PLOVDIV UNIVERSITY
"PAISII HILENDARSKI"

FACULTY OF PHYSICS AND TECHNOLOGY

DEPARTMENT OF ELECTRICAL POWER ENGINEERING AND COMMUNICATIONS "

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REMOTE LABORATORY FOR ELECTRONIC MEASUREMENT TECHNOLOGY

ABSTRACT

of a dissertation for the acquisition of an educational and scientific degree "DOCTOR"

Field of higher education:
5. Technical sciences

Professional field:
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Doctoral program:
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Scientific supervisor:
Prof. Dr. Eng. Rumen Kostadinov Popov

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The dissertation consists of 232 pages, including 142 figures, 6 tables, structured into an introduction, 5 chapters, general conclusions, scientific-applied and applied contributions, a list of the designations and abbreviations used, and a list of the author's publications. The list of cited literature includes 126 titles.

The numbering of formulas, figures, and tables in the abstract corresponds to that in the dissertation submitted of the scientific jury.

The dissertation was discussed and approved for defense at a meeting of the extended department council of the department "ELECTRICAL POWER ENGINEERING AND COMMUNICATIONS" at the UNIVERSITY OF PLOVDIV "PAISII HILENDARSKI" on 30.06.2026, Protocol No. 86.

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The materials related to the doctoral defense are available to interested parties at the office of the Faculty of Physics and Technology at the UNIVERSITY OF PLOVDIV "PAISII HILENDARSKI", room 213.

Scientific jury: Prof. Dr. Eng. Nadezhda Miteva Kafadarova
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Author: M. Eng. Angel Hristov Chekichev
Title: **REMOTE LABORATORY FOR ELECTRONIC MEASUREMENT TECHNOLOGY**

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GENERAL CHARACTERISTICS OF THE DISSERTATION

Relevance of the problem

The rapid development of information and communication technologies and the growing need for flexible forms of education position distance learning and virtual laboratories as key elements in modern engineering training. This is particularly important for a discipline such as Electronic Measurement Technology, where practical skills constitute a fundamental component of the learners' professional preparation. Limitations related to access to specialized laboratory equipment, its high cost, and the need for continuous maintenance hinder the effective implementation of traditional laboratory classes and necessitate the development of alternative technological solutions.

Virtual laboratories provide the opportunity to conduct real-time experiments regardless of the learners' location, offering a safe, accessible, and economically efficient environment for practical training. Despite the existence of various developments in this field, the implementation of such systems in engineering programs remains limited, highlighting the need to create effective models for remote laboratory environments tailored to the specifics of technical disciplines.

The relevance of the dissertation arises from the need to improve the quality of education in practice-oriented disciplines and from the necessity to ensure equal access to laboratory resources. Traditional laboratory classes are associated with numerous challenges—limited number of workstations, fixed time schedules, high equipment costs, and the impossibility of individual work outside the academic timetable. Modern information technologies create conditions for overcoming these limitations by building virtual laboratory environments that expand the possibilities of classical education and allow the integration of remote forms of practical training.

The present dissertation is focused on the development and investigation of a virtual laboratory in Electronic Measurement Technology, designed to provide a functional, accessible, and technologically sustainable environment for conducting laboratory exercises. The work aims to support the modernization of engineering education, enhance the efficiency of the learning process, and contribute to the preparation of highly qualified specialists capable of working within the framework of contemporary digital engineering practice.

Object and subject of the research:

The **object** of the present research is laboratory setups enabling real-time remote access to an environment for simulations and experimental studies of various electronic devices: Chebyshev and Butterworth filters, band-pass filter, peak detector.

The **subject** of the research is a comparative analysis of the theoretical, simulation, and experimental results obtained using different measurement schemes.

Purpose of the dissertation

The aim of the research is the design, implementation, and testing of tools and methods for remote conducting of laboratory exercises in the discipline Electronic Measurement Technology.

Tasks to achieving the aim:

1. Conduct a review of systems and tools used for building virtual laboratories.
2. Analyze the use of different software environments that enable the creation of remote and virtual laboratories.
3. Develop a methodology for studying different types of devices.
4. Design the hardware of the remote laboratory.
5. Create simulation models of the devices.
6. Develop software enabling remote access to the virtual and remote laboratories.
7. Create laboratory exercises and test the system.

Methods and tools used in the research

The dissertation applies theoretical, analytical, simulation, and experimental methods for studying a Butterworth polynomial filter, a Chebyshev filter, a band-pass filter, and a peak detector. Modern tools and software environments for modelling, simulation, and development of virtual measurement instruments are used.

Implementation and practical applicability

The developed system provides a reliable environment for remote learning and research, optimizes laboratory activities, reduces costs, and ensures equal access to real experiments, measurement resources, and empirical data.

Publications on the topic

The results of the dissertation have been published in five scientific articles: three in the proceedings of the international conference ICERI 2021 and 2022, two in the scientific works of SUB-Smolyan 2024.

Three of the publications were co-authored with the scientific supervisor, and two were written independently by the author.

Volume and structure of the dissertation

The dissertation consists of 232 pages, including 142 figures, 6 tables, structured into an introduction, five chapters, general conclusions, scientific-applied and applied contributions, a list of abbreviations and designations used, and a list of the author's publications. The list of cited literature includes 126 titles.

CONTENT OF THE DISSERTATION

CHAPTER 1. REVIEW OF SYSTEMS AND TOOLS FOR BUILDING VIRTUAL LABORATORIES

Chapter One presents a comprehensive analysis of the concepts and technologies related to remote and virtual laboratories, which are becoming key instruments for modernizing contemporary engineering education. On this basis, the need to develop a remote laboratory for the discipline Electronic Measurement Technology at the Faculty of Physics and Technology of Plovdiv University is substantiated, as the existing infrastructure does not provide sufficient opportunities for practical training.

The analysis of traditional laboratories reveals numerous limitations – high costs, restricted access, and insufficient resources – which hinder the effective acquisition of practical skills. In this context, remote and virtual laboratories emerge as a solution that expands accessibility and enables the simulation of complex measurement processes.

The importance of electronic measurement technology in modern industry is emphasized, where high accuracy and reliability are critical for technological processes. Therefore, training in this field requires a modern, technologically supported environment that fosters the development of practical competencies. The remote laboratory offers precisely such an environment – scalable, economically efficient, and easily integrated into the educational process. It enables students to design, configure, and analyze measurement systems in a controlled digital environment, including the exploration of scenarios that are difficult to implement under real conditions. This approach stimulates analytical thinking, creativity, and the ability to solve engineering tasks.

An international perspective is also considered, highlighting virtual laboratories as a means for collaboration and knowledge exchange among different academic communities. Improving the quality of education and creating conditions for research activities are among the key benefits of such infrastructure.

In conclusion, it is emphasized that the development of a remote laboratory represents a strategic step toward the sustainable advancement of engineering education and the preparation of specialists capable of meeting the requirements of the modern technological environment.

CHAPTER 2. METHODOLOGY OF THE RESEARCH

This chapter examines the methodology for developing, implementing, and evaluating a remote laboratory as an innovative tool for training in the discipline Electronic Measurement Technology. The focus is placed on creating an integrated educational environment that combines simulation technologies, remote access, and interactive functionalities with the aim of increasing the efficiency and accessibility of the learning process.

CONCLUSIONS FROM CHAPTER 2

The characteristics and specific features of active filters in the context of remote measurements have been analyzed, including their ability to suppress noise, provide precise selectivity, and allow parameter adjustment.

The principles of active filter synthesis have been examined in detail, with emphasis on the transfer function, polynomial approximations (particularly the Butterworth approximation), and algorithms for selecting the filter order based on specified frequency requirements. It is demonstrated how filter parameters are determined through mathematical relationships involving logarithmic and normalized calculations in order to achieve the desired characteristics and attenuation.

An analysis has been conducted of specific first- and second-order active filter circuits, examining their structure, frequency response, and amplification properties.

A methodology has been developed for calculating Butterworth and Chebyshev filters, a band-pass filter, and a low-pass Butterworth polynomial filter. Constructive considerations related to minimizing deviations and selecting appropriate operational amplifiers are outlined.

The features and characteristics of peak detectors, their operating principle, and their applicability have also been examined.

In conclusion, the developed methodology for building a remote laboratory environment – supported by an analytical and practice-oriented approach – demonstrates strong potential for improving the quality of engineering education. The combination of theoretical rigor and technological innovation provides a sustainable foundation for integrating modern educational practices into the university environment, while ensuring personalized access, flexibility, and efficiency in training within the discipline Electronic Measurement Technology.

CHAPTER 3. DESIGN OF THE REMOTE LABORATORY

Chapter Three of the dissertation is dedicated to the design of the remote laboratory, in which the main analog modules – Chebyshev and Butterworth filters, a band-pass filter, and a peak detector – are modeled and analyzed.

The design process is carried out through the close interaction of three software-hardware components: simulation in the Multisim development environment, creation of a virtual instrument in LabVIEW, and experimental verification. This three-stage validation ensures both consistency between the simulated real-world response of the system and functional compatibility between the virtual and physical environments. LabVIEW is used not only as an interface but as an active component for performing analysis, visualization, and real-time parameter control. The capabilities of the listed software-hardware components transform the virtual and remote laboratories from a substitute for the physical laboratory into a platform for experimental work, where theory and practice exist in continuous dialogue.

3.1 Design of the tested hardware modules

The design of the tested hardware modules is a fundamental step in the development of the remote laboratory, as it provides the necessary foundation for both simulation and experimental analysis.

This section presents the process of designing and implementing the printed circuit board of the second-order Butterworth low-pass polynomial filter, based on the calculations outlined above. Figure 3.1 shows the schematic diagram of the filter, which serves as the basis for the subsequent development of the printed circuit board topology.

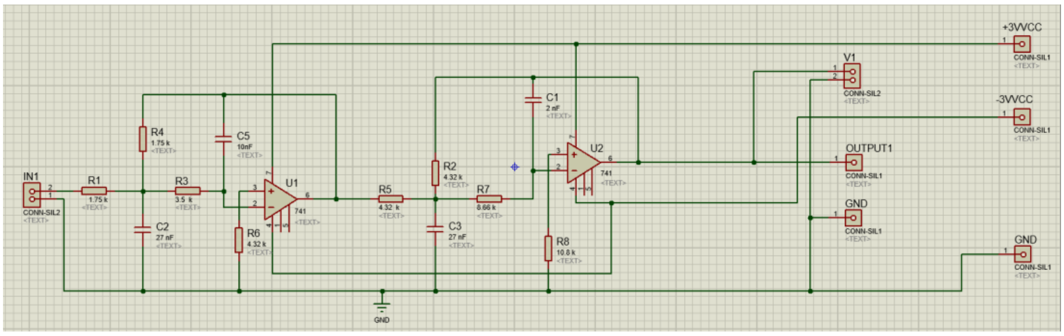


Figure 3.1. Schematic diagram of a second-order Butterworth polynomial low-pass filter

The following figure presents the topology of the conductive tracks of the filter, illustrating the structure and arrangement of the electrical connections on the printed circuit board.

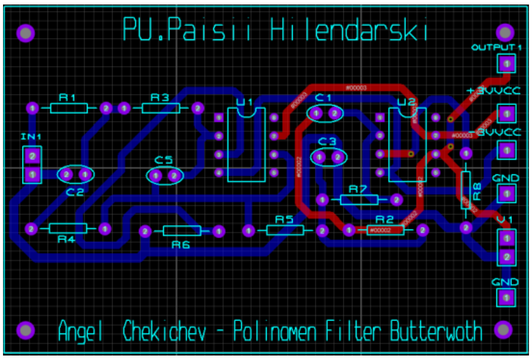


Figure 3.2. Topology of the printed circuit board of the second-order Butterworth polynomial low-pass filter

Figure 3.3 illustrates the physical implementation of the filter and the arrangement of the individual components on the printed circuit board.

