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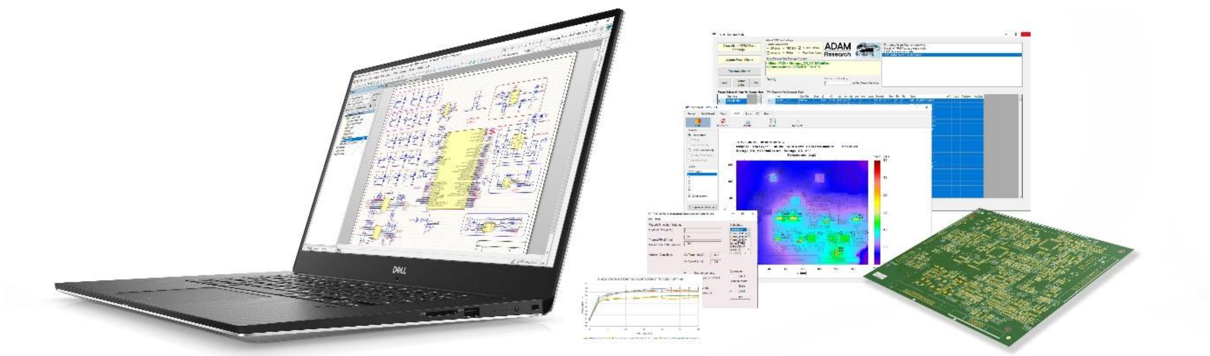

Efficient PCB production by thermal simulation

Jeffrey Gorissen

Promoters:

Prof. Fang Yu — Yangzhou University

MSc. Bart Stukken — PXL University College

Bachelor project academic year 2018-2019

The student takes full responsibility for this dissertation. Dissertation supervision and process coaching does not eliminate incomplete information and/or inaccuracies which have been taken into account in the final evaluation, but which have not been modified in the final version of the dissertation.

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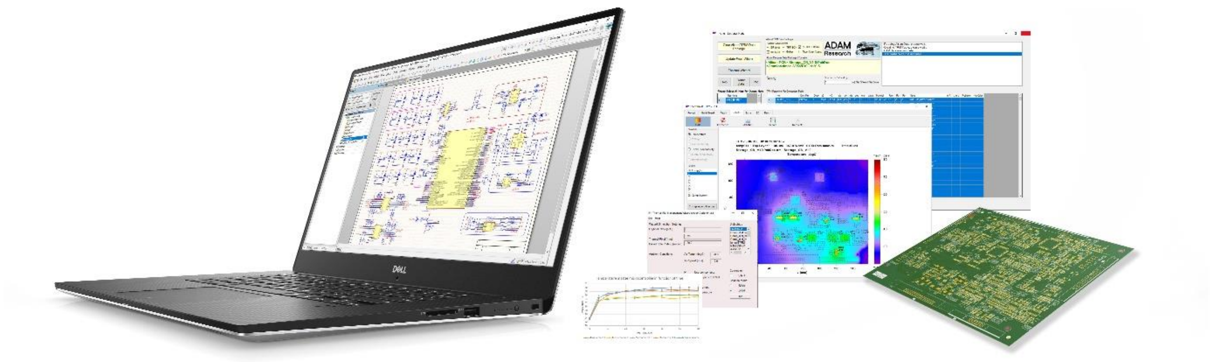

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I. Acknowledgements

This thesis is the milestone that signals the end of my Bachelor program in Electronics-ICT at PXL University College. This educational programme has been a journey that brought me much knowledge and pleasure. It was not always easy, this made it exciting and challenging. To be able to finish it off with an internship at Yangzhou University in China was a true honour.

The internship provided me with the chance to gain experience, knowledge and entrepreneurship. This on both professional and personal level. Of course, I would not have been able to complete this all on my own. Therefore, I will use this opportunity to thank the most important people that helped me get to this milestone.

First and foremost, I would like to thank my promotor from PXL University College, Bart Stukken. This is to thank him for his help, enthusiasm and problem-solving abilities. In times of need and urgency, he was there to support and guide me. I could not have wished for a better promoter.

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To all my teachers at PXL University College, thank you. Thank you for the little conversations, the friendly faces, the jokes, the tips, the tricks and all the pushes in the right direction. I truly enjoyed all of my Electronics-ICT classes.

Next, I would like to thank my parents and family. Especially my mother, Caroline Mulders, for always having faith in me and encouraging me to work hard and never give up. I may not have always shown it, but I am grateful to have you as my mother.

To finish off, I would like to thank my girlfriend, Laura Kuipers. I want to thank her for providing me with unfailing support and continuous encouragement throughout my years of study and through the process of researching and writing this thesis. It was not easy being so far apart for four months, yet we prevailed.

To all of you, mentioned or not, thank you very much. This accomplishment would not have been possible without you!

Jeffrey Gorissen

Yangzhou, June 4, 2019.

II. Abstract

Energy, especially green energy, has been a much-debated topic in the last years. Along with technological advances and new policies, the dependence on fossil fuels decreases as renewables see a strong increase. Due to the nature of renewable energy like wind and solar, the amount of power that is generated at any moment fluctuates a lot. Traditional power can be generated on demand. Renewable energy is dependent on geographical location and weather. Growing countries such as China struggle to keep up with the demand for power. Possible solutions exist and China is seizing the opportunity by enabling research groups to tackle the growing power problem on different fronts.

By using Photovoltaic/Battery/Grid systems people are able to bridge the fluctuating amounts of power generated by their system. A Photovoltaic system on its own generates peak power during noon. Before and after the middle of the day, the amount of power generated drops significantly. Most people work during the day and peak home power draw is in the morning and evening for respectively getting ready for work and coming home and cooking dinner. Being able to capture the energy produced during the day lowers grid stress. It enables you to use that power later during the day when you return for e.g. cooking dinner. Furthermore, it gives the consumer more control over his grid usage. Making it easy to use cheaper energy from the grid at night if required to top up the battery pack.

These systems heavily rely on electronics. From schematics and components to PCBs. These electronics are sensitive to heat. Which is the cause of many problems, and often leads to redesigns. In the case of making a Photovoltaic/Battery/Grid system, preventing temperatures to skyrocket is preferred. By not including active cooling the overall efficiency increases. In the research the benefits of thermal simulations on PCBs get discussed, using the Photovoltaic/Battery/Grid system as testing grounds. Adding this extra step can mean a revolution in the design process of PCBs.

The main question is how beneficial a thermal simulation is. An extra step does not seem logical at first. However, creating a feedback loop that catches problems before going into production is always beneficial. Additionally, when starting a project with thermal simulation in mind the additional time required to run a simulation is neglectable. In the research, the main PCB has a board size of approximately 125 mm by 158 mm. It is a four layer PCB using the two middle layers as ground plane and power plane. When running the simulation with a thermal resolution of 0,2 mm it takes about 7 minutes of CPU time. This while running on a mobile Intel Core i7-8750H to simulate the temperature.

When dialling in the settings and power usage perfectly, the accuracy of the simulations can reach up to ±5% of the actual temperatures. When only setting up the main components to be simulated, these results cannot be expected. However, the simulation still gives insight into how temperatures manifest in components and on the board itself.

III. Table of contents

I. Acknowledgements ... ii
II. Abstract ... iii
III. Table of contents ... iv
IV. List of figures ... v
V. List of tables ... vi
VI. List of abbreviations ... vii
Introduction ... 1
1 Background Information and Research Problem ... 2
1.1 Background Information ... 2
1.2 Research Problem ... 3
2 Materials and Research Method ... 4
2.1 Materials ... 4
2.1.1 Software ... 4
2.1.2 Hardware ... 5
2.2 Research Method ... 5
3 Integration ... 6
3.1 PV/Battery/Grid System ... 6
3.2 PCB ... 8
3.3 Components ... 9
3.4 Thermal simulation ... 13
4 Results ... 16
4.1 Case Study ... 17
Conclusion ... 19
Recommended Future Research ... 19
Bibliographical references ... 20
Appendices ... 21

IV. List of figures

Figure 1: Traditional PCB production process 3
Figure 2: Production process with simulations 5
Figure 3: Schematic representation of a PV/Battery/Grid System 6
Figure 4: Master PCB of the PV/Battery/Grid System 8
Figure 5: Requirements for thermal simulations 13
Figure 6: TRM-POWER parameter used by TRM 13
Figure 7: TRM AD2TRM script in Altium Designer 13
Figure 8: Thermal wizard 14
Figure 9: TRM - Results – Plots 14
Figure 10: Temperature master microcontroller in function of time 17

V. List of tables

Table 1: TMS320F2803x Microcontroller 9
Table 2: PCF8563 Real-Time Clock 9
Table 3: AT24C256 EEPROM Chip 9
Table 4: NE555D precision timer 10
Table 5: CAT706 Supervisory Circuits 10
Table 6: SN74LVC07AD buffer and line driver 10
Table 7: PMBT2907 PNP switching transistor 10
Table 8: TPS76733QD voltage regulator 11
Table 9: REF3033 voltage reference 11
Table 10: LM2903 dual differential comparator 11
Table 11: 74LVXC3245 dual–supply voltage interface transceiver 11
Table 12: LM239 precision-voltage comparators 12
Table 13: TL072 J-FET dual operational amplifier 12
Table 14: TL074 J-FET quad operational amplifier 12
Table 15: Comparison component temperatures; Load vs. Max 16
Table 16: Average temperature master microcontroller 17
Table 17: Results thermal simulations 18
Table 18: Simulation accuracy 18

VI. List of abbreviations

A

A, mA, mAh : Ampere, milli ampere, milli ampere hour

AC : Alternating Current

AD : Analog Digital

C

CPU : Central Processing Unit

D

DC : Direct Current

E

EEPROM : Electrically Erasable Programmable Read-Only Memory

I

IO : Input Output

P

PC : Personal Computer

PCB : Printed Circuit Board

PSDAB : Parallel-Serial Dual Active Bridge

PV : Photovoltaic

R

RTC : Real-Time Clock

S

SMD : Surface Mount Device

T

TI : Texas Instruments

TRM : Thermal Risk Management

V

V : Volt

W

W, mW , Wh : Watt, milli Watt, Watt hour

Introduction

This thesis is based on a project commissioned by Yangzhou University and executed by Master students. A Photovoltaic (PV)/Battery/Grid System is being developed. The main printed circuit board (PCB) of this project is used to elaborate on the benefits of thermal simulations for the efficiency of PCB production. To maintain easy readability this paper is divided into four chapters and a conclusion.

Background Information and Research Problem; this makes clear where this thesis is situated. It is the bigger picture behind the problem.

- Big picture
- Institution
- Problem

Materials and Research Method; everything that is used to complete this thesis is stated in this chapter. Hardware and software are mentioned under materials. The research method is a high-level explanation of how things fit together.

- Hardware used
- Software used
- High Level

Integration; the largest chapter of all. It is used to go into detail and explain the problem and address the solution. It addresses the technical side of this thesis. This results in a more detailed explanation of how things fit together.

- The big body of the thesis
- Technical
- Details

Results; a short chapter. While short, it provides the needed specifics, graphs and tables. This Chapter is all about numbers. These numbers will support the claims made in the final section.

- Specifics
- Graphs and tables
- Proof

Conclusion; this is why all the effort was made. The conclusion uses all the information gathered in the above-mentioned chapters. It summarizes and provides the answer to the questions asked in this thesis. In doing so, it is the final touch to wrap this thesis up.

