CZECH TECHNICAL UNIVERSITY IN PRAGUE

Faculty of electrical engineering
Department of micro-electronics

Automated Testbench for PCB

Master Thesis

Study Programme: Communication multimedia and electronics
Branch of study: Electronics

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Declaration

I declare that I have developed and written the enclosed Master Thesis completely by myself, and have not used sources or means without declaration in the text. Any thoughts from others or literal quotations are clearly marked. The Master Thesis was not used in the same or in a similar version to achieve an academic grading or is being published elsewhere.

In Prague, 27.5. 2016

I would like to thank my crew trainer Vojto and ex-boss Aleš for opportunity to work on such a project. Big thanks belong to Broňa for support and English correction. Also for English correction I would like to thank American girl Amanda. And I want to thank my advisor for valuable advice.

Anotace

Táto diplomová práca sa zaoberá problematikou praktického návrhu a realizácie testovacieho prípravku pre fyzioterapicku jednotku. Cieľom práce bolo navrhnúť a realizovať funkčný tester a vytvoriť vhodný užívateľský program pre daný tester. Následne vypracovať ekonomickú analýzu.

Summary

This diploma thesis deals with practical aspects of a Functional tester of Printed Circuit Board. The main goal was to design and create a Functional tester for Printed Circuit Board. Also to create suitable software for automated tester unit; and to construct an economic analysis.

List of symbols

V – Voltage
I – Current
R – Resistance
V_{GS} – Voltage gate source
η – Efficiency
V_{OUT} – Output voltage
V_{IN} – Input voltage
P_{LOSS} – Power loss
T_{ON} – On time interval
T_{S} – Switching period
I_{SINK} – Sink current

List of Abbreviations

PCB = Printed circuit board
IC = Integrated circuit
FT = Functional test
AVI = Automated visual inspection
ICT = In-circuit test
RMS = Root mean square
GUI = Graphical user interface
AVG = Average
SMT = Surface mount
SMD = Surface mount device
VISA = Virtual Instrument Software Architecture
LabVIEW = Laboratory Virtual Instrument Engineering Workbench
MATLAB = Matrix laboratory
CRC = Cyclic redundancy check
EMC = Electromagnetic compatibility
EMI = Electromagnetic interference
A/D = Analog/Digital
AXI = Automated X-ray inspection
JTAG = Joint Test Action Group
Vi = Virtual instrument
BGA = Ball grid array
AXI = Automated x-ray inspection

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1. Introduction

Electronic devices have become more complex and that requires more complex testing. Manual testing of electronic devices produced in high volume is very time-consuming. A more preferred choice is to use an automated tester unit. An automated tester unit decreases time consumption and increases profit. Another aspect is the size of the electronic components. Electronic components have become smaller and smaller and it is almost impossible to do a visual inspection via only the human eye. Therefore, it is necessary to use an automated tester unit.

The main purpose of this thesis was to design and make a functional tester for a physiotherapy treatment device. Another aim was to substitute manual testing for automated testing in the manufacturing process and to create suitable software with the ability to create test report with measured values and store logs.

1 Theoretical Aspects

1.1 Electronic devices

Devices that can control the flow of electrons are called electronic devices. Electronic devices consist of electronic components and connections between them. “An electronic component is any physical entity in an electronic system used to affect electrons or their associated fields in a desired manner consistent with the intended function of the electronic system.” [1] Electronic components can be categorized into two main groups: passive and active. There are three passive basic components: resistors, capacitors, inductors. There are many active components such as transistors, diodes, thyristors, transils. Electronic components are usually connected together by being soldered to a solder pad on a printed circuit board. By using electronic components it is possible to create a particular function like a rectifier, amplifier or comparator.

1.2 Printed circuit board

A printed circuit board (PCB) is a rigid or semi-rigid board, electrically connecting electrical components using conductive copper tracks. Copper is deposited onto a non-conductive substrate. Then the copper is etched to the required shape. PCB can be single sided, where copper is only on one side of the substrate, while on double sided PCB, copper is deposited on both sides of the substrate. Multi-layer PCB is a sandwich connection of double sided PCBs, between the conductive sides, the non-conductive material usually pre-preg is inserted. Conductors on different layers are connected by plated-through holes called vias. Alternatives to PCBs are wire wrap and point-to-point. PCBs require an additional layout design, but manufacturing and assembly can be automated. Manufacturing circuits by using the PCBs technique are cheaper and (in many cases) faster than other methods. PCBs have to comply with the standard ČSN EN 60194 [2].

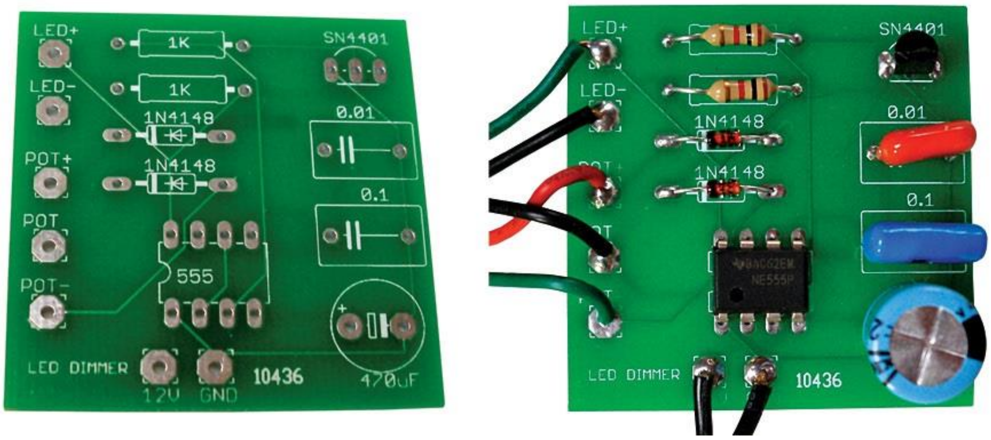


Fig. 1- Printed Circuit Board. Taken from [3]

1.3 Wire wrap

Wire wrap consists of an insulated board where electronic components are mounted. The components are connected by insulated wires which are wrapped by several turns around components or socket pins. This method is not optional to use in complex design, thus, it is no longer a very common method.

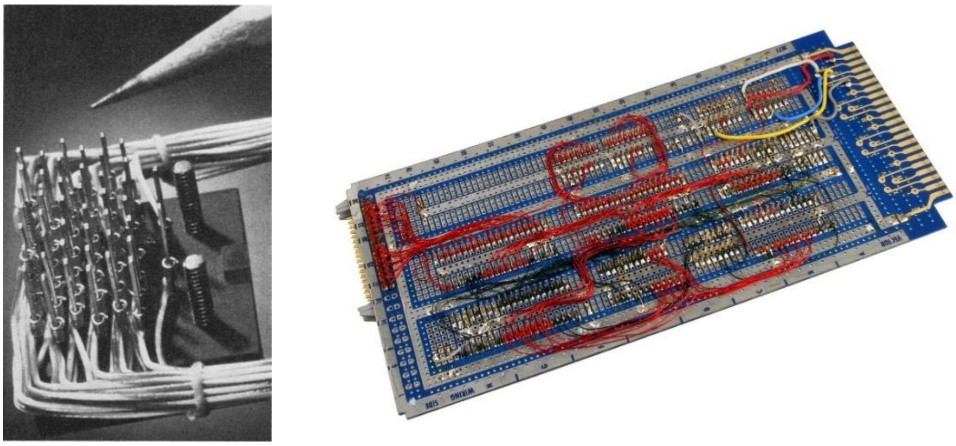


Fig. 2 - a) Rectangular wire wrap terminal b) A microprocessor system prototype wire wrap board. Taken from [4,5]

1.4 Point-to-point

Another alternative to PCB, is point-to-point construction. This method is non-automated and it was widely used before the invention of PCB. This is the simplest method for building electronic circuits. Pins of components are simply soldered together. In a simple design, it is very common but in complex designs it is very time-consuming and not easy to replicate.

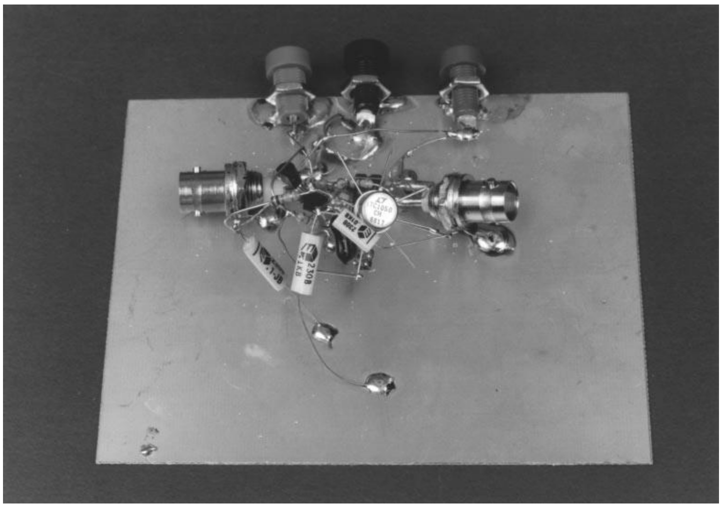


Fig. 3 - Point to point connection. Taken from [6]

1.5 Testing PCB

Nowadays, the testing of PCBs is a necessity. People require reliable devices; in general, a customer prefers to buy well-known products, because they expect that such a device is more reliable and functions properly without major problems. In the Czech Republic, there is a warranty lasting 24 months from the purchase of a device. If we want to achieve this goal, we have to test every single unit, PCB, software and device. In the testing process, we have to start at the very beginning, in other words, testing has to start during PCB assembly. Whether you produce a low volume or high volume of PCB, whether PCB is part of a car or a medical product, whether it is just basic PCB or very complex PCB, there is still a need to test it to ensure that it is working properly. Finding PCB assembly defects is a never-ending story. The trend is to improve assembling process, which impacts product quality and reduces manufacturing costs. Devices that are a higher quality are less often reclaimed which, therefore, decreases the amount of money used for repairing the devices. In general, there are several PCB test strategies. The most common tests today are Visual Inspection, In-Circuit Test and Functional Test as shown in Fig. [4]. Fig. [5] shows surface mounted board process inspections. In Tab. [1] it is possible to see tests in manufacturing process of PCB.

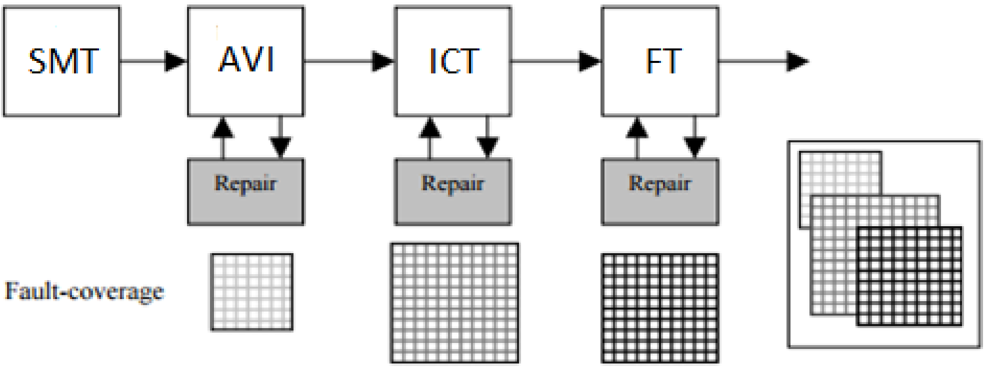


Fig. 4 -Test strategy. Taken from [7]

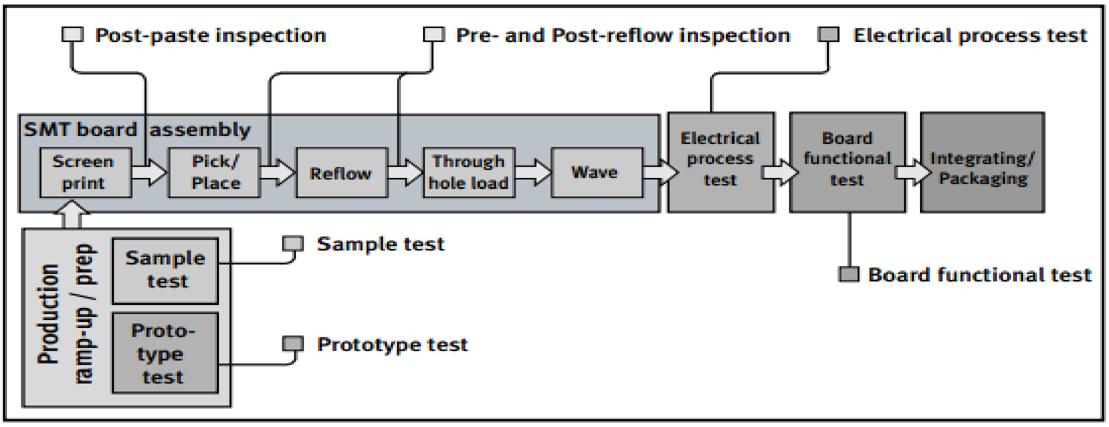
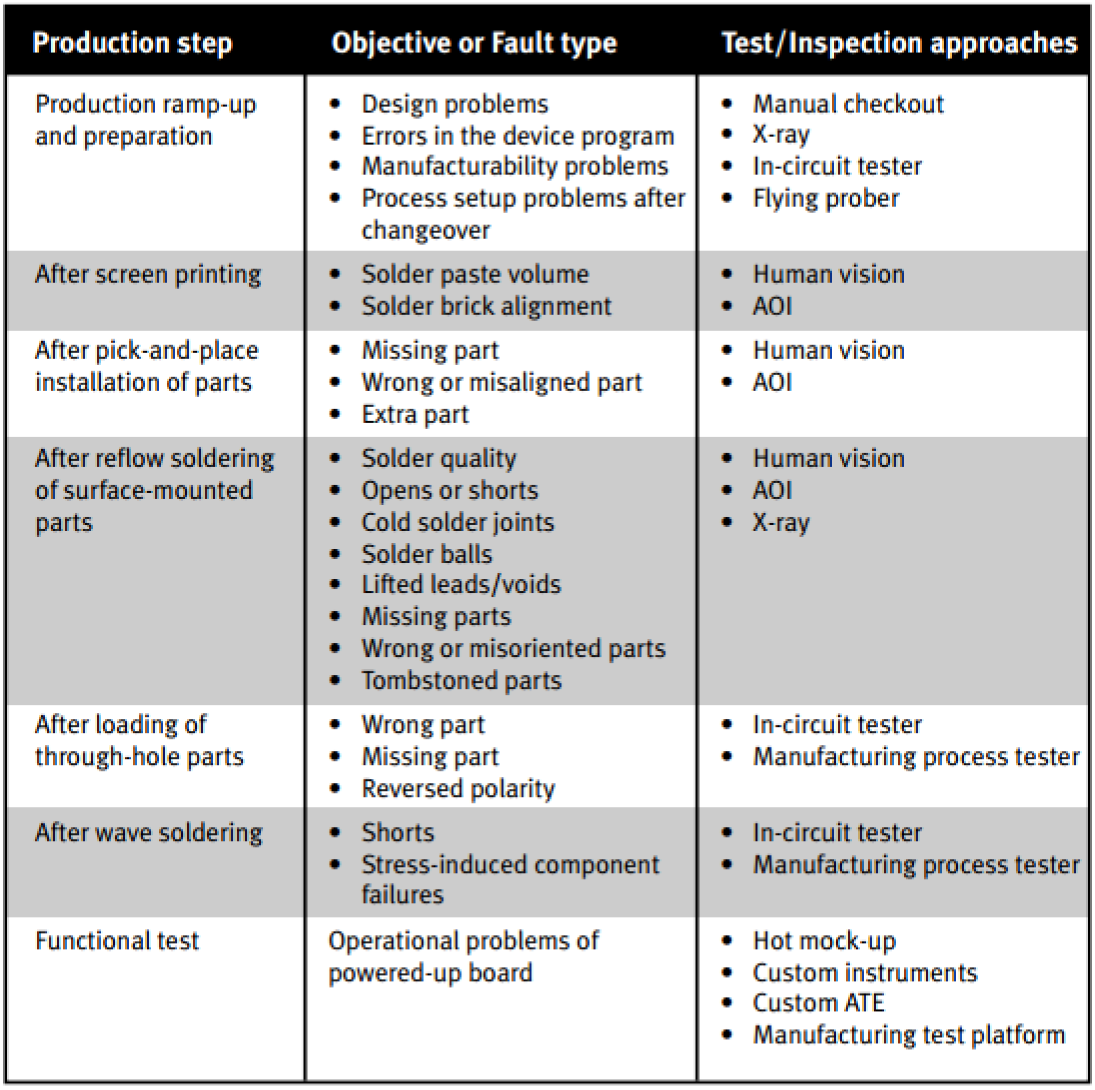


Fig. 5 - Surface mounted board process inspections. Taken from [8]



Production step	Objective or Fault type	Test/Inspection approaches
Production ramp-up and preparation	• Design problems • Errors in the device program • Manufacturability problems • Process setup problems after changeover	• Manual checkout • X-ray • In-circuit tester • Flying prober
After screen printing	• Solder paste volume • Solder brick alignment	• Human vision • AOI
After pick-and-place installation of parts	• Missing part • Wrong or misaligned part • Extra part	• Human vision • AOI
After reflow soldering of surface-mounted parts	• Solder quality • Opens or shorts • Cold solder joints • Solder balls • Lifted leads/voids • Missing parts • Wrong or misoriented parts • Tombstoned parts	• Human vision • AOI • X-ray
After loading of through-hole parts	• Wrong part • Missing part • Reversed polarity	• In-circuit tester • Manufacturing process tester
After wave soldering	• Shorts • Stress-induced component failures	• In-circuit tester • Manufacturing process tester
Functional test	Operational problems of powered-up board	• Hot mock-up • Custom instruments • Custom ATE • Manufacturing test platform

Tab. 1 - Tests and inspection in surface mounted manufacture. Taken from [8]

1.6 Visual inspection

It is necessary to detect manufacturing faults at the earliest possible opportunity. When PCB is fabricated, soldering of components is the next step in production order. It is good to use visual inspection (VI) for several points. Components like resistors, capacitors, transistors, and others are usually soldered automatically. It is necessary to ensure all components are in the correct place and soldered properly. Usually, this problem is solved by using visual inspection. Generally, a visual inspection will inform you if the components are there if they are correctly oriented, and possibly that the solder re-flow was corrected.

Visual inspection is a non-contact comparative technique. The image of a perfect PCB is stored in PC. This image is then compared to each board to be judged. If there is a match with the ideal PCB it is classified as an OK board, if not it is classified as a faulty board.
Historically, most visual inspections were done manually by humans. However, nowadays, it is very common to use Surface Mounted Device (SMD) components due to their smaller parasitic effects and smaller size which allow you to build smaller and lighter devices. Since the use of SMD has become ever more common, it has posed a problem for manual inspections as it is no longer plausible for human eyes to see defects and faults in such small components.

Visual inspection is possible to do manually or automatically. (AVI) Automatic Visual Inspection offers several benefits compared to manual (human) visual inspection. The main components of AVI include high-magnifying optical cameras, which can be vertical or angled, mounted above the PCB. The biggest motivation to use visual inspection is to find defects on the PCB. When the detection of a faultly PCB is missed or overlooked, this PCB then continues in the assembly process and will likely result in the the final product not working properly. This is a costly issue, as faulty final products need to be recalled and/or repaired which costs both time and money. Automatic visual inspection also reduces the sheer number of employees needed. Another advantage is the speed of inspection and accuracy. High-resolution cameras provide more reliable results than human operators. AVI can set different angles of cameras and lighting and detect solder shorts and joints, it can also detect the place of a fault. A new trend is to use AVI on the assembly line with equipment combined with a repair station. Fig. [6] shows an automated visual inspection tester unit.

1.6.1 Advantages of AVI

- Detection of:
    - Area defects
    - Component polarity
    - Component absence
    - Paste registration

- Precision
- Speed

1.6.2 Disadvantage

- Purchasing cost

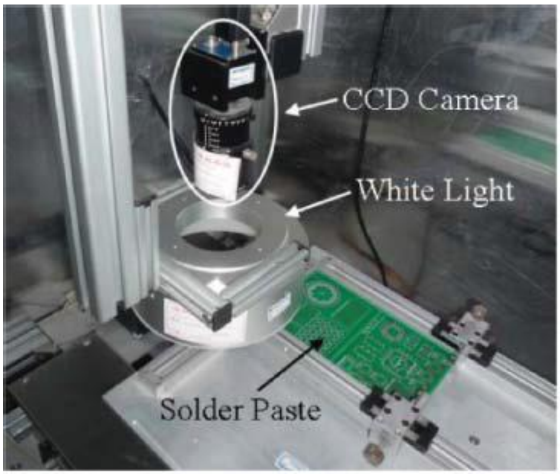


Fig. [6]- Automated visual inspection. Taken from [9]

1.7 X-ray in visual inspection.

X-ray visual inspection is based on the same principles as a classic visual inspection. An x-ray inspection system is a very powerful thing. Different spectrum allows detecting anomaly such as a corner case, rare errors such as opening on ball grid arrays (BGAs). Automated x-ray inspection (AXI) is also able to find faults such as opens, shorts (as shown in Fig. [7]), insufficient solder, excessive solder, missing electrical parts, and missing components. X-ray inspection systems are better suited to process development or laboratory applications, including the diagnosis for functional or field failures. However, x-ray inspection may not be suitable for production line use due to the system throughput being slower than typical production lines. The cost of x-ray systems is about three times the cost of AVI systems.

