AUTOMATED LOW RESISTANCE MEASUREMENT TO TEST THE RELIABILITY OF PLATED VIA HOLES OF UNPOPULATED CIRCUIT BOARDS

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Signature

EHRENWÖRTLICHE ERKLÄRUNG

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DANKSAGUNG

I would like to thank my boss Robert Lamprecht, my supervisor FH-Prof. DI Dr. techn. Manfred Pauritsch and Dr. Sc. Ing. Maris Zeltins for their moral support and for advice and action.

ABSTRACT

Setting up a measurement system capable of automatically measuring low resistance plated via holes of unpopulated circuit boards during a reliability test is the goal of this thesis. It should be possible to carry out up to 30 resistance measurements at the same time, while the circuit boards are stored in a climatic chamber to carry out a thermal cycling test. In addition, the measuring system must provide a measuring current of 1A trough the plated via holes.

The focus was to find a suitable low resistance measurement method and an appropriate circuit scheme for switching between several circuit boards. In addition, attention was paid to scalability to increase the number of measurements if necessary. Furthermore, a user interface should simplify and track the control of the measurement.

During the investigation, the constant-current method combined with the four-wire measurement method is best suitable for the use case, as shown in Section 2.1 and Section 3.2. The constant-current method was implemented with an external current source and a voltmeter, as described in Subsection 2.1.1. The voltage drop across the plated via holes, which occurs because of the provided current flow of the constant current source, is measured with the voltmeter. The current in series to all DUTs circuit switching applications was chosen to implement the measurement system, as explained in Paragraph 6.1.1.1.

Due to the measurement methods and circuit applications investigated in the thesis as well as the practical presentation of the measurement system, it is possible to carry out automated low resistance measurements on plated via holes of circuit boards.

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1 INTRODUCTION

To meet the reliability criteria of a printed circuit board, numerous low resistance measurements based on reliability tests, such as the thermal cycling test, must be carried out. An essential aspect of these tests is to measure the voltage drop in a plated through hole under the influence of a current flow.

For the thermal cycling test, the unpopulated circuit boards are stored for a defined time and temperature in a climatic chamber, which simulates environmental influences. In reliability tests such as low resistance measurement, the change in resistance is measured during a test where the temperature switches constantly. The storage is carried out in a climatic chamber, which simulates extreme changes in temperature between –40 C and +125 C for 1000 cycles. The circuit boards to be measured automatically switch between the cold and warm chambers of the climatic cabinet.

In the initial situation, the low resistance measurement is carried out before and after the temperature change test. This means that it is not possible to record the change in resistance over time. The measured values are read from the measuring device, noted by hand, and then transferred to a spreadsheet.

In the thesis, the question is to be investigated utilizing which measurement method is suitable to carry out an automatic low resistance measurement of 30 plated via holes of unpopulated circuit boards.

The theoretical study of the measurement method and the practical implementation of the devices and circuit scheme of the measurement system will be described. The wiring of the measuring devices and the entire measuring setup is implemented. The measuring instruments are programmed with the LabVIEW software so that all parameters relevant for the measurement can be defined via the main computer. The theoretical part examines low resistance measurement methods as well as possible errors that can occur with low voltage measurements. Thereby, the selection of the measurement method and the circuit structure is determined. In the practical part, the construction and wiring of the entire measuring system and the programming of the measuring devices are implemented using the LabVIEW programming language.

With the measurement system described in this thesis, it is possible to automatically measure the low resistance of plated via holes with measurement data output in a text file.

2 LOW RESISTANCE MEASUREMENT

To select the measuring device for the automated low resistance measurement system, the determination of the measuring method suitable for the area of application must first be made. According to the method and customer specification requirements, applying a current flow of 1 A through the unknown resistance for the measurement is necessary. Further steps leading to the selection of the measuring devices are shown in Section 7.

With the constant-voltage method, it is impossible to guarantee a constant current flow of 1 A through the resistance under test due to the unknown resistance value. In addition, the resistance constantly changes due to the temperature change test, therefore, it is not possible to provide a constant current with the voltage method as described in this chapter.

Due to the requirement to measure the resistance with a defined current, the constant-current method is selected for the automated low resistance measurement system, which is developed in this thesis. Furthermore, it is possible to make accurate low resistance measurements if it comes to the constant-current method by selecting the appropriate measuring method, as further described in Chapter 3.

2.1 Constant-Current Method

A constant DC supply and a voltmeter are needed to do a four-wire low resistance measurement with the constant current approach. The unknown resistor's current flow rate can also be modified.

Two-wire low-resistance measurements can also be made with an ohmmeter. Because of this, the available test current quantity is dependent on the measurement range. Nevertheless, it is possible to use a single device if the goal is to adjust the amount of test current by using an SMU instrument. This instrument is capable of performing an accurate four-wire measurement. The differences between two- and four-wire measurement methods are further described in Chapter 3.

To perform a low resistance measurement, the following subsections will describe single and combined measuring circuit schemes, depending on the desired area of application.[1]

2.1.1 Voltmeter and External Current Source

A current generated by an external power source provides a current flow through the unknown resistor. A voltmeter measures the dropping voltage which occurs through the resistor. Ohm's law is used to compute the resulting resistance from the measured voltage and current.

[1] Vgl. TEKTRONIX, INC. 5.0 (2016), Online-Source [30.June.2021], P. 79.

The following figure shows an external current source that is connected to the resistance under test in series. The current flow through the resistor causes a voltage drop which is measured with the parallel-connected voltmeter.[2]

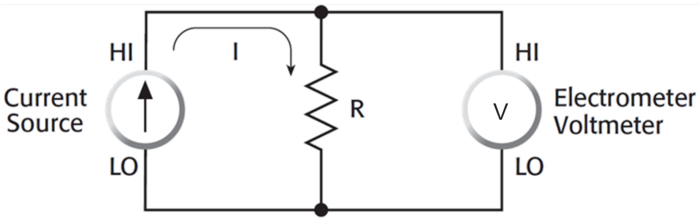


Figure 1: External Current Source and Electrometer Voltmeter, Source: TEKTRONIX, INC. 5.0 (2016), Online-Source [30.June.2021], P. 80 (slightly modified).

In some cases, it is advisable to use a constant current source and a voltmeter separate instead of a single instrument, depending on the user's need. If a portable use of the measurement system is required, then an Ohmmeter or SMU Instrument is preferred, as described in the following subsections. However, location-independent usage is not mandatory in many laboratory cases, so the use of separate devices is a better cost-effective choice as it is in the case of this thesis.

2.1.2 Ohmmeter

An Ohmmeter generates a current with a built-in current source and measures the occurring voltage across the resistance under test with an internal voltmeter. The resulting resistance is then calculated using the measured voltage and provided current by Ohm’s law. For comparison, a voltmeter and external current source allow for four-point measurements, whereas the Ohmmeter only allows for a two-point reading. The reason for this is the internal connection between the current source and the voltmeter so that they cannot be used separately, as one can see in the following circuit scheme of an Ohmmeter. [3]

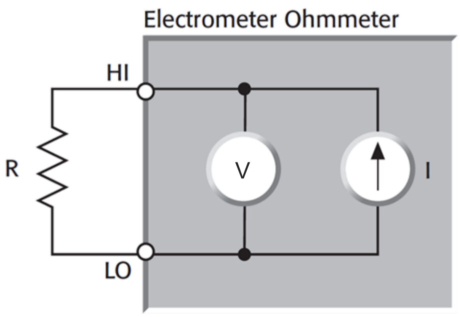


Figure 2: Ohmmeter Circuit Scheme, Source: TEKTRONIX, INC. 5.0 (2016), Online-Source [30.June.2021], P. 81 (slightly modified).

[2] Vgl. Thomas (2014), P. 119 – 120.

[3] Vgl. TEKTRONIX, INC. 5.0 (2016), Online-Source [30.June.2021], P. 81.

2.1.3 SMU Instrument

An source measuring unite (SMU) is capable of performing a resistance measurement in the two-wire or four-wire method. It is important to avoid error measurements for low resistance measurements due to long distances between the measurement device and resistance under test, which influence the wire resistance tremendous. Even if the distance is close, whether the wire resistance impacts the result depends on the measurement range. To avoid errors, the four-wire method should be preferred to the two-wire measurement method if the resistance under test is lower than 100, as explained in Chapter 3.

The following Figure shows the circuit schematic of an SMU instrument in the four-wire measurement method.

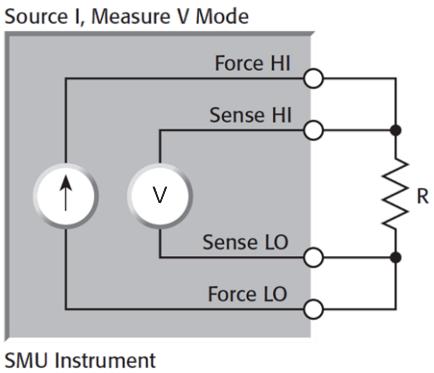


Figure 3: SMU Instrument Circuit Scheme, Source: TEKTRONIX, INC. 5.0 (2016), Online-Source [30.June.2021], P. 81 (slightly modified).

These autonomous remote sensing resistors are positioned in between HI Force and HI Sensing terminals and between the LO Force and LO Sensing terminals on some SMU instruments Using a single SMU instrument in remote mode may be further restricted because of this.[4]

Area of application, required flexibility and cost factors are decisive for the selection of whether a combined measuring device or two separate instruments are used.

2.2 Constant-Voltage Method

High resistance measurements can be made using the constant-voltage method, which requires the use of a constant DC voltage source and a low current instrument. In addition to measuring current, an ammeter with a built-in power supply may also compute resistance.

With this measurement method, a constant voltage source and an ammeter are connected in series to the unknown resistance, as shown in Figure 4. Due to the low internal resistance of the ammeter, the voltage drop across the ammeter can be neglected.

[4] Vgl. TEKTRONIX, INC. 5.0 (2016), Online-Source [30.June.2021], P. 80 – 81.

This means that almost all the voltage is applied to the resistance under test. The resistance is calculated from the measured current and the known voltage using Ohm's law.

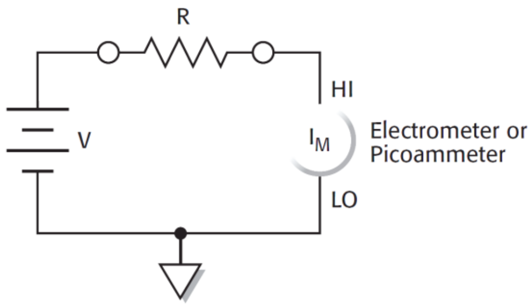


Figure 4: Constant-Voltage Method Circuit Scheme, Source: TEKTRONIX, INC. 5.0 (2016), Online-Source [30.June.2021], P.78.

It is not possible to apply a certain current flow through the unknown resistance with the CV method. The current amount depends on the resistance value and the applied voltage, so it is impossible to guarantee a constant voltage flow through the unknown resistance. In addition, the resistance value changes over time during the temperature influence of the reliability test. It means that a constant current flow is not possible when a voltage is applied. Due to the requirement of using a test current of 1 A, the constant-voltage method is not suitable for the low resistance measurement system.

The constant-voltage approach is superior than the constant-current method if the use case is to determine high resistance sources, because high resistance is frequently a function of the applied voltage.[5]

[5] Vgl. TEKTRONIX, INC. 5.0 (2016), Online-Source [30.June.2021], S. 78 – 79.

3 CONSTANT-CURRENT MEASUREMENT METHOD

As determined in Chapter 2, the constant-current method is best suited for the low resistance measurement system. Furthermore, it is possible to make accurate low resistance measurements in the constant-current method by selecting the appropriate measuring method.

The resistance values of single plated via holes of unpopulated circuit boards are commonly lower than 100 mΩ. Therefore, using a two-wire measurement method is not obligatory because the wire resistance will tremendously influence the measurement accuracy. The four-wire measurement application is consequently used, combined with the constant-current method as explained in this chapter.

3.1 Two-Wire Measurement

The simplest form of measuring the resistance is using a digital multimeter (DMM), which uses the two-wire measurement method. DMMs employ a method outlined in Section 2.1 to determine the unknown resistance of DUTs by supplying a constant current and measuring the voltage drop. Moreover, the test current of the DMM depends on the selected measurement range and is typically lower than 1 mA. The following table shows that the higher the unknown resistance value, the lower the test current of the DMM current source. Column one of the table illustrates different measurement ranges with corresponding test current in the second column. Measurement range and test current values based on KEITHLEY Model 2110 digital multimeter.

Measurement range	Test current
Ohm	**A**
100	$1 * 10^{-3}$
$1 * 10^{3}$	$1 * 10^{-3}$
$10 * 10^{3}$	$100 * 10^{-6}$
$100 * 10^{3}$	$10 * 10^{-6}$
$1 * 10^{6}$	$1 * 10^{-6}$
$10 * 10^{6}$	$100 * 10^{-9}$
$100 * 10^{6}$	$100 * 10^{-9}$

Table 1: Measurement Range and Test Current, Source: TEKTRONIX, INC 6.0 (2013), Online-Source [31.October.2021], S. 1 (slightly modified).

The following figure illustrates a simple two-wire measurement scheme without considering other influencing factors such as wire resistance. The current flow, which is provided by the internal constant current source (I) leads to a voltage drop across the DUT resistance. The voltmeter then measures this voltage drop (U_M) of the DMM. [6]

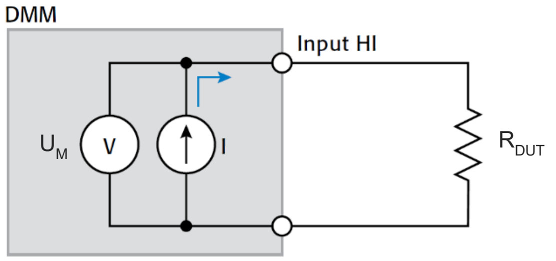


Figure 5: Two-Wire Measurement Circuit Scheme, Source: TEKTRONIX, INC 6.0 (2013), Online-Source [31.October.2021], P. 1 (slightly modified).

The unknown resistance is determined by using the ohm’s law based on the above circuit scheme, as shown in the following calculation:

$$R_{DUT} = \frac{U_M}{I} \qquad (1)$$

R_{DUT}/Ω	DUT Resistance
U_M/V	Measured Voltage
I/A	Source Current

The issue with two-wire measurement by employing constant current is that the DUT resistance is measured, and the resistance of both wires is taken into account in the measurement. As a result, the measurement accuracy is not given because of the resistance influence of the wires. This influencing factor cause a tremendous impact, mainly by measuring low resistance applications, which is explained in more detail by Calculation (4).

In addition to Figure 5, the following picture illustrates the influence of wire resistance using the two-wire method. As additional information, it should be mentioned that the following figure is used from an American publication, so the shown resistance schematic symbol is different from the commonly used European.[7]

[6] Vgl. TEKTRONIX, INC 6.0 (2013), Online-Source [31.October.2021], P. 1.

[7] Vgl. Thomas (2014), P.120 – 121.

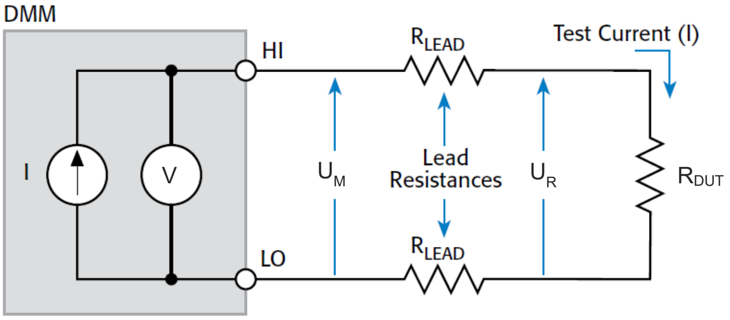


Figure 6: Two-Wire Measurement Circuit Scheme Considering Wire Resistance, Source: TEKTRONIX, INC 6.0 (2013), Online-Source [31.October.2021], P. 2 (slightly modified).

According to the circuit scheme above, the following equation demonstrates the wire resistance influence on the measured total resistance. The provided test current of the current source leads to a small voltage drop across the wires. Consequently, the measured voltage of (U_M) and (U_R) are not the same, which causes a measurement error.

Wire and DUT resistances are added together to calculate total resistance, as shown in the following equation.

$$R_{DUT} = \frac{U_M}{I} \qquad (2)$$

R_{LEAD}/Ω Wire Resistance

$$R_{Total} = R_{DUT} + (2 * R_{LEAD}) \qquad (3)$$

If the resistance under test is less than 100 Ω, two-wire resistance tests are nearly impossible since the lead resistance will entirely obliterate the resistance of interest.[8]

The following calculation example shows the influence of the total resistance if two 100 mΩ wires are used for measuring a 1 Ω resistance:

$$R_{Total} = R_{DUT} + (2 * R_{LEAD}) = \left(1 + (2 * 100 * 10^{-3})\right)\Omega = 1{,}2\Omega \qquad (4)$$

$$Error = \frac{R_{Total} - R_{DUT}}{R_{DUT}} * 100\,\% = \left(\frac{1{,}2 - 1}{1}\right)\Omega * 100\,\% = 20\,\% \qquad (5)$$

The calculation demonstrates that the two-wire measurement of a low resistance under test cause a 20 % error by affecting the total resistance.

According to internal company test measurements, the resistance values of single plated via holes of unpopulated circuit boards are commonly lower than 100 mΩ. Therefore, using a two-wire measurement method is not obligatory for the automated low resistance measurement system, which will be considered further in this thesis.

[8] Vgl. TEKTRONIX, INC 6.0 (2013), Online-Source [31.October.2021], P. 1.

3.2 Four-Wire Measurement

For low resistance sources, the four-wire measurement approach must be used to avoid altering the wire resistance measurement. When using this method, the DUT is supplied with continuous current and two sense wires measure the voltage drop across an unknown resistance. Wire resistance is eliminated because the constant current and voltage measuring channel is separated. However, the voltmeter's high impedance resistance still allows for a tiny sense of wire current flow, but it is minimal. [9] According to the literature, the current flow through the sense wire is typically less than 100 pA[10].

The following figure shows a four-wire measurement circuit scheme implemented with a digital multimeter.

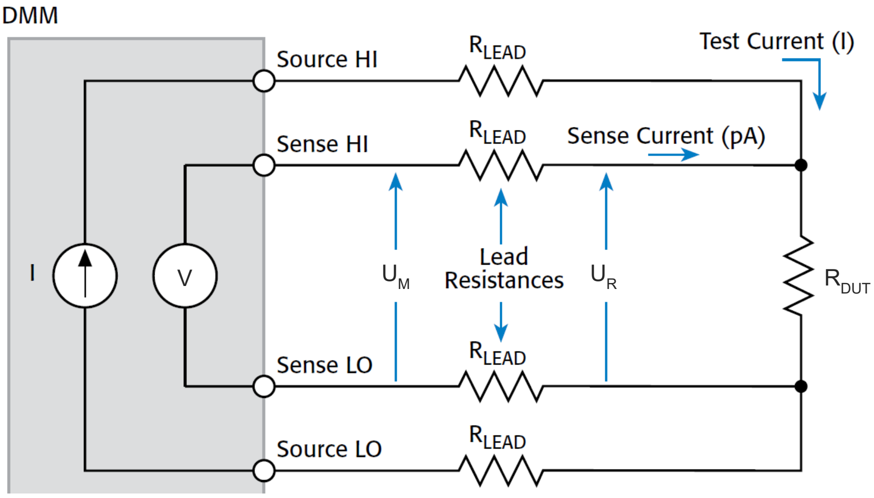


Figure 7: Four-Wire Measurement Circuit Scheme, Source: TEKTRONIX, INC 6.0 (2013), Online-Source [31.October.2021], P. 2 (slightly modified).

The following calculation demonstrates the negligible influence of the low sense current of 100 pA. Referring to Table 1, a 0,1 A test current is used to measure the example resistance of 1 Ω.

$U_M = R_{DUT} * (I_T - I_S)$	(6)	I_T/A	Test Current
$U_M = 1\,\Omega * (100 * 10^{-3} - 1 * 10^{-12})\,\mathrm{A} \approx 100 * 10^{-3}\,\mathrm{V}$		I_S/A	Sense Current
$U_R = R_{DUT} * I_{Test} = 1\,\Omega * 100 * 10^{-3}\,\mathrm{A} = 100 * 10^{-3}\,\mathrm{V}$	(7)		
$U_M = U_R$	(8)		

In conclusion, one can see that the measured voltage is equal to the resistance voltage. The four-wire measurement method is therefore used for precision measurements.[11]

[9] Vgl. Rainer (2016), P. 140.

[10] Vgl. TEKTRONIX, INC 6.0 (2013), Online-Source [31.October.2021], P. 2.

[11] Vgl. Thomas (2014), P. 121.

4 LOW RESISTANCE MEASUREMENT ERRORS

Low voltage measurements occur when it comes to measuring low resistance sources, as described in Chapter 2. For example, when using a 1 A test current to measure a $1 * 10^{-3}\,\mathrm{m\Omega}$ resistance, the dropping voltage across the DUT is $1 * 10^{-3}\,\mathrm{mV}$.

Low-voltage measurements can be skewed by offset voltage (DC) and noise sources (AC), but higher-voltage measurements don't suffer from these issues. Measurement errors can be caused by electrical noise, which is simply any unwanted signal. Static compensation can occur when the voltmeter is connected, and this can lead to erroneous or difficult-to-read measurement readings as a result of noise. Regardless of the situation, noise will have a substantial impact on measurement accuracy and hence, will result in large mistakes.

Using the offset corrected ohm's method, thermoelectric EMF voltages can be cancelled by the automated low-resistance measurement system. In this procedure, temperature differences between the measurement stations are avoided.

4.1 Error Sources on Voltage Measurements

The voltmeter should read zero if it is connected to a circuit with a low impedance and no voltage. However, non-zero DC offsets can arise from a variety of sources in the circuit.

Figure 8 shows voltage measurement effects by offset voltages that influence the accuracy of the measurement. The source voltage (U_S) and the source resistance (R_S) together results in a voltage source, which is connected to a voltmeter (U_M). When the DC offset voltage (U_{OFFSET}) is applied to the source voltage (U_S), the result is calculated as follows:

$$U_M = U_S \pm U_{OFFSET} \qquad (9)$$

U_M/V	Voltmeter
U_S/V	Source Voltage
U_{OFFSET}/V	DC Offset Voltage

The following equation shows how an error source can affect the voltage measurement, so an error of 5 % can quickly occur if an offset voltage is added to the circuit.

$$U_M = 5\,\mathrm{\mu V} - 250\,\mathrm{nV} \qquad (10)$$

$$U_M = (5 * 10^{-6}\,\mathrm{V}) - (250 * 10^{-9}\,\mathrm{V}) = 4{,}75 * 10^{-6}\,\mathrm{V}$$

$$U_M = 4{,}75\,\mathrm{\mu V}$$

Using the instrument zero (REL) function and shorting the ends of the test leads can help prevent inaccurate measurements caused by voltage offsets. With this method, constant offset voltages can be zeroed, although it may need to be zeroed frequently, especially in the case of thermoelectric, electromagnetic fields.[12]

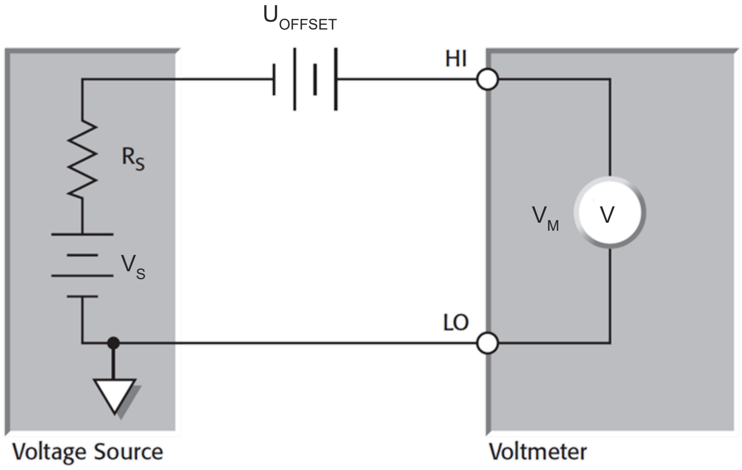


Figure 8: Effects of Offset Voltages on Voltage Measurement Accuracy, Source: TEKTRONIX, INC. 5.0 (2016), Online-Source [30.June.2021], P. 116 (slightly modified).