- Summary
- Answer
- Wrap-up

1 Background Information and Research Problem

1.1 Background Information

The world is transitioning from a fossil fuel addict to a clean and healthy way of producing energy. Global warming gets more and more attention. Youth and students have been marching the streets of cities around the world to ask politicians to stop looking the other way. Humanity has to make some significant efforts to be able to transition as fast as possible.

One of the larger countries in this battle is China. On first glance, China is not doing enough to aid in the preservation of the planet. With more than 1,386 billion Chinese as of 2017 and an estimated 1,420 billion Chinese at the time of writing this, China has the largest population on earth. The population covers more than 18% of the world population, which is at an estimated 7,714 billion. All of these people have a lot of needs. In our current society, most of those needs are based on energy. Shelters get build with power tools. Resources get mined with heavy machinery. Food gets cultivated using large amounts of water, fertilizer and artificial lighting. All of this relies on transport by trucks, boats, and airplanes. The power usage is only going up. [1]

The Chinese government is unable to keep up with the power demand and relies on cheap coal power. This, however, does not mean they are not making an effort to make clean, reliable and most importantly, green energy available to the population of the People's Republic of China. This is where universities, research groups, and companies come in. They are working hard to find new solutions to a problem that not only China but the entire world, is facing. By using young and innovative minds to carry forward new and interesting ideas, science keeps evolving.

Yangzhou University is one of the driving forces making innovation and new technologies possible. It is located only 240 kilometres from Shanghai and 73 kilometres from Nanjing, the capital of the Jiangsu province of the People's Republic of China, giving it a good central position. By erecting research groups, the university wants to enable people and companies to be able to create their own power without having to rely on the general power grid. The idea is to make PV systems, also known as solar panels, usable every hour of the day. The way to achieve this is to add a battery into the system. This PV/Battery/Grid System will enable the owners to collect, use and store solar energy.

When taking a closer look at any kind of these systems, a lot of electronics will be found. Electronics are part of the world as we know it. Without them, the world would look very differently. One of the most famous products coming from China are these electronics. When taking an even closer look, the electronics as we know them are not possible to think of without thinking of a PCB to hold and connect all of the components together. But, of course, the process of making a PCB is not environmentally-friendly. A lot of energy and chemicals go into making a single PCB. Often, to get a final PCB the designers go through multiple iterations to get everything perfect. This costs a lot of resources, time and money. Not only in the design process but especially in the production process. Resulting in wasted energy, resources, money and time. Typical errors in a finished PCB include human errors. However, one of the more difficult parameters to predict that comes to mind is temperature. Temperature is always a limiting factor in electronics.

1.2 Research Problem

The production process of a PCB is comprised of multiple steps, this can be seen in Figure 1. To start, electrical schematics have to be designed. Once this is done, the designing of the PCB can start. When the design is completed it gets shipped off to a PCB manufacturer. After production is finished testing of the PCB can start.

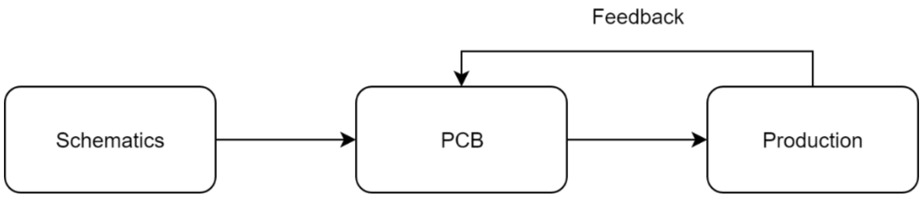


Figure 1: Traditional PCB production process

As mentioned earlier, the temperature is an important factor in electronics. Some components generate a lot of heat when used. In general, the more current or processes a component needs the more heat is generated due to resistance. More often than not PCBs are filled with hundreds of components, making it quite difficult to design a PCB with every heat expelling component in mind.

In the world of technology, failures due to exceeding the maximum temperature stated in the datasheets are daily occurrences. In datasheets, there are two main maximum operating temperatures to speak of. First, the package temperature translates to the temperature on the surface of the component. Second, the junction temperature refers to the temperature of the active junction. This junction is, generally, the hottest part of the component. Because of this, the junction temperature is the most important one to keep an eye on. When exceeding the stated maximum values, the risk of failures increases dramatically. Making sure that components do not stay near or at the maximum operating temperatures for a prolonged time is important to ensure performance and longevity. [2]

However, this is where the problem emerges. People can make good and educated guesses, but in order for those guesses to be good, a lot of experience is required. Therefore, designing a PCB with good thermal properties can take years, if not decades, to master. Even at this master level, new components get released with different properties and specifications on a daily basis. PCBs themselves can be made out of different insulating and conductive materials with their own properties as well. Because of this a PCB often goes through multiple iterations before being approved for mass production, especially when they incorporate large and complex schematics. Being able to prevent unnecessary iterations to make it into the production process would be a major advantage.

By knowing how the temperatures on a PCB and its components will manifest before going into production, adjustments can be made in the design to address the issue. This can be spreading out hot components, making certain traces bigger or changing out components altogether. Therefore, preventing faulty PCB designs to be produced. To achieve this goal there needs to be an additional step in the process "Thermal simulations and analyses of the PCB designs". Adding in this step will enable the designer to check and re-adjust before going into production.

By streamlining processes, steps often get removed. Adding a step might seem contra-intuitive at first. An extra step means more time is needed. The potential, however, is having a lot of savings in the PCB manufacturing process. No need to produce and transport PCBs that are destined to fail. Additionally, there is no time lost in producing and testing faulty PCBs, therefore, making up for time lost by simulating and analysing the PCB. Assessing how accurate these simulations are and how much time is needed to run them is a fundamental core in researching this addition into the production process.

2 Materials and Research Method

2.1 Materials

2.1.1 Software

The PCB design process is the combination of placing components and routing their electrical connections to connect the components physically. First, electrical schematics have to be made. These represent how every component is connected to each other electrically. Next, the layout of the components has to be determined, this is the placement of the components in a physical space. Finally, the PCB has to be routed. This is considered to be both art and science by many. The routing is making the electrical connections between components on the PCB. To do all of this, some software is required to make the process easier. The software used in this research to design circuits schematics and the PCB designs is Altium Designer 13. This is a well-known software package in the PCB use it. Being well known is not necessarily a good thing. Many consider Altium to be over-priced. This particular software package is used because Yangzhou University and the accompanying research group use it. Previously made projects and designs are also made using Altium. This research, therefore, continues with the use of Altium Designer 13. Others might want to use a more recent version of Altium Designer or software packages from other companies. [3], [4]

Additionally, a software package to simulate the temperatures of the PCB is required to validate that software simulations are able to give insight into the spread of heat in the PCB and its components. Multiple software packages are able to fulfil this need. However, this is not a comparison between the different software possibilities. The Thermal Risk Management (TRM) software used in this research was provided free of charge by ADAM Research for the duration required to complete this thesis. Students doing their bachelor or master thesis can apply for a free licence. This along with the short time frame, extensive documentation and YouTube tutorials ensured TRM by ADAM Research to be selected. Note that ADAM Research offers a two week trial version of their TRM software on their website after a simple request. [5]

Calculating the margin of error can only be achieved with data and data processing. To make all of this data visually attractive and easy to understand, graphs and tables have to be made. All of this is made easier with Microsoft Excel. It is a spreadsheet program developed by Microsoft. As with the previous software packages, there are a lot of alternative spreadsheet programmes available to the general public. Microsoft Excel is one of the most well-known spreadsheet programmes. It is used in Yangzhou University and PXL University College makes it freely available to all of their students. The software is also well-documented, and tutorials can readily be found on the internet. Because of this, Microsoft Excel will be used for data processing in this research.

2.1.2 Hardware

To run these software packages some processing power is needed. The use of a moderate or, preferably, high-performance personal computer (PC) is required to be able to make the experience smooth. The PC used in this research, a laptop, is a Dell XPS 15 9750. The specific model that is used has an Intel Core i7-8750H processor, 16 GB of random-access memory, NVIDIA GeForce GTX 1050 Ti Max-Q graphics card and a solid-state drive for data storage. In general, the more performance a PC can deliver, the faster the calculations. This leads to improved workflow and faster simulations. In this case, increasing performance directly impacts the time aspect of production and thus the cost aspect as well. [6]

For PCB designers to start using software to assess the thermal characteristics of their PCB designs, they need to be sure that the software gives them an accurate representation of the actual real-world temperature. In other words, the margin of error of the simulations compared to real life measurements has to be as small as possible. The best way to get a real-life measurement would be to make a thermal image of the PCB during load. This would require the use of a thermal imaging camera. These cameras have the ability to detect thermal radiation. This thermal radiation is actually the long-infrared spectrum and resides between 9000 and 14000 nanometres. Different amounts of radiation correlate with different temperatures. Preferably a thermal imaging camera system is used to measure the entire PCB at once. [7]

In this research, however, the temperature measurements are conducted with a non-contact digital infrared thermometer. This thermometer is only able to measure the temperature on one single spot for each measurement. The Smart Sensor AR320 infrared thermometer has a range of minus 32 degrees Celsius up to a positive 320 degrees Celsius. The accuracy claimed by the Smart Sensor AR320 is 2 degrees Celsius. Note that all these types of thermometers are only able to measure the surface temperature, known as the package temperature, of the components. They are not able to measure the internal temperature, known as the junction temperature, of the components or the PCB itself.

2.2 Research Method

The research revolves heavily around the thermal simulation of a PCB. This is an additional step compared to the traditional PCB production process and can be seen in Figure 2. Notice that the feedback loop moves back a step. Therefore, errors can be uncovered in an earlier stage.

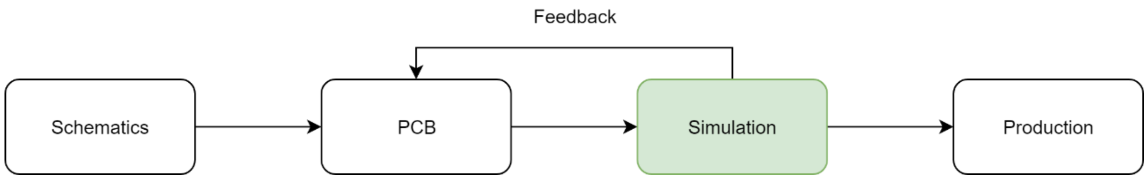


Figure 2: Production process with simulations

The thermal simulation uses the PCB files, Gerber files, that are required to manufacture the physical PCB. Taking these files, along with the used materials, drill information and heat properties, as an input and creating detailed heat maps of the temperature throughout the board as an output. In this research the efficiency of these simulations gets assessed on two main elements; Time and accuracy.

3 Integration

3.1 PV/Battery/Grid System

The PV/Battery/Grid System is being designed to provide power for a house and collect and store the excess energy for later usage in its batteries. A simplified overview of this system is represented in Figure 3 [8]. The system itself is made up out of four main components. The photovoltaic module delivers power. When needed the battery can store or release power. The inverter transforms the direct current (DC) into alternating current (AC) for common household loads. The Charge controller regulates the DC voltage and current for the battery and the inverter. This last component will be looked into with more detail compared to the other components. When enough power is produced and the battery is fully charged, the excess power can go to the grid. However, when there is not enough power being produced and the battery is depleted utility power can be used to power loads and to charge the battery.

