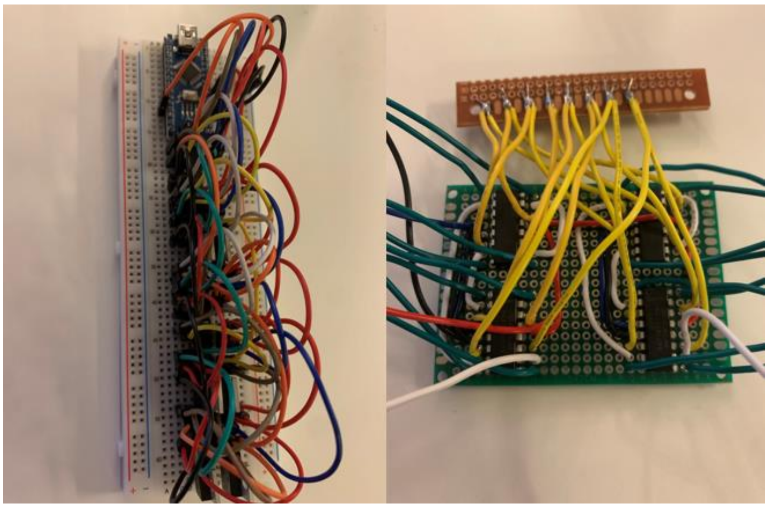
2021

Automatic Electrode Switch of Salt Watcher

Thesis Report



WaterschapScheldestromen

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Thesis project (CU08813V17)

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ABSTRACT

Out of the urgent need to monitor the status of soil salinization, the Zeeland government and Waterschap Scheldestromen established a salinity monitoring project called salt watcher. This thesis presents a research on the design of an automatic switch system, which is one of the 3 sub-projects of the salt watcher project. The aim of the thesis research is to design an automatic switch system which is capable to make switching between different possible measurement connections. The project is instructed following V-model design method.

The finished design, which is called the ‘bungalow’ switch system, is a switch system with logic control circuit and a flat layer of switches. The prototype built on the ‘bungalow’ design is tested and the results indicates that the designed system meets all the requirements and performed well for salinity measurement at high accuracy and low signal distortion.

Further research is still recommended on components storage lifetime test, decreasing system scale, , completing full-scale product test and integration between different projects.

FOREWORD

The related themes of this thesis report are: **electronic switch; switch circuit design; logic circuit design; Arduino software design.**

I would like to thank Jos Goossen, my in-company mentor, for his careful guidance, patient help and a lot of professional suggestions. He is such a generous person who selflessly shares knowledge.

I would like to thank M.B. Blok, my 1st examiner, for his generous help during the whole process of the project. He is always willing to give feedbacks and suggestions to anything I do not understand or cannot express clearly.

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I would like to thank Feifan Du, my best friend, for her warm encouragement to me. She is always a strong support when I am tired and exhausted and is always willing to share the experiences and feeling during the whole thesis project.

I would also like to thank Willem Haak, the advisor teacher in school, for gathering students from different projects, sharing the interesting stories and give helpful instructions and suggestions.

I can’t finish this thesis project without the help from all of you. And I hope you enjoy reading this report.

Kind regards,

Yuyao Tian

ABBREVIATION LIST

A	Ampere
COM	Common connection
DIP	Dual in-line package
EC	Electrical Conductivity
GND	Ground
I	Current
IC	Integrated circuit
I_{in}	Current injected
mA	Milliampere
ms	Millisecond
mW	Milliwatt
ns	Nanosecond
NC	Normally closed
NO	Normally open
Ω	Ohm
R_{on}	On resistance
SOIC	small outline integrated circuit
SPDT	Single Pole Double Throw
SPST	Single Pole Single Throw
t_{on}	Turn-on time
t_{off}	Turn-off time
V	Voltage
V_{cc}	Positive supply voltage
V_{ss}	Negative supply voltage

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1 INTRODUCTION

In this chapter, background information of the research and analysis of the problem will be given. Based on the analysis the research question of the project will be defined and the objective and boundaries of this project will be described.

1.1 BACKGROUND

The Netherlands, as a country where most of the area lies below sea level, managed to build up a safe and clean delta in the history (Van Westen, 2005). This feat is inseparable from the help of various water management agencies in the Netherlands. Waterschappen, as one of the agencies, are regional government bodies charged with managing water barriers, waterways, water levels, water quality and sewage treatment in their respective regions (WATERSCHAPPEN, 2021).

Fresh water has always been one of the most important issue for water management, due to its important role in agricultural irrigation (Van Westen, 2005). The picture Fig 1.1 below shows the groundwater bodies condition in Zeeland in 2017.However, according to Pauw's report (Pauw, 2020), fresh water source has been facing a great impact from the climate change in Zeeland during the last few years.

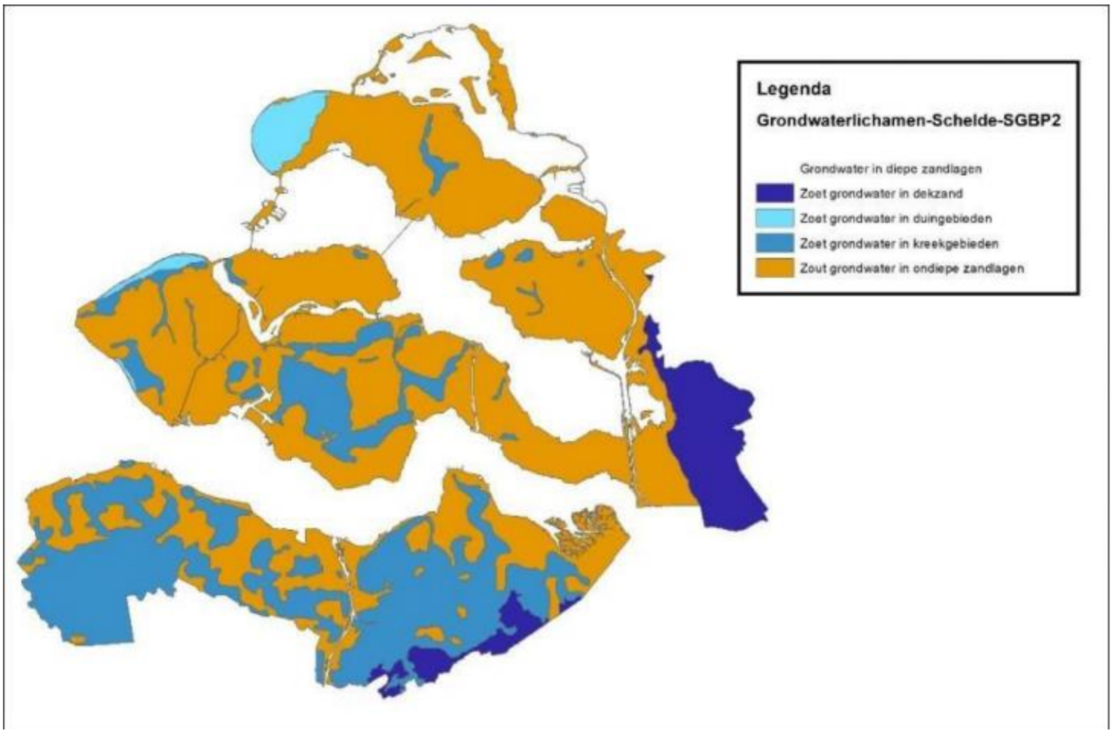


Figure 1.1 Groundwater bodies in Zeeland in 2017 (Pauw, 2020)

Another report (Delsman, et al., 2018)shows that climate change results in less rainfall during the summer. As a result, the groundwater is less replenished with fresh rainwater. The Zeeland underground naturally contains a lot of salt. Precipitation creates a freshwater layer on top of the heavier saline groundwater. Groundwater extraction in the summer can lead to salinization of the shallow groundwater. This makes groundwater less usable (Kotuby-Amacher, Koenig, & Kitchen, 2000).

A monitoring system is needed to measure this effect. Therefore dozens of sensors will soon be installed in Zeeland to measure trends in the salinization of the underground. Waterschap Scheldestromen, as the builder of the measuring system, is trying to find a sufficient design for the measuring system.

The measuring system, which is called salt watcher, contains 3 different parts: a measuring device, a measuring cable and a switch system which helps to connect between the electrodes on the measuring device and the measuring cable. The aim of this project is to design the electrode switch system of the salt watcher. The project began from February 1st ,2021 and ends on July 1st,2021.

1.2 PROBLEM ANALYSIS

Based on the background information, a complete description of the problem will be given in this chapter.

This project is part of the salt watcher project processed by Waterschap Scheldestromen and the Zeeland government, due to the concern about the soil salinity problem in Zeeland. The salt watcher is based on the Wenner method, which is commonly used when measuring soil salinity. In this 4-electrodes set, which is also called a Wenner set, 4 electrodes will be set with the same distance between each other. As Fig 1.2 shows, 2 of the electrodes outside will inject a current (the S symbol indicates the current source) and the 2 electrodes inside will measure the potential. With the value of the voltage, the current and the distance, the conductivity of the soil can be calculated (Frank, 1915).

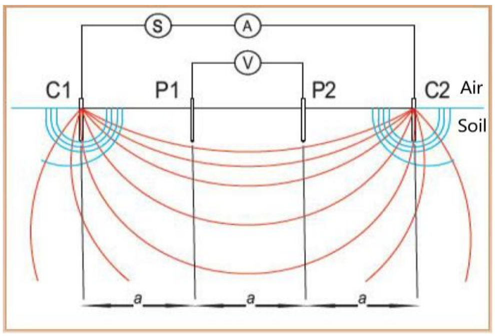


Figure 1.2 Principle of the salinity measuring electrode set (WATERSCHAPPEN, 2021)

The salt watcher contains 3 different parts: the measuring device, the electrode cable and the switch system connecting the other two parts. This project is a part of the salt watcher project, aiming to design the switch system for the salt watcher.

The measuring device will be designed and built as a replacement to a commercial soil salinity measuring device Chauvin-Arnoux-C. A-6460, as Fig 1.3 shows, which has 4 measuring terminals and uses Wenner method to measure the earth conductivity.

Figure 1.3 Chauvin-Arnoux-C. A-6460

In the salt watcher project, Wenner method will be used in a different way that all the electrodes to be measured will be set vertically underground. Fig 1.4 demonstrates an EC probe for soil conductivity measurements which is designed for the Chauvin-Arnoux-C. A-6460. As the manual (Eijkelkamp Soil & Water, 2018) said, the plugs ⑫ can be plugged into the terminals on Chauvin-Arnoux-C. A-6460, and four electrodes ⑥⑦⑧⑨ use Wenner method vertically. The two outside electrodes ⑥ and ⑨ are the current injection electrodes and the two inside electrodes ⑦ and ⑧ are voltage measuring electrodes(Other components on the figure are not related to the project so will not be introduced). By plugging this probe into different depths underground, the soil salinity of the depth between the four electrodes can be measured.

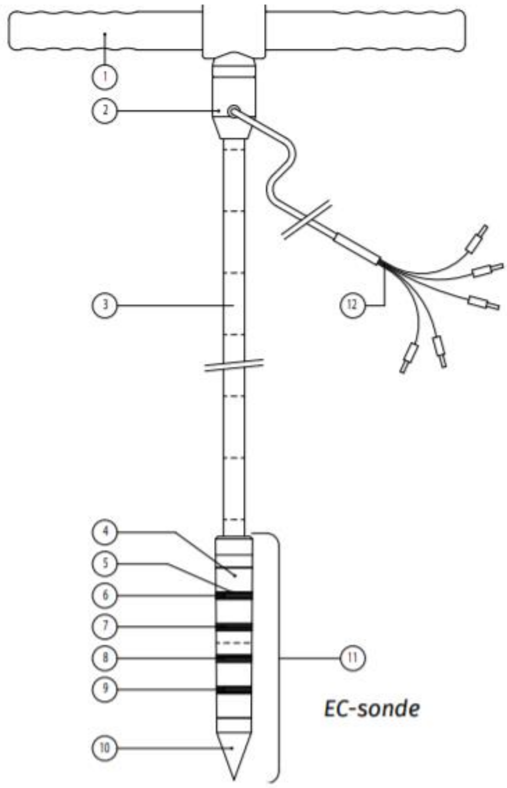


Figure 1.4 EC probe for soil conductivity measurements (Eijkelkamp Soil & Water, 2018)

In the salt watcher project, the manual process of digging this probe underground and changing the depth needs to be replaced. The electrode cable which contains the electrodes will be installed with a steel cone digging into the soil. The diameter of the cone is 36mm, and it limits the diameter of the electrode cable. Based on the diameter of the electrode cable and the diameter of the leads which connect each underground electrode to the terminal on the ground, it is estimated that the electrode cable can contain at most 26 electrodes. These electrodes will be permanently arranged underground at the same distance vertically. Fig 1.5 below shows a draft image of the electrode cable.

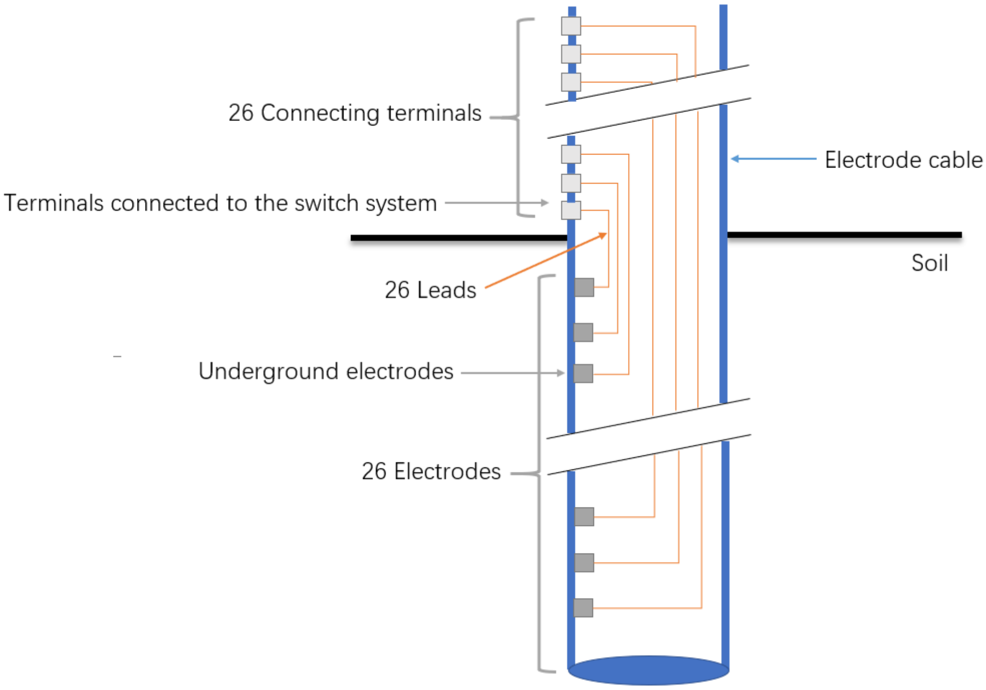


Figure 1.5 A draft image of the electrode cable

Within the 26 electrodes, every combination of 4 electrodes at the same distance can be connected to the measuring device and used to measure the soil salinity of the depth between them as the EC probe works.

By using the electrode cable, instead of digging into different depths with only four electrodes, the measuring device can be connected to any 4-terminal combination and to measure soil salinity of different depths easily. Fig 1.6 shows the situations using different electrode sets with the shortest distance to measure soil salinity on different depths. By switching between different 4-electrode sets on different depths and taking measurements periodically, a clear image of soil salinity changes on different depth in time can be given.

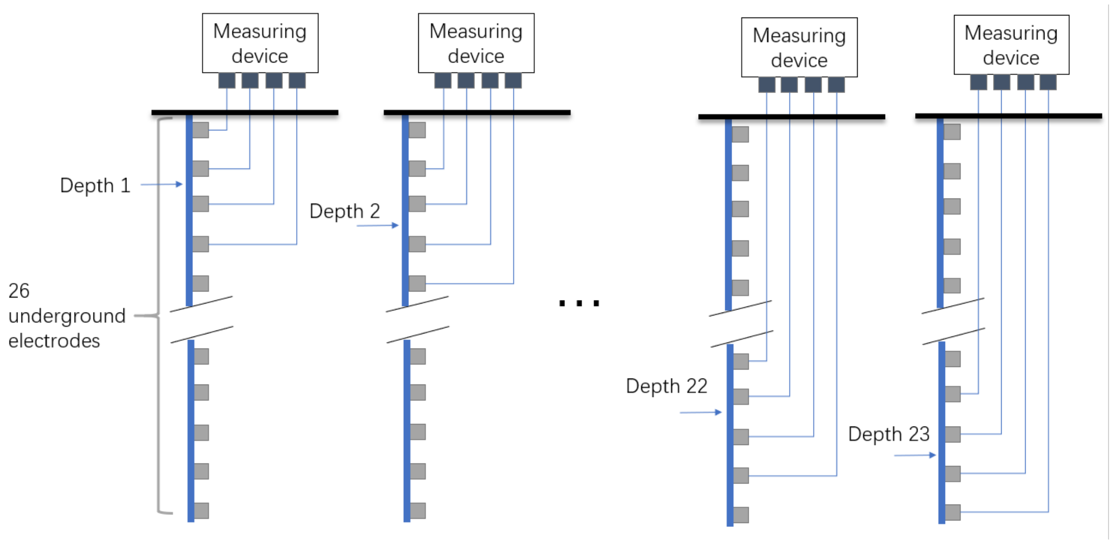


Figure 1.6 The different connecting possibilities of Wenner sets at the shortest distance

Traditionally, the measurement will be taken manually. But for the salt watcher, it means the operator is required to connect the 4 terminals of the measuring device to each possible Wenner set within the 26 underground measured electrodes and switch from one set to another by hand. This manual process is extremely time-consuming and needs to be taken on dozens of monitoring points all over Zeeland. It shows a necessity to replace the manual connecting and switching process with an automatic method. Therefore an automatic switch system is required. Fig 1.7 below shows the expected structure of the whole salt watcher system. The switch system will connect the 4 leads from the terminals on the measuring device to 4 chosen leads connecting to the underground electrodes and switch between different 4-electrode combinations.

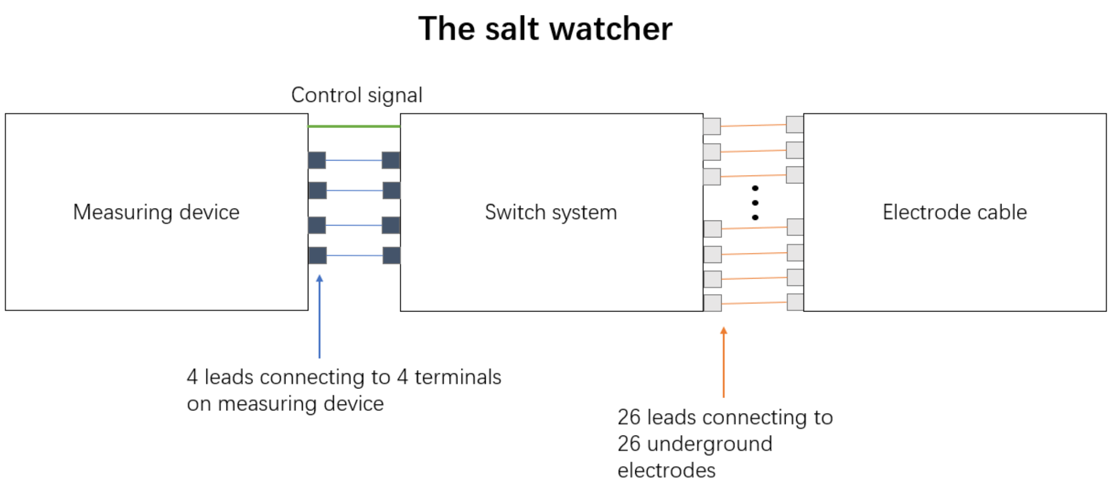


Figure 1.7 the expected structure of the salt watcher

The aim of this project is to design an automatic switch system for the salt watcher. The measuring device will be designed by a project taken by Pinqi Guo and the electrode cable will be designed by the electrode cable project team. The final products of 3 projects are supposed to be integrated into a complete salt watcher.

Problems:

1. Despite that the Wenner method (or any other 4-electrode salinity measuring method) is used in the salt watcher, it is also required to keep the flexibility for other kinds of 4-electrode salinity measuring method. So the switch possibility will not be restricted to only the possible Wenner sets within 26 adjacent underground electrodes but also to all the other 4-electrode combinations. It requires the capability of the switch system to connect each of the 4 terminals of the measuring device to any chosen underground electrode.

2. The measuring process requires the analog potential and current signals passing through the measuring system and the electrode cable. So the switch system should be also able to transfer analog signals between the 4 terminals on the measuring device and the chosen 4 underground electrodes.

3. The measuring device is supposed to be built on a programmable microcontroller, which means the control of the switching process will be taken by the measuring device. So control signals will come from the measuring device to the switch system and the switching process should be designed to follow control signals from a microcontroller.

4. Eventually, the switch system will be integrated into the salt watcher system, which makes the integration between separate projects also a problem. A clear integration plan before designing is necessary to ensure the final integration to the measuring system and electrode cable.

As a conclusion of all these problems, the main problem of this project can be derived: What is the design for an automatic analog switch system which can connect 4 terminals from the measuring device to any possible combination of 4 electrodes within 26 underground measured electrodes, switch between different 4-electrode sets following control signals from a microcontroller and can be intergrated into the salt watcher?

1.3 RESEARCH QUESTIONS

In this chapter, the main question and sub questions are defined.

1.3.1 MAIN QUESTION

The main question is derived from the problem analysis:

What is the design for an automatic analog switch system which can connect 4 terminals from the measuring device to any possible combination of 4 electrodes within 26 underground measured electrodes, switch between different 4-electrode sets following control signals from a microcontroller and can be intergrated into the salt watcher?

1.3.2 SUB QUESTIONS

The 5 sub questions are derived from the main question and problem analysis:

1) What kind of system design is capable to connect 4 terminals from the measuring device to any possible combination of 4 electrodes within 26 measured electrodes and switch between different 4-electrode sets following control signals from a microcontroller?
2) What kind of system design can be intergrated into the salt watcher?
3) What sub systems design is needed for the system design?
4) What components is needed to build the designed subsystems?
5) What tests can confirm the components choice?
6) What assembly plan and tests can confirm the subsystem design?
7) What assembly plan and tests can confirm the system design?

1.4 OBJECTIVES&DELIVERABLES

The objectives of this project are:

1) An automatic electrode swtich system design which can be used in the salt watcher connecting the measuring device and the electrode cable.
2) Discussion and suggestion on the realizibility of the designed system and further possible improvements of the design.

To achieve the objectives, these are the deliverables of this project

1) The whole design of the automatic electrode switch system
2) A score matrix of the chosen components
3) A prototype of the designed switch system
4) A test plan designed for the system and the components
5) The report of the test results

6) Discussion and recommendation based on the test results
7) The final report of the project

2 THEORETICAL FRAMEWORK

In this chapter, basic theories and research that is related to this project will be described.

2.1 WENNER METHOD

Wenner method is a measuring method which is used to measure earth resistivity.

For the situations that the resistivity is needed of a considerable part of the earth to extend to a considerable depth, or the part of the earth to be measured should not be interfered, the Wenner method is suitable (Frank, 1915). In this project, it will be the measuring method for soil salinity.

According to the method (Frank, 1915), four holes with 4 electrodes at the end terminals are evenly distributed in a straight line. The diameter of the electrodes does not exceed 10% of the distance between the electrodes, and they all extend to approximately the same depth, which is usually the depth where the resistivity is going to be measured. One electrode is placed in each hole, so the electrode is in electrical contact with the earth only near the bottom, as shown in figure 2.1. This figure does not represent how this method is used in this project, as explained in Chapter1.2. In the salt watcher, the electrodes will be set vertically underground, but the principal of the method remains the same, so it will not be explained again in this chapter.

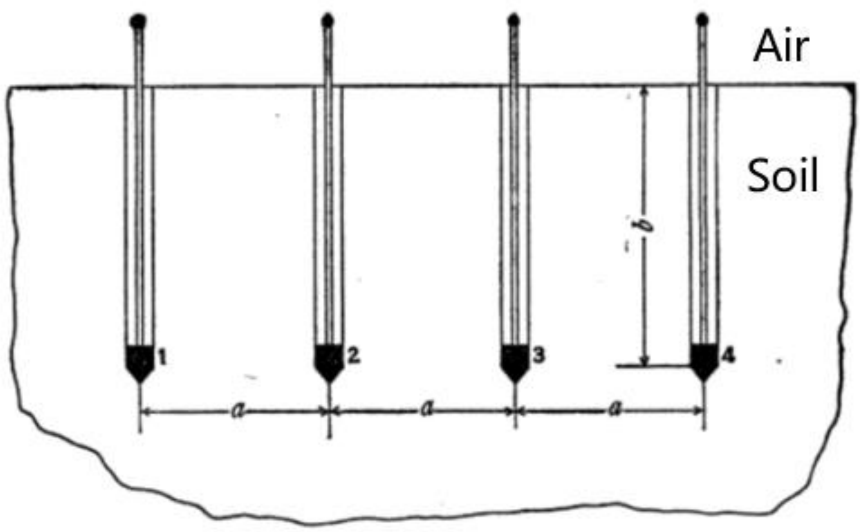


Figure 2.1 Wenner method electrode set (Frank, 1915)

Therefore, if the depth of the hole, the distance between the holes and the resistance are measured (using 1 and 4 as the current injection terminals, 2 and 3 as the potential measuring terminals, normally the two input electrodes are both outside, and the output electrodes inside), the data is available to calculate the effective resistivity nearby.

Assuming a is the distance between the holes, b is the depth of the holes, p is the resistivity, n is the ratio of b to a, and R is the measured resistance (measured potential V divided by current I), then

$$\rho = \frac{4\pi a R}{1 + \frac{2a}{\sqrt{a^2+4h^2}} - \frac{a}{\sqrt{a^2+h^2}}}$$

where the denominator has a value between 1 and 2 depending on the value of a and b. So in case b is much large in comparison with a,

$$\rho = 4\pi aR\ [\Omega.m]$$

and in case b is much smaller in comparison with a,

$$\rho = 2\pi aR\ [\Omega.m]$$

2.2 MULTIPLEXER/DEMULTIPLEXER

To realize the required switch function, the system should be able to transmit analog signals between 4 terminals to 4 chosen electrodes within 32 electrodes. Which leads to a question: Is there any existing switch system that is capable to switch between different analog signal channels?

Multiplexer and demultiplexer are commonly used electronic components, which are capable to select analog or digital signals (ElectronicsTutorials). A multiplexer is capable to select one signal form several input signal channels (normally 2^n) and output that signal to the single output channel. A demultiplexer, which is opposite to multiplexer, is capable to select one output channel to output the single input signal. Fig 2.2 demonstrates the function of a multiplexer.

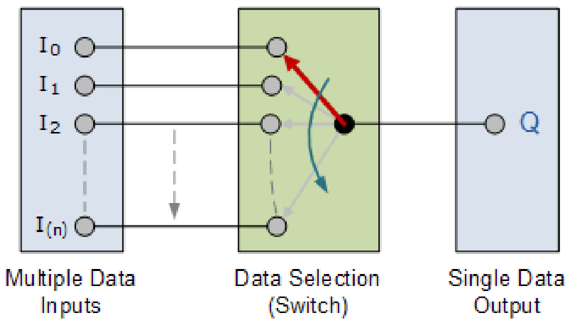
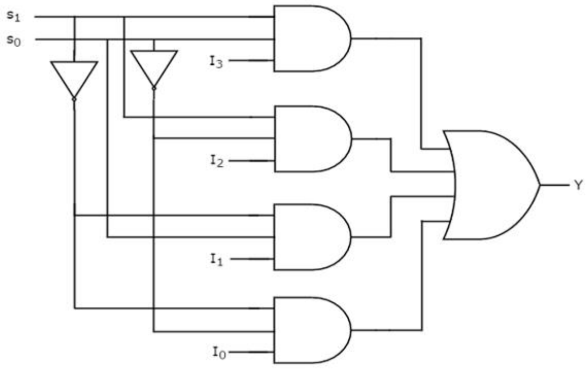


Figure 2.2 Function diagram of a multiplexer (ElectronicsTutorials)

The principle of multiplexer and demultiplexer is a logic circuit combination with n logic input to control 2^n signal channels. It translates the n-digit binary input signal to a particular connection between the one chosen input/output channel and a single output/input (David Harris, 2010). Fig 2.3 shows a typical logic circuit diagram of a 4:1 digital multiplexer. The circuit is designed based on the Boolean truth table.