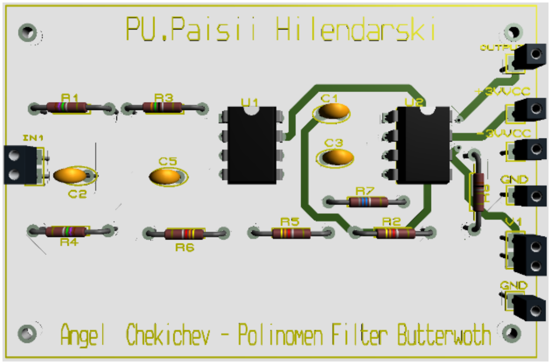


Figure 3.3. Physical implementation of the second-order Butterworth polynomial low-pass filter

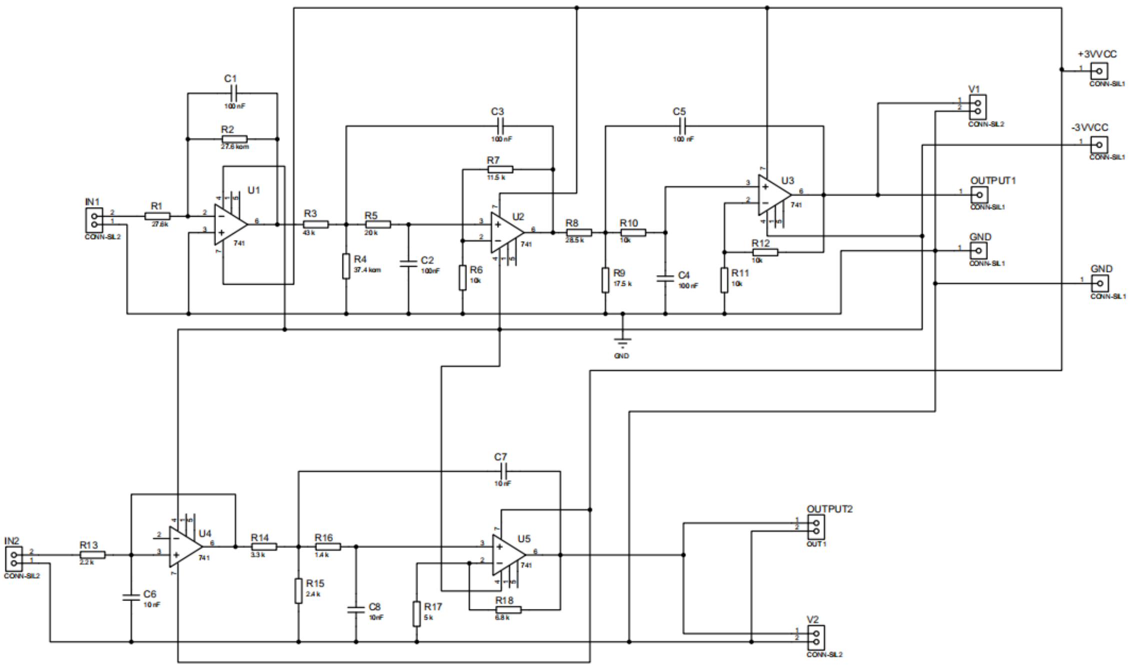


Figure 3.6. Chebyshev filter of third and fifth order

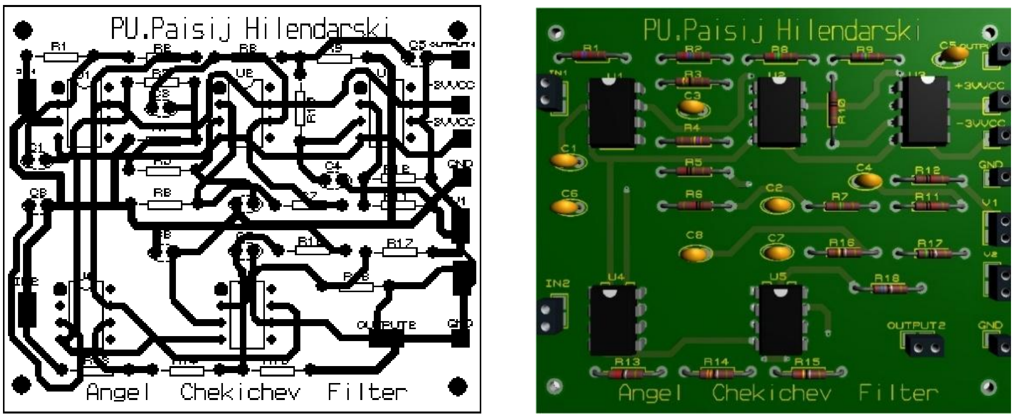


Figure 3.7. Topology of the printed circuit board and physical implementation of the third- and fifth-order Chebyshev filter

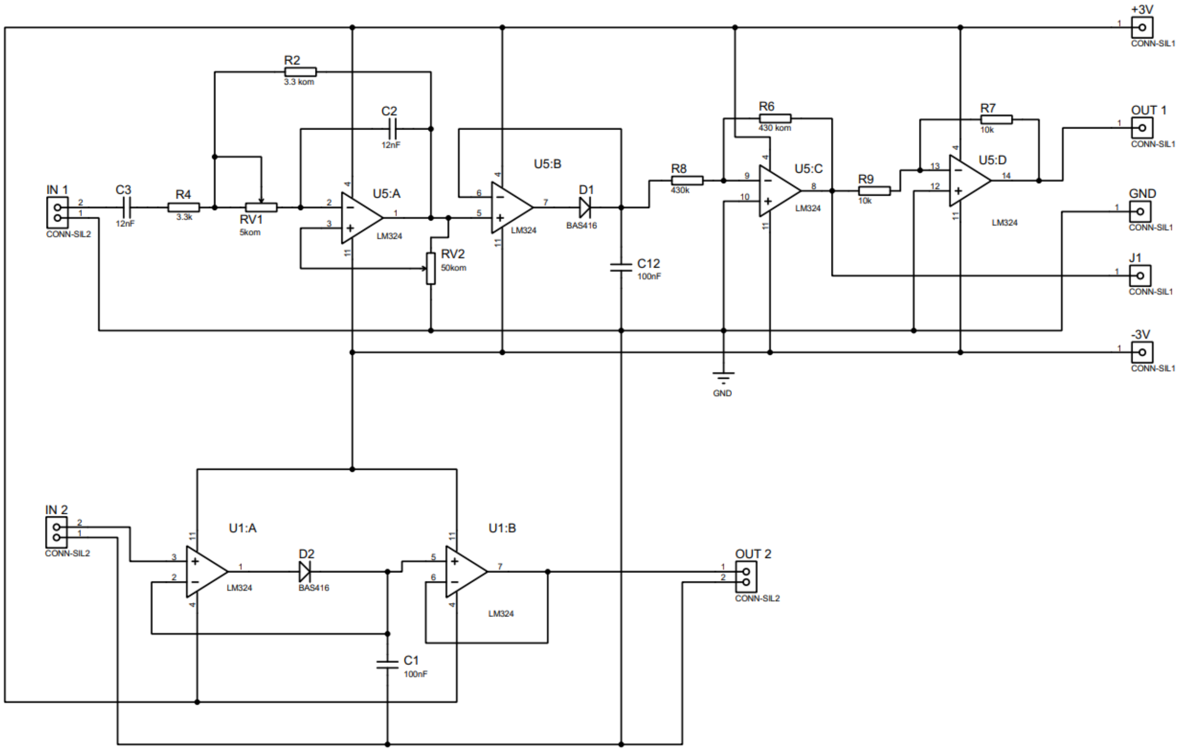


Figure 3.8. Band-pass filter and peak detector

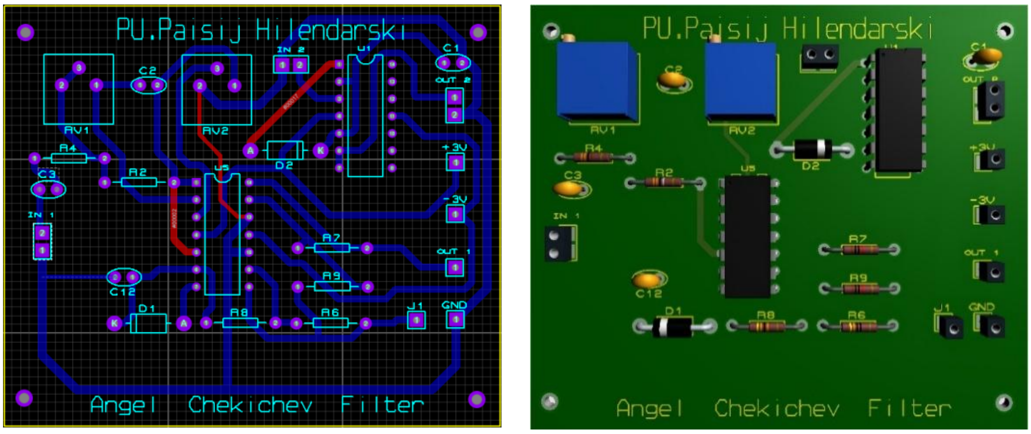


Figure 3.9. Topology of the printed circuit board and physical implementation of the band-pass filter and peak detector

The following figures illustrate the control block implemented through a programmable logic device, which performs the coordination of channel selection, the processing of input and output signals, and the management of the system's actuators in order to ensure correct and reliable operation of the designed system.

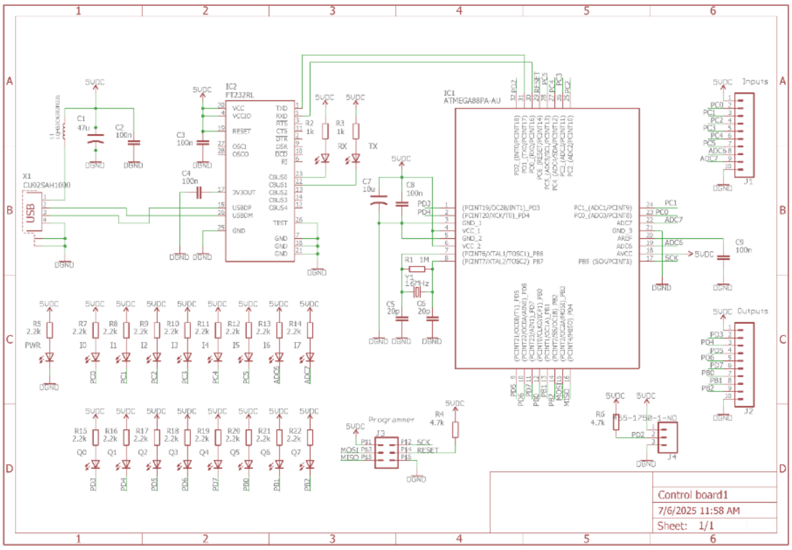


Figure 3.10. Schematic diagram of the control block

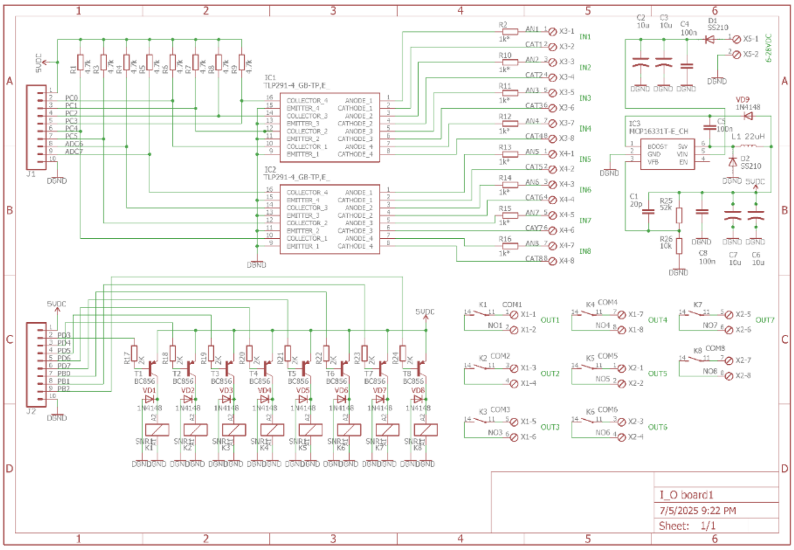


Figure 3.11. Schematic diagram of the input and output interfaces for signal control

The power supply block (Fig. 3.13) is implemented as a linear stabilized power supply with several independent output voltages. Its main purpose is to convert the alternating mains voltage into stabilized direct voltages suitable for powering electronic devices.