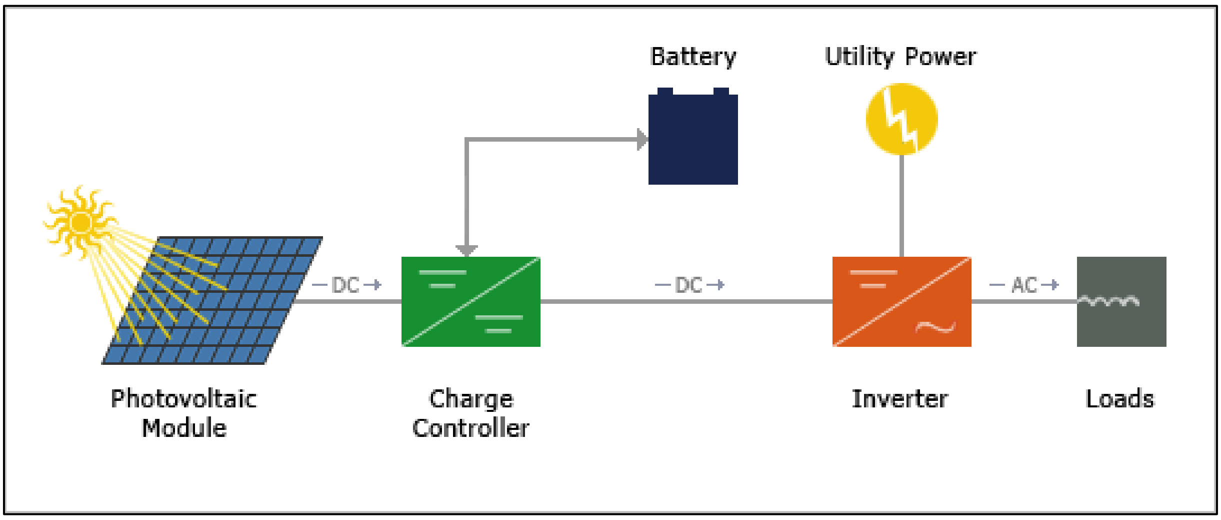


Figure 3: Schematic representation of a PV/Battery/Grid System

PV modules exist in many form factors. All of which can have different specifications. Solar panels are able to convert the energy of photons into electrical energy. Photons are able to do this by knocking electrons out of the semiconductor material. These free electrons on their turn create a difference in potential. [9]

The battery pack used in a PV/Battery/Grid system is not unlike the battery in your mobile phone or laptop. The main differentiation is the capacity and the peak power draw of the battery. The batteries for PV/Battery/Grid Systems start at 4 kWh and go up to 14 kWh.

Example: An average smartphone with a capacity of 3000 mAh and a nominal voltage of 3,7 V has a Wh-rating of 11,1 Wh, see (1). When assuming no losses in charging the lowest capacity of 4 kWh can fully charge this phone about 360 times, see (2).

$$3000\,mAh * 3{,}7\,V = 11100\,mWh \qquad (1)$$

$$4000\,Wh\,/11{,}1\,Wh = 360{,}36 \qquad (2)$$

As the name suggests the inverter inverts DC to AC or AC to DC. This is necessary to run household appliances, like washing machines and refrigerators, as these do not run on DC power. Converting AC back to DC is required to charge the battery when the PV system is inadequate.

The system that Yangzhou University is developing has a charge controller based upon the Parallel-Serial Dual Active Bridge (PSDAB) circuit. This circuit technology has some significant improvements over alternative circuits used in the past. The two alternative options are the DC-DC Bidirectional converter without electrical isolation and the Isolated DC-DC bidirectional converter and are explained in order. After this, the usage of the PSDAB is clarified.

In this first method, a bidirectional half-bridge type circuit is generally used. In the case where the battery pack voltage is low, the voltage becomes relatively large with respect to the DC high voltage on the input side. This limits the voltage adjustment range and also reduces the voltage and thus conversion efficiency. In addition, without electrical isolation between the battery and the DC bus, there is a safety hazard. Having efficiency and safety issues, this circuit is not used in the project. [10]

In the second method, a double active bridge circuit is used. Since a high-frequency isolation transformer is being used, the voltage adjustment range and safety problems existing in the first method are solved by this addition. However, when the voltage is relatively high, the voltage stress on the switch tube on the high voltage side is also relatively large. For this reason, it is necessary to select a switch tube that can withstand a higher voltage level. These switch tubes do exist, but they have a relatively large switch on resistance, or a high voltage drop. They bring an additional cost with them as well, making them less interesting. It would also cause the switch tube on the low voltage side to be relatively large. The current stress is then also enlarged causing the switch tubes to generate more heat. Thus, dropping the efficiency of the system. Therefore, the existing circuit topology is insufficient in the application of a high transformation ratio. [10]

In the field of power electronics and electrical engineering, the PSDAB circuit is used to realize high step-up conversions of, relatively speaking, low voltage battery packs to high voltage DC. Furthermore, it supports a bidirectional flow of energy. This means that electricity can flow into and out of the battery pack. The PSDAB circuit is based on the existing dual active bridge circuits, maintaining all of the advantages of those circuits. Yet, it overcomes the shortcomings of those particular designs. The PSDAB circuit also incorporates the transformer isolation to maintain a high safety level. In short, it has two dual active bridge circuits connected in series on the input side and connected in parallel on the output side. This causes the high voltage stress of the high voltage side switch tube and the current stress of the low voltage side switch tube to be correspondingly solved. The advantages are that the switch tube with a lower withstand voltage level can be used on the high voltage side. Because of this, the conduction loss is reduced, and the current is shunted on the low voltage side. In doing so, the conduction loss of the low side switch tube is also reduced. Important to note is that the temperature of the switch tubes cannot exceed 80 degrees Celsius, or they are prone to explode. [11]

This circuit has multiple advantages including safety, wide voltage adjustment range and high efficiency compared to the previously mentioned methods. This is the case in applications where the voltage is relatively large. In addition, since the circuit is symmetrical on both sides and can realize the bidirectional flow of energy, it is suitable for use as a DC-DC converter circuit in a two-way charger for charging and discharging a low voltage battery pack. [11]

3.2 PCB

The PCB in this research is an existing board designed by students of Yangzhou University. This PCB went through the standard design process. Electrical schematics were made after the features had been decided on. After this, the PCB layout and routing were done. Finally, the PCB design files were sent off to a PCB manufacturer for production and shipped to Yangzhou University.

This master PCB is the brains of the system, see Figure 4. It contains the central processing unit (CPU) to run the software. The master PCB is built up from seven different electrical schematics that are all connected to each other. Two of these schematics are for analogue-to-digital (AD) sampling circuits. Next up, the drive circuit is used to control other circuits on other PCBs. Continuing, there an input-output (IO) circuit is also incorporated in the master PCB. This circuit enables the input and output of signals. There are two processors on the PCB. The processors used are two TMS320F2803x Piccolo™ chips from Texas Instruments (TI). These contain a high-efficiency 32-Bit CPU. Both processors have their own circuit; a master and a slave circuit. The power circuit provides energy for all these circuits and their components.

With the production process completed, assembly and testing started. However, alterations were made to the electrical schematics and pin layout based upon the data collected in the tests. Because of this, the board had to be updated. And this version must go through the entire process on its own. Actions on the PCB taken in this research were limited to performing the layout update of the PCB from version one to version two. Inherently, there is no substantial difference between these versions.

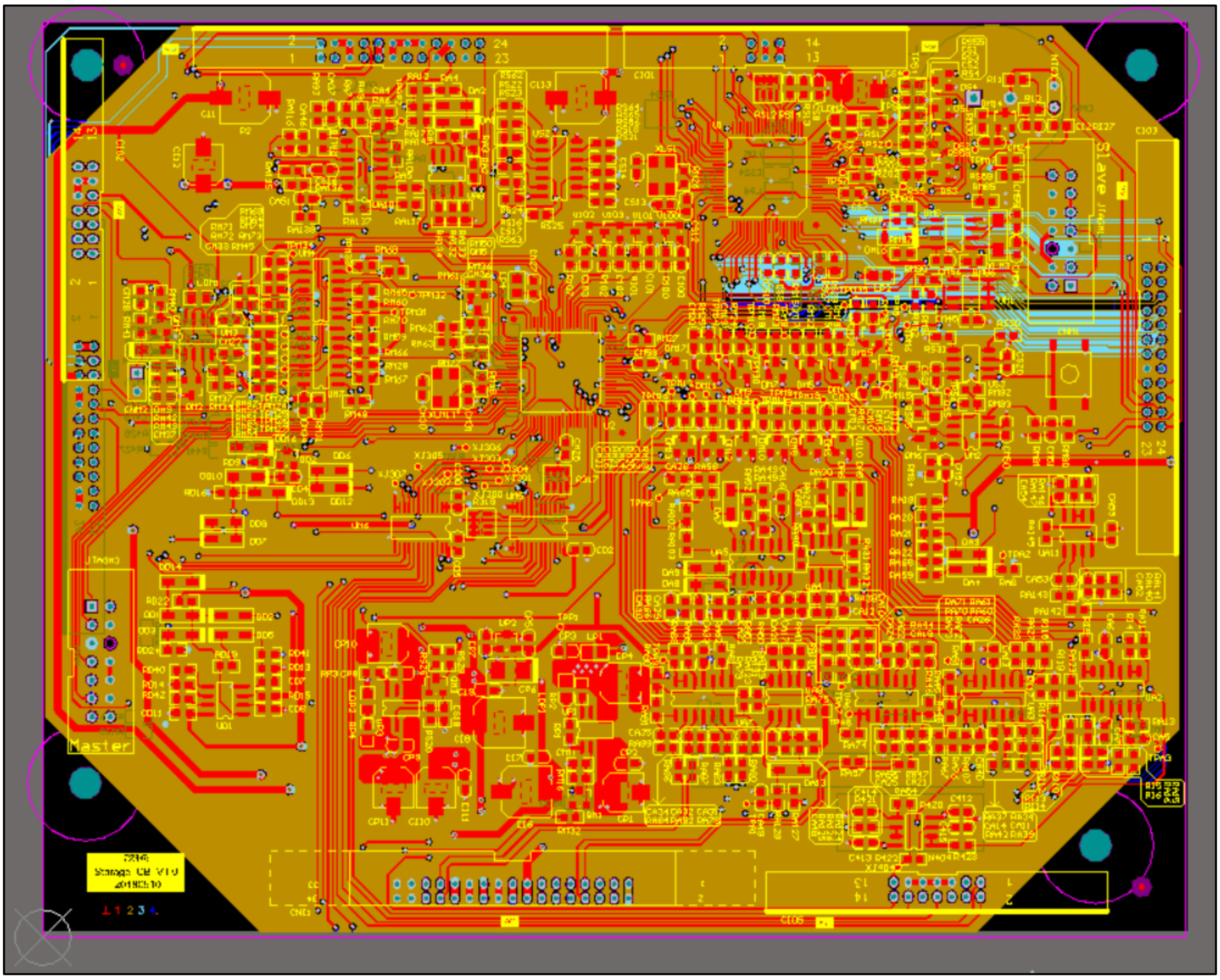


Figure 4: Master PCB of the PV/Battery/Grid System

3.3 Components

The simulation of this PCB is done with a limited number of components. It is nearly impossible to do this for each and every component on this PCB given the period of time available. Therefore, the most important active components are selected and researched for their power dissipation. These components originate from six of the seven schematics that make up the PCB, see 3.2. Only the components of the IO schematic are not included. No active components are found in this part of the PCB. Note that the following power values are for heat dissipation as found in the datasheets. Therefore, these values might differ from actual power consumption numbers.