4.2 Thermoelectric EMFs

Thermoelectric voltages are one of the most prominent sources of low-voltage measuring inaccuracy. Varying circuit components at different temperatures and conductors made of different materials are the primary factors that cause these voltages to be generated. Different temperatures might be observed between the connection sites in Thermal Cycling resistance measurement. Temperature swings in the lab or a draft near the test circuit can also produce these thermoelectric voltages. The outcome's precision can be influenced by small microvoltage differences caused by temperature gradients.

A table summarizing the Seebeck coefficients (Q_{AB}) of several materials that affect the equation is shown below. EMF generation is reduced when conductors are made of the same material.

For example, crimping copper sleeves or lugs on copper wires yields into copper-to-copper junctions, that produce negligible thermoelectric EMFs. Additionally, the links must be kept clear of oxides. Connectors made of crimped copper are known as "cold-welded," and their seebeck coefficient may is ≤0.2 µV/°C. One mV/°C is possible for Cu-CuO couplings.[13]

[12] Vgl. TEKTRONIX, INC. 5.0 (2016), Online-Source [30.June.2021], P. 115 – 116.

[13] Vgl. TEKTRONIX, INC. 5.0 (2016), Online-Source [30.June.2021], P. 116.

The fact that dissimilar materials are connected does not affect this thesis's measurement system; therefore, it will not be discussed in detail.

The following table shows the Seebeck Coefficient dependent on paired materials.

Paired materials	Seebeck coefficient
	μV/°C
Cu - Cu	≤0.2
Cu - Ag	0.3
Cu - Au	0.3
Cu - Pb/Sn	1–3
Cu - Si	400
Cu - Kovar	~40–75
Cu - CuO	~1000

Table 2: Seebeck Coefficient with Respect of Copper, Source: TEKTRONIX, INC. 5.0 (2016), Online-Source [30.June.2021], P. 116 (slightly modified).

4.2.1 Current Reversal Method

This method uses a potential difference calculation to cancel thermoelectric EMFs with a current reversal. As one can see in Figure 9 and Figure 10, a current source and a voltmeter are used for carrying out the current reversal measurement. Therefore, the polarity of the current source will switch between the two measurements. As a result, one get a positive polarity measurement voltage (U_{M+}) for positive applied current and a negative polarity measurement voltage (U_{M-}) if the polarity of the current source is reversed.[14]

Here, the voltage drop across the circuit (U_{M+}) is being measured by means of a voltmeter, as is shown in the following figure due to a positive polarity applied current flow (I) of the current source.

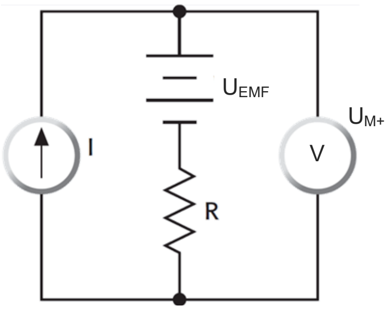


Figure 9: Positive Polarity Measurement, Source: TEKTRONIX, INC. 5.0 (2016), Online-Source [30.June.2021], P. 135 (slightly modified).

[14] Vgl. TEKTRONIX, INC. 5.0 (2016), Online-Source [30.June.2021] P.133.

An example of how positive polarity voltage is measured can be seen in the following calculation shown in Figure 9.

$U_{M+} = U_{EMF} + R * I$	(11)	U_{M+}/V	Positive Polarity Measurement Voltage
		U_{EMF}/V	Thermoelectric EMF Voltage

In contrast to Figure 9, the following figure shows a negative polarity measurement, where a voltmeter is used to measure the voltage drop across the circuit (U_{M-}) due to of a reversed applied current flow (I) of the current source.

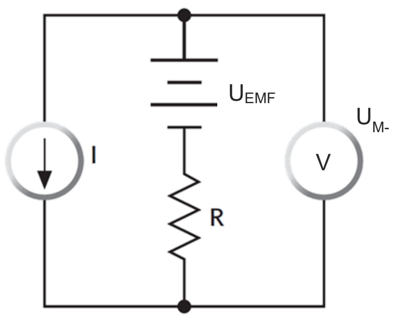


Figure 10: Negative Polarity Measurement, Source: TEKTRONIX, INC. 5.0 (2016), Online-Source [30.June.2021], P. 135 (slightly modified).

The following calculation illustrates how the negative polarity voltage measurement is composed, shown in Figure 10.

$U_{M-} = U_{EMF} - R * I$	(12)	U_{M-}/V	Negative Polarity Measurement Voltage

The two measurements of Equation (11) and Equation (12) can be combined to eliminate the thermoelectric EMF of a low resistance measurement application. Therefore, the following equation is used:

$$U_M = \frac{U_{M+} - U_{M-}}{2} \qquad (13)$$

By calculating the resistance value with the following equation, the thermoelectric voltage (U_{EMF}) is eliminated.[15]

$$\mathrm{R} = \frac{U_{M+} - U_{M-}}{2 * I} = \frac{(U_{EMF} + R * I) - (U_{EMF} - R * I)}{2 * I} \qquad (14)$$

Suppose it comes to canceling the thermoelectric EMF via the current reverse method. In that case, it is crucial to use a voltmeter with a fast response speed compared to the temperature change of the measured circuit. Otherwise, slight temperature changes would affect the thermoelectric voltage measurement, which causes fault resistance values.

[15] Vgl. TEKTRONIX, INC. 5.0 (2016), Online-Source [30.June.2021] P.135.

4.2.2 Offset Compensated Ohm's Method

Similar to the current reversal procedure, the thermoelectric voltage is eliminated using two distinct measurements. The second measurement is made without any applied current rather than with a reversed current, as with the current reversal method.

The following picture illustrates one measurement cycle of the offset compensated ohm's method. One can see a graph of the current source output, which changes within one measurement cycle from current *On* to current *Off.* One measurement cycle consists of measuring the total voltage of the circuit as well as measuring the thermal offset while the current source is *Off*.

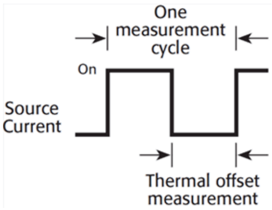


Figure 11: One Measurement Cycle of the Offset Compensated Ohm's Method, Source: TEKTRONIX, INC. 5.0 (2016), Online-Source [30.June.2021], P. 138.

The composition of one measurement cycle has already been described in the previous picture. Further, the following figures will show measurement circuit schemes with source current *On* and *Off*.

The following figure shows a voltage measurement with the offset compensated ohm's method by applying a source current. The dropping voltage across the resistor and any occurring thermoelectric EMF voltages, which are caused by the applied current flow of the power source, are measured by the voltmeter.[16]

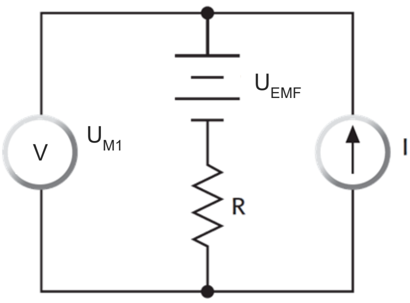


Figure 12: Voltage Measurement with Current Source *On*, Source: TEKTRONIX, INC. 5.0 (2016), Online-Source [30.June.2021], P. 138 (slightly modified).

The following equation results from the circuit scheme above, which shows a power source to apply a current through an unknown resistor. The dropping voltage is calculated as follows, by which an influencing thermoelectric EMF voltage is also measured:

$$U_{M1} = U_{EMF} + R * I \qquad (15)$$

U_{M1}/V Measurement Voltage with Current Source On

[16] Vgl. TEKTRONIX, INC. 5.0 (2016), Online-Source [30.June.2021], P. 137.

As mentioned above, the offset compensated ohm's method requires a second measurement without applying a current. Compared to Figure 12, the following circuit scheme does not carry out the thermal offset measurement without a power source. The second cycle thus only measures the thermoelectric EMF voltage.

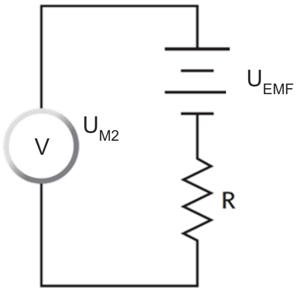


Figure 13: Voltage Measurement with Current Source *Off*, Source: TEKTRONIX, INC. 5.0 (2016), Online-Source [30.June.2021], P. 138 (slightly modified).

Since there is no current flow, there is no voltage drop across the resistor, and only the thermoelectric EMF voltage is measured, as one can see in the following equation.

$$U_{M2} = U_{EMF} \qquad (16)$$

U_{M2}/V Thermal Offset Measurement Voltage

The offset compensated ohm's measurement process cancels the thermoelectric EMF, as one can see by the following calculation.

$$U_M = U_1 - U_2 \qquad (17)$$

$$U_M = (U_{EMF} + R * I) - U_{EMF} = R * I \qquad (18)$$

$$R = \frac{U_M}{I} \qquad (19)$$

Occurring thermoelectric EMF voltages can be eliminated using the automated low resistance measurement system's ohm compensation method. This method avoids error measurements caused by different temperatures between connection points of the measurement.

5 THERMAL CYCLING TEST, TCT

The main goal for this thesis is to prepare a low resistance measurement system, to perform an online TCT test, also known as measuring the thermal shock test, as described in the this chapter.

The term online is used in several AT&S internal documents or customer specifications and means that a resistance measurement of unpopulated circuit boards will be executed at a fixed interval during the whole climate chamber storage. Therefore, the dropping voltage which occurs through a current carrying plated via hole will be measured. The unpopulated circuit boards are stored for a defined time and temperature in a climatic chamber during the whole measurement process, which simulates environmental influences. The goal of the TCT is to stress base material and the plating process to evaluate the reliability of the circuit board.

Apart from the low resistance measurement, there are also test setups where the high resistance of circuit board structures are measured to evaluate the insulation of the base material. For instance, the conductive anodic filament (CAF) test measures insulation resistance between several plated holes.

There are numerous different climate chamber tests to evaluate the reliability of base materials. Each test setup evokes different failures on the base material of circuit boards. In this chapter only the TCT is dealt with, as this is relevant for the measurement system.

5.1 Preconditioning

Preconditioning is mandatory to imitate the circuit board assembly process. The baking process is used to dry the specimens to reduce circuit board moisture, which can influence the resistance measurement during the reliability chamber tests.[17] Base material moisture emerges during different production processes, for example, lamination, plating, coating, surface finish and cleaning. These production processes affect the base material so it absorbs moisture. The overall moisture of the printed circuit board is negligible low as delivered condition but can affect the resistance measurement during the thermal shock test.

5.1.1 Drying/Baking

Baking is mostly used as the main moisture removal process by using high temperature. [18] It's an easy and effective method done by a PCB baking oven or in combination with a climate chamber before starting the main test. Specimens should dry in an oven for 6 h at 105 °C to 125 °C.[19]

[17] Vgl. IPC International, Inc. 1.0 (2020), Online-Source [23.June.2021] P. 2.

[18] Vgl. Millennium Circuits Limited (2021), Online-Source [05.November.2021].

[19] Vgl. IPC International, Inc. 1.0 (2020), Online-Source [23.June.2021] P. 2.

5.1.2 Reflow

The reflow test is designed to simulate the thermodynamic effects which occur during soldering thermal excursions. The maximum temperature of the solder reflow process can cause damage to PCBs; hence this test method measures the PCB's reflow sensitivity. Thermal stress causes the vapor pressure of moisture in PCBs to rise significantly, especially during the soldering process. PCB flaws such as internal delamination, cracks, and land lifting can occur under particular pressure situations.[20] The thesis focuses exclusively on the implementation of the measurement system, so errors caused by stress tests are not examined more closely.

The following figure shows a reflow oven that uses forced air convection to heat the PCBs to a specific temperature.

Figure 14: Air Reflow Oven MR260, Source: http://mechatronika.com.pl/en/products/ovens/mr260.html, Online-Source [10. November.2021].

Depending on the customer specification, different reflow temperature profiles are used to stress the specimens. According to IPC-TM-650 2.6.27B Specification, 6 reflow cycles should be done by each PCB.

[20] Vgl. IPC International, Inc. 4.0 (2020), Online-Source [05.November.2021], P. 1 – 9.

A typical 260 °C reflow profile is shown in the following diagram. It shows that the target preheat time (t1) is 210 s until reaching the preheat temperature (T1) of 230 °C. After 270 s the reflow, oven should reach the peak reflow time (t2) at target reflow temperature (T2) of 260 °C. The cool-down start time (t3) of the reflow profile starts after 330 s.

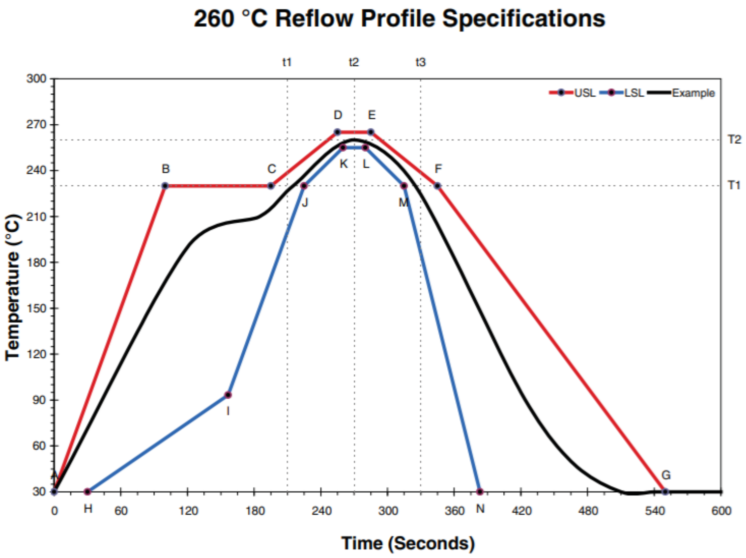
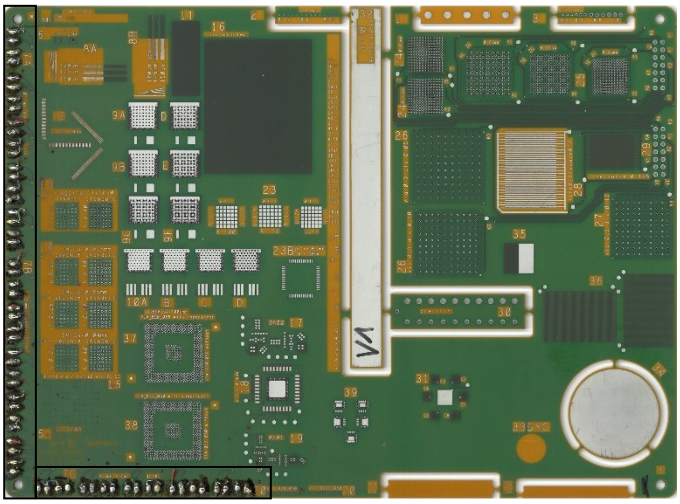


Figure 15: 260 °C Reflow Profile Specifications, Source: IPC International, Inc. 4.0 (2020), Online-Source [05.November.2021], P. 4.

5.1.3 Soldering

After preconditioning by drying/baking and reflow process, as described in the subsections before, it is possible to prepare the test boards for the soldering process. The connection points of the holes to be measured must be soldered by hand, as one can see in the following figure. After soldering the wires the test boards can be connected to the measurement system as shown in Section 7.5.



5.2 Main Test

Tests such as the thermal cycling test are used in order to determine the effects of temperature fluctuations or several temperature changes on an object.

To determine effects on permanent temperatures, a test with high temperature or cold temperature should be used. There are different test methods with defined test parameters, which are designed for stressing the specimen. For this thesis, only the change of temperature tests are considered; therefore permanent temperature tests will not describe in more detail.

Parameters such as high and low temperature for change conditioning, dwell time for how long the parts will stay at the certain temperature level, temperature change rate to switch between the defined temperature levels, and the number of total temperature cycles will affect the device under test to determine the influence the change of temperature.[21]

According to chamber temperature and time, one TCT cycle is shown in the following figure.

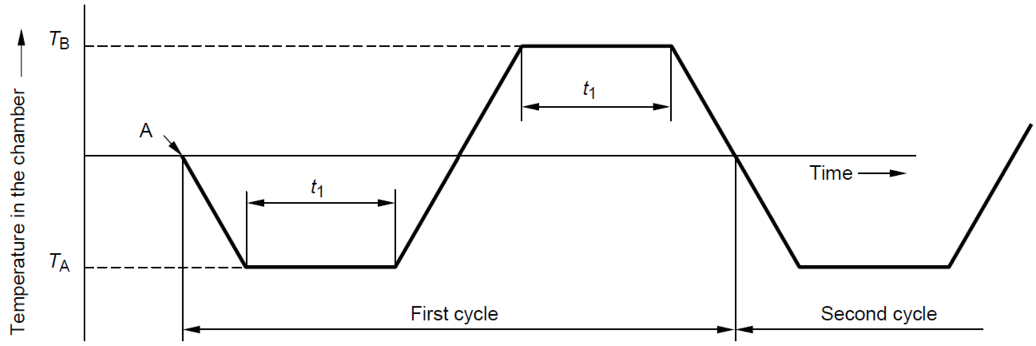


Figure 16: TCT Cycle; Source: International Electrotechnical Commission (IEC) (2009), Online-Source [14.Juy.2021], P. 15.

The terms thermal cycling test (TCT) and thermal shock test (TST) are sometimes used interchangeably, but there is a little contrast between the different tests. The variation between these two tests is just the sample change rate, defined by the IPC-TM-650 2.7.6.2 test manual.

It is defined that the transition between the cold and hot chamber of the thermal cycling test has a sample change rate of less than 1 °C per second as measured on the surface of the test specimen. In contrast, the temperature change rate of the thermal shock test is 1 °C or more per second. [22]

Other parameters such as high and low temperatures or even the test time can be varied between these two methods. As agreed between user and supplier, there are many possible temperature parameters or total test times.

Three types of temperature chamber cycling are available: single, dual, and triple. This type of single chamber cycling uses a fixed chamber to heat or cool the load, which can be heated or cooled by the

[21] Vgl. International Electrotechnical Commission (IEC) (2009), Online-Source [14.Juy.2021], P. 6.

[22] Vgl. IPC International, Inc. 1.0 (2020), Online-Source [23.June.2021], P. 1.

introduction of hot or cold air. A moving platform transports the load between two chambers that are kept at a constant temperature in dual-chamber cycling. The load is shifted between three chambers in triple-chamber thermal cycling.[23]

Thermal cycling test Chamber with dual-chamber cycling is shown in the following image.

Figure 17: CTS Thermal Cycling Test Chamber with Dual-Chamber Cycling, Source: https://www.cts-umweltsimulation.de/produkte/schock-tss.html, Online-Source [29.June.2021].

Tests are carried out to determine how well components and solder connections can endure the physical strains caused by the alternating high and low temperatures. Mechanical stress can permanently alter electrical and/or physical properties.[24]

To clarify misunderstandings, the term thermal cycling test is also associated with the term temperature cycling test. The same applies to the term thermal shock test and temperature shock test. For simplicity, the term thermal cycling test (TCT) is always used in this thesis.

5.2.1 Parameter

This chapter is in addition to Section 5.1, which has already described the difference between the term TCT and TST. An explanation of the test technique, including parameters and specifications, as well as results evaluation and a measurement of thermal shock resistance, may be found in this part.

In order to determine how well a material can withstand fast temperature changes, the thermal shock resistance test is used. With this method, it is possible to demonstrate how well the base material and chemical plating processes of circuit boards withstand temperature changes.[25]

[23] Vgl. JEDEC Solid State Technology Association (2014), Online-Source [29.June.2021], P. 1.

[24] Vgl. JEDEC Solid State Technology Association (2014), Online-Source [29.June.2021], P. 1.

[25] Vgl. IPC International, Inc. 2.0 (2013), Online-Source [29.June.2021], P. 102.

One differentiates between two types of temperature exposure, air-to-air and liquid-to-liquid. On the one hand, the extreme temperature changes are performed by heating an environmental chamber by air, and on the other hand, temperature-controlled liquid baths are used to fulfill specified test conditions.[26]

The use of the air-to-air method with continually measuring the thermal shock resistance is mandatory for reliability tests at AT&S plant Fehring.

AT&S distinguishes according to the test complexity and hardware requirements into thermal cycling test Level A (without electrical measurements), Level B (with ex-situ electrical measurements) and Level C (with in-situ electrical measurements), as one can see in Table 3.

Level A testing is a simplified test without carrying out a resistance measurement. The circuit boards are just subjected to the temperature change test chamber.

Level B testing is with a simplified non-continuous resistance measurement because the measurement will be carried out ex-situ before and after the thermal cycling test.

Due to the automated low resistance measurement system, it is possible to fulfill the requirements of test level C. The level C testing is with a continuous resistance measurement where the measurement will be carried out in-situ of the thermal cycling test chamber.

Item	**Types**	**Level A** without electrical measurements	**Level B** with ex-situ electrical measurements	**Level C** with in-situ electrical measurements
Resistance measurement	No	✓		
	Non-continuously		✓	
	Continuously			✓
In-situ / Ex-situ	Ex-situ		✓	
	In-situ			✓

Table 3: Overview of Test Setups, Source: Own representation.

When the TCT test is used, a distinction is made between qualification and quality conformance parameters. The quality conformance, also known as acceptance testing, is used for periodical checks of already qualified base materials or even finished circuit boards to determine that quality is maintained. It is important to show that the quality continues after a certain period, for example, one year. Therefore, the following requirements of Table 4 must be complied.

[26] Vgl. United States Military Standards, dt. (2015), Online-Source [29.June.2021], P. 45.

The table shows a comparison between qualification and acceptance testing requirements. As one can see, qualification requirements are mostly determined as agreed between user and supplier. In contrast, standard quality conformance conditions are given by specification.[27]

<table>
<tr><th>Item</th><th>Qualification</th><th colspan="2">Quality Conformance Acceptance Testing</th></tr>
<tr><td>Drying</td><td colspan="3">24 h @ 125 °C</td></tr>
<tr><td>Reflow Simulation</td><td colspan="3">6 cycles, 230, 245 or 260 °C profile</td></tr>
<tr><td>Temperature Min</td><td>AABUS</td><td colspan="2">–40 °C, –55 °C (default), –65 °C</td></tr>
<tr><td rowspan="3">Temperature Max</td><td rowspan="3">AABUS</td><td rowspan="3">min. of:</td><td>Tg –10 °C</td></tr>
<tr><td>Reflow peak –25 °C</td></tr>
<tr><td>210 °C</td></tr>
<tr><td>Dwell Time</td><td colspan="3">15 min @ min temperature / 15 min @ max temperature</td></tr>
<tr><td>Sample Change Rate</td><td>>10 °C /min for both hot and cold</td><td colspan="2">>1 °C /sec for both hot and cold</td></tr>
<tr><td>Number of Cycles</td><td>AABUS</td><td colspan="2">100</td></tr>
<tr><td>Failure Threshold</td><td>AABUS</td><td colspan="2">5 %</td></tr>
<tr><td>Resistance Data</td><td colspan="3">1 reading/cycle near the end of the high temperature dwell</td></tr>
<tr><td>Temperature Data</td><td colspan="3">1 reading/cycle near the end of the high and low temperature dwells (sample)
1 reading/sec through 1 complete cycle (sample and media)</td></tr>
</table>

Table 4: Comparison of Qualification and Quality Conformance Testing, Source: IPC International, Inc. 1.0 (2020), Online-Source [23.June.2021], P. 4 (slightly modified).