Selection Lines		Output
S_1	S_0	Y
0	0	I_0
0	1	I_1
1	0	I_2
1	1	I_3

$$Y = S_1'S_0'I_0 + S_1'S_0I_1 + S_1S_0'I_2 + S_1S_0I_3$$

Figure 2.3 A typical logic circuit diagram of a 4:1 digital multiplexer

For an analog multiplexer, instead of directly using a logic output as the output channel, the translated digital signals will be used to control analog switches to choose the connected signal channel, as Fig 2.4 shows.

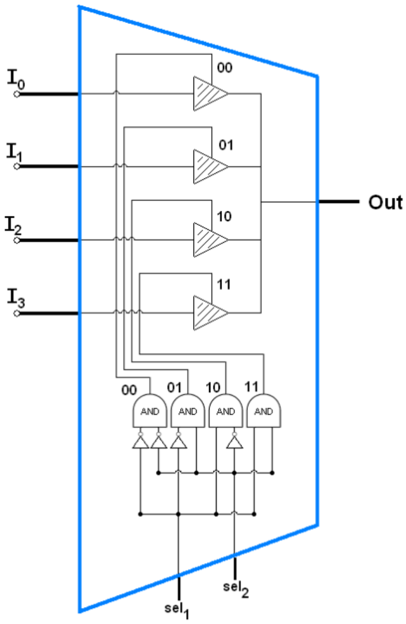


Figure 2.4 A typical circuit diagram of a 4:1 analog multiplexer

The commonly used multiplexers and demultiplexers types are 2:1, 4:1, 8:1 and 16:1 (Rhodes & Levy, 1979). In this project, 4 measuring terminals are connected to 26 electrodes, which means each measuring terminal need to be connected to 26 electrodes and choose one of the electrodes for signal transmission. To realize the function, a 32:1 analog multiplexer is necessary. There is no 32:1 multiplexer in the market, which means a combination of multiplexers is necessary to make a 32:1 multiplexer, or a logic circuit design based on the principle of multiplexers.

To make a 32:1 multiplexer, a combination of two 16:1 multiplexers and one 2:1 multiplexer is needed (Charles H. Roth, 2013). Fig 2.5 demonstrates the basic structure of the 32:1 multiplexer design.

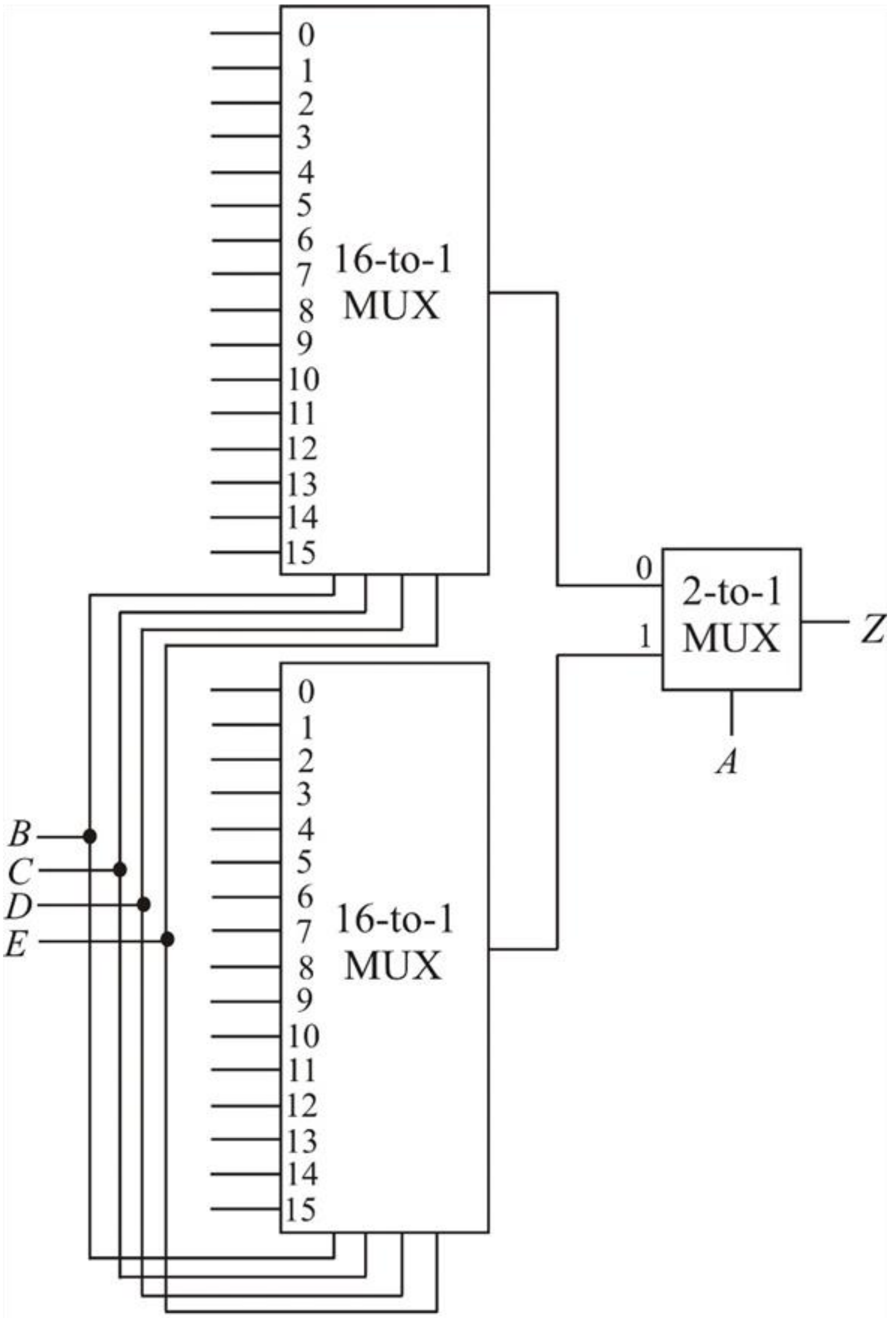


Figure 2.5 The basic structure of a 32:1 multiplexer (Charles H. Roth, 2013)

2.3 SWITCH

The switch system will be an automatic system, which means any type of manual switches is not suitable for the system. The salt watcher requires the switch system to transfer analog signals between the measuring device and the electrode cable, so the normally used automatic analog switch type will be introduced below. Further comparison on the detailed characteristics of each kind of switch will be made in the project.

2.3.1 ELECTROMAGNETIC RELAY

A relay is an electric switch. The current flowing through the relay coil creates a magnetic field, attracting the lever and changing the switch contacts. The coil current can be turned on or off, so the relay has two switch positions, most of which have double-throw switch contacts, as shown in fig 2.6 (Hewes, 2013).

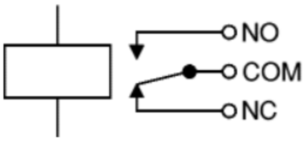


Figure 2.6 The electric symbol of a relay (Hewes, 2013)

Electromagnetic relay, which is also called reed relay, is a type of relay that use an electromagnet to control reed switches (Hewes, 2013). The contacts are made of magnetic materials, and the electromagnets act directly on the contacts without the need for an armature to move them. Compared with armature-based relays, reed relays have a much faster switching speed because the moving parts are small and light, although the switch bounce still exists. They are mechanically simple, so they have more reliability and longer life (Webster, 1999). Fig 2.7 shows the typical structure of a reed relay.

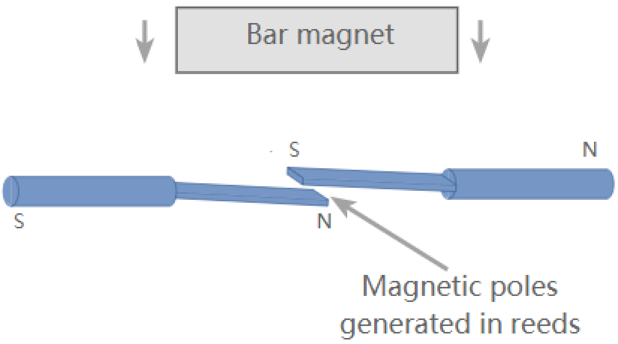


Figure 2.7 The typical structure of a reed relay (Polee)

2.3.2 SOLID-STATE RELAY

A solid-state relay is a non-contact relay in which a semiconductor control load flows through a solid-state switch. The silicon-controlled rectifier (SCR) or bidirectional silicon-controlled rectifier (TRIAC) that triggers the output terminal then conducts the load current, so it can accept low-voltage DC or AC signal input, and then conduct high-voltage, high-power output current. The function of the solid-state relay are isolating input and output, and controlling high-power output current (Chen N. , 2008).

Solid state relays have the advantages of high strength, impact resistance, strong vibration resistance, low input drive current, and can be easily installed on computers and digital control circuits. They are widely used in computer external link control devices, high-power thyristor triggers and industrial automation devices. Solid-state relay is also widely used in petrochemical industry, instrument equipment, various machinery, solenoid valve control, CNC machine tools, entertainment facilities and other automation equipment, especially suitable for harsh environments such as humidity and corrosion, and frequent switching (Chen M. , 2003). Fig 2.8 shows the structure of a solid-state relay.

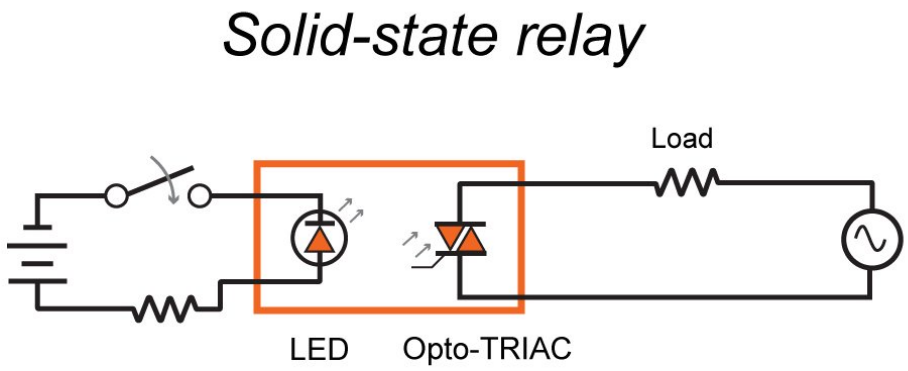


Figure 2.8 The typical structure of a solid-state relay (Arar, 2017)

2.3.3 ANALOG SWITCH

An analog switch is mainly used to complete the signal switching function in the signal link. The switch mode of the MOS tube is used to realize the signal link as turned off or on. Because its function is similar to a switch, it is realized with the characteristics of an analog device to become an analog switch (Horn, 1990). Fig 2.9 shows the typical structure of an analog switch.

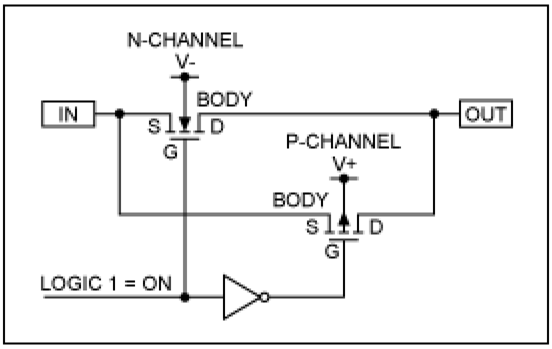


Figure 2.9 The typical structure of an analog switch (Munir, 2013)

Due to the switching performance of the MOS tube, the analog switch circuit can achieve a high turn-off impedance, generally a turn-off resistance of more than megaohm; and a very low on-resistance, generally several ohms, which can realize good signal link switching and disconnection isolation. According to different application requirements, analog switches can be divided into audio analog switches, video analog switches, digital switches, general analog switches, and so on (yangzh, 2017). The analog switch has the characteristics of low power consumption, fast switch speed, no mechanical contacts, small size and long service life (Horn, 1990).

2.4 MICROCONTROLLER

In the salt watcher a microcontroller Arduino will be used as the controlling device of the system. The switching system will be driven by the control signals from the microcontroller. The information of the microcontroller is introduced:

- Arduino

The Arduino is a commonly used open-source microcomputer, “the Arduino is an open hardware development board that can be used by tinkerers, hobbyists, and makers to design and build devices that interact with the real world” (Opensource.Com, 2020). It offers a large scale of modules and extensions that can be added to the main board to add required functions. Fig 2.10 shows an Arduino.

The digital pins of Arduino can be set to output mode, which allows them to provide a current for other electronic components. The maximum value of the provided current is around 40mA, which is enough to drive sensors, some kinds of LED lights and logic circuit, but is not enough for driving most relays, solenoids, or motors (Microchip Technology Inc., 2018).

Figure 2.10 An Arduino (Opensource.com, 2020)

3 METHOD

In this chapter, the design method and why it is chosen of the project will be introduced. The activities following the method will also be described.

3.1 DESIGN METHOD

V-model is occasioned in a thesis published in 1986 by Paul Rook (Using V Models for Testing., 2013). He used this method to design software by breaking it down into small pieces, programming individually to achieve the final product. Since its effectiveness, V-model remains to be one of the most efficient approaches for developing software.

As Fig 3.1 shows, V model has a characteristic structure that looks like “V”. It is a type of SDLC (System Development Life Cycle) model that works sequentially by the arrow. Each circle on the left of the arrow corresponds to the ones on the right. The process will go down into the next phase by passing the staged test. It implies if the designed results cannot pass the corresponding test, the projecting process should go back to the related design stage on the left side instantly and resume with the original direction until it is qualified so far.

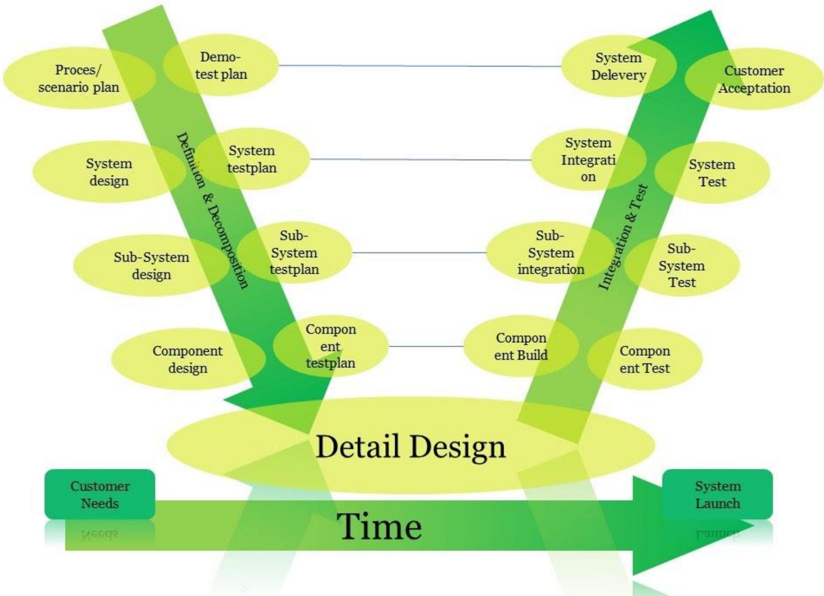


Figure 3.1 V-MODEL STRUCTURE (Haak, 2020)

By the iterative verification and validation, this method can ensure the final system launch will follow the customer needs.

3.2 JUSTIFICATION

The aim of the project is to find a feasible design for the automatic electrode switch system for the salt watcher. The 'design-integration-design (if tests failed)'cycle of V model ensures that the final product of the project will meet the desired requirements from the beginning. V model checks whether the system the subsystem and the components meet their requirements by testing during the entire project. First the requirements of the switch system will be determined and discussed with the client then these requirements will be translated to system requirements for the switch system. The subsystems and components will also be tested according to a test plan that is written based on the requirements of the system. After each test is passed, the integration will come to the next step so the components, the subsystems and the system will be tested gradually to make sure the feasibility and requirements can all be confirmed after the whole process of V model method.

3.3 ACTIVITIES & DELIVERABLES

In this chapter, the activities that will be taken in each phase and the deliverables of each activity will be described phase by phase. At which point the sub-questions will be answered will also be introduced.

3.3.1 PREPARATION PHASE

In this phase, the overview and based information about the project would be clear. The research proposal and project plan are completed during this phase. The main and sub-questions would be discussed in this phase. The table 3-1 below shows the activities and deliverables in this phase.

Table 3-1 Preparation Phase

Activities	Deliverables
Analyze the problem	Problem analysis of the switch system; Requirement list of the project; Validation plan
Research on the background information	Introduction Chapter of research proposal
Research on related theories and articles	Theoretical framework Chapter
Make the integration plan	The integration plan between different projects
Make the project plan	the project plan

The sub questions 'What kind of system design can be intergrated into the salt watcher?' is related to this phase.

3.3.2 DESIGN PHASE

System design Phase:

In this phase, the design of the main system will be completed, and the main functions will be explained. The main system is divided into several subsystems. The system test plan will be made. The table 3-2 below shows the activities and deliverables in this phase.

Table 3-2 System Design Phase

Activities	Deliverables
Make the input and output for the system	The function tree and diagram of the input and output of the whole system
Divide the system into several subsystems	The overview of the subsystems
Complete the system test plan	Test plan of the main system

The sub questions 'What kind of system design is capable to connect 4 terminals from the measuring device to any possible combination of 4 electrodes within 26 measured electrodes and switch between different 4-electrode sets following control signals from a microcontroller?' is related to this phase.

Subsystem design phase:

In this phase, the design of the subsystems will be completed, and the functions of the subsystem will be explained. The subsystems are divided into component phases. The table 3-3 below shows the activities and deliverables in this phase.

Table 3-3 Subsystem Design Phase

Activities	Deliverables
Make the input and output for the subsystems	The function tree and diagram about the input and output of subsystems
Divide the subsystems into component phases	The overview of the component phases
Write the subsystems test plan	Test plan of the subsystems

The sub questions 'What subsystems design is needed for the system design?' is related to this phase.

Component design phase:

In this phase, the design of the component will be completed. The table 3-4 below shows the activities and deliverables in this phase.

Table 3-4 Component Design Phase

Activities	Deliverables
Describe the components	List of components, components description
Write the component test plan	Test plan of the components

The sub questions 'What components is needed to build the designed subsystems?' is related to this phase.

3.3.3 EXECUTION PHASE

Component integration phase:

In this phase, the components will be ordered and tested. The table 3-5 below shows the activities and deliverables in this phase.

Table 3-5 Component integration phase

Activities	Deliverables
Order the components	The components
Test the components	The test data of the components

The sub questions 'What tests can confirm the components choice?' is related to this phase.

Subsystem integration phase:

In this phase, all parts of the component will make up each subsystem. The subsystems are tested with the test plans. The table 3-6 below shows the activities and deliverables in this phase.

Table 3-6 Subsystem integration phase

Activities	Deliverables
Assembly the components into subsystems	The assembled subsystems
Test the subsystem based on the test plan	The test data of each subsystem
Activities	Deliverables
The modification of the subsystems	The adjusted subsystems

The sub questions 'What assembly plan and tests can confirm the subsystem design?' is related to this phase

System integration phase:

In this phase, all parts of the subsystems will be integrated into the main system. The main system is tested with the test plan. The table 3-7 below shows the activities and deliverables in this phase.

Table 3-7 System integration phase

Activities	Deliverables
Assembly the sub-system into the main system	The assemble main system
Test the main system based on the test plan	The test data of the main system

The sub questions 'What assembly plan and tests can confirm the system design?' is related to this phase.

3.3.4 CONCLUSION PHASE

In this phase the test data of the whole system will be analyzed, and a conclusion will be given. Table 3-8 below shows the activities and deliverable of this phase.

Table 3-8 Conclusion Phase

Activities	Deliverables
Analyze the test data of the designed system	The result analysis of the tests; the conclusion of the designed system
Discuss on the conclusion	Discussion of the results; Recommendation for further improvements

The sub question 'What tests and results can confirm the components choice, the sub system design the system design and the final prototype?' is related ot this phase.

4 RESULTS

In this chapter, the results of each activity will be demonstrated step by step.

4.1 PREPARATION

In this phase, the requirement list of the project is given. Based on the problem analysis and the research questions, the requirement list of this project is defined, as table 4-1 shows.

Table 4-1 Requirement list

No.	Requirements
1.	The electrode switch will connect between a measuring device with 4 terminals and an electrode cable with 26 electrodes.
2.	The electrode switch can receive a control signal of information of the chosen terminal and the chosen electrode that will be connected to the terminal.
3.	The electrode switch should send an error signal to the user if the chosen electrodes or terminal does not exist.
4.	The electrode switch should connect each of the 4 terminals on the measuring device to each chosen electrode.
5.	The electrode switch should disconnect the measuring device and the electrode cable when it is switching from one 4-electrode combination to another.
6.	The electrode switch should send a signal to the measuring system when the switching process is finished.
7.	The unchosen electrodes should not be connected to the terminals of the measuring device.
8.	The switch system should ensure the salinity measurement can be taken via the connection to the chosen electrodes.
9.	The electrode switch is compliable with the measuring system designed by another project which is supposed to work as the same way as chauvin-arnoux-c-a-6460-earth-resistance-tester.
10.	The electrode switch is compliable with the measuring cable designed by the electrode cable project group.

The requirements are derived from the research questions and discussed with the client. The focus of the requirements is to find a working concept design for the switch system. Therefore, the specific performance of the system is not taken as requirements but will be tested and discussed for further improvements. The requirement list gives a clear image of what are the expected functions of the final product of the project. This leads to a function overview of the system, as Fig 4.1 below shows.

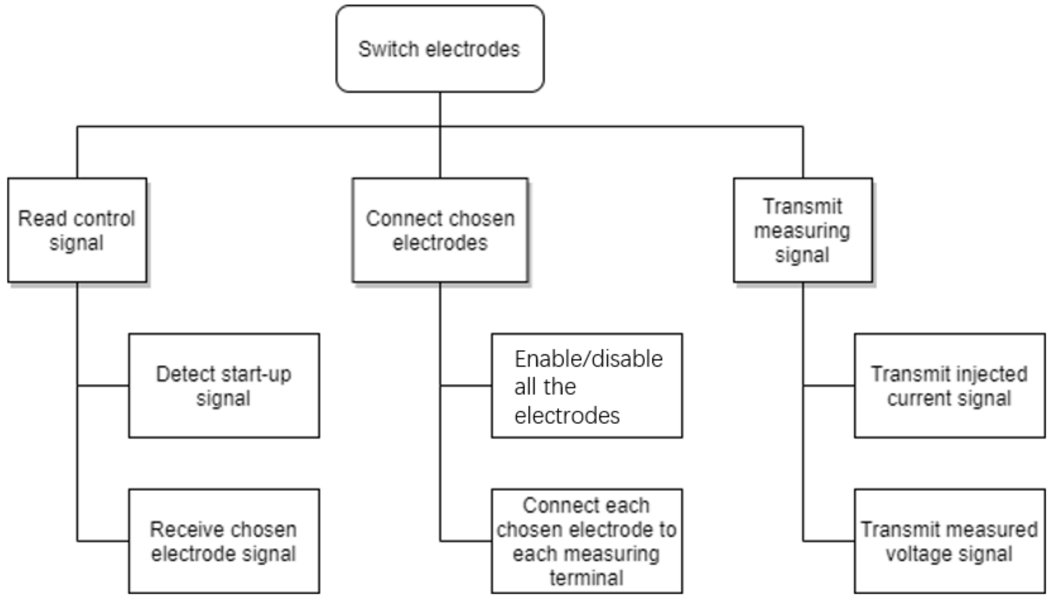


Figure 4.1 The function overview of the system

The function overview has been discussed with the other 2 project teams. It is determined that the main control system of the salt watcher, which will be built on a microcontroller, will not be designed in this project but in the measuring device project. Despite of the whole control software of the salt watcher, an external software design is still required for the switch system. This external software is required to test the performance of the switch system and integration with the measuring device. It will work as a function in microcontroller and can be integrated into the main controlling program of the salt watcher. Based on the requirement list and function overview, a validation plan of the system is defined, which is given in Appendix 1.

Because this project is one of the 3 parts of the salt watcher project, to ensure the integration between different projects, an integration plan is discussed with the other 2 project teams and the client. In the salt watcher project, the 3 different projects including this project, combines like different subsystems. So the integration plan is designed following the instructions of the system design phase of V-model. The determined integration plan is given in Appendix 2.

By taking the integration plan, following the system design and integration phase in V-model, the possibility of integration can be improved.

4.2 SYSTEM DESIGN

Based on the problem analysis and function overview, a system description is given, as Fig 4.2 shows.

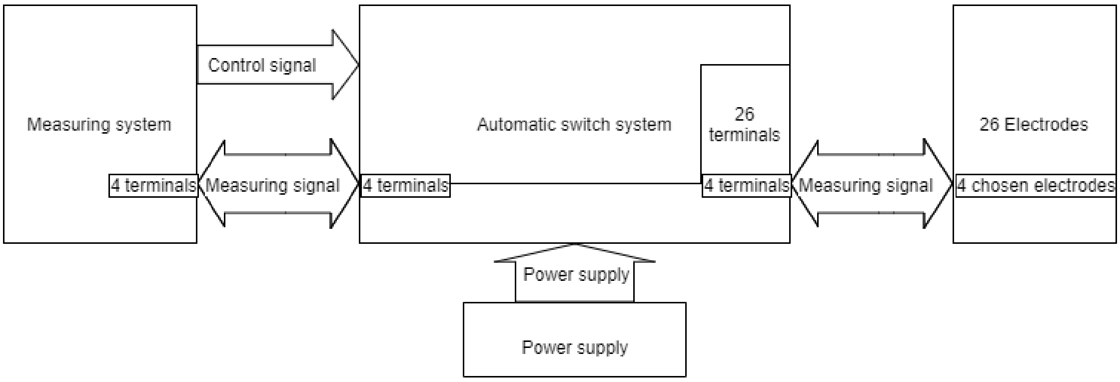


Figure 4.2 The system description of the switch system

The automatic switch system is the main system of this project. Fig 4.3 below shows the signal flowchart of the switch system.

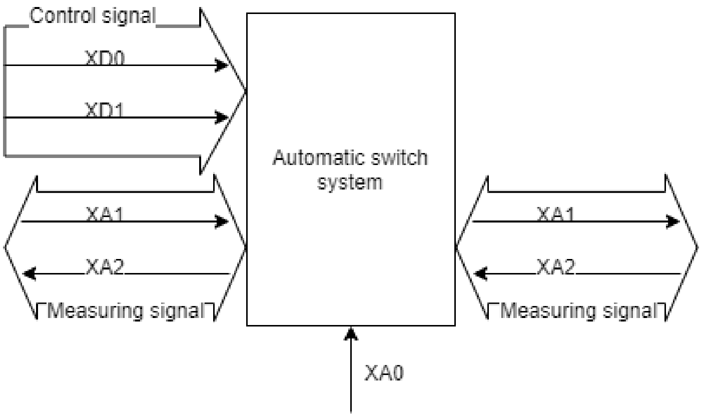


Figure 4.3 The signal flowchart of the switch system

There are only 2 measuring signals because 2 measuring terminals are used to inject current and the other to measure voltage. Table 4-2 below gives the variable list of the system.