Most noticeably on the PCB are the two microcontrollers. These are two TMS320F2803x Piccolo™ Microcontrollers. Ideal for their use case in the PV/Battery/Grid System. TI developed these specifically for processing and actuation to improve closed-loop performance in real-time control applications. They are marketed for use in applications such as industrial motor drives, solar inverters and digital power. More information about their power output can be found in Table 1. This microcontroller can be found in both the Master Circuit and the Slave Circuit.

TMS320F2803x	Value	Unit	Image
Operating temperature (MAX)	+150	°C	
Operating voltage	3,3	V	
Power (MAX)	500	mW	
Power (LOAD)	400	mW	
Power (IDLE)	100	mW	

Table 1: TMS320F2803x Microcontroller

The PCF8563 is a Real-Time Clock (RTC) optimized for low-power applications. For the RTC includes a programmable clock output. An interrupt output and voltage-low detector are also provided. The most important information used in this research can be found in Table 2. This component is part of the Master Circuit.

PCF8563	Value	Unit	Image
Operating temperature (MAX)	+85	°C	
Operating voltage	3,3	V	
Power (MAX)	300	mW	
Power (LOAD)	100	mW	
Power (IDLE)	30	mW	

Table 2: PCF8563 Real-Time Clock

The AT24C256 is an electrically erasable and programmable read-only memory (EEPROM) chip. It provides 262144 bits of storage. This component is part of the Master Circuit. As is the trend in this project, the chip is optimized for low power and low voltage operation. As can be seen in Table 3, power usage spikes when flashing the chip. Idle power usage is neglectable as only 6 µA is required in this state.

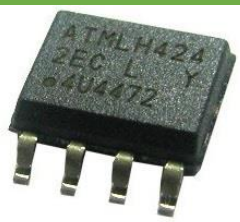
AT24C256	Value	Unit	Image
Operating temperature (MAX)	+125	°C	
Operating voltage	3,3	V	
Power (MAX)	170	mW	
Power (WRITE)	100	mW	
Power (READ)	70	mW	
Power (IDLE)	1,98e-2	mW	

Table 3: AT24C256 EEPROM Chip

The NE555D precision timer is able to produce accurate time delays and oscillations. More information in Table 4. This component is part of the Master Circuit.

NE555D	Value	Unit	Image
Operating temperature (MAX)	+150	°C	
Operating voltage	5	V	
Power (MAX)	1125	mW	
Power (LOAD)	500	mW	
Power (IDLE)	50	mW	

Table 4: NE555D precision timer

The CAT706 provides the reset and monitoring functions for the electronic system of the master circuit. This component can be found in the Master Circuit and in the Slave Circuit. The power dissipation of this chip can be seen in Table 5. It keeps an eye on the system voltage and maintains a reset output until that voltage reaches the device's specified trip value. Then, it maintains the reset output active condition until the device's internal timer allows the system power supply to stabilize.

CAT706	Value	Unit	Image
Operating temperature (MAX)	+85	°C	
Operating voltage	3,3	V	
Power (MAX)	470	mW	
Power (LOAD)	66	mW	
Power (IDLE)	10	mW	

Table 5: CAT706 Supervisory Circuits

The SN74LVC07AD buffer and line driver from TI is used to amplify an analog or digital signal by driving the input to the transmission line. For the power dissipation see Table 6. This component is part of the Master and Slave Circuit.

SN74LVC07AD	Value	Unit	Image
Operating temperature (MAX)	+150	°C	
Operating voltage	5	V	
Power (MAX)	500	mW	
Power (LOAD)	250	mW	
Power (IDLE)	120	mW	

Table 6: SN74LVC07AD buffer and line driver

The PMBT2907 is a PNP switching transistor in a small SOT23 Surface-Mounted Device (SMD) plastic package. It has a maximum total power dissipation of 250 mW, see Table 7. It is rated up to 40 V and up to 600 mA. This component is part of the Master Circuit.

PMBT2907 & PMBT2222	Value	Unit	Image
Operating temperature (MAX)	+150	°C	
Operating voltage	3,3	V	
Power (MAX)	250	mW	
Power (LOAD)	125	mW	
Power (IDLE)	25	mW	

Table 7: PMBT2907 PNP switching transistor

The TPS76733QD is a low-dropout linear regulator. It is used in the Power Circuit. It regulates 5 V down to 3,3 V. This voltage regulator has a max current rating of 1 A, see Table 8. Potentially a lot of thermal power when operated at maximum specifications.

TPS76733QD	Value	Unit	Image
Operating temperature (MAX)	+125	°C	
Operating voltage	5	V	
Power (MAX)	5	W	
Power (LOAD)	400	mW	
Power (IDLE)	100	mW	

Table 8: TPS76733QD voltage regulator

The REF3033 is a precision low-power low-dropout voltage reference in a SOT23-3 package. The small size and low power consumption (50 µA IDLE, see Table 9) make it ideal for portable and battery-powered applications. It is used in the Power Circuit.

REF3033	Value	Unit	Image
Operating temperature (MAX)	+150	°C	
Operating voltage	5	V	
Power (MAX)	225	mW	
Power (LOAD)	125	mW	
Power (IDLE)	2,5e-2	mW	

Table 9: REF3033 voltage reference

The LM2903 is a dual differential comparator. It consists of two independent voltage comparators. It is used in the Power Circuit. The chip, used in the Power and AD Circuit, has a high maximum power dissipation value as can be seen in Table 10. However, under normal load it is significantly lower.

LM2903	Value	Unit	Image
Operating temperature (MAX)	+125	°C	
Operating voltage	12	V	
Power (MAX)	600	mW	
Power (LOAD)	240	mW	
Power (IDLE)	72	mW	

Table 10: LM2903 dual differential comparator

The MC74LVXC3245 is a dual–supply voltage interface transceiver. It is especially well suited for real-time configurable IO applications. The maximum power dissipation can be seen in Table 11. This component is used in the Drive Circuit.

MC74LVXC3245	Value	Unit	Image
Operating temperature (MAX)	+150	°C	
Operating voltage	5	V	
Power (MAX)	1	W	
Power (LOAD)	500	mW	
Power (IDLE)	100	mW	

Table 11: 74LVXC3245 dual–supply voltage interface transceiver

The PMBT2222 is a PNP switching transistor in a small SOT23 SMD plastic package. Just like the PMBT2907, it has a maximum total power dissipation of 250 mW, see Table 7. It is rated up to 40 V and up to 600 mA. This component is part of the Drive Circuit.

The LM239 is a precision-voltage comparator. The maximum total power dissipation can be observed in Table 12. The comparator has been designed specifically to operate from a single power supply over a wide range of voltages. Operation from split power supplies is also possible. It can be found in the AD Sampling Circuit.

LM239	Value	Unit	Image
Operating temperature (MAX)	+150	°C	
Operating voltage	±12	V	
Power (MAX)	720	mW	
Power (LOAD)	360	mW	
Power (IDLE)	72	mW	

Table 12: LM239 precision-voltage comparators

The TL072 is a low noise J-FET dual operational amplifier used in the AD Sampling Circuit. In Table 13 the maximum total power dissipation values are listed.

TL072	Value	Unit	Image
Operating temperature (MAX)	+105	°C	
Operating voltage	±12	V	
Power (MAX)	680	mW	
Power (LOAD)	400	mW	
Power (IDLE)	50	mW	

Table 13: TL072 J-FET dual operational amplifier

The TL074, like the TL072, is a low noise J-FET dual operational amplifier used in the AD Sampling Circuit. The TL074 is the quad version. This, as can be seen in Table 14, leads to a bigger SOT-14 package. Further, a maximum temperature of 70 °C limits the maximum power output to the same level as the TL072. This component is part of the AD Sampling Circuit.

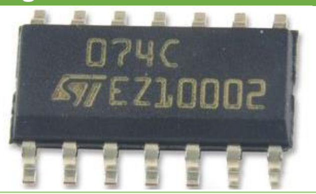
TL074	Value	Unit	Image
Operating temperature (MAX)	+70	°C	
Operating voltage	±12	V	
Power (MAX)	680	mW	
Power (LOAD)	400	mW	
Power (IDLE)	50	mW	

Table 14: TL074 J-FET quad operational amplifier

3.4 Thermal simulation

For the thermal simulations to make sense it must make the process more efficient. As seen in Figure 5, the additional cost, resources and time required do not seem to add up in this equation. Someone has to be paid to run these simulations, which requires time. The software itself has to be licenced and installed. One has to learn to work with it before being able to produce meaningful simulations.

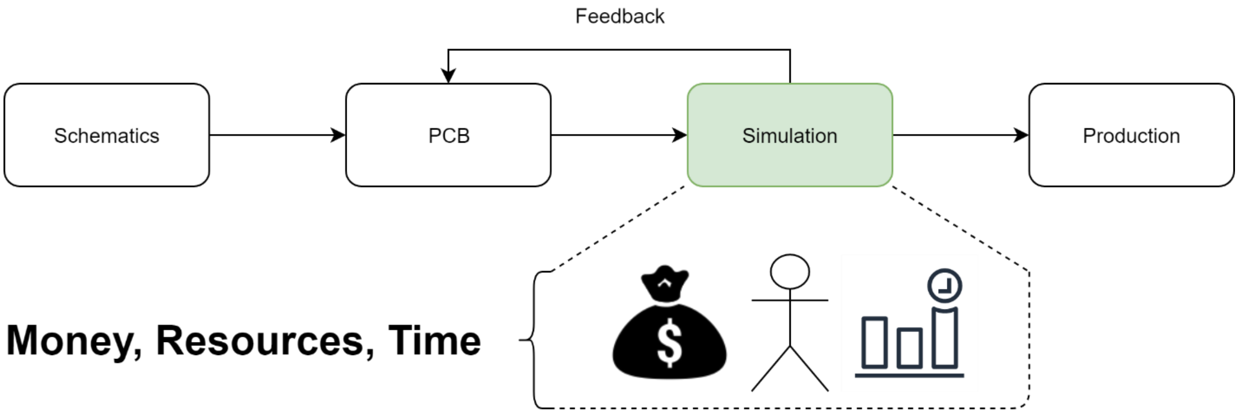


Figure 5: Requirements for thermal simulations

As mentioned in 2.1.1 TRM by ADAM Research is used to perform the thermal simulations. Performing simulations on existing projects are not as easy as when you start a new project with thermal simulations in mind. TRM works by analysing the power ratings of components in the schematics of your design. This works by reading the parameters, see Figure 6, of the components. In existing projects, you have to start from zero. Making adding these parameters to every single component a hassle. The load values of the components, as seen in 3.3, are used to simulate the PCB in this project. All of these values are used by TRM in order to simulate the temperature of the PCB.