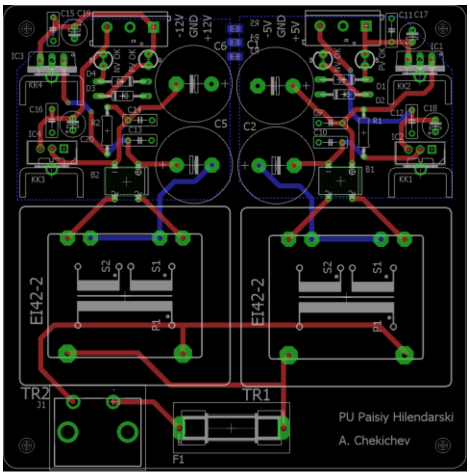


Figure 3.13. Topology of the printed circuit board of the power supply block

3.2 Development of simulation models

In this part of the dissertation, simulation models are developed in the Multisim environment, through which the various Butterworth filters, Chebyshev filters, the band-pass filter, and the peak detector are implemented.

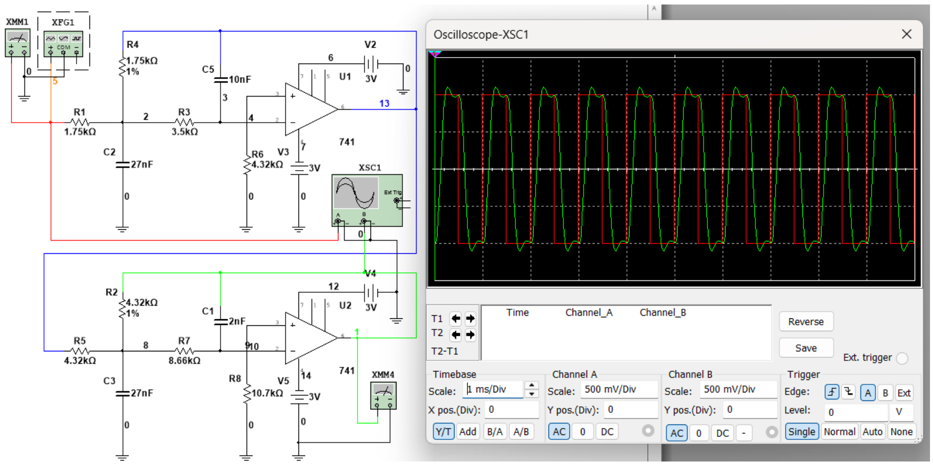


Figure 3.15. Simulation model of the second-order Butterworth polynomial low-pass filter for a rectangular input signal at 1 kHz

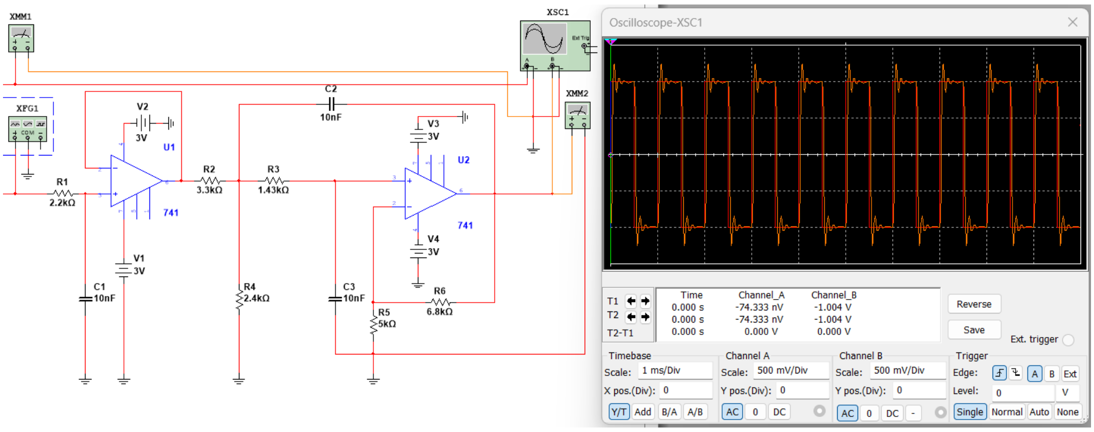


Figure 3.18. Simulation model of the third-order Chebyshev low-pass filter for a rectangular input signal at 1 kHz

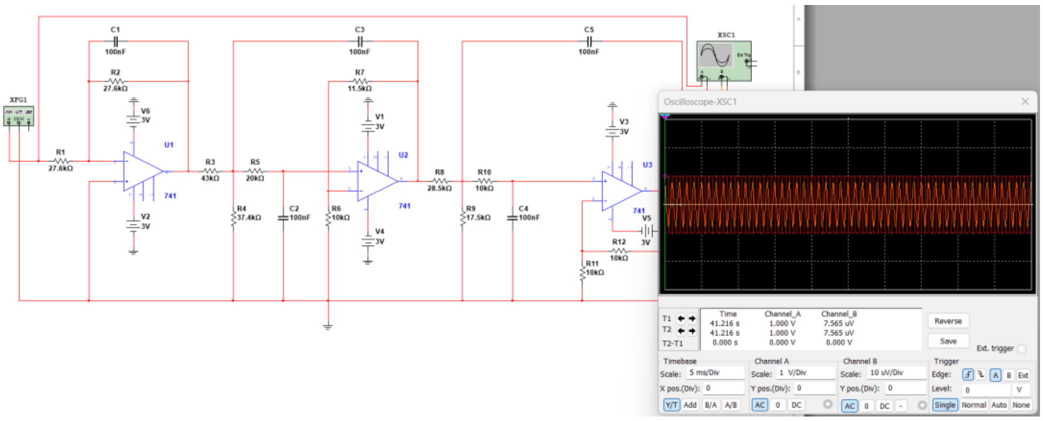


Figure 3.22. Simulation model of the fifth-order Chebyshev low-pass filter for a rectangular input signal at 1 kHz

Conclusions:

The simulation model of the second-order Butterworth filter demonstrates classical behavior with a maximally flat amplitude response in the passband and the absence of ripple. For a sinusoidal input signal, minimal phase shift and negligible attenuation are observed, corresponding to the theoretically expected flat frequency characteristic. When rectangular and triangular input signals are applied, smoothing of the high-frequency harmonic components is evident, and the output signal acquires a more sinusoidal form. This confirms the effective suppression of high-frequency components and demonstrates the low-pass selective nature of the structure.

The third-order Chebyshev low-pass filter exhibits a steeper transition-band characteristic compared to the Butterworth filter. The simulation results confirm the presence of faster attenuation outside the passband, which is typical for this type of approximation. The time-domain response to non-sinusoidal signals shows more pronounced transient processes and slight amplitude irregularities, resulting from the allowed ripple in the passband.

For the fifth-order Chebyshev filter, even stronger selectivity is observed. As the filter order increases, a significantly steeper characteristic and improved suppression of unwanted frequency components are achieved. This is confirmed by the shape of the output signal under rectangular and triangular excitation, where high-frequency harmonics are strongly reduced.

Finally, the results illustrate the theoretical relationships between filter order, approximation type, and frequency-response selectivity. Increasing the filter order improves the steepness of the transition band and the ability to suppress unwanted frequencies, but at the cost of more complex dynamics and increased phase shift. The Butterworth filter provides better passband flatness, while Chebyshev filters offer higher selectivity.

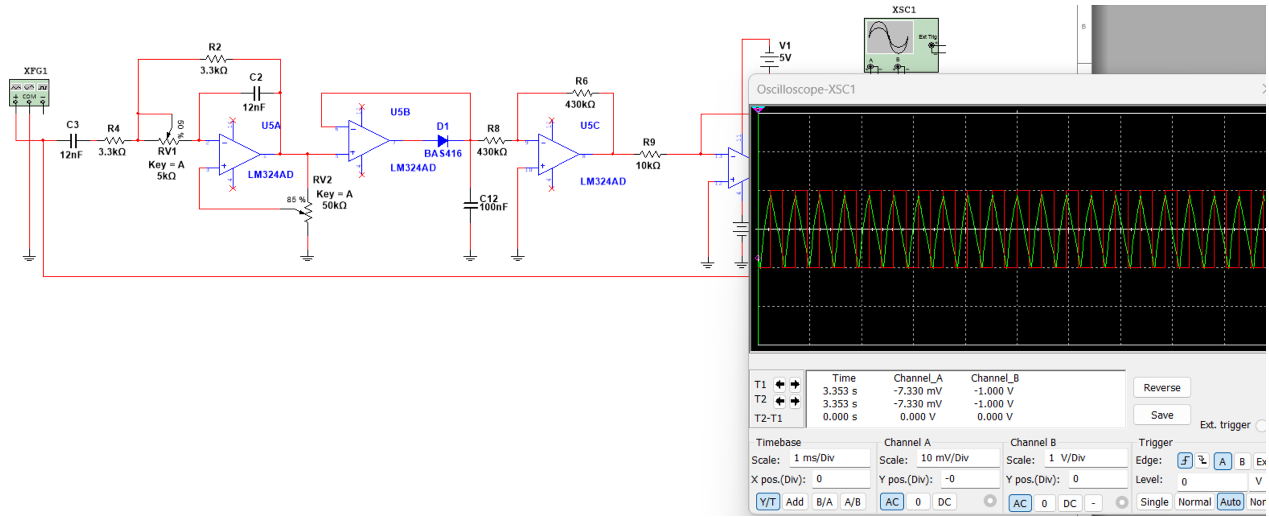


Figure 3.25. Simulation model of the band-pass filter for a rectangular input signal at 2.1 kHz

<u>Conclusions:</u>

The implemented band-pass filter demonstrates typical selective behavior, characterized by passing signals within a narrow frequency range around 2.1 kHz and attenuating frequency components outside this region. When a sinusoidal signal with a frequency equal or close to 2.1 kHz is applied, the output exhibits maximum amplitude and minimal distortion; therefore, the operating point of the filter corresponds to the designed center frequency.

For non-sinusoidal input signals (rectangular and triangular), a clearly pronounced spectral selection is observed. Since these signals contain a significant number of harmonic components, the band-pass filter passes the fundamental harmonic if it falls within the region around 2.1 kHz and effectively suppresses the remaining ones. As a result, the output signal acquires a quasi-sinusoidal form, which directly demonstrates the frequency selectivity of the designed system.

From a dynamic perspective, a phase shift between the input and output signals is observed, dependent on the frequency and the quality factor of the filter.

It can be concluded that the developed band-pass filter operates correctly at a center frequency of approximately 2.1 kHz, providing selective transmission of signals within the specified range and effective suppression of spectral components outside it.

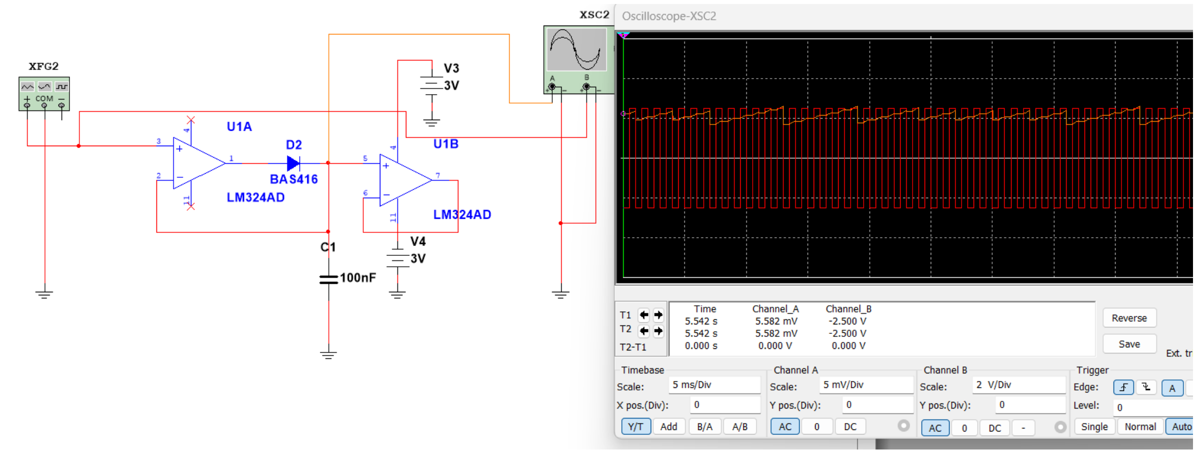


Figure 3.28. Simulation model of the peak detector for a rectangular input signal at 1 kHz

Conclusions:

In the presented circuit, a peak detector is implemented using two LM324 operational amplifiers, a diode, and a 100 nF capacitor. The operational amplifiers are powered from ±3 V, and the applied input signal is sinusoidal, triangular, or rectangular with a frequency of 1 kHz, an amplitude of 2.5 V, and a positive offset of 5 V. This means that the signal varies approximately between 2.5 V and 7.5 V.