The following table gives an overview of cold and hot chamber cycle parameters.

Step per cycle	Chamber	Sample Temperature	Cycle count
1	Cold	$-55^{+0}_{-5}\,\mathrm{C}$	AABUS
2	Transfer	-	
3	Hot	$+125^{+5}_{-0}\,\mathrm{C}$	
4	Transfer	-	

Table 5: Cycle Parameter, Source: Own representation.

First and subsequent temperatures cycles will be measured for changes in resistance. Unless otherwise stated, the maximum percentage change in resistance between the first and subsequent cycles shall be 5%.[28]

[27] Vgl. IPC International, Inc. 1.0 (2020), Online-Source [23.June.2021], P. 4.

[28] IPC International, Inc. 1.0 (2020), Online-Source [23.June.2021], P. 4.

The following flow chart shows the procedure of a thermal cycle test. Three main parts separate the chart as follows: Before Testing, During Testing, and After Testing.

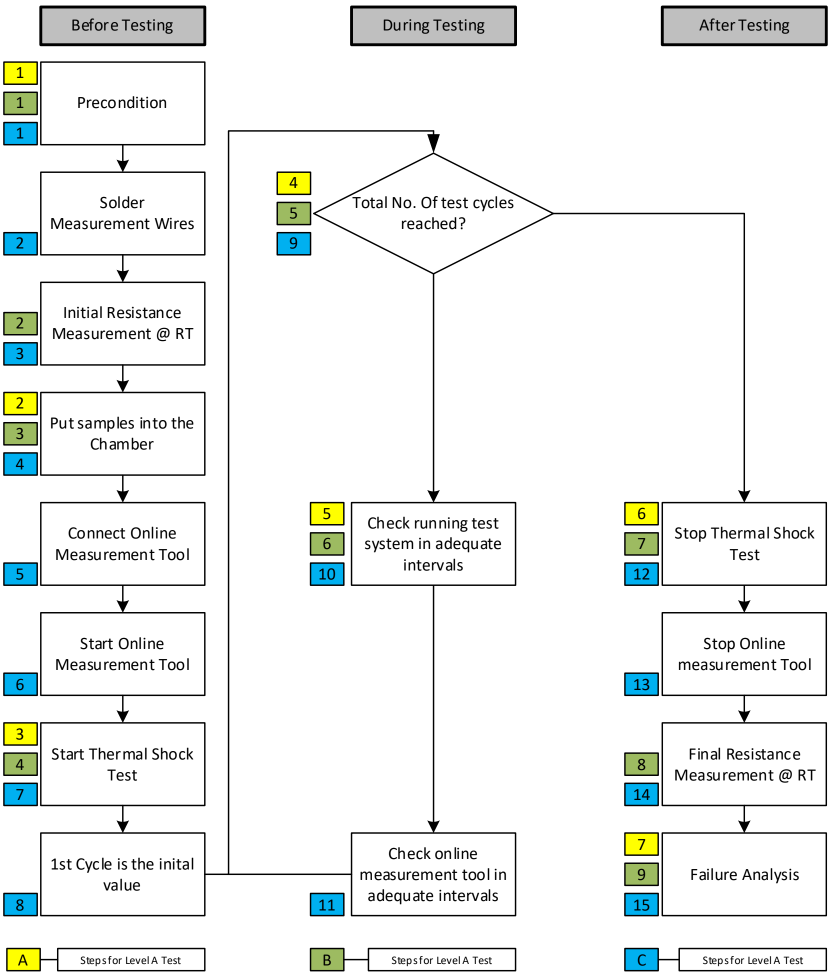


Figure 18: Procedure of the TCT Test, Source: Own representation.

The first step is to carry out the preconditioning, which is described in Section 5.1. After removing the moisture of the circuit board test samples by drying and performing a reflow sensitivity test, the samples are ready to solder the measurement wires. Next, an initial resistance measurement is carried out at room temperature. This initial resistance value is used to calculate the resistance change rate, that Equation (21) shows(21). After completing the measurement, the samples will be put into the climatic chamber, and soldered wires will connect to the connection terminals of the online measurement system. The thermal cycling test and online measurement program can be started at the same time after completing the preconditioning, soldering the wires, placing the circuit boards into the chamber, and wiring the cables. After starting the test, it is essential to check the running test in adequate intervals to prevent troubles and long downtimes. If the set-up cycle count of the thermal cycling test chamber has reached its limit, the program will automatically stop. Also, the automated low resistance measurement system will stop automatically after the last cycle. A final resistance measurement will be done at room temperature before the final step, analyzing the failure, can be done. Therefore, the next chapter deals with the evaluation of the tested circuit boards in more detail.

5.2.2 Evaluation

The internal AT&S specification describes the failure analysis procedure, which will not be further described in this thesis. This chapter gives an overview of further evaluation steps after finishing the test, according to AT&S internal specifications and IPC-TM-650 2.6.7.2.

The evaluation step is crucial to be able to make a statement about the test result. First, an optical inspection will be done to check the surface and solder mask of the circuit boards, and blister and cracks of the solder mask are not allowed. Second, depending on the required test level, the resistance change rate is calculated.

Level A testing

- Optical inspection for blisters and cracks of the solder mask
- Cross-sectioning of min. 3 PTHs or other specified laser holes to detect cracks in the plating

Level B testing

- Optical inspection for blisters and cracks of the solder mask
- Cross-sectioning of failed samples
- Calculate the resistance change rate ($\Delta\mathrm{R}$) according to the below equation
- $\Delta\mathrm{R}$ acceptance criteria is <5 %[29]

$$\Delta\mathrm{R} = \frac{R_F - R_I}{R_I} * 100 \qquad (20)$$

$\Delta R/\Omega$	Resistance Change Rate
R_F/Ω	Final Resistance
R_I/Ω	Initial Resistance

Level C testing

- Optical inspection for blisters and cracks of the solder mask
- Cross-sectioning of failed samples
- Calculate the resistance change rate ($\Delta\mathrm{R}$) to determine the reliability of the measured plated via holes of unpopulated circuit boards according to the following equation
- $\Delta\mathrm{R}$ acceptance criteria is <5 %

$$\Delta\mathrm{R} = \frac{R_C - R_I}{R_I} * 100 \qquad (21)$$

R_C/Ω	Cycle Resistance

[29] Vgl. IPC International, Inc. 1.0 (2020), Online-Source [23.June.2021], P. 4.

5.2.3 Failure

If the resistance change rate of an tested via is >5 %, as described in the subsection before, then it is necessary to further analyze the plated hole by an laboratory cross-section. With an cross-section analysis it is possible to detect failures inside of the PCB. Furthermore, it is feasible to visually check plated via holes to find different failures. The cause of changes in resistance are very often cracks which negatively affects the interconnection of plated holes.

As one can see in the following figure, there is a corner crack of a drilled hole which can negatively influence the resistance of the plated hole.

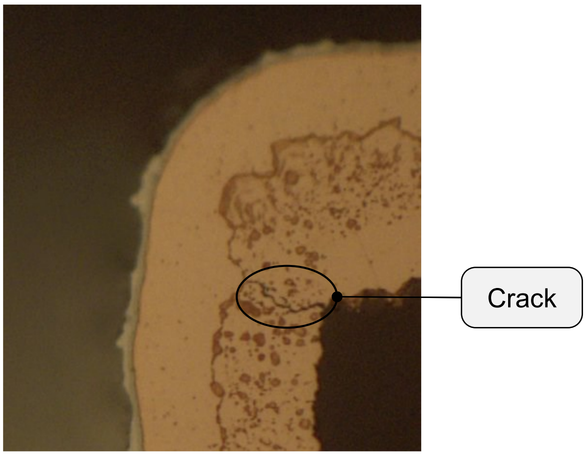


Figure 19: Corner crack of a plated drill hole, Source: Own representation.

In comparison to Figure 19, the following picture shows a connection crack of a filled via hole. The crack on the figure is tremendous because it breaks the plated connection of the hole, which can lead to an interruption in the flow of current.

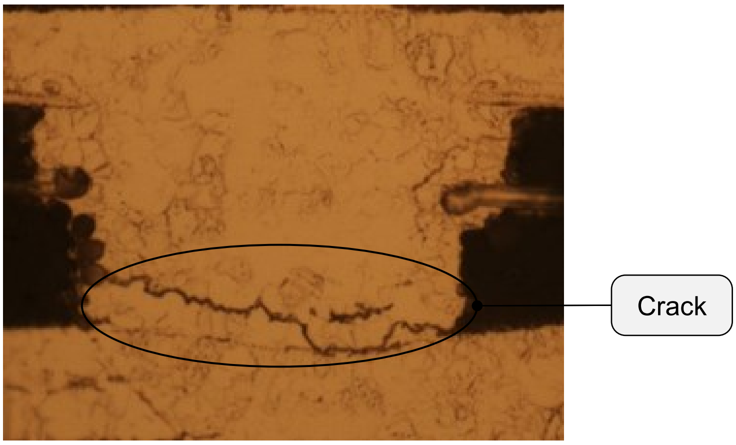


Figure 20: Connection crack of a plated via hole, Source: Own representation.

6 EQUIPMENT USED FOR MEASUREMENT-SYSTEM

The KEITHLEY 2200-20-5 DC Power Supply unit provides a constant current of 1 A for the measurement. Due to the current applied to the circuit board, a certain voltage drop occurs, depending on the plated via hole resistance size.

The low voltage drop, less than 1 mV, is measured with the integrated multimeter of the KEITHLEY 3706A System Switch/Multimeter. To automatically measure several via hole structures, the KEITHLEY 3706A is used to switch automatically between the connected DUTs during the measurement process.

The KITHLEY 3721 Multiplaxer Card is installed in the KEITHLEY 3706A System Switch/Multimeter to measure a total of 30 circuit board structures automatically. To provide a constant current flow of 1 A, all plated via hole structures are connected in series to the KEITHLEY 2200-20-5 DC Power Supply. To prevent an interruption of the current flow the KEITHLEY 3740 Switch Card is used to bridge via holes based on the event of defects, which can occur during the period of the reliability test.

6.1 KEITHLEY 3706A System Switch/Multimeter

For automated testing of electronic products and components, the 3700A Series, scalable instrument quality switching and multi-channel measurement solutions are perfect.

Because it contains six card slots and a built-in digital multimeter, the Model 3706A System Switch/Multimeter is adaptable. One mainframe can accommodate up to 576 two-wire multiplexer channels or 2688 one-pole matrix crosspoints thanks to the availability of six additional card slots. With a resolution of 26 bits, the Model 3706A internal multimeter measures up to $7\frac{1}{2}$ digits in precision. KEITHLEY 3706A System Switch/Multimeter has a high-performance internal multimeter to suit the rigorous application requirements of a functional test systems or stand-alone data acquisition and measurement applications. In addition, for remote PC control, ethernet, GPIB, and USB are all enabled for simple connectivity. Additional control of external devices is provided by fourteen programmable digital I/O lines on the board.

The System Switch/Multimeter provides faster stress testing, data collecting, and functional testing with a range of general plug-in cards.

Because the multimeter doesn't require a card slot, one can keep all six mainframe slots occupied at all times. This ensures that the signal line from each card channel to the multimeter is of excellent quality because the multimeter is connected to the mainframe's analog backplane."

The voltmeter's typical measurement value is shown in the following mathematical example by calculating the typical resistance of the DUT (R_{DUT}) of $\leq 1\,\mathrm{m\Omega}$ at a specified test current (I_T) of $1\,\mathrm{A}$.

$$I_T = 1\,\mathrm{A}$$

$$R_{DUT} = 1\,\mathrm{m\Omega}$$

$$U_M = R_{DUT} * I_S = 1\,\mathrm{A} * 1 * 10^{-3}\,\mathrm{A} = 1 * 10^{-3}\,\mathrm{V} \qquad (22)$$

$$U_M = 1\,\mathrm{mV}$$

U_M/V	Voltmeter
R_{DUT}/Ω	Device Under Test Resistance
I_S/A	Test Current

In Figure 21, one can see the supported built-in measurement functions with measurement capabilities of the high-performance multimeter. The KEITHLEY 3706A System Switch/Multimeter is used to measure the DC voltage of the device under test in the situation of low resistance connections like plated through holes. Typical resistance values of DUTs are around $1\,\mathrm{m\Omega}$; therefore, the DC voltage measurement capability of the multimeter, ranging from 10 nV to 300 V as shown in the following figure, is sufficient for this application.

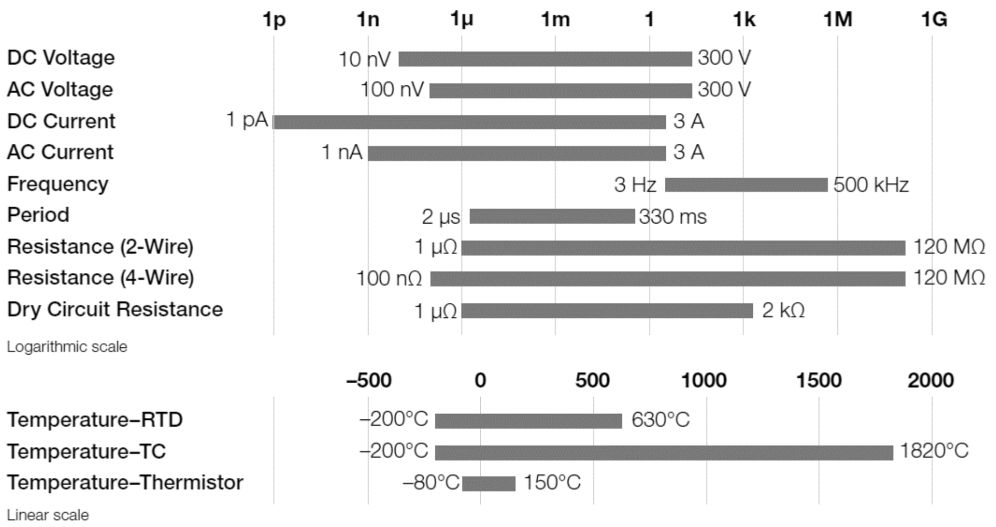


Figure 21: Measurement Capabilities of the High-Performance Multimeter, Source: TEKTRONIX, INC. 1.2 (2019), Online-Source [30.June.2021], P. 1.

Due to its scalability and flexibility, the Keithley 3706A System Switch/Multimeter is ideally suited for automated measurement of electrical components.[30]

[30] Vgl. TEKTRONIX, INC. 1.2 (2019), Online-Source [30.June.2021], P. 1.

Figure 22 shows the front panel of the System Switch/Multimeter equipped with a $7\frac{1}{2}$ digit multimeter. As mentioned above, there are six card slots at the rear panel side of the KEITHLEY 3706A.

Figure 22: Front Panel of KEITHLEY 3706A System Switch/Multimeter, Source: TEKTRONIX, INC. 1.2 (2019), Online-Source [30.June.2021], P. 1.

As one can see on the rear panel of Figure 23, there are six card slots available. The picture represents four cards, and two card slots are unused and protected with slot covers.

The automated low resistance measurement system slot 4, as one can see on the rear panel, is equipped with KEITHLEY 3721 Multiplexer Card as described in Subsection 6.1.1 below. Additionally, KEITHLEY 3740 Switch Card is equipped to slot 5, which is described in more detail in Subsection 6.1.3.

Slots 1 to 3 and slot 6 are already used for another measurement application, which is not necessary for this thesis to elaborate on it in more detail. In addition to the numbered picture of Figure 23,

Item	Description
1	Analog Backplane AMPS Fuse
2	Slots
3	TSP-Link Connector
4	Instrument Fuse
5	Power Connector
6	Digital I/O Port
7	GPIB Connector
8	Ethernet Connector
9	USB Connectors
10	Analog Backplane Connector

Table 6 shows a description of the rear panel features, with items appropriate to the picture.

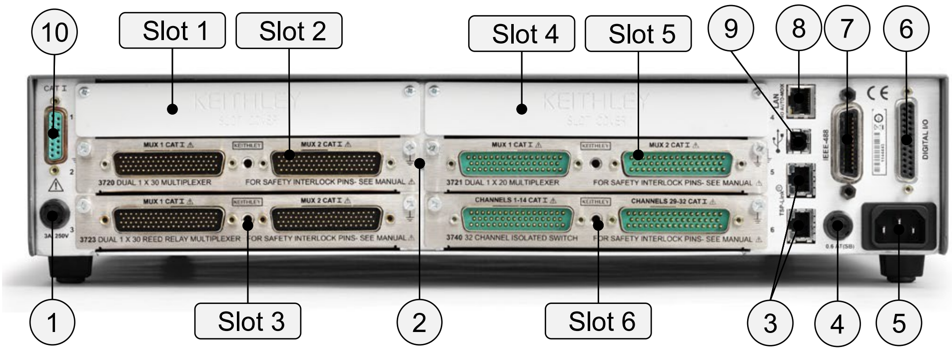


Figure 23: Rear Panel Connectors of KEITHLEY 3706A System Switch/Multimeter, Source: Based on TEKTRONIX, INC. 1.1 (2018), Online-Source [06.July.2021], P. 83.

Item	Description
1	Analog Backplane AMPS Fuse
2	Slots
3	TSP-Link Connector
4	Instrument Fuse
5	Power Connector
6	Digital I/O Port
7	GPIB Connector
8	Ethernet Connector
9	USB Connectors
10	Analog Backplane Connector

Table 6: Rear Panel Feature Description, Source: TEKTRONIX, INC. 1.1 (2018), Online-Source [06.July.2021], P. 83 (slightly modified).

6.1.1 Current Path Circuit Switching Applications

The following subsection will discuss the difference between two major current circuit path applications for applying current to each DUT. The chapter will compare the current circuit path in series to all DUTs with the method where the current path is switched to each DUT separately. The effort for soldering the wires as well as current path interruptions will be considered.

Suppose a break of the plated via hole occurs due to a fault in the chemical plating process or a current path interruption because of the circuit board base material change during the reliability test. In that case, it is necessary to take this influencing factor into account, which will be further described in this chapter.

The *Current in Series to all DUTs* circuit scheme is chosen for this thesis's automated low resistance measurement system. The focus was on the reduced preparation time of the circuit boards due to soldering two wires instead of soldering four wires to each DUT, which will be further explained in the following paragraphs. Because of the bridging detection process of the LabVIEW program, the increased programming effort was not a decisive factor.

The thesis will not describe the programming of the bridge process in more detail.

6.1.1.1 Current in Series to all DUTs

The following circuit scheme will illustrate how the current is applied to the DUTs in the Series. The positive and negative output of the KEITHLEY 2200-20-5 DC Power Supply is connected to the first and last DUT of the measurement, as one can see in the following figure at Item 1. DUTs between the power supply joints are connected to each other in series, so the current flow of the hole path is the same throughout. One can see the series connection of all DUTs in Figure 24, where the current path is marked with red lines.

The method requires less wire soldering effort if all DUTs are connected in Series, because the operator must solder just two measurement wires to each DUT. This is a mandatory factor for choosing the suitable method, if it comes to saving preparation time of the circuit boards before the operator can start the measurement.

The main problem of this method is an interruption of the current flow due to a DUT error. Instead of the explained method in Paragraph 6.1.1.2, where the current circuit path is switched to each DUT separately, it is necessary to keep the current path straight in case of a broken DUT. For this situation, the illustrated circuit scheme shows the connection between DUTs and the bridging channels, which keeps the current flow of the circuit maintained. The DUTs are wired to COM and NO contacts of the bridge card, as one can see at Item 2 of the following picture because the switch will close and bridge the fault DUT if an interruption of the current path occurs due to do of a broken DUT. As a result, this maintains further measurements, as the current flow is still applied in series to all plated via holes.

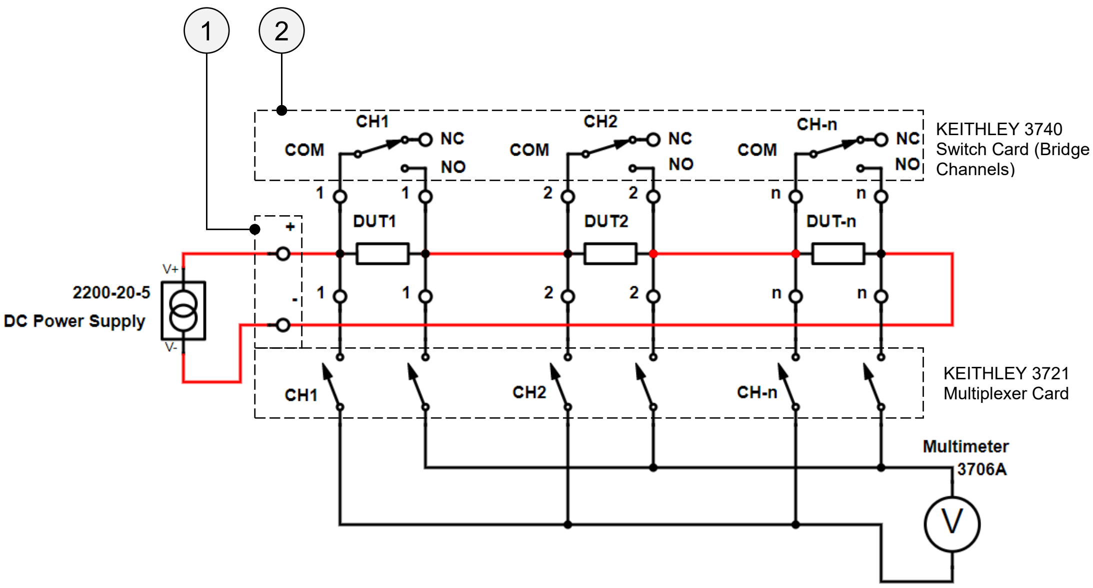


Figure 24: Current Circuit Path in Series to all DUTs, Source: Own representation.

The detection of a fault DUT will be automatically done by the *Bridge VI* of the *Bridge* state of the LabVIEW program using KEITHLEY 3740 Switch Card in combination with the CC and CV mode of the KEITHLEX 2200-20-5 DC Power Supply shown in Figure 61. The VI will detect the broken DUT and close the appropriate channel for next measurements to fix the current flow interruption. After completing the bridge process, the reliability test will continue by executing further measurements.

6.1.1.2 Current Switched to each DUT Separately

As already explained in the chapter above, connecting the DC power supply in series to all DUTs to apply the current flow. Another possibility is to switch the current path to each DUT separately. This method uses a current switching card, as one can see in the following figure at Item 1, to apply the current path to each sample instead of using a switching card to bridge defect DUTs.

This method requires 4 soldered wires to each device under test, instead of 2 soldered wires as explained with the *Current in Series to all DUTs* method in Paragraph 6.1.1.1. It is necessary to solder 2 wires to apply the current flow and 2 wires to measure the dropping voltage across the DUT. The preparation time of each circuit board under test is thus doubled, compared to the explained method above, where it is necessary to solder 2 wires instead. The soldering preparation time of the circuit boards is tremendous increased, but joining the soldered wires to the connection terminals of the measurement system, which one can see in Figure 49, is doubled. Further preparation time comparison is explained in Paragraph 6.1.1.3.

The LabVIEW program would not be as complex as the current in series circuit method because the error DUT detecting process would be omitted. In this case, it is just necessary to set up a LabVIEW current path closing mechanism with a suitable current switching card. Measuring a DUT means that the measurement channel must first close the current switch to apply a current flow through the DUT, followed by closing the respective Channel of the KEITHLEY 3721 Multiplexer Card to carry out the voltage measurement with the KEITHLEY 3706A System Switch/Multimeter internal multimeter.

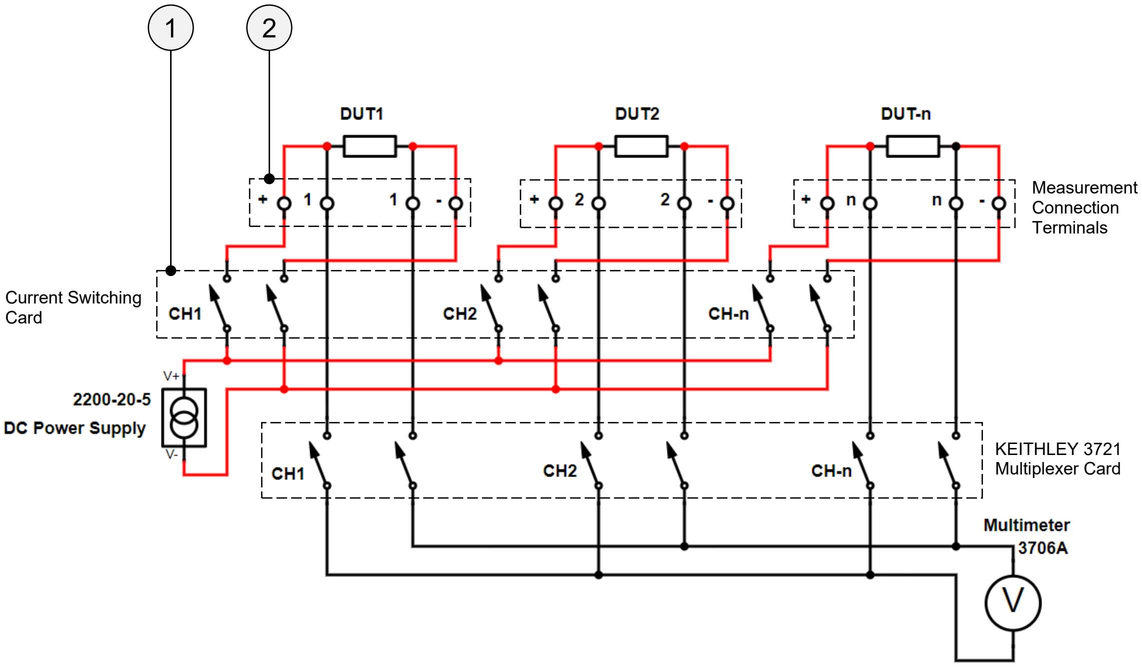


Figure 25: Current Circuit Path Switched to Each DUT Separately, Source: Own representation.

As one can see in the current circuit path scheme of Figure 25 at Item 2, the method requires 2 current and 2 measurement connection terminals for each DUT. The positive and negative output of the DC power supply is switched with a current switching card, as one can see at Item 1, to each DUT of the measurement. Also, two wires of each switching channel of the KEITHLEY 3721 Multiplexer Card are connected to each DUT.

6.1.1.3 Preparation Time Comparision

Comparing the preparation time of both methods without considering the LabVIEW programming effort, operator preparation costs, and LabVIEW programming costs comes to the following conclusion as shown in Table 7.

Item	Current in Series to all DUTs	Current Switched to each DUT
	min	min
Wire preparation	20	40
Wire soldering	90	180
Wire connecting to terminals	30	60
	140	280

Table 7: Comparison of Preparation Time, Source: Own representation.

From internal AT&S experience, one can say that the soldering process for 30 DUTs with the *Current in Series to all DUTs* method takes about 90 minutes. That means soldering of 60 wires in total is required, because it is necessary to solder 2 wires for each DUT. In comparison, soldering of 120 wires is required with the *Current Switched to each DUT* method, which doubles the solder preparation time from 90 min to 180 min, as one can see in calculation Table 7. If we take the preparation time as an important factor into account, it is decisive to choose the appropriate method. The 2-wire soldering process will tremendously reduce the preparation time, which positively impacts circuit boards need to be processed and tested quickly especially in base material qualification tests or production line process decisions, where a quick result is required.

For developing the automated low resistance measurement system, the *Current in Series to all DUTs* scheme is chosen for this thesis.

6.1.2 KEITHLEY 3721 Multiplexer Card

For general-purpose switching and temperature readings, the 3721 Multiplexer Card has two independent banks of 120 two-pole multiplexers. The analog backplane connection relays automatically connect the two banks to the Series 3700A mainframe backplane and optional DMM. The KEITHLEY 3721 can be used as a single 140 two-pole multiplexer via this connection, or it can be expanded via card-to-card extension to accommodate much bigger combinations. This model has a variety of additional options. For current measurements, two more fused channels are provided. A 40-channel common-side ohm’s measurement capability is also included in the 3721. The 3721-ST (screw terminal) attachment supports automatic cold junction compensation (CJC) for thermocouple type measurements. D-sub male connectors are used for signal hookups on the 3721. Disconnectable 3721-ST attachment required for screw terminal or automatic CJC installation.[31]

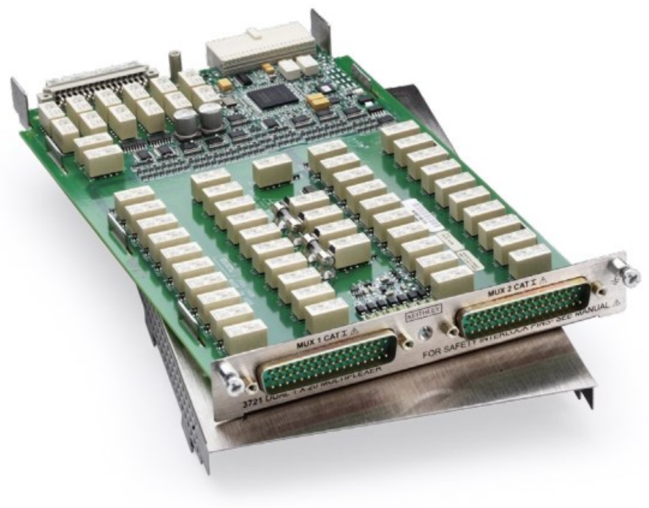


Figure 26: KEITHLEY 3721 Dual 1×30 Multiplexer Card, Source: TEKTRONIX, INC. 1.2 (2019), Online-Source [30.June.2021], P. 22.

The following circuit diagram depicts a four-wire common side ohm mode switching design, as shown.

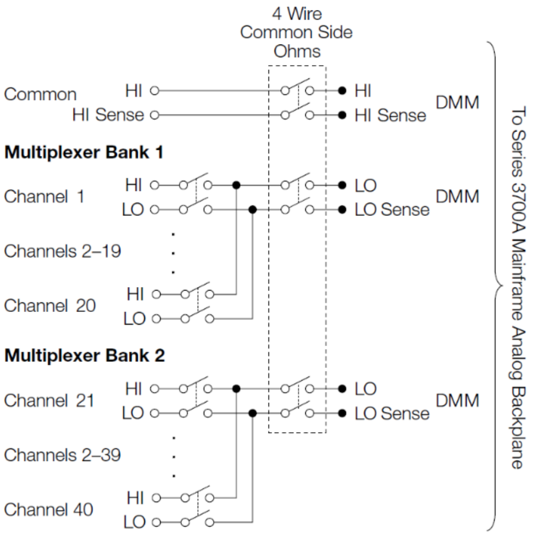


Figure 27: KEITHLEY 3721 Four-Wire Common Side Ohm Mode Circuit Scheme, Source: TEKTRONIX, INC. 1.2 (2019), Online-Source [30.June.2021], P. 23.

For the case of the low resistance measurement system, it is impossible to perform the resistance measurement with four-wire common side ohm mode because the KEITHLEY 3706A cannot provide a constant current, which is mandatory according to the customer and international specification requirements. Therefore the KEITHLEY 3721 Multiplexer Card is used in a two-pole mode in combination with the KEITHLEY 2200-20-5 DC power supply.

[31] Vgl. TEKTRONIX, INC. 1.2 (2019), Online-Source [30.June.2021], P. 22.

6.1.3 KEITHLEY 3740 Switch Card

The purpose of the 3740 Switch Card is to bridge fault DUTs that failed during the reliability test. As already described, the current source is connected in series to all DUTs; therefore, if a connection is opened due to hole cracks, the current flow would be interrupted for all remaining DUTs.

The general-purpose form C channels in the 3740 are useful for routing power or other control devices. The 3740 offers 28 of these. Four additional high current form A channels are available for use with larger currents and higher power (up to 7 A). Jumpers can be used to route any general-purpose signal to the Series 3700A mainframe backplane, which has terminal blocks on the card for this purpose. The user-accessible terminal blocks allow for custom setups. Additionally, a temperature sensor is built-in to monitor operational temperatures, preventing overheating that could compromise system requirements.

The 3740 has two 50-pin male D-sub connectors that are used to link the various signals. In order to make screw terminal connections, utilize the 3740-ST accessory. [32]

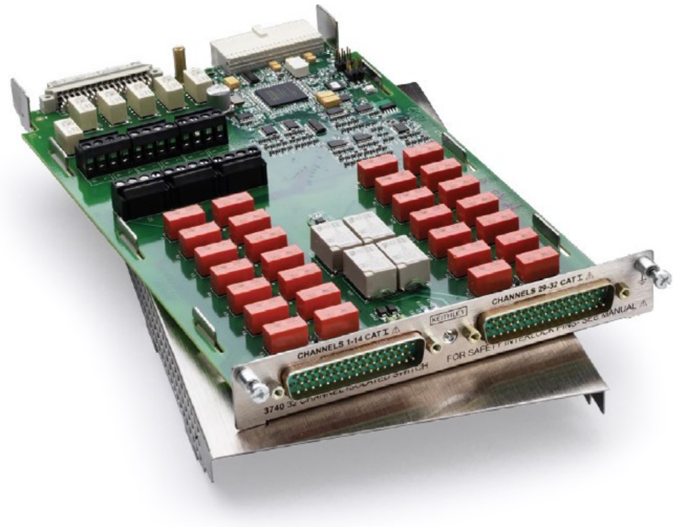


Figure 28: KEITHLEY 3740 32-Channel Isolated Switch Card, Source: TEKTRONIX, INC. 1.2 (2019), Online-Source [30.June.2021], P. 46.

6.2 KEITHLEY 2200-20-5 DC Power Supply

The following section gives an overview of front and rear panel features and an explanation of a cost-effective calculation.

6.2.1 General Device Description

Programmable DC power supply: The KEITHLEY 2200-20-5 can deliver a wide range of current outputs. An external power supply can be used to test through hole resistance as a constant current source or a constant voltage source, depending on the application. The KEITHLEY 2200-20-5 DC Power Supply has a

[32] Vgl. TEKTRONIX, INC. 1.2 (2019), Online-Source [30.June.2021], P. 46.

maximum output power of 100 W and can deliver a DC voltage of 20 V and a current of 5 A. Via hole resistance can be measured with this device, which can supply a constant DC current of 1 A.[33]

Figure 29 shows a picture of the front panel to describe the features of the device.

Figure 29: Front Panel of the KEITHLEY 2200-20-5 DC Power Supply, Source: TEKTRONIX, INC. 2.0 (2017), Online-Source [21.July.2021] P. 20.

In addition to the numbered picture of the front panel, Table 8 shows a description of the panel features, with items appropriate to the picture.

Item	Name	Description
1	Display	Shows information
2	Information	The top row shows the output, bottom row settings. Left column for voltage and right column for the current display.
3	Arrow Keys	Navigation
4	Navigation Wheel	Increase and decrease digits
5	Output Connectors	High, low, and ground connection
6	Save and Recall Keys	Store function
7	Numeric Keypad	Number keys for entry
8	V-Set, I-Set, Shift, and Output On/Off Keys	Set voltage and current and switch output On/Off
9	Power Switch	Turn instrument On/Off

Table 8: Front Panel Feature Description, Source: TEKTRONIX, INC. 2.0 (2017), Online-Source [21.July.2021], P. 20-21 (slightly modified).

[33] Vgl. TEKTRONIX, INC. 2.1 (2011), Online-Source [07.July.2021], P. 1.

The following figure shows a picture of the rear panel to describe the features of the device.

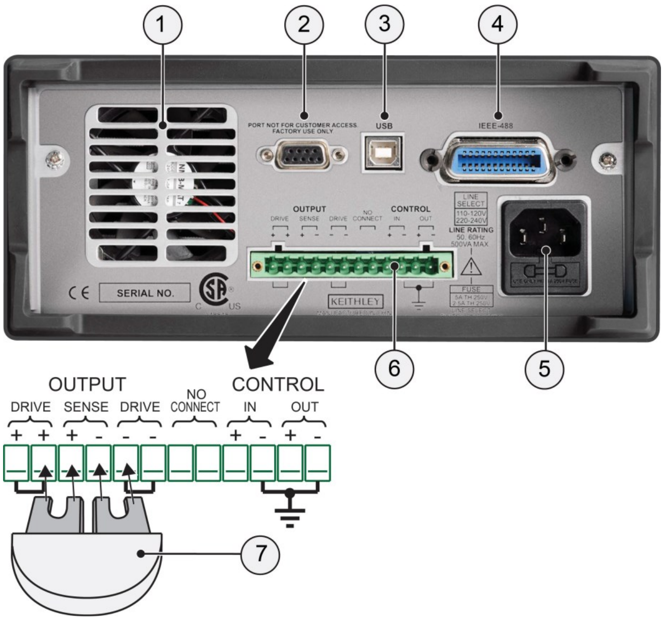


Figure 30: Rear Panel of the KEITHLEY 2200-20-5 DC Power Supply, Source: TEKTRONIX, INC. 2.0 (2017), Online-Source [21.July.2021], P. 28.

In addition to the numbered picture of the rear panel,

Item	Name	Description
1	Cooling Vents	Exhaust vent for internal cooling
2	Factory Test Port	For factory changes
3	USB Device Port	Remote control and data transfer to a PC
4	GPIB Connector	Remote control and data transfer to a PC
5	110 V/220 V Power Connector	Power input
6	12-Pin Connector	Using sources
7	Shorting Clips	For shorting

Table 9 shows a description of the panel features, with items appropriate to the picture.

Item	Name	Description
1	Cooling Vents	Exhaust vent for internal cooling
2	Factory Test Port	For factory changes
3	USB Device Port	Remote control and data transfer to a PC
4	GPIB Connector	Remote control and data transfer to a PC
5	110 V/220 V Power Connector	Power input
6	12-Pin Connector	Using sources
7	Shorting Clips	For shorting

Table 9: Rear panel feature description, Source: TEKTRONIX, INC. 2.0 (2017), Online-Source [21.July.2021], P. 29 (slightly modified).

6.2.2 Cost-Effective Calculation

The following calculation compares a SMU device capable of performing accurate four-wire measurements with a DC power supply in combination with the KEITHLEY 3706A System/Switch Multimeter. In both cases, a system switch/multimeter must be used anyway for switching 30 DUTs. Furthermore, the switch is equipped with a build-in voltmeter, so it is possible to measure the voltage drop of a single DUT caused by the supplied current flow of the DC power supply[34]. According to the device applications, comparing the KEITHLEY 2460 Source Measure Unit with the KEITHLEY 2200-20-5 DC Power Supply makes sense.

According to customer specifications, it is necessary to provide a constant current flow of 1,1 A to measure the resistance under test. Based on the providing current requirement, the following two devices were chosen from Figure 76 and Figure 77 in Appendix 2. The most cost-effective way is by using the KEITHLEY 2200-20-5 DC Power Supply in combination with the build-in voltmeter of the KEITHLEY 3706A System Switch/Multimeter, as one can see in the following comparison price list table.

Device name	List Price
KEITHLEY 2200-20-5 DC Power Supply	€ 1030,-[35]
KEITHLEY 2460 Graphical Series SMU Source Meter	€ 8740,-[36]

Table 10: Chosen Devices for Cost-Effective Comparing, Source: Own representation.

As a result, cost savings of € 7700,- are achieved by combining and taking into account the capabilities of the measuring devices, instead of buying a one-device solution.

6.3 KEITHLEY KUSB-488B USB to GPIB Converter

IEEE-488.1 and IEEE-488.2 standards are supported by the USB to GPIB converter. An IEEE data transfer rate of 1.5 MB/s can be achieved with the USB port of the product. Thanks to the plug and play system, with the built-in 2-meter USB cable, the converter does not require an external power supply. The device driver supplied ensures smooth communication between the measuring device and PC. In addition to installing the driver, the *Keithley GPIB Configuration Utility* software is also installed. With the help of the software, settings such as bus address or input/output times can be easily configured.

[34] Vgl. Rainer (2016), P. 140.

[35] TEKTRONIX, INC. 2.2 (2021), Online-Source [02.November.2021].

[36] TEKTRONIX, INC. 8.0 (2021), Online-Source [02.November.2021].

The two measuring instruments presented in Chapter 6 are connected via IEEE, which will be described in the following section. The communication between measuring devices and PC takes place with a subsequent connection with the USB to GPIB converter so that all instruments can be controlled individually with any computer.[37]

Figure 31: USB to GPIB Converter KEITHLEY KUSB-488B, Source: TEKTRONIX, INC. 4.0 (2018), Online-Source [02.June.2020], P. 5.

6.4 GPIB Interface

A shielded cable equipped with standard GPIB connectors, as shown in Figure 32, is used for communication of the two devices. To allow many parallel connections to one instrument, stack the connectors like the example of Figure 33.[38]

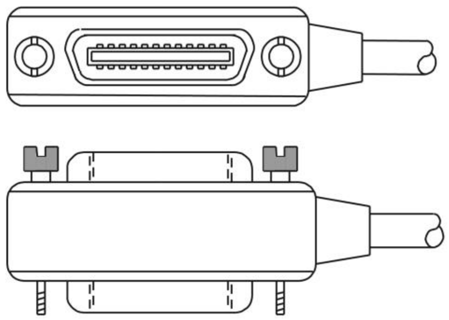


Figure 32: Representation of a GPIB Connector, Source: TEKTRONIX, INC. 1.1 (2018), Online-Source [06.July.2021], P. 85.

[37] Vgl. TEKTRONIX, INC. 3.0 (2017), Online-Source [30.June.2021], P. 5 – 7.

[38] Vgl. TEKTRONIX, INC. 1.1 (2018), Online-Source [06.July.2021], P. 85.

One can see an example of how numerous devices are connected in parallel by looking at the following figure. Devices must not be connected in a loop pattern, which makes connecting easier. If the GPIB cable is plugged into the wrong device, it doesn't make any difference.

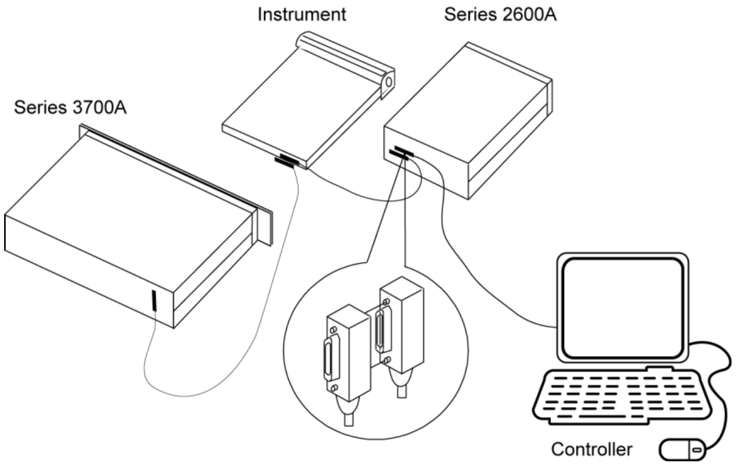


Figure 33: Example of Multiple Parallel Connections, Source: TEKTRONIX, INC. 1.1 (2018), Online-Source [06.July.2021], P. 86.

7 WIRING OF THE MEASUREMENT SYSTEM

In this chapter, the core elements for wiring the entire measuring system are explained in detail. The connection of the KEITHLEY 3706A System Switch/Multimeter and KEITHLEY 2200-20-5 DC Power Supply, as well as the wiring of the distribution board, are illustrated. Furthermore, the hole measurement system assembly will be shown to get an overview of the final system. The chapter is also crucial to see how the connection between the measuring tower and connection distribution board is given.

7.1 Circuit Overview

The following figure shows the measurement circuit of the automated low resistance measuring system. One can see the connection between KEITHLEY 2200-20-5 DC Power Supply, device under test, KEITHLEY 3721 Multiplexer Card, KEITHLEY 3740 Switch Card, internal voltmeter of KEITHLEY 3706A System Switch/Multimeter, and the measurement connection terminals which are in the distribution board according to Figure 49 Item 1. Since this is a four-wire resistance measurement, the circuit can be divided into current and measurement paths, shown in Figure 36 and Figure 37 in more detail. These two areas combined results in the whole measuring system.

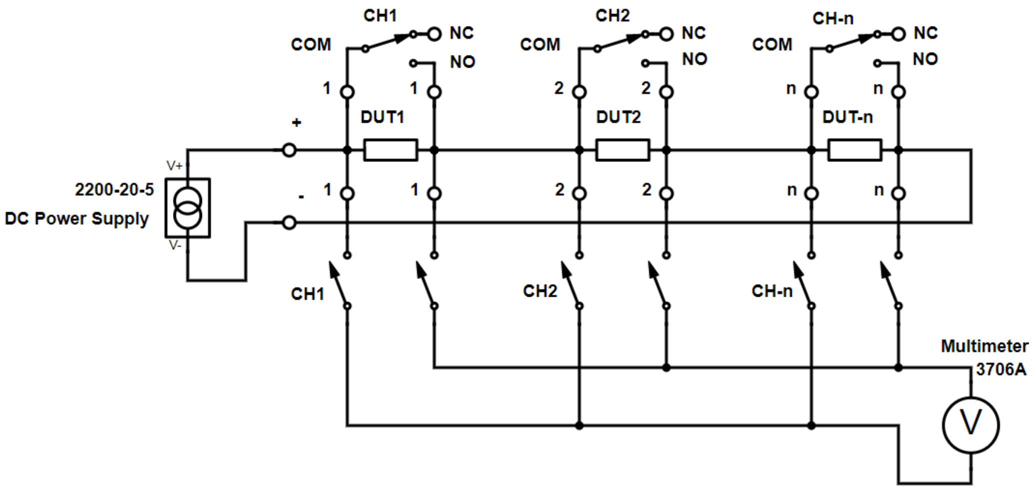


Figure 34: Automated Low Resistance Measurement Circuit, Source: Own representation.

The following figure illustrates the wiring of 50-pin D-sub cables for better understanding. One can see that the 50-pin D-sub connection is required between the DUTs and both cards of the 3706A System Switch/Multimeter.

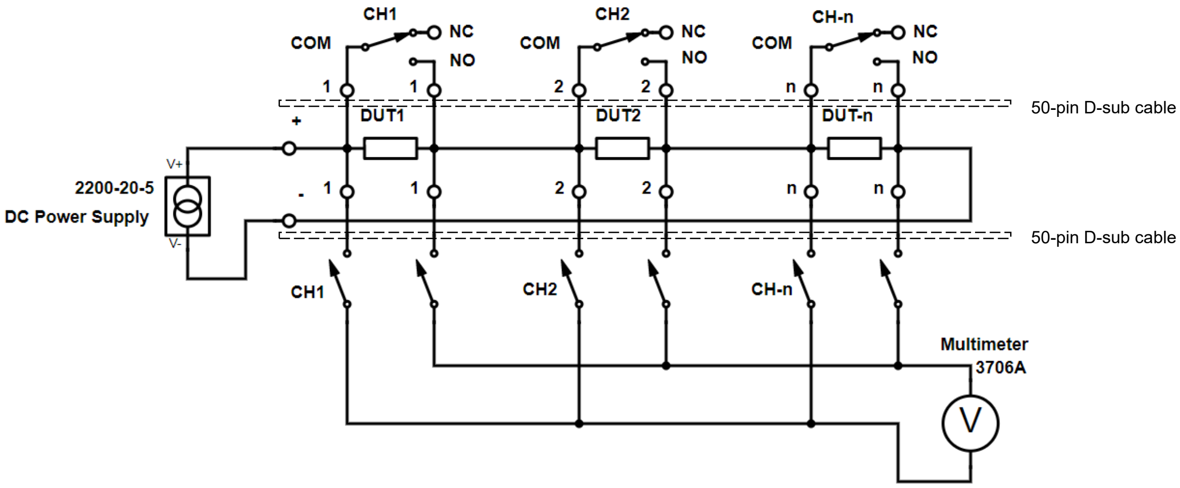


Figure 35: Circuit with 50-Pin D-Sub Cable Illustration, Source: Own representation.

As explained above, the measurement circuit can be divided into two parts. The first part of the circuit is the current path, as shown in the image below with *red* lines. The positive and negative output of the DC power supply, as explained in Section 7.4, is connected to two separate terminals at the connection distribution board. All DUTs are connected to the positive and negative terminal in series, so a defined constant current can be applied for the measurement process. One can see the series connection of all DUTs in the following picture, marked with *red* lines.

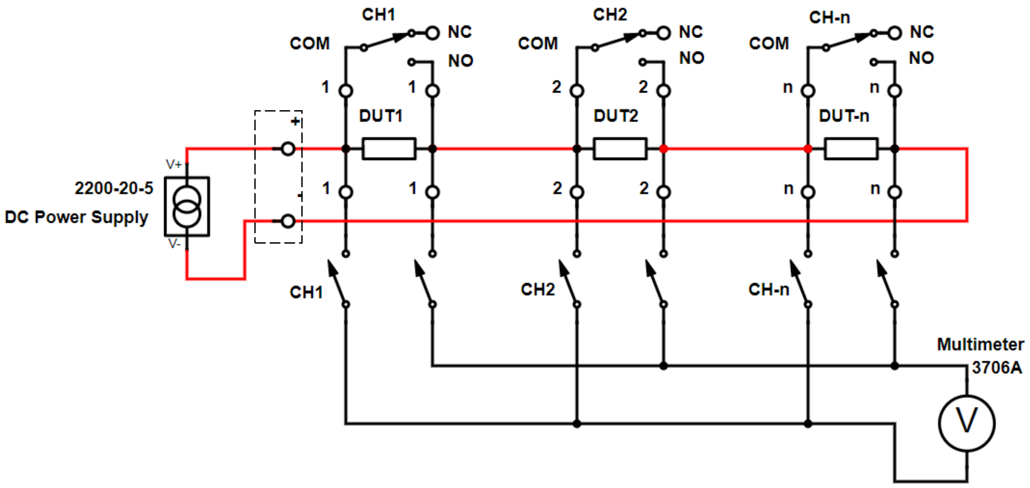


Figure 36: Current Circuit Path of KEITHLEY 2200-20-5, Source: Own representation.

Part two of the circuit is the measurement path, illustrated in the following figure with *blue* lines. After applying a constant current to the DUTs, the KEITHLEY 3721 Multiplexer Card is responsible for switching between each channel so that the internal multimeter of the KEITHLEY 3706A System Switch/Multimeter can measure the voltage drop of each DUT. The channel switch and measurement of all DUTs will be performed automatically after starting the LabVIEW program, which is further explained in Chapter 8.

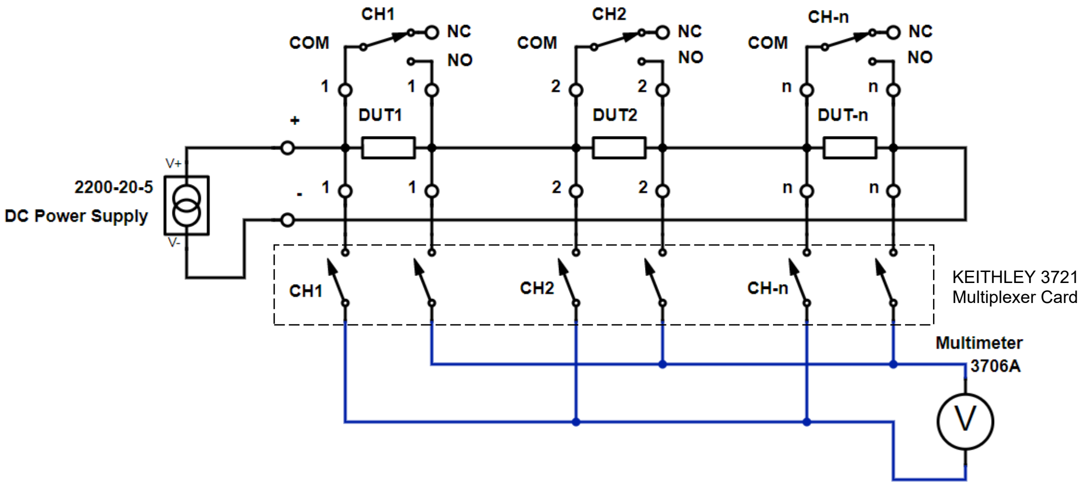


Figure 37: Measurement Circuit Path of KEITHLEY 3706A, Source: Own representation.

In addition to the current and measurement paths, one can see in Figure 38 another path which is rather necessary to keep the current path straight in case of a broken DUT, than for carrying out the measurement. The *blue* lines of the below-illustrated circuit show the connection between DUTs and KEITHLEY 3740 Switch Card. The DUTs are wired to COM and NO contacts of the card because it is necessary to bridge fault DUTs if an interruption of the current path occurs.

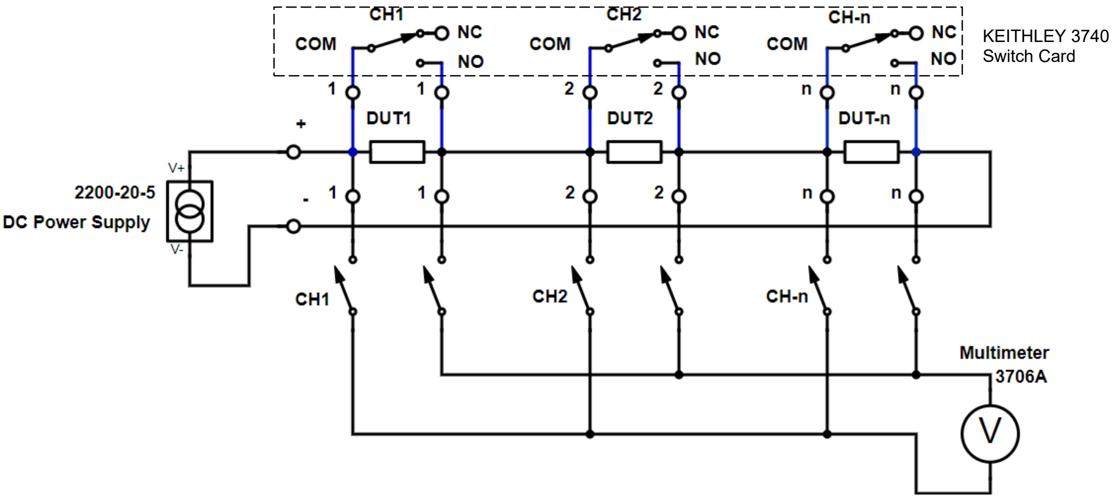


Figure 38: Bridging Circuit Path of KEITHLEY 3740, Source: Own representation.

7.2 Measurement System Overview

To have a suitable workplace, a tower for stand-alone devices and 32-inch racks is used for the structure of the measurement system itself. There are already devices that are used for another measurement setup, as one can see in the following figure at Item 1. For example, two medium voltage power supply, a high resistance multimeter, and a picoammeter for different measurement applications. These devices can be used regardless of the automated low resistance measurement system.

Item 2 shows the stand-alone KEITHLEY 2200-20-5 DC Power Supply for providing a constant current flow to measure the unknown resistance, which is demonstrated in more detail in Section 6.2 for describing the purpose, and Section 7.4 for explaining the wiring.

Item 3 shows the KEITHLEY 3706A System Switch/Multimeter, which fits in the 32-inch racks. It is mandatory for carrying out the automated switching between several DUTs and is described in more detail in Section 6.1, and Section 7.3 shows the applied cards and the associated wiring.

For carrying out the LabVIEW program, to get an overview of the whole measurement process and to see the status of the reliability test, the main laptop is used, as one can see in Item 4 of Figure 39.

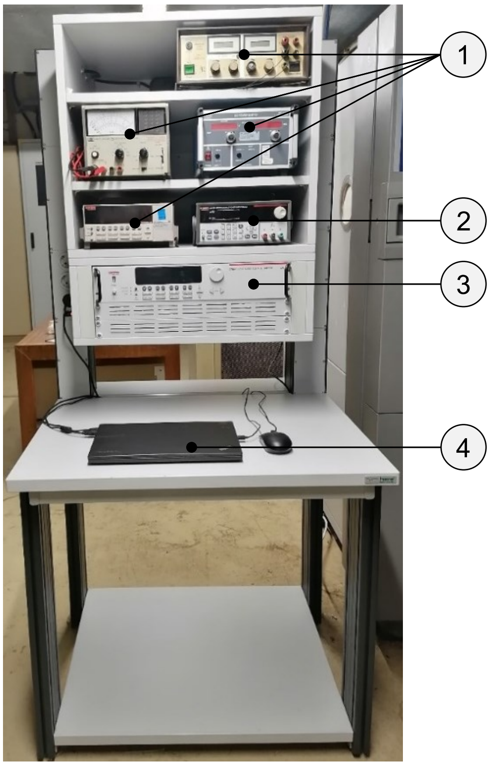


Figure 39: Front of the Measurement Tower, Source: Own representation.

On the back of the measurement tower are two connection distribution boards, as shown in the following figure of Item 1. The distribution boards are used for another measurement application and have nothing to do with the low resistance measurement system described in this thesis.

Item 2 shows four 50-pin D-sub cables connected to the switching cards of KEITHLEY 3706A which are further demonstrated in Figure 44. Also, two 1.5 mm² cables connected to the DC power supply are routed to the distribution board. The cables are routed to the connection distributor board via a pipe, as shown in Figure 41 Item 4.

The picture below also shows a part of the GPIB connection cable, which is mandatory for communication between devices and laptops. There is further information about the GBIP connection provided in Section 6.4.

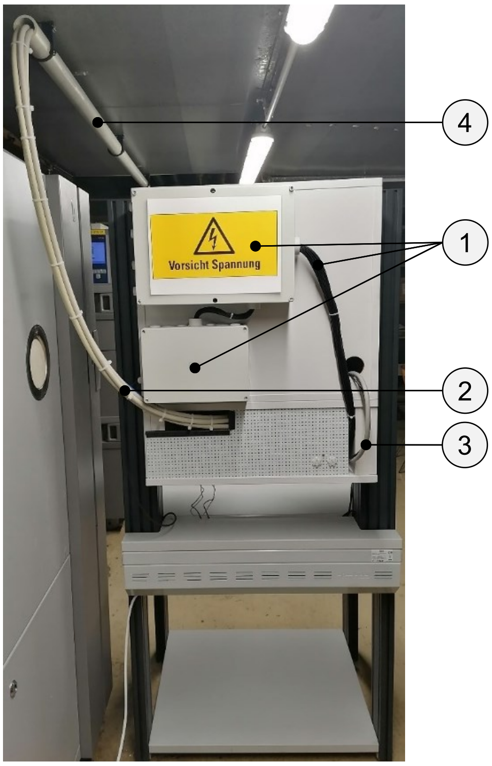


Figure 40: Back of the Measurement Tower, Source: Own representation.

Figure 41 shows the measurement tower from the view of the connection distribution board, as one can see in Item 2. As already explained above, two blue cables of the power supply that provide a constant current and four 50-pin D-sub cables of the system switch/multimeter are routed via a pipe, as demonstrated in Item 1.

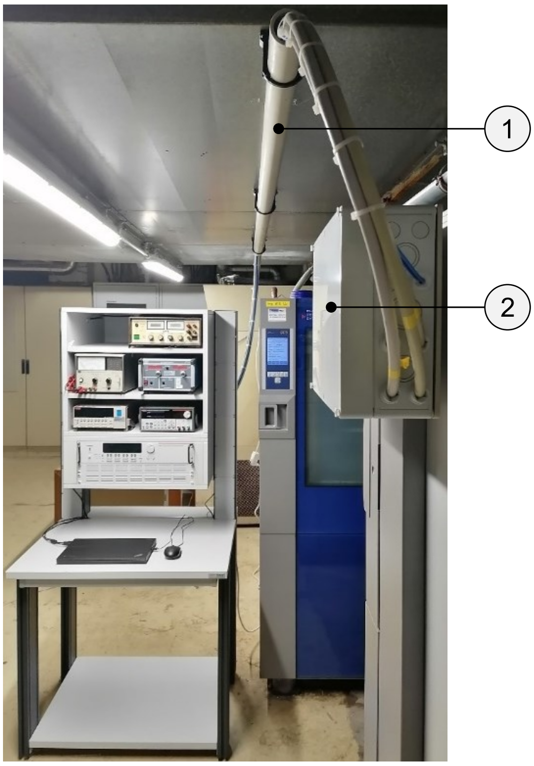


Figure 41: Measurement Tower View from the Connection Distribution Board, Source: Own representation.

The measuring cables, which were connected to the terminal strips of the distribution board, are fed into the climate chamber via a pipe, as one can see at Figure 42 Item 1. In Section 7.5 we'll go through the specifics of how to connect the measurement cable.

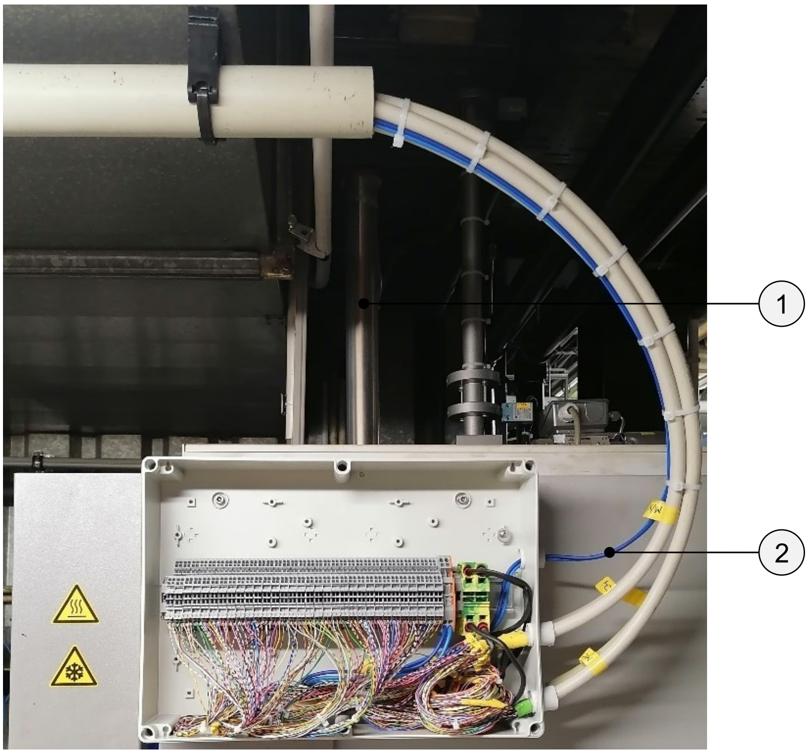


Figure 42: Cable Inlet View of the Climate Chamber, Source: Own representation.

7.3 KEITHLEY 3706A System Switch/Multimeter

As already explained in Section 6.1, the system switch/multimeter is equipped with two switching cards to carry out the low resistance measurement. As one can see in the following picture, card slot 4 is equipped with KEITHLEY 3721 Multiplexer Card, and card slot 5 is equipped with Card KEITHLEY 3740 Switch Card. Each card has 2 female 50-pin D-sub connectors which in the further are used for wiring the measurement system.

As an explanation, but not relevant to the further thesis, one can further see at the picture that card slots 1 to 3 are already equipped with switching cards that are connected with SMA plugs for a high resistance measurement application, and card slot 6 is unused and protected with a cover.

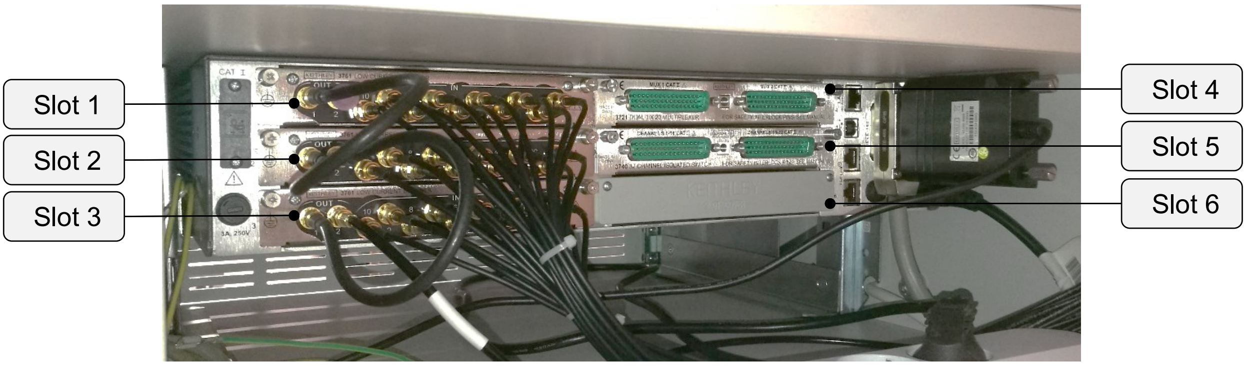


Figure 43: Equipped Rear Panel Card Slots of the System Switch/Multimeter, Source: Own representation.

Figure 44 shows the connection of the four D-sub female plugs to 50-pins male D-sub cables at card slot 4 and 5 of the system switch/multimeter.

MUX1 and MUX2 are female D-Sub connectors for multiplexer card KEITHLEY 3721. The card is responsible for the main measurement and is capable of switching between 30 channels. The D-sub connectors J3 and J4 are for the KEITHLEY 3740 Switch Card, which is used to bridge broken via holes to prevent the current bath from being interrupted. That means after an automatic detection of a broken via, the concerned interrupted current path will be a bridge to maintain the current flow.

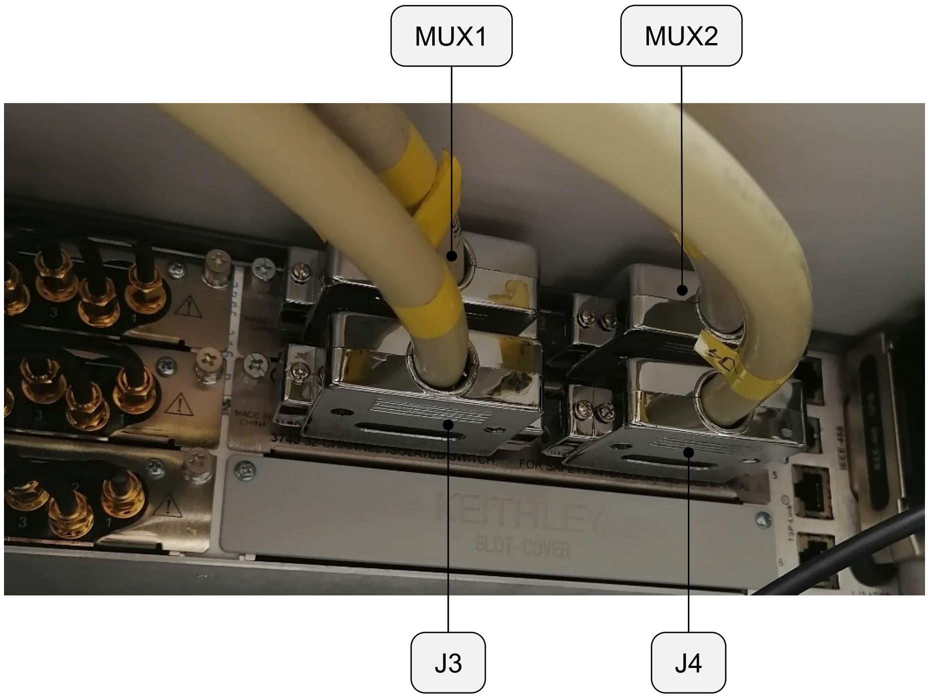


Figure 44: KEITHLEY 3706A Rear Panel With Connected D-Sub Cables, Source: Own representation.

To address both cards right channels, one must follow the pin assignment according to Figure 45 and Figure 46. It is important to connect pin 33 (+ILK) and pin 50 (-ILK) to remove the backplane interlock of the card for the MUX1 D-sub connector. To remove the backplane interlock of the MUX2 D-sub connector, one have to shorten pin 1 (+ILK) and 34 (-ILK) of the MUX2 D-sub connectors. It is possible to use the internal multimeter of KEITHLEY 3706A System Switch/Multimeter only after shortening the pins.

As one can see in the following picture, there are always two pairs that belong together. In the example of MUX1, pin 1 and 34 (1H and 1L) are used to address Channel 1. Following the pin assignment is crucial because of the fixed internal circuit connection of the Model 3721 Card.

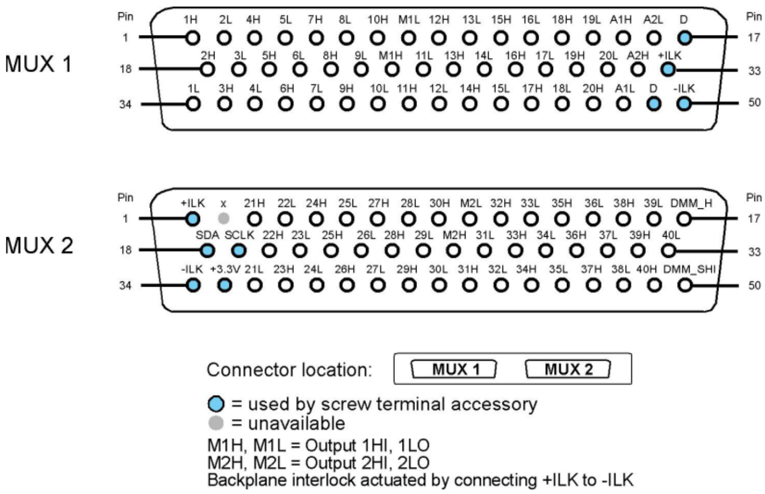


Figure 45: D-Sub Connection Information for Model 3721, Source: TEKTRONIX, INC. 1.0 (2016), Online-Source [24.September.2021], P. 30.

Next the D-sub connection information for Model 3721, the following figure shows the Model 3721 Multiplexer Card switching schematic. On the card, one'll find an analog backplane 1 digital multimeter input and an analog backplane 2 digital multimeter sense. That provides an internal voltage measurement without the need for an external multimeter. Channel 1 for example, consists of high (HI) and low (LO) signals used to perform an internal voltage measurement of these channels.

A D-sub connection diagram for a Model 3740 may be seen below. There are usually three pins that belong together, however the Model 3740 Switch Card's NO contacts will work just as well to bridge the defect via holes as shown. For example, pin 18 (NO1) and 34 (COM1) are used for Channel 1. Pin 1 (NC1) of Channel 1 is not needed, so the cable remains unused.

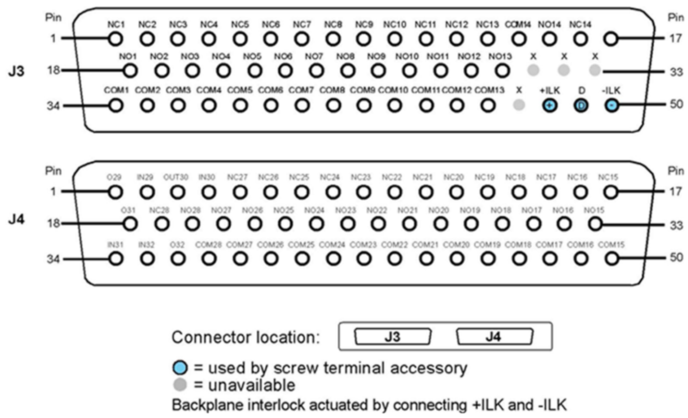


Figure 46: D-Sub Connection Information for Model 3740, Source: TEKTRONIX, INC. 1.0 (2016), Online-Source [24.September.2021], P. 109.

In addition to the D-sub connection information of Model 3740, the following figure provides a switching schematic for the Model 3740 Switching Card. For example, as one can see at Channel 1 at the following figure, each channel consists of a pair of 3 contacts, COM, NC, and NO contacts. The NC contact is not used for the measurement system because it is necessary to bridge the via hole if a defect occurs, which means a interruption of the current path.

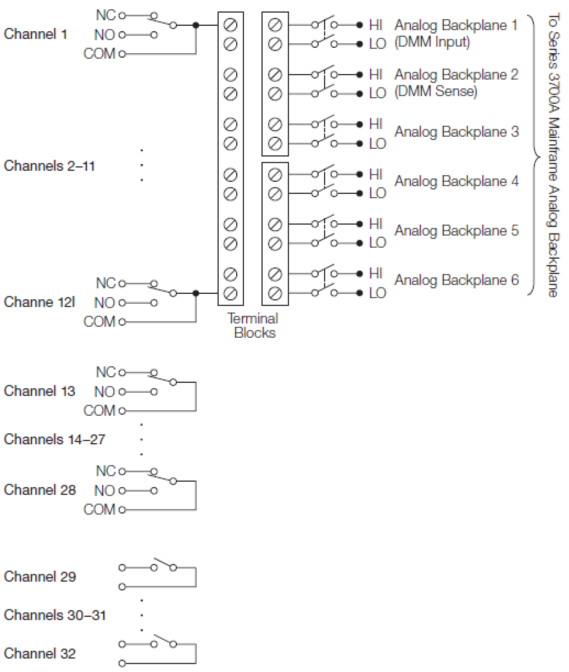


Figure 47: Switching Schematic for Model 3740, Source: TEKTRONIX, INC. 1.2 (2019), Online-Source [30.June.2021], P. 46.

The used plugs of the 50-pin D-sub cables for the measurement system were delivered already soldered. The other end of the cable was without a plug because it is used for wiring the distribution board, as one can see in Section 7.5. It was extremely time-consuming to find the right cable pairs for each channel because the pairs were not labeled at all. It was necessary to open the plug to know which soldered cable pairs were for which channel. The problem is that the twisted pairs were soldered without labeling the other end of the cables, so it was impossible to effortlessly figure out the right cable pairs. By looking at the soldered plug and using the D-Sub connection information of Figure 45 and Figure 46, it was possible to find the fitted pairs. Using the continuity test function of a multimeter, it was possible to check if the correct wire is used for the right pins.

The following figure is just for illustration of a 50-pin D-sub cable.

7.4 KEITHLEY 2200-20-5 DC Power Supply

In addition to Section 6.2, the following section will describe the implementation of the power supply in the measurement system. As further explained, the KEITHLEY 2200-20-5 is used to provide a constant current flow during the measurement process of the plated via holes. According to customer specifications, it is mandatory to use a current flow of 1,1 A for the evaluation of the unknown resistance. The DC power supply is capable of providing a maximum current of 5 A; therefore, the specification requirement is absolutely achieved. Instead of using the front panel banana output connectors, as shown in Figure 29 Item 5, we use the 12-pin connector at the rear panel. This is because the measuring system is not used on a mobile basis, so it is better to use rear panel measurement device connections for fixed wiring. In addition, unintentional removal of the banana plug can be avoided, preventing further mistakes during the hole climatic chamber test. To use the rear panel current output, it is crucial to remove the shorting clip, as shown in Figure 48 Item 7. The 12-pin connectors Drive + and Drive - are used to provide a constant current flow. One can see the further wiring description of the DC power supply in Section 7.4.

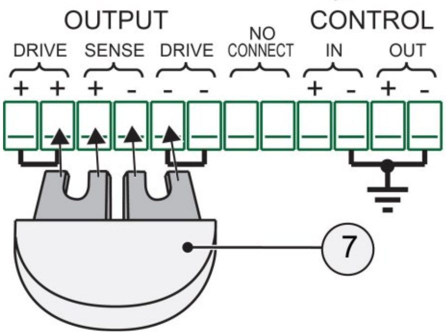


Figure 48: Rear Panel of the KEITHLEY 2200-20-5 DC Power Supply, Source: TEKTRONIX, INC. 2.0 (2017), Online-Source [21.July.2021], P. 28.

7.5 Measurement Connection Distribution Board

The distribution board is used to connect the test boards with the measurement system. As already explained in Chapter 5, the test boards are stored for a given amount of time in the climate chamber to simulate the influence of the environment.

Sixty (60) terminals are available for connecting 30 DUTs to the automated measurement. That means that there are 2 terminal pairs available for each DUT, as shown in Figure 49 Item 1. In addition, one can also see at Item 4, the four 50-pin D-sub cables which are fed into the distributor. The wires of the D-sub cables are connected to the terminals to provide the assembly of the DUTs to the switching cards of the KEITHLEY 3706A System Switch/Multimeter.

Two terminals connect the DUTs in series to the constant current source, which are demonstrated with Item 2. Accordingly, Item 3 shows two blue cables used to provide the constant current from the DC power supply output, as already explained in Section 7.4.

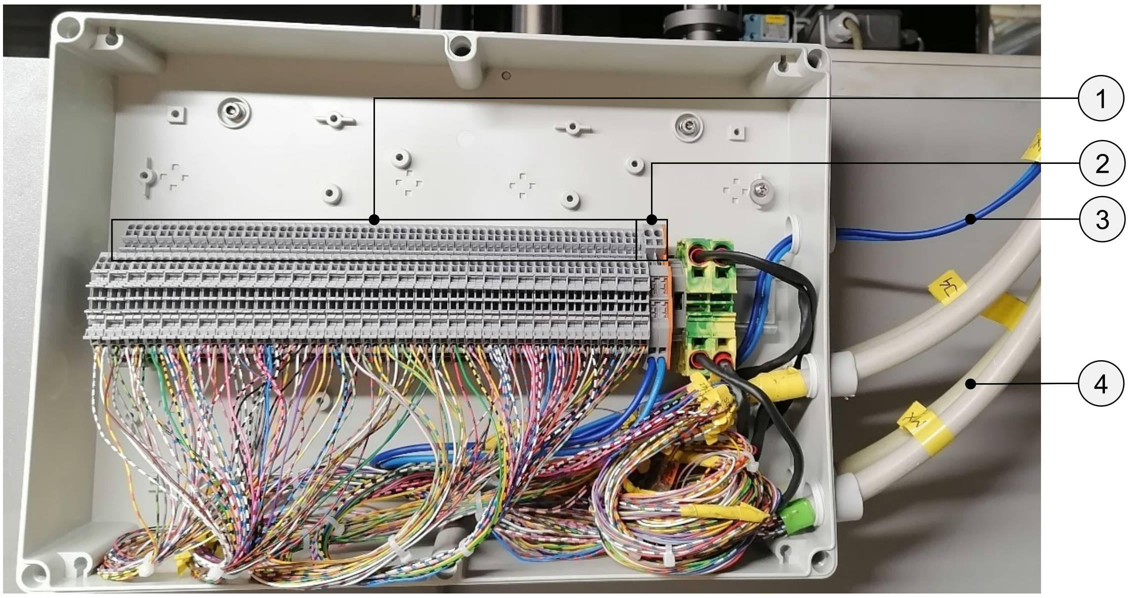


Figure 49: Connection Distribution Board, Source: Own representation.

The following picture shows a detailed view of the main terminals such as switching, current source, and grounding.

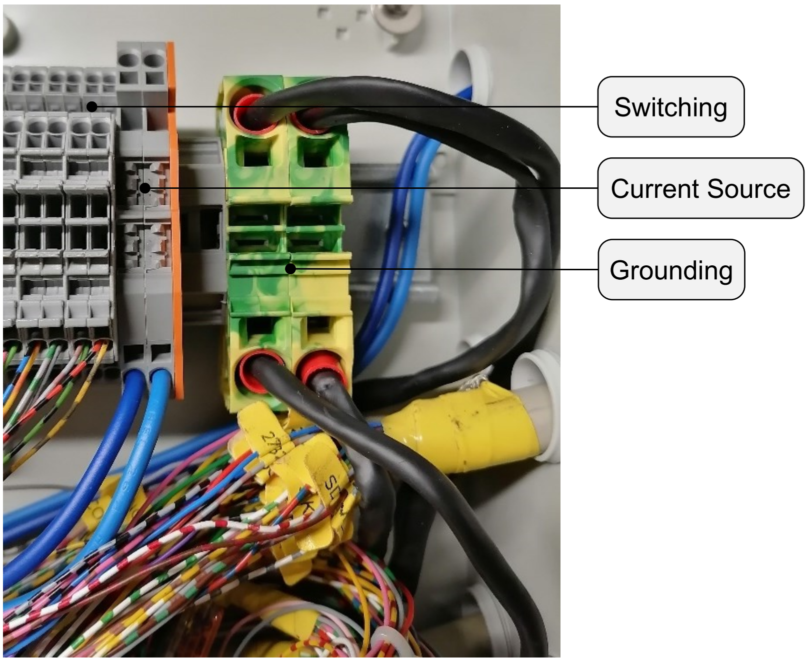


Figure 50: Detailed Terminal Picture, Source: Own representation.

7.6 KEITHLEY KUSB-488B USB to GPIB Converter

The Ni-488 driver preinstalled with the LabVIEW software must be uninstalled using the *NI Package Manager* application so that the new KI-488 driver can be installed for using the KEITHLEY KUSB-488B USB to GPIB Converter.

The measuring devices and the KUSB-488B Converter are connected with an IEEE-488 GBIP cable. The addresses of the recognized measuring instruments must be set with the *KI-488 Configuration Utility* program. The set addresses are then assigned to the respective measuring instrument in the LabVIEW program.

All above applications are automatically preinstalled with the LabVIEW software or the KI-488 driver. No additional installations are, therefore, necessary.

8 LABVIEW MEASUREMENT PROGRAM

In the following figure, the entire measurement process is shown graphically using a flow chart. The LabVIEW programming sequence cannot be seen in the graphic but is shown with the state diagram of Figure 66. Only operating and setting options, as well as the entire run of measurement, are shown.

Before starting the measurement, all parameters such as scan list, test current, bridge slot, measurement interval, test time, and file path must be set. The automatic measurement can then be carried out using the *START* button. After starting the program, a resistance measurement of all defined channels is automatically carried out. The measurements are then carried out in the previously set measurement interval with a defined measurement current. In addition, measured values are saved in the selected directory after each measurement process. After the test time has been reached, the measuring program is ended automatically.

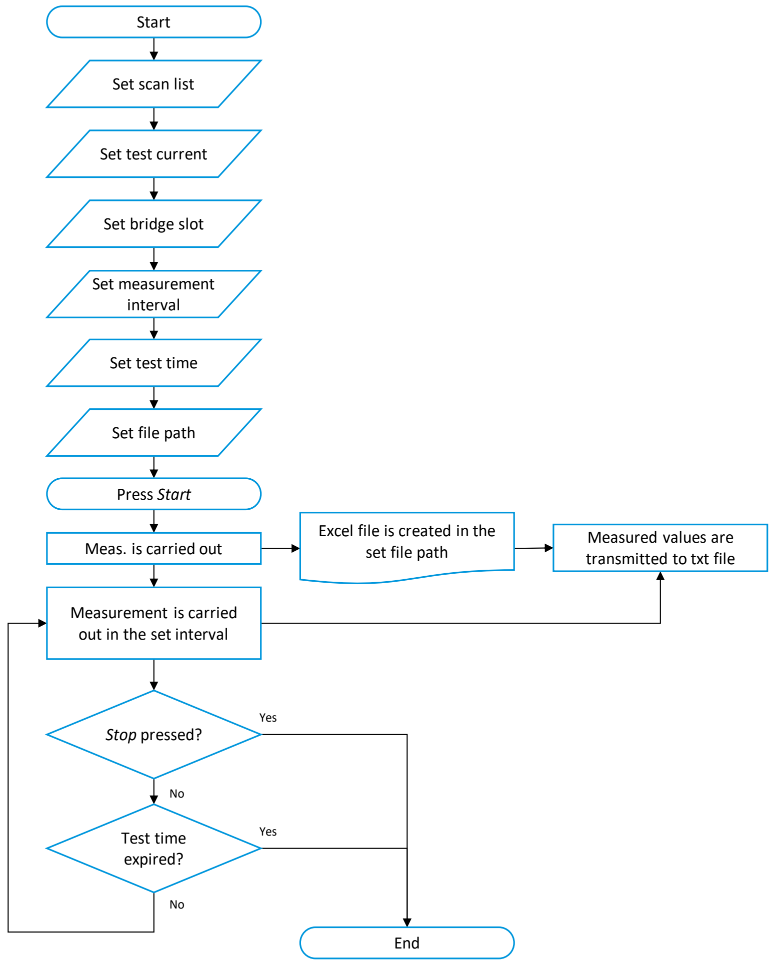


Figure 51: Flow Chart of the Measurement Process, Source: Own representation.

8.1 Measurement Program User Interface

The use of tabs is mandatory to get a better user experience due to improved operability. The interface is better structured, and thus, it is easier to select needed configuration options or monitoring features. The interface is divided into three main areas, which are shown in the following subsections. The *Information* tab is just for documentation and important knowledge that the operator of the measurement program has quick access to important information.[39]

8.1.1 Overview Tab

The *Overview* tab is essential to have quick access to important information about the executing measurement. The program can be started or stopped with dedicated buttons. In addition, the status of the measurement process is shown with LED displays. Further information such as the remaining time of the entire test, the time until the next measurement, and the number of measurements carried out are displayed. The LED *Resistance measurement in progress* is significant for the operator, whether a measurement is currently being carried out or not. Because the measurement file mustn't be opened during the saving process of the measured resistance values. Otherwise, it would lead to failure or missing data.

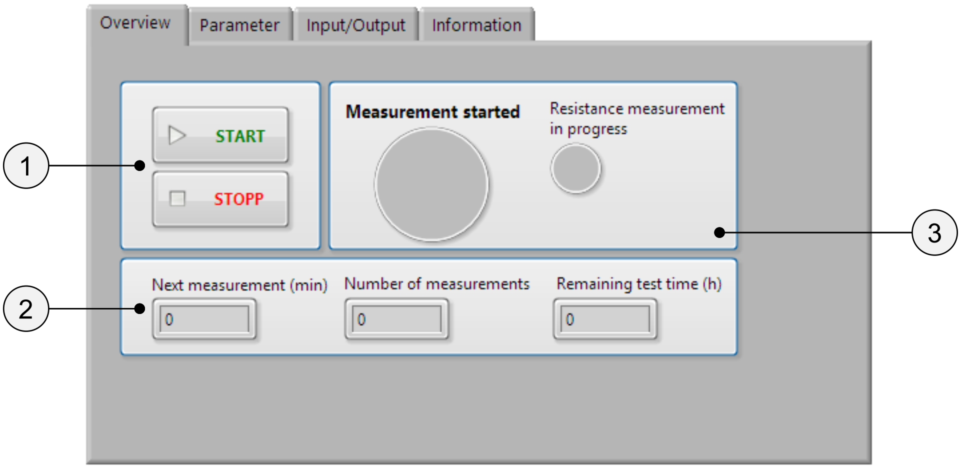


Figure 52: Tab *Overview* of User Interface, Source: Own representation.

Item 1: The *START* button can be used to start the LabVIEW measurement program. It is possible to stop the present execution of a program by pressing the *STOP* button.

Item 2: Relevant information such as the remaining time of the entire test in hours *(Remaining test time)*, the time until performing the next measurement in minutes *(Next measurement),* and the total number of executed measurements *(Number of measurements)* are displayed.

Item 3: The status of the program and furthermore the resistance measurement execution is shown with dedicated LED displays.

[39] Vgl. Georgi/Metin (2009), S.190 – 191.

8.1.2 Parameter Tab

The following tab contains setting options to set desired requirements for the measurement. Settings for the test current, number of channels, test time in hours, measurement interval in minutes, and the text file's storage directory must be done in the *Parameter* tab.

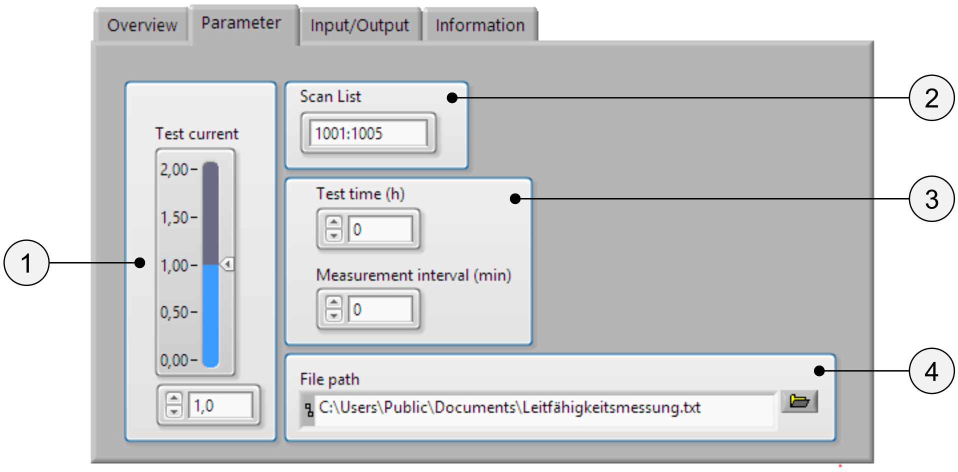


Figure 53: Tab *Parameter* of User Interface, Source: Own representation.

Item 1: Desired test current can be set up to 2 A.

Item 2: The required measurement channels can be set by inserting a scan list with a specific variable format. The slot number (S) and the channel number (CCC) are both part of the channel list format (SCCC). The second column of the following table shows different channel list examples, followed by an associated slot number and channel number. If channel list pairs are separated by a comma as illustrated by Item 1 of the table, it means that just the selected channels are used. On the other hand, if the channels are separated by a semicolon as demonstrated by Item 3, it means that all channels are included within the selected area. Further, a combination of multiple single-channel selections and area selections are also possible, as shown by Item 2.

Item	Channel List *SCCC*	Slot number *S*	Channel number *CCC*
1	1003, 2030, 3005	1 2 3	3 30 5
2	1002:1030, 2010	1 2	2 to 30 30
3	1001:2012	1 2	1 to 30 2 to 12

Table 11: Scan List Example, Source: Own representation.

Item 3: The time for the whole measurement in hours *(test time)* and the time to repeat the measurement in minutes *(Measurement interval)* can be set.

Item 4: The measurement data are saved as a text file in the selected file directory *(File path)*. The storage of the measured values is explained in more detail in Subsection 8.3.4.

8.1.3 Input/Output Tab

Both devices, in respective KEITHLEY 3706A System Switch/Multimeter and KEITHLEY 2200-20-5 Power Supply, as well as operator computer and KEITHLEY KUSB-488B USB to GPIB Converter are connected to one another with an IEEE-488 GBIP cable, as already explained for theoretical usage in Section 6.4 and wiring component in Section 7.6.

After restarting the LabVIEW software or the devices, it is crucial to select the GPIB addresses using the drop-down menu of the *Input/Output* tab, as one can see in the following figure.

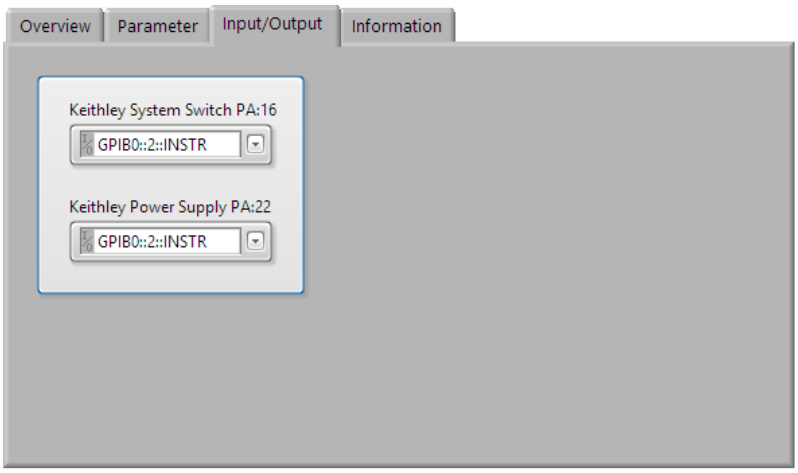


Figure 54: Tab *Input/Output* of User Interface, Source: Own representation.

The following table shows GPIB addresses for the system switch/multimeter and DC power supply. The first column of the table contains the name of the device with the respective GPIB address in the second column.

Device	GPIB address
System Switch/Multimeter KEITHLEY 3706A o Multiplexer Card KEITHLEY 3721 o Switch Card KEITHLEY 3740	16
Power Supply KEITHLEY 2200-20-5	22

Table 12: Device GPIB Addresses, Source: Own representation.

8.2 Main Program

Basically, the LabVIEW measurement program was implemented with a state machine, as described in Subsection 8.3.1. As further explained in Subsection 8.1.2, a certain state is executed and processed depending on the parameter input. The following figures only serve as an overview of the LabVIEW main program in which the structure of the state machine can be seen. The basic structure and function of a LabVIEW state machine is explained in more detail in Subsection 8.3.1.

8.2.1 Program Sequence

The following figure shows the state machine of the measurement program. The sample picture is with an almost empty state because it should just illustrate the state machine itself. The shown state contains an increment block that starts at value 0 and counts +1 after each execution of the state, as one can see in Item 2 of the picture. This simple method makes it possible to count the number of measurements with each execution of the *Resistance measurement* state. Item 4 shows the output variable, which displays the current number of measurements on the user overview interface, as one can see in Figure 52.

The while loop contains a timer VI for querying the remaining test time, as one can see with Item 3, and a *STOP* button. Both elements are connected within the framework of a state query and will call the *Stop* state, as shown in Figure 62, by a true value of the *Timer* VI or pressing a *STOP* button. Depending on requirements, these are called up in each state.

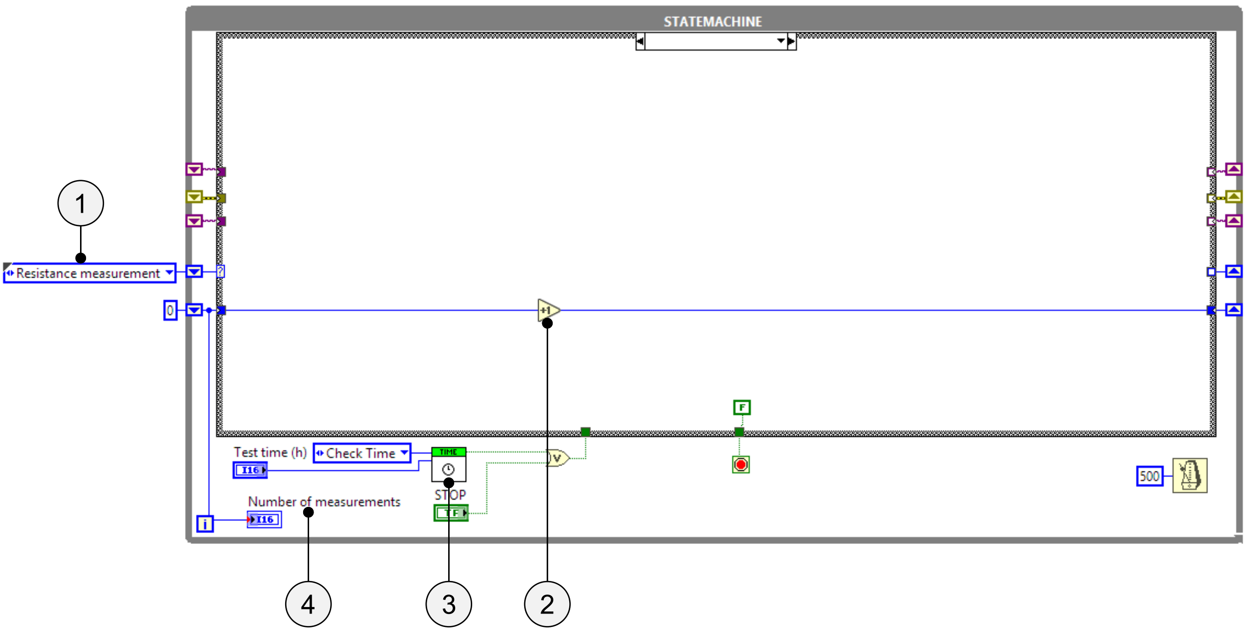


Figure 55: State Machine of Main Program with Empty State, Source: Own representation.

As one can see in the figure above at Item 1, the selection board of the state machine is connected with the *Resistance measurement* enum. It means that after starting the program and executing the status query process of all measuring devices, the first state *Resistance measurement* is carried out.

The following image shows the status query of the system switch/multimeter and DC power supply. This step is important to check the device connections. The initialize process is carried out by provided manufacturer LabVIEW VIs of both measurement devices.

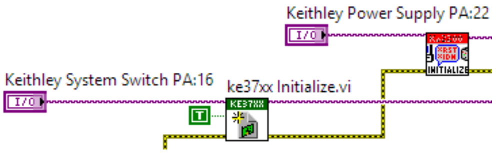


Figure 56: Device Query, Source: Own representation.

After the query process of the devices, the first state *Resistance measurement* is executed, as one can see in the following image.

Before the switching process of the measurement starts, the test current is set by the *Source_set* VI, as shown in Item 2 of the following figure. A measurement is then carried out with the previously selected cards and channels, as one can see with Item 1. As explained in Section 4.3.4, the measured values are afterward transferred as a 2D array to a VI for storage in a text file.

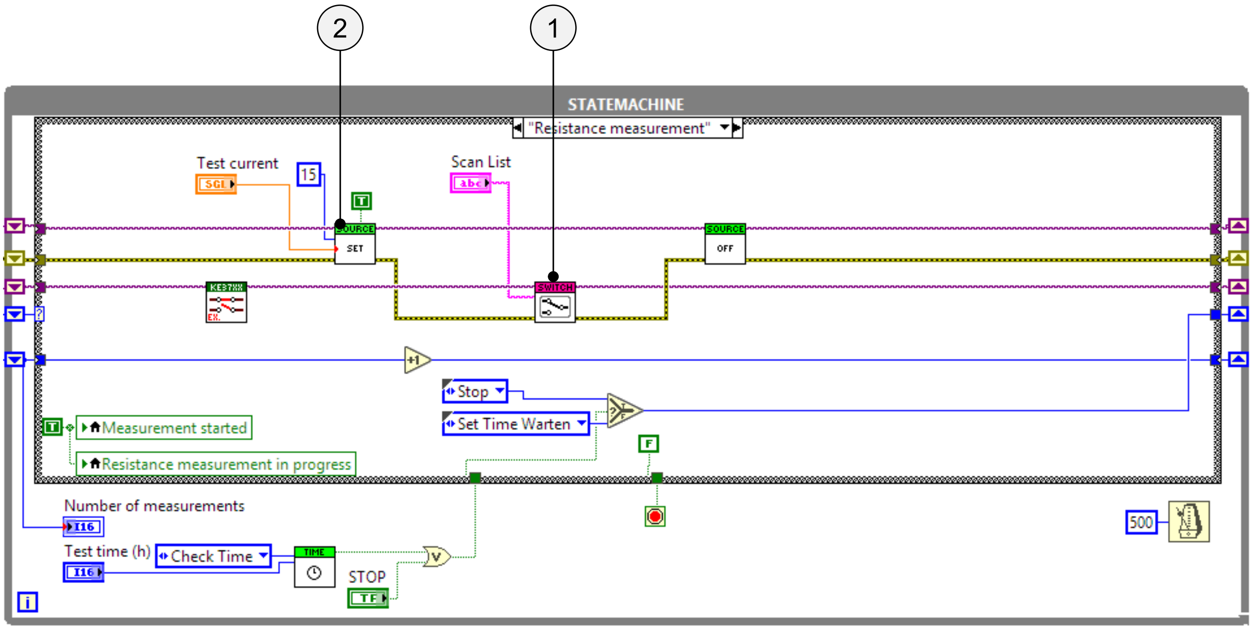


Figure 57: *Resistance measurement* State, Source: Own representation.

After the first measurement, the state *Set Time Warten* is called, as shown in the following figure. The *FGV_Time_Leitfähigkeitsmessung* VI, as shown in Figure 58 Item 1, is executed with the enum input variable *Set time*. This sets the programmed VI timer to zero, used as a reference time in the next state, as one can see in Figure 59.

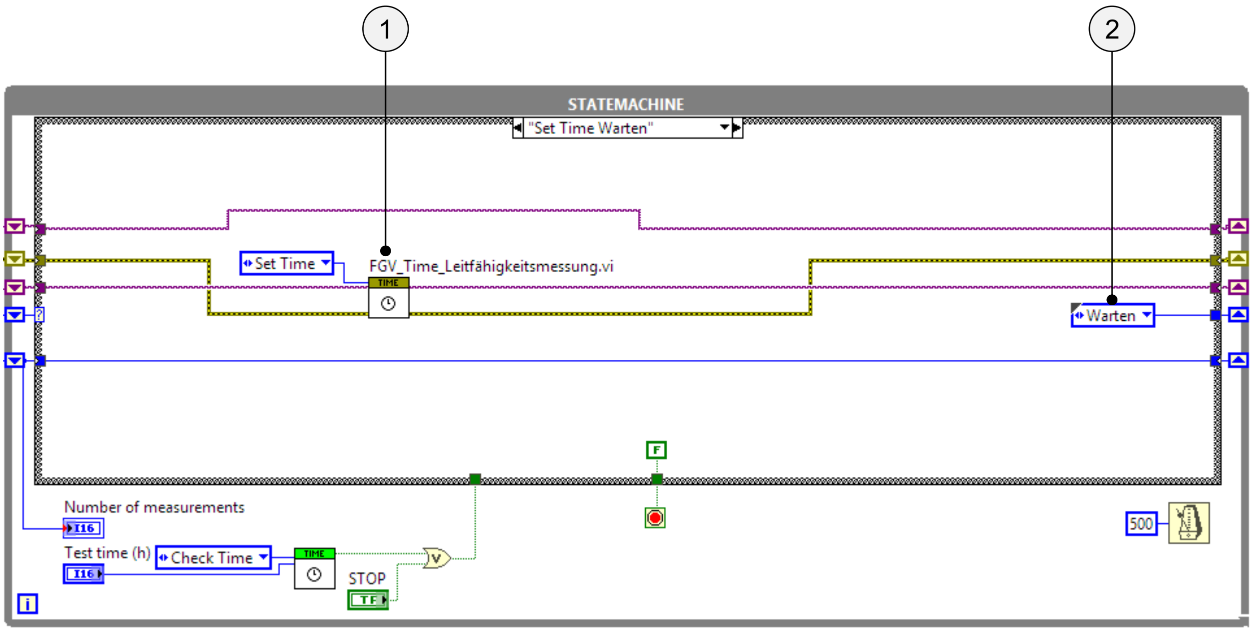


Figure 58: *Set Time Warten* State, Source: Own representation.

As illustrated in Figure 59 Item 2, the state *Warten* is loaded into the shift register of state *Set Time Warten*, which then sends the data to the state selector in the case structure. According to this, the next state *Warten* is called and processed as shown in Figure 59.

As explained above, the *FGV_Time_leitfähigkeitsmessung* VI is used again, but this time, the enum input variable *Check Time* is used to calculate the remaining time for the next measurement. The VI is also used to show the elapsed time of the last measurement on the user overview interface, as one can see in Figure 52. If the waiting time of the VI is expired, the boolean VI output changes from *false* to *true* value. The connected output is sent to the *true/false* selector, shown at Item 1 of the following illustration, and opens the next stade *Mode*. As long as a *false* value is present at the selector, the state *Warten* will continue to be repeated.

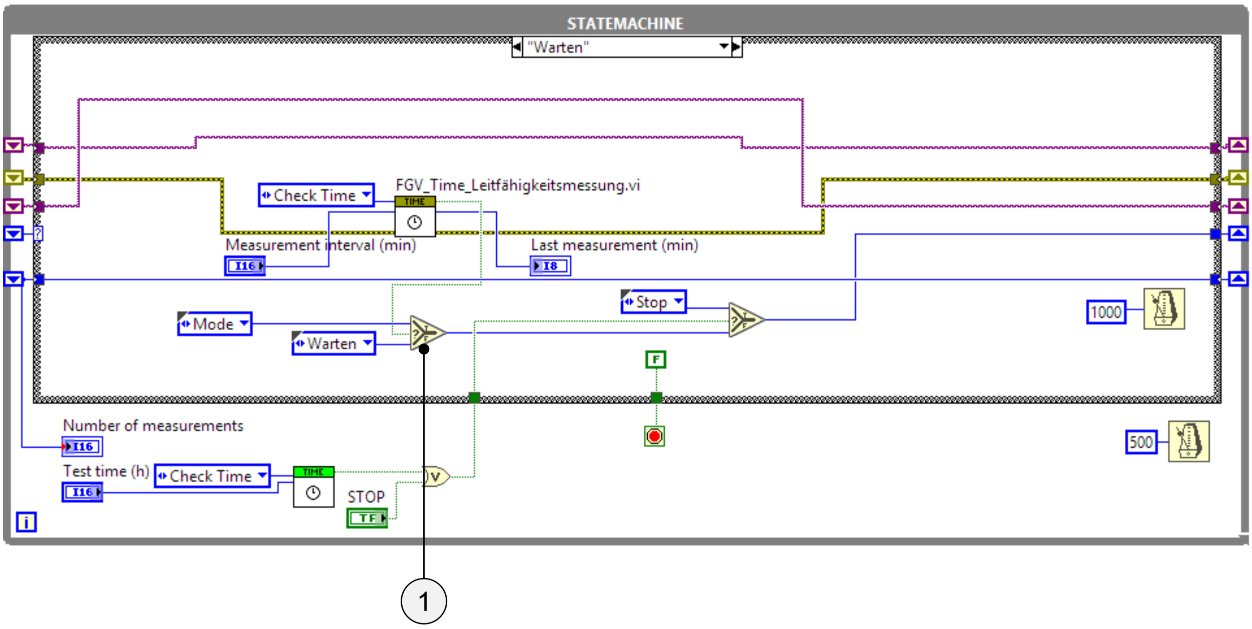


Figure 59: *Warten* State, Source: Own representation.

If the current output of the power supply is shorted, then the device is operating in constant current (CC) mode. A continuous current flow is required for the measurement in this mode. Whether the power supply is in CC or CV mode, Mode VI is responsible for checking the power supply's status. If there is an interruption of the current path due to a broken via hole, then the mode of the power supply changes to CV. As long as the circuit is not opened resulting from a failure, the *Resistance measurement* state is called by the *true/false* selector and can be executed again to perform the measurement. If there is a failure of the circuit path detected by the *Mode* VI, then, however, the *Bridge* state is called.

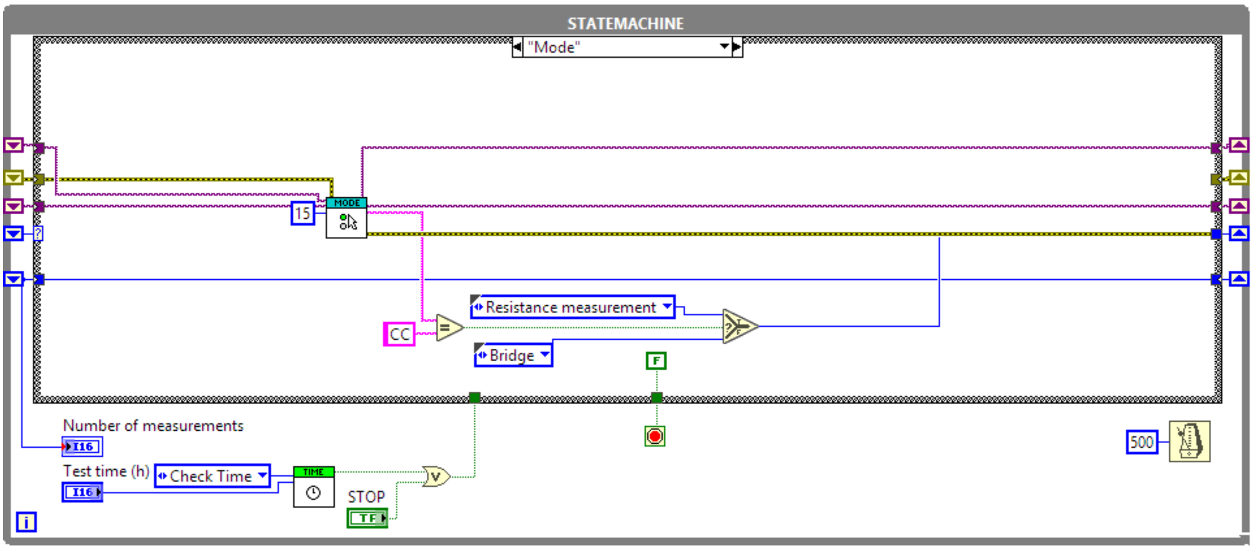


Figure 60: *Mode* State, Source: Own representation.

The *Bridge* VI of the following *Bridge* state will detect the broken DUT and close the appropriate channel for the next measurements to fix the current flow interruption, as shown in Figure 38. The responsible error can be detected by closing all contact of the KEITHLEY 3740 Switch Card after another and using the CC and CV mode of the power supply in combination. After executing the bridge process, the state *Resistance measurement* is called for further measurements.

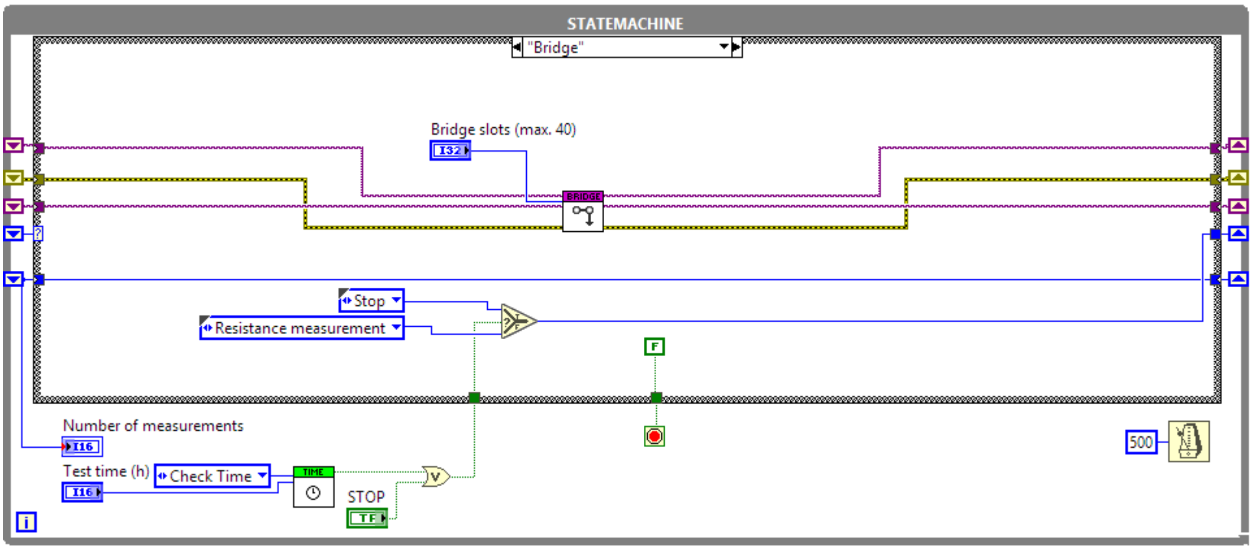


Figure 61: *Bridge* State, Source: Own representation.

Each of the above-mentioned states is followed by the next shown in the list. In order to stop the execution of the LabVIEW measurement application, use the stop state. The true boolean of the *Stop* state is connected to the stop of the while loop, which interrupts the loop and thus terminates the program.

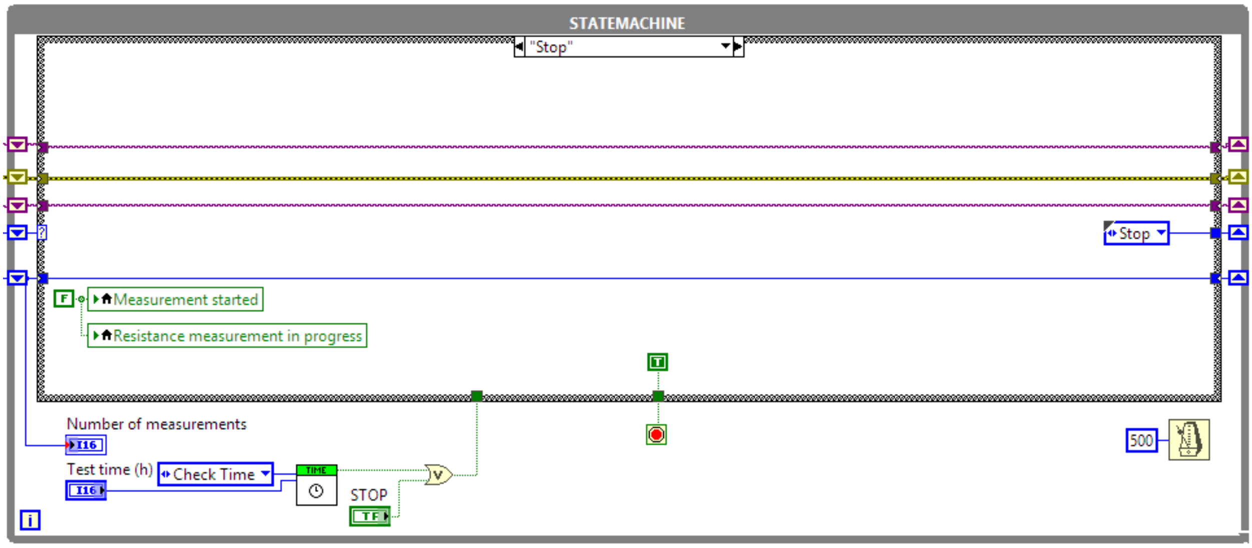


Figure 62: *Stop* State, Source: Own representation.

8.2.2 Use of Driver

Via the links given in Appendix 1 of this thesis, the drivers of the respective measuring instruments provided can be downloaded as a *.zip* file. The zip files must be copied to the following directory *C:\Program Files (x86)\National Instruments\LabVIEW 2019\instr.lib.* The desired drivers must be only unpacked in the destination folder; otherwise, they will not be correctly adopted by the LabVIEW software.

After successfully unpacking the files in the destination folder and restarting the LabVIEW application, the instrument drivers can be accessed from the LabVIEW function palette, as one can see in the following picture.

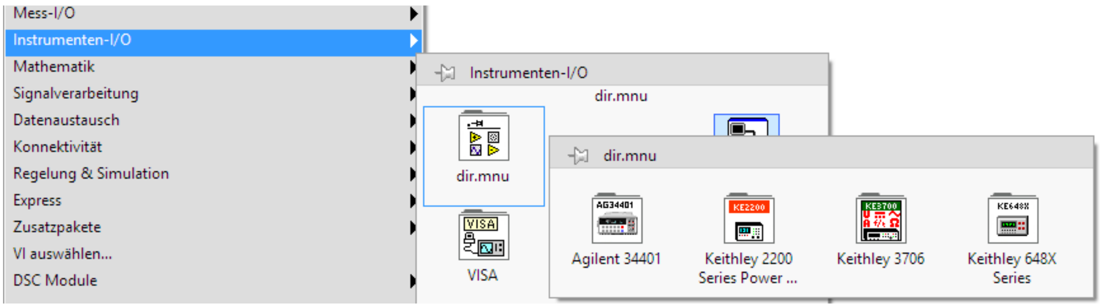


Figure 63: Function Pallet for Using Device VIs, Source: Own representation.

Created SubVIs provided by the device manufacturer can be used as drag & drop for programming support. According to the usage of the SubVI, it is possible to edit and assemble the VIs to ones need.[40]

[40] Vgl. National Instruments (2003), Online-Quelle [17.März.2020], S.42.

8.3 Variables and Data Concept

When programming the measuring system, variables and data concepts were used. The main program and the entire measurement procedure are implemented with the help of a state machine. Since there are several states such as stress, automatic and manual measurement, as well as waiting times during the automated measurement, the programming was implemented with a state machine. This makes the measurement program clear and also more comprehensible and understandable.

The use of local variables and the storage of the automatically recorded measured values are explained in Subsection 8.3.2 and Subsection 8.3.4. From the individual measured values, a 2D array is created for transfer to an eternal storage file.

8.3.1 State Machine

The state machine is implemented with a while loop containing a case structure. Each state is implemented as a separate frame within the case structure and called by a unique designation, called enum, at the selection port. The surrounding while loop allows all states of the case structure to be processed. Each state must provide a return value, indicating which is its subsequent state. This return value is returned via a shift register of the while loop so that the respective state in the current loop run is called. The end of the program is implemented by canceling the while loop.[41]

The following are two illustrations of a state machine:

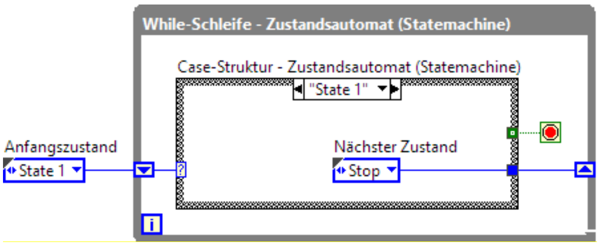


Figure 64: Example of a State Machine with State *State 1*, Source: Own representation.

The case selector of the case structure is filled with the initial state, *State 1,* via the shift register so that this state is processed. The shift register is filled with the next state *Stop* and forwards the information to the case selector of the case structure so that the state *Stop* is called and processed.

The *Stop* state interrupts the while loop and thus terminates the program, as one can see in the following figure.

[41] Vgl. Georgi/Text (2009), 351 – 352.

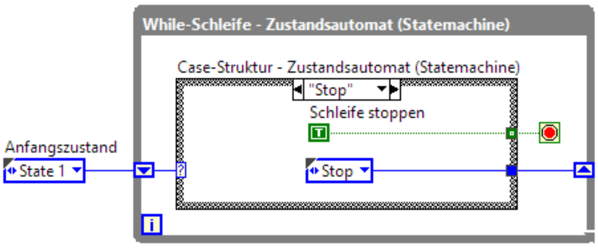


Figure 65: Example of a State Machine with State *Stop*, Source: Own representation.

The entire measurement process is implemented in the LabVIEW program with a state machine. The state machine consists of 5 states. The relationships of the states and the criteria for the execution of the next state, are shown in the following state diagram.

Following an explanation of the state diagram for better understanding. After starting the LabVIEW measurement program, the first state *Resistance measurement* is executed. When the measurement process is completed and thus of the state, the state machine's next state *Set Time Warten* is called. After resetting the timer and thus ending the current state, case *Warten* is called. The case is running till the set time for the next measurement is expired. To see if the power supply is set to constant voltage (CV) or constant current (CC), select the next *Mode* state. Depending on the status of the device, either the state *Resistance measurement* and thus repeating the whole process or state *Bridge,* due to an interruption of the current path, *is* called. The *Bridge* state will perform a check of all DUTs to determine the cause of the current disturbance. After bridging and completing the fault DUT, the state *Resistance measurement* is called again to perform a measurement and repeat the hole state machine cycle. Each state is linked to the *Stop* state to end the LabVIEW measurement program if the test time is expired or the *STOP* button on the user interface is pressed, as shown in Figure 52.

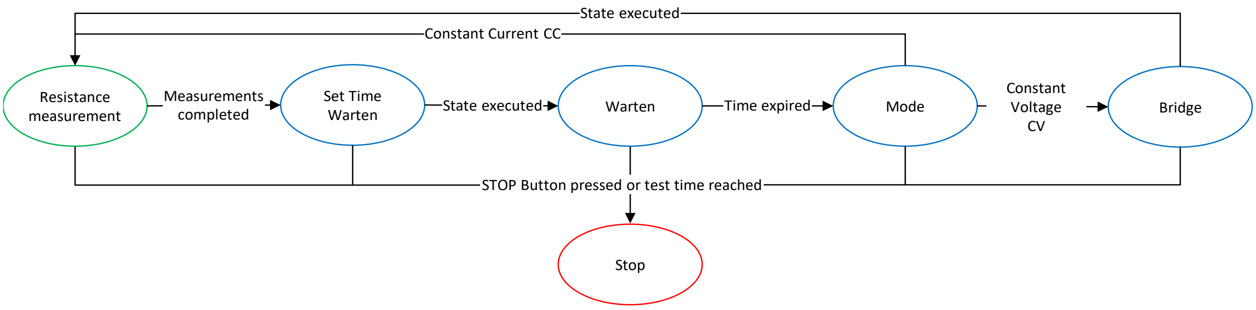


Figure 66: State Diagram oft LabVIEW State Machine, Source: Own representation.

8.3.2 Local Variables

To be able to track the current status of the measurement program, LED indicators, as shown in Figure 52, are used in the front panel. Local variables are used to obtain a query of the respective state of the state machine by means of the LED of the front panel. Through local variables, front panel objects can be accessed from multiple parts of a Virtual Instrument (VI), and data can be exchanged between structures of the block diagram that cannot be connected directly.[42]

In the event of an unscheduled termination of the program, the LEDs in the front panel can be still active after restarting. To prevent, all LEDs are disabled with FALSE constants immediately after running the LabVIEW program.

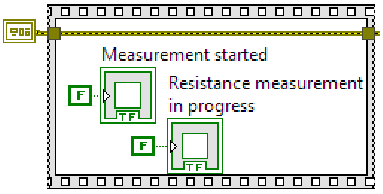


Figure 67: Local Variables Created by LED Block Diagram, Source: Own representation.

Via the local variables of the LED block diagram connections, it is possible to access the LED from several points of the state machine. All relevant cases contain the following block diagram, as shown in Figure 68. With boolean constants, the LEDs of the front panel are switched on or off via the corresponding local variables.

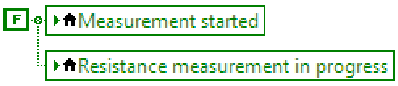


Figure 68: Control of Front Panel LEDs Via Local Variables, Source: Own representation.

[42] Vgl. National Instruments (2003), Online-Source [14.September.2021], P. 203.

8.3.3 Arrays

Multiple instances of the same data type are stored in an array under the same name. There is a wide variety of components and dimensions. The dimensions of an array are the length, height, or depth of the data that make up the array.

Arrays of the following dimensions can be used to contain numeric, bool, path, text, waveform, and cluster data.

One-dimensional array: The array is also known as a vector.

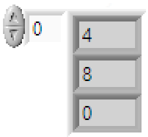


Figure 69: Example of a Numeric 1D Array, Source: Own representation.

Two-dimensional array: The array is also known as a matrix.

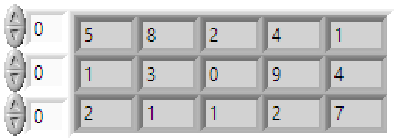


Figure 70: Example of a Numeric 2D Array, Source: Own representation.

Higher-dimensional array: LabVIEW can also create higher dimension arrays, for example 4 and 5 dimensions, but their practical use is often irrelevant.[43]

8.3.4 Storage of Data Variables

Due to the standard use of text files (.txt) on the company's Windows computers, all measured values are stored in a text file. A diagram can graphically illustrate the measured values by opening the data into an excel file. After the first measurement cycle, the LabVIEW measurement program creates a *.txt* file in the selected directory to save all measurement values. The directory is set in the *Parameters* tab, as shown in Figure 53.

[43] Vgl.Georgi/Text (2009), P. 73.

As one can see in the following figure, the input variable *Scan List* is crucial to defining which channels measure the DUT. The scan list input field is set in the *Parameters* tab, as shown in Figure 53.

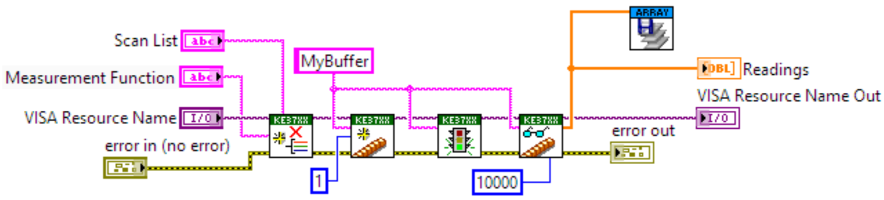


Figure 71: LabVIEW Switching and Measurement Process VI, Source: Own representation.

To transfer the measurement values of the cache clearly and continuously into a *.txt* file, all measured values must be stored in one line. For this purpose, the stored data of the 2D array is transposed into a horizontal 1D array. The following figure shows the VI for transposing all measured values into one line.

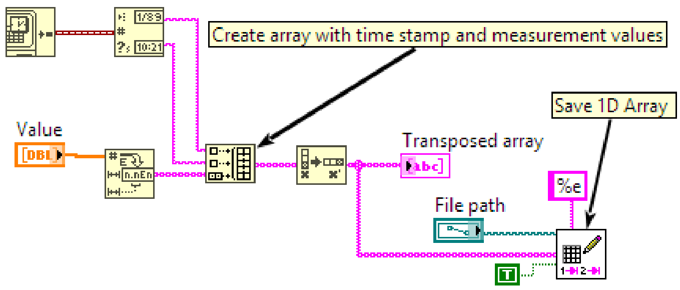
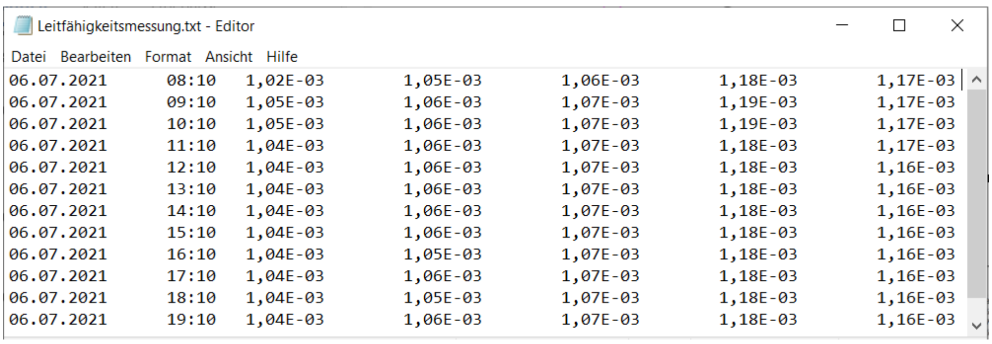


Figure 72: LabVIEW Saves Measurement Values VI, Source: Own representation.

8.3.5 Example Measurements

All measured data stored in the cache of the multimeter are transferred to an automatically created *.txt* file. LabVIEW VI, which is shown in Figure 72, establishes a timestamp at each row with date and time. The following figure illustrates raw data measurement values in a text file, wherein total 12 cycles with 5 channels were measured. The first and second rows save the timestamp followed by resistance values begin at the third column with Channel 1.


Leitfähigkeitsmessung.txt - Editor

Datei Bearbeiten Format Ansicht Hilfe

06.07.2021	08:10	1,02E-03	1,05E-03	1,06E-03	1,18E-03	1,17E-03
06.07.2021	09:10	1,05E-03	1,06E-03	1,07E-03	1,19E-03	1,17E-03
06.07.2021	10:10	1,05E-03	1,06E-03	1,07E-03	1,19E-03	1,17E-03
06.07.2021	11:10	1,04E-03	1,06E-03	1,07E-03	1,18E-03	1,17E-03
06.07.2021	12:10	1,04E-03	1,06E-03	1,07E-03	1,18E-03	1,16E-03
06.07.2021	13:10	1,04E-03	1,06E-03	1,07E-03	1,18E-03	1,16E-03
06.07.2021	14:10	1,04E-03	1,06E-03	1,07E-03	1,18E-03	1,16E-03
06.07.2021	15:10	1,04E-03	1,06E-03	1,07E-03	1,18E-03	1,16E-03
06.07.2021	16:10	1,04E-03	1,05E-03	1,07E-03	1,18E-03	1,16E-03
06.07.2021	17:10	1,04E-03	1,06E-03	1,07E-03	1,18E-03	1,16E-03
06.07.2021	18:10	1,04E-03	1,05E-03	1,07E-03	1,18E-03	1,16E-03
06.07.2021	19:10	1,04E-03	1,06E-03	1,07E-03	1,18E-03	1,16E-03

Figure 73: Text File Raw Data Measurement Values, Source: Own representation.

For a better visual representation of the measured values, the raw data from the text file are copied to a formatted excel template, as one can see in the following figure. Using an excel template with a headline is recommended to get a faster evaluation of the data. The first column of the diagram shows the cycle count, followed by the current date and time of measurement. All the following columns contain the measured values of the respective channels.

Cycle	Date	Time	CH1	CH2	CH3	CH4	CH5
	dd.mm.yyyy	hh:mm	Ω	Ω	Ω	Ω	Ω
1	06.07.2021	08:10	1,02E-03	1,05E-03	1,06E-03	1,18E-03	1,17E-03
2	06.07.2021	09:10	1,05E-03	1,06E-03	1,07E-03	1,19E-03	1,17E-03
3	06.07.2021	10:10	1,05E-03	1,06E-03	1,07E-03	1,19E-03	1,17E-03
4	06.07.2021	11:10	1,04E-03	1,06E-03	1,07E-03	1,18E-03	1,17E-03
5	06.07.2021	12:10	1,04E-03	1,06E-03	1,07E-03	1,18E-03	1,16E-03
6	06.07.2021	13:10	1,04E-03	1,06E-03	1,07E-03	1,18E-03	1,16E-03
7	06.07.2021	14:10	1,04E-03	1,06E-03	1,07E-03	1,18E-03	1,16E-03
8	06.07.2021	15:10	1,04E-03	1,06E-03	1,07E-03	1,18E-03	1,16E-03
9	06.07.2021	16:10	1,04E-03	1,05E-03	1,07E-03	1,18E-03	1,16E-03
10	06.07.2021	17:10	1,04E-03	1,06E-03	1,07E-03	1,18E-03	1,16E-03
11	06.07.2021	18:10	1,04E-03	1,05E-03	1,07E-03	1,18E-03	1,16E-03
12	06.07.2021	19:10	1,04E-03	1,06E-03	1,07E-03	1,18E-03	1,16E-03

Figure 74: Excel File Formatted Measurement Values, Source: Own representation.

It is also possible to set up the excel template to automatically display the data in a diagram, as one can see in the following figure. The graph shows an online TCT measurement of 14 channels over a period of 1000 cycles. The x-axis of the graph represents the time in cycles, and the y-axis the measured resistance value in ohm’s. One can see that the values stay constant over the whole measurement period.

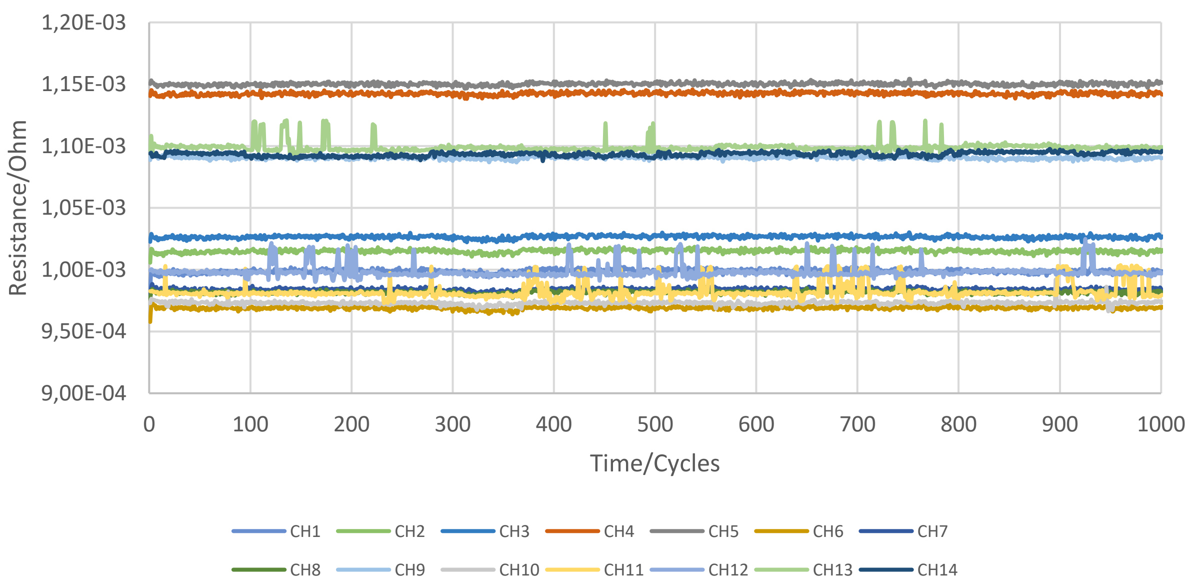


Figure 75: Measurement Diagram, Source: Own representation.

9 EXECUTIVE SUMMARY

The goal was to build an appropriate measurement system capable of automatically measuring up to 30 circuit boards. In addition, the amount of measuring channels must be easily expandable if required. It also had to be taken into account that a measuring current of 1 A is guaranteed. Based on these main requirements, different methods were discussed in the theoretical part of the thesis.

First, to select the appropriate measuring device for the automated low resistance measurement system, the determination of the measuring method suitable for the area of application must be made. Chapter 2 has compared the advantages and disadvantages of the constant-current and constant-voltage method. It was determined that the constant-voltage method is not suitable to guarantee a continuous current flow of 1 A through the resistance under test due to the unknown resistance value. [44] Due to the requirement to measure plated via holes with a defined current, the constant-current method is selected to further investigate the measurement system.

After a closer examination of the method in Section 2.1, it turned out that a voltmeter in combination with an external power source is the most suitable for the required application, as described in Subsection 2.1.1. A current generated by an external power source provides a current flow through the unknown resistor. A voltmeter measures the dropping voltage which occurs through the resistor, as one can at Figure 1. Using Ohm's law, the computed resistance is based on the known current and observed voltage. [45]

After choosing the appropriate power source application, the two-wire and four-wire measurements of the constant-current method were further determined in Chapter 3. The two-wire measurement by applying constant current has the issue that the resistance of the DUT is measured, and the resistance of both wires are taken into consideration in the measurement, as illustrated in Figure 6. [46] Wire resistance on low-resistance sources might be adversely affected if the four-wire approach is not used. Figure 7 illustrates the method's usage of two source wires to supply the DUT with a constant current and two sense wires to measure the voltage drop across this unknown resistance. As a result, the elimination of wire resistance is achieved by separating the constant current and voltage measuring path. [47] Due to the factors mentioned, the four-wire measurement method was implemented for the measuring system.

After that, several challenges with low resistance measurement error were examined in Chapter 4. Thermal EMF voltages are a common source of low-voltage measurement inaccuracy, and are discussed in Section 4.2. These voltages are generated once completely different circuit components are at different temperatures and when conductors manufactured from dissimilar materials are connected. In the case of the thermal cycling resistance measurement, different temperatures can occur between the connection points. The difference in temperature gradients can lead to few microvolts, which influences the accuracy

[44] Vgl. TEKTRONIX, INC. 5.0 (2016), Online-Source [30.June.2021], S. 78–79.

[45] Vgl. Thomas (2014), P. 119 – 120.

[46] Vgl. TEKTRONIX, INC 6.0 (2013), Online-Source [31.October.2021], P. 1.

[47] Vgl. Rainer (2016), P. 140.

of the outcome. [48] One method to avoid thermoelectric EMFs is to use the offset compensated ohm's method, as described in Subsection 4.2.2. The thermoelectric voltage can be eliminated using two different measurements. There are some similarities between this method and the current reversal method, however the second measurement is taken without any applied current. [49] Due to the LabVIEW programming of the devices, the offset compensation is easy to implement, therefore, the measurement system use the current reversal method, as explained in Subsection 4.2.1.

After determining the power-source method, constant-current measurement method, and considering low resistance measurement errors, the next step was to set up the used equipment and choose the suitable current path circuit switching application. It was crucial to determine the current path circuit switching applications, as described in Subsection 6.1.1, to save preparation time for the soldering process of the circuit boards. The *Current in Series to all DUTs* circuit scheme was chosen for the automated low resistance measurement system, which is determined in Paragraph 6.1.1.1. The advantage of this method is the reduced preparation time of the circuit boards due to soldering two wires, as illustrated in Figure 24, instead of soldering four wires to each DUT, as shown in Figure 25.

The KEITHLEY 2200-20-5 DC Power Supply unit provides a constant current flow of 1 A through the unknown resistance, as one can see in Figure 36. To automatically switch between several plated via holes, Section 6.1 describes the KEITHLEY 3706A System Switch/Multimeter, which switches between the connected DUTs during the measurement process. In addition, the voltage drop is measured with the integrated multimeter of the KEITHLEY 3706A. Further, KEITHLEY 3721 Multiplexer Card is installed in the KEITHLEY 3706A System Switch/Multimeter to measure a total of 30 circuit board structures automatically, as explained in Subsection 6.1.2. Figure 37 shows the switching path and the voltage measurement of KEITHLEY 3706A. To prevent an interruption of the current flow due to the serial connection of all DUTs, Figure 38 illustrates the circuit connection of the KEITHLEY 3740 Switch Card, which is additionally installed to bridge defects via holes.

The illustration of the measurement system setup, including the wiring of the devices and distribution board, is shown in Chapter 7. Last but not least, the LabVIEW program is explained in Chapter 8.

To summarize, the measurement system is capable of carrying out an automatic low resistance measurement to test the reliability of plated via holes of unpopulated printed circuit boards.

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[48] Vgl. TEKTRONIX, INC. 5.0 (2016), Online-Source [30.June.2021], P. 116.

[49] Vgl. TEKTRONIX, INC. 5.0 (2016), Online-Source [30.June.2021], P. 137.

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LIST OF FIGURES

LIST OF TABLES

LIST OF ABBREVIATIONS

AABUS	As Agreed Between User And Supplier
CC	Constant Current
COM	Common Marked
CV	Constant Voltage
DMM	Digital Multimeter
DUT	Device Under Test
HAST	High Accelerated Stress Test
IST	Interconnect Stress Testing
MUX	Multiplexer
NC	Now Close
NO	Now Open
Online TCT	Interval Resistance Measurement During Thermal Cycling Test
PCB	Printed Circuit Board
PTH	Thermal Cycling Test
TST	Thermal Shock Test
VI	Virtual Instrument

APPENDIX 1:

Download link USB TO GPIB Converter *KEITHLEY KI-488* driver

https://de.tek.com/accessory/kusb-488b-software

Download link Picoampere meter *KEITHLEY 6485* driver

http://sine.ni.com/apps/utf8/niid_web_display.download_page?p_id_guid=4BD008D8D7747004E05400144FF9A492

Download link System/Switch Multimeter *KEITHLEY 3706A* driver

https://www.tek.com/product/3706-software/3700-3700a-series-native-labview-2009-driver-version-112-project-style

Following link leads to a free online schematic drawer (Electrical circuit drawer), which is used for all circuits in this thesis.

https://www.digikey.com/schemeit/project/

APPENDIX 2:

Model	Description	Number of Outputs	Maximum Voltage	Maximum Current	Connectivity	List Price
2200-20-5	Power Supply, 20 Volts, 5 Amps	1	20V	5A	USB, GPIB	1,030 € Configure & Quote
2200-32-3	Power Supply, 32 Volts, 3 Amps	1	32V	3A	USB, GPIB	1,060 € Configure & Quote
2200-72-1	Power Supply, 72 Volts, 1.2 Amps	1	72V	1.2A	USB, GPIB	1,060 € Configure & Quote
2200-60-2	Power Supply, 60 Volts, 2.5 Amps	1	60V	2.5A	USB, GPIB	1,240 € Configure & Quote
2200-30-5	Power Supply, 30 Volts, 5 Amps	1	30V	5A	USB, GPIB	1,240 € Configure & Quote

Figure 76: KEITHLEY Keithley 2200 DC Power Supply price list, Source: TEKTRONIX, INC. 2.2 (2021), Online-Source [02.November.2021].

Model	Touchscreen	Channels	Max Current Source/Measure Range	Max Voltage Source/Measure Range	Measurement Resolution (Current / Voltage)	Power	List Price
2450	Yes	1	1A	200V	10fA / 10nV	20 W	5,640 € Configure & Quote
2460	Yes	1	7A	100V	1pA / 100nV	100 W	8,740 € Configure & Quote
2470	Yes	1	1A	1100V	10fA / 100nV	20 W	9,810 € Configure & Quote
2461	Yes	1	10A	100V	1pA / 100nV	1000W	9,900 € Configure & Quote

Figure 77: KEITHLEY 2400 Graphical Series SMU price list, Source: TEKTRONIX, INC. 8.0 (2021), Online-Source [02.November.2021].

Appendix 2:

Value	Time (Seconds)	Temperature (°C)	Description
t1	210 ± 15	–	Target preheat time
t2	270 ± 10	–	Target peak reflow time
t3	330 ± 15	–	Target cool-down start time
t3 - t1	120 ± 30	–	Target time above T1
T1	–	230	Maximum preheat temperature
T2	–	260 ± 5	Target reflow temperature
Point	**Time (Seconds)**	**Temperature (°C)**	**Description**
A	0	30	Upper specification limit values
B	100	230	
C	195	230	
D	255	265	
E	285	265	
F	345	230	
G	550	30	
H	30	30	Lower specification limit values
I	157	93	
J	225	230	
K	260	255	
L	280	255	
M	315	230	
N	383	30	
Segment	**Slope (°C / second)**		**Description**
A-B & I-J	2.0		Maximum preheat rate
H-I	0.5		Minimum preheat rate
F-G	-1.0		Minimum cool-down rate
M-N	-3.0		Maximum cool-down rate

Figure 78: 260 °C Reflow profile, Source: IPC International, Inc. 4.0 (2020), Online-Source [05.November.2021], P. 3.