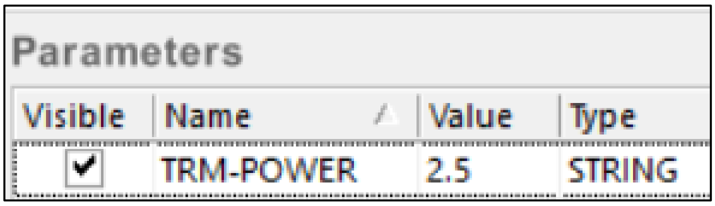


Figure 6: TRM-POWER parameter used by TRM

For Altium designer, TRM comes with a script to automate the export your Gerber, component and drill data to TRM. This data together with the TRM-POWER parameters gets used in the simulations. The AD2TRM script, see Figure 7, makes this process fast and reliable. [5]

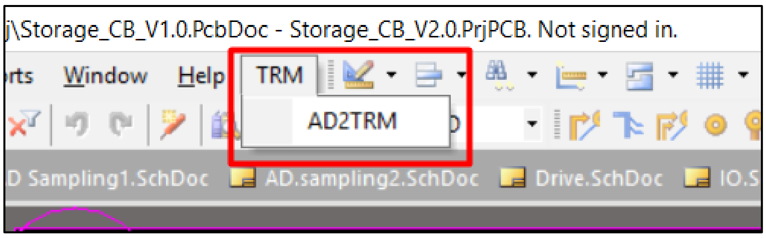


Figure 7: TRM AD2TRM script in Altium Designer

The next step, after the script completes the data set, is to start the thermal wizard as explained in the manuals provided by the developer. This step is very straightforward as can be seen in Figure 8. This opens up the wizard. The most important options here are the type of dielectric used in the intended production version, air temperature, air speed and the thermal pixel size. The temperature for each simulation is set to 20 °C. Air speed is set to 0,0 m/s to simulate a passive system. This pixel size determines how much detail the simulation will deliver. The standard is 0,2 mm, this means that there will be one pixel per 0,2 mm of PCB. Lowering this will increase the resolution. However, also increase the CPU time required.

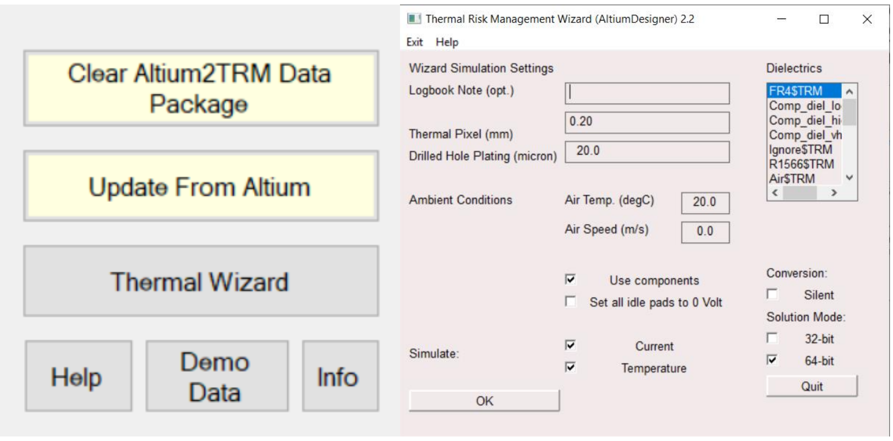


Figure 8: Thermal wizard

After completing the simulation, TRM provides a lot of processed data. The plot, as seen in Figure 9, is one of the most insightful tools. It offers an understanding of how the heat dissipation of the components affects the board. This includes the spreading of heat to other components. For a more detailed of the plot please look at appendix A. Detailed view thermal simulation (LOAD).

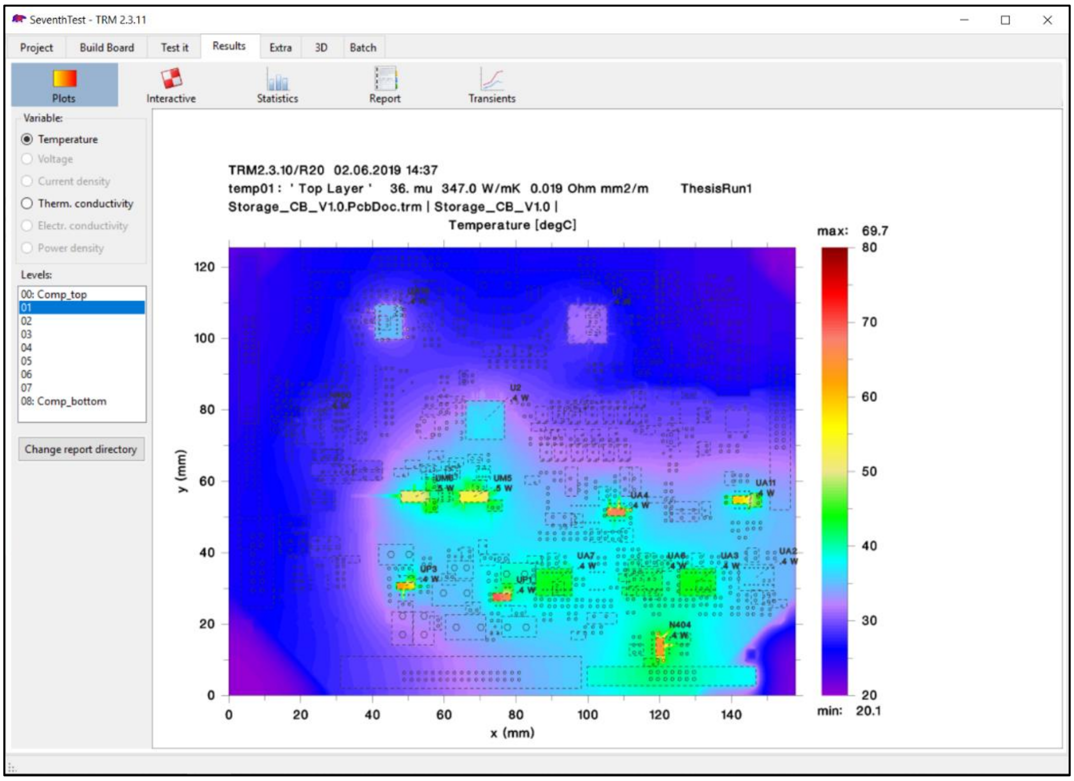


Figure 9: TRM - Results – Plots

The interactive tab takes this understanding even further. It is possible to choose from three different colour palettes. The temperature range can be adjusted to bring out fine detail. Temperatures can be consulted for each pixel that is simulated. For the master microcontroller under regular load, this can be seen in appendix B. Detailed view microcontroller (LOAD). Here the temperatures on the four corners and on the centre of the chip are displayed.

Additionally, backgrounds can be selected to enable a layover of the traces and pads. The perk that this option brings to the table is enormous. Thermal images often lack contrast as thermals can be seen as gradients. With the traces and pads overlaid it is easier to see which components are depicted in the thermal simulation. For this please consult appendix C. Detailed view, background enabled.

When the maximum values, as seen in section 3.3, for each component are used to simulate the temperatures on the PCB. The result is an unrealistic simulation. It is practically impossible for these components to run at these values for any significant period of time. Multiple components used in the project include thermal restriction circuits. Therefore, this is only to illustrate the possibilities of using simulations. Note that in the ambient conditions for both simulations' airflow is set to 0,0 m/s.

Without any active cooling, certain components heat up very rapidly. The PCB will not be able to spread out this heat as effectively as under normal load. This can be seen in appendix D. Detailed view thermal simulation (MAX).

4 Results

The thermal simulation of the PCB under load conditions can be seen in appendix E. Detailed view temperatures load. The components we are most interested in are the master microcontroller and the hottest component. The master microcontroller has a temperature of 36,70 °C according to the interactive mode. The hottest component is the right TPS76733QD at 69,46 °C. All components, see Table 15, are well within their recommended operating temperature range.

Next, the simulation using the maximum power dissipation values of the components. The thermal simulation of the PCB can be seen in appendix F. Detailed view temperatures max. Four components, marked red, are exceeding their maximum temperatures as can be seen in Table 15. Three components, marked yellow, are close to their maximum temperature but do not exceed it. However, their life expectancy could be negatively impacted.

The master microcontroller, in this case, is still well within its temperature range. However, the TPS76733QD can be assumed to have failed long before reaching the stated temperature of 511,74 °C. This is multiple hundreds of degrees hotter than the maximum temperature of 125 °C stated in the datasheet.

For component number seven, eight and fifteen we see 3 different temperatures. Both in the load and max situation (appendix E. and Appendix F.). These components are in both cases identical, TL072s. The hottest, number seven, must be affected by the heat of its neighbouring component. Just as number fifteen. Number eight is not affected as much as the other two. Component number nine and ten have a particularly large influence in the simulation under maximum load. Components in their vicinity double in temperature. Components that are found further away do not see the same increase.

Both reports of the simulations are able to provide more information. The CPU time required for the normal load simulation is 386,0 seconds. While the CPU time for the maximum load simulation is 308,2 seconds. When factoring in the time to go through the wizard, it takes about 7 minutes to simulate a design.

#	Component name	Max temp. (°C)	Simulation Load (°C)	Simulation Max (°C)
1	TL074	70	35,26	45,79
2	TMS320F2803x (Slave)	150	31,42	35,30
3	TMS320F2803x (master)	150	36,70	50,92
4	MC74LVXC3245	150	51,90	102,39
5	MC74LVXC3245	150	53,85	104,92
6	LM239	150	35,91	59,23
7	TL072	105	66,84	107,65
8	TL072	105	59,35	87,31
9	TPS76733QD	125	62,78	467,82
10	TPS76733QD	125	69,46	511,74
11	TL074	70	43,59	86,82
12	LM2903	125	37,91	68,34
13	TL074	70	42,04	65,42
14	TL074	70	42,69	63,34
15	TL072	105	64,62	103,98

Table 15: Comparison component temperatures; Load vs. Max

4.1 Case Study

In this case study, the accuracy of the simulations is tested. By comparing real-world measurements with the results of the simulation. Real-world measurements are taken with the Smart Sensor AR320 infrared thermometer, see 2.1.2 Hardware. The temperature is taken in the centre of the master microcontroller. Simulation measurements are done for each ambient temperature of the real-world measurements. Here, the temperature is also checked in the centre of the microcontroller. This leads to five unique simulations.

Temperature measurements taken of the master microcontroller during five test runs in five-minute intervals are represented in the graph in Figure 10. After half an hour the temperatures stabilize. No major changes can be detected. Only nominal variations are observed after this point. For a detailed table please consult appendix G. Detailed table temperature measurements. Here the ambient temperatures for each measurement can be seen as well.