The first operational amplifier works together with the diode as a precision rectifier. When the input voltage increases, the diode conducts and the capacitor charges to the instantaneous maximum value. When the input decreases, the diode becomes reverse-biased and the capacitor retains the reached voltage. Due to the absence of a discharge resistor, the capacitor discharges only through input currents and leakage paths.

The oscilloscope trace shows the characteristic “stepped” or serrated shape of the voltage across the capacitor. This indicates that it recharges at each new higher peak and holds the value between pulses.

The second LM324 is configured as a voltage follower. Its purpose is to isolate the capacitor from the load. The oscilloscope trace shows that the output voltage follows the capacitor voltage, which confirms that the buffer stage operates correctly within the permissible range.

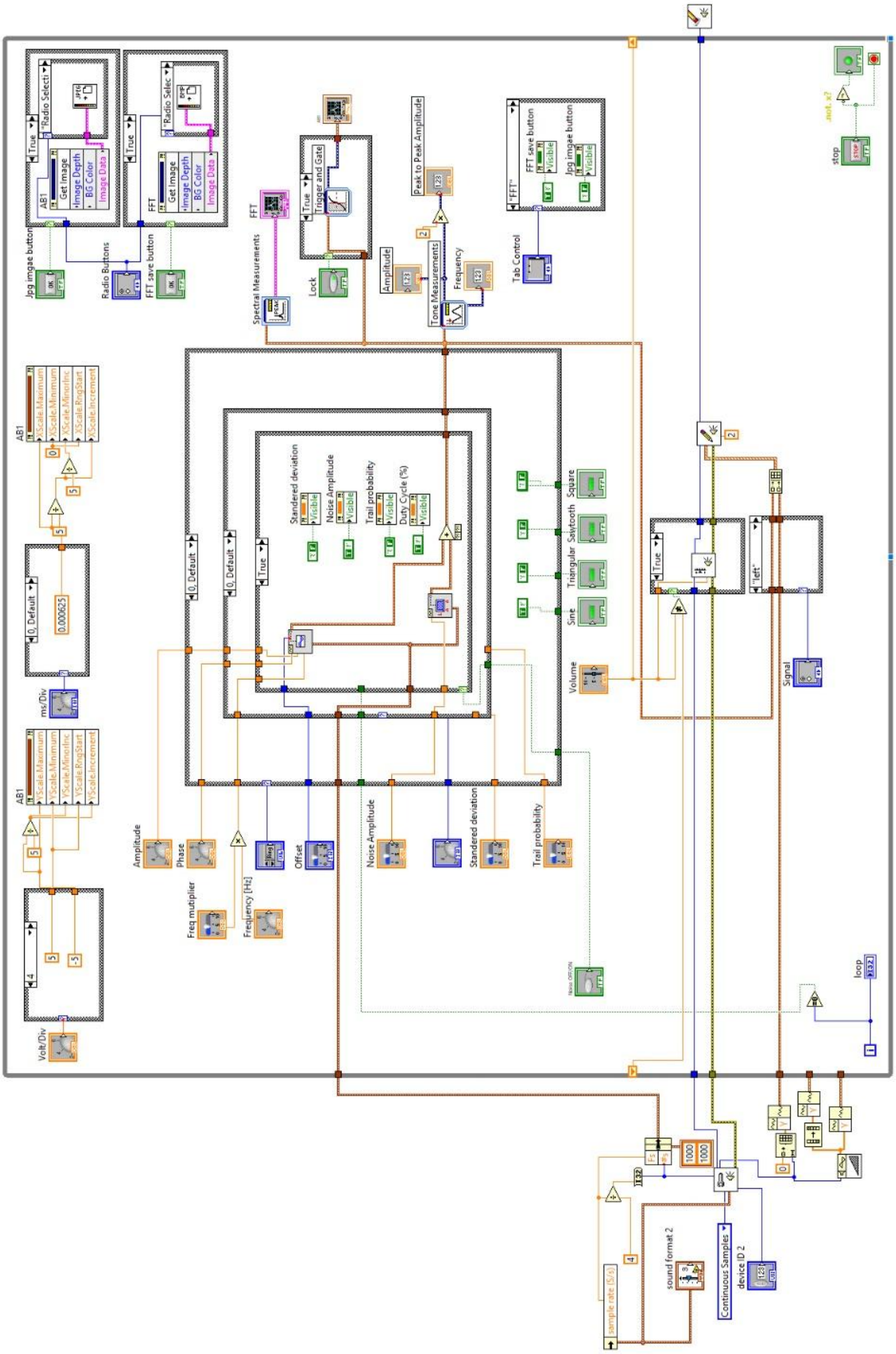
3.3 Design of the virtual instrument in LabVIEW

In this part of the dissertation, a virtual instrument is designed using LabVIEW. It utilizes the available hardware and software to facilitate signal analysis, experimentation, and verification of different types of signals.

3.3.1. Development of a function generator in LabVIEW

The development of the function generator in LabVIEW involves creating a component responsible for signal simulation and the generation of various waveform types.

The complete block diagram of the implemented function generator is as follows:



3.4 Remote access to the virtual laboratory environment

Students work in virtual machines (VMs) preconfigured with LabVIEW and a specialized virtual instrument, which ensures a standardized, controlled, and uniform environment for all participants. Access to these VMs is provided through a web interface implemented using Apache Guacamole and the VNC protocol, allowing operation from various devices without the need for local installations or specific Windows versions. Each virtual machine functions as an isolated and secure environment, independent of the hardware and settings of the students' devices, ensuring consistency and security of the work.

After logging in with a unique account, the student selects their VM and loads the desktop directly in the browser, from where LabVIEW can be launched to perform simulations, analyses, and data processing. All files and results are stored within the virtual environment, ensuring repeatability and compliance with academic requirements. To support simultaneous access for a large number of students, cloned VMs with separate VNC ports and passwords are used, guaranteeing independent work without conflicts. This architecture enables centralized management, easy maintenance, and rapid updates of the tools, which is particularly important for large groups.

The main advantages include equal access, high security, scalability, and minimization of technical issues related to local installations. The limitations are reduced to the need for a stable internet connection and sufficient server resources to support all concurrent sessions.

Figure 3.79. Block diagram of the remote access to the virtual laboratory environment

3.5 CONCLUSIONS FROM CHAPTER 3

This chapter develops a comprehensive concept for building a virtual laboratory based on integrated interaction between analytical synthesis, simulation modeling, and hardware implementation. The methodological contribution lies in applying a three-stage engineering verification process – mathematical modeling, simulation, and physical realization – which ensures a high degree of consistency between theory and practice.

The practical validity of the approach is confirmed through the synthesis, simulation, and implementation of second-order Butterworth filters and third- and fifth-order Chebyshev low-pass filters. The obtained results show that increasing the filter order improves selectivity and the suppression of harmonic components, while simultaneously leading to a more complex dynamic response. It is established that Butterworth filters provide a uniform passband frequency characteristic, whereas Chebyshev filters achieve a steeper transition region at the expense of controlled ripple. The experimental results match the theoretical calculations within acceptable technological tolerances, confirming the validity of the approximation models used. The physical realization on printed circuit boards demonstrates the applicability of the methodology when using standard component values and tolerances, highlighting the importance of topology, feedback paths, and supply bypassing for frequency stability.

The implemented band-pass filter with a center frequency around 2.1 kHz and the peak detector exhibit the expected selective and measurement characteristics consistent with theoretical predictions.

The developed virtual instrument in LabVIEW provides a function generator, automated measurements, spectral analysis, and oscilloscope visualization, while enabling integration with real hardware. The completed design, modeling, experimental implementation, and virtual instrumentation demonstrate the feasibility of constructing an integrated virtual laboratory environment.

CHAPTER 4. RESULTS OF THE EXPERIMENTAL INVESTIGATIONS

The fourth chapter of the dissertation presents the results of the experimental investigations aimed at validating the developed remote laboratory system and assessing its practical applicability. The main objective of the investigations is to confirm the effectiveness of the methodologies proposed in Chapter 2, to verify the operation of the hardware solutions implemented in Chapter 3, and to analyze the obtained results using the employed measurement equipment and the tools for process control and monitoring.

4.1. Validation of the data

To validate the correct operation of the signal generator and the system, it is necessary to confirm that the generated signals correspond to the specified parameters – signal shape, amplitude, and frequency – as well as that these parameters are measured accurately by the employed measurement instrument. For this purpose, a Siglent SDS1052DL digital oscilloscope with a 50 MHz bandwidth is used as the reference measurement device.

4.2. Configuration and setup for conducting the experimental investigations

As part of the experiment, a personal computer is used with the LabVIEW software installed on it, along with the experimental circuit. The computer controls the generator software, the signal-generation process, and the operation of the measurement instrument for independent recording, visualization, and analysis of the measured data.

Figure 4.1. The input and output of the computer used during the measurements and analysis

The connection between the computer and the equipment is established via an AUX cable. On the remote experimental stand, separate input and output connectors (fig. 4.2) are provided for delivering the signal from the computer to the system and its subsequent processing within the measurement circuit.

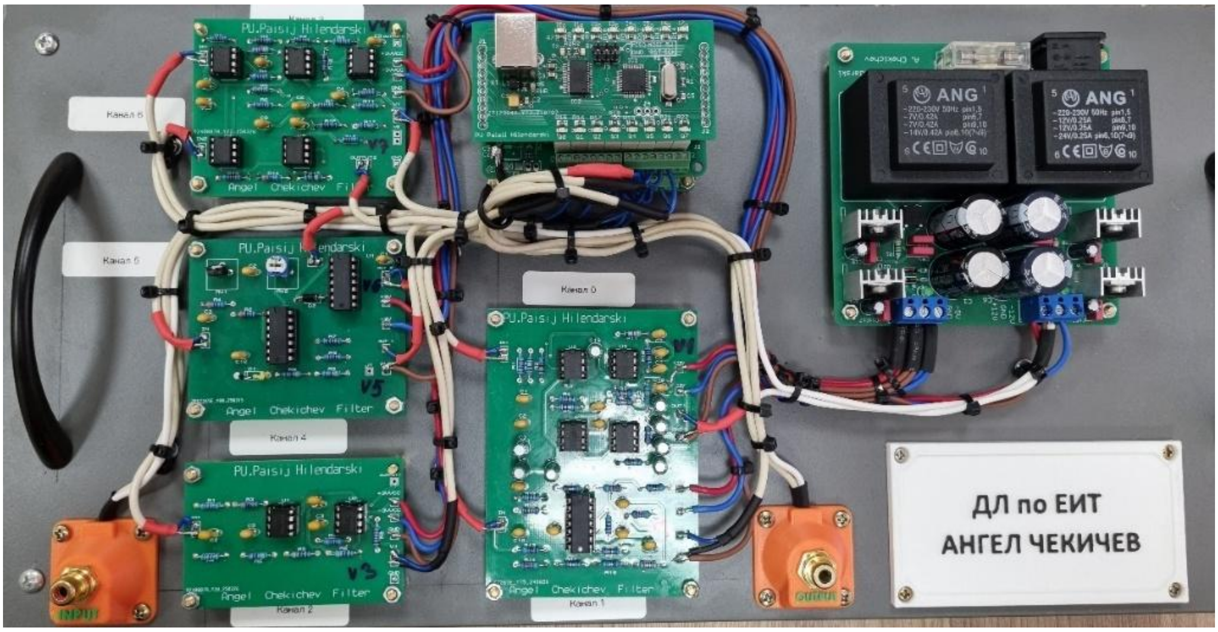


Figure 4.2. Remote experimental stand

Figure 4.3 presents the main window of the function generator and its primary control elements. Through this interface, the parameters of the generated signal are configured, which are required for conducting the experiment and for its subsequent measurement and analysis.