Table 4-2 Variable list of system description

from	to	variables	symbol	value
Power supply	Switch system	Supply voltage	XA0	5V DC (For Arduino)
	Switch system	Chosen electrode signal	XD1	0V/5V

Measuring system		Start-up signal	XD0	5V
		Injected current signal	XA1	Determined by measuring device project
Switch system	Electrode Cable	Injected current signal	XA1	Determined by measuring device project
Electrode Cable	Switch system	Measured voltage signal	XA2	To be measured
Switch system	Measuring system	Measured voltage signal	XA2	To be measured

As described in chapter 4.1, the main controlling system will be put in the measuring system. So the signals from and to the users are passing through the measuring system via the external software function designed in this project. Therefore, the final product of the switch system will not have a direct connection to the user but only to the measuring device and the electrodes. Fig 4.4 demonstrates how the external software designed by this project is integrated into the salt watcher.

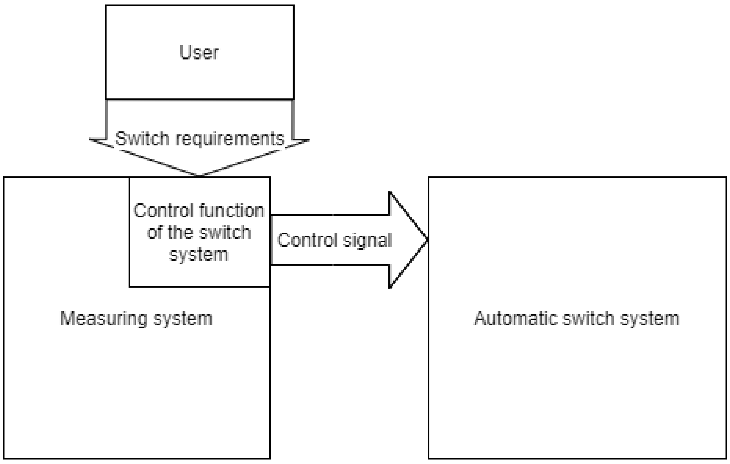


Figure -.4.4 Control signal flowchart

A detailed system test plan is made following the function overview and the system description. The system test plan is given in Appendix 3.

4.3 SUBSYSTEM DESIGN

After the function overview is defined, the functions are divided into different subsystems following the different requirement on the functions. The system is divided into 3 subsystems: the external control function, the master switch and the switch circuit, as Fig 4.5 below shows.

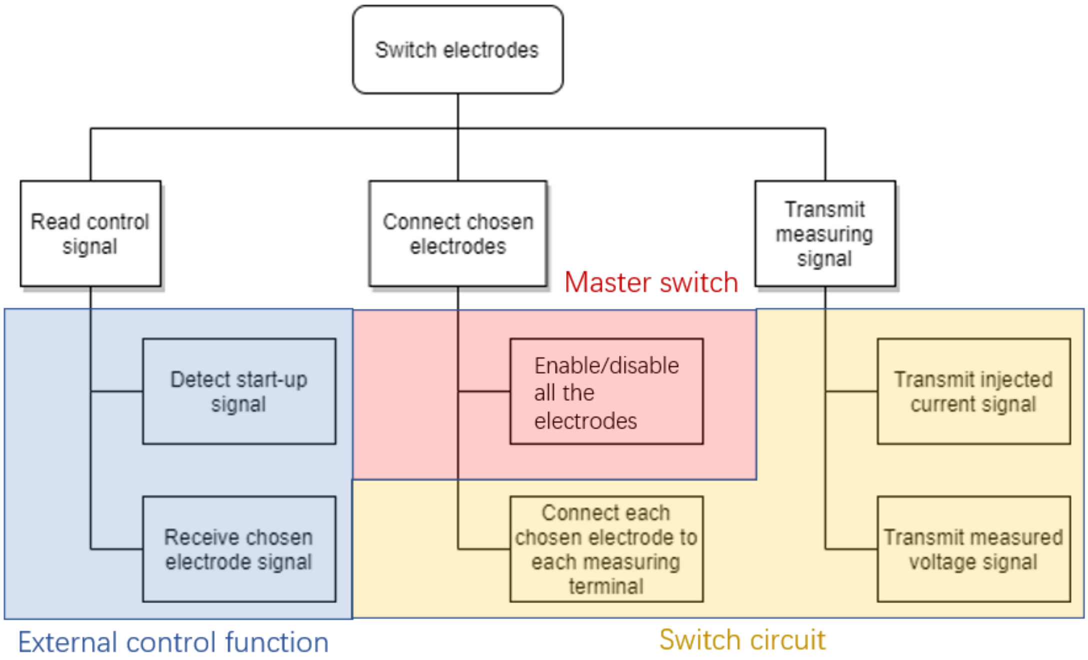


Figure 4.5 The system division

After the functions are divided, detailed subsystem descriptions are defined, as Fig 4.6 shows.

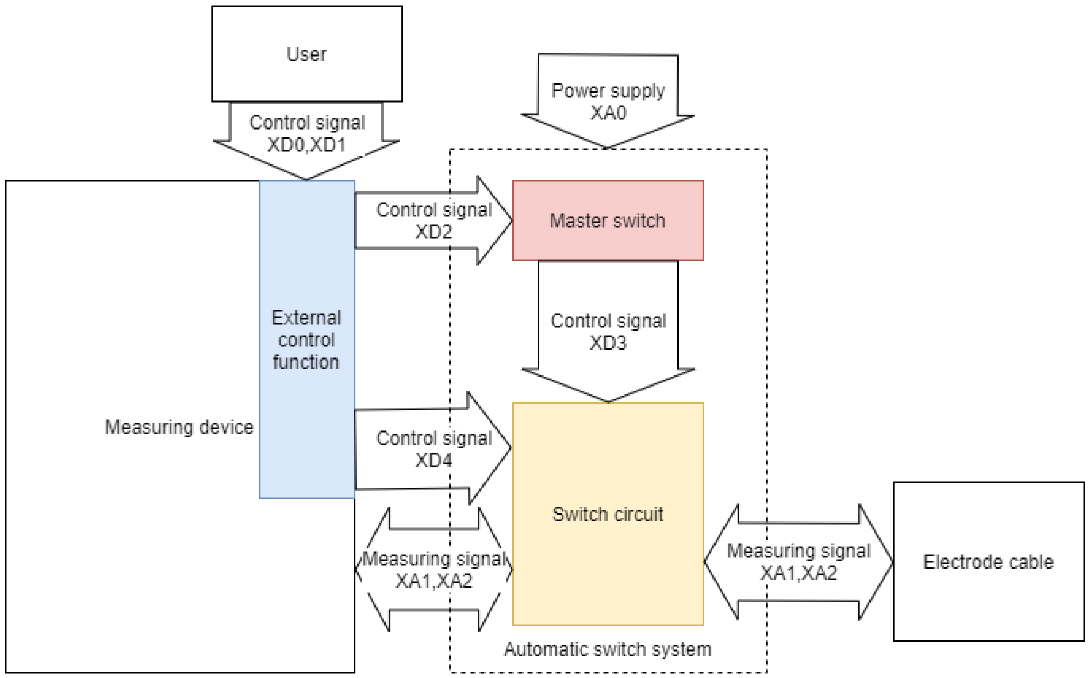


Figure 4.6 The subsystem description

Table 4-3 shows the variable list of the subsystems.

Table 4-3 Variable list of subsystem description

from	to	variables	symbol	value
Power supply	Switch system	voltage	XA0	5V DC (For Arduino)
User	External control function	Chosen electrode signal	XD1	0V/5V
		Start-up signal	XD0	5V DC
External control function	Switch circuit	Electrode connection control signal	XD4	Determined by the switch circuit design
External control function	Master switch	Master switch control signal	XD2	0V/5V DC
Master switch	Switch circuit	Switch on/off signal	XD3	0V/5V DC
Switch circuit	Electrode Cable	Injected current signal	XA1	Determined by measuring device project
		Measured voltage signal	XA2	To be measured
Measuring device	Switch circuit	Injected current signal	XA1	Determined by measuring device project
		Measured voltage signal	XA2	To be measured

The design of the subsystems will be introduced below. In the 3 subsystems, the external control function design can only be defined after the master switch and switch circuit design is defined.

4.3.1 SWITCH CIRCUIT SUBSYSTEMS

The master switch function is based on the switch circuit design, so the focus is to define an appropriate design for the switch circuit. The aim is to connect the 4 measuring terminals to each combination of 4 electrodes within 26 electrodes. Instead of a switch circuit that can connect 4 terminals to 4 electrodes, the system can be simplified: to separately connect each terminal to a chosen electrode of 26 electrodes. As Fig 4.7 shows, the 4 separate switch circuits connect each terminal to 26 electrodes. Then the problem turns to: what switch circuit design is capable to connect one terminal to the chosen electrode within 26 electrodes.

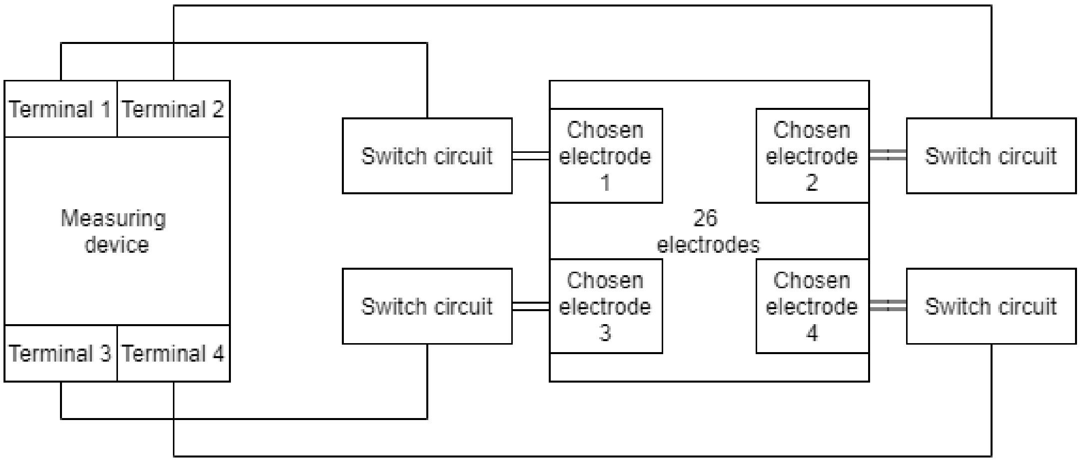


Figure 4.7 Simplified switch circuit subsystem

To realize the functions of the switch circuit design, 2 different design is given as options.

The first design is called ‘pyramid’. This design is based on SPDT (Single Pole Double Throw) switches. As shown in Fig 4.8, this kind of switch has a COM (Common connection) terminal(1) and whether the NC (Normally closed) terminal(2) or the NO (Normally open) terminal(8) is on is determined by the logic input of the control signal(6).

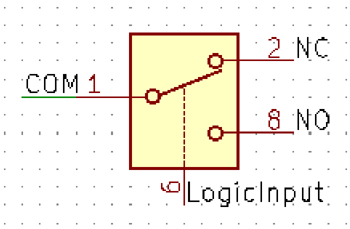
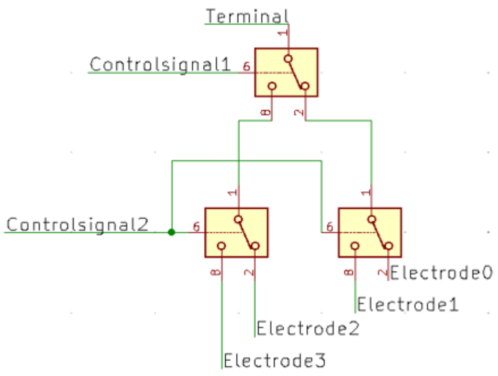
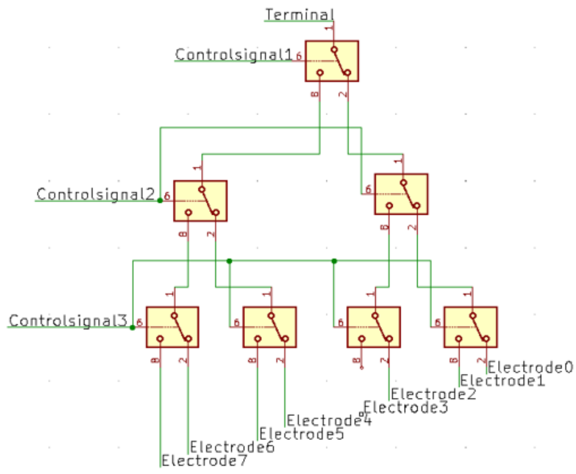


Figure 4.8 An SPDT switch

In this design, the switch on the higher layer from the left connects the NC and NO terminals to the COM terminal of the switches on the lower layer, which makes the design looks like a pyramid. The principal schematic of this design is shown below in Fig 4.9.



A 2-layer 'Pyramid'



A 3-layer 'Pyramid'

Figure 4.9 Principal schematic of 'pyramid' design

Switches on the same layer share one control signal. The schematic demonstrates that this design is capable to connect 1 measuring terminal to 2^n electrodes with n-layer pyramid. In a 3-layer pyramid, by changing the logic input on the three control signals, the switch circuit can connect 1 measuring terminal to the chosen electrode within 8 electrodes. Table 4-4 shows the truth table when the control signal input changes.

Table 4-4 Truth table of the 3-layer pyramid design

Input			Output
Control signal 1	Control signal 2	Control signal 3	Connected electrode No.
0	0	0	0
0	0	1	1
0	1	0	2
0	1	1	3
1	0	0	4
1	0	1	5
1	1	0	6
1	1	1	7

In this design, each measuring terminal is connected to all the electrodes individually, so for the 4 measuring terminals in salt watcher, 4 such pyramid is needed to make every possible connection. For each pyramid, when a new layer is added, the capable electrode amount will be doubled. To connect one terminal to 26 electrodes, a 5-layer pyramid is required, which can connect at most 32 electrodes. This pyramid requires at least 1+2+4+7+13=27 SPDT SPDT switches and 5 control signals for each measuring terminal. The whole switch circuit will contain 27*4=108 SPDT switches and 5*4=20 control signals.

The second design is called ‘bungalow’. This design uses SPST (Single Pole Double Throw) switches. As shown in Fig 4.10, an SPST-NO switch contains a COM terminal(2), an NO terminal(3) and a logic input(1) to control if the switch is closed or open.

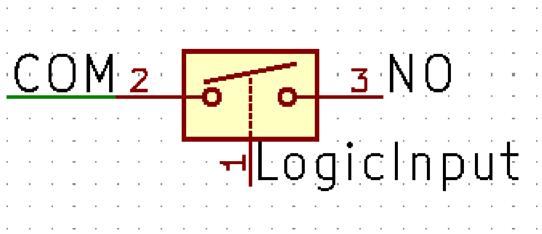


Figure 4.10 SPST-NO swtich

In this bungalow design, SPST-NO switches are used. The COM terminals (2) of the SPST switches are all connected to the measuring terminal and the NO terminals (3) of the switches are connected to different electrodes.

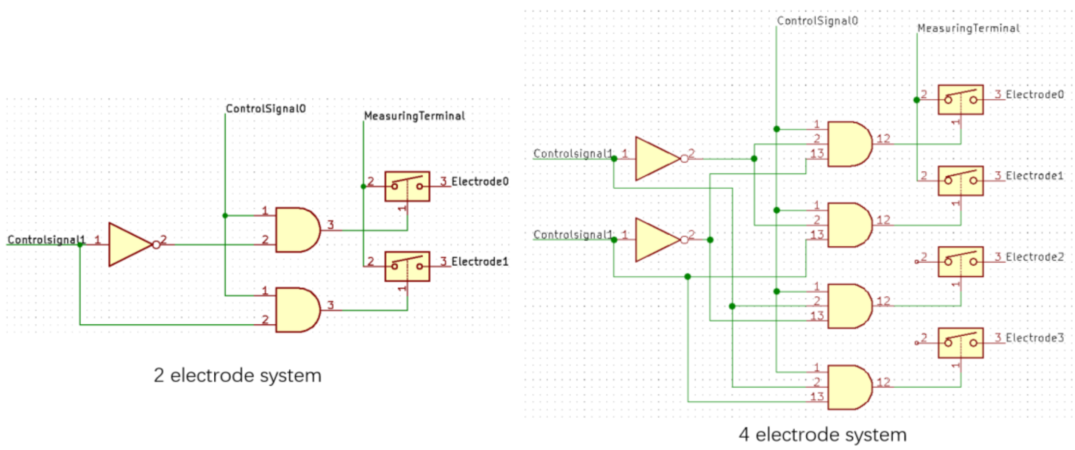


Figure 4.11 Principal schematic of ‘bungalow’ design

The input control signals will be translated as a 2-digit number to a specific position by the logic circuit. Fig 4.11 and 4.12 shows the principal schematic of the bungalow design with 2, 4 and 8 electrodes.The ‘bungalow’ design always contains only one layer of switches. The amount of switches is the same as the amount of electrodes, also the same as the AND gates. With every added control signal, the electrode amount that can be connected will be doubled.

The logic circuit in this design works as the same way as a decorder, despite of the master control signal which works as the master switch subsystem, which control the switch on/off of the whole circuit. This is the reason why a integrated chip decoder is not used in this design.

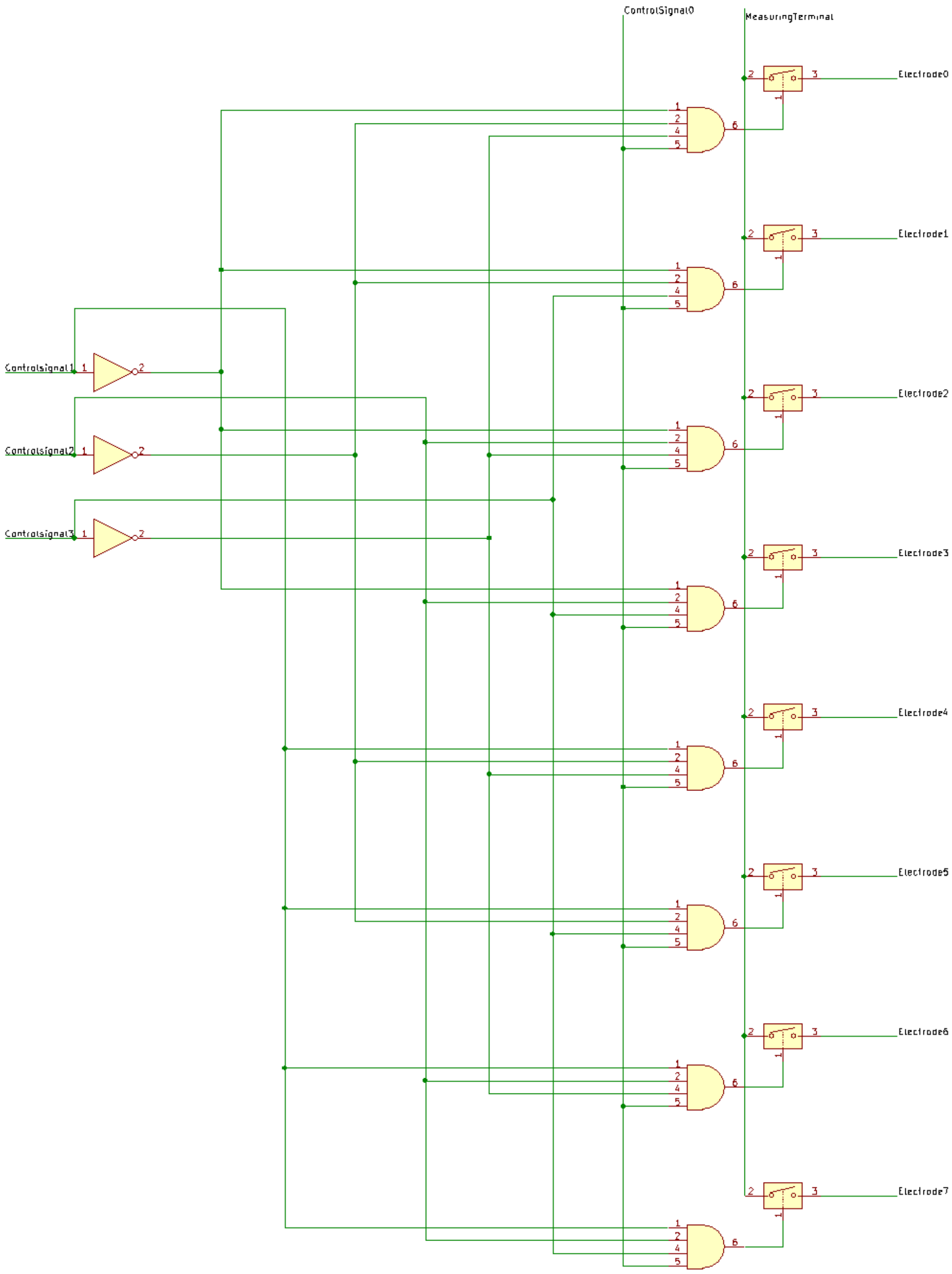


Figure 4.12 Principal schematic of 8-electrode 'bungalow' design

Control signal 0 is the master switch of all the digital input. In the 8 electrodes design, the control signals 1, 2 and 3 are transferred through a logic circuit and are translated from a 3-bit binary number (000_2-111_2) to a decimal number (0-7), which will close the switch of the chosen number of the electrode. Table 4-5 shows the truth table of the bungalow design.

Table 4-5 Truth table of the bungalow design with 8 electrodes

Input				Output
Control signal 0	Control signal 1	Control signal 2	Control signal 3	Connected electrode No.
0	x	x	x	x
1	0	0	0	0
1	0	0	1	1
1	0	1	0	2
1	0	1	1	3
1	1	0	0	4
1	1	0	1	5
1	1	1	0	6
1	1	1	1	7

Like the pyramid design, in the bungalow design each measuring terminal is connected to all the electrodes individually, so for the 4 measuring terminals in salt watcher, 4 such bungalows are needed to make every possible connection. To connect one terminal to 26 electrodes, 5 control signals are required, which can connect at most 32 electrodes. This bungalow requires 26 SPST switches, 26 AND6 gate, 5 control signals and 5 Not gate. The whole switch circuit will contain 26*4=104 SPST switches and 5*4=20 control signals.

After the 2 subsystem designs are given, a comparison between the 2 design is needed. The characteristics that are concerned for a switch system are decided based on Chapter 2.2 and discussion with experts from Waterschap. A comparison list is made to decide which design is more suitable for the switch system. Table 4-6 shows the comparison list of the 2 switch circuit designs.

Table 4-6 Comparison between two designs

Characteristics	Pyramid design	Bungalow design
Signal fidelity	Worse: The resistance of the serial connected switches will be summed and have higher influences on the signal.	Better: The signal will only pass through 1 switch, making a lower impact on the signal.

Characteristics	Pyramid design	Bungalow design
Robust	Worse: Serial connection means one broken switch can cause the whole system broken.	Better: the logic control circuit and the analog signal transferring circuit are separated. Higher robust.
System scale	Similar: similar component amount required for both design	Similar: similar component amount required for both design
Switching process control	Worse: have no master switch for disconnection when changing the control signal value	Better: The master switch can disconnect all the electrodes to make sure the changing control signal will not cause unexpected connections.

Based on the comparison, the bungalow design is chosen as the subsystem design for the switch circuit. And the master switch subsystem is integrated into the switch circuit. Because the Bungalow design is using the same principle of multiplexer, there is also an option to use multiplexers instead of the logic circuit. This option will be discussed in the component choice chapter.

Because of the complexity of the switch circuit design for a 4-terminals-to-26-electrodes system, it is discussed with the client and decided that the prototype of the system will only connect 4 terminals to 8 electrodes. Theoretically, for the switch circuit design, the electrode amount will not influence the switch performance of the whole system. So the prototype test results will be taken as a proof of concept for this design. The subsystem test plan is given in Appendix 4.1.

4.3.2 MASTER SWITCH SUBSYSTEM

The function of the master switch subsystem is simple: Enable and disable all the electrodes following a control signal.

As described in previous design, an external input terminal of each AND gate works as the master switch, as Fig 4.13 shows.

When a low logic signal is input in ControlSignal0, all the AND gate will output low logic signal, disabling all the switches and electrodes. When a high logic signal is input in ControlSignal0, all the switches and electrodes will be enabled.

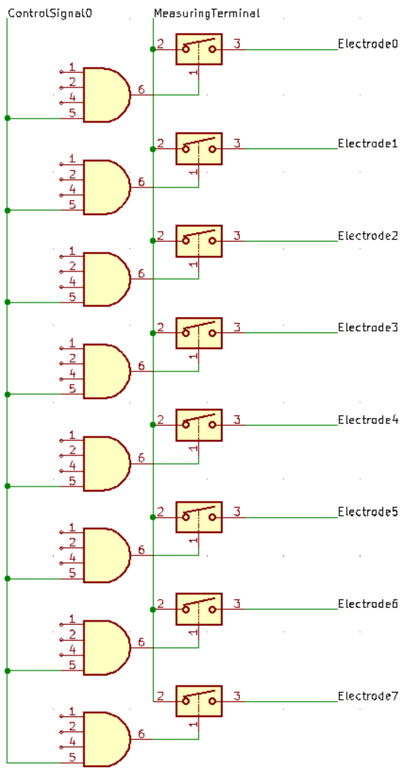


Figure 4.13 The design of master switch

The test plan of master switch subsystem is given in Appendix 4.2.

4.3.3 EXTERNAL CONTROL FUNCTION SUBSYSTEM

Based on the requirement of the switch circuit design, the specific input and output variables of the control software system can be determined, as shown in Fig 4.14.

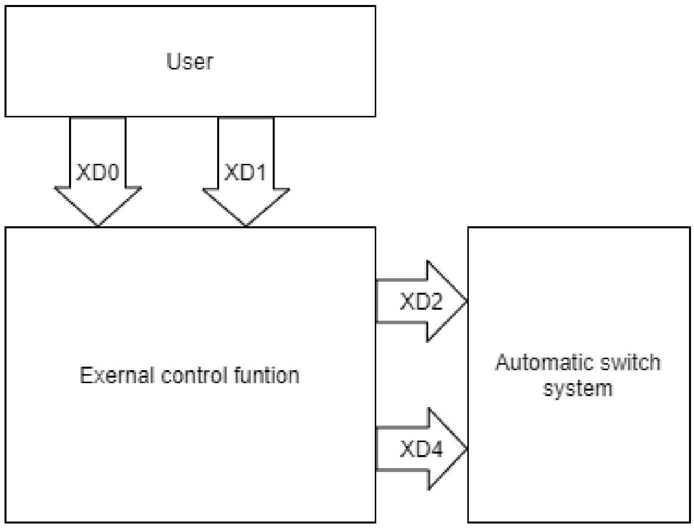


Figure 4.14 The control software subsystem description

The variable list of the external control function is given in table 4-7.

Table 4-7 Variable list of external control function

from	to	variables	symbol	value
User	External control function	Electrode number signal	XD1	10-digit numbers
		Start-up signal	XD0	5V DC
External control function	Automatic switch system	2-digit control signal	XD4	Logic signal translated from electrode number
		Master switch control signal	XD2	0V/5V DC

Following the subsystem description and the required signal value defined by the switch subsystem design, a software diagram can be designed, as shown in Fig 4.14. This function is designed for a 4-terminals-8-electrode system, so it will be used to test the final prototype of this project. The test plan for the control function subsystem is listed in Appendix 4.3.

It is determined by the measuring device project that Arduino is used to build the salt watcher control system. So the external control function is built on an Arduino board.

Based on the subsystem description, the functions of the control systems are:

1. Receive the electrode number signals.
2. Disable all the electrodes when switching.
3. Calculate and output the required 2-digit control signal.
4. Enable all the electrodes after the control signals are output correctly.

A program flowchart of the system can be defined based on the functions, as Fig 4.15 shows.

Based on the flowchart, a software diagram can be made as Fig 4.16 shows. The detailed software code is demonstrated in Appendix 5.

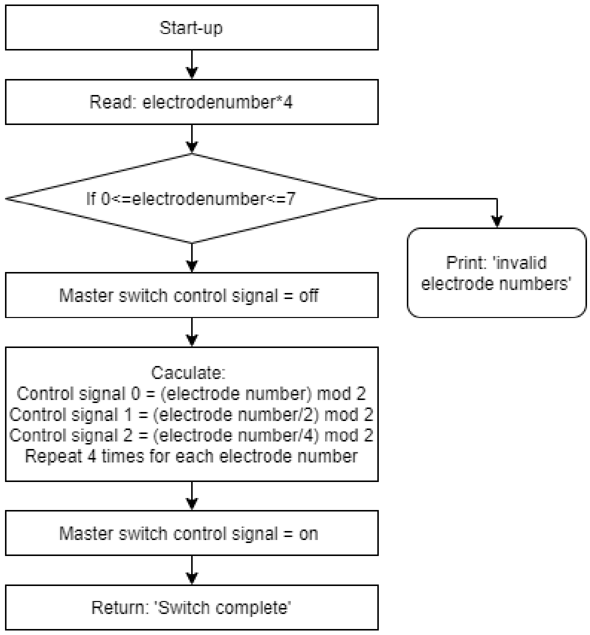


Figure 4.15 Program flowchart of an 8-electrode switch system

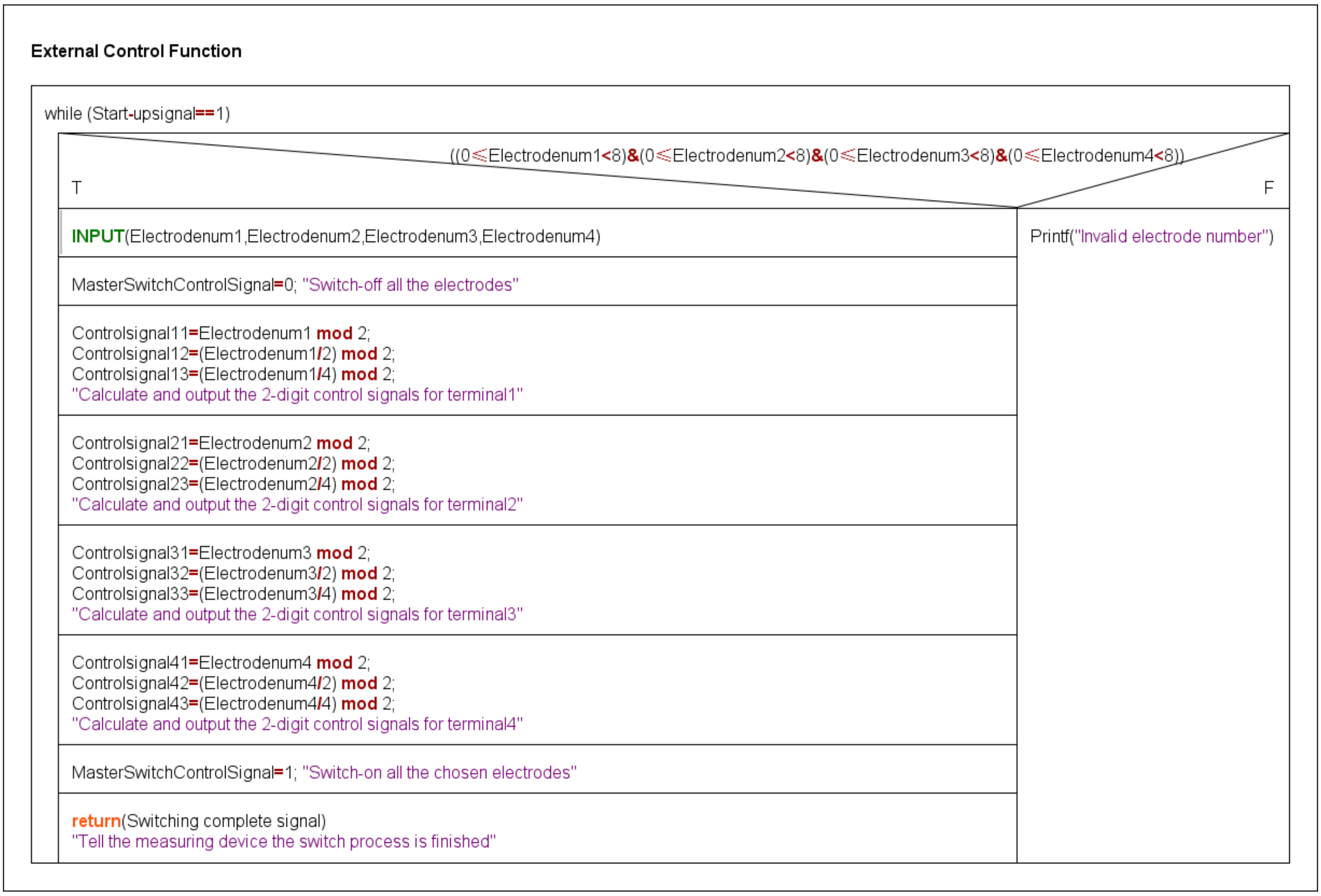


Figure 4.16 The control software diagram

4.4 COMPONENT DESIGN & TEST

In Chapter2.2 and 2.3, different types of switches that can transfer analog signal are introduced. But there is still a challenge to choose appropriate components for the specific design. In this chapter, the specific characteristics to be tested will be determined to choose the suitable components for the designed system.

The tested characteristics are chosen based on an instruction document (Analog Devices, 2011) and the specific requirements on this system from the previous design. The chosen characteristics and the reason why they are chosen are listed in table 4-8 below.

Table 4-8 Determination of the tested characteristics

Tested characteristics	Explanation of the characteristics and why it is chosen
R_{on} average	The average value of the on resistance. This value demonstrates at what extent the switch will influence the measuring result.
R_{on} flatness	The changing range of the on resistance value. This value demonstrates how unstable is the influences of the switch on the measuring result.
Signal distortion	The wave changes between the input signal and output signal. This value demonstrates the influence of the switch on the AC analog signal waveform which will be used in the measuring device.
Cost	The cost of the component. Considering the large amount requirement, cost can be an important characteristic of the switch.
Switching lifetime	Value of how many times of switching the component can process. This value demonstrates the limitation for the component switching times.
Storage lifetime	Value of how long the component can be stored and keep workable. This value demonstrates if the component is possible to be left in the system not used for a long period between two measurements.
Power consumption	The driving power of the switch. This value demonstrates how much power will the switch taken during measuring.
Switch time	The value of how long the component needs to take one switching process. It demonstrates how rapid the switch process can be.

3 types of switches are chosen to be tested: reed relay, soli-state relay and analog switch. However, among the 3 chosen types of switches that is capable for analog signal transfer,

there are still thousands of choices on the market. The components that are chosen to represent each switch type to be tested are based on these requirements:

1. DIP packaged: The building of the test platform requires high flexibility, DIP packaged products can be easily plugged in and out and also easily soldered, which gives the most flexibility when testing.

2. Best seller on online component suppliers: Considering the possible large number of components for the final product, it is important to have a stable and high-quality supplier for the components. Choosing the best seller on online component suppliers can ensure the enough supply of the chosen components in the future.

3. Low on resistance: On resistance is one of the most important characteristics of a switch that influences the transferred analog signal.

4. Reasonable supply voltage: The final product will not contain a huge power supply, so the supply voltage range is restricted to +-15V.

Based on these requirements, 3 different components that represent each type of the switch are chosen. TQ2-L2-5VDC is the chosen signal relay. LCC120 is the chosen solid-state relay. MAX319CPA is the chosen analog switch. Official datasheets of the three chosen components are given in appendix 6.

It is discussed in Chapter 2.2 that multiplexer is also an optional solution for this switch system. There are two options: logic and analog multiplexer.

Logic multiplexers can be used to replace the logic switch circuit design. Theoretically, it works as same as the switch circuit subsystem. Fig 4.17 shows a structure of 32:1 multiplexer. However, there is no available DIP-packaged logic multiplexer on the market. So it is not chosen to build the designed system, but as an option for further product that may be designed on a PCB board and capable for other types like SOIC packaged components.

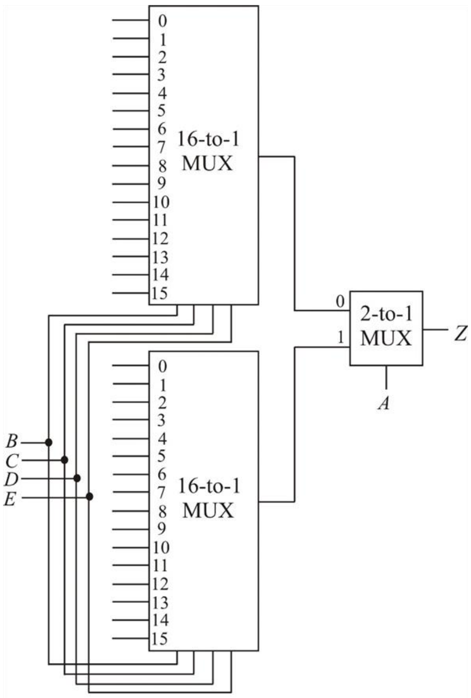


Figure 4.17 The basic structure of a 32:1 multiplexer (Charles H. Roth, 2013)

The principle of an analog multiplexer is an integrated logic multiplexer with a set of analog switches, so the working principle is basically the same with the bungalow design. On the market, the lowest on resistance of available DIP-packaged analog multiplexers is 200Ω, which is much higher than the chosen switches. So analog multiplexer is not chosen to build the prototype.

After the components are chosen and the characteristics to be tested are determined, a test plan is given for the components. Appendix 7 gives detailed test plan for the components.

The components are tested on a soldered platform. Therefore, the influence of the resistance of the connecting circuit is minimized. Fig 4.18 demonstrates the test platform of the components.

Following the test plan, a thorough data of all the tested characteristics of each component is given. Based on the test results, a scoring list for the components is made, as table 4-9 below shows.

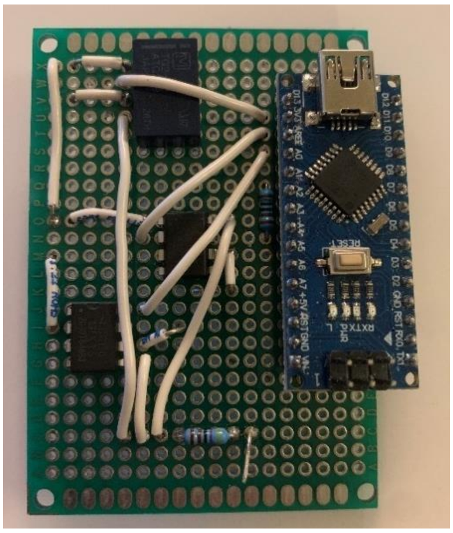


Figure 4.18 The testing platform for the conponents

*Higher score indicates better performance.
*The specific test result of each characteristic is given in the brackets.
*Cost is estimated based on SOIC packaged components, due to its significant lower price and better performance compared with the DIP packaged components.

Table 4-9 Scoring list of the chosen components

Characteristics	**Signal Relay(TQ2-L2)**	**Solid Relay(LCC120)**	**Analog Switch(MAX319)**
R_{on} average	3 (nearly 0 Ω)	2 (12 Ω)	2 (23 Ω)
R_{on} flatness	3 (nearly 0 Ω)	2 (2.4 Ω)	3 (0.8 Ω)
Signal distortion	3 (no distortion)	2 (stable distortion)	2 (stable distortion)
Cost	1 (2euro/channel)	1 (2.5euro/channel)	3 (0.4euro/channel)
Switching lifetime	2 (10^5)	3 (no limit)	3 (no limit)
Storage lifetime	Not clear	Not clear	Not clear
Power consumption	2 (200mW)	3 (100mW)	2 (200mW)
Switch time	1 (5ms)	2 (1ms)	3 (70ns)
Total score	16	15	18

Detailed test results of the components and calculation can be found in appendix 8. The R_{on} average is calculated based on the changing injected DC current and voltage measured on the switch. R_{on} flatness is the difference between the maximum measured R_{on} value and the minimum value. Power supply is calculated based on the supply voltage and current.

According to the scoring list of the chosen components, the signal relay has a high performance on transferring analog signal, The Solid relay performed the worst because of the noticeable on resistance and the worst R_{on} flatness. The analog switch also has a noticeable on resistance, but it barely changes with the changing input voltage and current, so it should be much easier to eliminate that stable influence in the measurement. Fig 4.13 shows the R_{on} change of the 3 components.

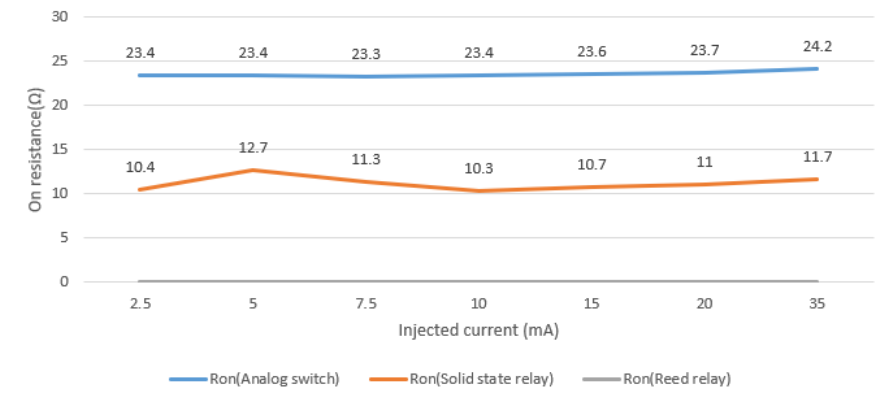


Figure 4.19 The R_{on} change with different injected current

The analog switch also cost much less than the other two types, which is quite important for the salt watcher system that may contain hundreds of switches.

As a conclusion, based on the test result and discussion, analog switch shows a better performance considering all the tested characteristics. So it is considered as the most suitable component for the switch system and is chosen to build the final prototype.

For the external control function, Arduino is used as the hardware component, which is determined by the measuring device project.

4.5 SUBSYSTEM TEST & SYSTEM TEST

After the components are chosen, the subsystems are built and tested following the subsystem design and test plans. Fig 4.14 shows the built subsystems. The logic circuit is built on bread boards considering that the logic signal will not be influenced by the connecting resistance of bread boards. The parts that transfer analog signal are soldered to avoid this influence. An assembly plan is made based on the system design and the chosen components. Appendix 9 gives the detailed assembly plan of the system.

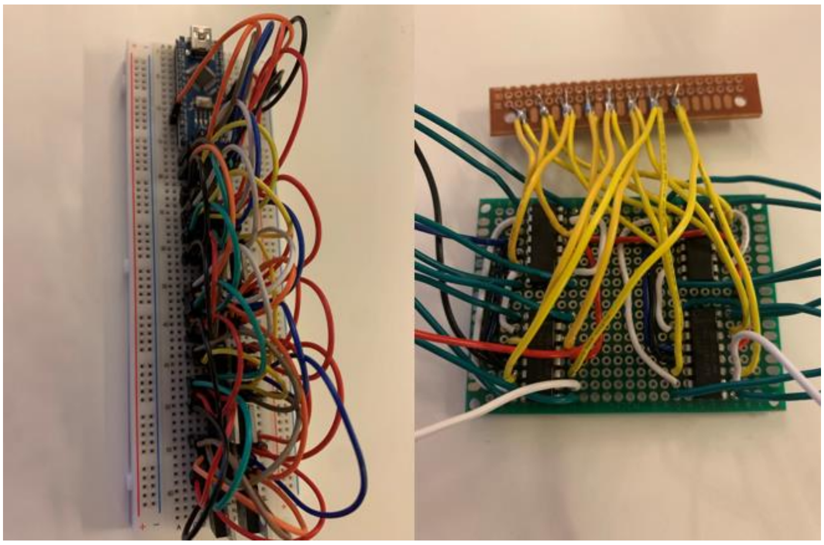


Figure 4.20 The built subsystems

The control function subsystem is tested. The test result shows it works as expected. Since there is no difference to test the switch circuit subsystem with an external logic supply or the control function subsystem, it is decided that the subsystems is directly integrated to the prototype and tested following the system test plan in Appendix 3. Fig 4.15 shows the prototype test platform.

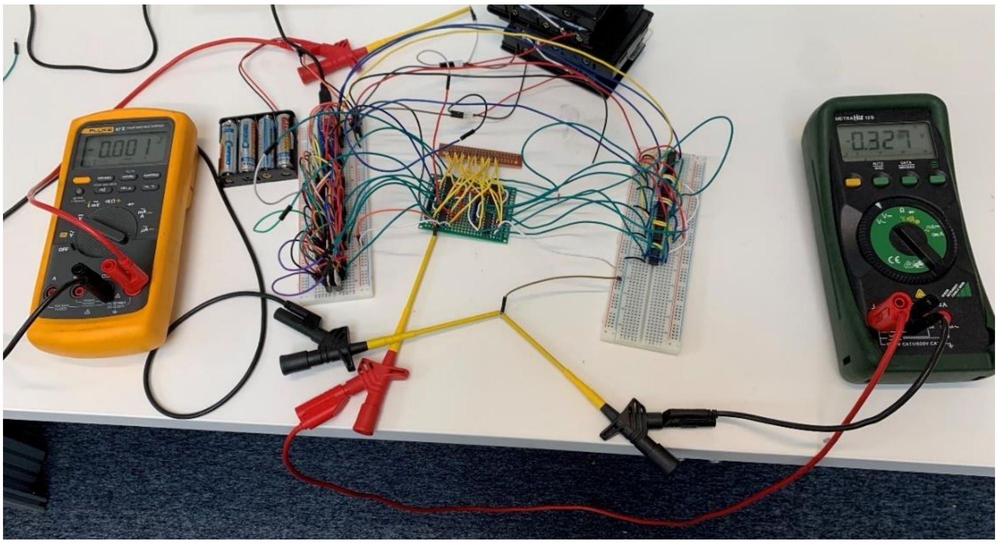


Figure 4.21 Test on the prototype

The prototype, as designed, is capable to connect 4 measuring terminals to the chosen 4 electrodes within 8 electrodes. The switch process is controlled by the input electrode numbers in the Arduino function.

It is tested separately on both the performance of the 2 current injection terminals and the performance of the 2 voltage measuring terminals. The separate tests give a clear view of the influences of the designed switch system on the measurement.

For the current injection test, it is important how the R_{on} change with different injected current. The lower and more stable R_{on} is, the easier the salt watcher can eliminate the influence of R_{on} on the measured soil resistance.

The R_{on} change of the prototype with different injected current is shown in Fig 4.16.

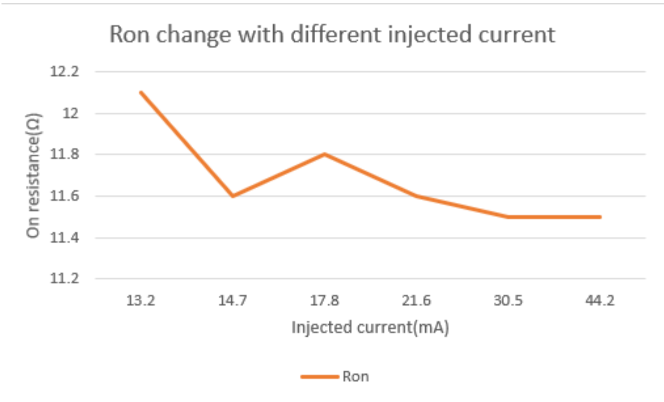


Figure 4.22 R_{on} change of prototype with different injected current

For the voltage measuring test, the focus is on the accuracy of measurement. The prototype is injected a stable current and the measuring terminals are switched between different electrodes to test the influence on accuracy of measurement using the prototype.

The tested characteristic of the prototype is shown in table 4-10.

Table 4-10 The test result of the prototype

Characteristics	**Result on current injection terminals**	**Result on voltage measuring terminals**
R_{on} average	11.67 Ω	/
R_{on} flatness	0.60 Ω	/
Signal distortion	Low	Low (High frequency noise)
Measurement error	/	Average 1.09% Maximum 3.6%
Cost	3 euro/channel	
Switch time	Less than 1ms	

The detailed test result of the prototype can be found in Appendix 12.

Based on the test results of the prototype, a checklist of the requirements is made to check whether the requirements are meet or not, as table 4-11 shows.

Table 4-11 Checklist of the requirements

No.	Requirements	Results	Checklist
1.	The electrode switch will connect between a measuring device with 4 terminals and an electrode cable with 26 electrodes.	The prototype can connect between 4 measuring terminals and 8 electrodes. Theoretically, the design also works with 26 electrodes.	✔
2.	The electrode switch can receive a control signal of information of the chosen terminal and the chosen electrode that will be connected to the terminal.	The external control function can receive a control signal of information of the chosen terminal and electrode to be connected.	✔
3.	The electrode switch should send an error signal to the user if the chosen electrodes or terminal does not exist.	The software design of the external control function can send an error signal of wrong input.	✔
4.	The electrode switch should connect each of the 4 terminals on the measuring device to each chosen electrode.	The prototype can connect each of the 4 terminals on the measuring device to each chosen electrode.	✔
5.	The electrode switch should disconnect the measuring device and the electrode cable when it is switching from one 4-electrode combination to another.	The prototype will disconnect the measuring device and the electrode cable when it is switching from one 4-electrode combination to another.	✔
6.	The electrode switch should send a signal to the measuring system when the switching process is finished.	The external control function will send a signal to the measuring system when the switching process is finished.	✔
7.	The unchosen electrodes should not be connected to the terminals of the measuring device.	The unchosen electrodes are not connected to the terminals of the measuring device.	✔
8.	The switch system should ensure the salinity measurement can be taken via the connection to the chosen electrodes.	The test result shows no problem in current injection. The accuracy of measuring is also within a reasonable extent.	✔
9.	The electrode switch is compliable with the measuring system designed by another project which is supposed to work as the same way as chauvin-arnoux-c-a-6460-earth-resistance-tester.	The external control function is the software integrated into the measuring system. The test on the system shows that it works well with the required output and input signals from the measuring device project. The integration is theoretically confirmed.	✔
10.	The electrode switch is compliable with the measuring cable designed by the electrode cable project group.	The electrodes with resistance between each other simulate the real electrode cable. The resistance tested in within the range of the earth resistance estimated by the electrode cable team. The switch system is compliable with the electrode cable.	✔

5 DISCUSSION

The results of the project and the method that is used are discussed in this chapter.

5.1 RESULTS DISCUSSION

Components: The comparison list of different types of switches gives a clear image of the performance and why the component is chosen. There is a concern on the switching and storage lifetime of the 3 components. However, there is not enough time for this project to test the lifetime of the components, so the data is directly taken from the datasheet. For the storage lifetime, there is little existing research on the influence of long-time storage on the switch performance, and it is also not possible to be tested during this project.

Another consideration is that there is a high chance that the eventual built switch system of the salt watcher will use SOIC packaged components which have much better performance and cheaper than the DIP packaged ones. There is a chance of It will eliminate the difference on the on resistance of the 3 types and make the analog switch even standing out.

Subsystems: Based on the test result of the control software and the switch circuit, they both work as expected in the test plan.

System (Prototype): Although the salt watcher contains 26 electrodes, considering the time limitation of this project, the prototype only contains 8 electrodes. Which should not be a problem for confirming the concept of the design. Because the chosen design has a flat structure and theoretically will not show any performance difference when changing the electrode number.

When the prototype is tested on the measuring performance, the test result shows that it works as expected both in current injection and voltage measurement. When used to inject current, the signal distortion caused by on resistance is quite low and stable and can be easily eliminated by calculation. When used to measure voltage, the measuring accuracy is quite high and stable.

Although multiplexer is not chosen as a component in this project, there is a choice that for the final product of the automatic switch to use logic multiplexers to replace the present logic circuit (which has the same function). There is SOIC packaged logic multiplexer on the market that is suitable for PCB soldering. For the 32 electrodes system, using multiplexer can significantly reduce the scale of the system and reduce the cost.

The test result shows that the prototype is compliable with the measuring device and electrode cable based on the simulated test platform. By the end of the project, the prototype of the electrode cable is not finished so the integration can not be tested in real yet.

Based on the test results, the tested prototype meets all the requirement.

5.2 METHOD DISCUSSION

V-model, as the chosen design method for the project, has played its own role successfully during the whole project. The convincing result of the final prototype gives a strong evidence that V-model is sufficient in delivering feasible system design based on a structured V circle. The requirements of the system are well analyzed and following the whole design process. The well-designed test plans ensured that the final products would meet all the requirements if the tests passed. The whole design process is systematical, logical and efficient.

6 CONCLUSSION & RECOMMENDATIONS

The conclusion of the project and recommendation for further research is given in this chapter.

6.1 CONCLUSION

The aim of the project is a feasible design for the automatic switch system of salt watcher which can connect 4 terminals from the measuring device to any possible combination of 4 electrodes within 26 underground measured electrodes, switch between different 4-electrode sets following control signals from a microcontroller and can be intergrated into the salt watcher. The 'bungalow' design, which is a switch system with logic control circuit and a flat layer of SPST-NO switches, is chosen as the basement of the switch system. The prototype built on the 'bungalow' design is tested and the results indicates that the designed system meet the requirements:

The system is capable to connect 4 terminals to 4 chosen electrodes within 26 electrodes following the control signals from Arduino, works well in current injection and voltage measurement and compliable with the measuring device and electrode cable systems.

6.2 RECOMMENDATIONS

- The storage lifetime of the components are not tested in this project due to the fact that not much research has been made of the storage influence on the switch performance. It can be a research during the real usage of the automatic switch system.
- Further test on the same type of components with different package is recommended. A designed PCB board with SOIC packaged switch can significantly reduce the cost and improve the switch performance.
- The caculation shows the final switch system still contains hundreds of components, which can make the system quite complicated. If the final product is built on PCB board, logic multiplexer is an option to replace the present logic circuit and reduce the scale of the system.
- The prototype only contains 8 electrodes. As mentioned in Chapter 4.3.3, theoretically the change of electrode amount will not influence the performance of the switch system. Further research on the performance with a complete product with 26 electrodes is still recommended.

- Although the measuring ability is confirmed, there is still a stable high frequency noise existing when measuring voltage. Further research on the reason of the noise is recommended. A possible solution to the noise is adding a low-path filter since the noise's frequency is much higher than the injected current signal.

- Although the integration of the 3 projects is theoretically confirmed, it is still not tested due to the process of the 3 projects is not syhchronous. Further test on the integration of 3 projects after the prototype are all finished is recommended.

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APPENDIX

APPENDIX 1 VALIDATION PLAN

Validation plan for automatic switch

Aims

The aim is to confirm the system is capable to connect 4 terminals from the measuring device to any possible combination of 4 electrodes within 26 measured electrodes and switch between different 4-electrode sets following control signals from a microcontroller.

Variables

Property	Vary and/or measure?
Start-up signal	Vary
Injected current signal	Vary
Chosen electrodes	Vary
Output digital signal	Measure
Error signal	Measure
Ready signal	Measure
Total control signal	Measure
Measured voltage signal	Measure

Testing tools

Platform: Arduino, oscilloscope

Software: Arduino IDE, Smart Scope

Methods

The steps are performed by the following contents:

1. Connect the switch system with the measuring device and measured electrodes.
2. If the switch function is called with 4 electrode number in Arduino, the system will start running.
3. If one of the 4 electrode numbers is out of range, stop the system and send back an error signal.

4. If the 4 numbers are all within range, calculate the binary number for each number.
5. If the binary numbers are being output, disconnect all the electrodes and terminals.
6. If the switch is finished, connect the electrodes.
7. If the electrodes are connected, return a ready signal.

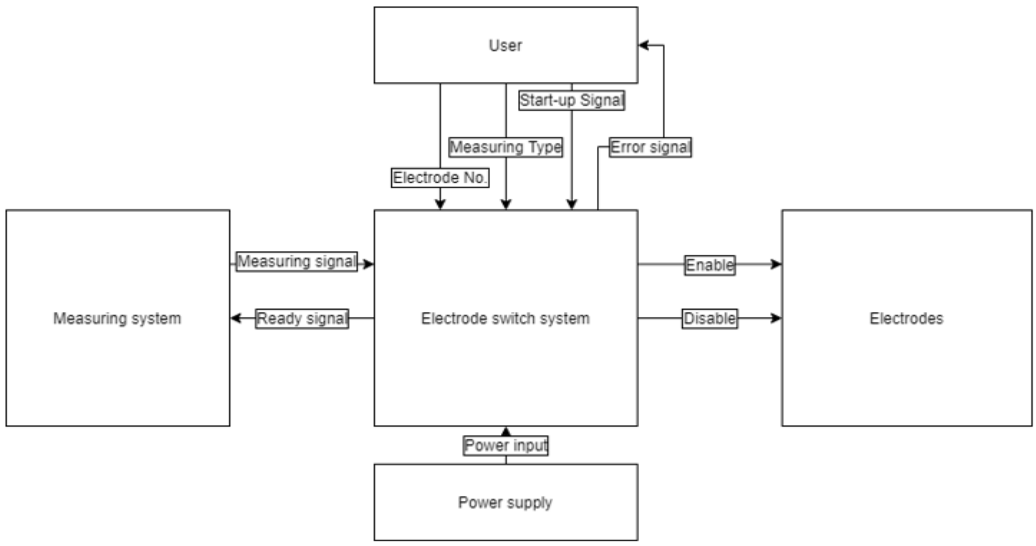
Expected results

The system should compile with the measuring device and measured electrodes. It should stop and send an error signal if wrong numbers are input. When write numbers input the all the output should be shut down when switching. After the switching only the chosen electrodes should connect to the terminals and the system should send back a ready signal.

APPENDIX 2 INTEGRATION PLAN

Integration Plan:

1. To schedule periodical meetings between different project teams to keep every project informed with the latest update of different projects.
2. To discuss on the function analysis of each system to make sure no duplicate function in different projects and after the integration of the 3 project the final product will meet the requirements of the salt watcher.
3. To discuss on the system description of each project and compare every input and output signals and hardware connections between 3 systems. Make sure the inputs and outputs from every system match the other systems.
4. To discuss on the value of the required signals and make sure the signal types and signal values all matched each other.



APPENDIX 3 SYSTEM TEST PLAN

System test plan for automatic switch

Aims

The aim is to develop system design which is capable to connect 4 terminals from the measuring device to any possible combination of 4 electrodes within 26 measured electrodes and switch between different 4-electrode sets following control signals from a microcontroller.

1. If the switch function is called with 4 electrode number in Arduino, the system will start running.
2. If one of the 4 electrode numbers is out of range, stop the system and send back an error signal.
3. If the 4 numbers are all within range, calculate the binary number for each number.
4. If the binary numbers are being output, disconnect all the electrodes and terminals.
5. If the switch is finished, connect the electrodes.
6. If the electrodes are connected, return a ready signal.

Variables

Property	Vary and/or measure?
Start-up signal	Vary
Input control signal	Vary
Injected current signal	Vary
Output voltage signal	Measure
Closed switch number	Measure
On resistance	Measure
On resistance flatness	Measure
Signal distortion	Measure

Testing tools

Platform: Arduino, oscilloscope

Software: Arduino IDE, Smart Scope

Methods

The steps are performed by the following contents:

1. Connect the platform to the PC and download the software.
2. Send a start signal with 4 electrode numbers out of range and check if the system stops and send back error signal.
3. Send a start signal with 4 electrode numbers within range and check if the system starts running.
4. Measure Every digital output to check if they are all shutdown when the switching is processing.
5. Measure the calculated digital output to check if the chosen electrode is connected.
6. Measure the other digital outputs to ensure all the other electrodes are disconnected.
7. Check if the system returns a ready signal.
8. Inject a current to the COM terminals and to measure the voltage on the electrodes to measure the current injection ability.
9. Inject a current to the electrodes and measure the voltage using the oscilloscope to observe the signal distortion when used for measuring.

Expected results

The system should stop and send an error signal if wrong numbers are input. When write numbers input the all the output should be shut down when switching. After the switching only the chosen electrodes should connect to the terminals and the system should send back a ready signal. When used as current injection Terminals, the measured voltage should be the same as the calculated value based on the on resistance and the electrode resistance value. When used as the voltage measuring terminals, the measured result should at an accuracy higher than 95% based on the calculated result following the electrode resistance value. The signal distortion should within 5% compared to the average value.

APPENDIX 4 SUBSYSTEM TEST PLAN

APPENDIX 4.1 SWITCH CIRCUIT TEST PLAN

Subsystem test plan for switch circuit

Aims

The aim is to confirm the switch ability of the designed switch circuit and to test the influence of the system to the measurement. The system should turn on the chosen switch based on the input digital control signal following the truth table.

Variables

Property	Vary and/or measure?
Input control signal	Vary
Injected current signal	Vary
Output voltage signal	Measure
Closed switch number	Measure
On resistance	Measure
On resistance flatness	Measure
Signal distortion	Measure

Testing tools

Platform: Logic input supply, oscilloscope, multimeter

Software: Smart Scope

Methods

The steps are performed by the following contents:

1. Connect a logic signal supply to the circuit.
2. Set the logic control signal following the truth table.
3. Measure if the chosen switch is closed and unchosen switches are opened based on the truth table.
4. Inject a current to the COM terminals and to measure the voltage on the electrodes to measure the current injection ability.

5. Inject a current to the electrodes and measure the voltage using the oscilloscope to observe the signal distortion when used for measuring.

Expected results

The chosen switch should be closed following control signal and the truth table. The unchosen switches should be opened. The injected current should be as the same value with measured on the electrodes. The measured voltage should follow the proportion of the resistance between the injected electrodes and the electrodes COM terminals connect.

APPENDIX 4.2 MASTER SWITCH TEST PLAN

Subsystem test plan for master switch

Aims

The aim is to confirm the ability of the master switch subsystem to enable and disable all the switches and electrodes.

Variables

Property	Vary and/or measure?
Master switch control signal	Vary
Digital control signal of each switch	Measure
Opened switch	Measure

Testing tools

Platform: Logic input supply, multimeter

Methods

The steps are performed by the following contents:

1. Connect a logic signal supply to the circuit.
2. Set the master switch control signal value to low.
3. Change control signal of all the switches following the truth table of the switch circuit and check if all the switches are disabled.
4. Set the master switch control signal value to high.

5. Change control signal of all the switches following the truth table of the switch circuit and check if all the switches are enabled.

Expected results

When the master switch control signal is set low, all the switches should be disabled and no matter what the other control signals change no electrodes will be connected to the terminals. When the master switch control signal is set high, all the switches should be enabled and set on following the input control signal and the truth table.

APPENDIX 4.3 EXTERNAL CONTROL SYSTEM TEST PLAN

Subsystem test plan for external control system

Aims

The aim is to confirm the functions of the designed control program for the switch system.

1. The program is called with four electrode numbers.
2. If the electrode numbers are invalid, the function will return an error signal.
3. If the electrode numbers are valid, the required binary control signal will be calculated and output following the truth table.
4. When the switch is processing, the master switch control signal will keep low to disable all the electrodes.
5. After all the control signals are set to required value, the master switch control signal will be set high to enable the chosen electrodes.

Variables

Property	Vary and/or measure?
Input electrode numbers	Vary
Error signal	Measure
Master switch control signal	Measure
Output control signal	Measure

Testing tools

Platform: Arduino, multimeter

Software: Arduino IDE

Methods

The steps are performed by the following contents:

1. Run the program on the Arduino board.
2. Input a set of invalid electrode numbers and check if the program stopped and returned error message.
3. Input a set of valid electrode numbers.
4. Check if the master switch control signal keeps low when the control signal is changing.
5. Check if the desired control signals are output following the input electrode number and the truth table.

Expected results

The program should send 'Invalid electrode numbers' when invalid numbers are input. The master switch control signal will keep low when the switching is processing. The control signals should follow the input electrode number.

APPENDIX 5 CONTROL SYSTEM PROGRAM

(Platform: Arduino IDE)

```
int masterswitch = 2;
int controlsignalA[] = {3,4,5};
int controlsignalB[] = {6,7,8};
int controlsignalC[] = {9,10,11};
int controlsignalD[] = {12,13,14};

void setup()
{
   pinMode(2,OUTPUT);
   pinMode(3,OUTPUT);
   pinMode(4,OUTPUT);
   pinMode(5,OUTPUT);
   pinMode(6,OUTPUT);
   pinMode(7,OUTPUT);
   pinMode(8,OUTPUT);
   pinMode(9,OUTPUT);
   pinMode(10,OUTPUT);
   pinMode(11,OUTPUT);
   pinMode(12,OUTPUT);
   pinMode(13,OUTPUT);
   pinMode(14,OUTPUT);
   digitalWrite(2,LOW);
}

void Connect_electrodes(int electrodeA,int electrodeB,int electrodeC, int electrodeD)
{
   int i=0;
   if((0<=electrodeA<8)&(0<=electrodeB<8)&(0<=electrodeC<8)&(0<=electrodeD<8))
   {
      digitalWrite(masterswitch,LOW);
      for(i=0;i++;i<3)
      {
         if((electrodeA%2)==0)
         {
            digitalWrite(controlsignalA[2-i],LOW);
         }
         else
         {
            digitalWrite(controlsignalA[2-i],HIGH);
```

```
        }
        electrodeA = electrodeA/2;
        if((electrodeB%2)==0)
        {
          digitalWrite(controlsignalB[2-i],LOW);
        }
        else
        {
          digitalWrite(controlsignalB[2-i],HIGH);
        }
        if((electrodeC%2)==0)
        {
          digitalWrite(controlsignalC[2-i],LOW);
        }
        else
        {
          digitalWrite(controlsignalC[2-i],HIGH);
        }
        electrodeC = electrodeC/2;
        if((electrodeD%2)==0)
        {
          digitalWrite(controlsignalD[2-i],LOW);
        }
        else
        {
          digitalWrite(controlsignalD[2-i],HIGH);
        }
        electrodeD = electrodeD/2;
      }
      digitalWrite(masterswitch,HIGH);
    }
    else
    {
      Serial.print("Invalid electrode number!");
    }
}

void loop()
{
    Connect_electrodes(0,1,2,3);
}
```

APPENDIX 6 DATASHEETS OF THE CHOSEN COMPONENTS

Analog switch: MAX319CPA

19-0185; Rev 1; 11/94

MAXIM

Precision, CMOS Analog Switches

MAX317/MAX318/MAX319

General Description

The MAX317/MAX318/MAX319 are precision, CMOS, monolithic analog switches. The single-pole single-throw (SPST) MAX317 is normally closed (NC), the SPST MAX318 is normally open (NO), and the single-pole double-throw (SPDT) MAX319 has one normally open and one normally closed switch. All three parts offer low on resistance (less than 35Ω), guaranteed to match within 2Ω between channels and to remain flat over the analog signal range (Δ3Ω max). They also offer low leakage (less than 250pA at +25°C and less than 6nA at +85°C) and fast switching (turn-on time less than 175ns and turn-off time less than 145ns).

The MAX317/MAX318/MAX319 are fabricated with Maxim's new improved silicon-gate process. Design improvements guarantee extremely low charge injection (10pC), low power consumption (35μW), and electrostatic discharge (ESD) greater than ±2000V. The 44V maximum breakdown voltage allows rail-to-rail analog signal handling capability.

Applications

- Sample-and-Hold Circuits
- Guidance and Control Systems
- Heads-Up Displays
- Test Equipment
- Military Radios
- Communications Systems
- Battery-Powered Systems
- PBX, PABX

Features

- ♦ Low On Resistance <20Ω Typical (35Ω Max)
- ♦ Guaranteed Matched On Resistance Between Channels <2Ω
- ♦ Guaranteed Flat On Resistance over Analog Signal Range Δ3Ω Max
- ♦ Guaranteed Charge Injection <10pC
- ♦ Guaranteed Off-Channel Leakage <6nA at +85°C
- ♦ ESD Guaranteed > 2000V per Method 3015.7
- ♦ Single-Supply Operation (+10V to +30V) Bipolar-Supply Operation (±4.5V to ±20V)
- ♦ TTL-/CMOS-Logic Compatible
- ♦ Rail-to-Rail Analog Signal Handling Capability

Ordering Information

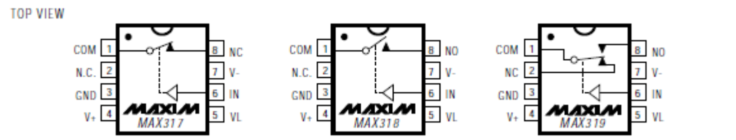
PART	TEMP. RANGE	PIN-PACKAGE
MAX317CPA	0°C to +70°C	8 Plastic DIP
MAX317CSA	0°C to +70°C	8 SO
MAX317CJA	0°C to +70°C	8 CERDIP
MAX317C/D	0°C to +70°C	Dice*
MAX317EPA	-40°C to +85°C	8 Plastic DIP
MAX317ESA	-40°C to +85°C	8 SO
MAX317EJA	-40°C to +85°C	8 CERDIP
MAX317MJA	-55°C to +125°C	8 CERDIP

Ordering Information continued on last page.

* *Contact factory for dice specifications.*

Pin Configurations/Functional Diagrams/Truth Tables

TOP VIEW



MAX317	
LOGIC	SWITCH
0	ON
1	OFF

MAX318	
LOGIC	SWITCH
0	OFF
1	ON

MAX319		
LOGIC	NC	NO
0	ON	OFF
1	OFF	ON

N.C. = No Connect
NC = Normally Closed

SWITCHES SHOWN FOR LOGIC "0" INPUT

MAXIM — Maxim Integrated Products 1

Call toll free 1-800-998-8800 for free samples or literature.

Precision, CMOS Analog Switches

MAX317/MAX318/MAX319

ABSOLUTE MAXIMUM RATINGS

Voltage Referenced to V-
V+ ....+44V
GND ....+25V
V_L ....(GND - 0.3V) to (V+ + 0.3V)
IN, COM, NC, NO..................(V- - 2V) to (V+ + 2V) or 30mA, whichever occurs first
Continuous Current (any terminal) 30mA
Peak Current, NC, NO, COM
(pulsed at 1ms, 10% duty cycle max)..........................100mA
ESD ....±2000V

Continuous Power Dissipation (T_A = +70°C) (Note 1)
Plastic DIP (derate 9.09mW/°C above +70°C)............727mW
SO (derate 5.88mW/°C above +70°C) 471mW
CERDIP (derate 8.00mW/°C above +70°C) 640mW
Operating Temperature Ranges:
MAX31_C_ _...0°C to +70°C
MAX31_E_ _..-40°C to +85°C
MAX31_MJA...-55°C to +125°C
Storage Temperature Range ....-55°C to +150°C
Lead Temperature (soldering, 10sec) ....+300°C

Note 1: All leads are soldered or welded to PC board.

Stresses beyond those listed under "Absolute Maximum Ratings" may cause permanent damage to the device. These are stress ratings only, and functional operation of the device at these or any other conditions beyond those indicated in the operational sections of the specifications is not implied. Exposure to absolute maximum rating conditions for extended periods may affect device reliability.

ELECTRICAL CHARACTERISTICS — Dual Supplies

(V+ = 15V, V- = -15V, V_L = 5V, GND = 0V, V_{INL} = 0.8V, V_{INH} = 2.4V, T_A = T_{MIN} to T_{MAX}, unless otherwise noted.)

PARAMETER	SYMBOL	CONDITIONS		TEMP.		MIN	TYP (Note 2)	MAX	UNITS
Analog-Signal Range	V_{COM}, V_{NO}, V_{NC}	(Note 3)				-15		15	V
On Resistance	R_{ON}	V_{COM} = ±12.5V, $I_{(NC\ or\ NO)}$ = -10mA, V+ = 13.5V, V- = -13.5V		T_A = +25°C	C, E		20	35	Ω
					M			30	
				T_A = T_{MIN} to T_{MAX}				45	
On Resistance Match Between Channels (Note 4)	R_{ON}	$I_{(NC\ OR\ NO)}$ = -10mA, V_{COM} = 10V or -10V, V+ = 15V, V- = -15V		T_A = +25°C				2	Ω
				T_A = T_{MIN} to T_{MAX}				3	
On Resistance Flatness (Note 4)	R_{ON}	$I_{(NC\ OR\ NO)}$ = -10mA, V_{COM} = 5V or -5V, V+ = 15V, V- = -15V		T_A = +25°C				3	Ω
				T_A = T_{MIN} to T_{MAX}				5	
NO or NC Off Leakage Current	$I_{NC(OFF)}$ or $I_{NO(OFF)}$	V+ = 16.5V, V- = -16.5V, V_{COM} = ±15.5V, V_{NC} or V_{NO} = ±15.5V		T_A = +25°C		-0.25		0.25	nA
				C, E		-6		6	
				M		-20		20	
COM Off Leakage Current	$I_{COM(OFF)}$	V+ = 16.5V, V- = -16.5V, V_{COM} = ±15.5V, V_{NC} or V_{NO} = ∓15.5V	MAX317, MAX318	T_A = +25°C		-0.25	-0.1	0.25	nA
				C, E		-6		6	
				M		-20		20	
			MAX319	T_A = +25°C		-0.75	-0.1	0.75	
				C, E		-10		10	
				M		-60		60	
COM On Leakage Current	$I_{COM(ON)}$	V+ = 16.5V, V- = -16.5V, V_{NC} or V_{NO} = V_D = ±15.5V	MAX317, MAX318	T_A = +25°C		-0.4		0.4	nA
				C, E		-10		10	
				M		-40		40	
			MAX319	T_A = +25°C		-0.75		0.75	
				C, E		-10		10	
				M		-60		60	

2 MAXIM

Precision, CMOS Analog Switches

MAX317/MAX318/MAX319

ELECTRICAL CHARACTERISTICS — Dual Supplies (continued)

(V+ = 15V, V- = -15V, V_L = 5V, GND = 0V, V_{INL} = 0.8V, V_{INH} = 2.4V, T_A = T_{MIN} to T_{MAX}, unless otherwise noted.)

PARAMETER	SYMBOL	CONDITIONS	TEMP.	MIN	TYP (Note 2)	MAX	UNITS
LOGIC INPUT							
Logic Input Current (Input Voltage High)	I_{IH}	V_{IN} = 2.4V		-0.5	0.005	0.5	µA
Logic Input Current (Input Voltage Low)	I_{IL}	V_{IN} = 0.8V		-0.5	0.005	0.5	µA
DYNAMIC							
Turn-On Time	t_{ON}	MAX317, MAX318, Figure 2, V_{COM} = ±10V	T_A = +25°C		100	175	ns
			T_A = T_{MIN} to T_{MAX}			250	
Turn-Off Time	t_{OFF}	MAX317, MAX318, Figure 2, V_{COM} = ±10V	T_A = +25°C		60	145	ns
			T_A = T_{MIN} to T_{MAX}			210	
Transition Time	t_{TRANS}	MAX319, Figure 3, V_{NO} = ±10V, V_{NC} = ±10V	T_A = +25°C			175	ns
			T_A = T_{MIN} to T_{MAX}			250	
Break-Before-Make Interval	t_D	MAX319, Figure 4, V_{NO} = V_{NC} = ±10V	T_A = +25°C	5	13		ns
Charge Injection	Q	V_{GEN} = 0V, Figure 5	T_A = +25°C		3	10	pC
Off Isolation (Note 5)	OIRR	R_L = 50Ω, C_L = 5pF, f = 1MHz, Figure 7	T_A = +25°C		68		dB
Crosstalk (Note 6)		R_L = 50Ω, C_L = 5pF, f = 1MHz, Figure 8	T_A = +25°C		85		dB
COM Off Capacitance	$C_{COM(OFF)}$	V_{COM} = 0V, f = 1MHz, Figure 8	T_A = +25°C		8		pF
Off Capacitance NC or NO	$C_{(OFF)}$	V_{COM} = 0V, f = 1MHz, Figure 8	T_A = +25°C		8		pF
Channel-On Capacitance COM Terminal	$C_{COM(ON)}$	V_S = 0V, f = 1MHz, Figure 9 — MAX317, MAX318	T_A = +25°C		30		pF
		V_S = 0V, f = 1MHz, Figure 9 — MAX319			35		
SUPPLY							
Positive Supply Current	I+	V_{IN} = 0V or 5V, V+ = 16.5V, V- = -16.5V	T_A = +25°C	-1	0.0001	1	µA
			T_A = T_{MIN} to T_{MAX}	-5		5	
Negative Supply Current	I-	V_{IN} = 0V or 5V, V+ = 16.5V, V- = -16.5V	T_A = +25°C	-1	-0.0001	1	µA
			T_A = T_{MIN} to T_{MAX}	-5		5	
Logic Supply Current	I_L	V_{IN} = 0V or 5V, V+ = 16.5V, V- = -16.5V	T_A = +25°C	-1	0.0001	1	µA
			T_A = T_{MIN} to T_{MAX}	-5		5	
Ground Current	I_{GND}	V_{IN} = 0V or 5V, V+ = 16.5V, V- = -16.5V	T_A = +25°C	-1	-0.0001	1	µA
			T_A = T_{MIN} to T_{MAX}	-5		5	

Precision, CMOS Analog Switches

MAX317/MAX318/MAX319

ELECTRICAL CHARACTERISTICS — Single Supply

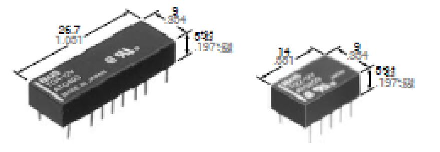
($V+ = 12V$, $V- = 0V$, $V_L = 5V$, $GND = 0V$, $V_{INH} = 2.4V$, $V_{INL} = 0.8V$, $T_A = +25°C$, unless otherwise noted.)

PARAMETER	SYMBOL	CONDITIONS	MIN	TYP (Note 2)	MAX	UNITS
SWITCH						
Analog-Signal Range	V_{COM}, V_{NO}, V_{NC}	(Note 3)	0		12	V
Drain-Source On Resistance	$R_{(ON)}$	$I_{(NC\ or\ NO)} = -10mA$, $V_{COM} = 3.8V$, $V+ = 10.8V$		40	100	Ω
DYNAMIC						
Turn-On Time	t_{ON}	$V_{COM} = 8V$, Figure 2		110		ns
Turn-Off Time	t_{OFF}	$V_{COM} = 8V$, Figure 2		40		ns
Break-Before-Make Time Delay	t_D	MAX319, $R_L = 1000Ω$, $C_L = 35pF$, Figure 4		60		ns
Charge Injection	Q	$C_L = 10nF$, $V_{GEN} = 0V$, $R_{GEN} = 0V$, Figure 5		2	10	pC
SUPPLY						
Positive Supply Current	I+	$V+ = 13.2V$, all channels on or off, $V_{IN} = 0V$ or $5V$, $V_L = 5.25V$		0.0001		µA
Negative Supply Current	I-	$V+ = 13.2V$, all channels on or off, $V_{IN} = 0V$ or $5V$, $V_L = 5.25V$		0.0001		µA
Logic Supply Current	I_L	$V_L = 5.25V$, all channels on or off, $V_{IN} = 0V$ or $5V$		0.0001		µA
Ground Current	I_{GND}	$V_L = 5.25V$, all channels on or off, $V_{IN} = 0V$ or $5V$		-0.0001		µA

Note 2: Typical values are for **design aid only**, not guaranteed, not subject to production testing.
Note 3: Guaranteed by design.
Note 4: On resistance match between channels and flatness are guaranteed only with bipolar-supply operation.
Note 5: Off Isolation = $20\log_{10}\left(\frac{V_{COM}}{V_{NC} \text{ or } V_{NO}}\right)$, V_{COM} = output, V_{NC} or V_{NO} = input to off switch.
Note 6: Between any two switches.

signal relay: TQ2-L2-5VDC

Panasonic ideas for life	LOW PROFILE 2 FORM C RELAY	TQ RELAYS



FEATURES

- **High sensitivity:**
  2 Form C: 140 mW power consumption (single side stable type)
  4 Form C: 280 mW power consumption (single side stable type)
- **Surge voltage withstand: 1500 V FCC Part 68**
- **Sealed construction allows automatic washing**
- **Self-clinching terminal also available**
- **M.B.B. contact types available**

SPECIFICATIONS

Contact

			Standard (B.B.M) type		M.B.B.type
Arrangement			2 Form C	4 Form C	2 Form D
Initial contact resistance, max. (By voltage drop 6 V DC 1A)			50 mΩ		
Contact material			Gold-clad silver		
Rating	Nominal switching capacity (resistive load)		1 A 30 V DC 0.5 A 125 V AC		1 A 30 V DC
	Max. switching power (resistive load)		30 W, 62.5 V A		30 W
	Max. switching voltage		110 V DC, 125 V AC		110 V DC
	Max. switching current		1 A		
	Min. switching capacity *1		10 μA 10 mV DC		
Nominal operating power	Single side stable		140 mW (3 to 12 V DC) 200 mW (24 V DC) 300 mW (48 V DC)	280 mW (3 to 24 V DC) 400 mW (48 V DC)	200 mW
	1 coil latching		100 mW (3 to 12 V DC) 150 mW (24 V DC)	200 mW	—
	2 coil latching		200 mW (3 to 12 V DC) 300 mW (24 V DC)	400 mW	—
Expected life (min. operations)	Mechanical (at 180 cpm)		10^8		10^7
	Electrical (at 20 cpm) (1 A 30 V DC resistive)	1 A 30 V DC resistive	2×10^5		10^5
		0.5 A 125 V AC resistive	10^5		—

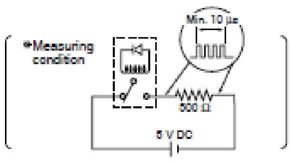
Note:
*1 This value can change due to the switching frequency, environmental conditions, and desired reliability level, therefore it is recommended to check this with the actual load. (SX relays are available for low level load switching [10 μA 1 mV DC – 10 mA 10 V DC])

Remarks
* Specifications will vary with foreign standards certification ratings.
*1 Measurement at same location as "Initial breakdown voltage" section.
*2 By resistive method, nominal voltage applied to the coil; contact carrying current: 1 A.
*3 Nominal voltage applied to the coil, excluding contact bounce time.
*4 Nominal voltage applied to the coil, excluding contact bounce time without diode.
*5 Half-wave pulse of sine wave: 11 ms; detection time: 10 μs.
*6 Half-wave pulse of sine wave: 6 ms.
*7 Detection time: 10 μs.

Characteristics

		Standard (B.B.M) type	M.B.B.type
Initial insulation resistance*1		Min. 1,000 MΩ (at 500 V DC)	
Initial breakdown voltage	Between open contacts	750 Vrms for 1 min. (Detection current: 10 mA)	300 Vrms for 1 min. (Detection current: 10 mA)
	Between contact and coil	1,000 Vrms for 1 min. (Detection current: 10 mA)	
	Between contact sets	1,000 Vrms for 1 min. (Detection current: 10 mA)	
FCC surge voltage between open contacts		1,500 V	
Operate time [Set time]*3 (at 20°C)		Max. 3 ms (Approx. 2 ms) [Max. 3 ms (Approx. 2 ms)]	
Release time [Reset time]*4 (at 20°C)		Max. 3 ms (Approx. 1 ms) [Max. 3 ms (Approx. 2 ms)]	
M.B.B. time*8		—	Min. 10 μs.
Temperature rise*2 (at 20°C)		Max. 50°C	
Shock resistance	Functional*5	Min. 490 m/s² {50G}	
	Destructive*6	Min. 980 m/s² {100G}	
Vibration resistance	Functional*7	176.4 m/s² {18G}, 10 to 55 Hz at double amplitude of 3 mm	
	Destructive	294 m/s² {30G}, 10 to 55 Hz at double amplitude of 5 mm	
Conditions for operation, transport and storage*9 (Not freezing and condensing at low temperature)	Ambient temperature	–40°C to +70°C –40°F to +158°F	–40°C to +50°C –40°F to +122°F
	Humidity	5 to 85% R.H.	
Unit weight	2 Form C:	Approx. 1.5 g .053 oz	
	4 Form C:	Approx. 3 g .106 oz.	—

*8 M.B.B. time:



*9 Refer to 6. Conditions for operation, transport and storage mentioned in AMBIENT ENVIRONMENT (see catalog).

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TQ

ORDERING INFORMATION

EX. TQ 2 H — L2 — 2M — 3V

Contact arrangement	Terminal shape	Operating function	MBB function	Coil voltage (DC)
2: 2 Form C 4: 4 Form C	Nil: Standard PC board terminal H: Self-clinching terminal	Nil: Single side stable L: 1 coil latching L2: 2 coil latching	Nil: Standard (B.B.M.) type 2M: 2M.B.B. type	3, 4.5, 5, 6, 9, 12, 24, 48* V

*48 V coil type: Single side stable only

Notes: 1. AgPd stationary contact types available for high resistance against contact sticking. When ordering, please add suffix "-3" like TQ2-12V-3.

2. M.B.B. contact types are available only for TQ2 type.

TYPES AND COIL DATA (at 20°C 68°F)

1. Standard (B.B.M.) type

2 Form C type

1. Single side stable

Part No.		Nominal voltage, V DC	Pick-up voltage, V DC (max.)	Drop-out voltage, V DC (min.)	Nominal operating current, mA (±10%)	Coil resistance, Ω (±10%)	Nominal operating power, mW	Max. allowable voltage, V DC
Standard PC board terminal	Self-clinching terminal							
TQ2-3 V	TQ2H-3 V	3	2.25	0.3	46.7	64.3	140	4.5
TQ2-4.5 V	TQ2H-4.5 V	4.5	3.38	0.45	31.1	144.6	140	6.7
TQ2-5 V	TQ2H-5 V	5	3.75	0.5	28.1	178	140	7.5
TQ2-6 V	TQ2H-6 V	6	4.5	0.6	23.3	257	140	9
TQ2-9 V	TQ2H-9 V	9	6.75	0.9	15.5	579	140	13.5
TQ2-12 V	TQ2H-12 V	12	9	1.2	11.7	1,028	140	18
TQ2-24 V	TQ2H-24 V	24	18	2.4	8.3	2,880	200	36
TQ2-48 V	TQ2H-48 V	48	36	4.8	6.25	7,680	300	57.6

2. 1 Coil latching

Part No.		Nominal voltage, V DC	Set voltage, V DC (max.)	Reset voltage, V DC (min.)	Nominal operating current, mA (±10%)	Coil resistance, Ω (±10%)	Nominal operating power, mW	Max. allowable voltage, V DC
Standard PC board terminal	Self-clinching terminal							
TQ2-L-3 V	TQ2H-L-3 V	3	2.25	2.25	33.3	90	100	4.5
TQ2-L-4.5 V	TQ2H-L-4.5 V	4.5	3.38	3.38	22.2	202.5	100	6.7
TQ2-L-5 V	TQ2H-L-5 V	5	3.75	3.75	20	250	100	7.5
TQ2-L-6 V	TQ2H-L-6 V	6	4.5	4.5	16.7	360	100	9
TQ2-L-9 V	TQ2H-L-9 V	9	6.75	6.75	11.1	810	100	13.5
TQ2-L-12 V	TQ2H-L-12 V	12	9	9	8.3	1,440	100	18
TQ2-L-24 V	TQ2H-L-24 V	24	18	18	6.3	3,840	150	36

3. 2 Coil latching

Part No.		Nominal voltage, V DC	Set voltage, V DC (max.)	Reset voltage, V DC (min.)	Nominal operating current, mA (±10%)	Coil resistance, Ω (±10%)	Nominal operating power, mW	Max. allowable voltage, V DC
Standard PC board terminal	Self-clinching terminal							
TQ2-L2-3 V	TQ2H-L2-3 V	3	2.25	2.25	66.7	45	200	4.5
TQ2-L2-4.5 V	TQ2H-L2-4.5 V	4.5	3.38	3.38	44.4	101.2	200	6.7
TQ2-L2-5 V	TQ2H-L2-5 V	5	3.75	3.75	40	125	200	7.5
TQ2-L2-6 V	TQ2H-L2-6 V	6	4.5	4.5	33.3	180	200	9
TQ2-L2-9 V	TQ2H-L2-9 V	9	6.75	6.75	22.2	405	200	13.5
TQ2-L2-12 V	TQ2H-L2-12 V	12	9	9	16.7	720	200	18
TQ2-L2-24 V	TQ2H-L2-24 V	24	18	18	12.5	1,920	300	28.8

Notes: 1. Specified value of the pick-up, drop-out, set and reset voltage is with the condition of square wave coil pulse.

2. Standard packing: Tube: 50 pcs.; Case: 1,000 pcs.

3. In case of 5 V transistor drive circuit, it is recommend to use 4.5 V type relay.

4. AgPd stationary contact types available for high resistance against contact sticking. When ordering, please add suffix "–3" like TQ2-12V-3.

TQ

4 Form C type

1. Single side stable

Part No. Standard PC board terminal	Part No. Self-clinching terminal	Nominal voltage, V DC	Pick-up voltage, V DC (max.)	Drop-out voltage, V DC (min.)	Nominal operating current, mA (±10%)	Coil resistance, Ω (±10%)	Nominal operating power, mW	Max. allowable voltage, V DC
TQ4-3 V	TQ4H-3 V	3	2.25	0.3	93.8	32	280	4.5
TQ4-4.5 V	TQ4H-4.5 V	4.5	3.38	0.45	62.2	72.3	280	6.7
TQ4-5 V	TQ4H-5 V	5	3.75	0.5	56.2	89	280	7.5
TQ4-6 V	TQ4H-6 V	6	4.5	0.6	46.5	129	280	9
TQ4-9 V	TQ4H-9 V	9	6.75	0.9	31.1	289	280	13.5
TQ4-12 V	TQ4H-12 V	12	9	1.2	23.3	514	280	18
TQ4-24 V	TQ4H-24 V	24	18	2.4	11.7	2,056	280	36
TQ4-48 V	TQ4H-48 V	48	36	4.8	8.3	5,760	400	57.6

2. 1 Coil latching

Part No. Standard PC board terminal	Part No. Self-clinching terminal	Nominal voltage, V DC	Set voltage, V DC (max.)	Reset voltage, V DC (min.)	Nominal operating current, mA (±10%)	Coil resistance, Ω (±10%)	Nominal operating power, mW	Max. allowable voltage, V DC
TQ4-L-3 V	TQ4H-L-3 V	3	2.25	2.25	66.6	45	200	4.5
TQ4-L-4.5 V	TQ4H-L-4.5 V	4.5	3.38	3.38	44.4	101.2	200	6.7
TQ4-L-5 V	TQ4H-L-5 V	5	3.75	3.75	40	125	200	7.5
TQ4-L-6 V	TQ4H-L-6 V	6	4.5	4.5	33.3	180	200	9
TQ4-L-9 V	TQ4H-L-9 V	9	6.75	6.75	22.2	405	200	13.5
TQ4-L-12 V	TQ4H-L-12 V	12	9	9	16.7	720	200	18
TQ4-L-24 V	TQ4H-L-24 V	24	18	18	8.3	2,880	200	36

3. 2 Coil latching

Part No. Standard PC board terminal	Part No. Self-clinching terminal	Nominal voltage, V DC	Set voltage, V DC (max.)	Reset voltage, V DC (min.)	Nominal operating current, mA (±10%)	Coil resistance, Ω (±10%)	Nominal operating power, mW	Max. allowable voltage, V DC
TQ4-L2-3 V	TQ4H-L2-3 V	3	2.25	2.25	133	22.5	400	4.5
TQ4-L2-4.5 V	TQ4H-L2-4.5 V	4.5	3.38	3.38	88.9	50.6	400	6.7
TQ4-L2-5 V	TQ4H-L2-5 V	5	3.75	3.75	80	62.5	400	7.5
TQ4-L2-6 V	TQ4H-L2-6 V	6	4.5	4.5	66.6	90	400	9
TQ4-L2-9 V	TQ4H-L2-9 V	9	6.75	6.75	44.4	202.5	400	13.5
TQ4-L2-12 V	TQ4H-L2-12 V	12	9	9	33.3	360	400	18
TQ4-L2-24 V	TQ4H-L2-24 V	24	18	18	16.7	1,440	400	36

Notes: 1. Specified value of the pick-up, drop-out, voltage is with the condition of square wave coil pulse.
2. Standard packing: Tube: 25 pcs.; Case: 500 pcs.
3. In case of 5 V transistor drive circuit, it is recommend to use 4.5 V type relay.
4. 1 coil latching and 2 coil latching types are also available by request. Please consult us for details.
5. AgPd stationary contact types available for high resistance against contact sticking. When ordering, please add suffix "–3" like TQ2-12V-3.

2. M.B.B. type

Single side stable

Part No. Standard PC board terminal	Part No. Self-clinching terminal	Nominal voltage, V DC	Pick-up voltage, V DC (max.)	Drop-out voltage, V DC (min.)	Nominal operating current, mA (±10%)	Coil resistance, Ω (±10%)	Nominal operating power, mW	Max. allowable voltage, V DC
TQ2-2M-3 V	TQ2H-2M-3 V	3	2.4	0.3	66.7	45	200	4.5
TQ2-2M-4.5 V	TQ2H-2M-4.5 V	4.5	3.6	0.45	44.4	101	200	6.7
TQ2-2M-5 V	TQ2H-2M-5 V	5	4	0.5	40	125	200	7.5
TQ2-2M-6 V	TQ2H-2M-6 V	6	4.8	0.6	33.3	180	200	9
TQ2-2M-9 V	TQ2H-2M-9 V	9	7.2	0.9	22.2	405	200	13.5
TQ2-2M-12 V	TQ2H-2M-12 V	12	9.6	1.2	16.7	720	200	18
TQ2-2M-24 V	TQ2H-2M-24 V	24	19.2	2.4	8.3	2,880	200	36

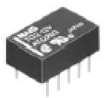
Notes: 1. Specified value of the pick-up, drop-out, set and reset voltage is with the condition of square wave coil pulse.
2. Standard packing: Tube: 50 pcs.; Case: 1,000 pcs.
3. In case of 5 V transistor drive circuit, it is recommend to use 4.5 V type relay.
4. AgPd stationary contact types available for high resistance against contact sticking. When ordering, please add suffix "–3" like TQ2-12V-3.

TQ

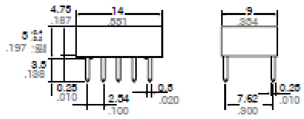
DIMENSIONS

mm inch

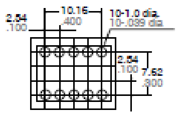
1) 2 Form C, 2 Form D



Standard PC board terminal

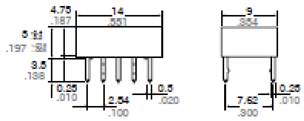


PC board pattern (Copper-side view)



Tolerance: ±0.1 ±.004

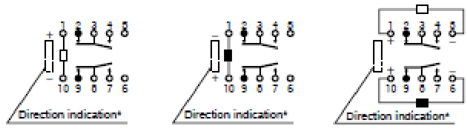
Self-clinching terminal



General tolerance: ±0.3 ±.012

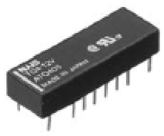
Schematic (Bottom view)

• Single side stable (Deenergized condition) • 1-coil latching (Reset condition) • 2-coil latching (Reset condition)

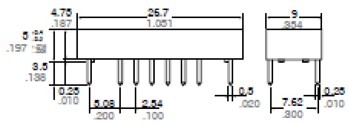


*Orientation stripe typical-located on top of relay

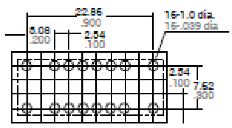
2) 4 Form C



Standard PC board terminal

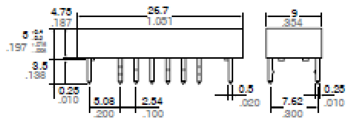


PC board pattern (Copper-side view)



Tolerance: ±0.1 ±.004

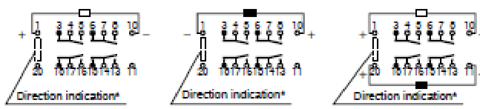
Self-clinching terminal



General tolerance: ±0.3 ±.012

Schematic (Bottom view)

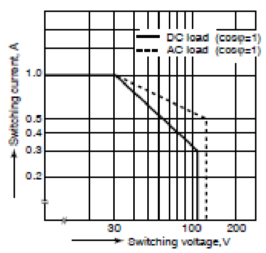
• Single side stable (Deenergized condition) • 1-coil latching (Reset condition) • 2-coil latching (Reset condition)



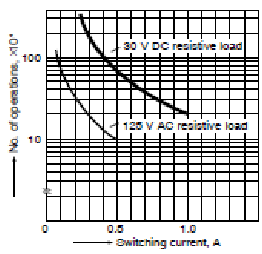
*Orientation stripe typical-located on top of relay

REFERENCE DATA

1. Maximum switching capacity

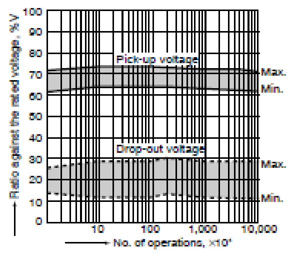


2. Life curve



3. Mechanical life

Tested sample: TQ2-12V, 10 pcs.



Solid relay: LCC120

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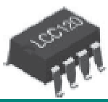


LCC120
1-Form-C OptoMOS® Relay

Parameters	Ratings	Units
Blocking Voltage	250	V_P
Load Current	170	mA_{rms} / mA_{DC}
On-Resistance (max)	20	Ω

Features
- 3750V_{rms} Input/Output Isolation
- 1-Form-C Solid State Relay
- Low Drive Power Requirements (TTL/CMOS Compatible)
- High Reliability
- Arc-Free With No Snubbing Circuits
- FCC Compatible
- VDE Compatible
- No EMI/RFI Generation
- Small 8-pin Package
- Machine Insertable, Wave Solderable
- Surface Mount Tape & Reel Versions Available

Applications
- Telecommunications
  - Telecom Switching
  - Tip/Ring Circuits
  - Modem Switching (Laptop, Notebook, Pocket Size)
  - Hook Switch
  - Dial Pulsing
  - Ground Start
  - Ringing Injection
- Instrumentation
  - Multiplexers
  - Data Acquisition
  - Electronic Switching
  - I/O Subsystems
- Meters (Watt-Hour, Water, Gas)
- Medical Equipment—Patient/Equipment Isolation
- Security
- Aerospace
- Industrial Controls

Description
LCC120P is a 250V, 170mA, 20Ω, 1-Form-C relay. It is ideal for applications focused on peak load current handling capablilities.

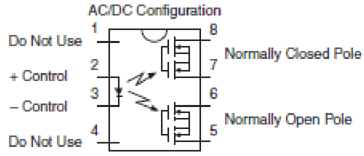
This device is perfect for applications where a signal needs to be switched between two different lines. The small 8-lead package makes it an ideal space-saving replacement for a 1-Form-C electromechanical relay (EMR).

Approvals
- UL Recognized Component: File E76270
- CSA Certified Component: Certificate # 1175739
- EN/IEC 60950-1 Certified Component: TUV Certificate B 09 07 49410 004

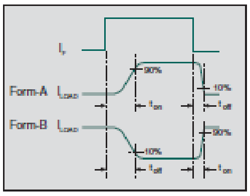
Ordering Information

Part #	Description
LCC120	8-Pin DIP (50/Tube)
LCC120S	8-Pin Surface Mount (50/Tube)
LCC120STR	8-Pin Surfact Mount Tape & Reel (1000/Reel)

Pin Configuration



Switching Characteristics for a Form-C Device



IXYS INTEGRATED CIRCUITS DIVISION

LCC120

Absolute Maximum Ratings @ 25°C

Parameter	Min	Max	Unit
Blocking Voltage	-	250	V_P
Reverse Input Voltage	-	5	V
Input control Current	-	50	mA
Peak (10ms)	-	1	A
Input Power Dissipation [1]	-	150	mW
Total Power Dissipation [2]	-	800	mW
Isolation Voltage, Input to Output	3750	-	V_{rms}
Operating Temperature	-40	+85	°C
Storage Temperature	-40	+125	°C

[1] Derate linearly 1.33mW / °C.
[2] Derate linearly 6.67mW / °C.

Absolute Maximum Ratings are stress ratings. Stresses in excess of these ratings can cause permanent damage to the device. Functional operation of the device at conditions beyond those indicated in the operational sections of this data sheet is not implied.

Electrical Characteristics @ 25°C

Parameter	Conditions	Symbol	Min	Typ	Max	Units
Output Characteristics						
Load Current						
Continuous, AC/DC Configuration	-	I_L	-	-	170	mA_{rms} / mA_{DC}
Peak	t=10ms	I_{LPK}	-	-	±400	mA_P
On-Resistance, AC/DC Configuration	I_L=170mA	R_{ON}	-	16	20	Ω
Off-State Leakage Current	V_L=250V_P	I_{LEAK}	-	-	1	µA
Switching Speeds						
Turn-On	I_F=10mA, V_L=10V	t_{on}	-	-	5	ms
Turn-Off		t_{off}	-	-	5	
Output Capacitance	V_L=50V, f=1MHz	C_{OUT}	-	50	-	pF
Input Characteristics						
Input Control Current to Activate	I_L=170mA	I_F	-	-	10	mA
Input Control Current to Deactivate	-	I_F	0.4	0.7	-	mA
Input Voltage Drop	I_F=10mA	V_F	0.9	1.2	1.4	V
Reverse Input Current	V_R=5V	I_R	-	-	10	µA
Common Characteristics						
Capacitance, Input to Output	-	$C_{I/O}$	-	3	-	pF

APPENDIX 7 COMPONENTS TEST PLAN

Components test plan for automatic switch

Aims

The aim is to find the most suitable component for the switch system design

Variables

Property	Vary and/or measure?
Injected voltage	Vary
Injected resistance	Vary
Voltage on switch	Measure
Injected current	Measure
On resistance	Measure
Switch time	Measure
Signal distortion	Measure

Testing tools

Platform: function generator, oscilloscope

Software: Smart Scope

Methods

The steps are performed by the following contents:

1. Connect the platform to the PC and to the tested component
2. Send a 5VDC signal and change the resistance from 100Ω to 2000Ω to change the injected current and check voltage on switch to calculate the on resistance change.
3. Send an AC signal with 1.5V 1kHz square wave(determined by the measuring device project team), change the resistance from 100Ω to 2000Ω to change the injected current and check voltage on switch and observe signal distortion.
4. Set the resistance to 1000Ω and send an AC signal from 1.5V to 10V 1kHz square wave to change the injected current and check voltage on switch and observe signal distortion.
5. Record the switch time.

Expected results

The on resistance average value and flatness value, the switch time, the power consumption of the component, the signal distortion and the switch time.

APPENDIX 8 COMPONENTS TEST RESULTS

Test1 (5VDC change resistance)

Analog Switch

test 4 (single channel)	Vin(V)		Resistance(Ω)		Vs(mV)	I(mA)	On Resistance(Ω)
Analog switch	3.42		100		855	35.3	24.22096317
			220		464	19.6	23.67346939
			320		351	14.73	23.82892057
			440		265	11.14	23.78815081
			540		215	9.19	23.39499456
			660		176	7.54	23.34217507
			760		159	6.65	23.90977444
			880		136	5.75	23.65217391
			980		120	5.15	23.30097087
			1100		108	4.66	23.17596567
			1200		102	4.29	23.77622378
			1320		91	3.9	23.33333333
			1420		86	3.62	23.75690608
			1540		79	3.33	23.72372372
			1640		73	3.12	23.3974359
			1760		68	2.93	23.20819113
			1860		65	2.78	23.38129496
			1980		61	2.6	23.46153846

$R_{on} = (V_{com} – V_r)/I_{in}$

R_{on}_average = Sum(R_{on})/N = 23 Ω

R_{on}_flatness = Max(R_{on}) – Min(R_{on}) = 0.8 Ω

Solid state relay

test 4 (single channel)	Vcom	Vs(mV)	I(mA)	On Resistance(Ω)
Solid-state relay	4.657	487	41.7	11.67865707
	4.988	237	21.59545455	10.97453168
	5.083	164	15.371875	10.66883513
	5.152	119	11.43863636	10.40333797
	5.188	99.5	9.423148148	10.55910386
	5.22	80.8	7.786666667	10.37671233
	5.227	71.5	6.783552632	10.54019979
	5.249	60.6	5.895909091	10.27831316
	5.258	55.4	5.30877551	10.43555146
	5.267	48.7	4.743909091	10.26579537
	5.275	45.1	4.35825	10.34819021
	5.281	41.2	3.969545455	10.3790221
	5.283	38.3	3.693450704	10.36970656
	5.289	35.6	3.411298701	10.43590817
	5.292	33.2	3.206585366	10.35369286
	5.296	30.9	2.991534091	10.32914854
	5.299	29.2	2.833225806	10.30627348
	5.303	27.6	2.664343434	10.35902491

$R_{on} = (V_{com} – V_r)/I_{in}$

R_{on}_average = Sum(R_{on})/N = 10.6 Ω

R_{on}_flatness = Max(R_{on}) – Min(R_{on}) = 1.3 Ω

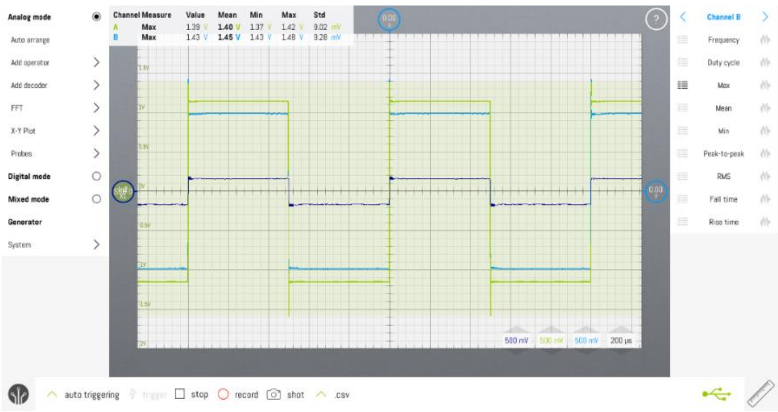
Signal relay

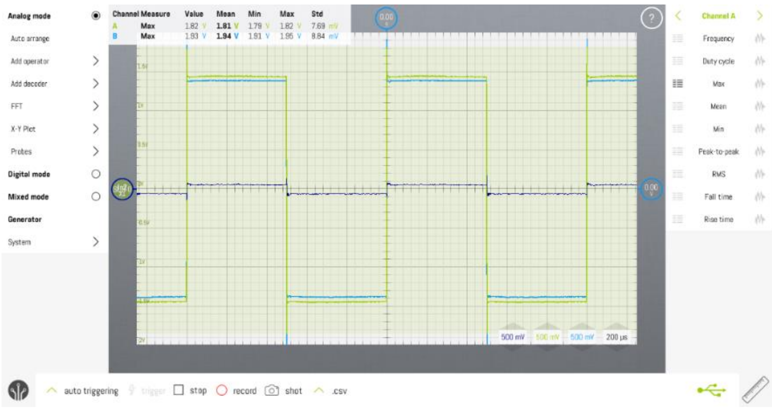
On resistance are all 0

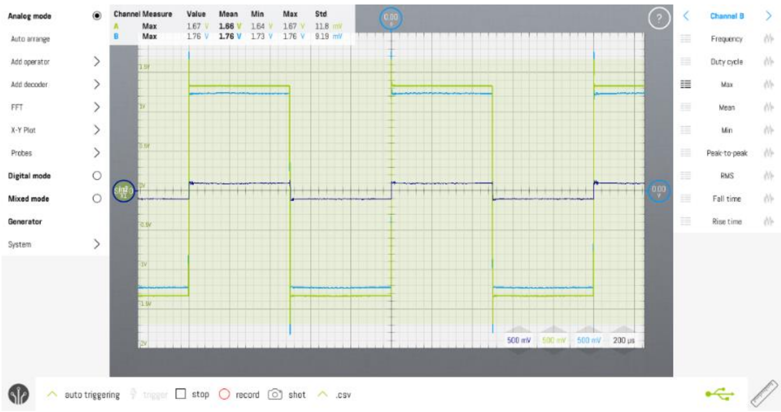
Test2 (1.5V AC change resistance)

*The purple signal is the difference between input and output signal.

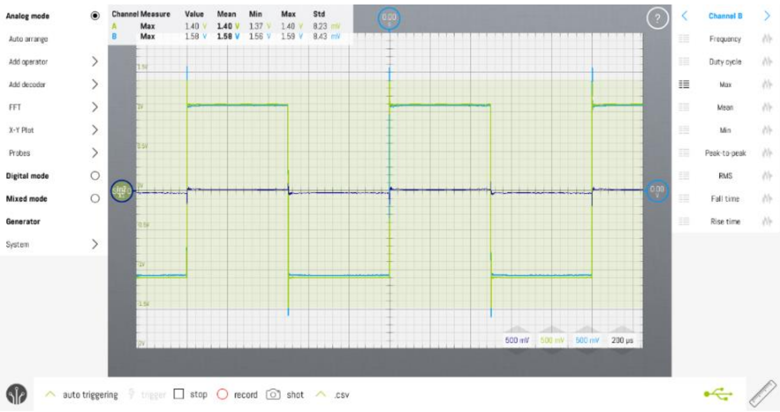
Analog switch (Stable distortion with the proportion of on resistance and load resistance)

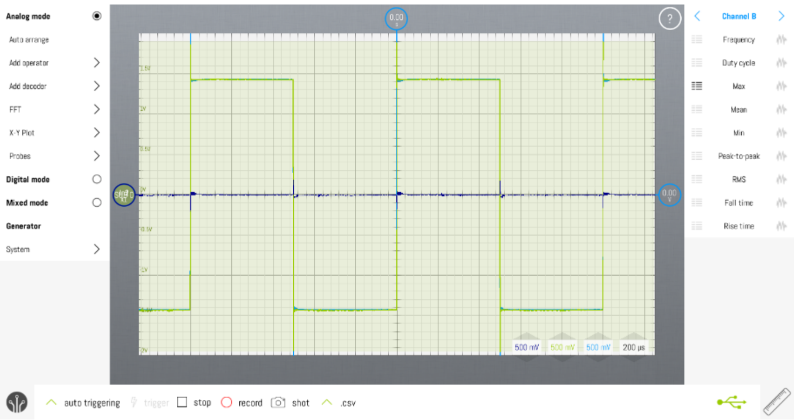


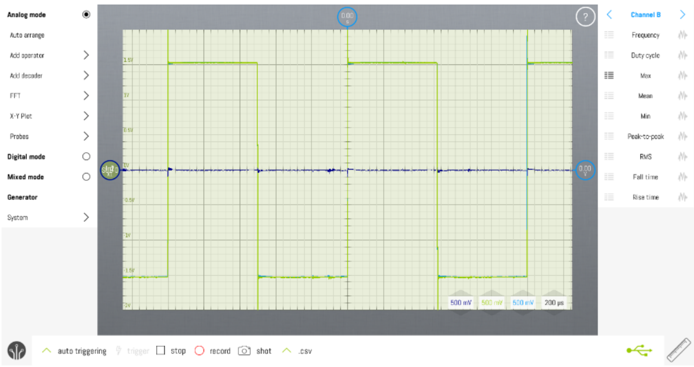


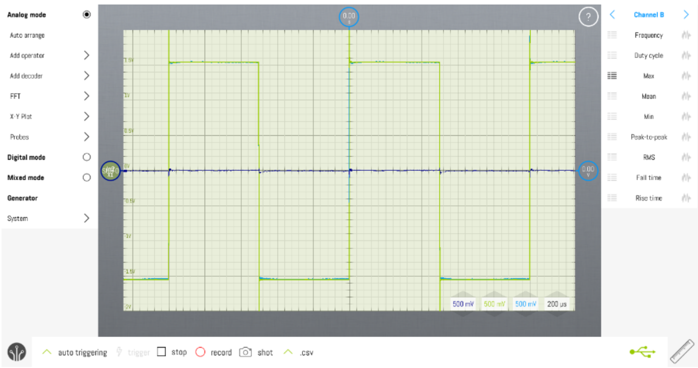


signal relay (no distortion)

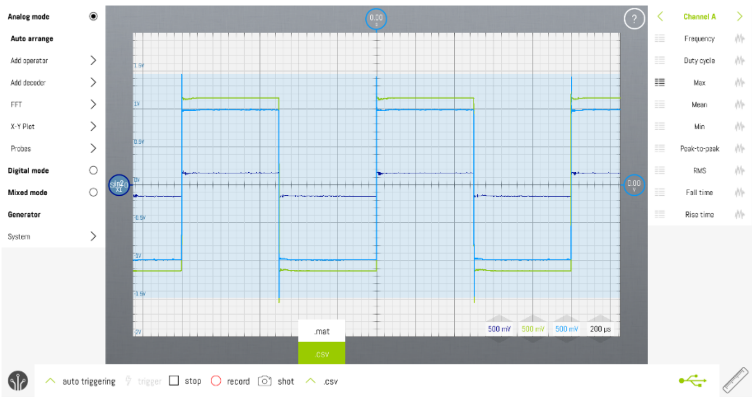


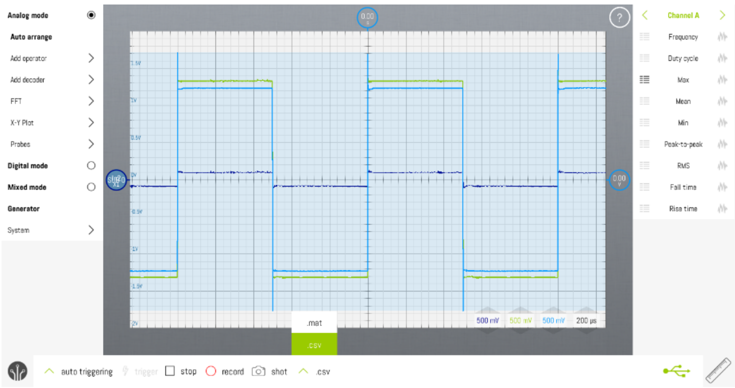


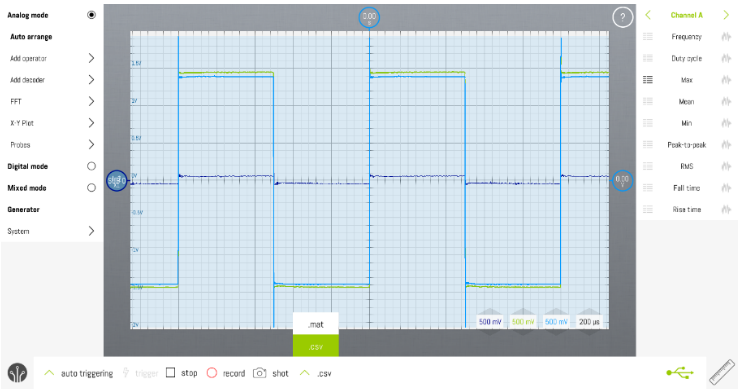




Solid relay (Stable distortion with the proportion of on resistance and load resistance)




Analog mode
Auto arrange
Add operator
Add decoder
FFT
X-Y Plot
Probes
Digital mode
Mixed mode
Generator
System
Channel A
Frequency
Duty cycle
Max
Mean
Min
Peak-to-peak
RMS
Fall time
Rise time
.mat
.csv
500 mV
500 mV
500 mV
200 µs
auto triggering
trigger
stop
record
shot
.csv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Fall time
Rise time
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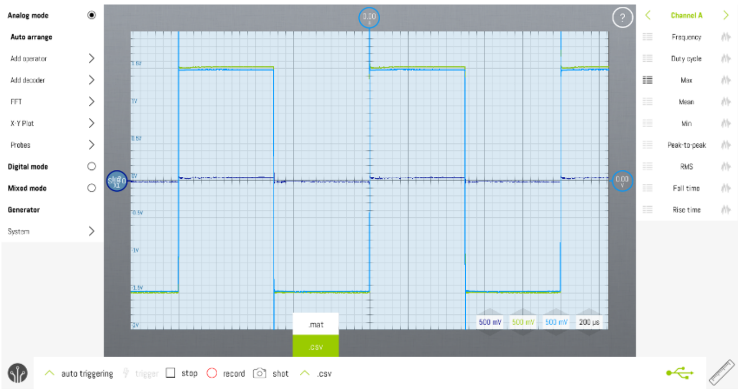
.csv
500 mV
500 mV
500 mV
200 µs
auto triggering
trigger
stop
record
shot
.csv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FFT
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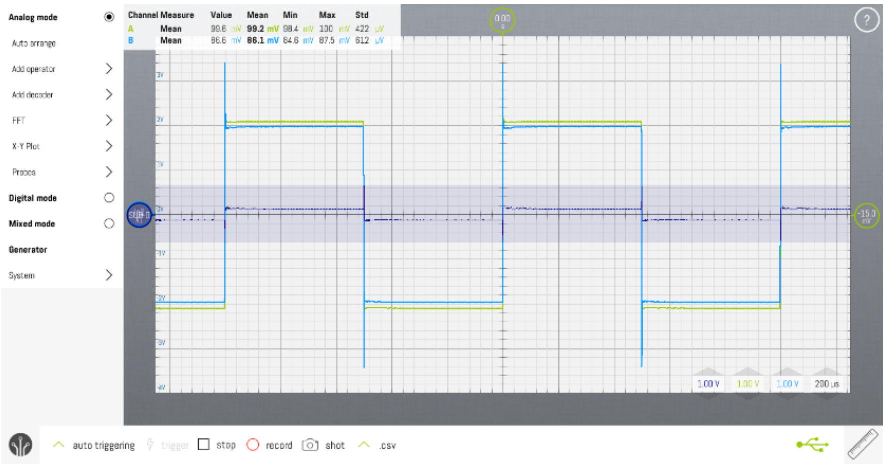
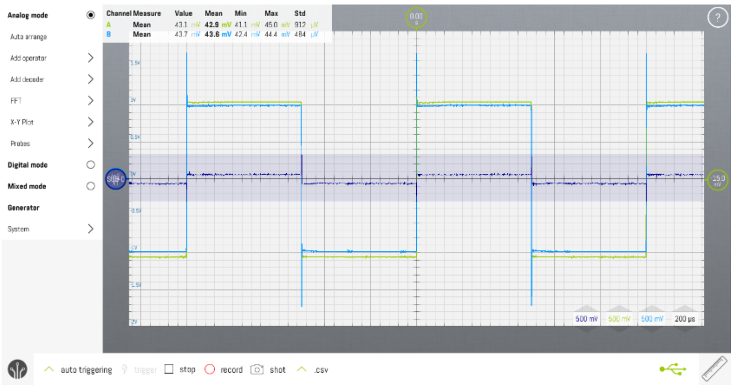
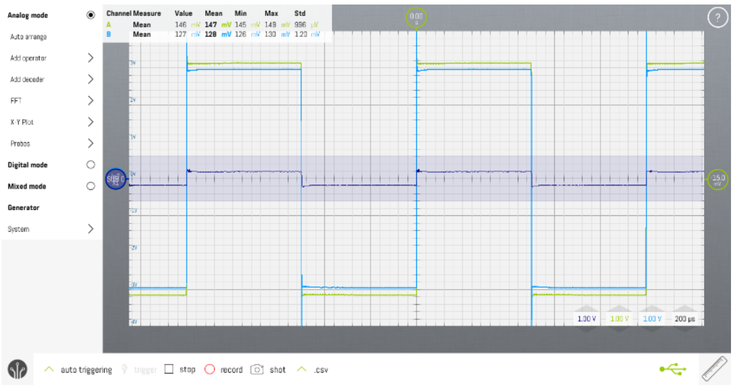
RMS
Fall time
Rise time
.mat
.csv
500 mV
500 mV
500 mV
200 µs
auto triggering
trigger
stop
record
shot
.csv

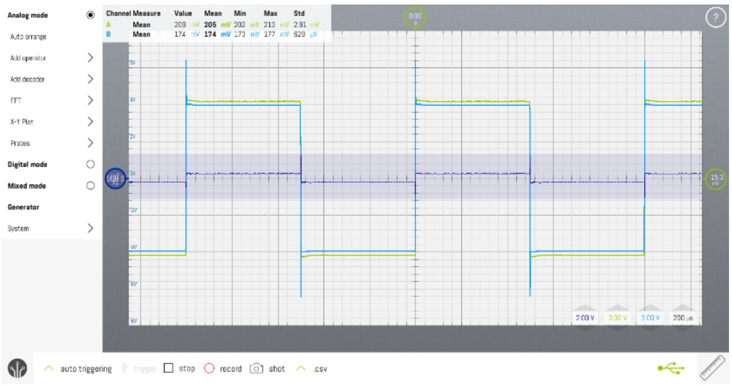
AC signal load resistance 1kΩ V change

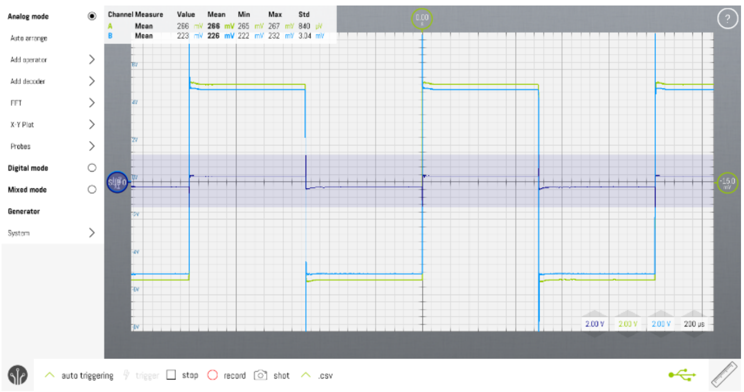
Analog switch (Stable distortion with the proportion of on resistance and load resistance)

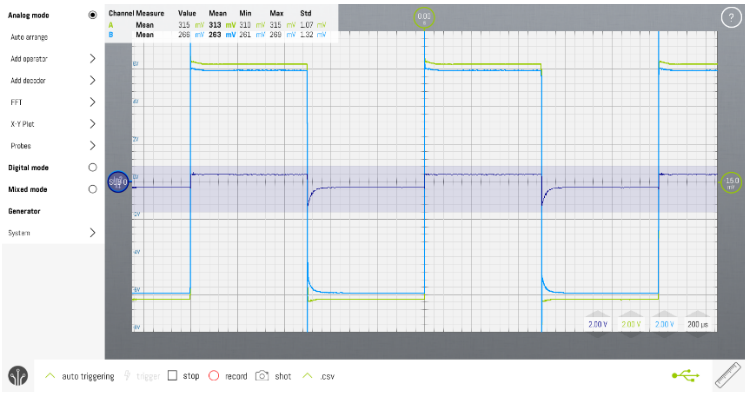








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Add operator
Add decoder
FFT
X-Y Plot
Probes
Digital mode
Mixed mode
Generator
System
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trigger
stop
record
shot
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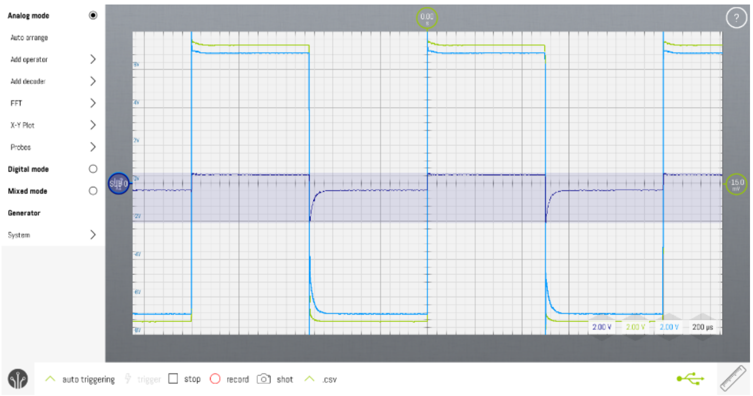
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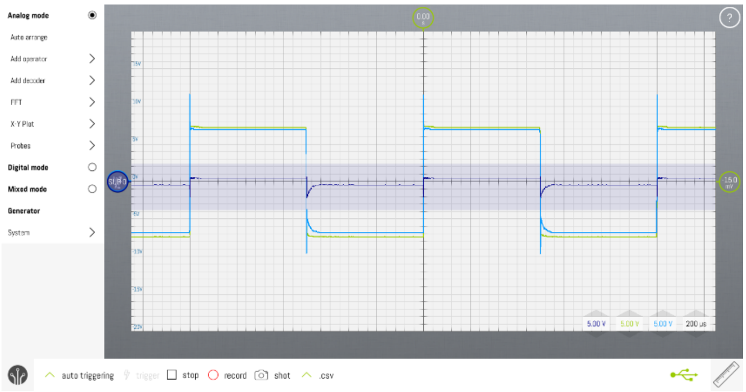
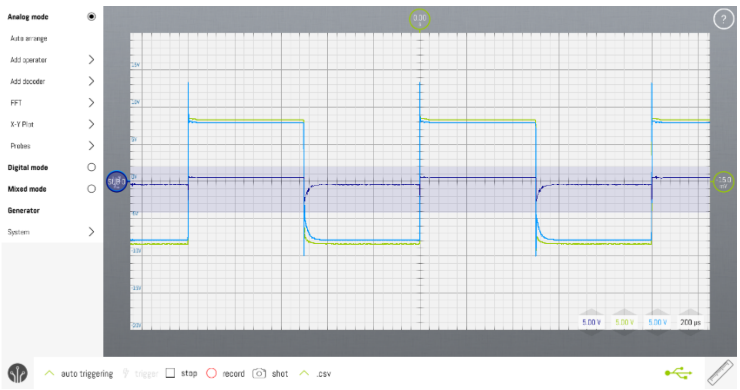
Add decoder
FFT
X-Y Plot
Probes
Digital mode
Mixed mode
Generator
System
2.00 V
2.00 V
2.00 V
200 µs
auto triggering
trigger
stop
record
shot
.csv


Analog mode
Auto arrange
Add operator
Add decoder
FFT
X-Y Plot
Probes
Digital mode
Mixed mode
Generator
System
5.00 V
5.00 V
5.00 V
200 µs
auto triggering
trigger
stop
record
shot
.csv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Add decoder
FFT
X-Y Plot
Probes
Digital mode
Mixed mode
Generator
System
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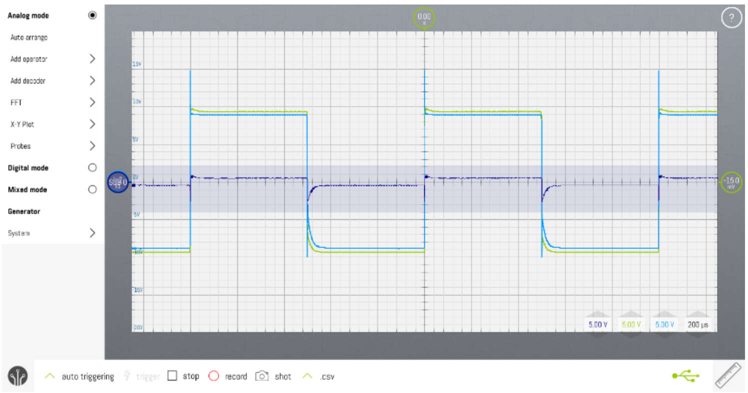
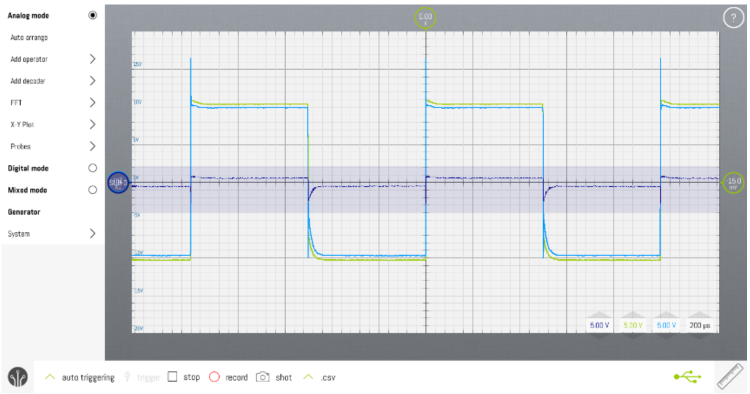
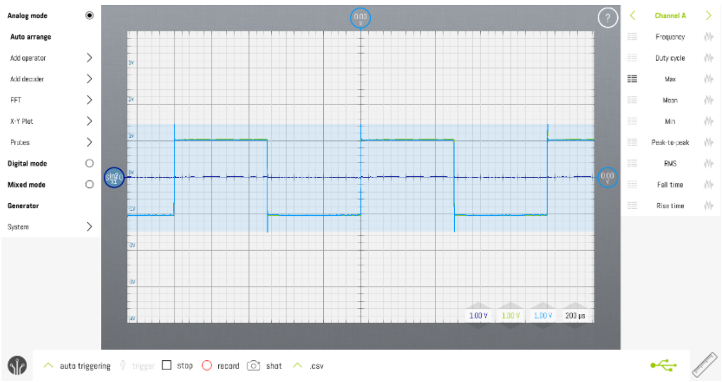
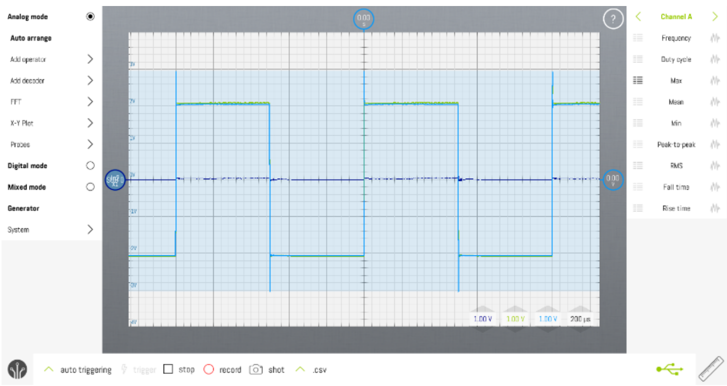
5.00 V
5.00 V
200 µs
auto triggering
trigger
stop
record
shot
.csv

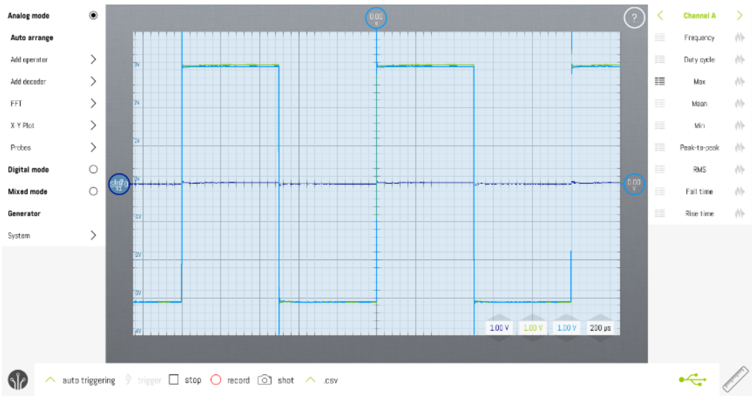




signal relay (No distortion)






Analog mode
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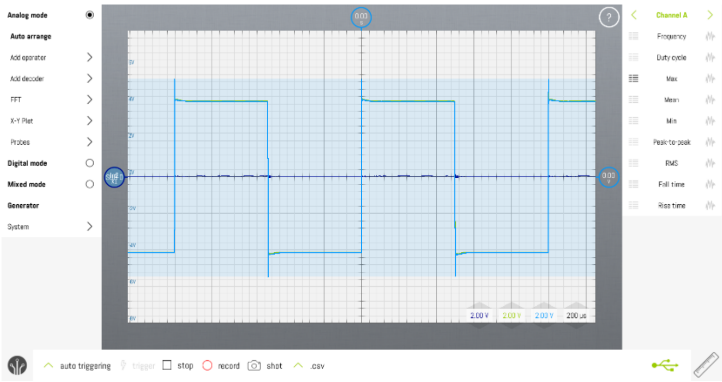
Add decoder
FFT
X-Y Plot
Probes
Digital mode
Mixed mode
Generator
System
Channel A
Frequency
Duty cycle
Max
Mean
Min
Peak-to-peak
RMS
Fall time
Rise time
1.00 V
1.00 V
1.00 V
200 µs
auto triggering
trigger
stop
record
shot
.csv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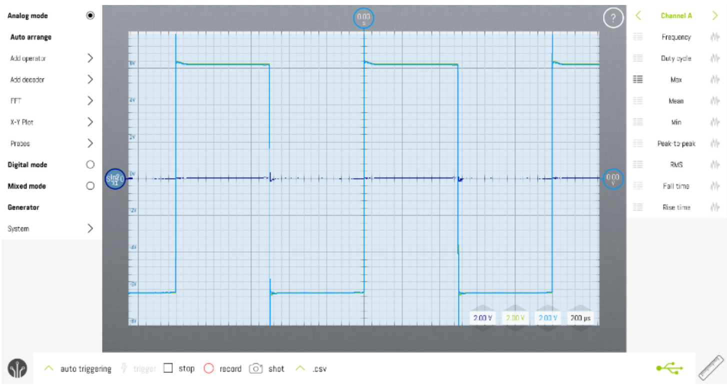
Add decoder
FFT
X-Y Plot
Probes
Digital mode
Mixed mode
Generator
System
Channel A
Frequency
Duty cycle
Max
Mean
Min
Peak-to-peak
RMS
Fall time
Rise time
2.00 V
2.00 V
2.00 V
200 µs
auto triggering
trigger
stop
record
shot
.csv


Analog mode
Auto arrange
Add operator
Add decoder
FFT
X-Y Plot
Probes
Digital mode
Mixed mode
Generator
System
Channel A
Frequency
Duty cycle
Max
Mean
Min
Peak-to-peak
RMS
Fall time
Rise time
2.00 V
2.00 V
2.00 V
200 µs
auto triggering
trigger
stop
record
shot
.csv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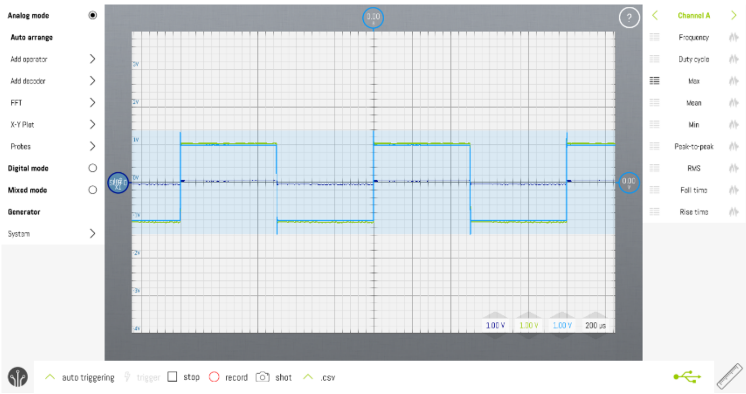
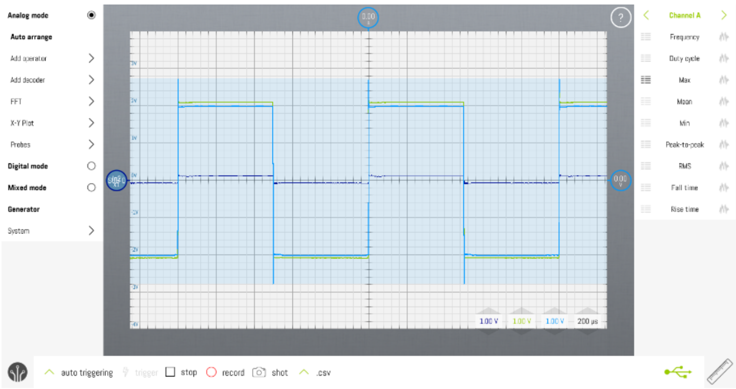
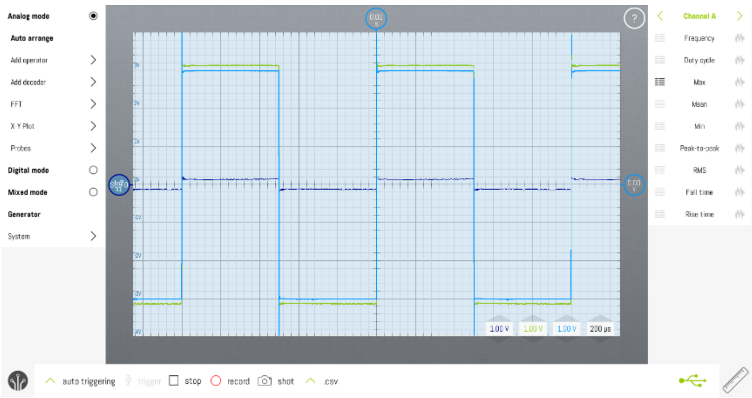
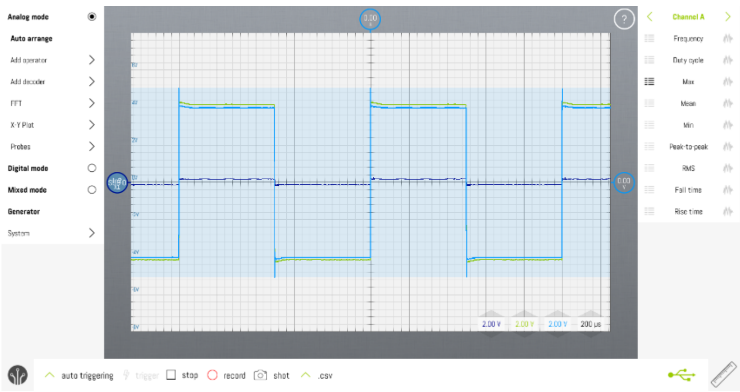
Add decoder
FFT
X-Y Plot
Probes
Digital mode
Mixed mode
Generator
System
Channel A
Frequency
Duty cycle
Max
Mean
Min
Peak-to-peak
RMS
Fall time
Rise time
2.00 V
2.00 V
2.00 V
200 µs
auto triggering
trigger
stop
record
shot
.csv

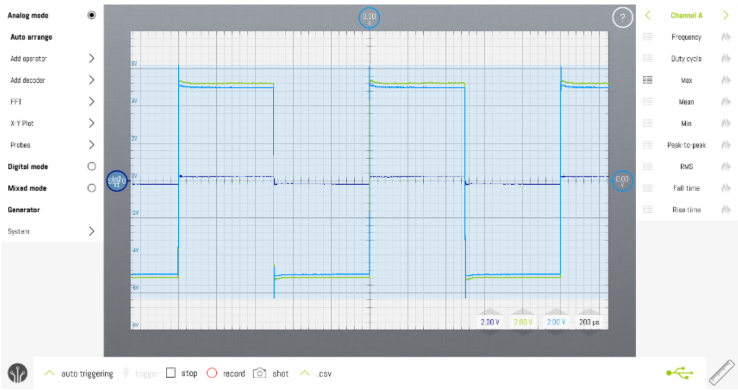
solid relay (Stable distortion with the proportion of on resistance and load resistance)

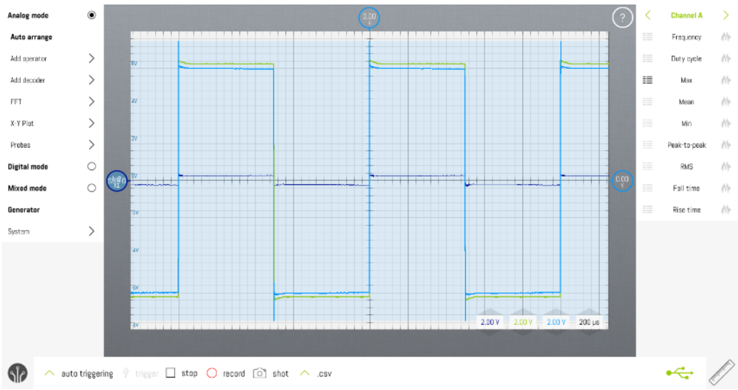









Analog mode
Auto arrange
Add operator
Add decoder
FFT
X-Y Plot
Probes
Digital mode
Mixed mode
Generator
System
Channel A
Frequency
Duty cycle
Max
Mean
Min
Peak-to-peak
RMS
Fall time
Rise time
2.00 V
2.00 V
2.00 V
200 µs
auto triggering
trigger
stop
record
shot
.csv


Analog mode
Auto arrange
Add operator
Add decoder
FFT
X-Y Plot
Probes
Digital mode
Mixed mode
Generator
System
Channel A
Frequency
Duty cycle
Max
Mean
Min
Peak-to-peak
RMS
Fall time
Rise time
2.00 V
2.00 V
2.00 V
200 µs
auto triggering
trigger
stop
record
shot
.csv

APPENDIX 9 SUBSYSTEMS TEST RESULT

Test result of the control function subsystem:

Input	Output	
Electrode number	Control signal	message
0	000	x
1	001	x
2	010	x
3	011	x
4	100	x
5	101	x
6	110	x
7	111	x
8	x	"Invalid electrode number"

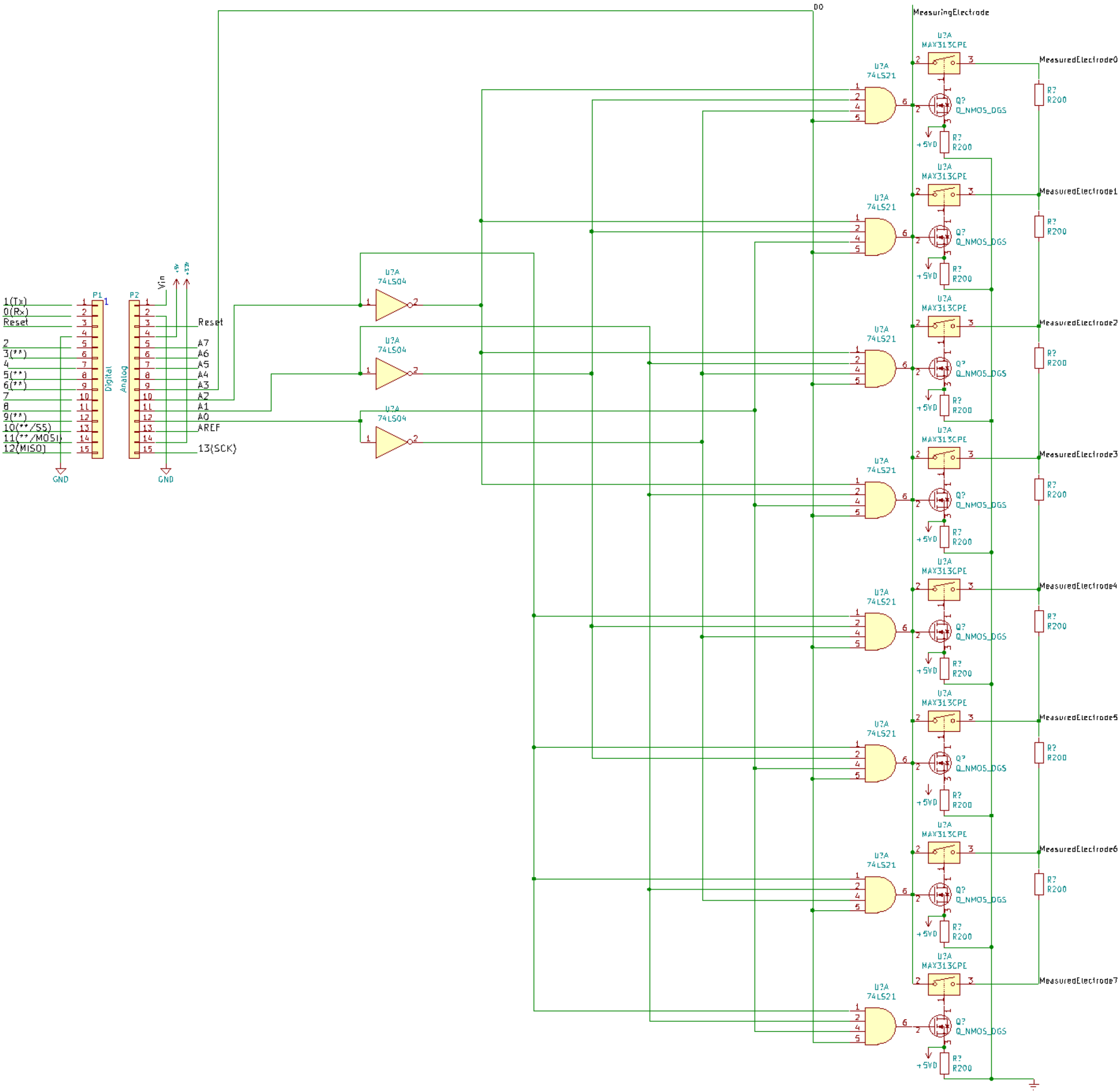
Test result of the master switch:

Input		Output
Master switch control signal	Switch circuit control signal	Connected electrode number
0	x	x
1	000	0
1	001	1
1	010	2
1	011	3
1	100	4
1	101	5
1	110	6
1	111	7

Test on the switch circuit is taken in the prototype test in Appendix 11.

APPENDIX 10 ASSEMBLY PLAN

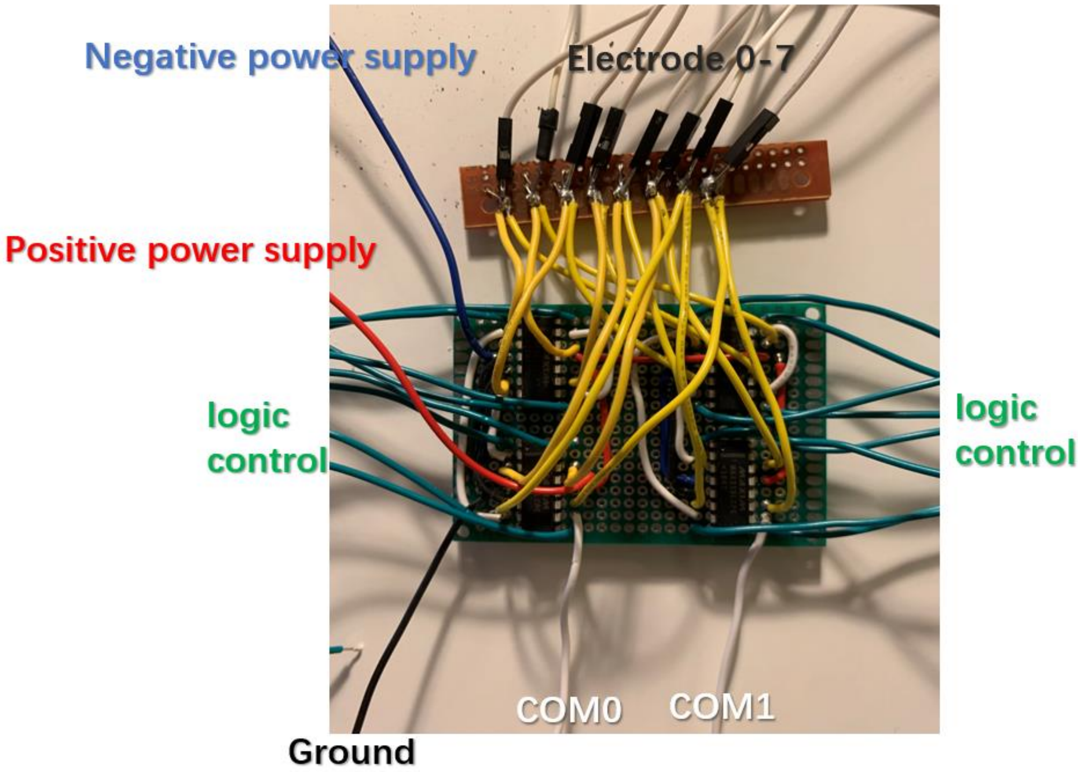
The assembly plan of one switch system



The final prototype contains 4 separate switch system each connecting 1 terminal to 8 electrodes. The arduino board and the 8 electrodes are the common components for 4 systems.

APPENDIX 11 PROTOTYPE TEST RESULT

The prototype description:



The resistance between each 2 electrodes:

Electrode number	0 and 1	1 and 2	2 and 3	3 and 4	4 and 5	5 and 6	6 and 7
Resistance between 2 electrodes(Ω)	100	150	220	270	330	370	430

5VDC signal input test on different channel (change injected current to test R_{on} change)

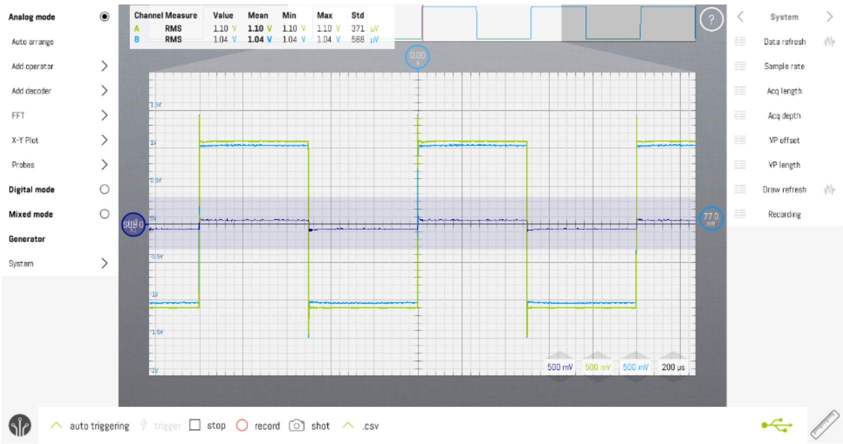
Vcom	Vr		Iin	Ron
4.93	4.42	100	44.2	11.5384615
4.93	4.58	150	30.53333333	11.4628821
5.01	4.76	220	21.63636364	11.5546218
5.02	4.81	270	17.81481481	11.7879418
5.02	4.85	330	14.6969697	11.5670103
5.04	4.88	370	13.18918919	12.1311475

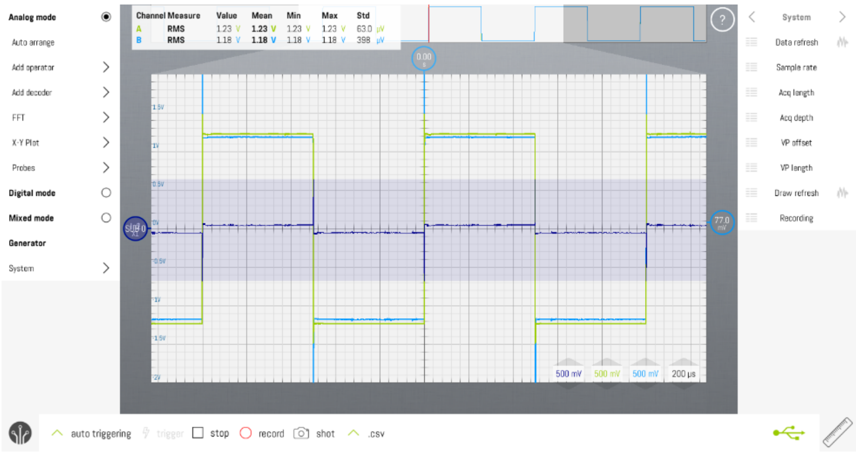
$R_{on} = (V_{com} - V_r)/I_{in}$

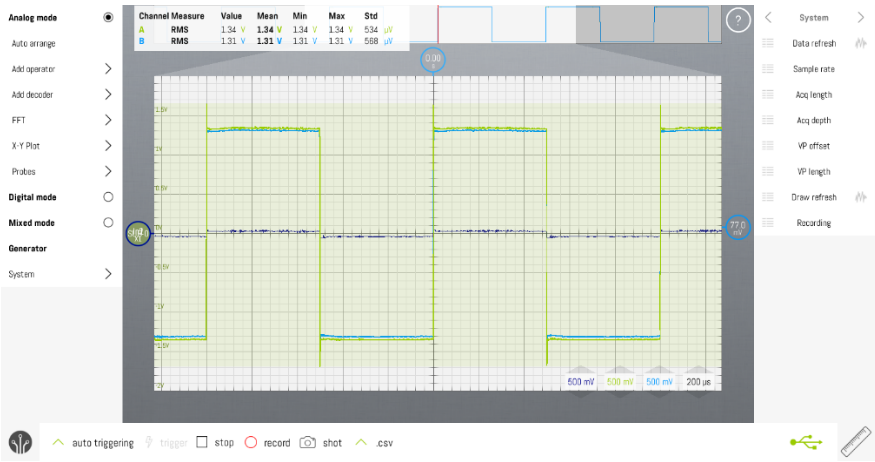
R_{on}_average = Sum(R_{on})/N = 11.67 Ω

R_{on}_flatness = Max(R_{on}) – Min(R_{on}) = 0.60 Ω

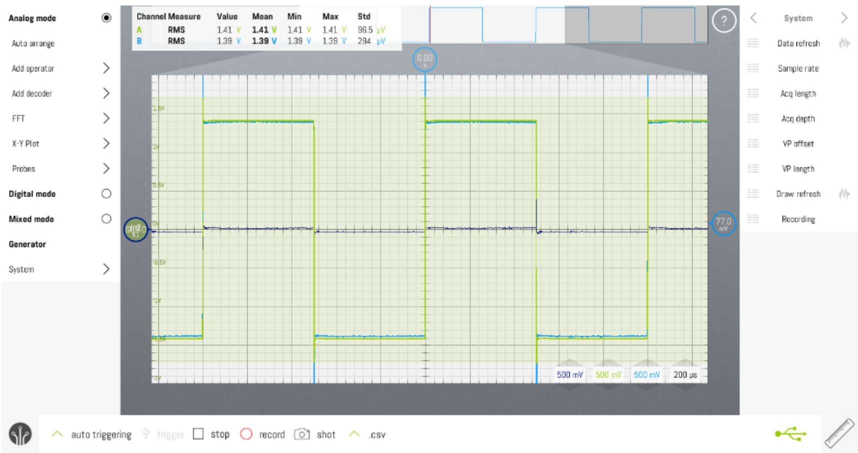
1.5V 1kHz AC signal input test on different channel (change injected current to observe the signal distortion)





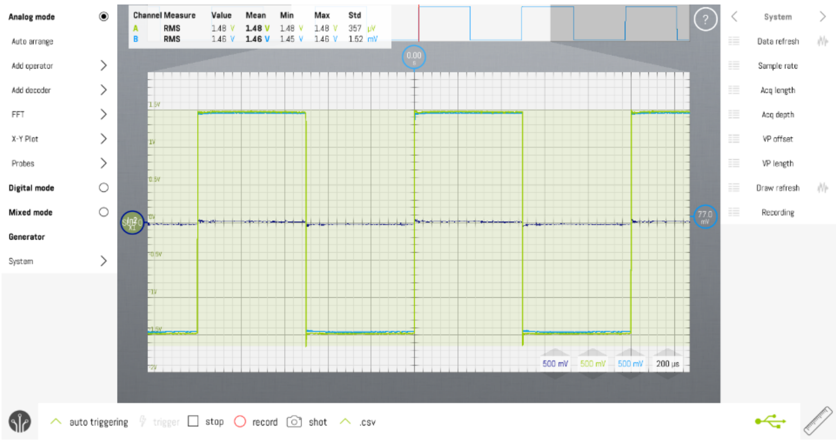

Analog mode
Auto arrange
Add operator
Add decoder
FFT
X-Y Plot
Probes
Digital mode
Mixed mode
Generator
System
Channel Measure Value Mean Min Max Std
A RMS 1.34 V 1.34 V 1.34 V 1.34 V 534 µV
B RMS 1.31 V 1.31 V 1.31 V 1.31 V 568 µV
Data refresh
Sample rate
Acq length
Acq depth
VP offset
VP length
Draw refresh
Recording
500 mV 500 mV 500 mV 200 µs
auto triggering
trigger
stop
record
shot
.csv

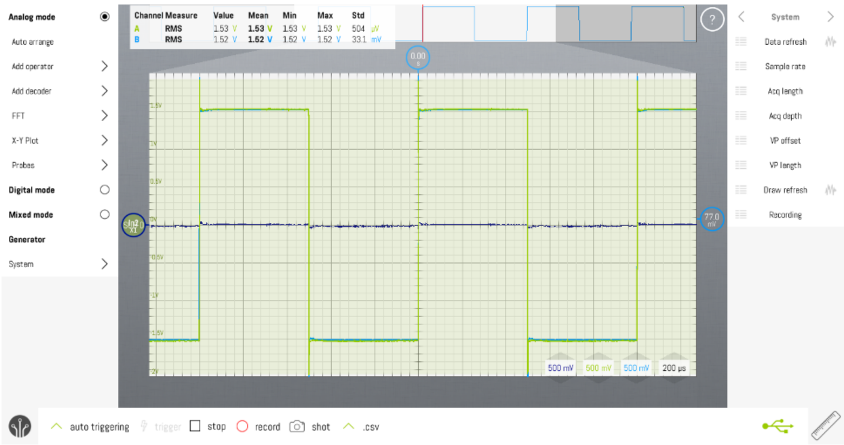

Analog mode
Auto arrange
Add operator
Add decoder
FFT
X-Y Plot
Probes
Digital mode
Mixed mode
Generator
System
Channel Measure Value Mean Min Max Std
A RMS 1.39 V 1.39 V 1.39 V 1.39 V 344 µV
B RMS 1.36 V 1.36 V 1.36 V 1.36 V 70.0 µV
Data refresh
Sample rate
Acq length
Acq depth
VP offset
VP length
Draw refresh
Recording
500 mV 500 mV 500 mV 200 µs
auto triggering
trigger
stop
record
shot
.csv

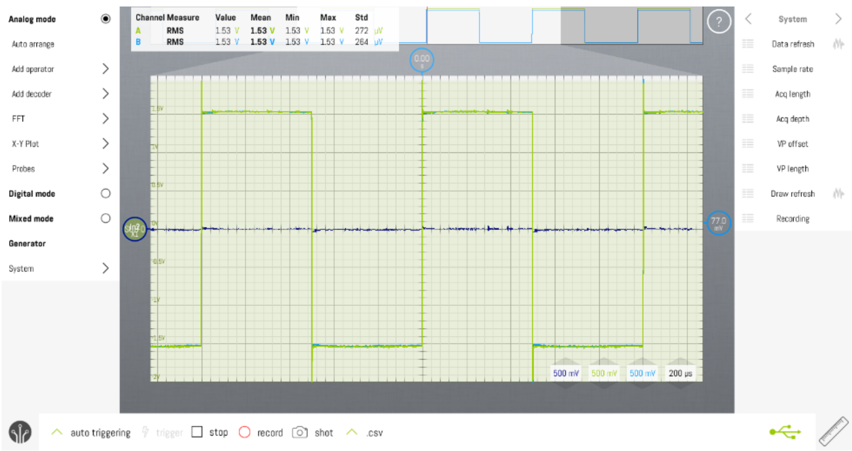

Analog mode
Auto arrange
Add operator
Add decoder
FFT
X-Y Plot
Probes
Digital mode
Mixed mode
Generator
System
Channel Measure Value Mean Min Max Std
A RMS 1.41 V 1.41 V 1.41 V 1.41 V 96.5 µV
B RMS 1.39 V 1.39 V 1.39 V 1.39 V 294 µV
Data refresh
Sample rate
Acq length
Acq depth
VP offset
VP length
Draw refresh
Recording
500 mV 500 mV 500 mV 200 µs
auto triggering
trigger
stop
record
shot
.csv


Analog mode
Auto arrange
Add operator
Add decoder
FFT
X-Y Plot
Probes
Digital mode
Mixed mode
Generator
System
Channel Measure Value Mean Min Max Std
A RMS 1.45 V 1.45 V 1.44 V 1.45 V 256 µV
B RMS 1.42 V 1.42 V 1.42 V 1.42 V 184 µV
System
Data refresh
Sample rate
Acq length
Acq depth
VP offset
VP length
Draw refresh
Recording
500 mV 500 mV 500 mV 200 µs
auto triggering
trigger
stop
record
shot
.csv


Analog mode
Auto arrange
Add operator
Add decoder
FFT
X-Y Plot
Probes
Digital mode
Mixed mode
Generator
System
Channel Measure Value Mean Min Max Std
A RMS 1.47 V 1.47 V 1.46 V 1.47 V 472 µV
B RMS 1.45 V 1.45 V 1.45 V 1.45 V 166 µV
System
Data refresh
Sample rate
Acq length
Acq depth
VP offset
VP length
Draw refresh
Recording
500 mV 500 mV 500 mV 200 µs
auto triggering
trigger
stop
record
shot
.csv


Analog mode
Auto arrange
Add operator
Add decoder
FFT
X-Y Plot
Probes
Digital mode
Mixed mode
Generator
System
Channel Measure Value Mean Min Max Std
A RMS 1.48 V 1.48 V 1.48 V 1.48 V 357 µV
B RMS 1.46 V 1.46 V 1.45 V 1.46 V 1.52 mV
System
Data refresh
Sample rate
Acq length
Acq depth
VP offset
VP length
Draw refresh
Recording
500 mV 500 mV 500 mV 200 µs
auto triggering
trigger
stop
record
shot
.csv

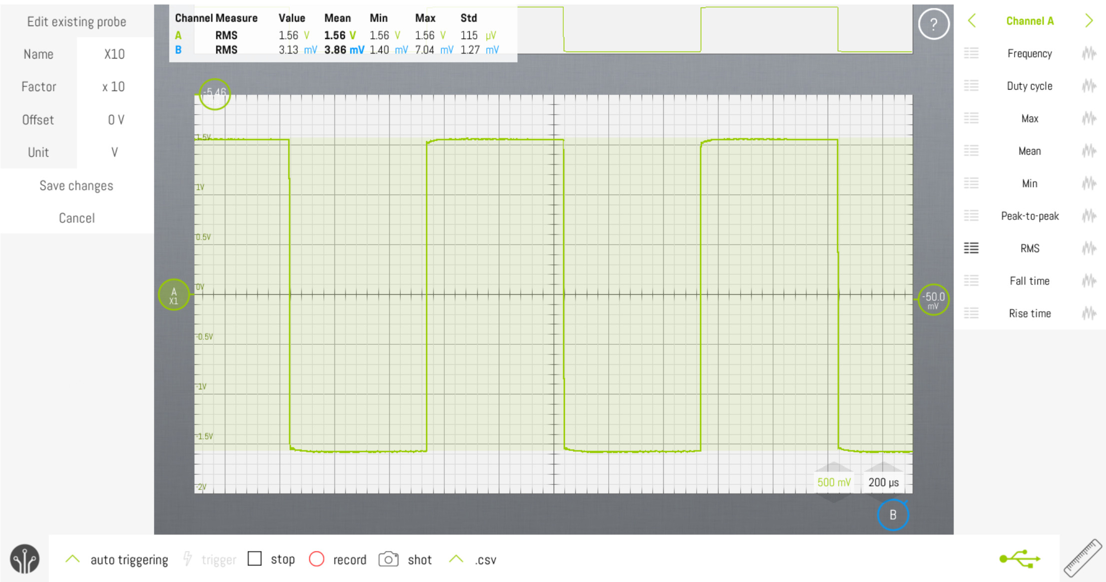




Result: the signal distortion is stable at the proportion of the load resistance and on resistance. The influence of on resistance can be eliminated on the current injection terminals.

Tests on measuring the middle voltage between 4 electrodes (A stable voltage is injected to electrode 0-8, which causes a stable injected current)

The injected voltage: 1.56V



R_{total} = 1870Ω

$I_{in} = V_{in}/ R_{total}$ = 0.834mA

The measuring probe is connected to COM0 and COM1 and switch between different electrode set to observe the signal distortion when measuring.

Measuring result of adjacent electrodes(01,12,23,34,45,56,67)

Error = 1- (1.56/1870*100)/84*1000*100% = 0.7%

Error = 1- (1.56/1870*150)/127*1000*100% = 1.5%

Error = 1- (1.56/1870*220)/184*1000*100% = 0.3%

Error = 1- (1.56/1870*270)/212*1000*100% = 0.6%

Error = 1- (1.56/1870*330)/279 *100% = 1.3%

Error = 1- (1.56/1870*370)/317*1000*100% = 3.6%

Measuring result of electrodes with interval of 2(02,13,24,35,46,57)

Error = 1- (1.56/1870*250)/211*100% = 1.2%

Error = 1- (1.56/1870*370)/311*100% = 0.7%

Error = 1- (1.56/1870*490)/397*100% = 3.0%

Error = 1- (1.56/1870*600)/491*1000*100% = 1.9%

Error = 1- (1.56/1870*700)/595*1000*100% = 1.9%

Error = 1- (1.56/1870*800)/688*1000*100% = 3.0%

Measuring result of electrodes with interval of 3(03,14,25,36,47)

Error = 1- (1.56/1870*470)/397*1000*100% = 1.2%

Error = 1- (1.56/1870*640)/524*1000*100% = 1.9%

Error = 1- (1.56/1870*820)/675*1000*100% = 1.3%

Error = 1- (1.56/1870*970)/807*1000*100% = 0.3%

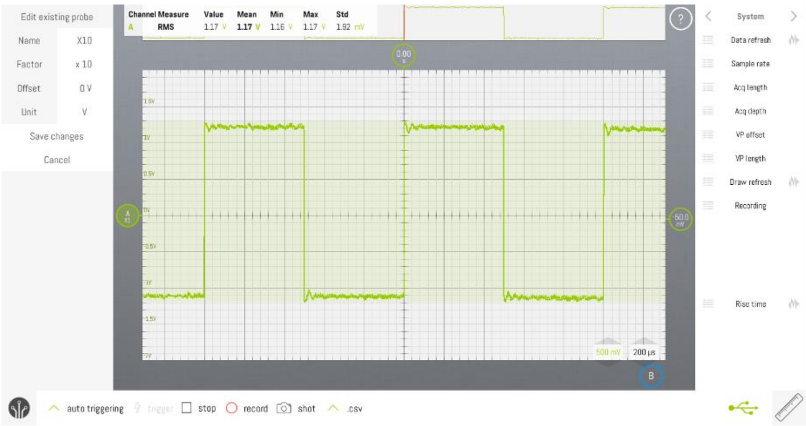
Error = 1- (1.56/1870*1130)/958*1000*100% = 1.6%

Measuring result of electrodes with interval of 4(04,15,26,37)

Error = 1- (1.56/1870*740)/606*1000*100% = 1.8%

Error = 1- (1.56/1870*970)/803*1000*100% = 0.8%

Error = 1- (1.56/1870*1190)/989*1000*100% = 0.4%



Error = 1- (1.56/1870*1400)/1170*1000*100% = 0.2%

Measuring result of electrodes with interval of 5(05,16,27)

Error = 1- (1.56/1870*1070)/889*1000*100% = 0.4%

Error = 1- (1.56/1870*1340)/1110*1000*100% = 0.7%

Error = 1- (1.56/1870*1620)/1350*1000*100% = 0.1%

Measuring result of electrodes with interval of 6(06,17)

Error = 1- (1.56/1870*1440)/1200*1000*100% = 0.1%

Error = 1- (1.56/1870*1770)/1480*1000*100% = 0.2%

Measuring result of electrodes with interval of 7(07)

Error = 1- (1.56/1870*1870)/1560*1000*100% = 0%

Error_average = 1.09%

Accuracy_average = 98.91%

Acuuracy_min = 96.4%