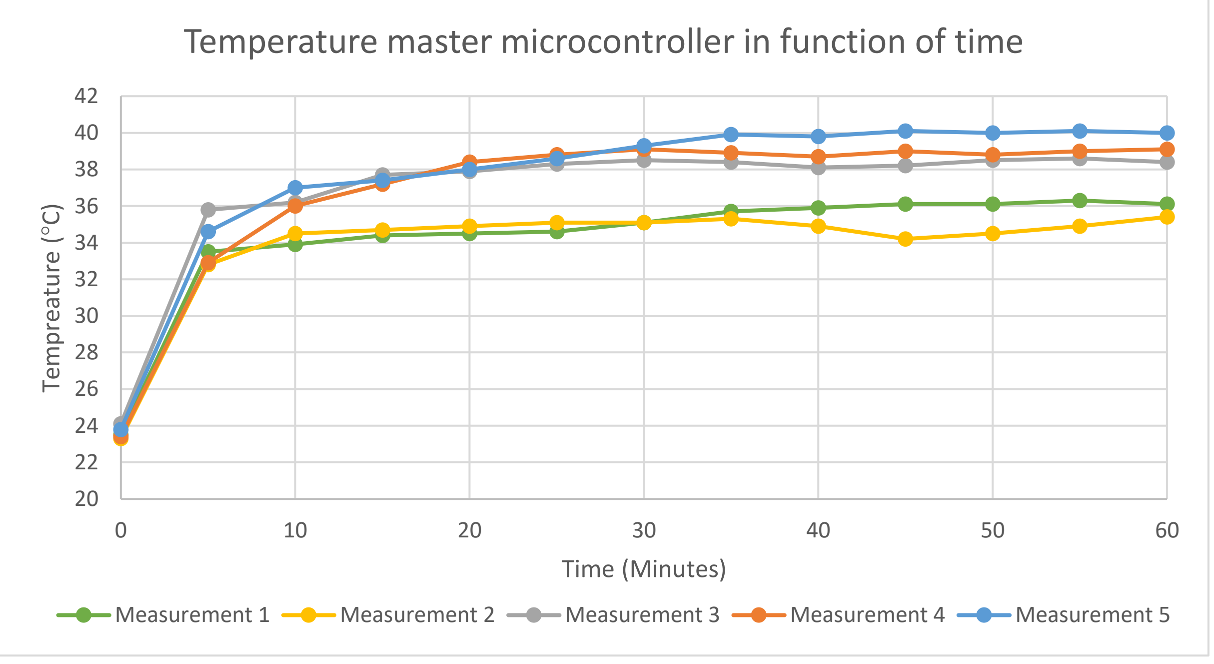


Figure 10: Temperature master microcontroller in function of time

For every measurement, the stable temperatures are used to calculate an average. The average values can be seen in Table 16. For the more detailed table please see appendix G. Detailed table temperature measurements.

Measurement number	1	2	3	4	5
Average temperature master microcontroller (°C)	35,90	34,90	38,39	38,94	39,89

Table 16: Average temperature master microcontroller

For each simulation, the temperature of the master microcontroller can be seen in Table 17, along with the ambient air temperature and the CPU time used in the simulation. These are the centre values as can be seen in appendix H. Detailed view case study simulations.

Simulation (#)	Ambient air temperature (°C)	Simulated Microcontroller temperature (°C)	Elapsed CPU time (seconds)
1	18,0	34,83	319,1
2	18,5	35,35	341,4
3	20,6	37,31	334,5
4	21,3	38,14	361,2
5	21,6	38,24	442,4

Table 17: Results thermal simulations

The accuracy of the simulations is determined by the amount of deviation from the real-world measurements. The complete results can be seen in Table 18. The measurements had an accuracy of ±2 °C as described in 2.1.2. Because of this, there are two additional columns in this table for both the "Average temperature master microcontroller (°C)" and for the "Error of the simulated vs. measured temperature" sections.

	Simulated temperature	Average temperature master microcontroller (°C)			Error (%) simulated vs. measured temperature		
Simulation	(°C)	-2 °C	-	+2 °C	-2 °C	-	+2 °C
1	34,83	33,90	35,90	37,90	-2,74	2,98	8,10
2	35,35	32,90	34,90	36,90	-7,45	-1,29	4,20
3	37,31	36,39	38,39	40,39	-2,54	2,80	7,62
4	38,14	36,94	38,94	40,94	-3,24	2,06	6,85
5	38,24	37,89	39,89	41,89	-0,94	4,13	8,70

Table 18: Simulation accuracy

Conclusion

This study was conducted to find an answer to the question: **“How useful are thermal simulations for efficient PCB production?”** This can be divided into two sub-questions.

Is it beneficial for efficiency?

By giving useful insight into the spread of temperatures in a PCB, thermal simulations already fulfil a large part of the potential they have. The time required to run a simulation is not significant. Especially when compared to the time to produce an entirely new version. Additionally, there is a cost reduction for not producing unnecessary PCBs.

Is it accurate? How accurate?

Yes, the simulations are accurate, to a certain extent. The accuracy is dependent on the precision of the heat dissipation values and the number of components. The case study shows that the highest error rate is 8,7 %. The lowest, however, is only 0,94 %. This is only for one component. Keep in mind that this is a range, due to the limit of the hardware used in this study. Therefore, the claimed accuracy of ±5 % by ADAM Research for TRM seems to be correct.

Recommended Future Research

The research in this paper only answers one question. Many questions remain to be answered. There is always room to improve as this is not the complete solution. Following are the points to be improved upon;

- TRM-POWER parameters for components in libraries
- Precise measurements with better tools
- Comparison between different PCB versions
- Cost of manufacturing
- Comparing different software packages
- Cost-performance software package(s)
- Measurements and simulations for other components

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Appendices

A. Detailed view thermal simulation (LOAD)

B. Detailed view microcontroller (LOAD)

C. Detailed view, background enabled

D. Detailed view thermal simulation (MAX)

E. Detailed view temperatures load

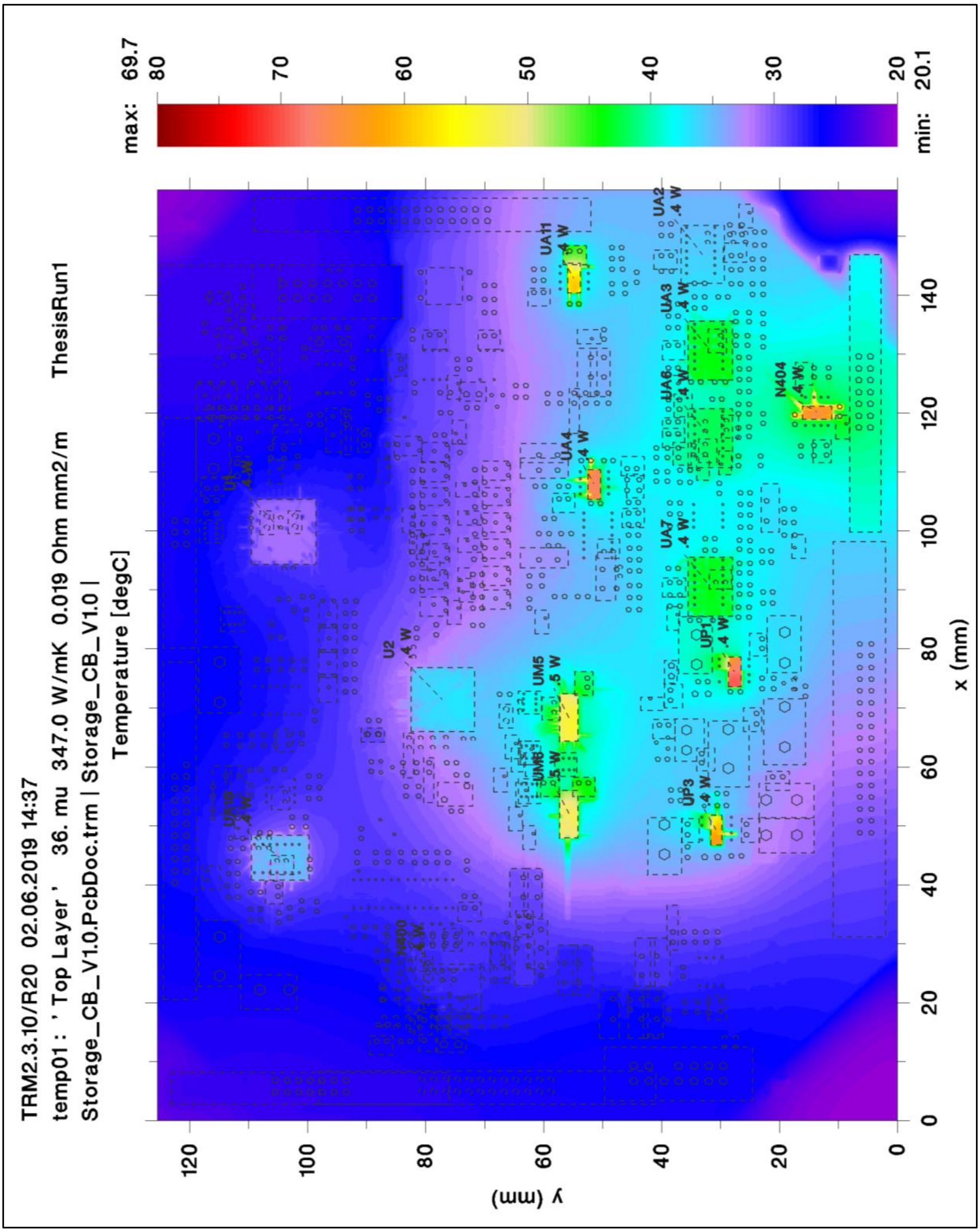
F. Detailed view temperatures max

G. Detailed table temperature measurements

H. Detailed view case study simulations

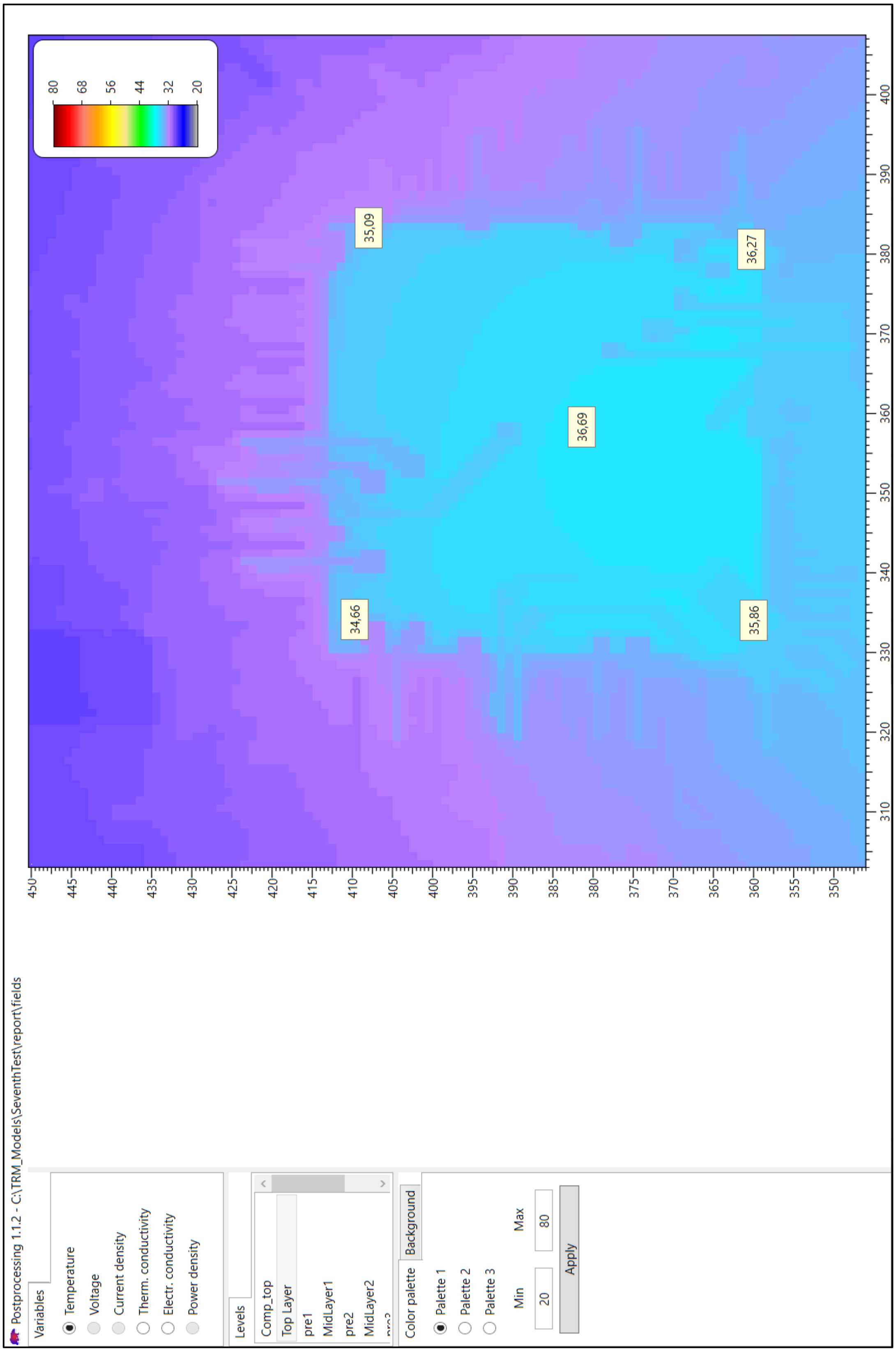
A. Detailed view thermal simulation (LOAD)