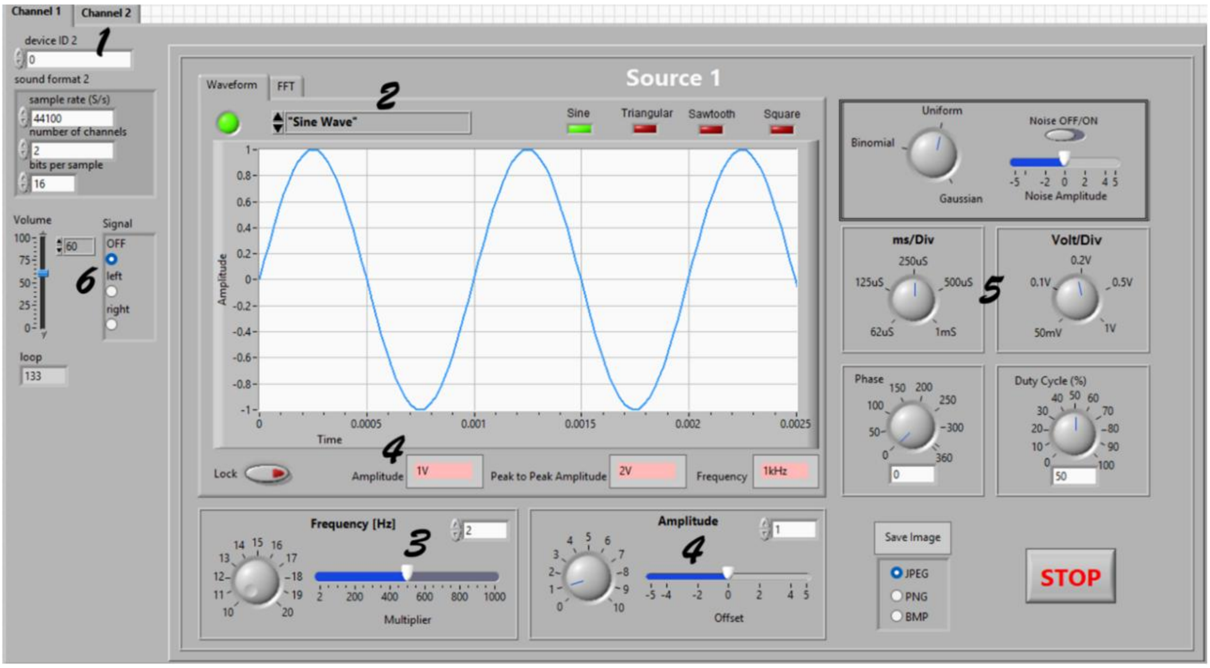


Figure 4.3. User interface of the function generator configured to generate a sinusoidal signal with a frequency of 1 kHz and an amplitude of 1 V

During the execution of the experiment, a single signal source (1) is used to generate the test signal. In the next step, the signal shape (2) is selected, and for the purposes of the measurement a sinusoidal waveform (Sine Wave) is chosen. This type of signal is widely used in testing and validation of measurement systems because it allows straightforward determination of key parameters such as amplitude, frequency, and phase characteristics.

The frequency of the generated signal is set to 1 kHz (3). The choice of this frequency enables stable observation of the signal and convenient measurement with the employed instrument. The amplitude is set to 1 V (4), which is sufficient for clear visualization and accurate measurement without risking overload of the instrument's input.

For proper observation of the signal on the screen, an appropriate adjustment of the scale divisions (5) must be performed. This regulates the vertical and horizontal sensitivity of the visualization so that the waveform is clearly visible and occupies a suitable portion of the screen for easy analysis of its parameters.

In the final step, the output channel (6) is selected through which the generated signal will be delivered to the measurement system. Correct channel selection is essential for proper connection between the generator and the measurement instrument and for ensuring reliable transmission of the signal to the instrument's input.

The user interface of the measurement program (Fig. 4.4) is designed for recording, processing, and visualizing the signals supplied from the output of the function generator and passing through the system. Through this interface, real-time monitoring of the input signal is performed, along with analysis of its key parameters—amplitude, frequency, and waveform.

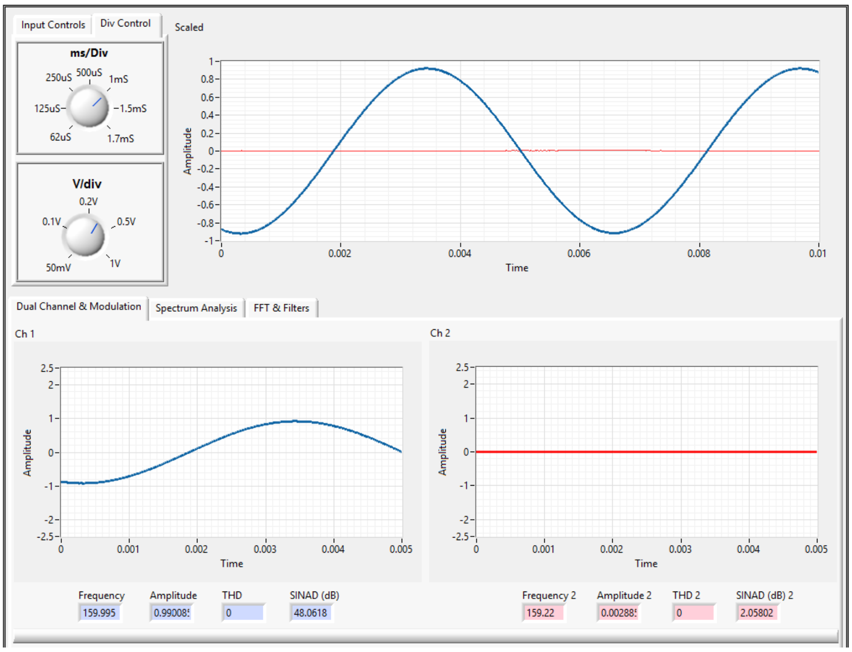


Figure 4.4. User interface of the measurement program

To enable switching between the individual channels or between the different functional circuits of the system, a specialized block diagram has been developed in the LabVIEW environment.

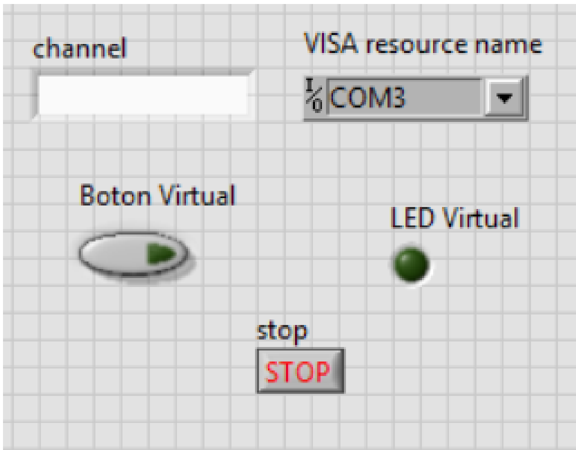


Figure 4.6. Front panel of the control algorithm

4.3. Results of the investigation

The investigation begins by applying a sinusoidal signal from the generator to the input of the corresponding filter. The amplitude of this signal is kept constant for all frequencies – 1 V in this case – to facilitate comparison between the input and the output. The signal frequency is then varied stepwise: frequencies of 1 Hz, 100 Hz, 200 Hz, 500 Hz, 800 Hz, 1 kHz, 1.5 kHz, and so on are set, with separate measurements performed for each frequency.

For every selected frequency, the input signal is first observed, followed by the output signal after the filter. This is done using an oscilloscope or the measurement environment, where both waveforms can be visualized simultaneously. The primary parameter measured is the signal amplitude. In many cases, the output signal exhibits a lower amplitude than the input, indicating that the filter attenuates the signal at that particular frequency.

Once the input and output amplitudes are measured, they are used to calculate the amplitude attenuation in decibels. This is performed using a logarithmic relationship that converts the ratio between the two voltages into a convenient scale.

$$A(f) = 20lg\left(\frac{U_{out}}{U_{in}}\right),$$

where:

- U_{in} is the measured input voltage; U_{out} is the measured output voltage.

In parallel with the amplitude measurement, the phase shift between the input and output signals is also determined.

$$\varphi = -360° \cdot f \cdot \Delta t,$$

where:

- φ – phase shift (in degrees); f – frequency (Hz); Δt – time delay (s).

Table 4.1 presents the experimentally determined amplitude-frequency (AFR) and phase-frequency (PFR) characteristics of the investigated filters at various frequencies in the range from 0 Hz to 10 kHz. The data were obtained through sequential measurement and calculation of the amplitude attenuation and phase shift of the output signal relative to the input.

Table 4.1. Experimental data

Frequency (Hz)	AFR Second-order Butterworth polynomial filter (dB)	Phase (°)	AFR Third-order Chebyshev filter (dB)	Phase (°)
1	0	0	0	0
100	-0.004	-4.72	-0.056	-1.15
200	-0.015	-9.41	-0.057	-2.29
500	-0.093	-23.73	-0.062	-5.75
800	-0.223	-37.52	-0.072	-9.18
1000	-0.346	-47.37	-0.080	-11.48
1500	-0.793	-74.59	-0.110	-17.51
2000	-1.26	-95.69	-0.146	-22.65
2500	-2.07	-121.87	-0.184	-28.48
3000	-3.52	-156.00	-0.221	-33.88
4000	-7.97	-196.89	-0.275	-44.98
5000	-13.74	-231.82	-0.274	-56.23
8000	-28.15	-279.29	0.056	-93.94
10 000	-35.52	-295.59	-0.415	-131.22
Frequency (Hz)	**AFR Fifth-order Chebyshev filter (dB)**	**Phase (°)**	**Band-pass filter (dB)**	**Phase (°)**
1	-2.37	178.03	-74.30	-102.22
100	-8.81	-46.75	-60.81	-176.94
200	-32.06	-171.85	-60.76	-177.84
500	-73.05	-237.37	-60.46	-177.31
800	-93.60	-250.48	-59.88	-176.00
1000	-104.13	-254.87	-59.30	-174.88
1500	-121.51	-260.11	-56.80	-170.41
2000	-133.94	-263.02	-52.28	-160.37

2500	-144.08	-264.96	-44.51	-86.94
3000	-151.93	-266.43	-55.25	-31.83
4000	-164.67	-269.16	-64.71	-5.31
5000	-174.14	-271.82	-70.38	-1.74
8000	-194.27	-284.21	-79.90	3.23
10 000	-203.42	-297.13	-84.17	5.24

The presented Table 4.1 contains experimental data for the amplitude-frequency (AFR) and phase-frequency (PFR) characteristics of several types of analog filters: a second-order Butterworth polynomial filter, a third-order Chebyshev filter, a fifth-order Chebyshev filter, and a band-pass filter. The analysis covers a wide frequency range – from 1 Hz to 10 kHz – which makes it possible to trace the behavior of the filters in both the passband and stopband regions. The comparative study is important because the choice of filter depends on specific requirements related to selectivity, phase linearity, and acceptable distortion levels.

The first filter examined is the second-order Butterworth filter. This type of filter is known for its maximally flat AFR in the passband. The data show that at low frequencies, in the range from 1 Hz to approximately 200 Hz, the attenuation is practically negligible and approaches 0 dB. This confirms the theoretical expectation of the absence of ripple in the passband. As the frequency increases – particularly beyond approximately 1 kHz – a gradual and monotonic rise in attenuation is observed. At 10 kHz, the attenuation reaches approximately -36 dB, which is relatively moderate for a second-order filter. The phase characteristic of this filter also changes smoothly, without abrupt transitions, indicating relatively good phase linearity.

The next filter analyzed is the third-order Chebyshev filter. Unlike the Butterworth filter, this filter exhibits ripple in the passband. The table clearly shows that even at low frequencies, small deviations in the AFR appear, although their amplitude is small. The main advantage of this filter is the sharper transition from the passband to the stopband. This is confirmed by the faster increase in attenuation with frequency compared to the Butterworth filter. The phase characteristic shows more pronounced variations, which is typical for Chebyshev filters. The presence of nonlinear phase may lead to signal distortion, especially in wideband applications. Nevertheless, the third-order Chebyshev filter offers a good compromise between selectivity and implementation complexity.

The analysis of the fifth-order Chebyshev filter reveals a different behavior. Even at relatively low frequencies around 200 Hz, the attenuation reaches values on the order of tens of decibels, indicating extremely high selectivity. As the frequency increases, the attenuation rises sharply, reaching values above -200 dB at 10 kHz. Such behavior is characteristic of higher-order filters, where the steepness of the frequency response increases significantly. The phase characteristic of this filter is highly nonlinear and exhibits abrupt changes. This results in considerable phase distortion, which may be critical in systems sensitive to signal phase. Despite this, this type of filter is extremely effective when the primary priority is the suppression of unwanted frequencies.

The band-pass filter represents a different class of system, in which only a specific frequency range is allowed to pass while frequencies outside it are attenuated. The data from the table show that at low frequencies the attenuation is very high, indicating that these frequencies lie in the stopband. As the frequency increases, a region is reached where attenuation decreases and the filter begins to pass the signal – approximately in the mid-frequency range. Beyond this region, attenuation increases again, marking the upper boundary of the passband. The phase characteristic of the band-pass filter is strongly frequency-dependent and exhibits complex dynamics, especially in the transition regions.

The comparative analysis of the examined filters clearly demonstrates the trade-off between passband smoothness and filter selectivity. The Butterworth filter offers the smoothest AFR but at the expense of slower attenuation. In contrast, Chebyshev filters provide a sharper transition between passband and stopband but introduce ripple and phase distortion. Increasing the filter order significantly improves selectivity but also increases implementation complexity and worsens phase characteristics.

In conclusion, the presented table and its analysis illustrate the fundamental principles of filter design. The observed relationships between frequency, attenuation, and phase correspond to theoretical models and confirm classical engineering approaches. The analysis highlights the importance of trade-offs in filter selection and the need to carefully match filter parameters to the requirements of the specific system.

The following graphical dependencies present the AFR and PFR obtained from the simulation study of the examined filter structures implemented in the Multisim software environment, as well as the experimentally measured characteristics from the real measurement system. This enables a precise comparative analysis between theoretical models and practical results.

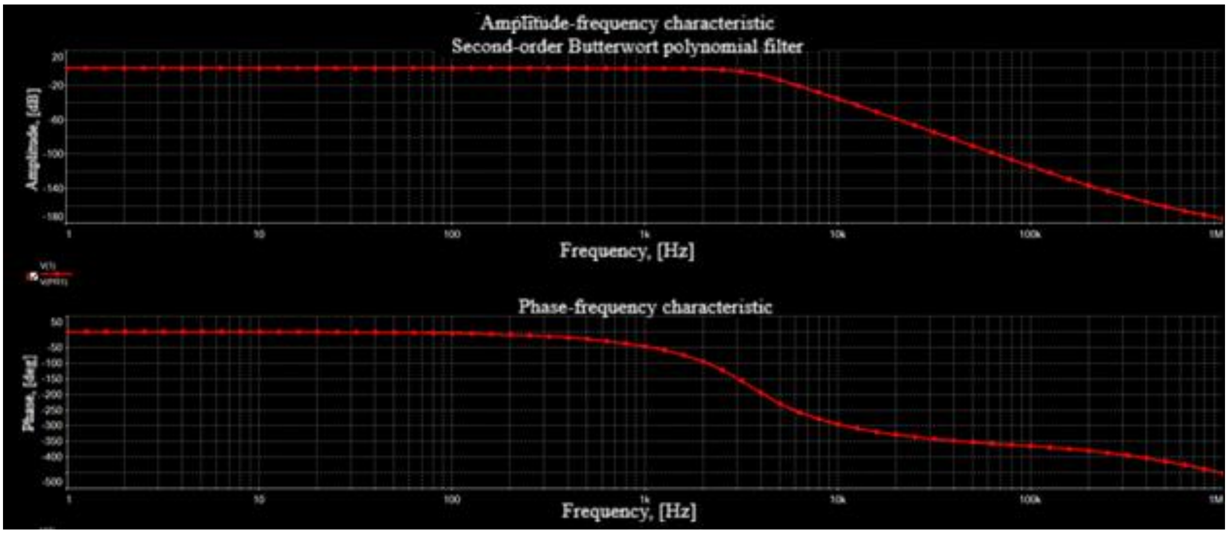


Figure 4.9. Amplitude-frequency and phase-frequency characteristics of the implemented second-order Butterworth polynomial filter in the Multisim environment

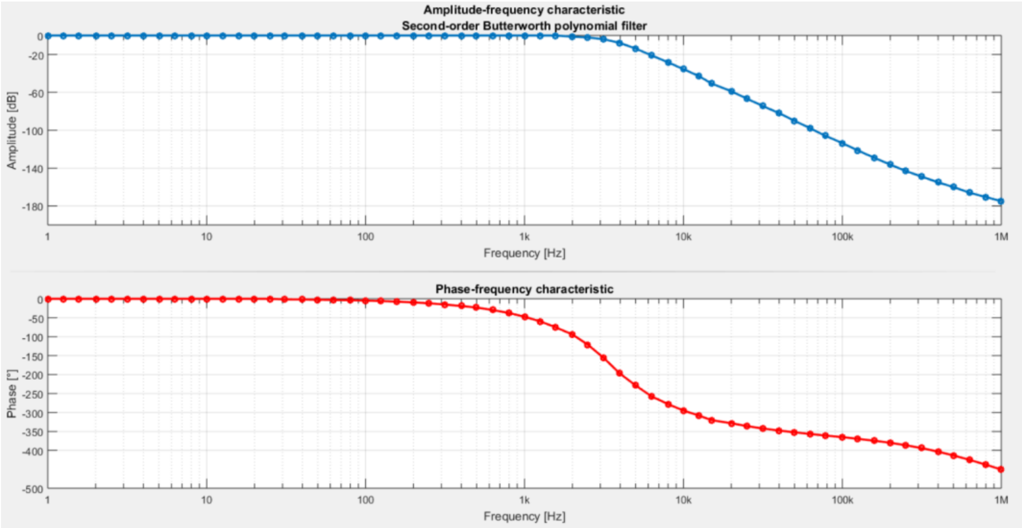


Figure 4.10. Measured amplitude-frequency and phase-frequency characteristics of the implemented second-order Butterworth polynomial filter

Figure 4.9 presents the simulated amplitude-frequency and phase-frequency characteristics of the second-order Butterworth polynomial filter implemented in the Multisim environment. Theoretically, this type of filter is characterized by a maximally flat AFR in the passband, without any ripple. The simulation results confirm this behavior, as the low-frequency range exhibits practically zero attenuation and a smooth phase variation. The transition to the stopband is gradual, with a relatively moderate slope, which is typical for second-order filters.

Figure 4.10 presents the experimentally measured characteristics of the same filter. The data from Table 4.1 show that at low frequencies (1–200 Hz), the attenuation is close to 0 dB, which coincides with the simulation. As the frequency increases, a smooth rise in attenuation is observed, reaching approximately –36 dB at 10 kHz. The phase characteristic also follows the expected gradual decline.

The comparison between simulation and experiment shows very good agreement. The small deviations observed can be attributed to real-world factors such as component tolerances, parasitic capacitances, and noise. Nevertheless, the overall behavior of the filter remains consistent.

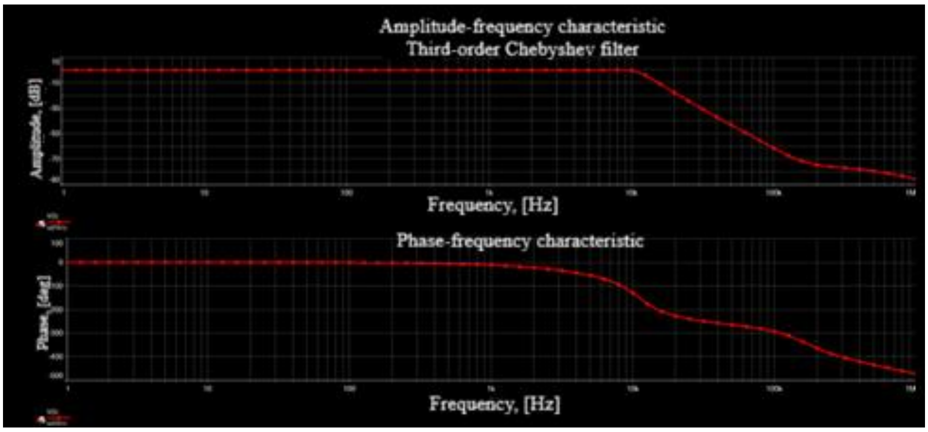


Figure 4.11. Amplitude-frequency and phase-frequency characteristics of the implemented third-order Chebyshev filter in the Multisim environment

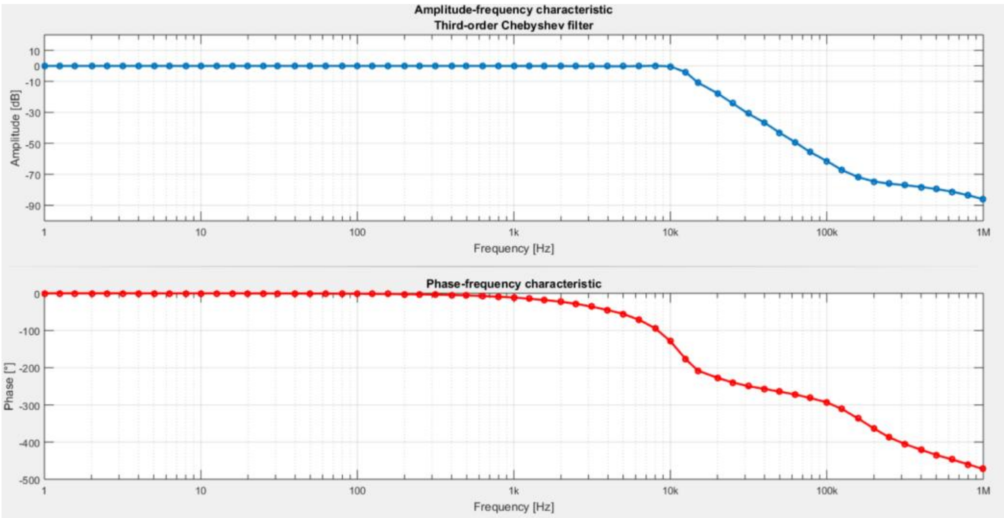


Figure 4.12. Measured amplitude-frequency and phase-frequency characteristics of the implemented third-order Chebyshev filter

Figure 4.11 presents the simulated characteristics of the third-order Chebyshev filter. The main feature is the presence of ripple in the passband, which is typical for this type of filter. The simulation shows a sharper transition to the stopband compared to the second-order Butterworth polynomial filter, which is a direct consequence of the higher order and the specific approximation.

Figure 4.12 contains the experimentally measured characteristics. The data show that the ripple amplitude is small but still noticeable. The attenuation increases more rapidly compared to the Butterworth filter, confirming the higher selectivity. The phase characteristic exhibits more pronounced nonlinearity.

The comparison reveals good agreement between simulation and measurement, with the differences being slightly more noticeable in the ripple region. The small deviations observed can be explained by real-world factors such as component tolerances, parasitic capacitances, and noise.

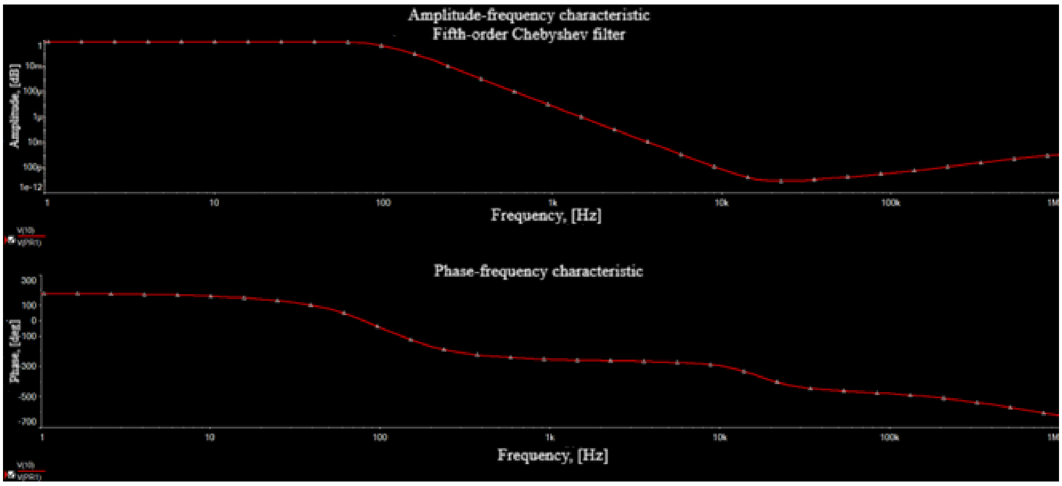


Figure 4.13. Amplitude-frequency and phase-frequency characteristics of the implemented fifth-order Chebyshev filter in the Multisim environment

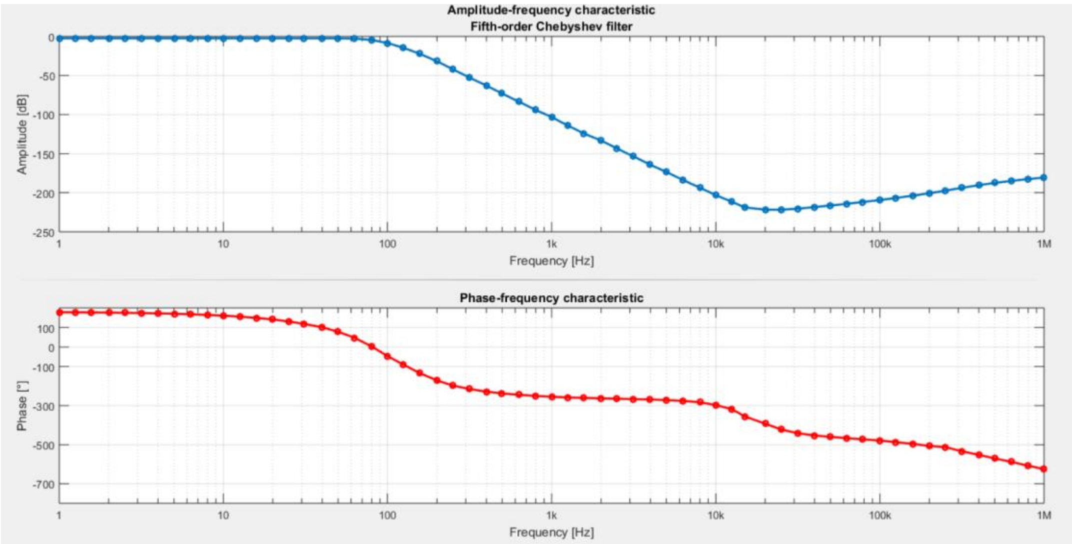


Figure 4.14. Measured amplitude-frequency and phase-frequency characteristics of the implemented fifth-order Chebyshev filter

Figure 4.13 presents the simulation of the fifth-order Chebyshev filter. As expected, this filter demonstrates an extremely steep amplitude-frequency characteristic. The transition between the passband and the stopband is abrupt, and the attenuation increases exponentially. The phase characteristic is highly nonlinear, exhibiting large phase shifts.

Figure 4.14 contains the experimental results. The data from Table 4.1 show that significant attenuation begins even at low frequencies, which is more pronounced compared to the simulation. At high frequencies, the attenuation reaches extremely large values (over -200 dB), confirming the high selectivity of the filter.

The comparison shows that although the overall shape of the characteristic matches, the differences relative to the simulation are more substantial. This is expected, as higher-order filters are more sensitive to parametric deviations. Small variations in component values lead to significant changes in the characteristic.

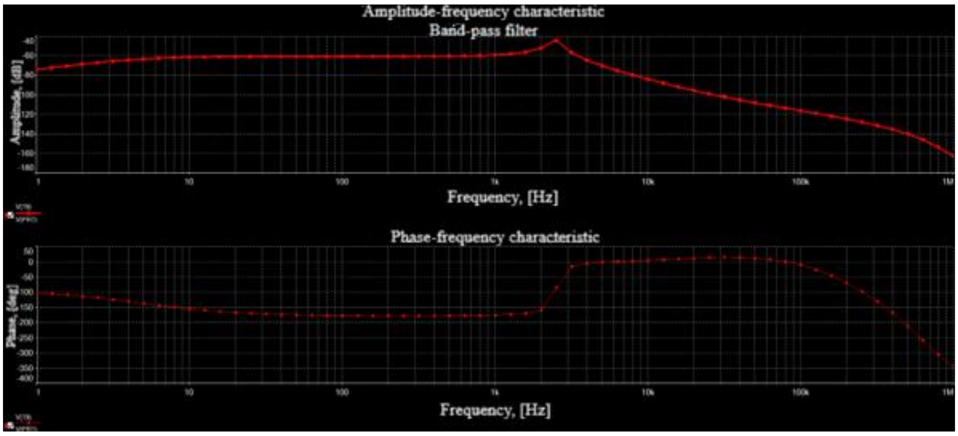


Figure 4.15. Amplitude-frequency and phase-frequency characteristics of the implemented band-pass filter in the Multisim environment

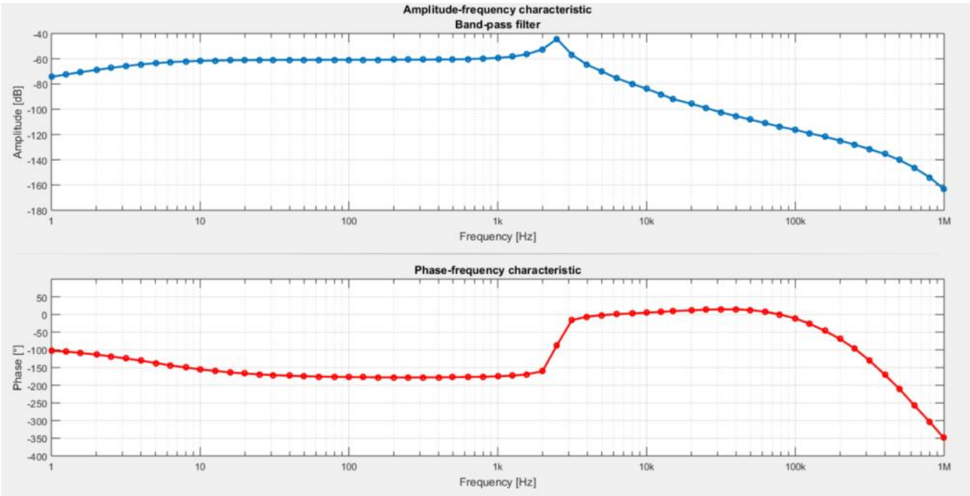


Figure 4.16. Measured amplitude-frequency and phase-frequency characteristics of the implemented band-pass filter

Figure 4.15 presents the simulated characteristics of the band-pass filter. As expected, a clearly defined passband region is observed, located in the mid-frequency range. Outside this region, the attenuation is significant. The shape of the AFR is typical for a band-pass filter, with a maximum at the center frequency.

The experimental results are shown in Figure 4.16. The data confirm the presence of a passband around 2 – 3 kHz, where the attenuation is minimal. At low and high frequencies, strong suppression is observed. The phase characteristic is complex and strongly dependent on frequency.

The comparison between simulation and measurement shows good agreement in terms of center frequency and bandwidth. Small differences in attenuation levels are observed, which can be explained by real-world losses and component inaccuracies.

The following figures present the experimental results obtained during the investigation of the Butterworth and Chebyshev filters, the band-pass filter, and the peak detector. The visualized graphs reflect the main measured parameters and the characteristic features of the experimental process.

Figure 4.17. Experimental setup of the signal generation and measurement system with the band-pass filter activated and a sine wave signal applied from the function generator

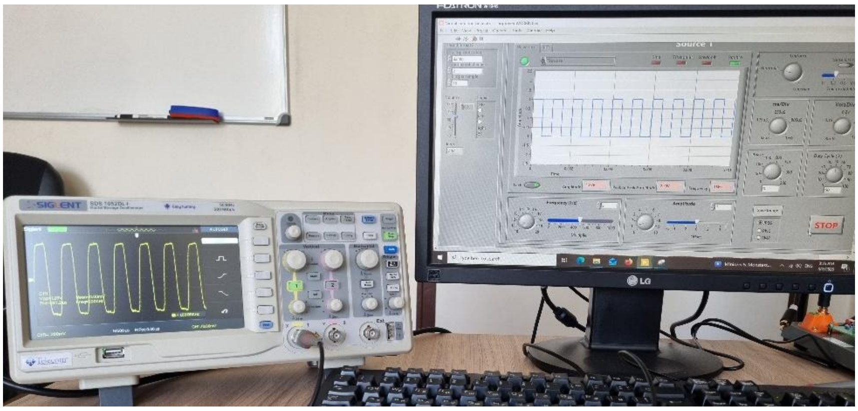


Figure 4.20. Experimental setup of the signal generation and measurement system with the band-pass filter activated and a square-wave signal applied from the function generator

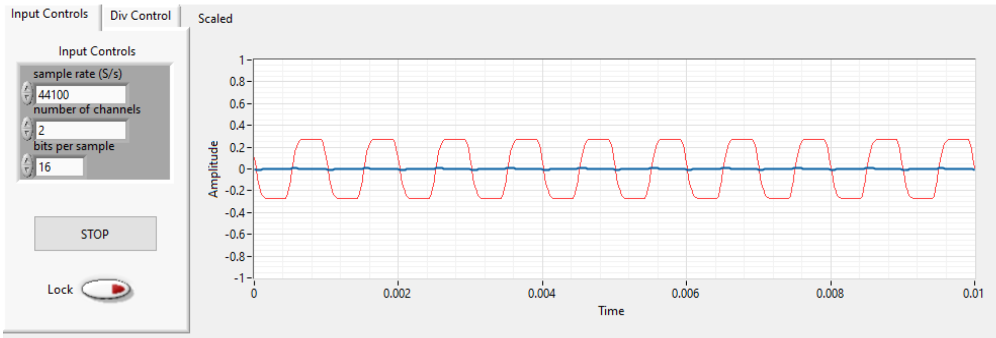


Figure 4.27. Measured signal of the system operating with the second-order Butterworth polynomial filter activated and a square-wave signal applied from the function generator

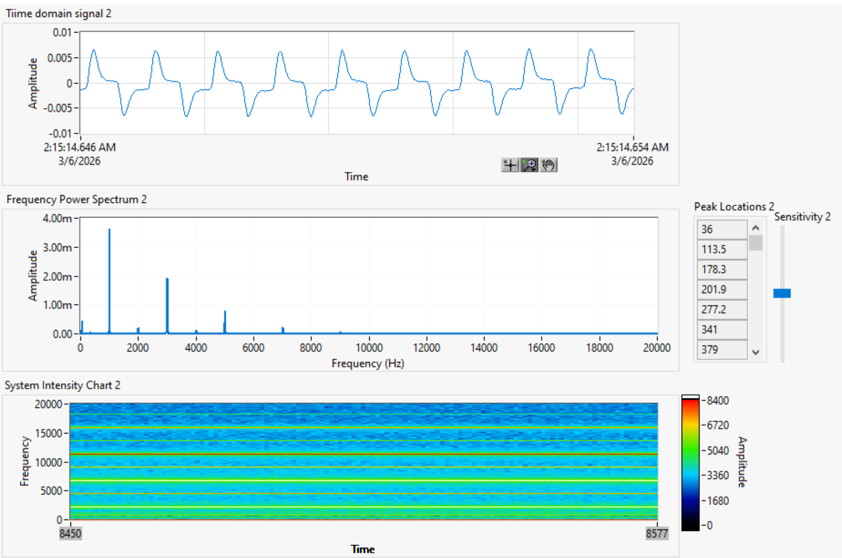


Figure 4.28. Graphical representation of the measured signal in the time and frequency domains, its intensity with the second-order Butterworth polynomial filter activated and a square-wave signal applied from the function generator

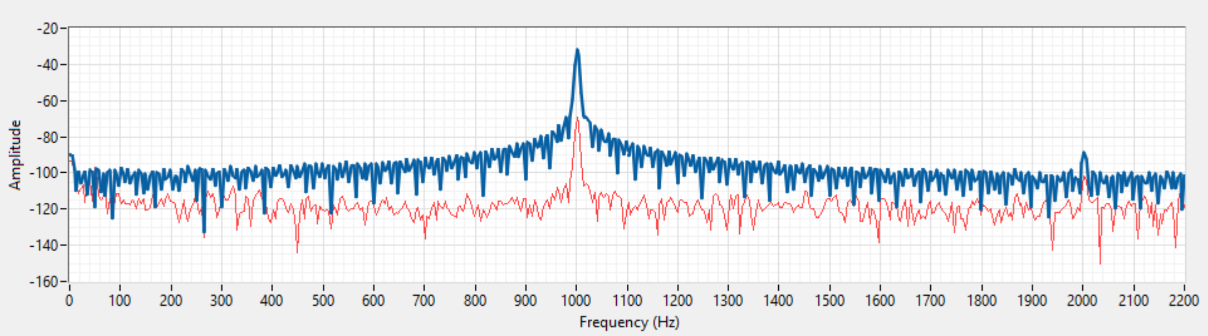


Figure 4.29. FFT transformation of the signal with the second-order Butterworth polynomial filter activated and a square-wave signal applied from the function generator (right channel – blue, left channel – red)

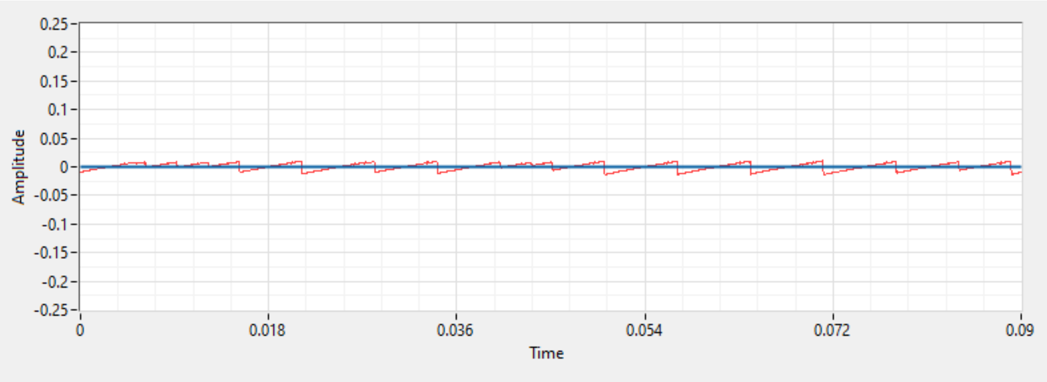


Figure 4.33. Measured signal of the system operating with the peak detector activated and a square-wave signal applied from the function generator

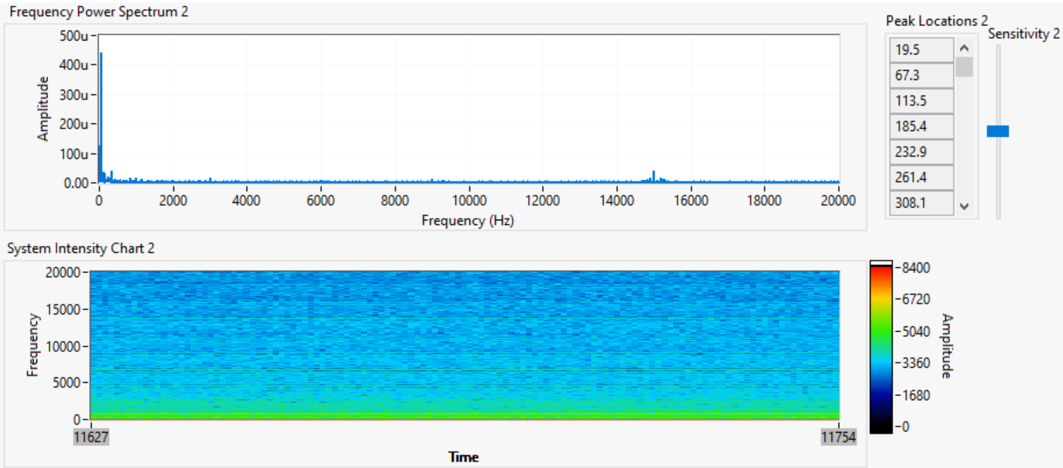


Figure 4.34. Graphical representation of the measured signal in the frequency domain, its intensity with the peak detector activated and a square-wave signal applied from the function generator

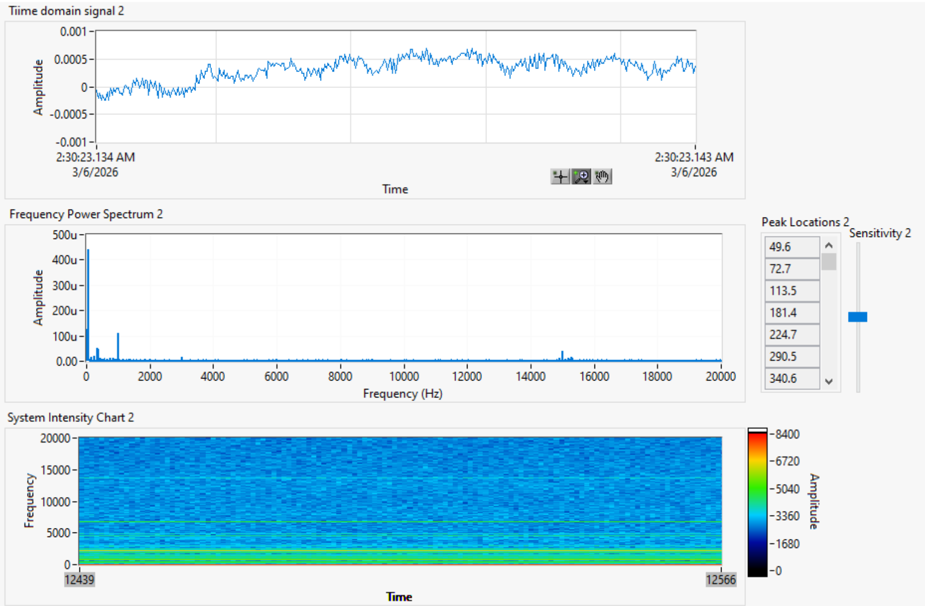


Figure 4.35. Graphical representation of the measured signal in the time and frequency domains, its intensity with the fifth-order Chebyshev filter activated and a sine-wave signal applied from the function generator

4.3 CONCLUSIONS FROM CHAPTER 4

The experimental results presented in chapter 4 allow the formulation of consistent and scientifically grounded conclusions that confirm both the correctness of the developed measurement system and the reliability of the applied methods for analyzing analog filters. The validation of the system demonstrates high measurement accuracy: the differences between the set parameters and the values recorded by the digital oscilloscope are minimal and fall within acceptable engineering tolerances. This proves that the configuration consisting of a generator, measurement equipment, and software processing ensures reliable signal reproduction and registration, with small deviations explained by real-world factors such as parasitic parameters, noise, and instrument limitations.

The experimental setup demonstrates high functionality thanks to the integration between LabVIEW and the hardware part, which enables automated control, real-time visualization, and efficient analysis. The developed control algorithm facilitates switching between different modes and filter configurations, enhancing the practical applicability of the system.

The obtained results confirm the theoretically expected behavior of the filters. The second-order Butterworth filter exhibits a smooth amplitude-frequency characteristic and good phase linearity. The Chebyshev filters demonstrate higher selectivity: the third-order version offers a reasonable compromise between steepness and ripple, while the fifth-order filter provides extremely high attenuation but with more pronounced phase nonlinearity. The band-pass filter clearly outlines its passband and effectively suppresses frequencies outside it, fully consistent with the theoretical model.

The comparison between the Multisim simulation results and the experimental measurements shows a high degree of correspondence, especially for the Butterworth filter. More significant deviations in higher-order filters are due to their sensitivity to component variations and parasitic effects. The FFT analysis further confirms the effectiveness of the filters: with a sinusoidal input, minimal distortions are observed, while for non-sinusoidal signals, high-frequency harmonics are suppressed, leading to smoothing of the waveform.

In summary, the developed experimental system proves to be a reliable tool for analyzing analog filters. The results correspond to the theoretical models and provide a solid foundation for practical application in engineering systems.

CHAPTER 5. CONCLUSIONS AND CONTRIBUTIONS TO THE DISSERTATION WORK

Scientific-applied contributions

1. **An integrated methodology has been developed for the design, modeling, and construction of a remote laboratory in "Electronic measurement technology,"** based on simulation models, virtual measurement instruments, and real experimental objects within a unified hybrid educational environment, ensuring a high degree of reliability and comparability of measurements.
2. **A generalized model of a virtual and remote laboratory environment has been proposed,** integrating software and hardware components into a unified architecture that enables simultaneous training, experimental investigation, and real-time analysis of electronic systems.
3. **A formalized approach has been developed for managing and configuring measurement processes in the LabVIEW environment,** providing flexible switching between different modes, structures, and signal-processing methods without the need for changes in the hardware configuration.
4. **A systematic comparative analysis has been performed between theoretical, simulation, and real experimental data,** which validates the accuracy, reliability, and effectiveness of the proposed laboratory system and demonstrates its applicability in engineering education.

Applied contributions:

1. **An integrated virtual laboratory platform has been developed and implemented,** providing remote access to real electronic measurement devices and experimental objects, thereby extending the traditional laboratory infrastructure and creating a new model for conducting practical sessions in engineering education.

2. **Functional circuits have been created** (Butterworth and Chebyshev active filters, band-pass filter, peak detector), optimized for remote control and repeated experimentation, enabling the investigation of real electronic processes within a virtualized laboratory environment.
3. **Simulation models of the electronic devices have been developed,** providing the possibility to compare theoretical, simulation, and experimental results, thereby supporting the validation of the laboratory methodologies and increasing the reliability of the training process.
4. **A virtual measurement complex has been created in the LabVIEW environment,** implementing realistic digital signal measurement and analysis and serving as the primary toolkit for remote laboratory exercises.
5. **The developed laboratory system has been adapted for implementation in academic programs in electronics, electrical engineering, and automation,** providing a standardized, scalable, and easily integrable platform for practical training in both in-person and remote formats.
6. **Three structured laboratory exercises have been developed,** formalizing the process of remote measurement and analysis, ensuring traceability of results, and supporting the development of practical competencies in engineering education.

LIST OF PUBLICATIONS RELATED TO THE DISSERTATION WORK

1. **A. Chekichev**, R. Popov, S. Asenov. (2021). THE VIRTUAL LABORATORIES AS A MEANS OF TRAINING STUDENTS IN ENGINEERING EDUCATION IN THE CONDITIONS OF COVID-19, ICERI2021 Proceedings, pp. 9234-9238

2. **A. Chekichev**, R. Popov, S. Asenov. (2021). USE OF THE LABVIEW VIRTUAL INSTRUMENT IN THE ENGINEERING EDUCATION, ICERI2021 Proceedings, pp. 9428-9432

3. **A. Chekichev**, A. Parushev, R. Popov. (2022). BUILDING A VIRTUAL INSTRUMENT FOR RESEARCH AND ANALYZING FILTERS IN LABVIEW AND MATLAB, ICERI2022 Proceedings, pp. 4795-4800

4. **Angel Chekichev**. (2024). OVERVIEW OF THE STANDARDIZATION ORGANIZATIONS, UNION OF SCIENTISTS IN BULGARIA – SMOLYAN, Scientific works Volume 4, 2024, ISSN:1314-9490 (online), pp. 46-57

5. **Angel Chekichev**. (2024). SOFTWARE PRODUCTS FOR VIRTUAL LABORATORIES, UNION OF SCIENTISTS IN BULGARIA – SMOLYAN, Scientific works Volume 4, 2024, ISSN:1314-9490 (online), pp. 58-69