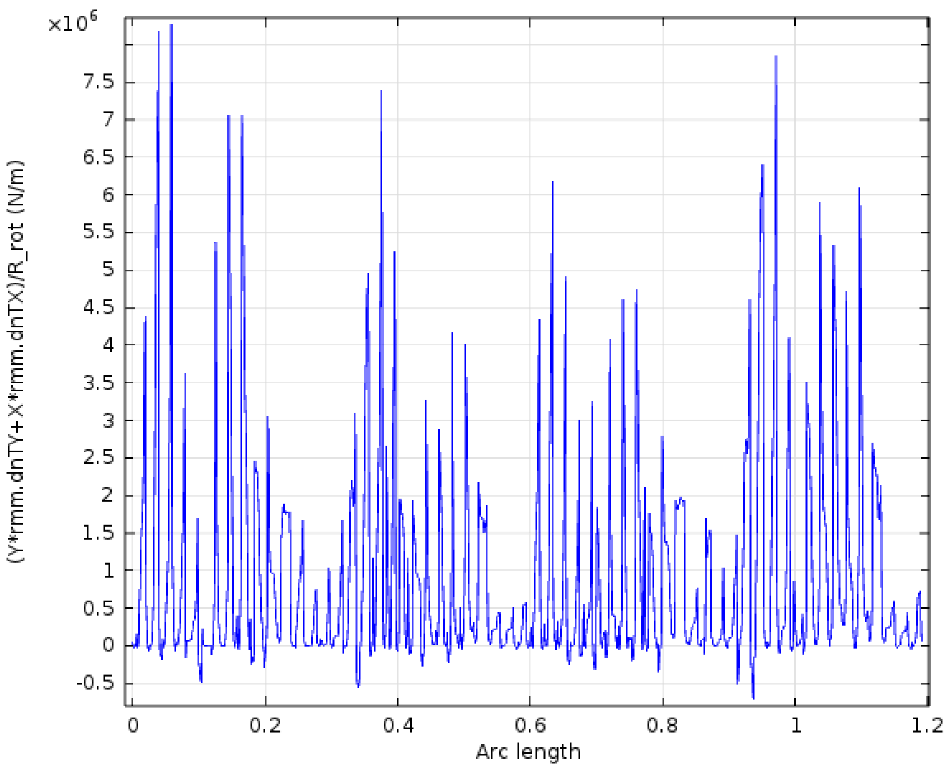


Fig. 5.40 – Distribution of the magnetic tension tensor in IM with five damaged rods

The found graph in the future should be analyzed in the software package **Matlab**.

It is necessary to export the built-in graphics to other programs:

1) In the tree **Model Builder→Component 1** Component 1 *(comp1)* → →**Results** Results →**Export** Export, choose **Plot**. In the parameters **Plot** (Fig. 5.41) choose **1D Plot group** and **Line Graph**

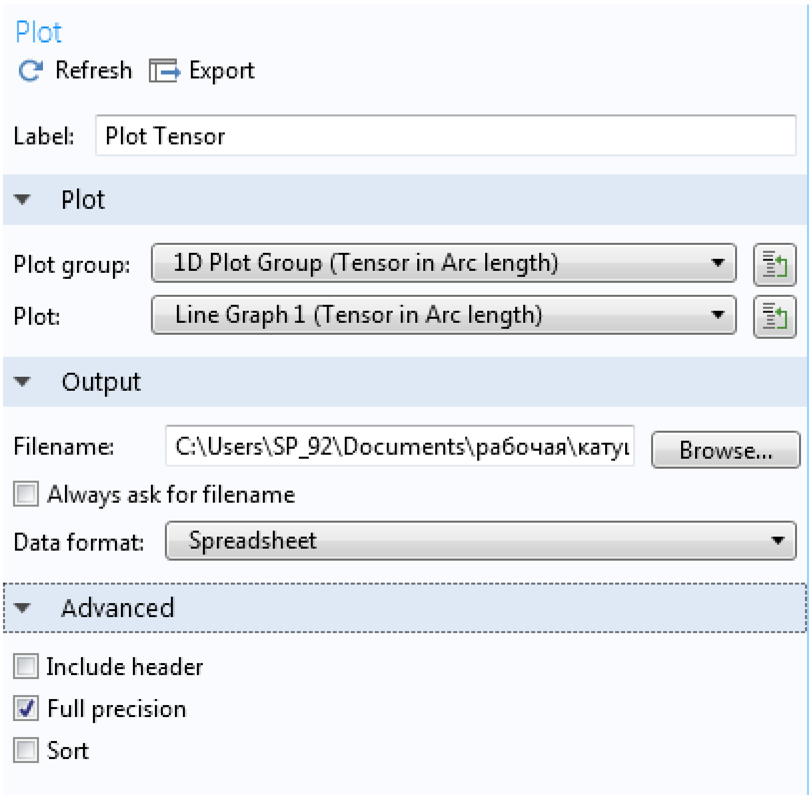


Fig. 5.41 –**Plot** parameters

2) With the button **Browse** Browse... specify name and place of saving file. The file will be saved with the extension ***.txt.**

Naming files from Comsol Multiphysics is recommended as follows:

```
Tensor_0st.txt
Tensor_5st.txt
Magnetic_flux_density_0st.txt
Magnetic_flux_density_5st.txt
```

To 4th point:

It is necessary to write the formulas and calculate the frequencies of the harmonics in the intact IM and IM, which has damaged rotor rods.

When researching the spectra of the magnetic tension tensor and magnetic induction it is necessary, knowing the frequency of harmonics, to determine the amplitudes of harmonics at these frequencies.

In particular, it is necessary to perform an analysis of changes in the following quantities **in the spectrum of vibrational forces** (i.e., the tensor of magnetic tension, that is, in the spectrum of vibrational acceleration, which is practically the same).

1) The amplitude of the constant component of the vibrational acceleration spectrum is – $\boldsymbol{a_o}$, which has a frequency f_{a0} = 0 Hz.

2) Amplitude of the rotating component of the vibrational acceleration spectrum – $\boldsymbol{a_{ob}}$, which has frequency f_{aob}, which is determined by the formula:

$$f_{a\_ob} = \frac{f_1}{p} \cdot (1 - S)$$

For example, for IM with a phase rotor (IMPR) such type as 4А355М4У4 with power 315 kW this frequency will be:

$$f_{a\_ob} = \frac{50\text{ Hz}}{3} \cdot 0{,}949 = 15{,}81\text{ Hz}$$

3) Amplitude of the double frequency component of the vibrational acceleration spectrum $\boldsymbol{a_{100}}$, which has a frequency f_{a_100}=100 Гц.

4) Amplitude of the toothed harmonic of vibrational acceleration $\boldsymbol{a_{Z1}}$, which has a frequency f_{Z1}, which is determined by the formula:

$$f_{a\_Z1} = \frac{f_1}{p} \cdot z_1 \cdot (1 + s)$$

For the studied IMPR this frequency will be:

$$f_{a\_Z1} = 16{,}66\text{ Hz} \cdot 54 = 899{,}64\text{ Hz}$$

According to research results [7] was found that:

- in poorly designed IM, or in a IM with damage of the rotor winding, lateral toothed harmonics appear around the main toothed harmonics from the jaggedness of the stator and rotor. Their amplitudes may be insignificant.
- in the spectra of the magnetic tension tensor, the lateral toothed harmonics, created by the toothed stator and rotor, and are located around the main toothed harmonics, shifted by a value of ± 100 Hz.
- in the magnetic induction spectra, the lateral toothed harmonics, created by the toothed stator and rotor, and located around the main toothed harmonics, shifted by a value of ± 50 Hz.

5) The amplitude of the lateral toothed harmonic of the magnetic tension tensor (vibrational acceleration) a_{Z1_1}, which lags behind the harmonic a_{Z1} at 100 Hz, and has a frequency:

$$f_{a\_Z1\_1} = f_{a\_Z1} - 100\text{ Hz} = 799{,}64\text{ Hz}.$$

6) The amplitude of the lateral toothed harmonic of the magnetic tension tensor (vibrational acceleration) a_{Z1_2}, which is ahead of the harmonic a_{Z1} at 100 Hz and has a frequency:

$$f_{a\_Z1\_2} = f_{a\_Z1} + 100\text{ Hz} = 999{,}64\text{ Hz}.$$

7) The tangential harmonic amplitude of the magnetic tension tensor (vibrational acceleration) $\boldsymbol{a_{Z2}}$, which has a frequency $\boldsymbol{f_{\_Z2}}$, which is determined by the formula:

$$f_{a\_Z2} = \frac{f_1}{p} \cdot z_2 \cdot (1 - s)$$

For this IMPR, this frequency will be:

$$f_{a\_Z2} = 16{,}67\ \text{Hz} \cdot 36 = 599{,}76\ \text{Hz}$$

8) The amplitude of the lateral toothed harmonic of the magnetic tension tensor (vibrational acceleration) a_{Z2_1}, which lags behind the harmonic a_{Z2} at 100 Hz, and has a frequency:

$$f_{a\_Z2\_1} = f_{a\_Z2} - 100\ \text{Hz} = 499{,}76\ \ \text{Hz}.$$

9) The amplitude of the lateral toothed harmonic of the magnetic tension tensor (vibrational acceleration) a_{Z2_2}, ahead of the harmonic a_{Z2} at 100 Hz and has the frequency:

$$f_{a\_Z2\_2} = f_{a\_Z2} + 100\ \text{Hz} = 699{,}76\ \text{Hz}.$$

Having determined the harmonics frequencies of the magnetic tension tensor, it is necessary to research the harmonics amplitudes of the magnetic tension tensor in the spectra of the magnetic tension tensor at these frequencies.

10) The root mean square value of the vibrational acceleration a_{SKZ}, which is determined by the formula:

$$a_{SKZ} = \sqrt{\frac{a_1^2 + a_2^2 + a_3^2 + \cdots + a_n^2}{n}}$$

11) The root mean square value of the noise harmonics of the vibrational acceleration spectrum $\boldsymbol{a_{SKZ\_SH}}$.

Noise harmonics called harmonics that are lower in amplitude of a certain set level (for example, 10-15% from the amplitude of the harmonic $\boldsymbol{a_{100}}$) and are not multiple to a basic harmonic $\boldsymbol{a_{100}}$ and to the toothed harmonics $\boldsymbol{a_{Z1}}$, $\boldsymbol{a_{Z2}}$.

At the same time, once constructing the spectrum of vibrational acceleration, determine the value of the axis **Y,** which will not cover the harmonics $\boldsymbol{a_0}$, $\boldsymbol{a_{100}}$, $\boldsymbol{a_{Z1}}$, $\boldsymbol{a_{Z2}}$ and will cover all the noise harmonics in the spectrum. Usually this value is 10-15% of the maximum amplitude of the harmonic in the spectrum.

This value must be written in absolute units in line:

```
y_for_SKZ_shum_lim_a = 0.5e5;
```

To find the quantitative signs of damage occurring in the spectra of the vibrational forces of the induction motor in case of damage, it is necessary to research the change in the amplitudes of certain harmonics and compare them with the amplitudes of harmonics in the intact induction motor.

Similarly, for magnetic induction it is necessary to additionally calculate the frequencies of all harmonics of magnetic induction (paragraphs 1 ... 9 for a magnetic tension tensor). In particular:

- the frequency of the main toothed harmonics of magnetic induction f_{b_Z1}, f_{b_Z2}, which will not change in comparison with the frequency of the magnetic tension tensor;
- the frequency of the lateral toothed harmonics of magnetic induction $f_{b\_Z1\_1}$, $f_{b\_Z1\_2}$, $f_{b\_Z2\_1}$, $f_{b\_Z2\_2}$, which are located around the main toothed harmonics are **shifted by a value ± 50 Hz;**
- for magnetic induction it is not necessary to determine the root mean square values of the spectra.

Having determined the frequency of the magnetic induction harmonics, it is necessary to research the amplitudes of the magnetic induction harmonics in the magnetic induction spectra at these frequencies. **Table 5.2** shows the result of what needs to be defined in 4th point.

Table 5.2 – Comparison of changes in amplitudes of vibroperturbing forces (magnetic tension tensor) harmonics and magnetic induction in IM, which has 5 damaged rods in comparison with undamaged IM.

For undamaged IM					For damaged IM					Coefficient of harmonic amplitude variation, p.u.
Magnetic tension tensor										
marking the harmonic amplitude	harmonic amplitude, H/м		marking the harmonic frequency	harmonic frequency, Hz	marking the harmonic amplitude	harmonic amplitude, H/м		marking the harmonic frequency	harmonic frequency, Hz	**damaged 5 rods.**
a0	1480	with the frequency	fa_0	0	**a0**	1100	with the frequency	fa_0	0	0,7
aob	6		fa_ob	23,875	**aob**	530		fa_ob	23,875	88,3
a100	1475		fa_100	100	**a100**	950		fa_100	100	0,6
aZ1	50		fa_Z1	900	**aZ1**	220		fa_Z1	900	4,4
aZ1_1	45		fa_Z1_1	800	**aZ1_1**	570		fa_Z1_1	800	12,7
aZ1_2	42		fa_Z1_2	1000	**aZ1_2**	170		fa_Z1_2	1000	4,0
aZ2	2860		fa_Z2	700	**aZ2**	510		fa_Z2	700	0,2
aZ2_1	1420		fa_Z2_1	600	**aZ2_1**	430		fa_Z2_1	600	0,3
aZ2_2	1440		fa_Z2_2	800	**aZ2_2**	570		fa_Z2_2	800	0,4
aSKZ	464,15	-	-	-	**aSKZ**	405,38	-	-	-	0,9
aSKZ_SH	24	-	-	-	**aSKZ_SH**	26,68	-	-	-	1,1
Magnetic induction										
marking the harmonic amplitude	harmonic amplitude, H/м		marking the harmonic frequency	harmonic frequency, Hz	marking the harmonic amplitude	harmonic amplitude, H/м		marking the harmonic frequency	harmonic frequency, Hz	**damaged 5 rods.**
b0	1480	with the frequency	fb_0	0	**b0**	1100	with the frequency	fb_0	0	0,7
bob	6		fb_ob	23,875	**bob**	530		fb_ob	23,875	88,3
b50	1475		fb_50	100	**b50**	950		fb_50	100	0,6
bZ1	50		fb_Z1	900	**bZ1**	220		fb_Z1	900	4,4
bZ1_1	45		fb_Z1_1	800	**bZ1_1**	570		fb_Z1_1	800	12,7
bZ1_2	42		fb_Z1_2	1000	**bZ1_2**	170		fb_Z1_2	1000	4,0
bZ2	2860		fb_Z2	700	**bZ2**	510		fb_Z2	700	0,2
bZ2_1	1420		fb_Z2_1	600	**bZ2_1**	430		fb_Z2_1	600	0,3
bZ2_2	1440		fb_Z2_2	800	**bZ2_2**	570		fb_Z2_2	800	0,4

Thus, in 4th point, it is necessary to write 20 formulas, and to determine 20 values for the intact IM and for the IM which has the damage.

It is necessary to show the change in these quantities in relative units. Moreover, the coefficients of harmonic's amplitudes variation must be determined according to Table 6.2 (from the computer workshop №6) (watch "To 7th point" in the computer workshop №5).

To 5th point:

In order to obtain the distributions and spectra of the distributions of the magnetic tension tensor for the intact IM and IM having damaged rotor's rod in the **MatLab** program, it is necessary to follow.

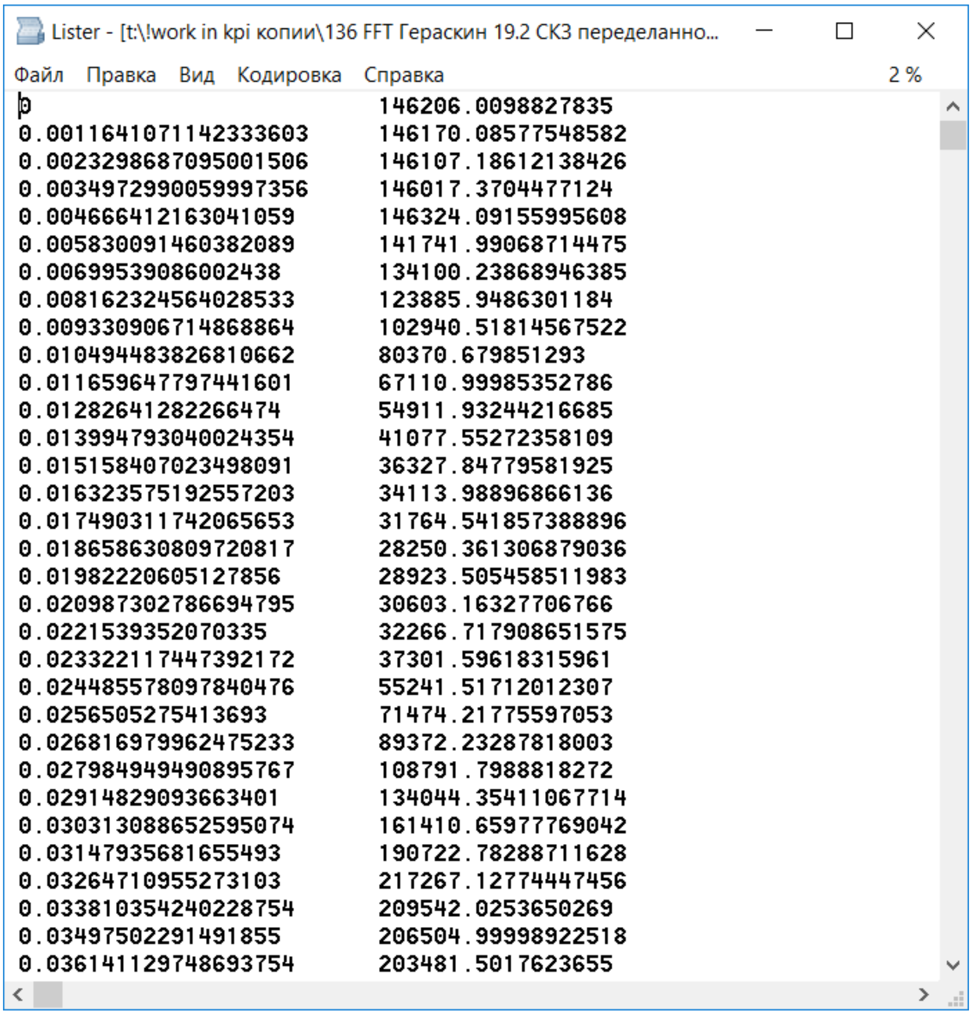
For correct and qualitative visual comparison of results, all distributions of quantities (and spectra of distributions) in a computer workshop must be constructed in the same range along the axes Y (amplitude of the magnitude) and X (frequency).

In order to do this, do the following.

- Initially, a distribution is constructed (both initially in Comsol and Matlab) for the variant with the highest value of the damage.
  That is necessary beforehand to determine the amplitude in the graph (or spectrum) with the highest damage of the IM rotor.
- First, the axis value is set to "automatically".
- And then knowing the limits on the axes for the variant of the IM with the highest damage, within these limits it is necessary to build distributions (or spectra) for the intact IM (and for IM with less damages – for computer workshop №6).
- That is, then you need to set the same limits in all subsequent charts along the axis of the Y axis manually.
- These limits will be different both in the study of distributions, and in the study of spectra, both in the study of the induction values and in the study of the magnetic tension tensor magnitudes.
- The boundaries for the frequency (along the X-axis) in the spectra should be chosen so that the numbers of frequencies of the toothed harmonics of the stator and rotor were covered.
- It is necessary to place 2 graphs or spectra next to each other for a comparison (Table 5.3).

Spectral processing of the distributions of the magnetic tension tensor and magnetic induction, obtained on the middle line of the air gap in the Matlab program.

An exported text file must not contain headers and should consist of only 2 columns: coordinate vectors X and Y (actually matrix **2**x**r21**, where **r21** – number of lines in the text file) (Fig. 5.41). You can view it, selecting this file and clicking the button **F3** in program **Total Commander**. Then it will be as shown in Fig. 5.42.


Lister - [t:\!work in kpi копии\136 FFT Гераскин 19.2 СК3 переделанно...

Файл Правка Вид Кодировка Справка 2 %

0	146206.0098827835
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0.011659647797441601	67110.99985352786
0.01282641282266474	54911.93244216685
0.013994793040024354	41077.5527235810 9
0.015158407023498091	36327.84779581925
0.016323575192557203	34113.9889686613 6
0.017490311742065653	31764.541857388896
0.018658630809720817	28250.361306879036
0.01982220605127856	28923.505458511983
0.020987302786694795	30603.1632770676 6
0.022153935207033 5	32266.717908651575
0.023322117447392172	37301.59618315961
0.024485578097840476	55241.51712012307
0.025650527541369 3	71474.21775597053
0.026816979962475233	89372.2328781800 3
0.027984949490895767	108791.7988818272
0.029148290936634 01	134044.3541106771 4
0.030313088652595074	161410.65977769042
0.031479356816554 93	190722.7828871162 8
0.032647109552731 03	217267.12774447456
0.033810354240228754	209542.0253650269
0.03497502291491855	206504.99998922518
0.036141129748693754	203481.5017623655

Fig. 5.42 – Exported text file

Spectral analysis of exported graph in the program **MatLab** is perform. This is done using the file **FFT_VtShEM_AD_Geraskin_217_Tensor_1.m.** For the correct operation of this file in the **Matlab** program, its name must be written in Latin, not contain any spaces (can be underlined) and do not start with digits. The names of the directories in the path to the file can be written and Cyrillic.

You need to make sure that the exported text file is in the same folder as the file **FFT_VtShEM_AD_Geraskin_217_Tensor_1.m.** Therefore, all analyzed text files must be copied to a folder for this purpose **136 FFT ВтШЕМ АД Гераскин А.А. 19.3 студентам.**

In the file **FFT_VtShEM_AD_Geraskin_217_Tensor_1.m** you must specify the name of the exported file:

`name_of_file ='Tensor_0st.txt'` (the student inserts the name of his file), the presence of text in the first line of the file `r1=1` (if there is no text) and the number of rows in it (this can be determined in advance by opening the explored * **.txt** file in **Microsoft Excel**, with the number of rows to be taken 1-2 less than the real):

```
r21=6390.
```

Need to set:

the amount of slip `skol=0.01;`
and rhe number of poles in IM: `p=2;`

It is not recommended to change the code for the program about:
1. removing duplicate strings;
2. fast Fourier Transform.

Getting different types of graphs is regulated by the parameter **s1:**
- if **s1=1** get a distribution,
- **s1=2** – spectrum and root mean square value of vibrational acceleration,
- **s1=3** – spectrum and root mean square value of vibrational velocity,
- **s1=4** – spectrum and root mean square value of vibrational movement.

File **FFT_VtShEM_AD_Geraskin_217_Tensor_1.m** can handle both a simple and a difference signal.

The distribution of the difference signal is a signal obtained by subtracting the signal ordinates of the vibration sensor of the intact IM from the IM signal, which is damaged.

The distribution of the difference signal can also be expanded into the spectrum.

To handle a simple signal, for example, **Tensor_0st** it is necessary in parameter **s2** choose **1**, while this:
- **plot** in the algorithm for the calculation of the difference signal should be inactive (disabled with the help of the sign %),
- **plot** at the end of the program (outputting results in case 1 for s1 = 1, Figure 5.43) must be active (not disabled by the help of the sign %),

This is necessary to get the correct distribution schedule.

Starting and executing the program code calculation in **Matlab** is doing by pressing **F5**.

```
switch s1
    case 1,  plot(x1, d1, 'k','LineWidth',1.5);
             grid on;
             set(gca,'YLim',[-0.5*10^6 11*10^6],'Layer','top') % Границы по оси у для распределения
             set(gca,'XLim',[0 x1_end],'Layer','top');  %Границы по оси х
```

Fig. 5.43 – Exported text file

At the end of the program (outputting results in case 1 for s1 = 1, Fig. 5.36) for adjusting the boundaries in the axes X and Y use the following lines:

```
set(gca,'YLim',[0*10^4 5*10^4]),
set(gca,'XLim',[0 x1_end],'Layer','top');
```

For signal distributions, the X-axis boundary is set automatically, and for the spectrum of signals, the X-axis border can be corrected.

For the preliminary convenient and easy definition of the boundaries in the axes of distributions and spectra, it is possible to turn off the borders (with the help of the sign %) in general before turning out the figures. Then the axis borders will set automatically.

And then you can adjust these limits by yourself.

In the **Matlab** program, it is recommended to close the drawings that were displayed on the results of previous calculations for the subsequent correct displaying of a new drawings.

The amplitudes of the studied harmonics in the spectra students determine independently by hand, increasing the scale of the figure. Also, the program provides for the simplification of the definition and output of harmonics amplitudes automatically. To do this, you need to use the **Excel** program to correctly write the numbers of the matrix `x1` elements. However, such automation of output results is not mandatory for students.

In order to obtain the vibrational acceleration spectrum it is necessary at the beginning of the program choose **s1=2**.

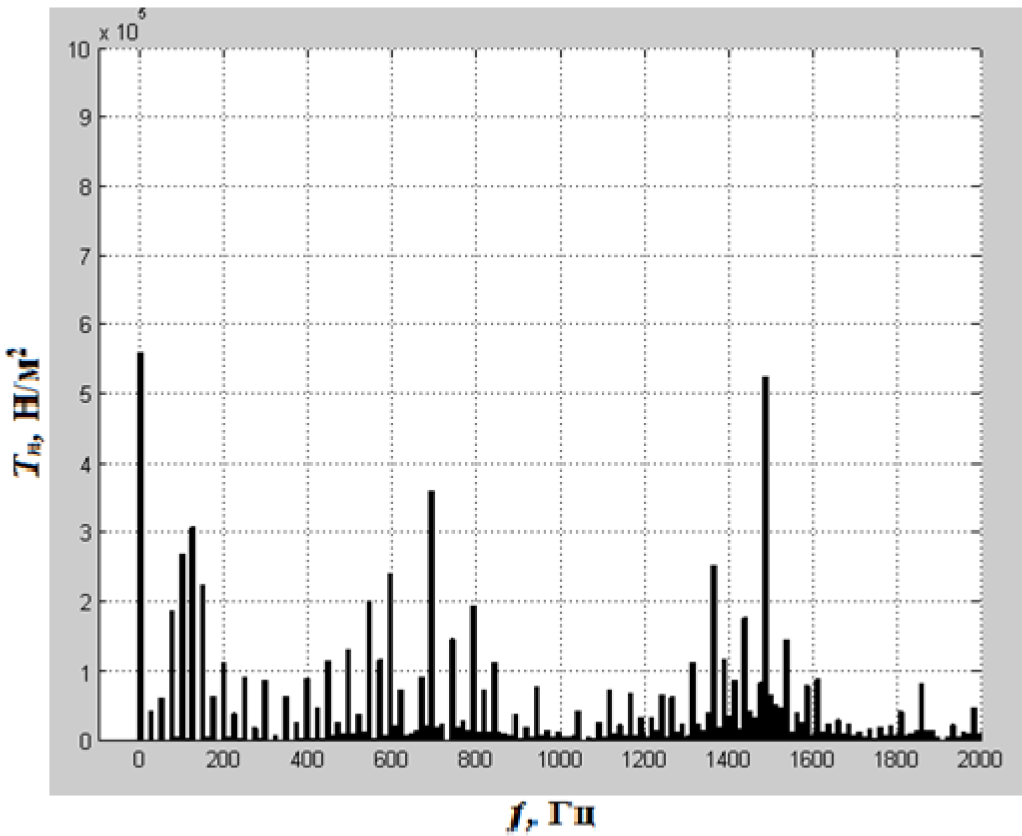


Fig. 5.44 – Spectrum of vibperturbing forces of IM, which does not have damaged rods

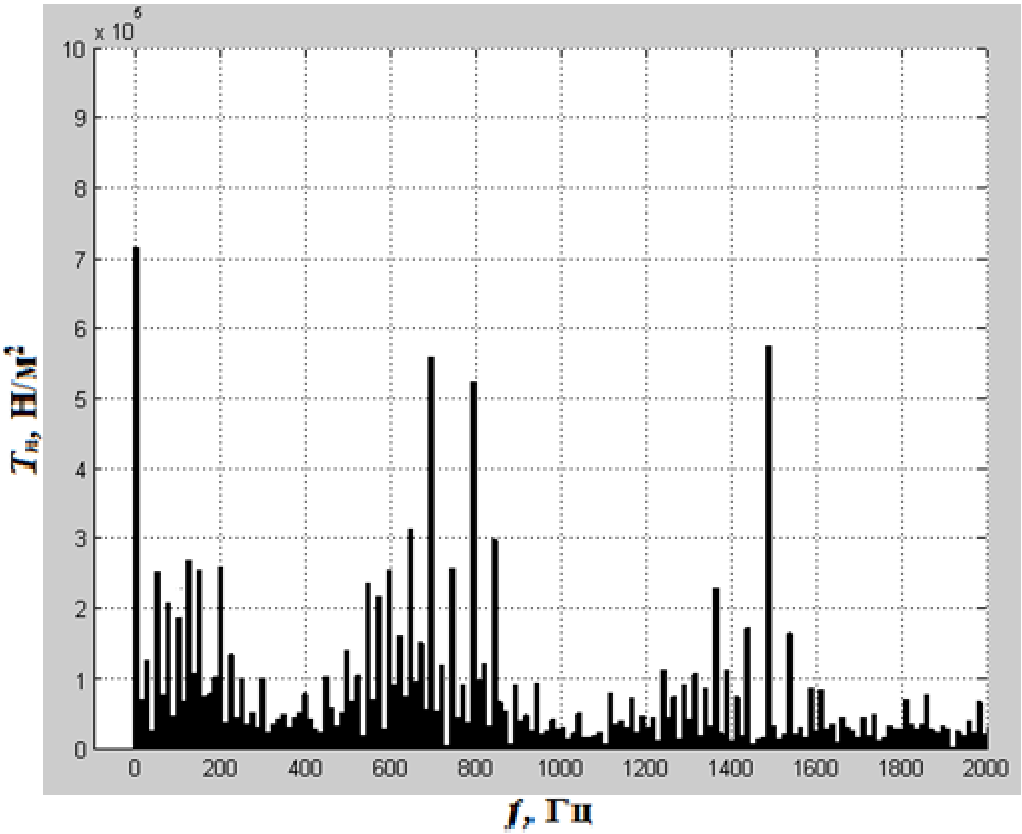


Fig. 5.45 – Spectrum of vibperturbing forces of IM, which has 3 damaged rods

To 6th point:

To create distributions and distributions spectra of a difference signal for the researched IM with damaged rotor rods, the **Matlab** program requires the following.

The algorithm for processing the differential signal is as follows.

1. During the processing of the differential signal we accept **s1=1**.
2. Select the file of intact IM

```
name_of_file =' Tensor_0st.txt';
```

3. Turn on **plot** in the algorithm to calculate the difference signal should be inactive (disabled with the help of the sign %).
4. At the end of the program we turn off **plot** (output of results in case 1 for **s1 = 1**, Fig. 5.46) with the help of the sign %.

```
switch s1
    case 1,  %plot(x1, d1, 'k','LineWidth',1.5);
             %grid on;
             %set(gca,'YLim',[-0.5*10^6 11*10^6],'Layer','top') % Границы по оси у для распределения
             %set(gca,'XLim',[0 x1_end],'Layer','top');  %Границы по оси х
```

Fig. 5.46 – of vibperturbing forces of IM, which has 3 damaged rods

5. First you need to record a signal of intact IM.

Choose **s2=1** and push **F5**. In this case, the spectrum is written to files **d1_undamaged.txt** та **x1_undamaged.txt** automatically.

6. Next it is necessary to write the spectrum of damaged IM.

To do this, specify a text file of the damaged machine spectrum

```
name_of_file ='Tensor_5st.txt';
```

value **s2=2** and click **F5**,

The signal distribution of the IM, which has the damage recorded in the files **d1_damaged.txt** and **x1_damaged.txt** automatically.

7. Specifying **s2 = 3**, we perform the subtraction of the two recorded signal distributions and get the differential signal of the vibration sensor.

In order to get the spectrum of this difference signal, you must **leave s2=3**, and change the parameter **s1 = 2.**

8. In order to analyze the spectra of a not difference signal, but distributions of damaged or undamaged IM it is need to be re-set triggers to: **s1 = 2**, **s2=1** and:

- **plot** in the algorithm of calculation of the difference signal should be inactive (disabled with the help of the sign %);
- **plot** at the end of the program (output results in case 1 for **s1 = 1**, Fig. 5.43) should be active (not disabled by the help of the sign %).

If the program does not perform the calculation and outputs an error **size H1**=2550 (number less than **r21**), then you need to set **rsorted=2550-2**. This is due to the fact that a *.txt file from **Comsol** contains duplicate items. To do this, an algorithm was used to remove these elements and create an array H1 for further processing.

The value **rsorted** must be less than **size H1** to number 2.

Similarly, distributions and spectra of magnetic induction distributions are analyzed. For research of the magnetic induction should not calculate the spectra of vibrational velocity and vibrational displacement.

When constructing distributions and spectra of magnetic induction distributions in the **Matlab** program, you must enable the string:

for distributions:

```
%ylabel('Тензор магнітного натягу,
Н/м','FontWeight','bold');
ylabel('Магнітна індукція, Тл','FontWeight','bold')
```

for spectra distributions:

```
%ylabel('Амплітуда гармоніки тензора магнітного натягу,
Н/м','FontWeight','bold');
```

```
ylabel('Амплітуда гармоніки магнітної індукції, Тл','FontWeight','bold');
```

and change subscriptions of the graph in the **Matlab** program for the correct displaying of signatures in the axes of the drawing.

To 7th point:

For numerical analysis of harmonics amplitudes changes in the spectra of the vibroperturbing forces for intact IM and IM which has damaged rotor's rods need to manually independently, increasing the scale of the figure, to determine the amplitudes of the studied harmonics in the spectra.

It is necessary to give a table (not a graph, since only 2 points), in which numerically compare the amplitudes of the studied harmonics in the vibroperturbing forces spectra for the intact IM and IM, which is damaged (see **Table 5.2**) for:

a. the normal component of the magnetic tension tensor;
b. normal component of magnetic induction.

It is necessary to show the change of these quantities in relative units. Moreover, the coefficients of harmonics amplitudes variation must be determined according to Table 6.2. (from computer workshop number 6).

To 8th point:

It is necessary to compare the spectra of damaged IM: vibrational acceleration, vibrational velocity and vibrational displacement.

Algorithm for obtaining spectra of vibrational velocity and vibrational displacement.

The algorithm of numerical transition from the vibrational acceleration spectrum to the vibrational velocity and vibrational displacement spectra is carried out by numerically integrating of the vibrational acceleration spectrum:

$$a = \omega \cdot v\,; \quad v = \frac{a}{\omega}$$

$$a = \omega^2 \cdot x\,; \quad x = \frac{a}{\omega^2} = \frac{v}{\omega}$$

These formulas are intended only for obtaining the appropriate spectra, but not for the RMS value. The RMS value is calculated separately according to the maximum allowable values given in the State Standards ([11], for IM with the rotation axis height H=160 mm):

$$a=2{,}8\ m/s^2$$
$$v=1{,}8\ mm/s$$
$$x=29\ mkm$$

The transition from vibrational velocity to vibrational displacement is carried out at 10 Hz frequency, and the transition from vibrational velocity to vibrational acceleration is carried out at a frequency of 250 Hz.

At the same time, the attached weight (the mass of the electric machine and the vibrational material objects) remains unchanged, and only the parameters of the oscillation of this mass change.

$$M_e = \frac{CKK\_a\,[м/c^2]}{2{,}8[м/c^2]\cdot\sqrt{2}\cdot\pi\cdot f_1}$$

To construct spectra of vibrational acceleration, vibrational velocity and vibrational displacement it is necessary to change the parameter **s1** to values **2, 3, 4.**

To 9th point:

You need to create a report about the implementation of a computer workshop in which present following.

1. Title letter, work objective and work program;
2. Induction motor parameters according to the task variant;
3. Screen of induction motor in the program Comsol Multiphysics (it's allowed b&w) (3 figures):
    a. Induction and isolines distribution of a magnetic field;
    b. Distribution of currents in windings and isolines of a magnetic field;
    c. Distribution of a Vector Magnetic Potential.
4. Formulas for determining the frequencies and calculating the frequencies of the harmonics of the studied IM:
    a. magnetic tension tensor (11 formulas);
    b. magnetic induction (9 formulas).
5. Schemes of currents distribution in the area of damaged rods obtained in the program **Comsol Multiphysics** for an intact IM and IM that is damaged (e.g., Fig. 5.45) (2 figures).
6. **Distribution** of vibroperturbing forces received in the program **Comsol Multiphysics** (4 figures):
    a. a normal component of the magnetic tension tensor;
    b. a tangential component of the magnetic tension tensor;
    c. a normal component of magnetic induction;
    d. a tangential component of the magnetic induction.
7. **Distributions** and **Spectra** of vibroperturbing forces obtained in the program **Matlab** for an intact IM and IM that is damaged (10 figures):
    a. a normal component of the magnetic tension tensor, (4 figures);
    b. a normal component of magnetic induction, (4 figures);
    c. **difference sigal** of the normal component of the magnetic tension tensor (only **the distribution** for the damaged IM);

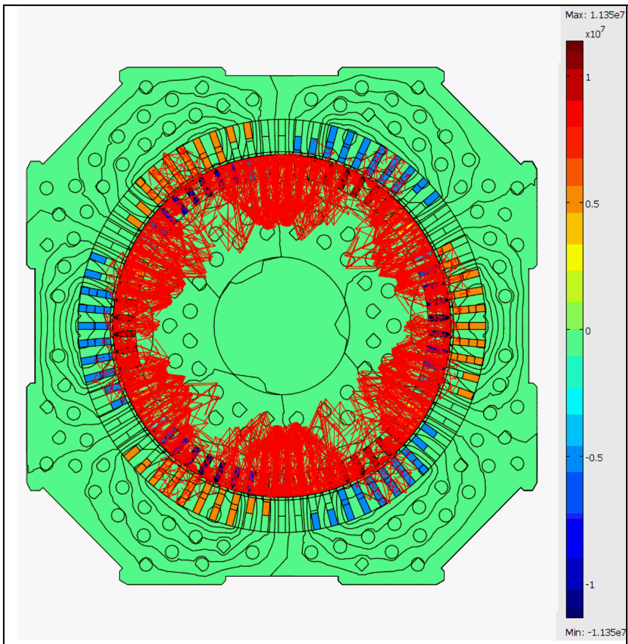
   d. **difference sigal** of the normal component of the magnetic induction (only **the distribution** for the damaged IM).

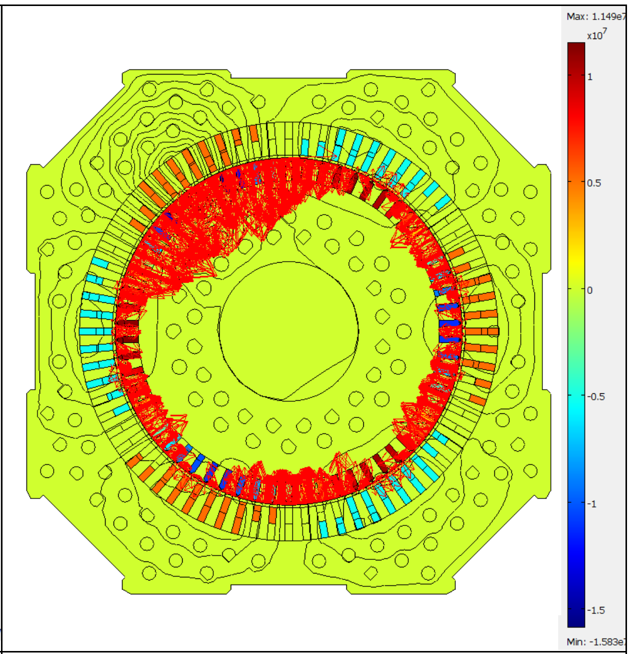
   Moreover:
   - all distributions of quantities (and spectra distribution) in a computer workshop should be constructed in the same range along the axes Y;
   - in the axes of Y, the parameter values **must be** correctly signed in all the figures (in the **Matlab**);
   - in the spectra of these two parameters only the intact IM must be signed the designation of frequencies along the X axis (in the **Paint** program or manually on the printed protocol of the workshop);
   - it is necessary to place 2 graphs or a spectrum next to each other for the comparison.

8. Give a table (not a graph, since only 2 points), in which numerically compare the studied harmonics amplitudes in the spectra of the vibroperturing forces for the intact IM and IM, which is damaged (watch **table 5.2**):
   a. a normal component of the magnetic tension tensor (11 variables);
   b. a normal component of magnetic induction (9 variables).
9. Spectra of vibrational acceleration, vibrational velocity and vibrational displacement only for the normal component of the magnetic tension tensor, obtained in the program **Matlab.** (3 figures)
10. Conclusions. In the conclusions it is necessary to explain the influence of IM's bars damages on the distributions and spectra distribution of the researched quantities. I order to protect the computer workshop, student must comment on the findings using protocol drawings.

Table 5.3 shows an example – a comparison of the vibroperturbing forces study results in the induction motor CTA-1200.

Table 5.3 Comparison of the vibroperturbing forces study results in the induction motor CTA-1200

<table>
<tr>
<td>


</td>
<td>


</td>
</tr>
<tr>
<td>a)</td>
<td>b)</td>
</tr>
<tr>
<td colspan="2">Fig. 5.47 – Spatial distribution of the vibroperturbing forces with electromagnetic origin: a) undamaged IM; b) IM with three damaged rods</td>
</tr>
</table>

Table 5.3 (continuation)

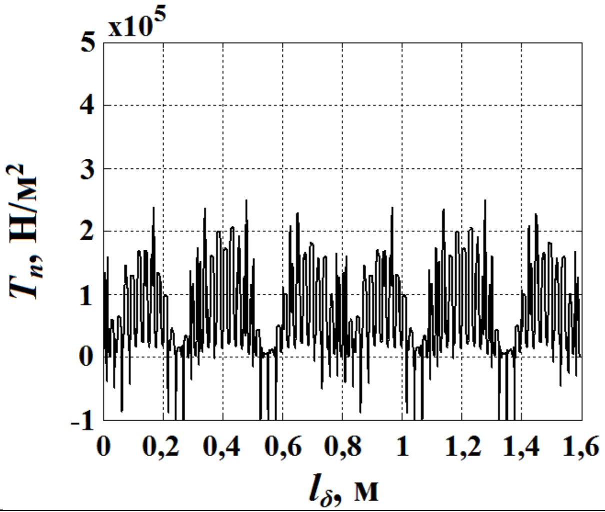
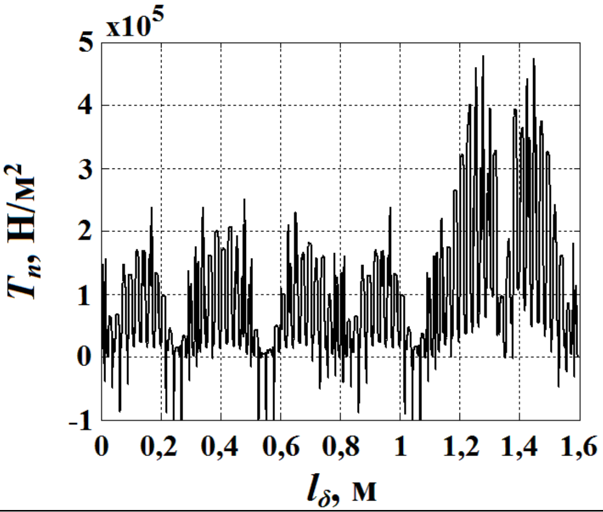
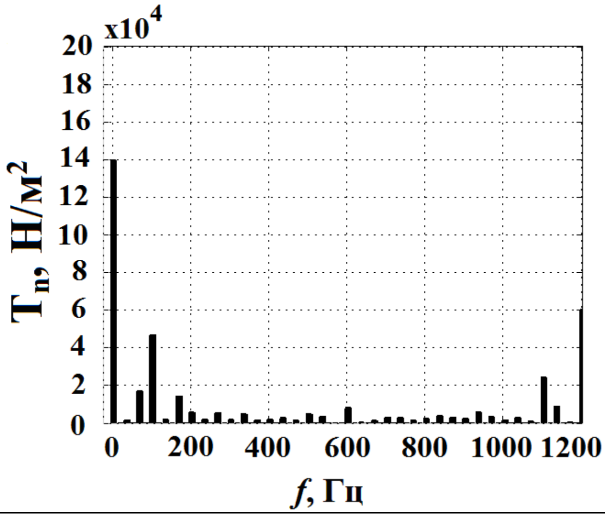
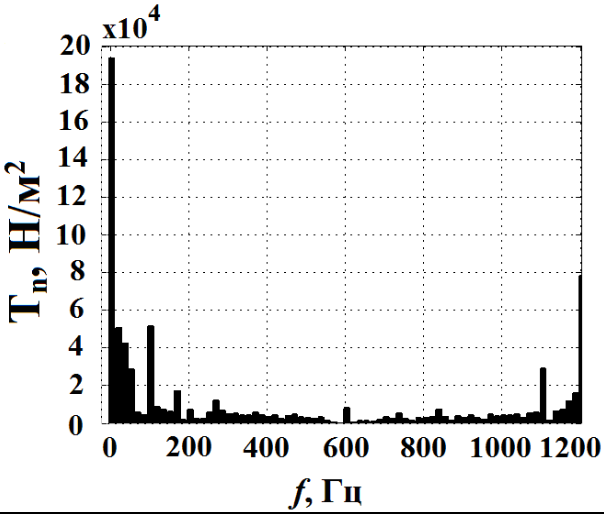
<table>
<tr><td>
</td><td>
</td></tr>
<tr><td>a)</td><td>b)</td></tr>
<tr><td colspan="2">Fig. 5.48 – Spatial distributions of the magnetic tension tensor normal component T_n along the stator cutting: a) undamaged IM; b) IM with three damaged rods
(Distributions must be presented in one scale on the axis Y)</td></tr>
<tr><td>
</td><td>
</td></tr>
<tr><td>a)</td><td>b)</td></tr>
<tr><td colspan="2">Fig. 5.49 – Spectra of spatial distributions of the magnetic tension tensor normal component T_n along the stator cutting: a) undamaged IM; b) IM with three damaged rods
(Spectra of distributions must be presented in one scale on the axis Y)</td></tr>
</table>

Table 5.3 (continuation)

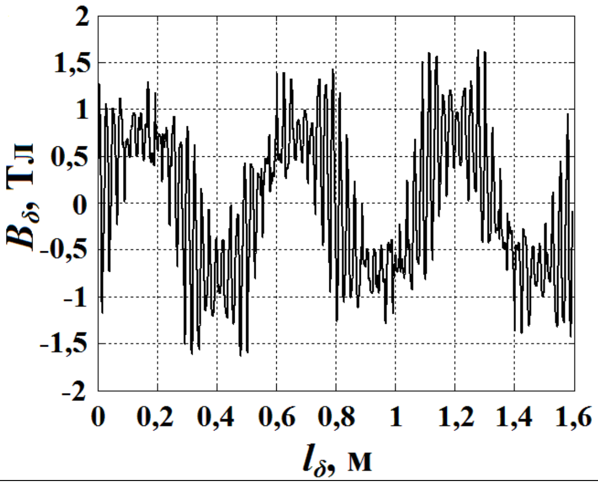
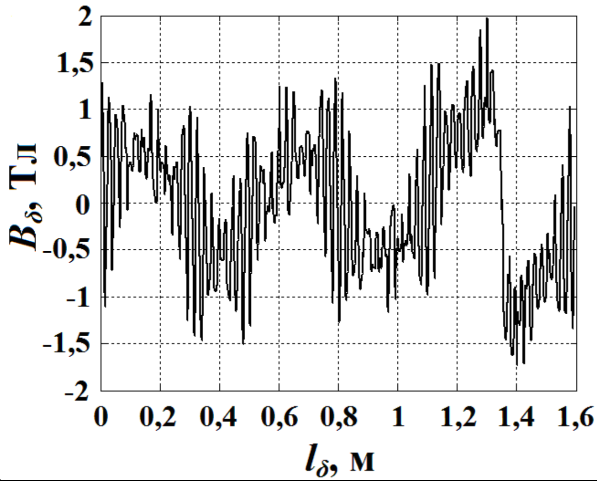
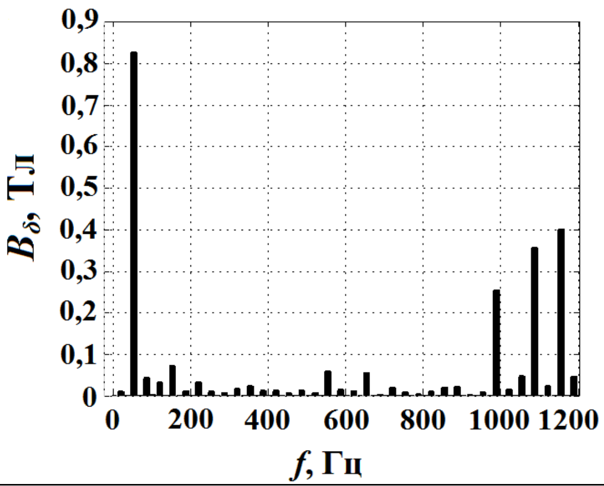
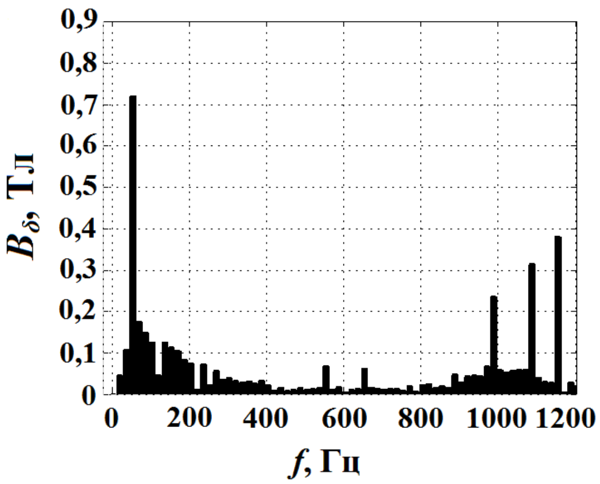
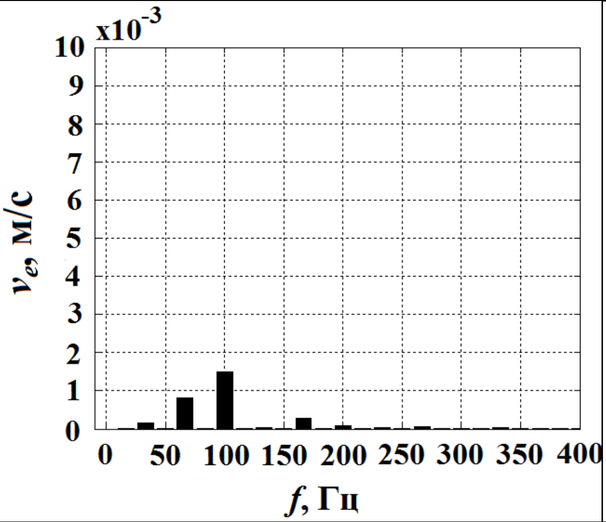
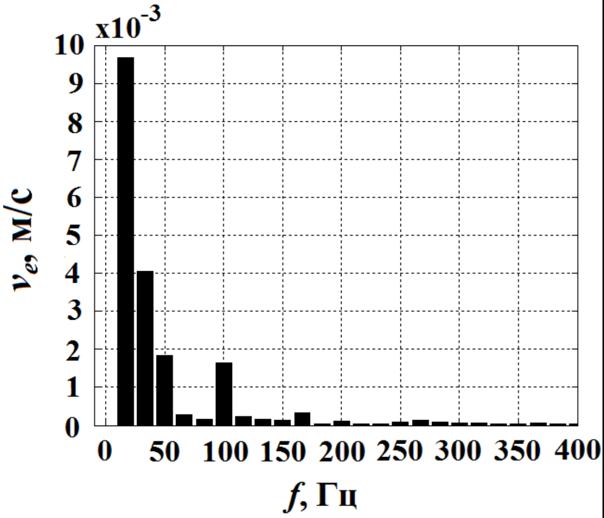
<table>
<tr><td></td><td></td></tr>
<tr><td>a)</td><td>b)</td></tr>
<tr><td colspan="2">Fig. 5.50 – Spatial distributions of the magnetic induction normal component B_n along the stator cutting: a) undamaged IM; b) IM with three damaged rods
(Distributions must be presented in one scale on the axis Y)</td></tr>
<tr><td></td><td></td></tr>
<tr><td>a)</td><td>b)</td></tr>
<tr><td colspan="2">Fig. 5.51 – Spectra of spatial distributions of the magnetic induction normal component B_n along the stator cutting: a) undamaged IM; b) IM with three damaged rods
(Spectra of distributions must be presented in one scale on the axis Y)</td></tr>
</table>

Table 5.3 (continuation)

	
a)	b)
Fig. 5.52 Spectrum of vibrational velocity for variants: a) undamaged IM; b) IM with three damaged rods	

Computer workshop №6

Research by the methods of mathematical modeling of the electromagnetic vibroperturbing forces spectra in an induction motor: intact and in the presence of a rotor static eccentricity in programs Comsol Multiphysics and MatLab

(4 hours)

Work objective. Analyze changes in the electromagnetic vibrperturbing forces signals spectra of an induction motor in the appearance of the rotor static eccentricity in the programs **Comsol Multiphysics** and **MatLab**.

Work program:

1. create a model of intact IM in the program **Comsol Multiphysics**;
2. simulate several (3 ... 5) values of the static eccentricity of the IM's rotor;
3. obtain schedules of the magnetic tension tensor normal component distribution along the IM rotor surface (or the line along the middle of the air gap in IM) for the intact IM and IM, which has a static eccentricity of the rotor;
4. write the formulas and calculate the harmonics frequency in the intact IM and IM, which has a static eccentricity of the rotor;
5. obtain distributions and spectra of the magnetic tension tensor for an intact IM and IM which has a static eccentricity of the rotor in the program **MatLab**;
6. numerically analyze the change in the harmonic's amplitudes in the vibroperturbing forces spectra for the intact IM and IM which has the static eccentricity of the rotor;
7. create a report about the implementation of a computer workshop. Protect your computer workshop.

Methodical instructions for the implementation of a computer workshop.

To perform this computer workshop, students should use the experience gained in a computer workshop №5.

In order to get acquainted with the work in this computer workshop, you must listen the information from the teacher about the computer workshop or watch the video [17].

In this computer workshop, the static eccentricity of the rotor in IM is studied (Fig. 6.1).

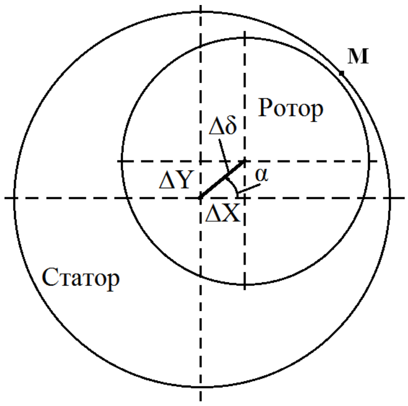


Fig. 6.1 – Eccentricity of the IM's rotor

The magnitude of eccentricity is convenient to characterize by the coefficient of relative eccentricity ε:

$$\varepsilon = \frac{\delta_{\max} - \delta_{\min}}{\delta_{\max} + \delta_{\min}},$$

where $\delta_{\max}, \delta_{\min}$ - maximal and minimal values of the air gap in the IM, *Δδ* – value, on which the axis of the rotor is displaced relatively to the stator axis.

$$\delta_{max} = \delta + \Delta\delta,$$

$$\delta_{min} = \delta - \Delta\delta,$$

The coefficient of relative eccentricity ε varies from 0 ($\delta_{\max} = \delta_{\min}$ – absence of eccentricity) to 1 ($\delta_{\min} = 0$–the rotor touches the stator).

The student should create a table for the IM according to the work variant (for example, as Table 6.1). Table 6.1 shows the numerical values of the quantities that characterize the eccentricity on an example of IM with δ = 6mm. In IM, the maximum value of the rotor displacement is such (2.9 mm) so that the rotor does not touch the line passing through the middle of the air gap in IM.

Table 6.1 Numerical values of the quantities characterizing the eccentricity of IM with δ=6 mm.

Parameter	Parameter's value			
Δδ, mm	0	1,3	2,5	2,9
δ_{max}*, mm*	6	7,3	8,5	8,9
δ_{min}*, mm*	6	4,7	3,5	3,1
Coefficient of comparative eccentricity ε	0	0,22	0,42	0,48

To 1st point:

It is necessary to create a model of intact IM in the program **Comsol Multiphysics** (watch 1st point of computer workshop №5).

To 2nd point:

It is necessary to simulate several (3 ... 5) variants of the rotor static eccentricity in the IM. In order to simulate several variants of the rotor static eccentricity in the IM, it is necessary to displace the rotor in the sketch in the **AutoCad** program. In this case, the displacement of the rotor must not exceed half of the air gap thickness so that the rotor does not intersect with the line in the middle of the air gap.

It should be noted that when the rotor is displaced in the model of IM in **Comsol Multiphysics**, the grid of finite elements will be completely rebuilt, resulting in a change in the number of calculation points on the graph of the magnetic tension tensor distribution (and induction). For each magnitude of the eccentricity, the value of **r21** in **Matlab** will be individual.

To 3rd point:

It is necessary to obtain schedules of magnetic tension tensor normal components distributions and magnetic induction along the surface of the IM's rotor (or the line along the middle of the IM's air gap) for an intact IM and IM, which has a static eccentricity of the rotor. See 3rd point of the computer workshop №5.

To 4th point:

It is necessary to write the formulas and calculate the harmonics frequencies of the magnetic tension tensor and magnetic induction in the intact IM and IM, which has a static eccentricity of the rotor. See 4th point of the computer workshop №5.

To 5th point:

It is necessary to obtain distributions and spectra of the magnetic tension tensor and magnetic induction for intact IM and IM, which has a static eccentricity of the rotor in the **MatLab** program. See 5th point of the computer workshop №5.

до п. 6:

It is necessary to numerically analyze the change in the harmonics amplitudes of the magnetic tension tensor and magnetic induction for an intact IM and IM, which has a static eccentricity of the rotor.

Bring a table and charts from **Excel**, which show the numerical change in the amplitudes of the studied harmonics in the spectra of the vibroperturbing forces and in the magnetic induction spectra for the intact IM and IM, which is damaged:

a. a normal component of the magnetic tension tensor;
b. a normal component of the magnetic induction,
Show the change of these quantities in absolute and relative units (Figures 6.5, 6.6).

Formulas for determining **the relative change** in vibroperturbing forces in the damaged IM compared with undamaged IM are formed as follows. All of harmonics amplitudes in the magnetic tension tensor spectrum of the damaged IM are compared with the corresponding amplitudes of the harmonics in the magnetic tension tensor spectrum of the intact IM in the relative units (Table 6.2).

The student selects the notation for these coefficients independently, for example:

For the purpose of visualizing the changes in the spectra of the studied values, the following factors should be introduced:

1) Coefficient of constant component change:

$k_0 = \frac{Tn_{\text{У\_0}}}{Tn_{\text{БМ\_0}}}$,

where $Tn_{\text{У\_0}}$- the amplitude of the magnetic tension tensor normal component of the damaged IM,

$Tn_{\text{БМ\_0}}$- the amplitude of the magnetic tension tensor normal component of the undamaged IM.

and so on.

Similar coefficients will be applied to the harmonics amplitudes of magnetic induction, except value of the RMS spectra.

Table 6.2 Definition of the formula for the coefficients of the relative change in the harmonics amplitudes

Harmonic amplitude		Harmonic frequency	Numerator	Denominator
			of the coefficient of harmonic amplitude relative change	
a_0	with the frequency	f_{a_0}=0 Hz.	The amplitudes of these harmonics in **damaged IM**	The amplitudes of these harmonics in **undamaged IM**
a_{ob}		f_{a_ob}	Amplitude of **rotational** harmonic in the spectrum of the magnetic tension tensor of the **damaged IM**	The amplitude of the **fundamental** harmonic of the dual **frequency of 100 Hz** in the magnetic tension tensor spectrum of the **undamaged IM** (for induction - the fundamental harmonic amplitude with the **frequency of 50 Hz** in the magnetic induction spectrum of **undamaged IM**)
a_{100}		f_{a_100}=100 Hz	The amplitudes of these harmonics in **damaged IM**	The amplitudes of these harmonics in **undamaged IM**
a_{Z1}		f_{a_Z1}		
a_{Z1_1}		$f_{a\_Z1\_1}$	The amplitudes of these harmonics in **damaged IM**	The amplitude of **the main stator's toothed harmonic** in the magnetic tension tensor spectrum of the **undamaged IM**
a_{Z1_2}		$f_{a\_Z1\_2}$		
a_{Z2}		f_{a_Z2}	The amplitudes of these harmonics in **damaged IM**	The amplitudes of these harmonics in **undamaged IM**
a_{Z2_1}		$f_{a\_Z2\_1}$	The amplitudes of these harmonics in **damaged IM**	The amplitude of **the main stator's toothed harmonic** in the magnetic tension tensor spectrum of the **undamaged IM**
a_{Z2_2}		$f_{a\_Z2\_2}$		
a_{SKZ}			RMS of the amplitudes of these harmonics in **damaged IM**	RMS of the amplitudes of these harmonics in **undamaged IM**
a_{SKZ_SH}				

To 7th point:

You need to create a report about the implementation of a computer workshop in which to present following.

1. Title letter, work objective and work program.
2. Induction motor parameters according to the task variant.
3. Formulas for determining the frequencies and calculating the harmonics frequencies of the studied IM:
   a. the magnetic tension tensor;
   b. the magnetic induction.
4. Screens of currents distribution in the area of the smallest air gap obtained in the program **Comsol Multiphysics** for an intact IM and IM that is damaged (for example, Fig. 6.2) (2 figures).
5. Vibroperturbing forces **distributions**, obtained in **Comsol Multiphysics** for intact IM and for IM, which has the maximum eccentricity (for example, Fig. 6.3) (4 figures):
   a. a normal component of the magnetic tension tensor;
   b. a normal component of the magnetic induction.
6. Vibroperturbing forces **distributions** and **the spectra distributions,** obtained in the program **Matlab** for intact IM and IM, which has the eccentricity (also intermediate values of eccentricities) (Fig. 6.3):
   a. a normal component of the magnetic tension tensor, (8 figures);
   b. a normal component of the magnetic induction, (8 figures).

   Moreover:
   - all distributions of quantities (and spectra distribution) in a computer workshop should be constructed in the same range along the axes Y;
   - along the axes Y, the parameters values **must be** correctly signed in all the figures (in the **Matlab**);
   - in the spectra of these two parameters only for the intact IM should be signed (in the **Paint** program or manually on the printed protocol) the designation of frequencies along the X axis;
   - it is necessary to place 2 graphs or a spectrum next to each other for the comparison.
7. Present the table and charts from **Excel**, which show the numerical change in the studied harmonics amplitudes in the spectra of the vibroperturbing forces of intact IM and IM, which is damaged:
   a. the normal component of the magnetic tension tensor;
   b. a normal component of magnetic induction.

   Show the change of these quantities in absolute and relative units (tables 6.4, 6.5, Figures 6.5, 6.6).
8. Conclusions. In the conclusions it is necessary to explain the influence of the magnitude of the eccentricity of the IM air gap on the distributions

and the distribution spectra of the researched quantities. To protect the computer workshop, you must comment on the findings using protocol drawings.

Table 6.3 shows an example – a comparison of the vibroperturbing forces study results in an induction motor in case of static eccentricity presence. In tables 6.4 and 6.5 and in Figures 6.5 and 6.6 an example is shown – the changes in the harmonics amplitudes of a magnetic tension tensor when the rotor's static eccentricity in relative units is changed.

Table 6.3 Comparison of the vibrational forces study results in the induction motor in case of static eccentricity presence.

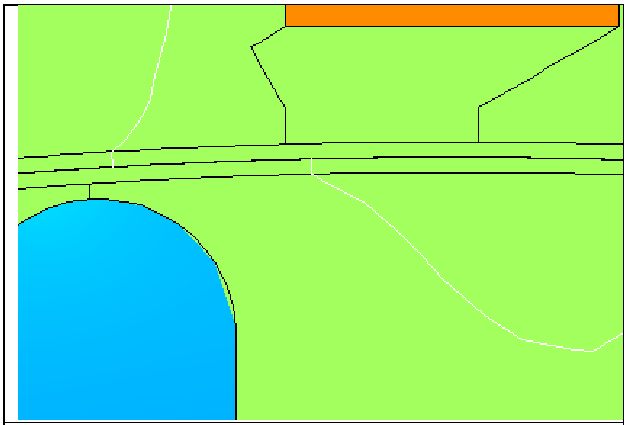
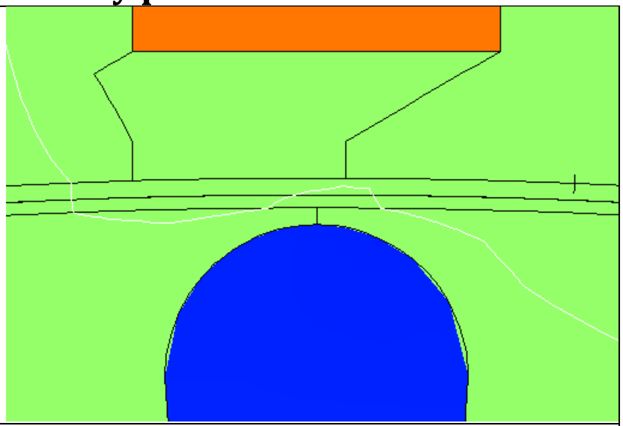
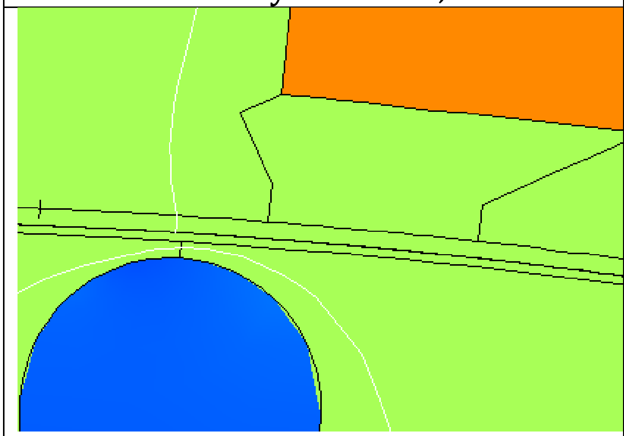
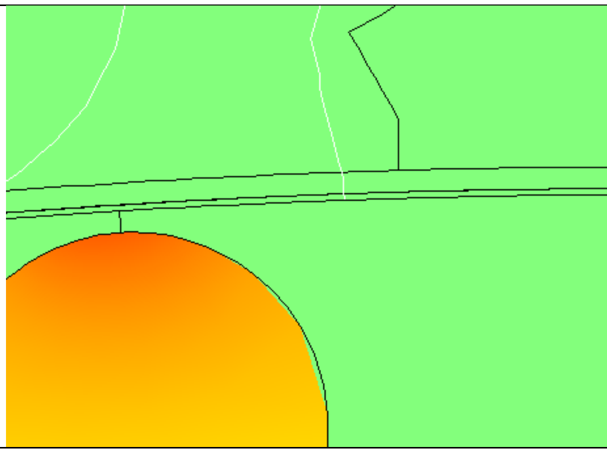
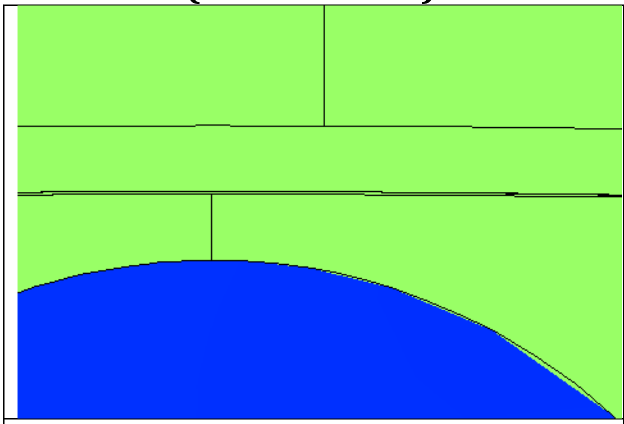
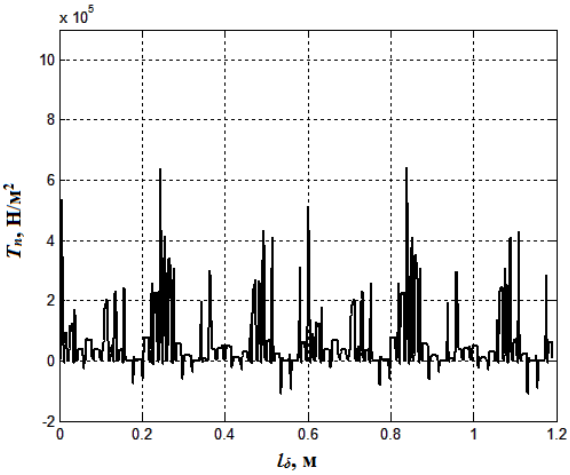
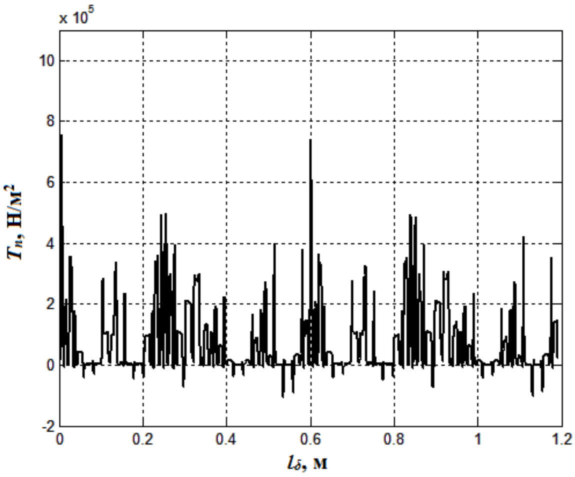
	
Eccentricity is absent, ε = 0	ε = 0.12
	
ε = 0.24	ε = 0.36

Table 6.3 (continuation)

<table>
<tr><td></td><td></td></tr>
<tr><td>ε = 0.48</td><td></td></tr>
<tr><td colspan="2">Fig. 6.2 – Pictures of the IM's active zone which has a different values of eccentricity in the area with the smallest air gap</td></tr>
<tr><td>
</td><td>
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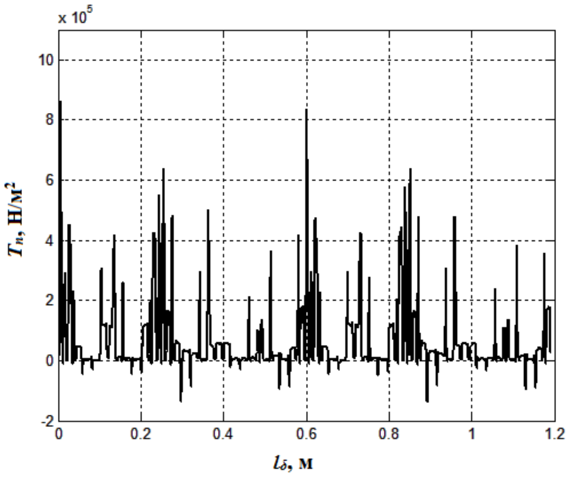
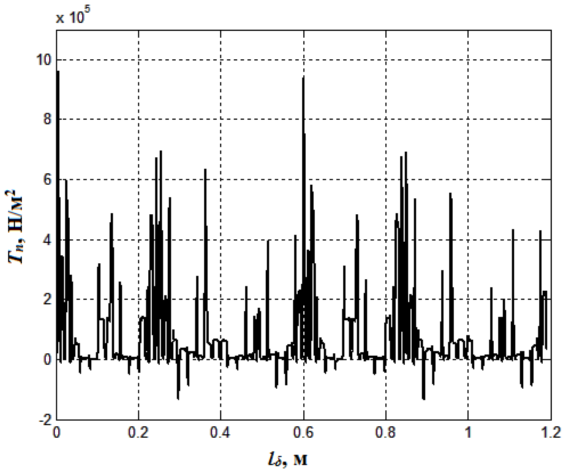
<tr><td>Eccentricity is absent, ε = 0</td><td>ε = 0.12</td></tr>
<tr><td>
</td><td>
</td></tr>
<tr><td>ε = 0.24</td><td>ε = 0.36</td></tr>
<tr><td colspan="2">Fig. 6.3 – Distributions of the magnetic tension tensor for an intact IM and IM, which has a static eccentricity of the rotor
(distributions must be presented in one scale along the Y axis)</td></tr>
</table>

Table 6.3 (continuation)

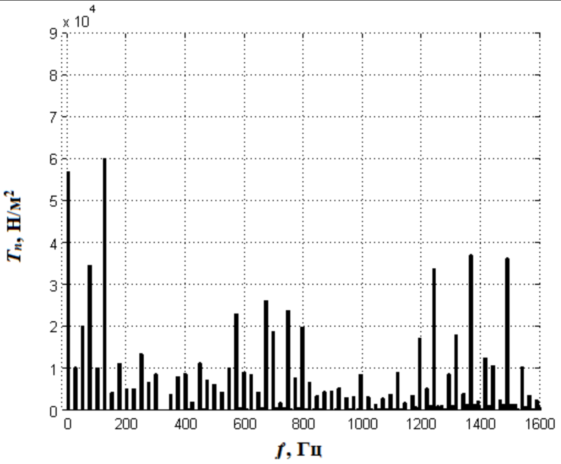
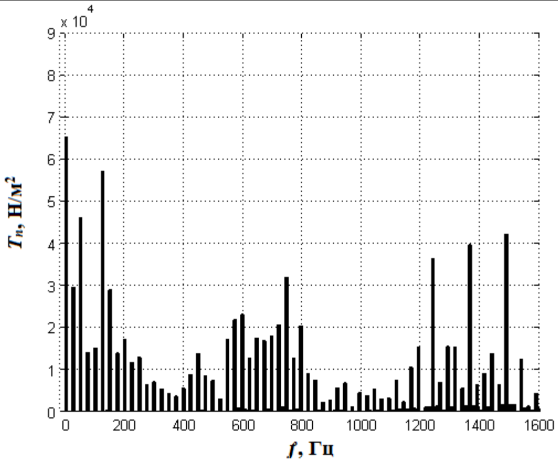
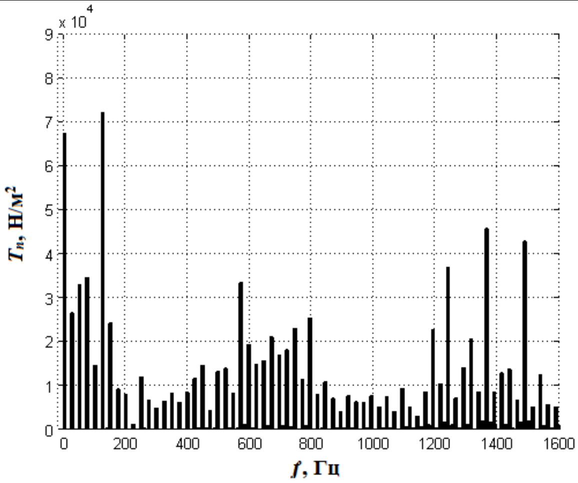
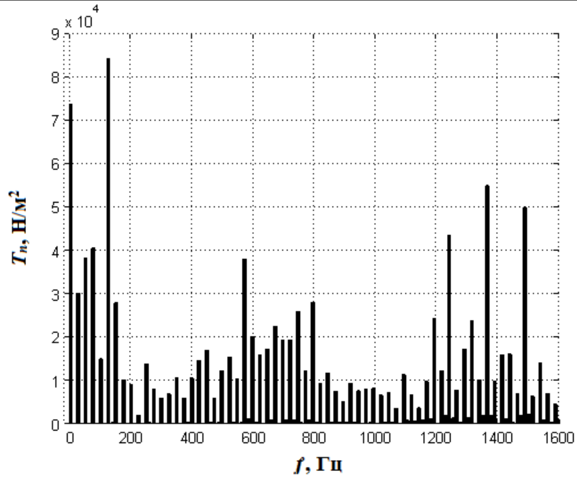
	
Eccentricity is absent, ε = 0	ε = 0.12
	
ε = 0.24	ε = 0.36
Fig. 6.4 – Spectra of magnetic tension tensor distribution for intact IM and IM, which has a static eccentricity of the rotor **(distribution spectra must be presented in one scale on the Y axis)**	

Table 6.4 – Changes in the harmonic's amplitudes of the magnetic tension tensor when changing the rotor's static eccentricity value in absolute units.

Coefficient of relative eccentricity ε	Tensor amplitudes of harmonic, N/m		
	a0	**aZ2**	**aSKZ_SH**
0	56800	10200	36200
0.12	65000	12600	42200
0.24	68000	14700	43000
0.36	73500	15000	50000

Table 6.5 – Changes in the harmonic's amplitudes of the magnetic tension tensor when changing the rotor's static eccentricity value in relative units.

Coefficient of relative eccentricity, ε	The coefficients of harmonic tensor amplitude variation		
	k0	**kZ2**	**kSKZ_SH**
0	1	1	1
0.12	1,14436	1,2352	1,1657
0.24	1,19718	1,4411	1,1878
0.36	1,29401	1,4706	1,3812

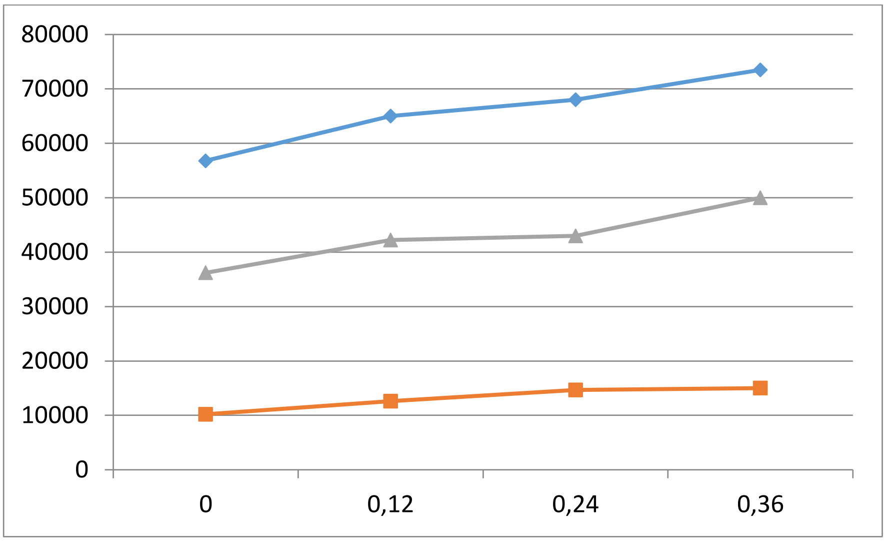


Fig. 6.5 – Changing the harmonics amplitudes of the magnetic tension tensor in absolute units.

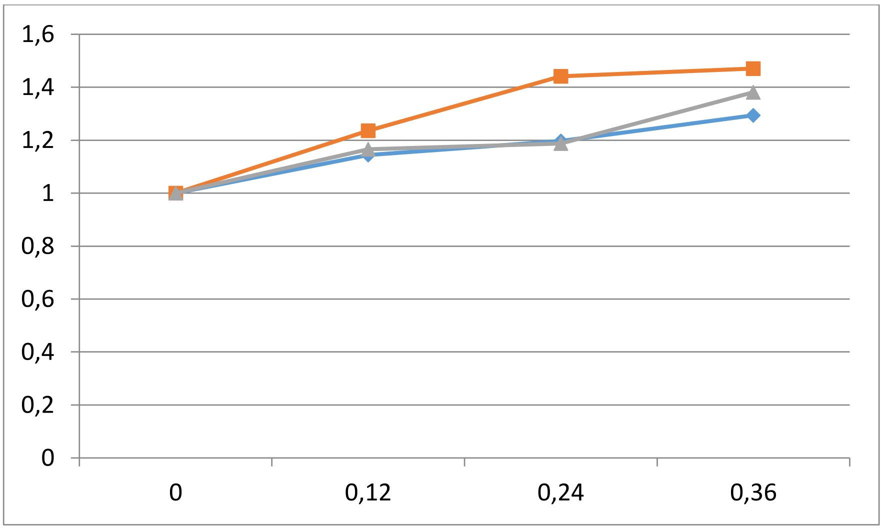


Fig. 6.6 – Changes in the harmonics amplitudes of the magnetic tension tensor in relative units.

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https://www.youtube.com

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