Note: Power values on the plot are rounded off.

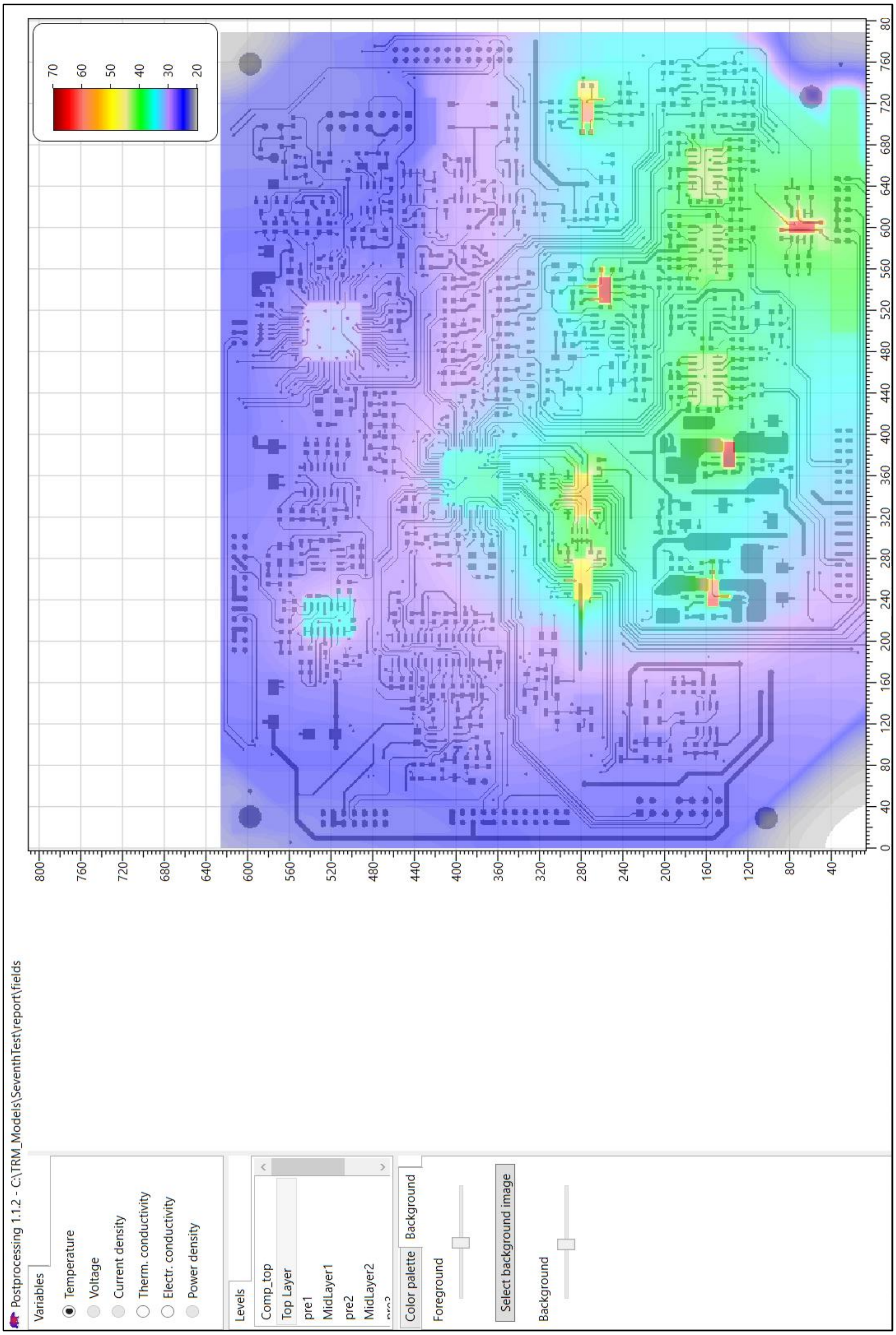


B. Detailed view microcontroller (LOAD)

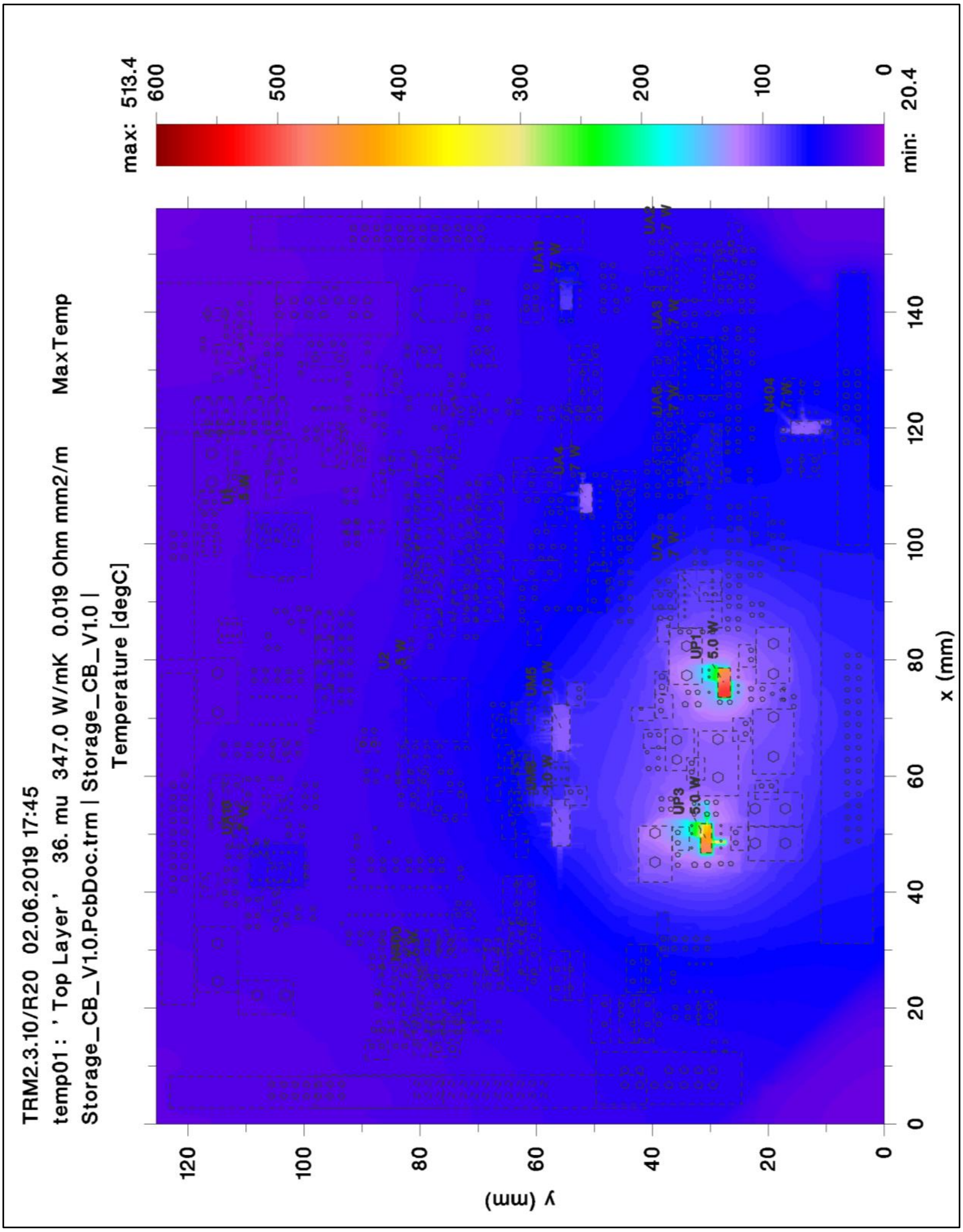
Note: Same colour palette as in appendix A.