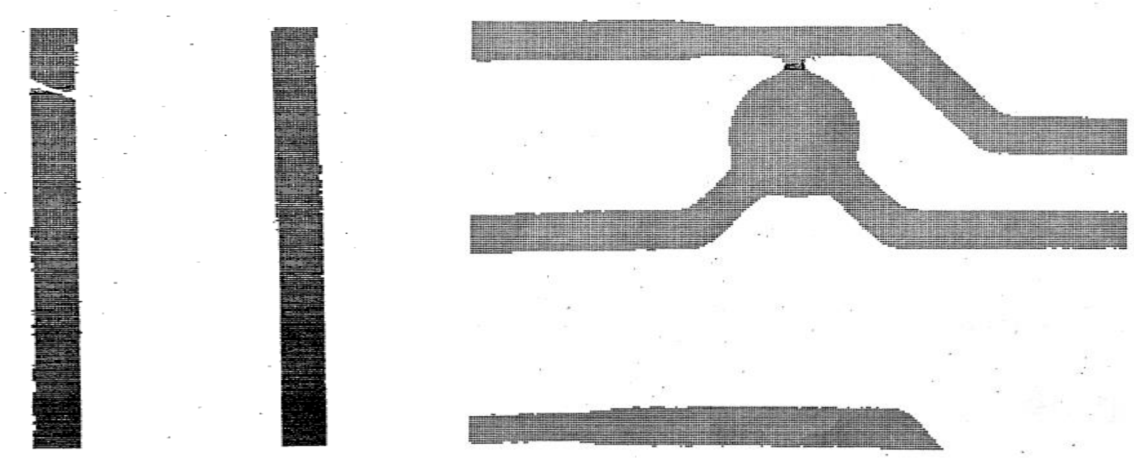


Fig. [7] a) Open connection b) short connection. Taken from [10]

1.8 In-circuit test

In-circuit test (ICT) is a powerful tool which provides useful and efficient circuit board test. In-circuit test is a test which performs a schematic verification by testing components of a PCB by electrical probe measuring resistance, capacitance, opens, shorts, voltage levels and analogue components such as operational amplifiers and other basic parameters. Some digital systems can also be measured, but as a result of the complexity of these systems, it can be very time-consuming and inefficient. Components are compared against software model or reference parameters of components. ICT costs a lot of time but it is very effective at finding manufacturing defects. In-circuit test can easily detect solder shorts, missing and wrong components, and also open connections. This method requires fixture for testing PCB, which can be expensive due to the demand of electrical connection to each electrical node or test point of the circuit. In-circuit test usually does not test the functionality of connectors. Thus, the connector's defects are not detected. It is possible to test connectors in this method but it usually consumes a lot of time compared to other tested components. ICT systems are usually expensive items. They are typically used for high volume production lines, usually in the range of 1000 pcs of PCBs or more. It is really important to conduct a cost analysis to ensure that the cost of the fixture is viable.

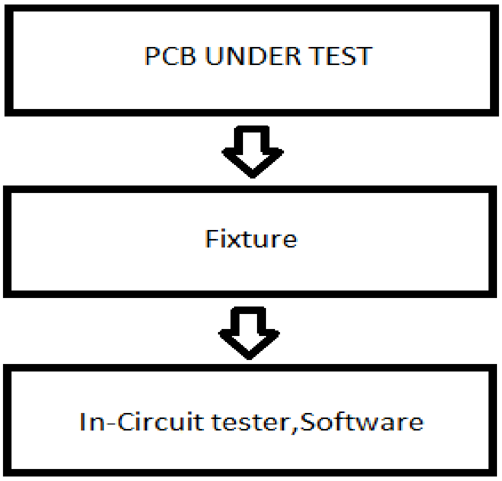


Fig. 8 -Basic concept of In-Circuit tester. Made by the author.

1.9 Fixture

Sometimes a fixture is called a Bed of Nails. Using a Bed of Nails In-circuit test equipment is possible to gain access to the circuit nodes on a PCB and measure the performance of the components. A Bed of Nails consists of a matrix of electrical probes, also called Pogo-pins. There can be 1000 or more Pogo-pins. A Bed of Nails requires accurate mechanical assembly to hold PCB in the correct place. The hold-down force can be provided manually or by vacuum holder, thus pulling the PCB downwards onto the nails. Vacuum fixtures provide better signal contact but they are more expensive. Tested PCB is usually covered by a protecting plexiglass cover in case of an explosion or high voltage danger. The other sides of the nails are connected to testing hardware like A/D converter or resistor grid. Usually, testing hardware is controlled by a computer. The computer also compares the measured data with reference data. Fixture principle is shown on Fig. [9].

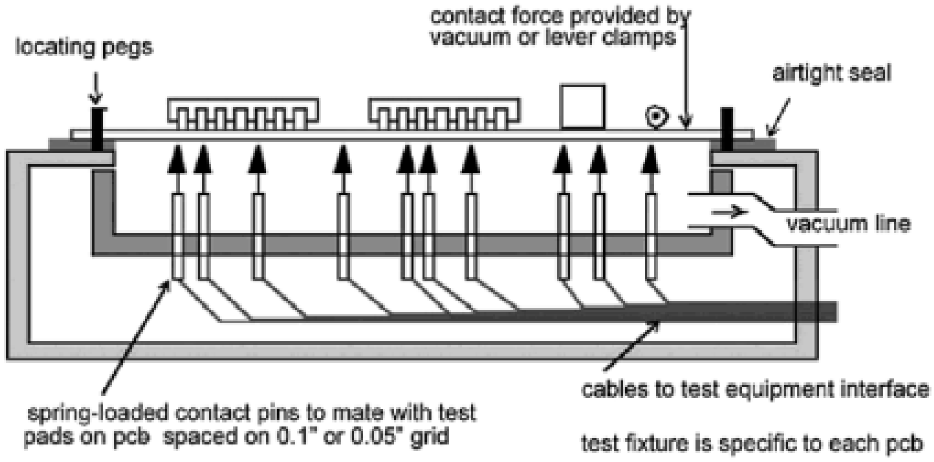


Fig. 9 -Bed of nails fixture principle. Taken from [11]

1.10 Flying probe tester

Another type of mechanics is flying probe tester**.** “In view of the issues of developing and manufacturing complete bed-of-nails access fixtures - they are costly and difficult to change if any component positions or tracks are moved - another approach is to use a roving or flying probe. This has a simple fixture to hold the board and contact is made via a few probes that can move around the board and make contact as required. These are moved under software control so any board updates can be accommodated with changes to the software programme. The type of tester required is dependent upon the manufacturing test process, the volume and the boards that are used.”[12]

1.11 Fault coverage

With access to all nodes on the board, it is possible to find nearly 100% of faults using In-circuit test. This is quite an ideal Fig.. One of the major reasons that it is not always possible to gain complete coverage of the board is a low value of capacitors. Low values of capacitance cannot be measured accurately at all. There is also a similar problem with inductors. If you want to measure capacity or inductance, you must consider the parasitic effect of PCB itself. As we know, in precise measurements it is necessary to measure at the correct test-points. Another issue is the parallel connection of components. Parallel connected components can be easily measured only if they are of the same type, for example, two resistors, etc. In the case of different parallel connections of components it is necessary to use a sequence of tests to measure DC voltage versus current injections, which can be complicated. For measurement quality of electrical contact, an extra test point is required. Another problem occurs when it is not possible to gain access to all nodes on the board. This may have an impact on some measurements.

1.11.1 In-circuit test advantages:

- Easy detection of manufacturing defects
    - solder shorts
    - open connections
    - missing components
    - wrong components
    - faulty integrated circuits
    - incorrect orientation of component

- Location of fault
- Test results easy to interpret
- Accuracy
- Speed of test

1.11.2 In-circuit test disadvantages:

- Cost of fixture
- Difficult to change fixture test probes positions
- With higher volume of test pins, test becomes more difficult
- Difficult to measure parallel connected components.
- Different types of PCBs require different software and fixture

1.12 Joint test application group

Due to multi-layer PCBs and BGA packaging, some test-points were made unavailable to probes. Nevertheless, it was still necessary to test these pins. “To find a solution to these problems, a group of European electronics companies formed a consortium in 1985 called the Joint Test Action Group (JTAG). The consortium devised a specification for performing boundary-scan hardware testing at the IC level. In 1990, that specification resulted in IEEE 1149.1, a standard that established the details of access to any chip with a so-called

JTAG port.”[13] JTAG was originally designed for testing boundary scan conditions of integrated circuits. The main purpose of JTAG has also been developed for debugging and firmware storing.

1.13 Functional test

Usually a functional test is the final step of the manufacturing plan. Functional Testing (FCT) is a technique that tests the functionality of the system or software and it should cover all scenarios including failure paths. Functional tests are designed to ensure that circuit functions are within specifications. It does not test if the PCB is good or faulty, if there are joints or cracks or if the value of the components is in tolerance. The functional tester interface to the PCB is usually via edge connector or a test-point probe. Testing through connectors can cause reliability issues, for example, connectors wear. Functional testing involves many of variabilities, making it very complex. It is possible to do many tests with different input parameters and compare the output signal with the expected results. It is easy to conduct 50 different test routines in one test. Testers usually include a device under test connectors or a bed of nails fixture. However, in this case, the number of pogo-pins is significantly lower than in-circuit test fixture.By using FCT it is possible to detect incorrect oscillator frequency, analog/digital signal distortion, amplifier gain, correct signal timing and communication problems such as USB, ethernet communication, etc.

1.13.1 Functional tester

Functional testers also include fixtures such as in-circuit tests. Functional testers generally comprise the system, hardware, and software. The functional tester includes the physical cabinet, interface to the device to be tested, central processing unit, and display unit. Hardware units are usually: power supplies, load, analog/digital converters, sensors, and many others. Measurement hardware has to be very accurate and designed for high-frequency signals, in order to measure fast signals like ethernet communication, etc. Another part of a functional testing system is the software development environment. The software has to control the whole process from the beginning. It has to initiate test, control measurement instruments, and also calculate results and judge them. The display unit should inform the operator about test processing.

1.13.2 Advantages of FCT

- Detection of:
    - Faulty integrations circuits
    - Communication problems of sub-circuits
    - Faulty signal generations
- Complexity
- Speed

1.13.3 Disadvantages of FCT

- Programming costs are typically higher that ICT
- High-speed equipment is more expensive
- Connectors reliability issues

2 Comparison of software products

It is possible to find many different types of software suitable for measurement and testing units. The most popular are Matlab and Labview. Labview is the product of National Instruments which is a worldwide company. Matlab is the product of Mathworks, also a well-known company. These two types of software can also control 3rd party measurement hardware, which is very useful. Historically, communication between different software environments was significant issue. This issue was eventually solved by industry driver standards.

2.1 Visa standard

Virtual Instrument Software Architecture, also known as VISA, is a widely used input/output application programming interface. VISA was originally standardized through the VXI Plug & Play Alliance. In 2002, the VXI Plug & Play Systems Alliance voted to become part of the IVI Foundation. All VISA updates are undertaken by the IVI Foundation. IVI (Interchangeable Virtual Instruments) are supported by the IVI Foundation. The VISA driver became the standard for virtual instrumentation. VISA test instrument drivers are widely used in many areas of the electronics test industry. The key advantages of using VISA are:

- Able to use standardised I/O layer for all I/O functions
- Allows use of different platforms on the same bus.
- Reduces programming errors, all follow the same interface rules.

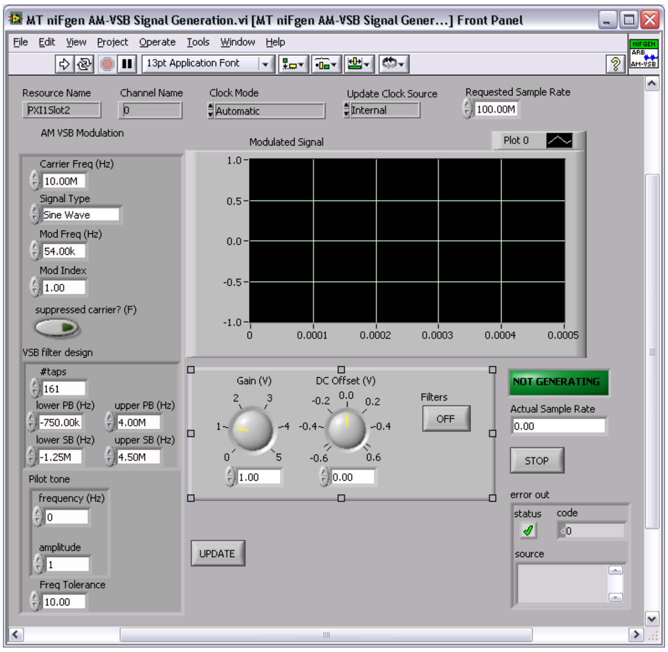
2.2 LabVIEW

Laboratory Virtual Instrument Engineering Workbench (**LabVIEW**) is a system-design platform for visual programming languages, created by the National Instruments company. LabVIEW is mostly used for instruments control and data acquisition. The LabVIEW project began in 1983 with the latest version being LabVIEW 2015. LabVIEW is unique based on the variety of tools available in a single environment, ensuring that compatibility is as simple as drawing wires between functions. National Instruments offers many measurement products which can be checked by LabVIEW. LabVIEW is widely supported by National Instruments and is very common in the data acquisition field. LabVIEW introduced a different structure of programming known as graphical programming. The main idea is to see the entire code at once. It should be more obvious to see how the program works. LabVIEW programs are called Virtual instrument (Vi). Every Vi consists of 3 basic parts:

- Front panel
- Block diagram
- Connector panel

2.2.1 Front panel

The front panel is the graphical user interface, which consists of controls and indicators. Controls allow users to control the input information to the Vi. Indicators indicate outputs of Vi which can be displayed, for example, oscilloscope signal.



Resource Name PXI1Slot2
Channel Name 0
Clock Mode Automatic
Update Clock Source Internal
Requested Sample Rate 100.00M
Carrier Freq (Hz) 10.00M
Signal Type Sine Wave
Mod Freq (Hz) 54.00k
Mod Index 1.00
#taps 161
lower PB (Hz) -750.00k
upper PB (Hz) 4.00M
lower SB (Hz) -1.25M
upper SB (Hz) 4.50M
frequency (Hz) 0
amplitude 1
Freq Tolerance 10.00
Gain (V) 1.00
DC Offset (V) 0.00
Actual Sample Rate 0.00
status ✓
code d0

Fig. 10 - Example of a Front Panel. Taken from [14]

2.2.2 Block diagram

The block diagram is the underlying code which controls the front panel. The block diagram contains graphical source code. All indicators and controls placed on the front panel will appear in the block diagram. The block diagram contains also structures and functions that represent classic programming methods, loops, and conditions which allow you to work with data.

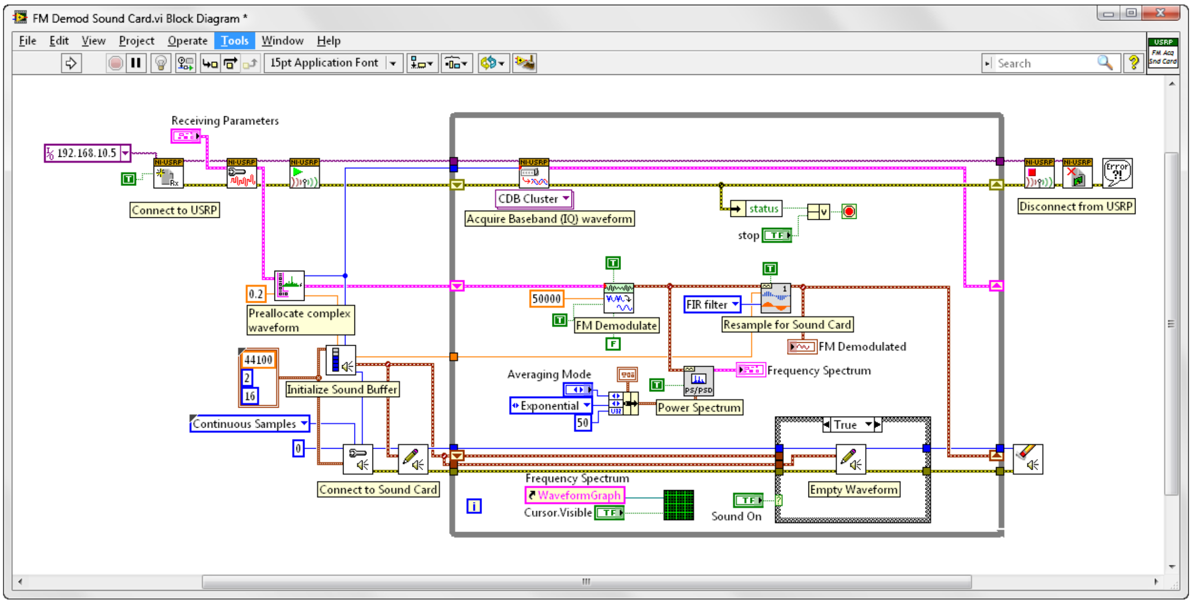


Fig. 11 - Example of Block Diagram. Taken from [15]

2.2.3 Connector panel

In some instances, it is necessary to create some function or method which is not in the LabVIEW library. In such cases there are two options. First, one can implement part of the C code in LabVIEW or second, one can use the connector panel. The connector panel allows you to build your own function or method which is called subVi. Generally, it is easy to create new functions and methods in LabVIEW library.

2.2.4 Advantages

- Graphical programming allows non-programmers to build programs with only a basic programming skills.
- Easy to learn.
- Parallel programming

- Widely supported by National Instruments.
- Many hardware components compatible with LabVIEW.
- Real-time programming
- FPGA programming
- Large libraries

2.2.5 Disadvantages

- LabVIEW is not managed by a third party standards committee such as ANSI, IEEE, ISO.
- Licensing
- Small applications have to start the runtime environment. This is a large and slow task.
- Not backward versions compatible. A VI generated in a newer version of LabVIEW cannot be opened in an older version.

2.3 MATLAB

Cleve Moler developed Matrix laboratory (MATLAB) in the late 1970s and the latest version, MATLAB 9, was released in 2016. MATLAB is a numerical computing environment programming language. In this program, it is possible to work with matrixes, implement data, algorithms, and create the user interface and interfacing with programs written C, C++, Java and others. The MATLAB application is using the MATLAB scripting language. The syntax of MATLAB application uses the Command Window as an interactive mathematical shell. MATLAB also supports developing applications with GUI. MATLAB is a programming environment that is designed for scientific purposes, simulations, parallel computing, etc. It includes computing, visualization, and programming in a user-controllable environment. Problems and solutions are most often expressed in terms of known mathematical relationships. Typical application areas are:

- Engineering calculations
- Algorithms creation
- Modeling and simulation
- Data analysis
- Scientific and engineering graphics
- Application development

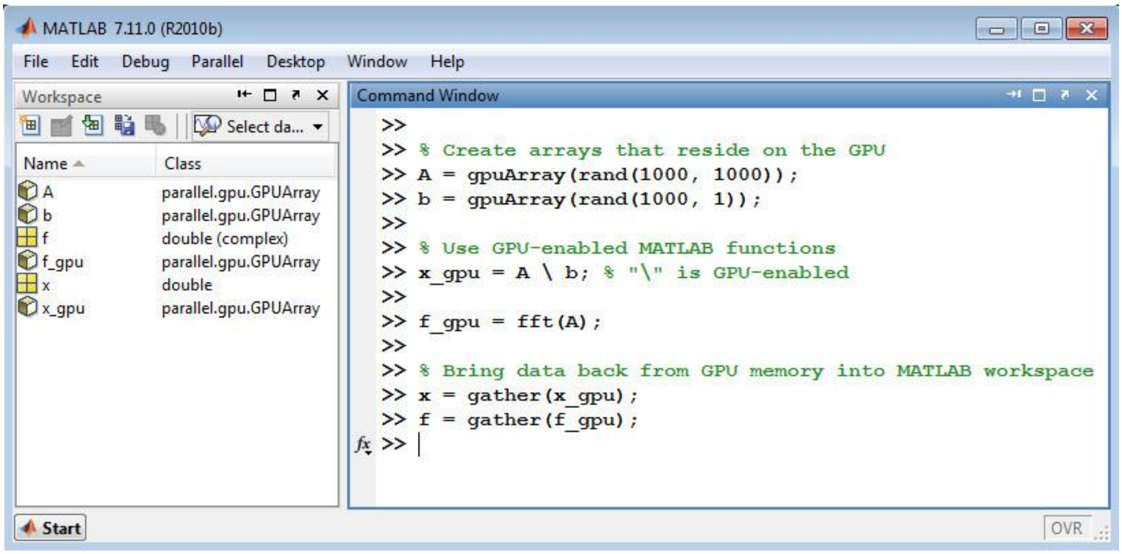
The main attribute is that all objects in MATLAB are elements of an array or matrix. These elements do not have to be just numbers but also variables and more complex structures, like pictures. The important aspects of MATLAB are function libraries, which are called toolboxes. Toolboxes always contain documentation and examples in the field of numerical mathematics. MATLAB supports object-oriented programming which allows you to develop complex applications faster than in other programming languages. Object-oriented programming significantly simplifies the creation of complex applications.

2.3.1 MATLAB advantages

- Huge algorithm library
- Advance data computing
- Widely supported
- Big base of users

2.3.2 MATLAB disadvantages

- Licensing
- Specific code structure



Name	Class
A	parallel.gpu.GPUArray
b	parallel.gpu.GPUArray
f	double (complex)
f_gpu	parallel.gpu.GPUArray
x	double
x_gpu	parallel.gpu.GPUArray

```
>>
>> % Create arrays that reside on the GPU
>> A = gpuArray(rand(1000, 1000));
>> b = gpuArray(rand(1000, 1));
>>
>> % Use GPU-enabled MATLAB functions
>> x_gpu = A \ b; % "\" is GPU-enabled
>>
>> f_gpu = fft(A);
>>
>> % Bring data back from GPU memory into MATLAB workspace
>> x = gather(x_gpu);
>> f = gather(f_gpu);
>>
```

Fig. 12 - MATLAB programming interface. Taken from [16]

2.4 Simulink

Simulink is a block diagram environment that uses MATLAB and its functions for the simulation of dynamic systems. Simulink has a slightly different user interface than MATLAB. While in MATLAB the most important factor is command line control, Simulink uses simple and intuitive graphical programming. This interface is a graphical block diagram tool with a customizable set of libraries. Simulink offers integration with MATLAB and can drive MATLAB or be scripted from it. Simulink is widely used in data sensing process and in the automatic control process.

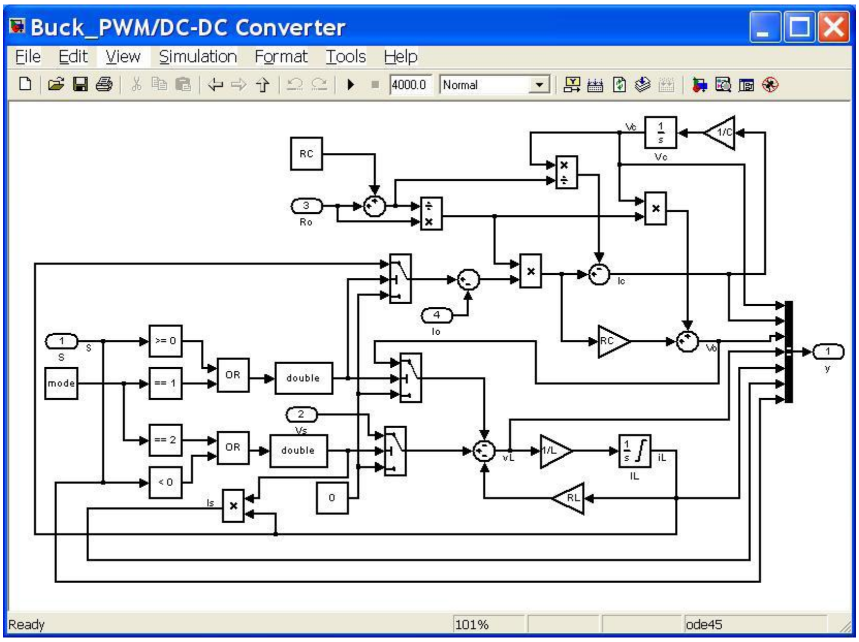


Fig. 13 - Simulink graphical interface. Taken from [11]

3 Automated tester unit

3.1 Tested PCB

The testing unit was built for PCB shown on Fig. [14]. Let’s name the tested PCB Electro-Gener. Electro-Gener is a product of Medical Technologies CZ a.s. company. The main purpose of Electro-Gener is physiotherapy treatment. PCB contains two identical channels, which can be called Master and Slave. Due to privacy of know-how, it is not allowed to show schematic of Electro-Gener. Electro-Gener was tested manually but it was a very time-consuming process. My task was to create an automatic functional testing unit with similar test configuration but with significantly less time consumption. The enitre test process can be divided into two main parts. In the first power sources and highly important nodes for accurate measuring of the functionality of the unit are tested. Usually, DC signals are tested. The second step tested the functionality of PCB. It means the communicaion packet is sent via master board to Electro-Gener to initiate therapy mode. Then functionality of output signal is measured. It measures amplitude, frequency, current, and shape of the output signal and many others. In the end, a report protocol with all measured values is created. Output signals period is in the range between ms to tens of µs.

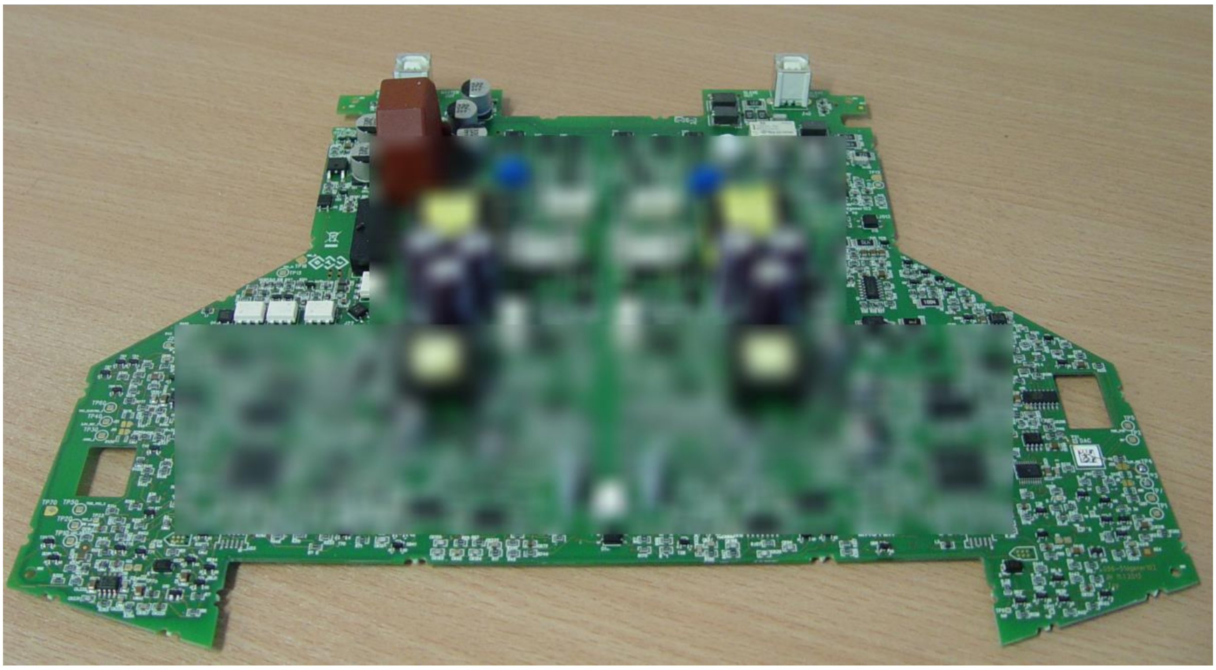


Fig. 14 - PCB under test. Made by author

3.2 Test points

Electro-Gener contains test-points which are necessary to test for functionality verification. Fig. [15] shows the positions of test-points on Electro-Gener PCB. It is important to note that test-points are in different shapes such as circles or squares, some of them are connectors pins. Different types of test-points require using different types of probes (pogo-pin). For circle test-points, it is common to use needle pogo-pins for connector crown (serrated) pogo-pins, to ensure better contact connection. In total, there are 37 test-points.

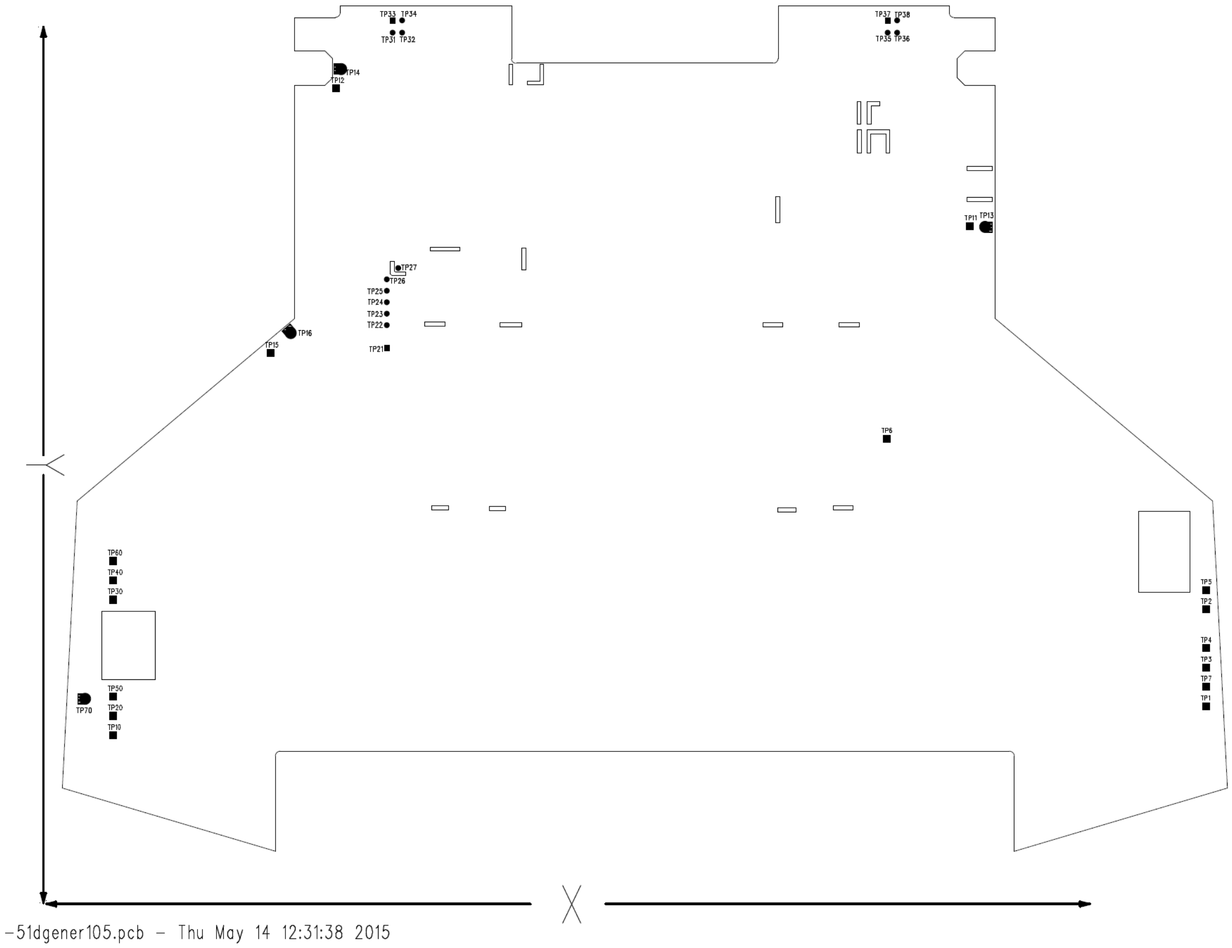


Fig. 15 - Positions of test-points. Made by author

3.3 Testing unit design

As previously discussed, Electro-Gener was tested manually at Medical Technologies CZ a.s. Thanks to it, all the information about output signal parameters were made available. The first step was to design the structure of the testing unit and choose all components which include also software environment. The second step was to select a company suitable for fixture construction. The main goal was to create a reliable automated tester unit of acceptable cost.

3.4 Data sensing

Due to previous experience with LabVIEW and National Instruments products, I decided to choose National Instruments components and software environment. Fast D/A converters are not required for sensing DC signals. The best choice was National Instruments product USB-6008. The USB-6008 provides basic functionality for data measurements. USB-6008 has 8 analog inputs with 12bits resolution and 10kS/s sample rate. 4 analog inputs can be used as differential channels. It includes also 2 analog outputs. And 12 digital input/output channels. The purpose of USB-6008 was to measure slow signals, usually DC voltage, for example, supply voltage. USB-6008 is also compatible with LabVIEW, which was the main requirement.
USB-6008 specification:

- 8 analog inputs (12-bit, 10 kS/s)
- 2 static analog outputs (12-bit); 12 digital I/O; 32-bit counter
- Bus-powered for high mobility; built-in signal connectivity
- Compatible with LabVIEW, LabWindows™/CVI, and Measurement Studio for Visual Studio .NET

To measure fast signals and high voltage signals, there were several options. The best two variants were to first, choose an NI product which is able to measure these required signals and second, choose a third-party product with similar parameters compatible with LabVIEW. During manual testing an oscilloscope was used for sensing fast signals. This inspired me to use it because most of the oscilloscopes can be controlled by LabVIEW using VISA drivers. I conducted a simple analysis where I compared oscilloscopes Rigol DS2072 with National Instruments unit PCI-6250. In a comparison of these two components, it is obvious that both have sufficiently high sample rates. However, there was a significant difference in price. Finally, I decided to use an oscilloscope for two main reasons. Firstly, the price of the oscilloscope was approximately 60% of the price of NI PCI-6250. Second, the oscilloscope can be used for another purpose or measurement. The output voltage of Electro-Gener is sensed by oscilloscope probe with ratio 100:1.

Rigol DS7072 specifications:

- 2 analog channels
- 70MHz bandwidth
- Maximum sample rate 2 GS/s.
- Maximum Memory Depth 56Mp
- USB host interface

NI PCI-6250 specifications:

- Analog Input Resolution 16bits
- On-Board Memory 4095 samples
- Maximum sample rate 1 MS/s

3.5 Schematic design

Fig. [16] shows a schematic block diagram of test-points multiplexing. It consists of NI USB-6008 which offers 8 analog inputs and 12 digital inputs/outputs. PCB under testing consists of four main parts: V vst, V TR, Master and Slave blocks. The description of this block diagram is simple. The first block represents NI USB-6008 with analog inputs (AI 0-7) and digital inputs/outputs (D0 0-12). The middle block represents tested PCB Electro-Gener which consists of four parts as aforementioned. The last block represents the resistor load. NI USB-6008 senses analog signals and sends them to a computer for signal processing. The digital outputs are used for switching relays which lead to load and to the test-points. Analog signals are impedance isolated by using an isolation amplifier. Output signals of PCB are sensed by an oscilloscope. A major issue is that each block has different ground potential. Measurement of each block's voltage requires connecting ground potentials to NI USB-6008. Connecting all grounds potential to NI USB-6008 completely destroys the electrical barrier between the blocks. This can cause the destruction of tested PCB. The main idea was to connect all ground potentials together in a time of no generation of output signals. The grounds connection is switched off after all DC voltage measurements of the blocks and the functional testing continues. The switching of relays is independent on Electro-Gener ground potential. Due to this, it is possible to control relays during the functional test. Testing units can be completely isolated from Electro-Gener by switching off all relays controlled by DO0 signal. Switching between Master and Slave test-points is allowed by relays controlled by DO1. Relays controlled by DO2, 4, 5, 6, 7, 8, 9, 10 are used to set a suitable load in different tests. The relay controlled by DO11 is used to turn on and turn off power supply of Electro-Gener.

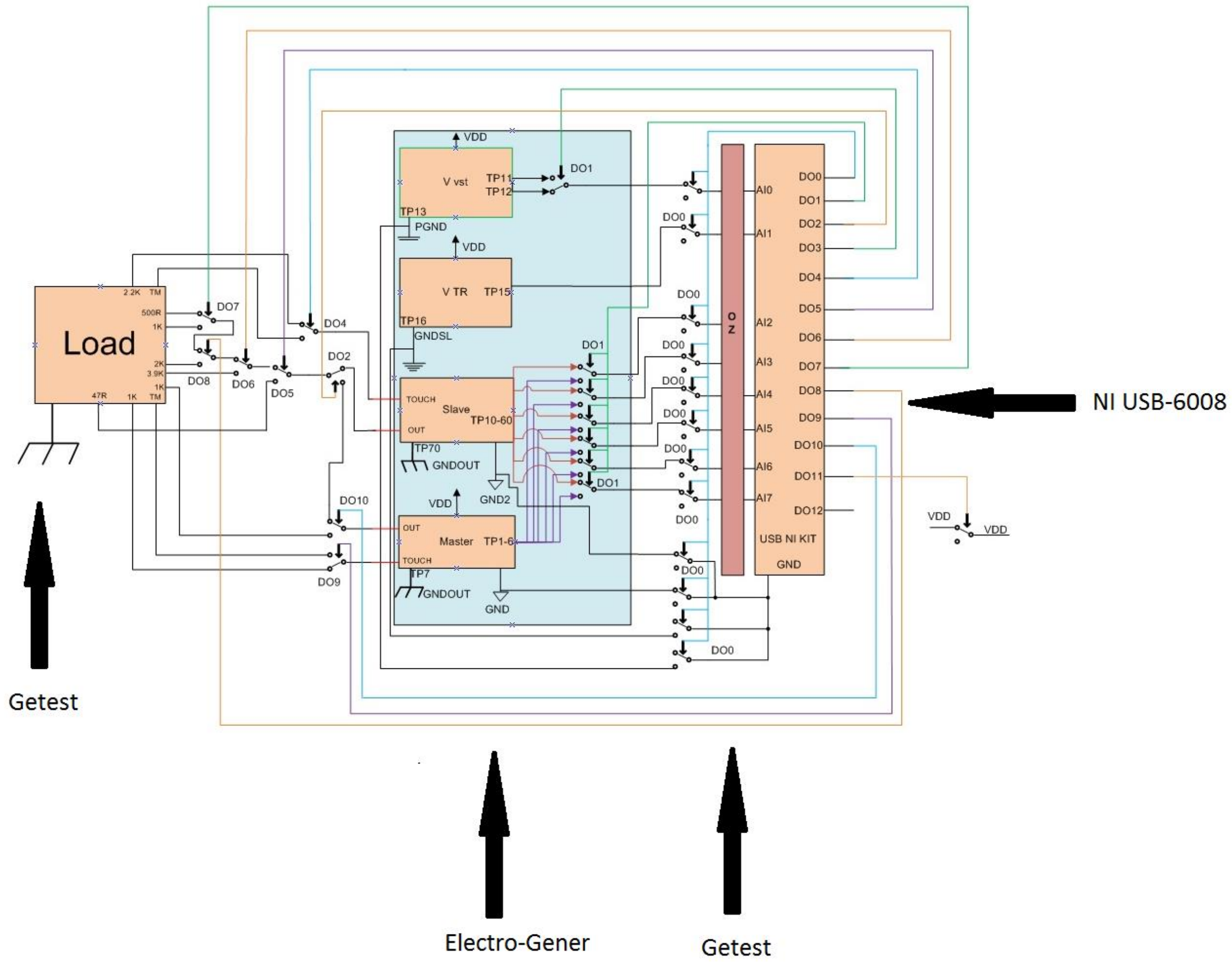


Fig. 16- Block diagram of test-point multiplexer. Made by author

3.6 Testing PCB schematic

Fig. [16] represents the hierarchical schematic design of testing PCB called, Getest. It consists of this sub-blocks: input supply filter, power sources, relays, master, slave, measure, check-lock.

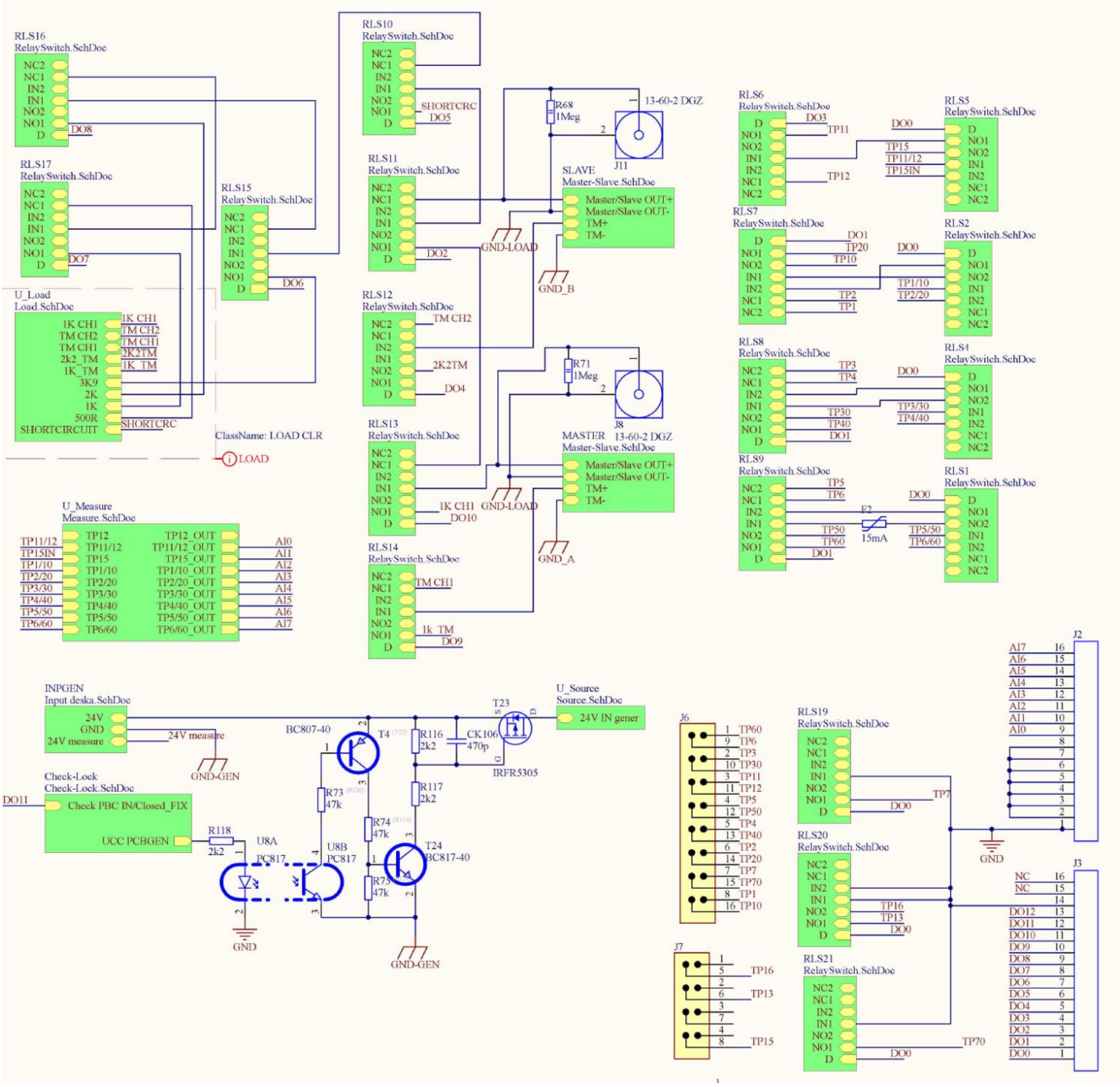


Fig. 17 - Hierarchic design of Getest. Made by author

3.6.1 Input supply filter

The main purpose of the supply filter is to achieve electromagnetic compatibility and electromagnetic interference. In the beginning, there are two blocking capacitors followed by fuse F1. DS3 is supposed to protect the circuit against the wrong polarity. CE1 is filtering capacitor, L1 is common-mode choke coil for suppression common mode noise followed by across the line capacitor CK96. A differential mode filter is created by ferrite beads FB1,2,3,4 and CK97,93 and R109 to suppress differential noise. R107 and R110 are used as a voltage divider for voltage measurement.

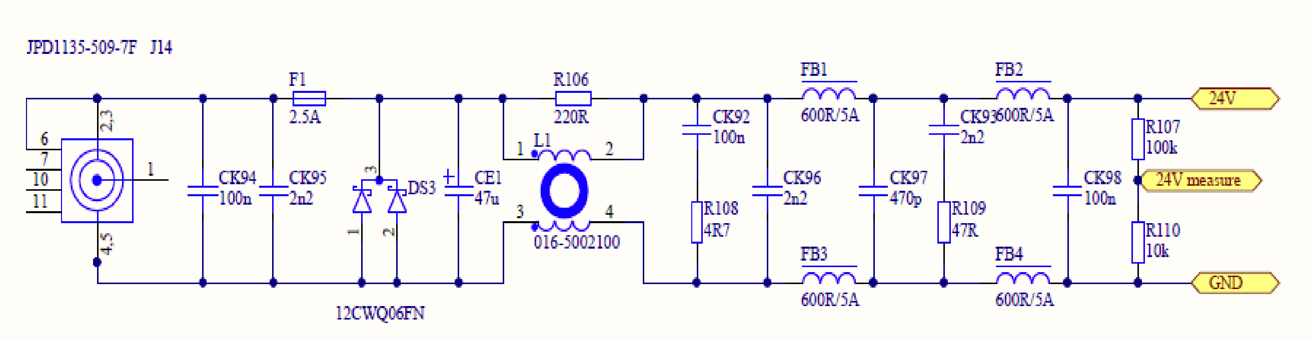


Fig. 18 - Input supply filter schematic. Made by author

3.6.2 Power supply 5,9V

Relays are supplied by 5 Volts. Operation amplifiers require operational supply voltage in a range of 4 to 16 Volts. I decided to supply it by 9 Volts. Integrated circuit L5973D was used. It is switching step-down converter. Using a linear step-down regulator would be inefficient. The nominal operating current of relay TX2SA-5-Z is 40 mA [26]. In the schematic design, there are 18 double relays used. The maximum power consumption of relays is given by the following formula:

$$I_{RELAYS} = N \times I = 18 \times 40 \times 10^{-3} = 0.72\,A \qquad 1)$$

$$P_{RELAYS} = N \times I \times V = 18 \times 40 \times 10^{-3} \times 5 = 3.6\,W \qquad 2)$$

N – Number of relays
I – Nominal operating current
V – Voltage
P – Power

Maximal calculated power consumption off all relays is almost 0.73 A. Input voltage source is 24 Volts source. The power loss at linear step-down regulator can be calculated by the following formula:

$$P_{LOSS} = (V_{IN} - V_{OUT}) \times I_{IN} = (24 - 5) \times 0.72 = 13.86\,W \qquad 3)$$

P_{LOSS} – Power loss
V_{IN} – Input voltage
V_{OUT} – Output voltage

Calculated Power loss was approximately 14 W. It is very difficult to cool such a power loss. In this case, it is better to use a switching power supply. Power loss at power switching supply is given by the following formula:

$$1 - \eta = 1 - \frac{P_{OUT}}{P_{OUT} + P_{CON\ LOSS}} \qquad \mathbf{4)}$$

η – Efficiency
P_{OUT} – Output power
$P_{CON\ LOSS}$ – Contact losses

Contact losses are a small number. In general, the power switching converter can achieve 90% efficiency. Fig. [19,20] shows the principle of a power switching converter.

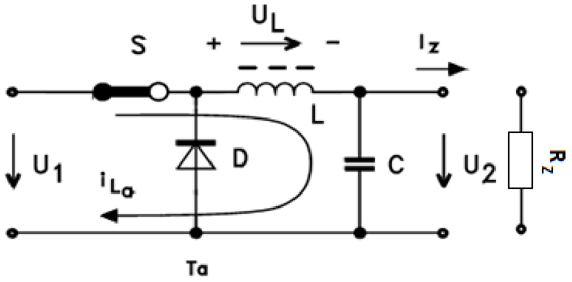


Fig. 19 - Principle of switching step-down converter. Switched on. Taken from [18]

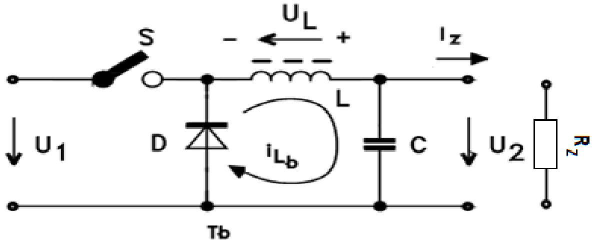


Fig. 20 - Principle of switching step-down converter. Switch off. Taken from [18]

Output voltage is given by the following formula:

$$V_{OUT} = \frac{T_{ON}}{T_S} \times V_{IN} \qquad \mathbf{5)}$$

T_{ON} – On time interval
T_S – Switching period
V_{IN} – Input voltage

One disadvantage of switching power supply is the higher ripple voltage in comparison to the linear step-down regulator. In this case, there is no need for extremely precise voltage supply. L5973D is working on the well-known principle shown in Fig. [19,20]. L5973D can achieve 89% efficiency [21]. This integrated circuit was used also for 9V power supply. Capacitor CK52 is used as blocking capacitor and CE2 is used as a filter capacitor. The output voltage is sensed through a voltage divider to feedback input pin. Duty cycle is changing in dependency of output-voltage. FB5 is used like a filter to suppress common mode noise. The output voltage is indicated by light emitted diode DL1,2.

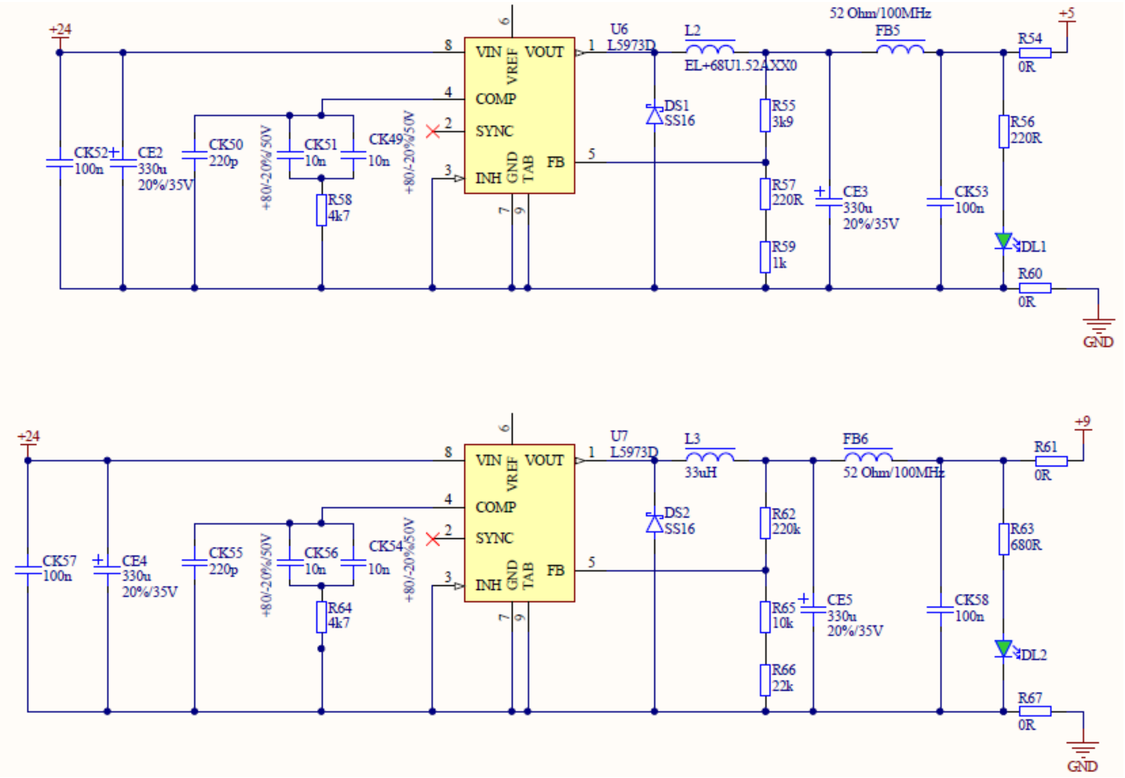


Fig. 21 - Schematic of 5, 9 V power supply. Made by author

3.6.3 Relay

A double relay TX2S2-5V-Z was used. Fig. [22] shows relay schematic. The relay is controlled by a transistor BSS138. R98 is used like switching current limitation protection. R99 is a pull-down resistor, it defines a default value. R98 and R99 are connected as a voltage divider. Voltage gate-source is given by formula:

$$V_{GS} = \left(\frac{R99}{R98 + R99}\right) \times U_{IN} = \left(\frac{22 \times 10^3}{2.2\ \times 10^3 + 22 \times 10^3}\right) \times\ 3.3 = 3\ V \tag*{6)}$$

V_{GS} – Voltage gate-source

BSS138 is N-MOS transistor with threshold voltage level 1.3 V [27]. NI USB-6008 digital output voltage level is 3.3 V. This voltage is divided to 3 V which is still in threshold voltage range of BSS138. NI USB-6008 current source limit is 8.5 mA. Value of R98 was calculated to comply this condition. NI USB-6008 current source is given by formula:

$$I = \frac{U}{R} = \frac{3.3}{24 \times 2k} = 136\ \mu A \qquad \textbf{7)}$$

Calculated current is 134µA which is in range. CK84 is blocking capacitor. Diode D17 is protection against voltage switching peaks.

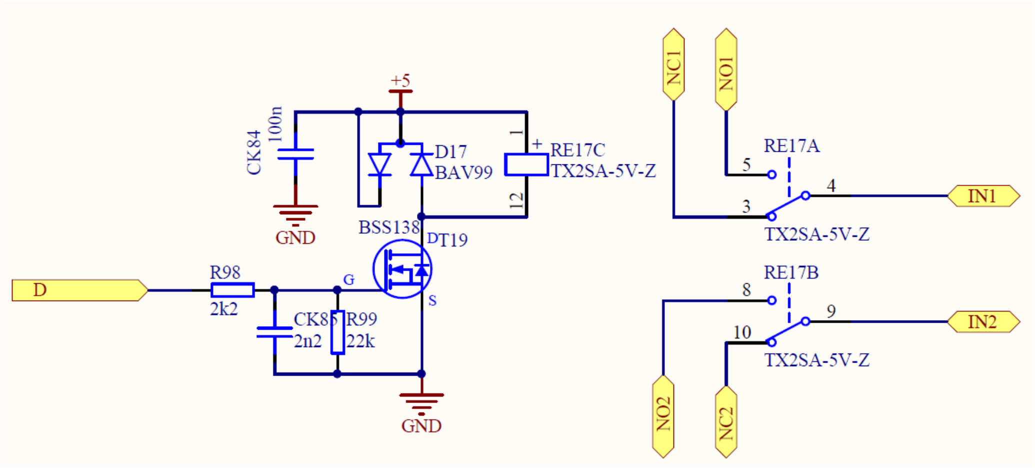


Fig. 22 - Schematic of relay. Made by author

3.6.4 Sensing PCB and lock

This sub-block schematic is designed for turn on and off the power supply voltage and detecting tested PCB in the fixture and for locking the fixture. The main idea is to turn on the power supply voltage after detecting PCB in tester unit and then to lock fixture. If PCB is detected, it is suitable to lock the fixture, in some tests there is 500 V which can be dangerous. It is also protection against accidental opening of the fixture. The lock is controlled by 24 V source. PCB is detected by NI USB-6008. Digital input is connected to J10. If J10,12 are shorted, Logic 1 will appear in the digital input. This information indicates inserted PCB in tester unit and closed fixture. Then Digital input is set to digital output and Logic 0 is set. This will turn off transistor T2 and open T3 which activates the lock. NI USB-6008 is able to operate with sink current -8.5 mA. Sink current can be calculated by the following formula:

$$I_{SINK} = \frac{U}{R} = \frac{5}{1000} = -5\,mA \qquad \textbf{8)}$$

R 69,70 are used as a voltage divider to achieve threshold voltage to open transistor T2.

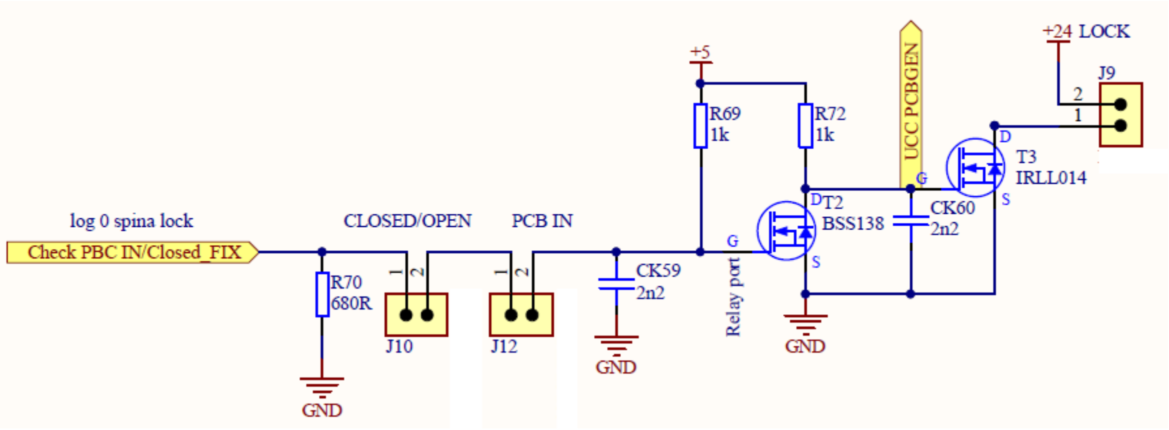


Fig. 23 - Schematic of Sensing PCB and lock. Made by author

3.6.5 Sensing circuits

NI USB-6008 maximum input voltage is 10 V. Maximum voltage level value on test-points is 24 V. It was necessary to divide input voltage. The test-points voltage is divided by voltage divider; operation amplifiers are used as an isolation amplifier. Diode D21 is overvoltage protection. CK11,12 are blocking capacitors. Resistor R25 is a current limitation. Operation amplifier is TLC274CD. There was no need to use high-speed OA due to sensing DC voltage. The main purpose of this sub-block was to isolate test-points and NI USB-6008 and also protect analog inputs against overvoltage. Fig. [24] shows the connection of isolation amplifier. This connection is used for all test-points except output therapy test-points and communication test-points. Other connections of isolation amplifiers are similar, only voltage dividers differ.

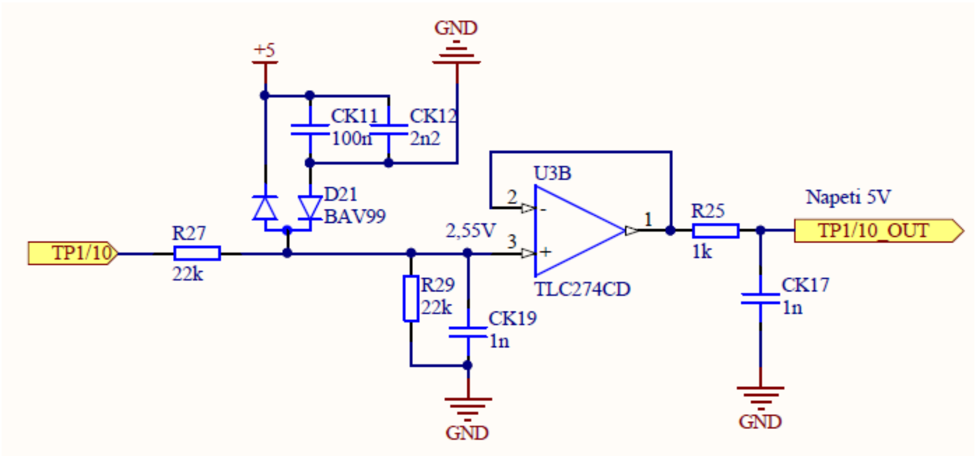


Fig. 24 - Schematic of sensing circuit. Made by author

3.6.6 Load

The primary Electro-Gener load is a human body, and the human body has capacitive behaviour. However, for testing correct functions of Electro-Gener it was sufficient to create an ohmic load. The load consists of power resistors with power loss 0.6, 5,10 W and touch-memory. Values of resistors are 500R, 1k, 2k, 2k2, 3k9. Values has been properly selected depending on the therapy voltage and current level. Since the PCB under test has two identical channels - and in two tests there are channels producing signals at the same time - it was necessary to build a load with such a performance. Touch memory DS2505 was used.

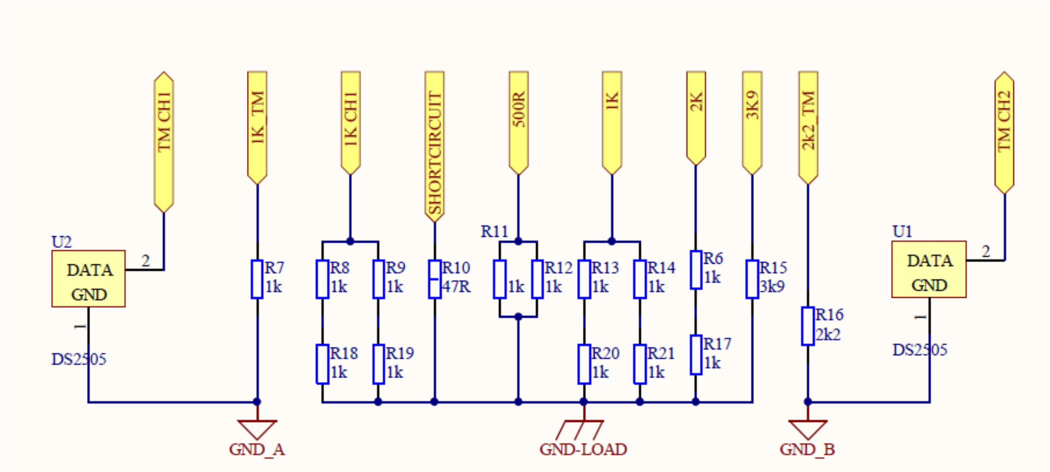


Fig. 25 - Schematic of Load. Made by author

3.7 Block diagram of tester unit

The tester unit consists of several sub-parts. Fig. [26] shows tester unit block diagram. Main voltage can be turned off by an emergency button. Main voltage is isolated by an isolation transformer. Multi-socket plug is used for two adapters; one supplies device under test and second supplies measure hardware. A communication board is connected to Getest PCB. NI USB-6008 is electrically isolated by USB ISO and connected to Getest. A USB hub was used to reduce the number of USB sockets, it is also electrically isolated by USB ISO. The computer is connected to the tester unit through a USB plug. Probes of oscilloscope senses output signal of Electro-Gener. Test-points are connected to Getest. Only the computer and oscilloscope are located out of the fixture. Tester unit consists of:

- USB isolator
- USB hub
- Communication board
- NI USB-6008
- USB ISO
- 2x adapter 24 V
- Emergency button
- Isolation transformer

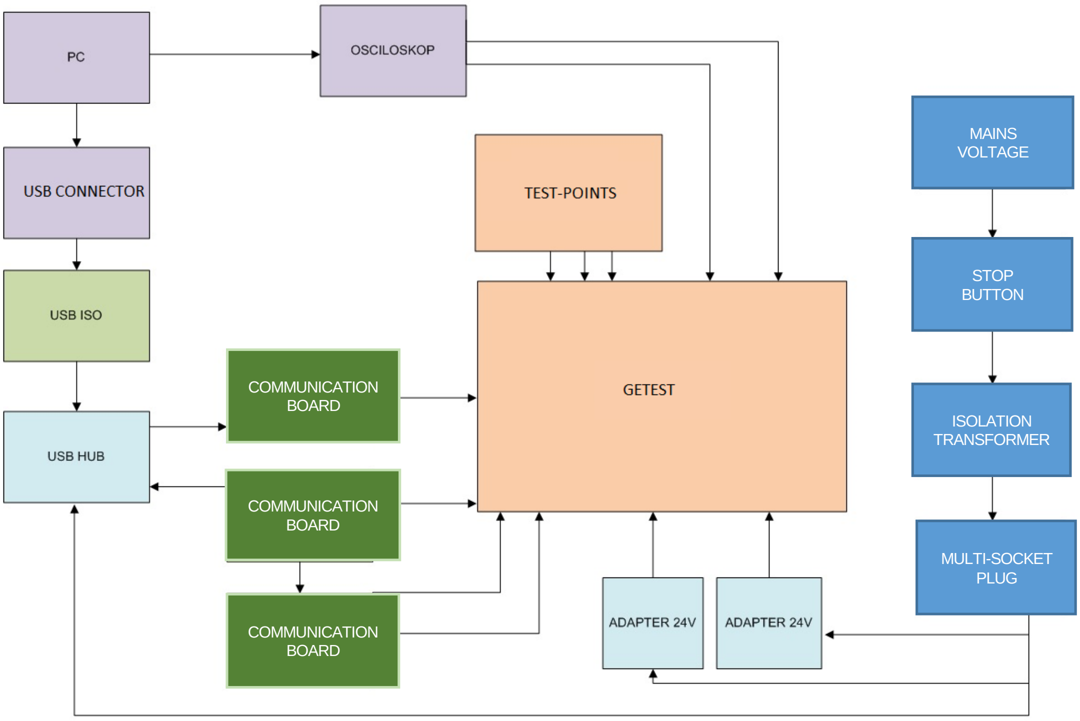


Fig. 26 - Tester unit block diagram. Made by author

3.7.1 Isolation transformer

An isolation transformer was used because there was an issue with connected grounds potentials of Electro-Gener. In high voltage test, it caused the destruction of operational amplifier on Getest PCB. The high voltage test generates exponential pulses with 500 V amplitude and 30 µs period. Such a fast signal can be easily coupled through the capacity to other parts of the tester unit. It was necessary to isolate sensing hardware which is the oscilloscope in this case. The main idea was to create a tester unit with as little equipment as possible. Due to this, it was electrically isolated hardware inside of the fixture over the oscilloscope. The using of isolation transformer turned out an effective solution. Wiring of isolation transformer represents a small capacity but it this case was sufficiently small and did not cause any side effect. Idec YW1B-V4E01R isolation transformer was used.

3.7.2 USB isolator

It was necessary to also isolate the USB connected hardware. It was possible to buy a commercial USB isolator. In the tester unit, two USB isolators are used and were made two tester units. In such a volume, it was suitable to design it. Through the USB, two units communicate; Communication board and NI USB-6008. A suitable integrated circuit ADUM4160BRWZ for this application was used. ADUM4160BRWZ is a full/low-speed 5KV USB digital isolator, USB2 compatible, bidirectional low and full speed rate. DC/DC converter was used SPU02L-05, it was chosen due to the capability to supply 0.4 A which were required. Electric isolation is 3 kV [28]. Fig. [27] shows a schematic of USB ISO.

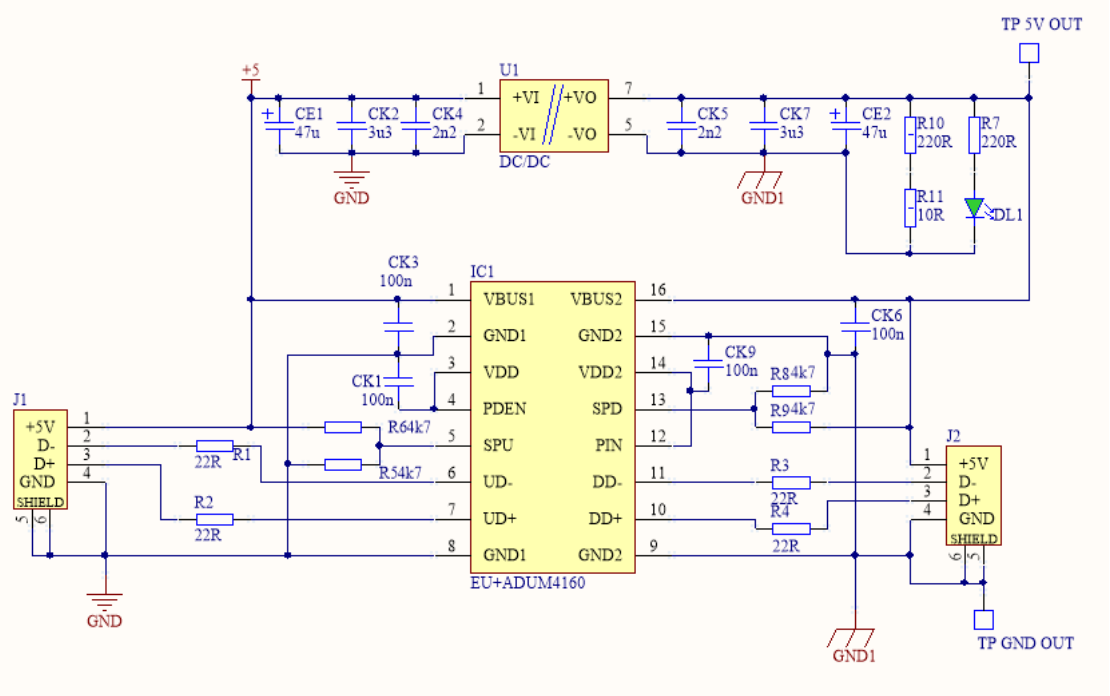


Fig. 27 - Schematic of USB isolator. Made by author

3.7.3 USB HUB

Tester unit was designed with minimum accessories. Using USB HUB reduced the number of USB slots requirements. USB Hub includes an active power supply. The active power supply is necessary due to the power consumption of NI USB-6008 and Communication board which can be higher than 0.5 A. 0.5 A is a maximum current of a USB slot on a PC. Active power assures that each slot can be supplied 0.5 A. USB HUB Hama 1:4 was chosen.

3.7.4 Communication Board

Communication Board simulates Master-board, in other words, by using a Communication Board it is possible to communicate with Electro-Gener. Communication Board is used to initiate therapy mode. Communication Board is connected to a computer and through LabVIEW it is possible to send communications packets to Electro-Gener. Communication Board is the internal product of Medical Technology, a.s. Due to the protection of know-how, it is not allowed to publish a schematic of Communication Board.

3.7.5 Adapter 24V

This adapter is an original accessory to Electro-Gener. As previously mentioned two adapters were used in the testing unit. By using these adapters, real conditions are simulated. One adapter is used for Electro-Gener PCB. The second one is used for testing PCB to supply relays and operation amplifiers. Due to the protection of know-how, it is not allowed to publish a schematic of 24 V adapter.

3.7.6 Emergency button

An emergency button was used as a safety accessory. It provides protection in case of explosion or fire of the PCB. By pressing the button, the tester unit’s power can be easily unplugged. LAS1-BY-11TSA button was used.

Emergency button parameters are:

- Operation voltage 250 V
- Operation current 5 A
- Latch

3.8 Fixture

The fixture was made by Technik partner s.r.o. company. Technik partner s.r.o. represents PTR company in the Czech and the Slovak Republic. It was necessary to prepare some requirements shown in table [2]. With this requirement and position of test-points, Technik partner was able to make the required fixture.

Fixture requirements:

Mechanism	Needle Contact Fields
PCB Contacting	Single-Sided,
Pressure	Circular Motion Combined With Linear Stroke
Control	Manual, Hand Grip With Locking In The Closed Position
Linear Stroke	18-20 mm
Opening Angle	80-85°
Max Height Of Components On The PCB	Min 35mm (5mm Bottom Side)
The Ability To Connect USB Connector	USB Type B (Male + Female) Min 80mm
Operational Voltage	500 V
Operational Current	Min 5a
Sensing-Pins Constructions	Replaceable Pogo-Pins,
Contacts	Test-Points
Type Of Pogo-Pins	Masher, Star, Chisel
Pogo-Pins Connections	Cooper Wire Min Length 450mm
Number Of Pogo-Pins	According To Number Of Test-Points
Access To PCB In Closed Position	Without The Access
Detection Of PCB	Pressure Contact
Detection Of Closed Fixture	Pressure Contact
Lifespan	Min 250 000 Cycles (2 Years X 1000 Cycles Per Day)
Fixture Lock	Lock Control By 24 V

Tab. 2 - Fixture requirements. Made by Author.

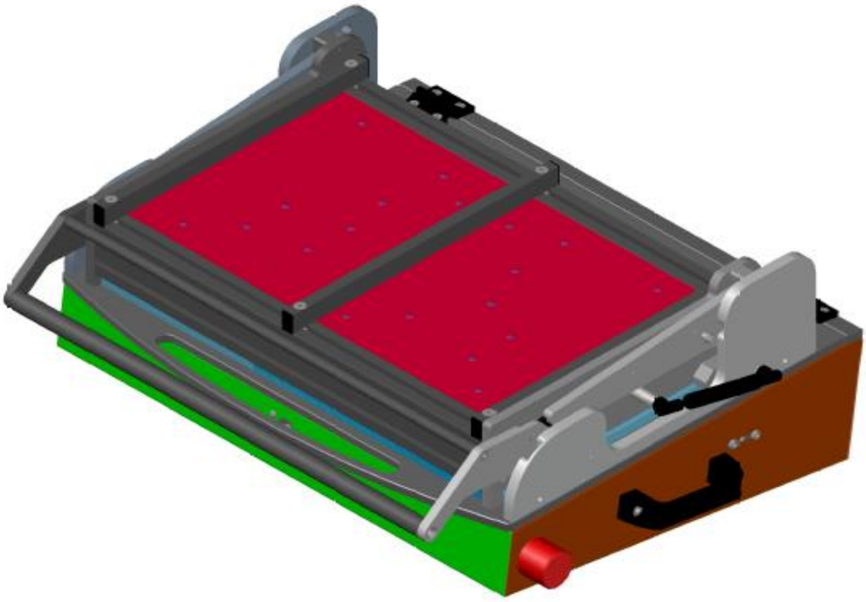


Fig. 28 - Fixture model, side view. Made by author

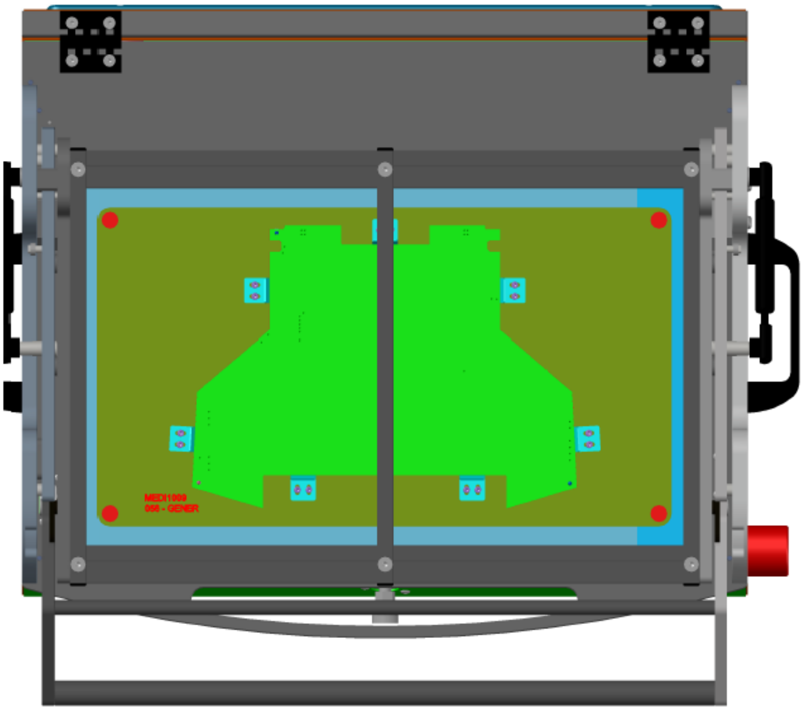


Fig. 29 - Fixture model, top view. Made by author

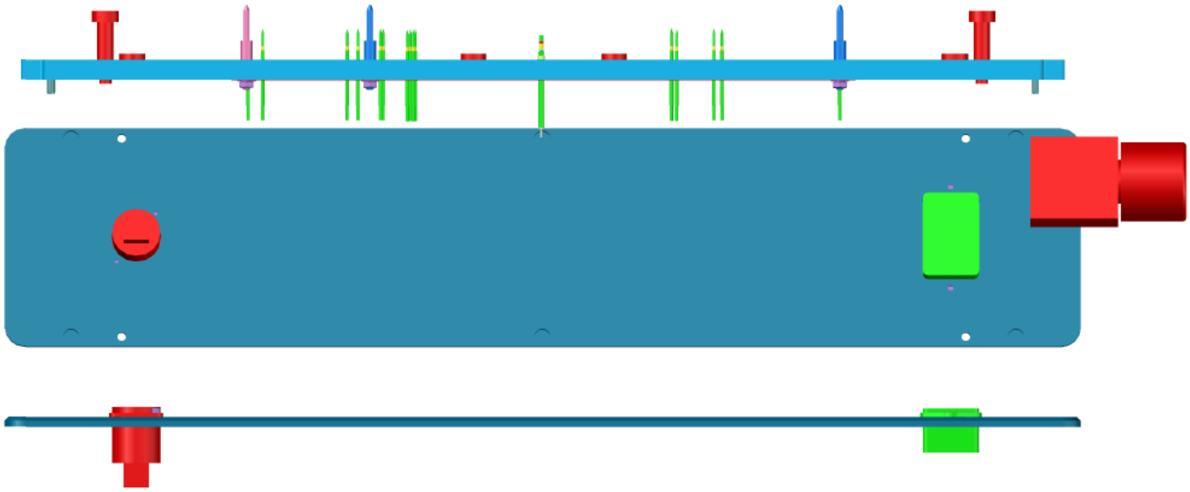


Fig. 10 - Fixture model, side cut view. Made by author

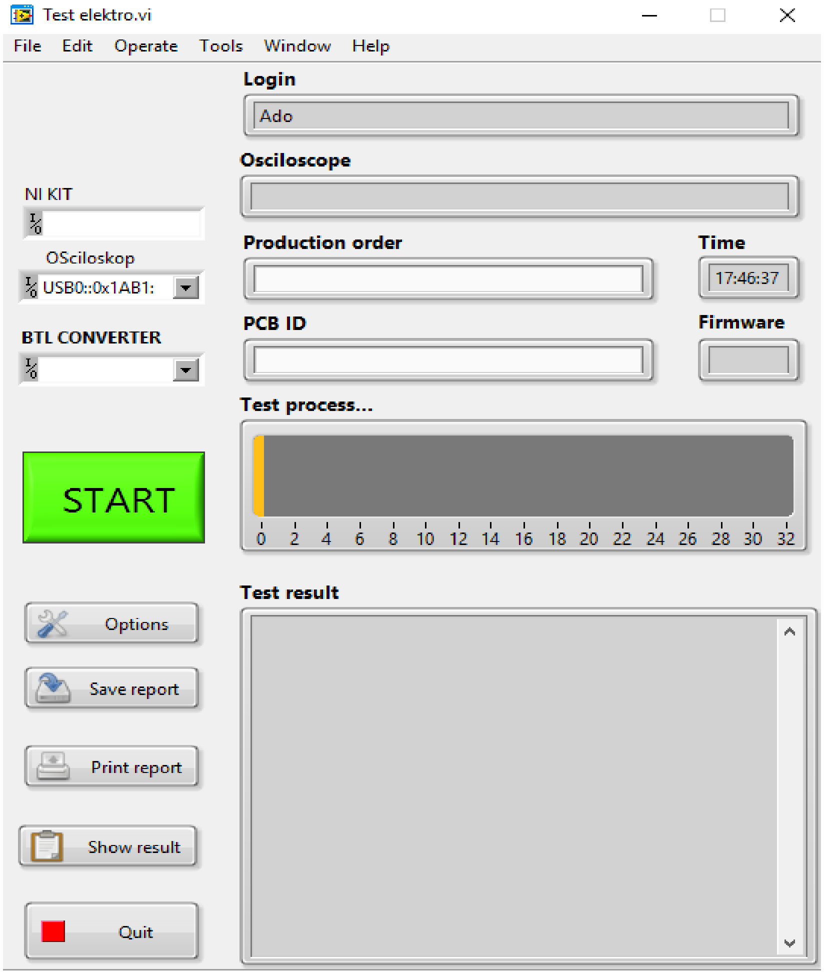
4 Software

4.1 Software environment

As previously discussed, I have some LabVIEW environment software experience. Medical technology uses LabVIEW as a standard software environment. To choose another software would be uneconomic due to the costs of purchasing a new software license. LabVIEW was the only reasonable choice. LabVIEW allows for the creation of .exe file, meaning there is a possibility to use this program on a computer without a LabVIEW license. The main goal was to create a user-friendly program with the capability to test PCB as fast as possible. At the end of the test, it creates a test report with all important data, stores logs, and has the ability to display measured data. One support program was built to create value limits, which is very suitable to be able to change values limits without changing the main program code.

4.2 Graphical user interface

Fig. [31] shows the graphical user interface (GUI). GUI is very simple but the operator has some options to set. GUI consists of several parts. Login bar and this bar is automatically filled in. This information determines who is responsible for a particular test. Oscilloscope bar displays name and model of the oscilloscope. Every PCB has a specific ID which has to be recorded in PCB ID bar. The firmware and time bars are also filled in automatically. All this information is used in test report to determine when was the test done, by who, with what firmware and by using which measurement equipment. The test process bar displays the current running test. NI kit shows the name of used NI USB-6008.



Login: Ado

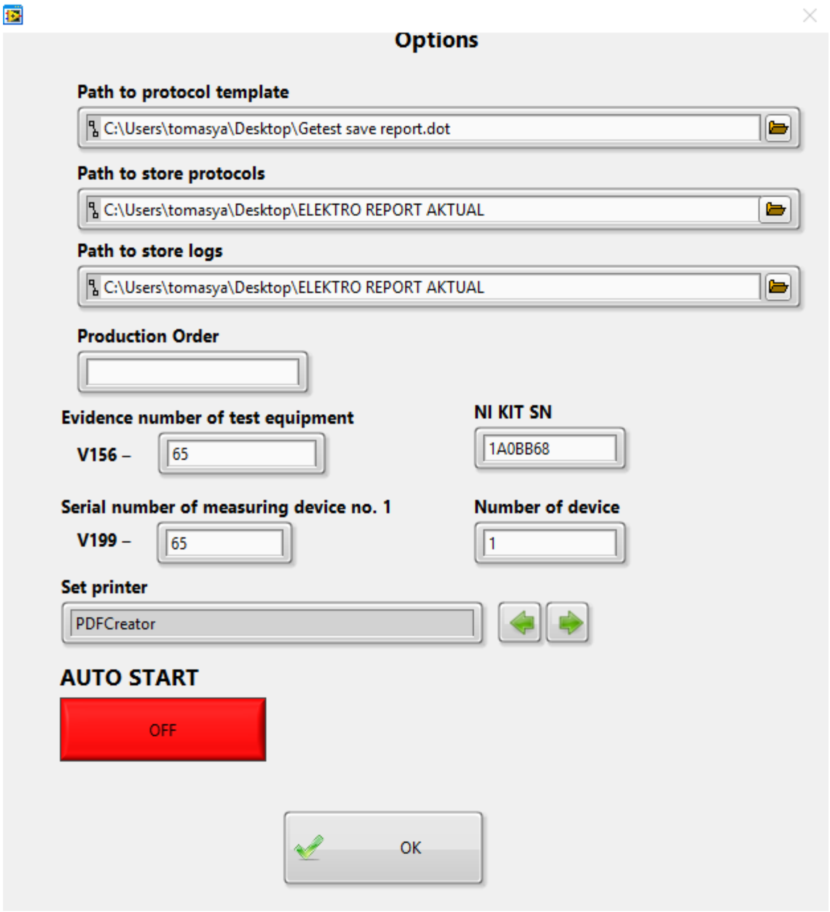
OScilloskop: USB0::0x1AB1:

Time: 17:46:37

Fig. 11 – Graphical user interface. Made by author

4.2.1 Options button

In the options menu, it is possible to set a protocol template, the path where to store the protocol and logs. It is possible to set the printer and the serial number of NI USB-6008. Also, a very useful feature is the auto start. This feature starts the test automatically when PCB is sensed and the fixture is closed, so there is no need to click on the start button.



Options

Path to protocol template: C:\Users\tomasya\Desktop\Getest save report.dot

Path to store protocols: C:\Users\tomasya\Desktop\ELEKTRO REPORT AKTUAL

Path to store logs: C:\Users\tomasya\Desktop\ELEKTRO REPORT AKTUAL

Production Order:

Evidence number of test equipment: V156 – 65

NI KIT SN: 1A0BB68

Serial number of measuring device no. 1: V199 – 65

Number of device: 1

Set printer: PDFCreator

AUTO START: OFF

Fig. 12 - Option menu. Made by author

4.2.2 Save report

Every successful test generates a test report. It is automatically saved. In the case of a fail result, there is still an option to save it by click on the button “save report”.

4.2.3 Print report

It is also possible to print the test report if necessary.

4.2.4 Show results

It is possible to view results of tested PCB without saving them first. Results are shown in the new pop-up window.

4.3 Block diagram

I used the Producer/Consumer design pattern. Producer/Consumer design pattern is shown in Fig. [33]. “The Producer/Consumer is based on the Master/Slave pattern. It is geared towards enhanced data sharing between multiple loops running at different rates. Basically Producer/Consumer pattern’s parallel loops are divided into two categories; those that produce data, and those that consume the data produced. This pattern is commonly used when is necessarily to acquire multiple sets of data to process in order. Producer/Consumer gives ability to easily handle multiple processes at the same time while iterating at individual rates. This pattern is unique because of buffering communication between application processes. When multiple processes are running at different speeds, buffered communication between processes is extremely effective.”[19]

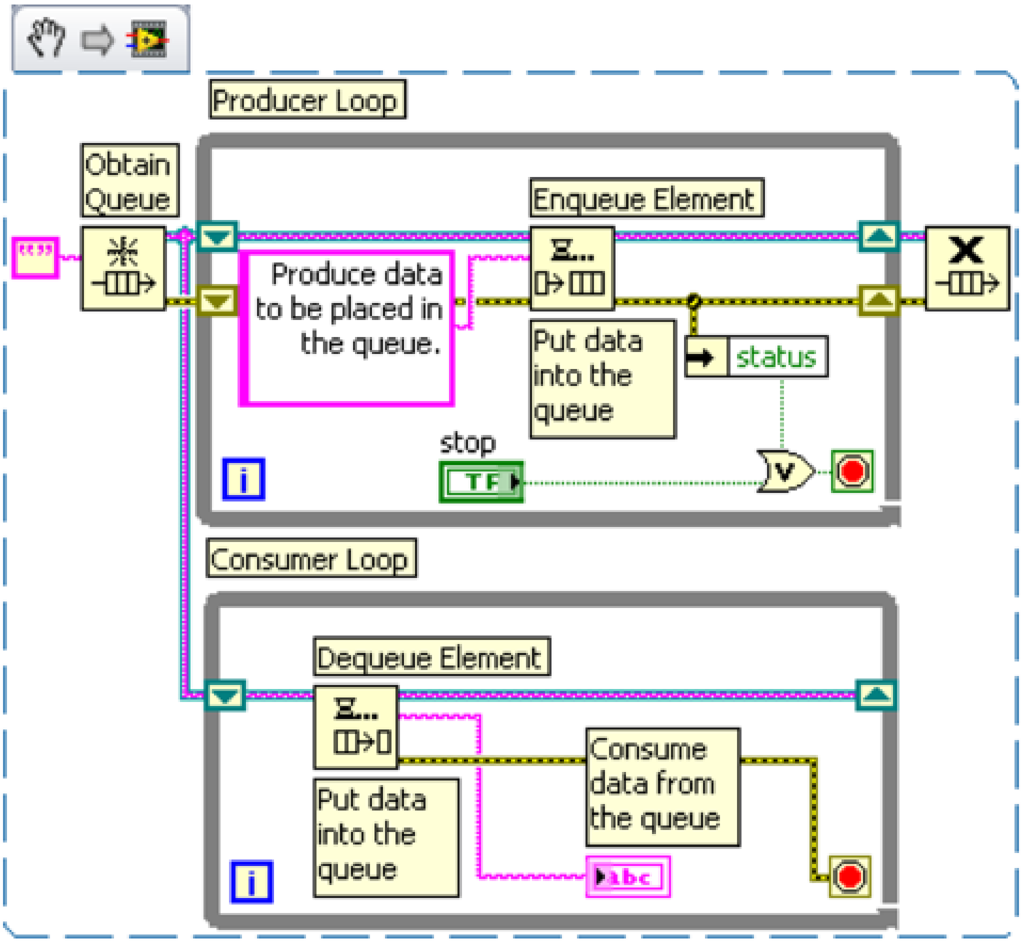


Fig. 13 - Consumer/Producer design pattern. Taken from [19]

4.4 Time Optimization

Every test was time optimized to achieve the best time consumption result. Testing hardware was designed as simple as possible and, therefore, was able to do time optimization by software. This is significant advantage. All delays are set by LabVIEW. The biggest problem was to set the configuration of the oscilloscope. It consumes most of the time but still, this time, is in the scale of seconds.

4.5 Test description

The whole test consists of 32 subtests. Electro-Gener is a two channel device, that means it contains two identical parts, which are called the Master and Slave. The test begins by testing DC voltage of power supply of Master and Slave parts. The test continues by testing Master part. The same subtests are implemented for Slave part. In the end, synchronization between channels is tested. Every single measured value is compared with upper and lower limit value, usually the limit is given by a medical standard, often 10% of referred value.

4.5.1 Master&Slave subtests:

- Power supplies
- Communication Master/Slave
- Crystal frequency
- Temperature
- Voltage mode
- Current mode
- Over voltage protection
- Over current protection
- Tens wave
- Sinus wave
- High voltage
- Touch memory detection
- Synchronization channel A
- Synchronization channel B

4.5.2 Measure power supplies

Power supplies voltages are divided by a voltage divider (see chapter 3.6.5.) to the required scale value and sensed by Ni USB-6008. All measured values are sent to the PC and each value is compared with upper and lower limit value.

4.5.3 Electro-Gener detection

A simple communication packet is sent to Electro-Gener via LabVIEW and the communication board (see chapter 3.7.4.). If Electro-Gener responds correctly, detection is OK. If not, it is faulty.

4.5.4 Crystal frequency

Due to bad crystal access, pogo-pins could not be used to contact crystal pins. Thus, a different measurement method was chosen. In this method, pulses with fold crystal frequency are generated. The frequency of these pulses depends on the crystal frequency. This measurement has to be very precise since the tolerance of crystal frequency is 0,001%. In other words, it was necessary to generate as many pulses as possible and measure their frequency. To measure frequency by oscilloscope was a problem due to many pulses. The oscilloscope started to round the value of frequency. The best method was to use long term oscilloscope memory and send waveforms to LabVIEW and calculate the frequency in LabVIEW. It sensed almost 35000 pulses and measured a pulse period of each pulse. The final value is the average value of all periods.

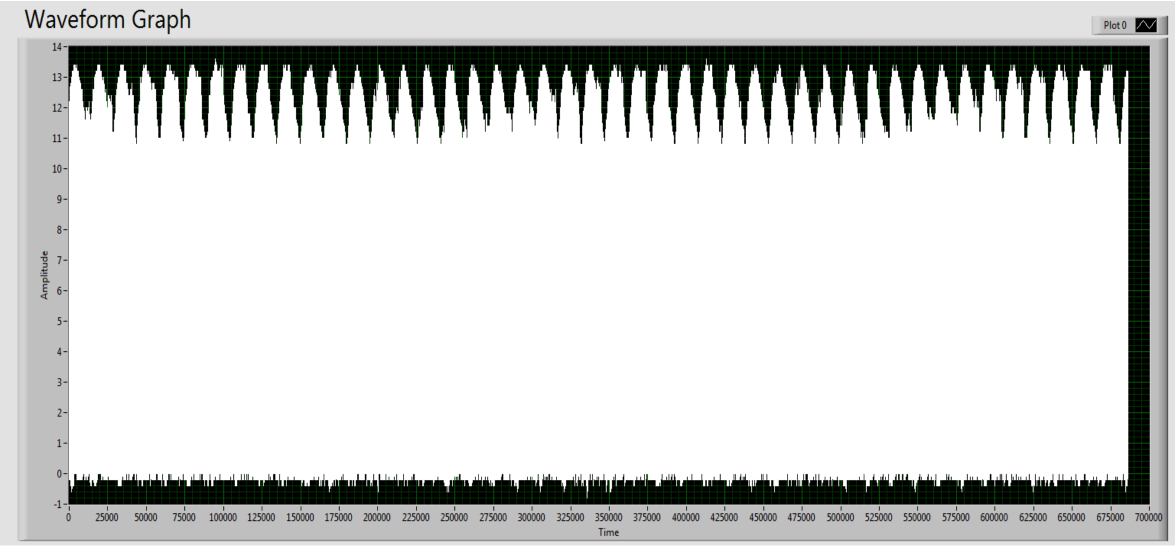


Fig. 14 - Waveform graph of all pulses. Made by author

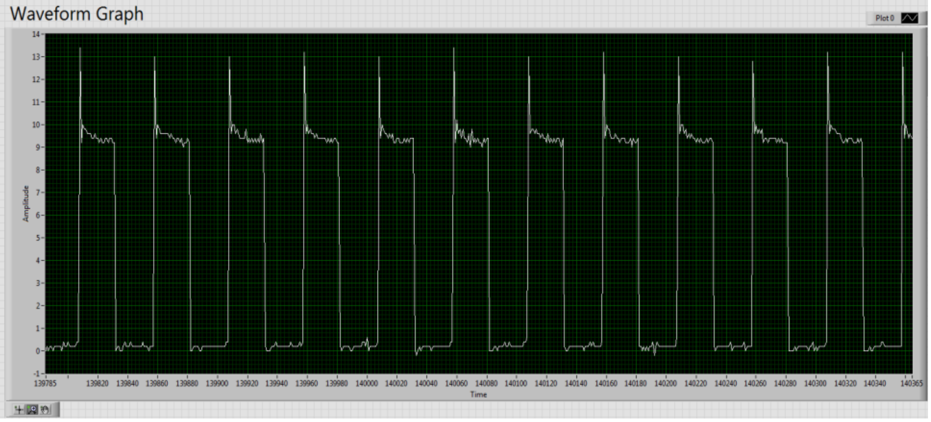


Fig. 15- Waveform graph, zoom in. Made by author

4.5.5 Temperature

Electro-Gener contains a temperature sensor. The temperature value is stored in Electro-Gener memory. Electro-Gener can respond to temperature requests. Information is sent to the PC and compared with limits values.

4.5.6 Voltage Mode

In voltage mode, the required voltage output is generated. There are generated several different voltage level values. All values are measured by oscilloscope and read values are sent to LabVIEW and compared with limits values.

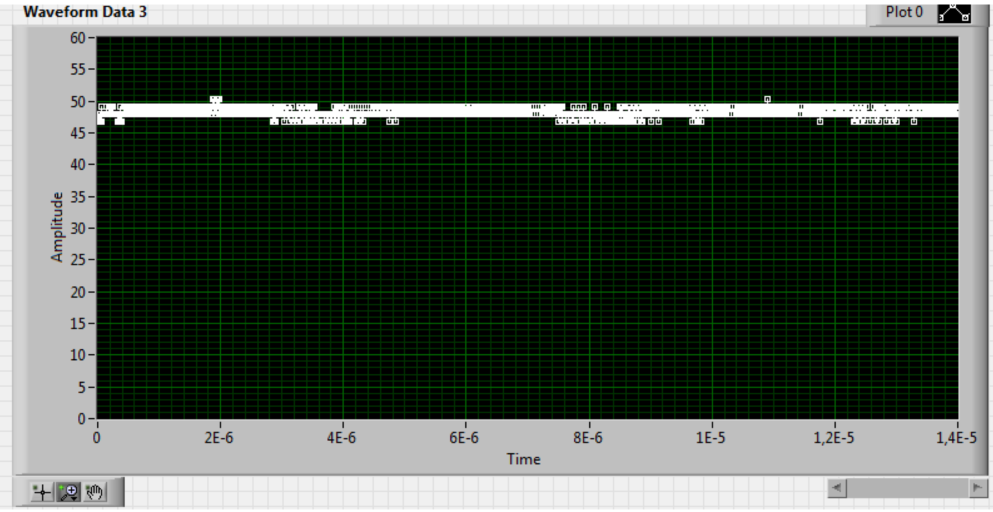


Fig. 16 - Waveform graph in Voltage mode. Made by author

4.5.7 Current mode

In current mode, the required current is generated. The current is sensed exactly like in voltage mode.

4.5.8 Overvoltage and overcurrent protection

In the case of overvoltage and overcurrent, there is a red protection byte from Electro-Gener memory.

4.5.9 Tens

In this test, positive and negative tenses are generated. Amplitude, positive and negative pulse width, RMS and AVG are measured by an oscilloscope. Red values are sent to LabVIEW and compared with limit values. Red waveform is shown on Fig. [37].

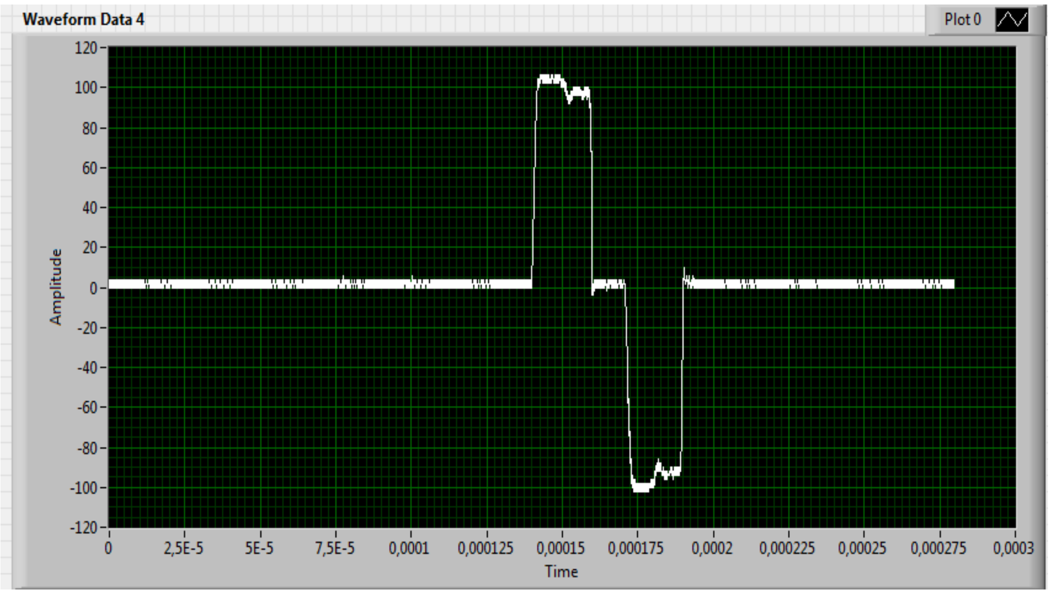


Fig. 17 - Waveform graph of tens pulse. Made by author

4.5.10 Sinus wave

In this test, a Sinus wave is generated. Amplitude, frequency, RMS and AVG are measured by an oscilloscope. Red values are sent to LabVIEW and compared with limits values. Red waveform is shown on Fig. [38].

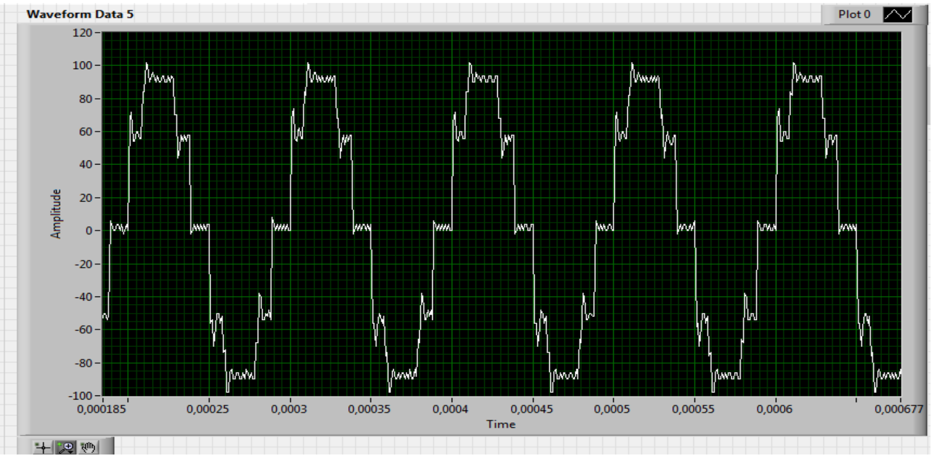


Fig. 18 - Waveform graph of sinus waveform. Made by author

4.5.11 High voltage

High voltage is an exponential waveform with a high voltage amplitude. The waveform is sent to LabVIEW. Due to the oscilloscope triggering problem, the pulse width and amplitude are measured in LabVIEW. It is also generated a negative high voltage therapy. Measured values are compared with limit values and written in a table of results. Red waveforms are shown on Fig. [39,40].

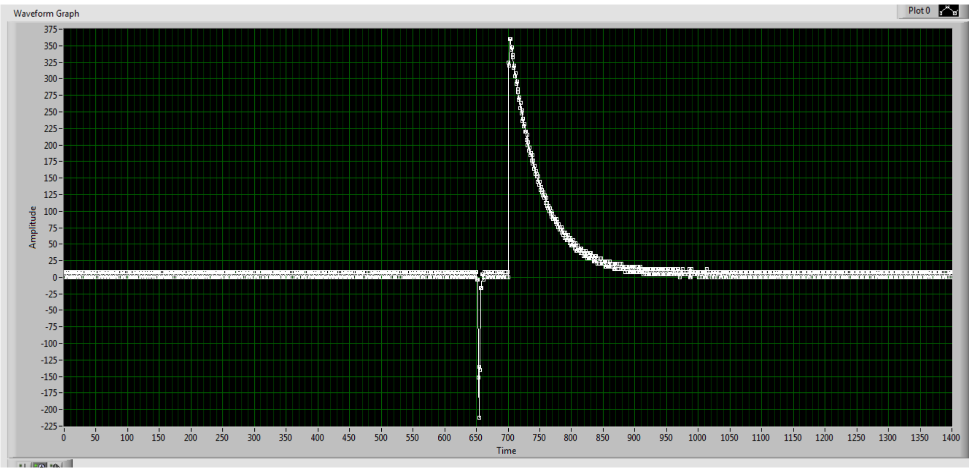


Fig. 19 - Waveform graph of positive HVT pulse. Made by author

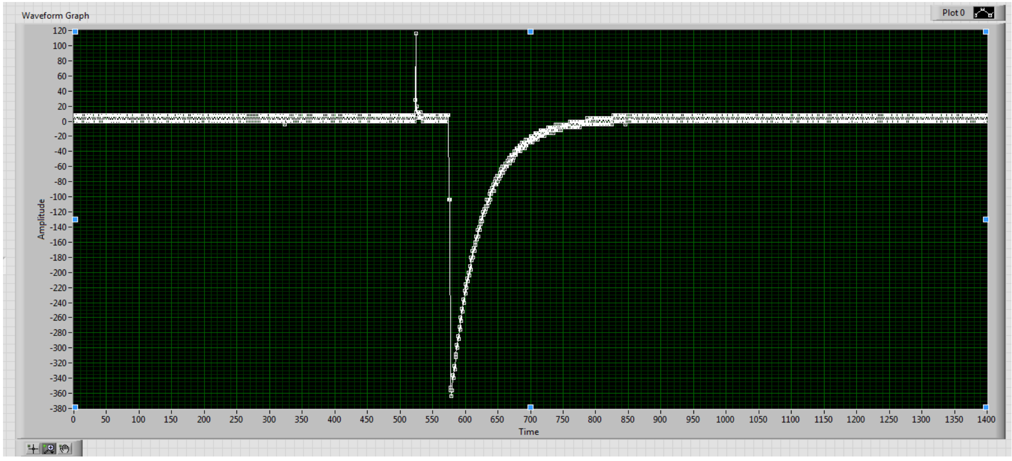


Fig. 20 - Waveform graph of negative HVT pulse. Made by author

4.5.12 Touch memory

The load also contains touch memory. DS2505 was used (see chapter 3.6.6.).
In touch memory test, Cyclic Redundancy Checks (CRC) is calculated. All accessories contain touch memory for identification. CRC is calculated by datasheet [20] formula.

4.5.13 Synchronization channel A

In this test, synchronization between Master and Slave channels is measured. In some therapy mode, it is forbidden to generate an output signal of both channels at the same time. It is tested if these channels are working in the 180 phase shift. In this test, the voltage level of both channels, frequency and phase shift are measured. All values are measured by the oscilloscope and compared with limits values.

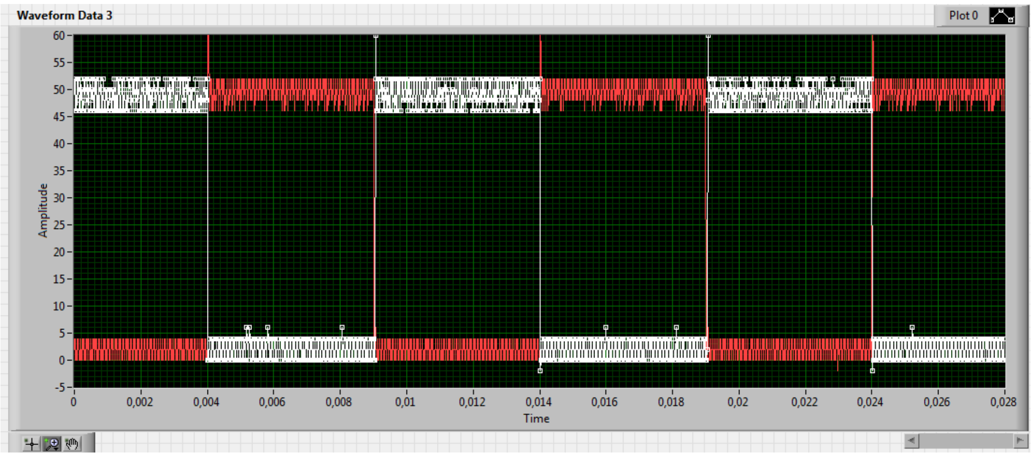


Fig. 21 - Waveform graph of synchronization channel A. Made by author

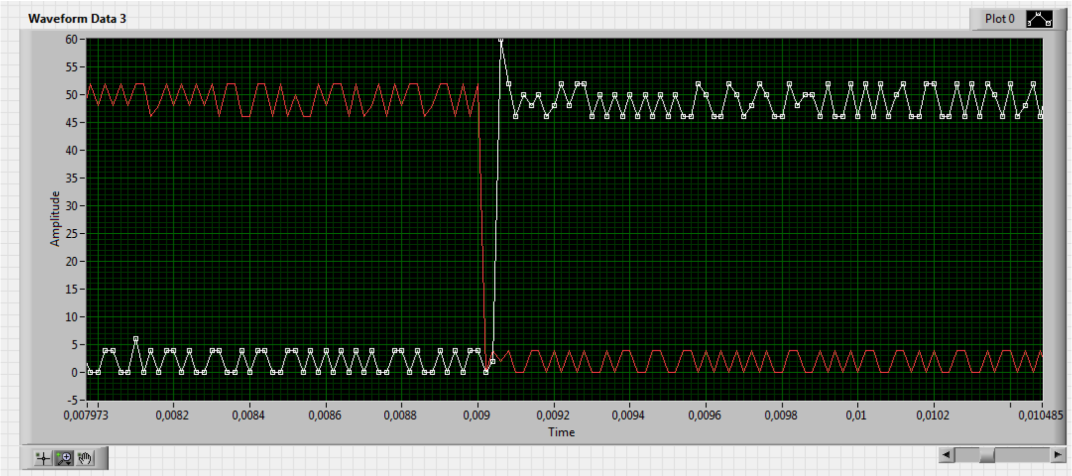


Fig. 22 - Waveform graph of synchronization channel A. Zoom in. Made by author

4.5.14 Synchronization Channel B

In this test, modulated signals are generated. The requirement was to measure the phase shift between signals envelope and frequency of pulses. The frequency of pulses was possible to measure by the oscilloscope but the frequency of envelope had to be measured in LabVIEW. Waveforms of both channels were sent to LabVIEW and frequency of envelope and the phase shift was calculated there. Results are compared with limits values.

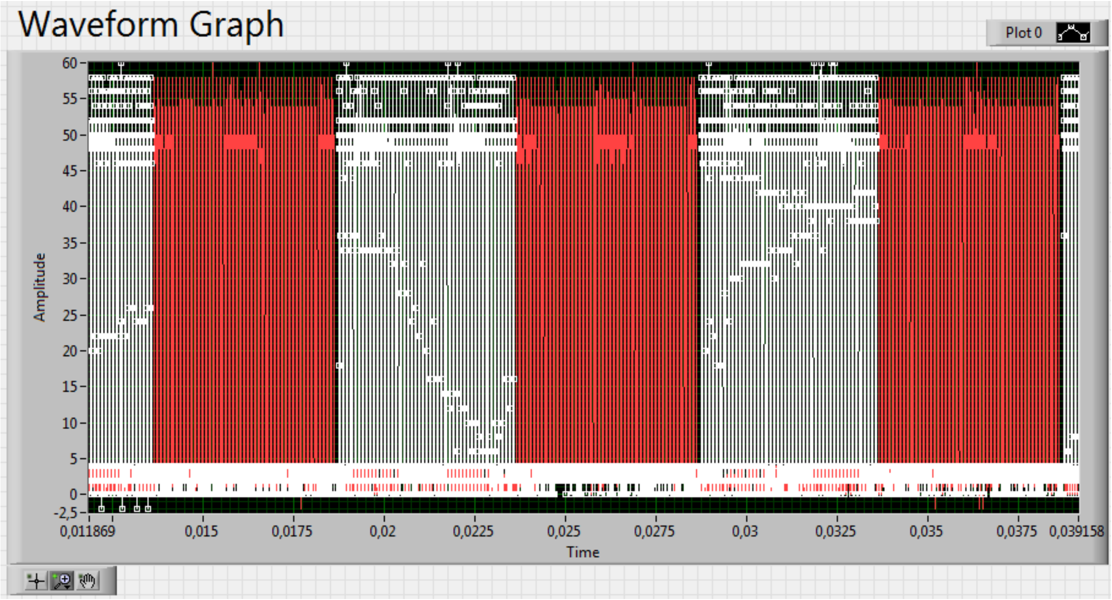


Fig. 23 - Waveform graph of synchronization channel B. Made by author

4.6 Calibration of automated testing unit

Every tester unit has to be calibrated to make sure that the tester unit is testing correctly. This tester unit has to be calibrated once every two years. All sub-parts of tester unit have to be calibrated by certificated equipment. PCB called Test-Getest was created to calibrate PCB Getest. The schematic design is shown in Fig. [44]. Test-Getest is elementary PCB. It was designed as simple as possible. It is necessary to test multiplexing and voltage sensing in Getest PCB. The reference voltage is connected to connectors J8, J10. J3 is connected to Getest PCB where it is possible to measure sensed voltage which has to respond to the required voltage. J7 is also connected to Getest and by J4, it is possible to test multiplexing in Getest. The oscilloscope, NI USB-6008, and 24V adapter are calibrated by internal regulations of Medical Technology a.s. The software is calibrated by using reference Electro-Gener PCB. All measured values have to be in the range of reference values.

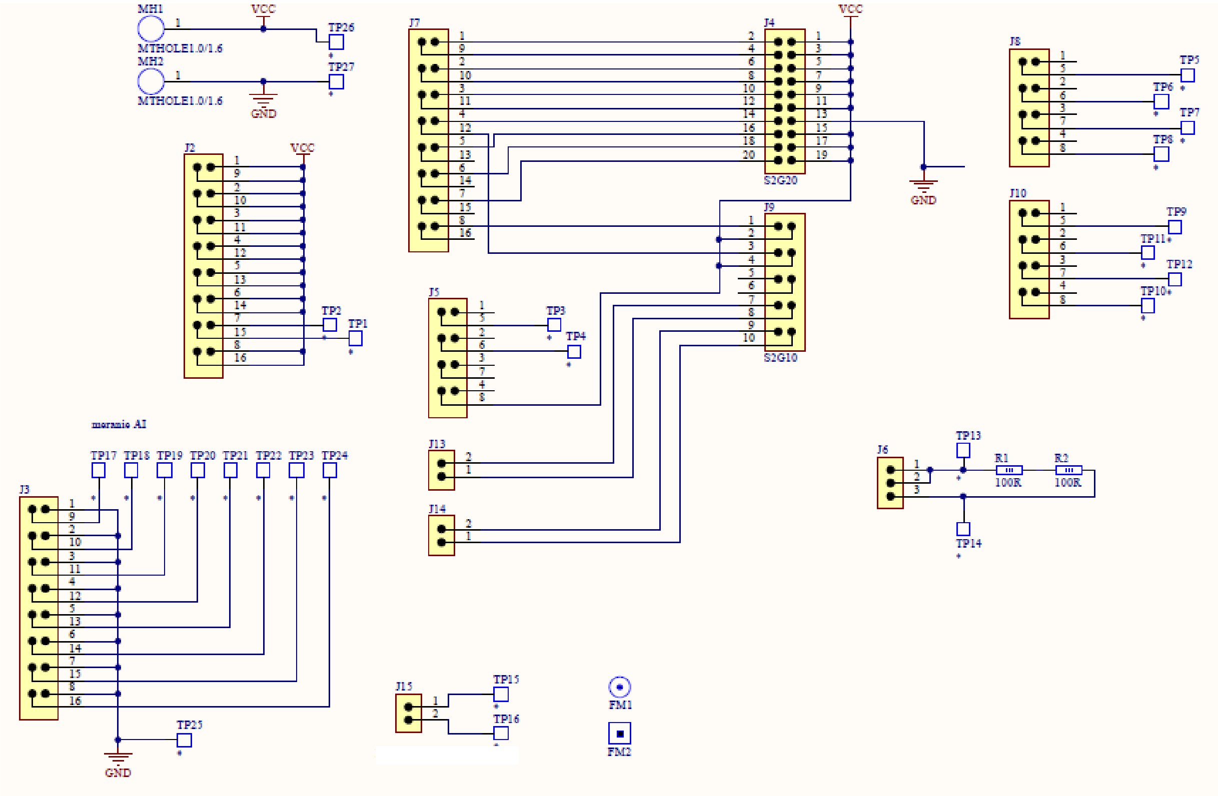


Fig. 24 -Test-Getest Schematic. Made by author

5 Economical study

The main goal while building the tester unit was to speed up testing of Electro-Gener PCB. As it was mentioned before, testing of Electro-Gener was done manually. Let's calculate the cost of PCB manual and automated testing. Manual testing is very time consuming and time costs money. It is not just time of an employee, but also office rental, training programs for employees, etc. Difficult work requires spending more time to train employees. The human factor is another aspect. Every stereotypic work causes a lot of mistakes. If production is at high volume it is necessary to employ many people. By automated testing, it is possible to reduce all of these aspects. In this case, the average time of manual Electro-Gener PCB testing was approximately 20 minutes. By using an automated tester unit the average testing time was approximately 3 minutes. Reduction (manual/automated) is 15 minutes. By using automated testing unit it is possible to measure more values in comparison to manual testing. This means testing of Electro-Gener is measured more precisely. Let's say production of Electro-Gener is 1000PCBs per year. One hour of employee work costs approximately 400CZK. For manual testing of 1000 PCBs, 300 hours are needed.

$$300\ hours\ x\ 400\ CZK = 120000\ CZK$$

For testing, this volume of PCBs by automated tester unit, 50 hours are needed.

$$50\ hours\ x\ 400\ CZK = 20000\ CZK$$

It is possible to save approximately 100 000 CZK per year, even though it is saved 250hours of an employee's work. This time can be spent on other tasks. The cost of the automated testing unit was approximately 200000CZK.

	Testing time of one PCB [min]	Time for testing 1000 PCBs [hours]	Cost [CZK]
Manual testing	20	300	120000
Automated testing	3	50	20000
Reduction	17	250	100000

Tab. 3 - Cost comparison of manual and automated testing

.

6 Conclusion

A functional tester unit for Electro-Gener was made. The main purpose was to make a tester unit which can test faster than manual testing. The biggest advantage is the speed of testing. By using the automated tester unit, the testing time can be decreased by approximately 17 minutes. In thousand volume production per year, it represents saving 100 000CZK in comparison to manual testing. The total cost of tester unit was approximately 200 000CZK. The return on investment is two years. Another advantage is precision. The tester unit includes more tests against manual testing. Thus, larger fault coverage is done.

One of the goals was to design a user-friendly tester unit. All sub-parts ofthe tester unit except the oscilloscope and computer are situated inside the fixture. This allows easier storage of the tester unit. Ni USB-6008 was used for sensing DC signals and oscilloscope Rigol DS2072 was used for sensing AC signals. Test-points are contacted by using pogo-pins which have suitable shape for different type of test-points. The fixture was created by Technik partner a.s. The software was created in LabVIEW software environment. The software allows for the storing of logs and the creation of test report protocol of measured values. The supported software was created for changing limits values. This allows for the changing of values of limits without changing the main code structure.

The tester is fully functional, however, it is not used in the manufacturing process yet. Beta version was tested in manufacturing process. Now it is necessary to upgrade some parts of the program.

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8 Attachment

8.1 TestGets PCB

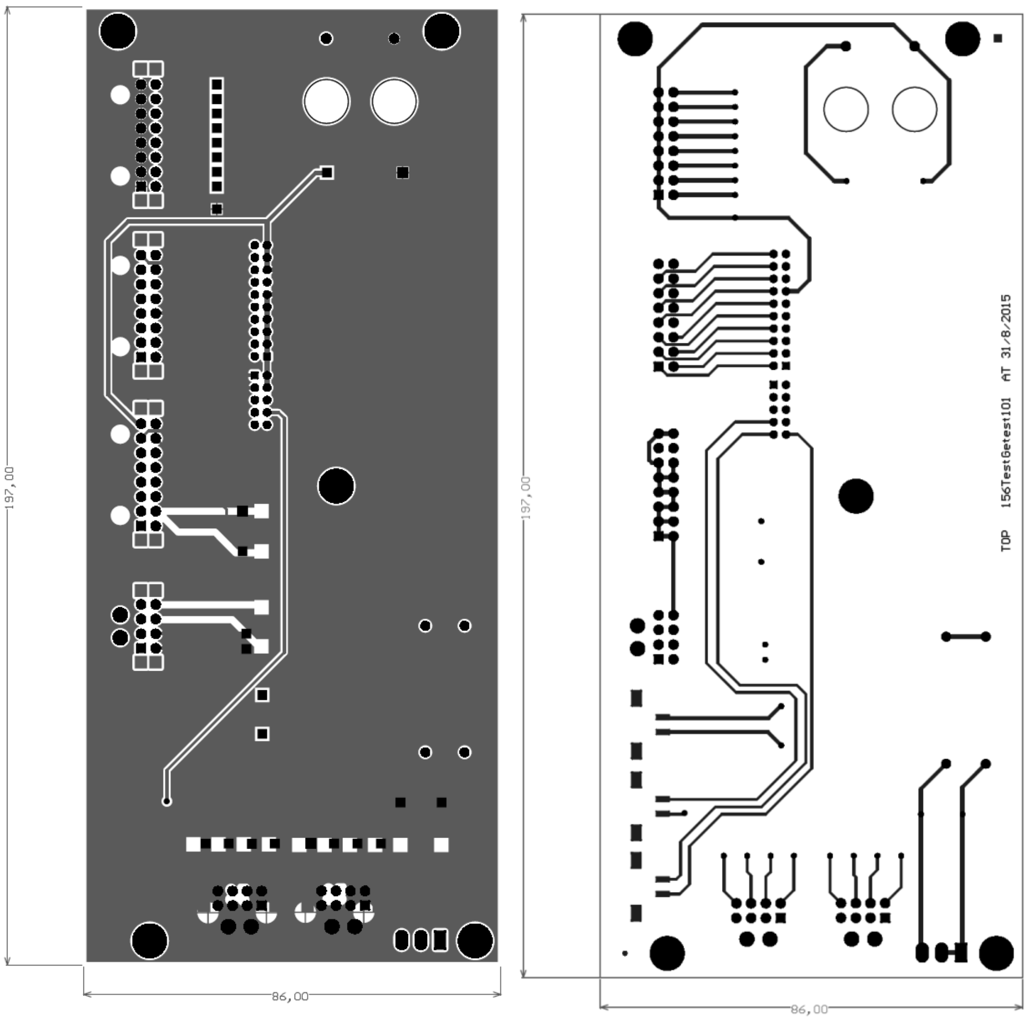

Fig. 45 - a) Test-Getest bottom layout. b) Test-Getest top layout.

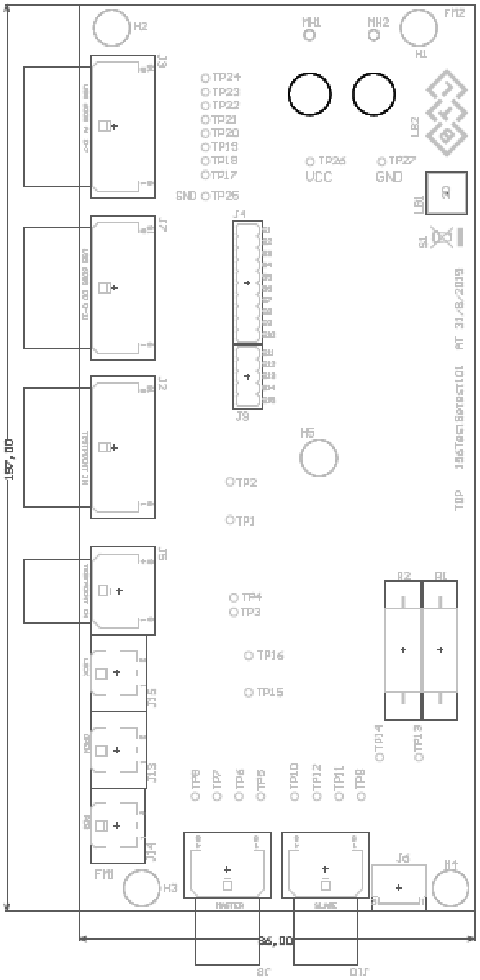

Fig. 46 - TesteGest component layout diagram

Comment	Designator
Fiducial Mark Circle	FM1
Fiducial Mark Square	FM2
W4230-16PDRTB0R	J2, J3, J7
S2G20	J4
EJ-W4230-08PDRTB0RXX0	J5
EJ-B03-VHJS0	J6
W4230-08PDRTB0R	J8, J10
S2G10	J9
EJ+W4230-02PSDTBRXX0	J13, J14, J15
100R	R1, R2

Tab. 4 - Table of Test-Getest components

8.2 USB ISO PCB

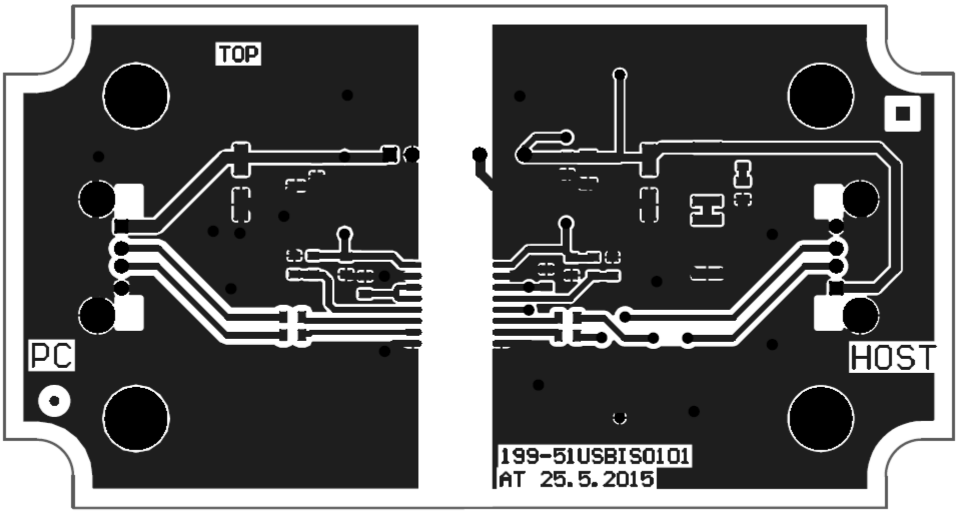

Fig. 47 - USB ISO top layer

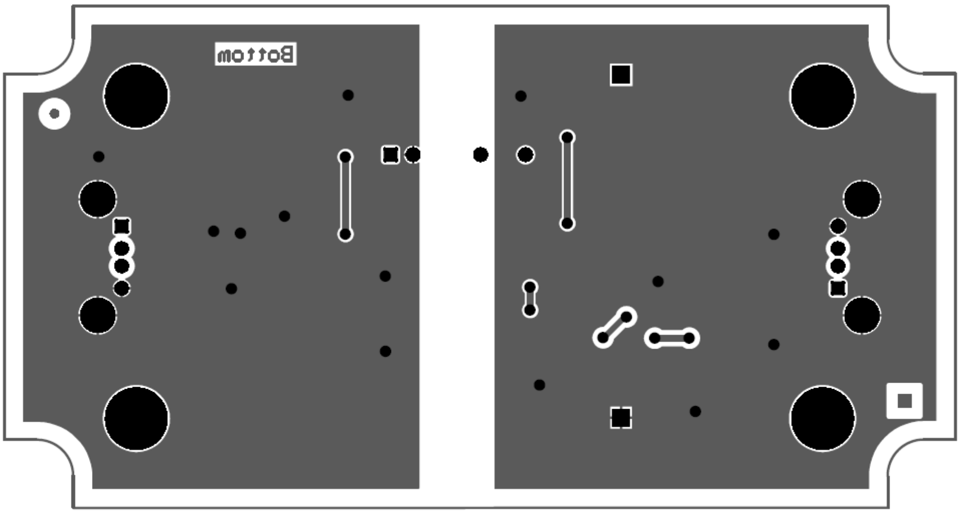

Fig. 48 - USB ISO bottom layer

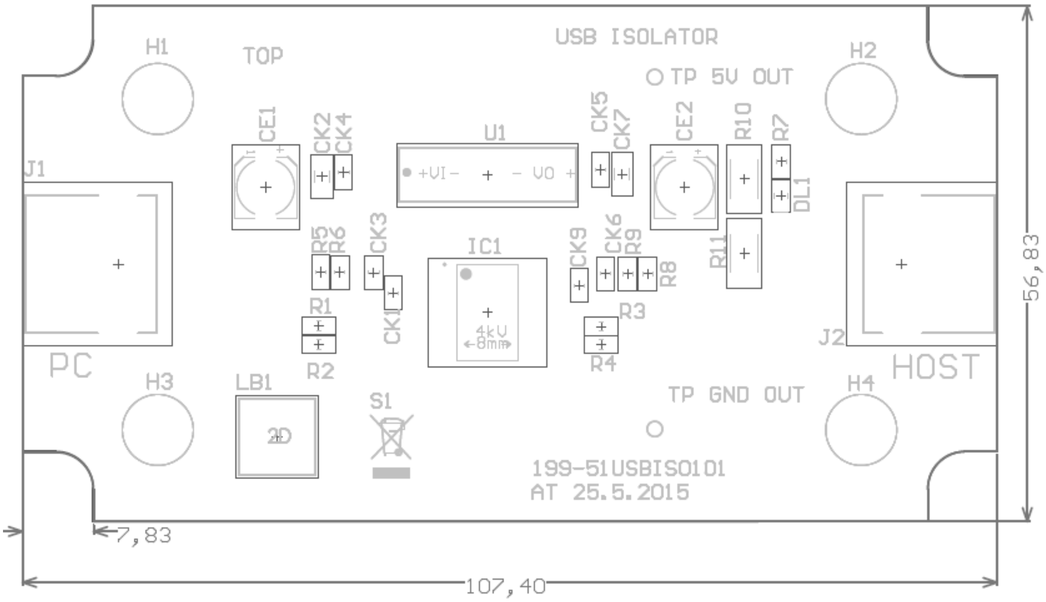

Fig. 49 - USB ISO component layout diagram

Value	Designator
47u	CE1, CE2
100n	CK1, CK3, CK6, CK9
3u3	CK2, CK7
2n2	CK4, CK5
GREEN	DL1
MTHOLE3.5	H1, H2, H3, H4
EU+ADUM4160	IC1
C8317-04AFHSW0R	J1, J2
22R	R1, R2, R3, R4
4k7	R5, R6, R8, R9
220R	R7
220R	R10
10R	R11
DC/DC	U1

Tab. 5 - Table of USB ISO components

8.3 Getest PCB

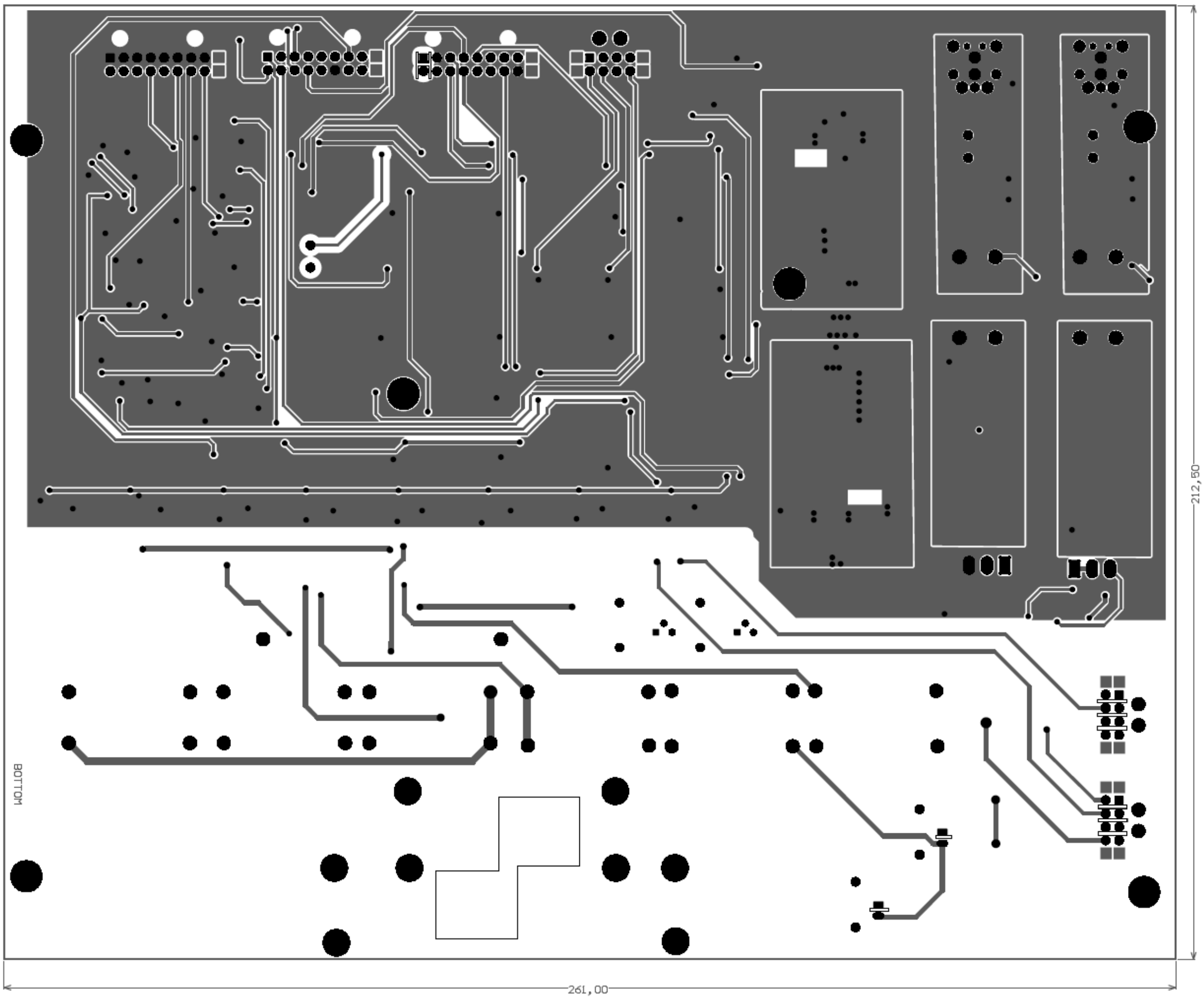

Fig. 50 - Getest bottom layer

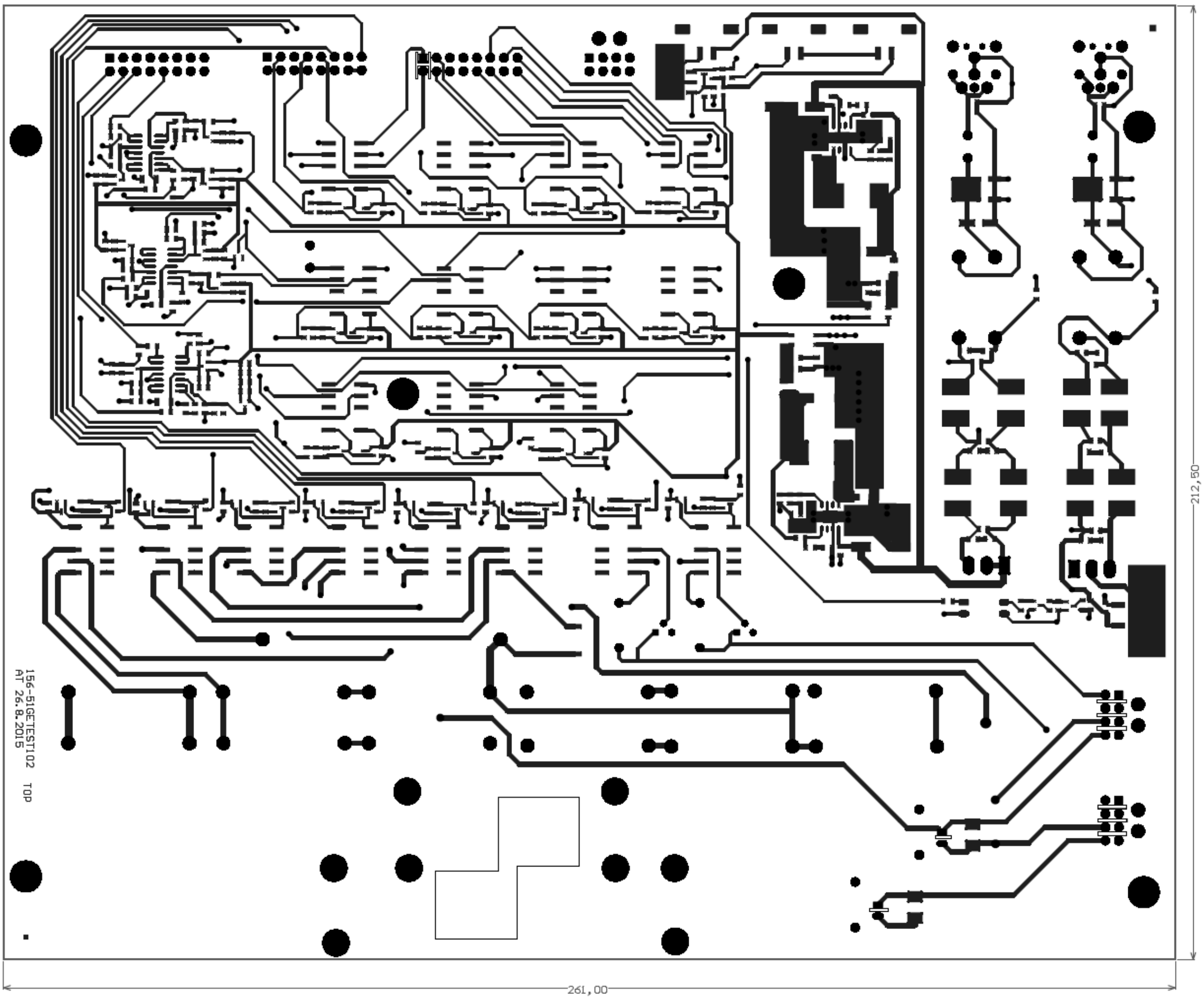

Fig. 51 - Getest component layout diagram

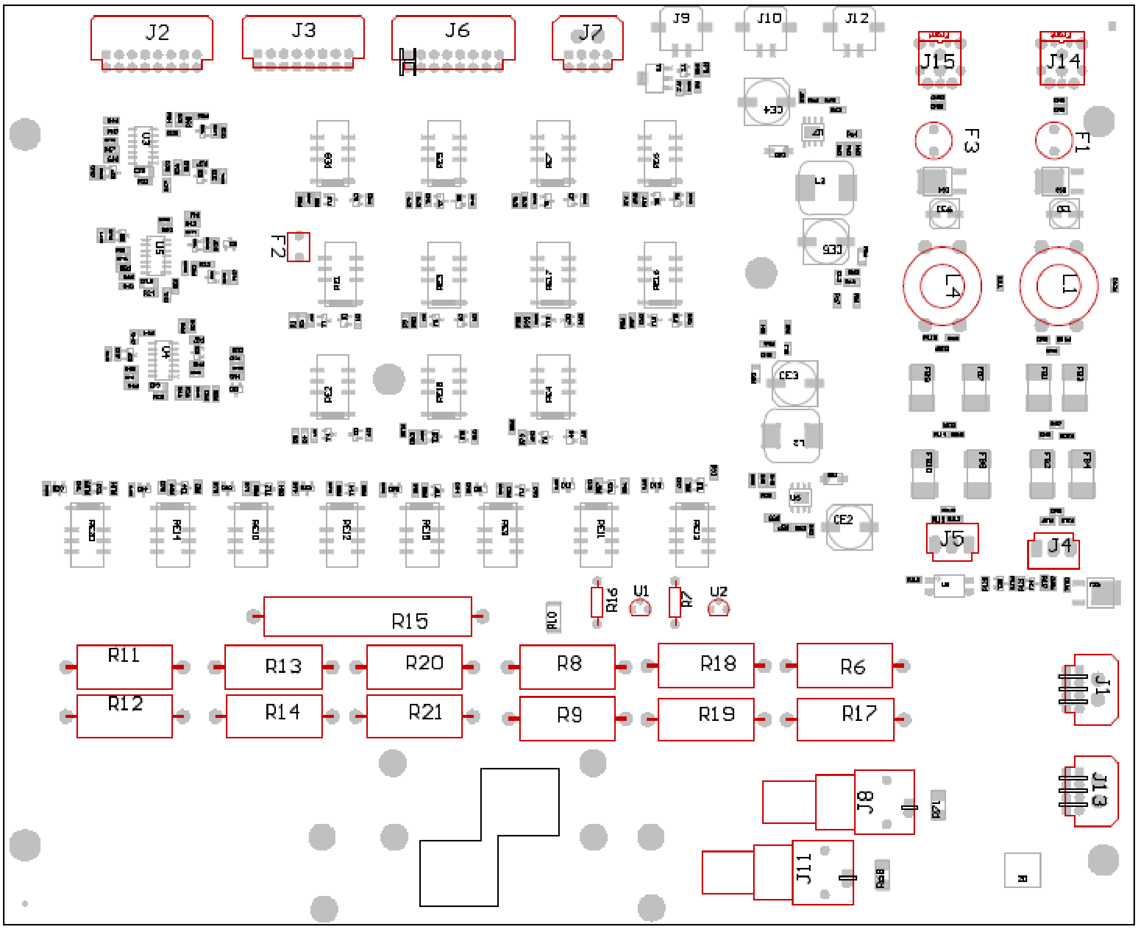

Fig. 52 - Getest component layout diagram

Value	Designator
MTHOLE3.2	1, 2, 3, 4, 5, 6, 7, 8
47u	CE1, CE6
330u	CE2, CE3, CE4, CE5
100n	CK1, CK3, CK5, CK7, CK11, CK13, CK15, CK23, CK25, CK27, CK35, CK37, CK43, CK48, CK52, CK53, CK57, CK58, CK62, CK64, CK66, CK68, CK70, CK72, CK74, CK76, CK78, CK80, CK82, CK84, CK86, CK90, CK92, CK94, CK98, CK99, CK101, CK105
2n2	CK2, CK4, CK6, CK12, CK14, CK16, CK24, CK26, CK28, CK36, CK38, CK44, CK47, CK59, CK60, CK61, CK63, CK65, CK67, CK69, CK71, CK73, CK75, CK77, CK79, CK81, CK83, CK85, CK87, CK91, CK93, CK95, CK96, CK100, CK102, CK103
1uF	CK8, CK9, CK10

1n	CK17, CK18, CK19, CK20, CK21, CK22, CK29, CK30, CK31, CK32, CK33, CK34, CK39, CK40, CK41, CK42, CK45, CK46
10n	CK49, CK51, CK54, CK56
220p	CK50, CK55
470p	CK97, CK104, CK106
BAV99	D1, D2, D3, D4, D5, D6, D7, D8, D9, D10, D11, D12, D13, D14, D15, D16, D17, D18, D20, D21, D22, D23, D24, D25, D26, D27, D28, D29
GREEN	DL1, DL2
SS16	DS1, DS2
12CWQ06FN	DS3, DS4
BZX84C5V6	DZ1
2.5A	F1, F3
15mA	F2
600R/5A	FB1, FB2, FB3, FB4, FB7, FB8, FB9, FB10
52 Ohm/100MHz	FB5, FB6
Fiducial Origin Circle	FO1
Fiducial Origin Square	fo2
MTHOLE3.5	H1, H2, H3, H4, H5, H6
EJ-W4230-08PDRTB0RXX0	J1, J13
EJ-W4230-16PDRTB0RXX0	J2, J3
EJ-B03-VHJS0	J4, J5
W4230-16PDRTB0R	J6
W4230-08PDSGB0R	J7
13-60-2 DGZ	J8, J11
EJ+W4230-02PSDT-BRXX0	J9, J10, J12
JPD1135-509-7F	J14, J15
016-5002100	L1, L4
EL+68U1.52AXX0	L2
33uH	L3
2k2	R1, R3, R5, R53, R74, R76, R78, R80, R82, R84, R86, R88, R90, R92, R94, R96, R98, R100, R104, R116, R117, R118
22k	R2, R4, R27, R29, R30, R32, R33, R38, R41, R42, R45, R46, R47, R48, R50, R51, R52, R66, R73, R75, R77, R79, R81, R83, R85, R87, R89, R91, R93, R95, R97, R99, R101, R105
1k	R6, R8, R9, R11, R12, R13, R14, R17, R18, R19, R20, R21
1k	R7
47R	R10
3k9	R15

2k2	R16
10R	R22, R23, R24
1k	R25, R26, R31, R34, R35, R39, R43, R44, R49, R59, R72
82k	R28
47k	R36, R119, R120, R121
100k	R37, R107, R112
18K	R40
0R	R54, R60, R61, R67
3k9	R55
220R	R56, R57, R106, R111
4k7	R58, R64
220k	R62
680R	R63, R70
10k	R65, R110, R115
1Meg	R68, R71
1k	R69
4R7	R108, R113
47R	R109, R114
TX2SA-5V-Z	RE1, RE2, RE3, RE4, RE5, RE6, RE7, RE8, RE9, RE10, RE11, RE12, RE13, RE14, RE15, RE16, RE17, RE18, RE20
BSS138	T1, T2, T4, T5, T6, T7, T8, T9, T10, T11, T12, T13, T14, T15, T16, T17, T18, T19, T20, T22
IRLL014	T3
IRFR5305	T23
BC817-40	T24
BC807-40	T25
DS2505	U1, U2
TLC274CD	U3, U4, U5
L5973D	U6, U7
PC817	U8

Tab. 7 – Table of Getest components

8.4 Tester unit pictures

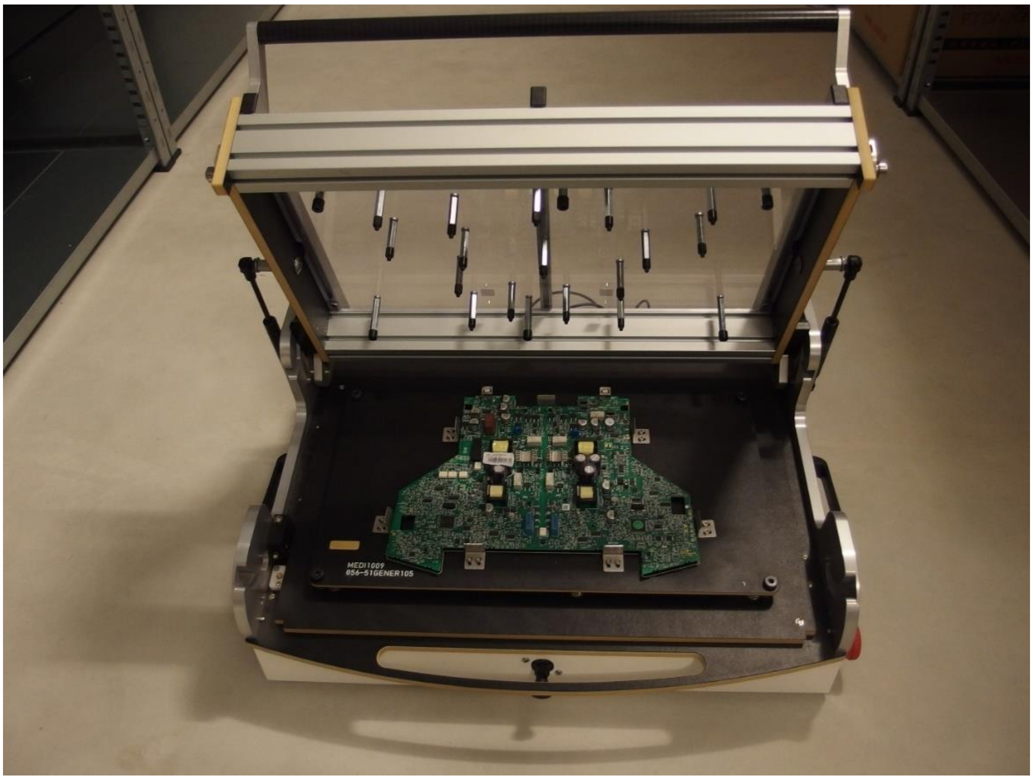

Fig. 52 - Front view of functional automated tester

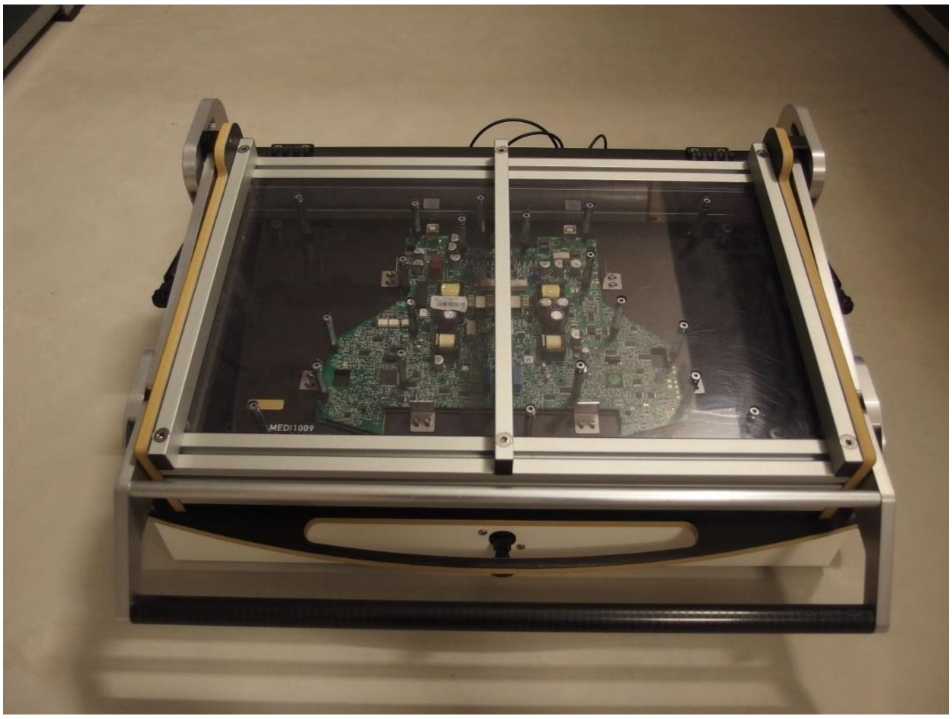

Fig. 53 - Front view of functional automated tester

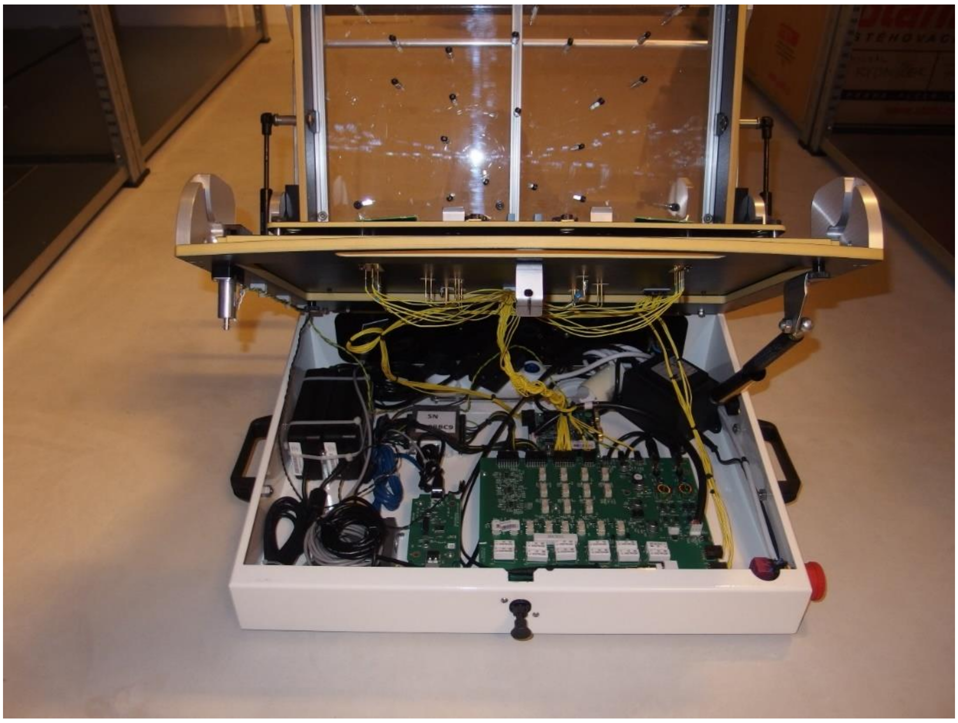

Fig. 54 - Front view of functional automated tester