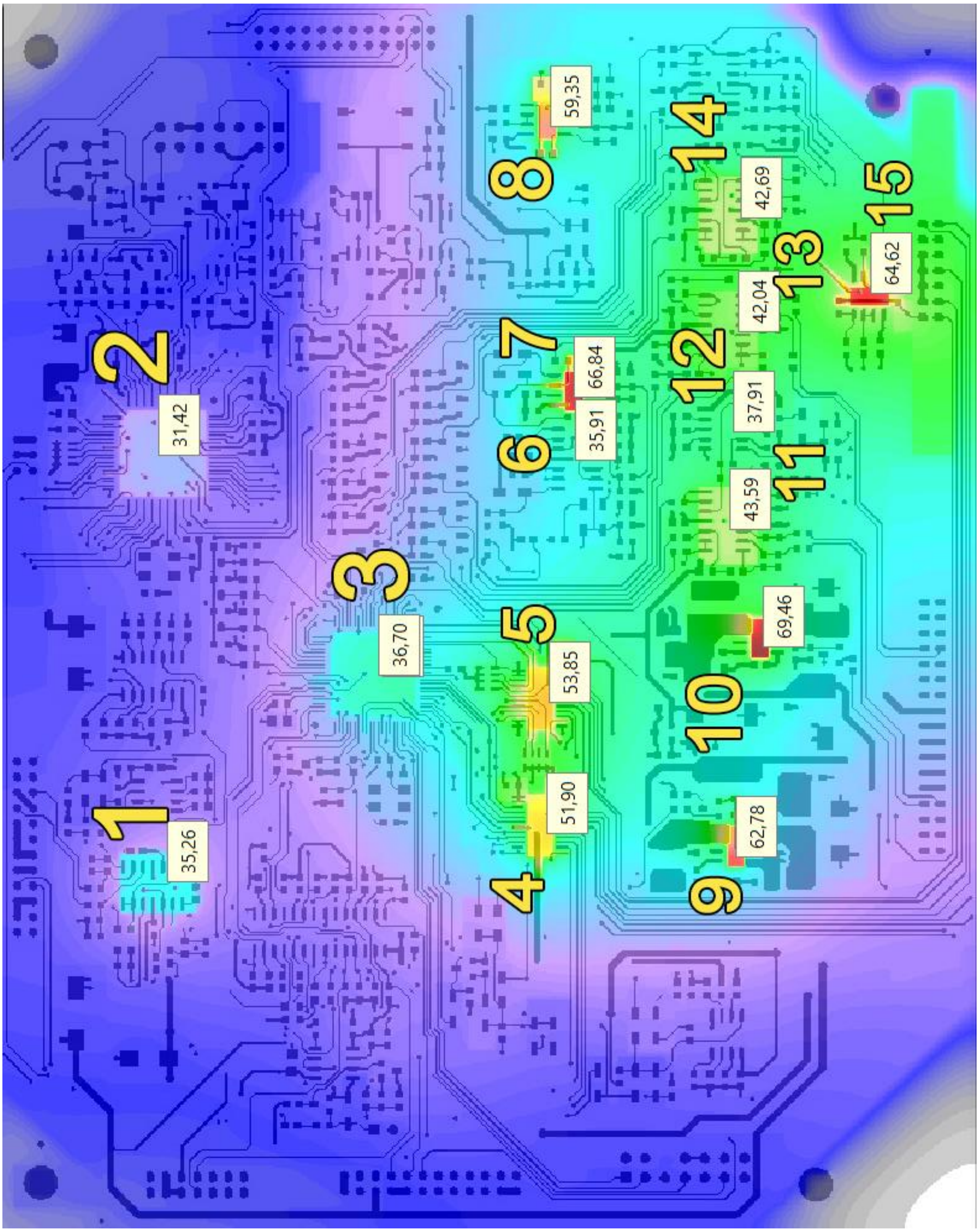
C. Detailed view, background enabled



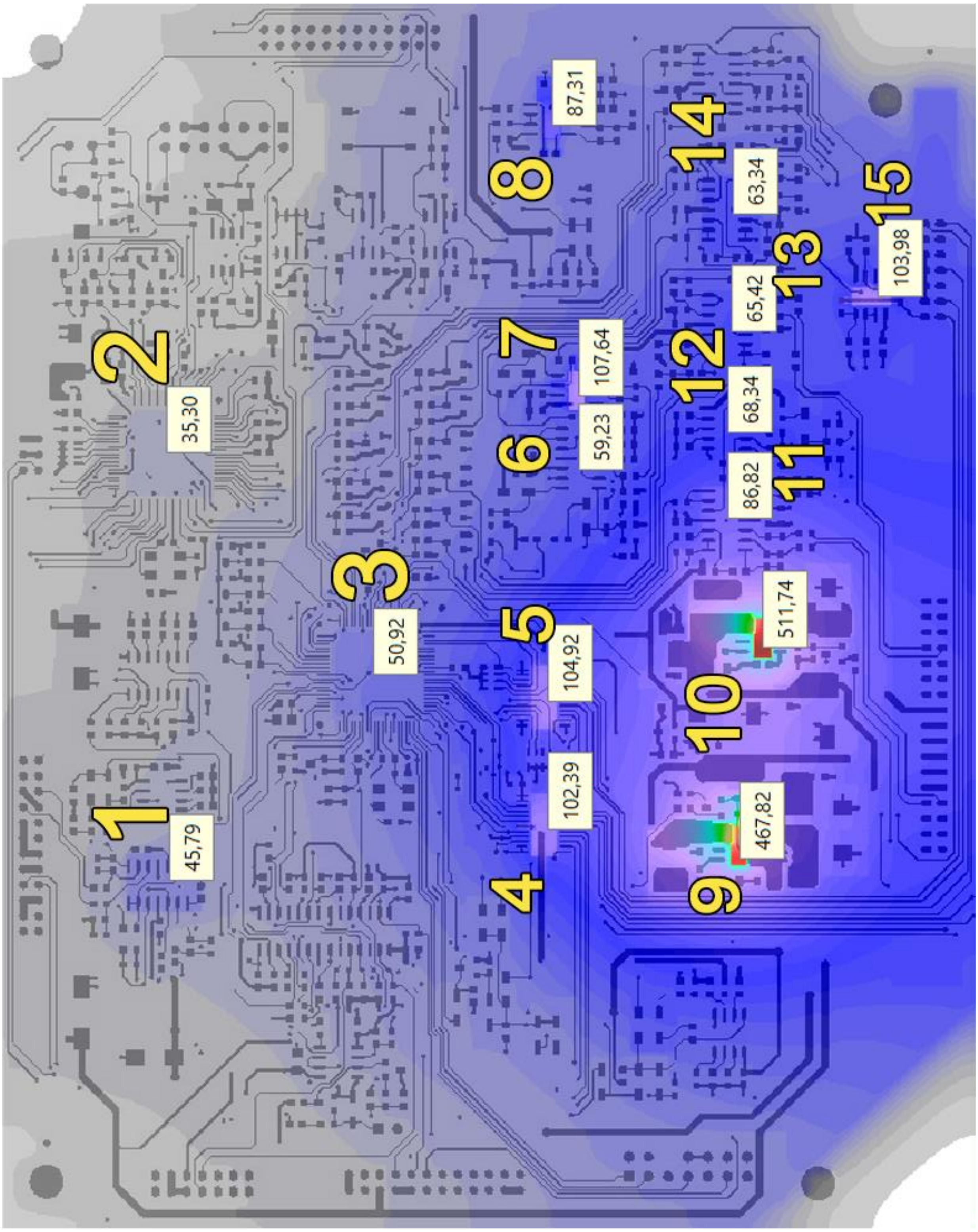
D. Detailed view thermal simulation (MAX)



E. Detailed view temperatures load



F. Detailed view temperatures max

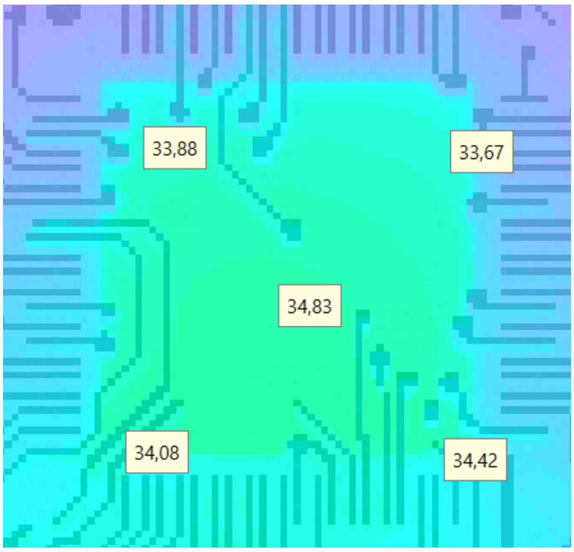


G. Detailed table temperature measurements

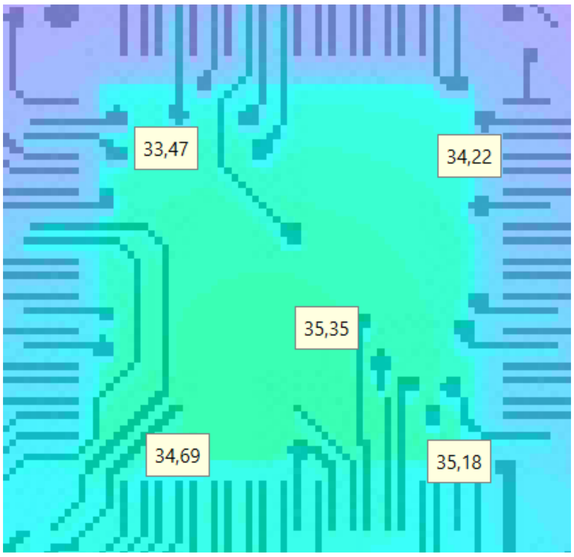
Ambient Temperature (°C)	18 (Measurement 1)	18,5 (Measurement 2)	20,6 (Measurement 3)	21,3 (Measurement 4)	21,6 (Measurement 5)
0 minutes	23,5	23,3	24,1	23,4	23,8
5 minutes	33,5	32,8	35,8	32,9	34,6
10 minutes	33,9	34,5	36,2	36,0	37,0
15 minutes	34,4	34,7	37,7	37,2	37,4
20 minutes	34,5	34,9	37,9	38,4	38,0
25 minutes	34,6	35,1	38,3	38,8	38,6
30 minutes (stable)	35,1	35,1	38,5	39,1	39,3
35 minutes (stable)	35,7	35,3	38,4	38,9	39,9
40 minutes (stable)	35,9	34,9	38,1	38,7	39,8
45 minutes (stable)	36,1	34,2	38,2	39,0	40,1
50 minutes (stable)	36,1	34,5	38,5	38,8	40,0
55 minutes (stable)	36,3	34,9	38,6	39,0	40,1
60 minutes (stable)	36,1	35,4	38,4	39,1	40,0

H. Detailed view case study simulations

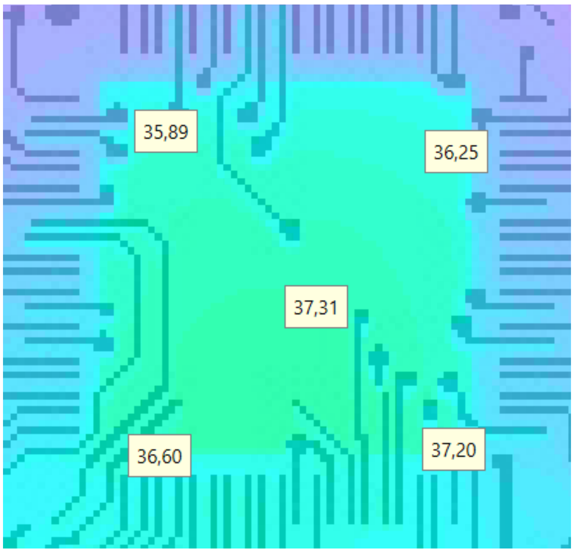
Microcontroller case study simulation 1:



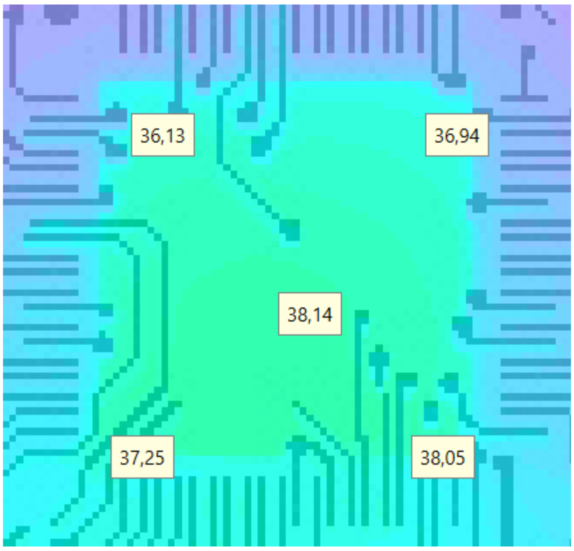
Microcontroller case study simulation 2:



Microcontroller case study simulation 3:



Microcontroller case study simulation 4:



Microcontroller case study simulation 5: