

**UNIVERSITY OF WEST BOHEMIA IN PILSEN
DEPARTMENT OF ELECTRICAL ENGINEERING**

Department of Applied Electronics and Telecommunication

DIPLOMA THESIS

Design of Inverter for Hand Tools Wireless Charger

Original (copy) of the assignment

Abstract

This paper goes through the design of an inverter for hand held tools wireless charger. The resulting device should be compact and able to recharge devices at up to 600W with a high efficiency. Such system could be used to recharge cordless power tools but could also be applied to most other battery powered device like laptops or drones. Such charger can also be useful in case of harsh environment which prohibit the use of connectors like in explosive or medical area.

The first part of this paper focus on component choices to fulfil requirements such as space constraints, heat dissipation and electromagnetic compatibility. The second part is about printed circuit board layout and the issues encountered during the design. The third part cover the possibility of control and the programming of the inverter. And finally, the last part describes the realisation and testing of the inverter.

Key words

Induction charger, single-phase full bridge inverter, resonant transformer, silicon-carbide mosfet, high frequency switching, electromagnetic compatibility, wireless power transfer.

Declaration

I declare that I have elaborated this diploma thesis independently, using the professional literature and sources listed in the list, which is part of this diploma thesis.

I further declare that all the software used to resolve this bachelor / diploma thesis is legal.

.....

signature

In Pilsen at 5.6.2019

Quentin Cassier

Thanks

I would like to thank the supervisor of the thesis Ing. Zavřel Martin for this opportunity and for his guidance and advices.

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Introduction

The paper covers the design of an inverter for a wireless charger. Specific attentions were brought to compactness, efficiency and robustness. As such, the main difficulties encountered were the lack of space, the thermal dissipation and the lack of time. In this document we will explain how we managed with those problems.

In a first part, will be a short analysis of the constraints and of the existing wireless charger technologies. The second part focus on the selection of the components and their dimensioning. The third part describe the layout of the circuit board. The fourth is about the control and programming. And the last one is about the construction and testing of the inverter.

Symbols and abbreviations list

<i>EMC</i>	Electromagnetic compatibility
<i>EMI</i>	Electromagnetic interference
<i>DC</i>	Direct current
<i>AC</i>	Alternative current
<i>PCB</i>	Printed circuit board
<i>PWM</i>	Pulse width modulation
<i>Mosfet</i>	Metal oxide semiconductor field effect transisto
<i>IGBT</i>	Insulated Gate Bipolar Transistor
<i>P_{cond}</i>	Power dissipated due to conduction losses
<i>P_{sw}</i>	Power dissipated due to switching losses
<i>I</i>	current
<i>R_{DSon}</i>	Resistance of Mosfet in passing state
<i>α</i>	Duty cycle
<i>Q_{Gtot}</i>	Gate charges
<i>IC</i>	Integrated Circuit

1 Project description

In this first part, we will analyse the requirements of this project, take a look at nowadays induction chargers and describe how we planned to fulfil them.

1.1 Inverter goals and specifications

The goal of the inverter is to be part of a wireless charger to recharge a lightweight electric scooter. However, this thesis is part of a development project for the implementation in hand held tools. The role of the inverter is to transform a DC input voltage into a suitable signal to power an induction transformer. The said signal needs to be square signal of 100V at a frequency of about 500kHz. Because this is for laboratory testing, the inverter has to be made to handle 150V and 15A. The transformer and the control algorithm are developed in a different project.

On a mechanical side, because this charger is made for handheld powertools, it has to be about the same size as the battery of a cordless drill. The exact dimension specifications are 67mm large by 115mm long with 20mm height for the PCB plus an additional height to fit a heatsink.

1.2 Voltage inverters

A voltage inverter is a device which convert a *DC* voltage in an *AC* voltage. The waveform can be sinusoidal, square or of diverse shapes and at frequencies varying from a few Hz to several kHz.

Voltage inverters are often use for variable frequency drive of motors or for uninterruptible power supplies. However, these applications require characteristics very different than our needs.

1.2.1 Main Characteristics

The main characteristics of an inverter are:

- Frequency
- Voltage Amplitude

- Power delivered
- Waveform
- Efficiency
- Physical characteristics

The main method to achieve a waveform other than square is via a modulation such as *PWM*. However, this is not needed in our case and the *PWM* carrier needs to be at much higher frequency than the signal desired which is impossible in our case.

An inverter is mainly composed of switches, a control circuit, an input filter or capacitor bank and eventually some sensing circuit. The switches have two states, a blocking and a passing state. They allow to apply a desired voltage to the output of the inverter. The control circuit is coordinating the states of the switches to apply the desired voltage at the output. The filter or the capacitor bank allows to keep the input voltage stable during operation.

1.2.2 Topologies

What we call topology is the number of switches, their nature and the way they are connected. There are three types of switches, the bipolar transistor, the *IGBTs* and the *MOSFETs*. Bipolar are mostly outdated and not used for this application. *IGBT* are rugged and used particularly for high voltage as the *MOSFETs* can only withstand up a limited voltage.

The most important parameter is the number of outputs. For a three phase there are 3 outputs, 1 for a single-phase in half bridge and 2 for a single-phase full bridge.

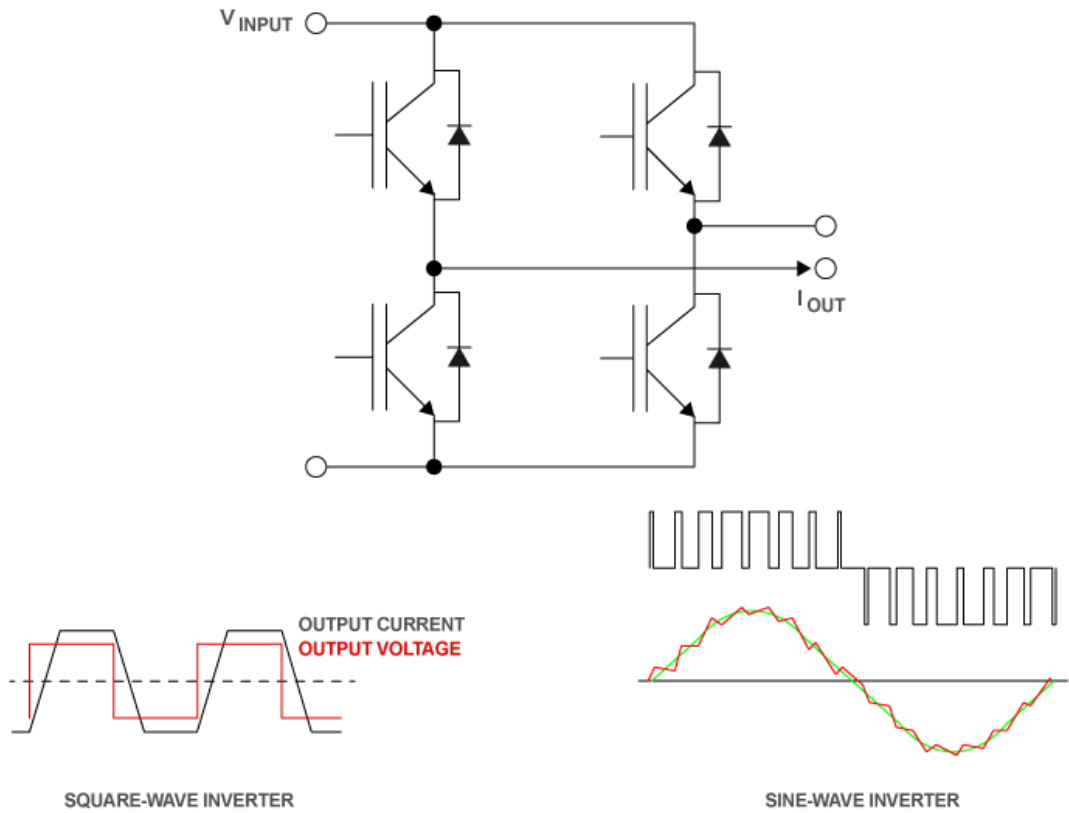
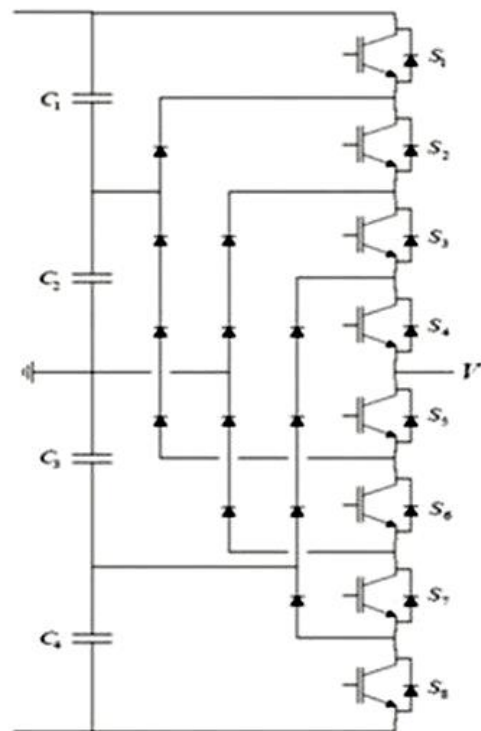


Fig. 1 Fullbridge of IGBT

Some other rare or specific topologies exist such as the multilevel inverters:

Fig. 2 Multilevel IGBT topology

However, for this project, the topology had already been decided by the teacher as a fullbridge of Mosfet. The exact selection of the switches will be discussed later.



1.2.3 Control options

The inverter needs to vary the amount of power delivered. It can be to counteract exterior perturbation such as a variation of the input voltage, to compensate power losses in the inverter or to accommodate to the needs of the circuit on the load side.

Low frequency inverters generally use a PWM modulation which allows to vary the output power by adapting the duty cycle. In our inverter, the switches operate at the same frequency as the output and the duty cycle has to remain 50% to obtain voltage symmetry. Hence, we have to find alternative methods of control.

1.2.3.1 Phase shifting

In a full bridge topology, there are two outputs that are switched out of phase to have voltage between the two that is twice the DC voltage. If the outputs were in phase, there would be identical potentials on both outputs resulting in no difference.

By changing the phase shift, we can vary the amount of time with output voltage available. A smaller phase shift reduces the amount of time per period during which power is delivered to the load. This technique also improves slightly efficiency by soft switching some of the *Mosfets*. This technique is mostly used in switch mode power supplies.

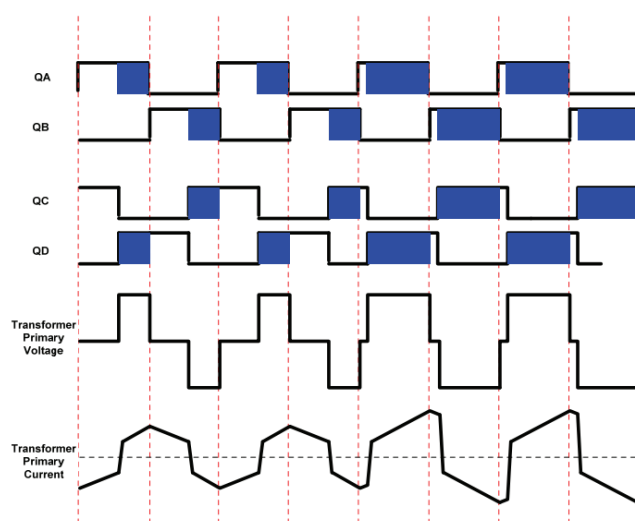


Fig. 3 Effect of different phase shifts

1.2.3.2 Frequency variation

This technique is specific to resonant load. It uses the frequency characteristic of a resonant transformer. The frequency is kept slightly higher than the exact resonant frequency of the load. A higher frequency will operate the load in a more inductive mode with less voltage gain. This technique is used for high efficiency LLC converters.

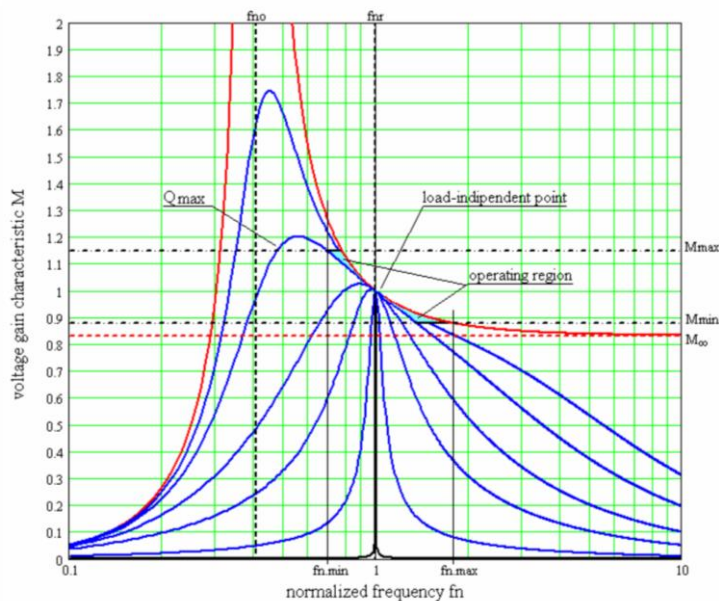


Fig. 4 Voltage gain as fonction of frequency and load

1.3 Induction charging

Induction charging has been around for some time. It is mostly used to recharge smartphones and portable devices. Different standards exist such as Qi, Alliance for Wireless Power (A4WP), Power Matters Alliance (PMA) and Airfuel.

All of them use a resonating coil and high switching frequency (above 100kHz). The main difference is how the power is regulated and how the secondary side is giving a feedback to the primary. Qi uses fast variation of the load while Airfuel uses Bluetooth low energy to send information between the receiving system and the sending system. For the control technique, whether it uses frequency variation, phase shifting or another technique is not disclosed.

1.4 Planning

To achieve the goals, the work was planned as follow:

In a first time, research was made on inverters topologies and their control, on existing induction chargers technologies and on their applications. The results of this researchs have already been explained earlier in this report.

In a second time, we will compare the possibilities for the main components, such as the *Mosfets*, the drivers and the heatsink. From there, we should have a good idea of what are the needed characteristics for the input filter, the power supplies and sensors.

Once the schematic is finished, the PCB will be routed and manufactured. A software needs to be written to operate the prototype. Once the board is received, components will be soldered. Followed by the testing of the prototype.

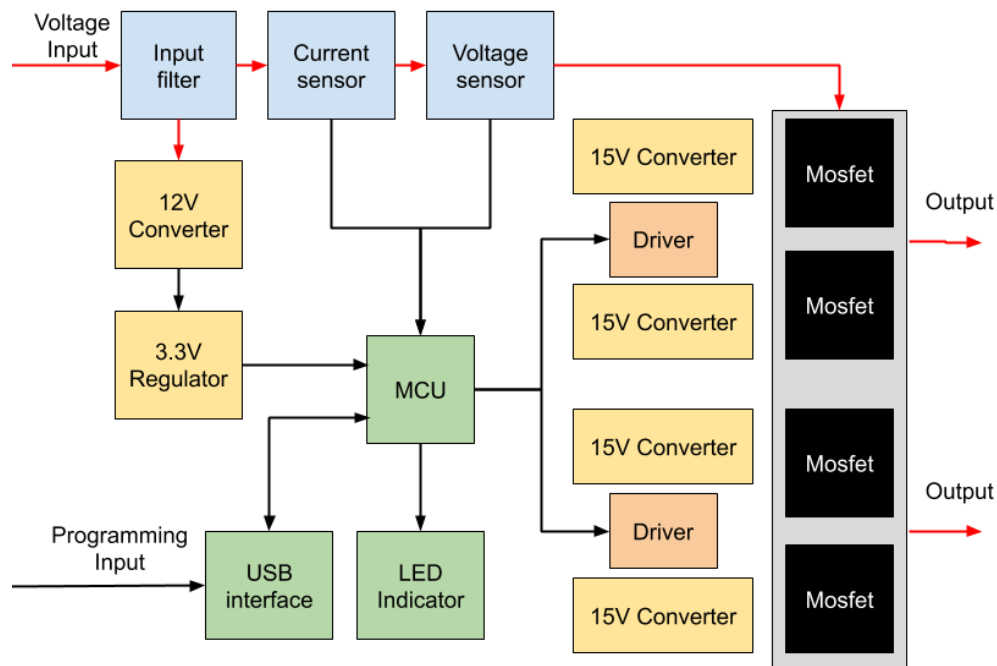


Fig. 5 Fonctionnal diagram of the inverter

To sum up the planification:

Preliminary research:

- Research existing technologies
- Research existing inverters
- Research applications

Board design:

- Compare Switches
- Find adequate drivers
- Find adequate heatsink
- Design the input filter
- Design the power supplies
- Find a voltage sensor
- Find a current sensor
- Finish the schematic
- Routing

Testing:

- Write program
- Build the prototype
- Test the prototype

The next pages of this report will follow the realisation of this plan and the unplanned steps that we faced during the project.

2 Design of the schematic

The schematic of a *PCB* is a diagram on which every component is represented by a symbol. By connecting them to each other, we can see every part of the circuit and its operation. This is a necessary step to plan the *PCB* and to help during the routing.

2.1 KiCad software

KiCad will be used to do the schematic and the routing. Many other softwares are available however this one has many advantages. It is a widely known open source software that is supported by companies and organisations such as the CERN and the University of Grenoble.



Fig. 6 Logotype of Kicad software

Being an open source software means that it can be used without fees but the main drawback is that it doesn't include as much features as an expensive licensed software such as Altium. However, another advantage of KiCad in our situation is that I already know how to use it while learning a new software would take an excessive amount of time.

2.2 Selection of Switching element

The switches are responsible for allowing current to flow or not and thus applying a desired voltage to the outputs of the inverter. The microcontroller command them through a driver.

2.2.1 Comparison criterions

Switches can have different natures but they all have the same goal of blocking current flow or allowing current flow. But some do it better than others. Some are capable of flowing more current, some can withstand higher voltage while they are blocking but of course price tend to increase too.

These are the main parameters to take in account:

- Voltage handling
- Current handling
- Switching speed
- Conduction losses
- heat dissipation
- Operating temperature
- Form factor
- Price
- Availability

For some characteristic such as the voltage and current handling, we simply need them to be higher than our specified maximum of 150V and 15A. On the other hand, the lower the losses will result in higher efficiency and consequently lower temperature.

2.2.2 Technologies Comparison

Different technologies of switch are available. The main modern switches usable in our application are *IGBTs* and *Mosfets*. The first one can immediately be eliminated as they are rather slow and wouldn't cop with the high switching frequency. *Mosfets* are much more efficient at this low voltage but high switching frequency.

2.2.3 Comparison table

To compare the available components, an excel file was made with the predicted amount of losses, the price and some other characteristics. The chosen components have the required voltage and current capability but range from 30€ to 1,78€ at the retailer.

To calculate the losses, we used usual formulas:

The conduction losses $P_{cond} = R_{DSon} \times I^2 \times \alpha$

Switching losses can be calculated in two ways, with gate charges and drive current or with rise and fall time. For the first method, we don't know the drive current yet so we assumed it to be a strong 3A. The second methode use rise and fall time given in the datasheet for a current proposed by manufacturer and that is different for each datasheet.

Switching losses with gate charges $P_{sw} = Q_{Gtot} \times I_{DS} \times U_{DS} \times F_{sw} \div I_G$

Switching losses with rising and falling time $P_{sw} = \frac{T_{Rise} + T_{Fall}}{2} \times U_{DS} \times I_{DS} \times F_{sw}$

Because the load is resonant, we also need to take in account diode conduction losses:

$$P_{Diode} = I \times (T_{Fall} + T_{Rise}) \times V_{Diode} \times F_{sw}$$

Trying to find the best Mosfet, we compared some conventional silicon references, the newer silicon carbide and gallium nitride. Watching the following table, we could think that the Toshiba TPH2900ENH is the best choice as it has the lowest losses and is relatively affordable. However, even at 14,1W of dissipation in a worst-case scenario, its

SMD package makes it difficult to dissipate the heat. In addition, the strong space constraint doesn't allow to use many thermal vias or large smd package. The best through holes Mosfets are the TP65H035WS and the C3M0065090J. The first one being slightly more efficient but its price is much higher than the C3M0065090. In the end we choose the second one for the rest of the project.

Even with higher losses per *Mosfets* the efficiency should remain relatively high:

$$Eff = \frac{V_{out} \times I_{out}}{V_{out} \times I_{out} + P_{tot} \times 4}$$

With the highest losses calculated at 22,1W per *Mosfets* using the gate charges, we can obtain a theoretical efficiency of 96,2% at maximum voltage and current.

The table next page was made using Microsoft Excel to automatically calculate the losses and to do the comparison explained above.

Mosfet comparison table:

	Reference	Techno	Voltage	Rds on	Qgtot	Tr	Tf	Vdiode	Rth	Price	Package	Pcond	Psw from Qg	Psw from DT	Pdiode	Ptot from Qg	Ptot from DT
Wolfspeed	C3M0120090J	SiC	900V	0,17	2E-08	9E-09	5E-09	4,4	1	6,75	TO247	19,1	6,5	7,9	0,5	26,1	27,5
Wolfspeed	C3M0065090J	SiC	900V	0,09	3E-08	1E-08	6E-09	4,4	1	10,5	TO247	10,1	11,4	9,0	0,5	22,1	19,7
Wolfspeed	C3M0030090K	SiC	900V	0,037	9E-08	2E-08	9E-09	4,5	1	30,8	TO247	4,2	32,6	17,4	1,0	37,8	22,6
Wolfspeed	E3M0065090D	SiC	900V	0,09	3E-08	1E-08	9E-09	4,4	1	12	TO247	10,1	11,4	11,3	0,7	22,2	22,0
Rohm	SCT3030AL	SiC	650V	0,04	1E-07	4E-08	3E-08	3,2	0,44	24,72	TO247	4,5	39,0	38,3	1,6	45,1	44,4
Semikron	SK25MH120	SiC	1200V	0,124	1E-07	4E-08	3E-08	5,2	1	Samples	PM	14,0	41,3	38,3	2,7	57,9	54,9
Semikron	SK45MH120	SiC	1200V	0,076	2E-07	8E-08	6E-08	5,2	1	Samples	PM	8,6	80,6	78,8	5,5	94,6	92,8
ST micro	SCTH35N65	SiC	650V	0,065	7E-08	1E-08	9E-09	4,5	0,72	NA	SMD	7,3	27,4	12,9	0,8	35,5	21,0
ST micro	SCTH90N65	SiC	650V	0,025	2E-07	2E-08	4E-08	3,5	0,45	NA	SMD	2,8	58,9	30,4	1,4	63,1	34,6
infineon	IPB600N25N	Si	250V	0,14	3E-08	1E-08	8E-09	1,2	1.1	2,76	TO220	15,8	10,9	10,1	0,2	26,8	26,0
IXYS	IXFP36N20X3	Si	200V	0,108	2E-08	3E-08	2E-08	1,4	0,73	2,82	TO220	12,2	7,9	28,1	0,5	20,6	40,8
Toshiba	TPH6400ENH	Si	200V	0,1	1E-08	5E-09	5E-09	1,2	2,19	1,78	SMD	11,3	4,2	6,0	0,1	15,5	17,3
Infineon	BSC500N20N	Si	200V	0,085	4E-08	5E-09	7E-09	0,9	1,3	2,1	SMD	9,6	13,1	6,8	0,1	22,8	16,4
Toshiba	TPH2900ENH	Si	200V	0,05	2E-08	8E-09	1E-08	1,2	1,6	2,66	SMD	5,6	8,3	11,3	0,2	14,1	17,1
Vishay	SiR610DP	Si	200V	0,0672	3E-08	2E-08	2E-08	0,77	0,9	2,13	SMD	7,6	9,4	24,8	0,3	17,2	32,6
Infineon	IGOT60R070	GaN	600V	0,1	6E-09	9E-09	1E-08	2,2	1	22,55	SMD	11,3	2,2	12,4	0,4	13,8	24
Transphorm	TPH3212PS	GaN	650V	0,148	1E-08	8E-09	5E-09	2	1,2	12,43	TO220	16,7	5,3	7,0	0,2	22,1	23,9
Transphorm	TP65H035WS	GaN	650V	0,082	2E-08	1E-08	1E-08	1,8	0,8	17,35	TO220	9,2	9,0	14,1	0,3	18,6	23,6

2.3 Mosfet drive circuit

To use the mosfets, the commanding signal need to go through a driving circuit. Its role is to supply the desired command voltage and current at the gate of the Mosfet to get it to switch correctly. More current will makes it switch faster and will lower the switching losses but it also worsen the *EMC*. Not enough voltage may result in the *Mosfets* being not fully switched creating more conduction losses. In our case we also need to provide an isolation between the power side with the mosfet and the signal side with the microcontroller.

Different circuits are available with different pros and cons. However our choice has always been to use a driver IC on recommendation of the teacher.

2.3.1 Types of driving circuit

There are 3 main types, transformer circuits, optocoupler coupled and magnetic or capacitive coupled integrated circuit driver.

2.3.1.1 Transformer

The transformer based originate from Bipolar and IGBT inverters. They require a complete circuit but can become bulky and expensive. On the other hand, they are very robust and immune to EMI.

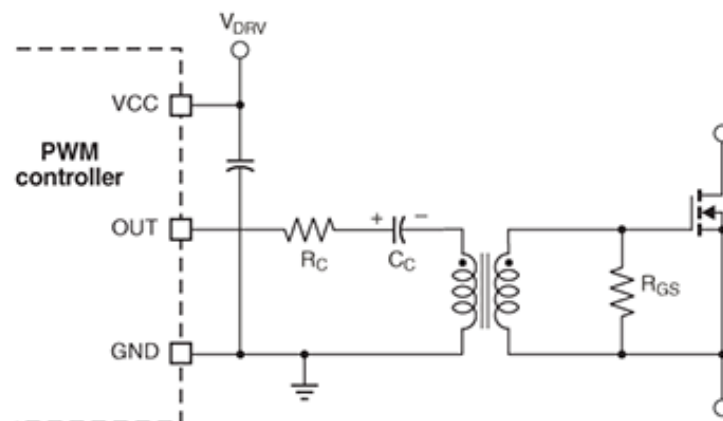


Fig. 7 Gate driver using a transformer

2.3.1.2 Optocoupler IC

Optocoupler based circuit are drivers that convert the command signal to a light signal to provide the isolation. It is smaller, simpler and less expensive but they are relatively slow as the propagation delay is generally superior to 1 μ s.

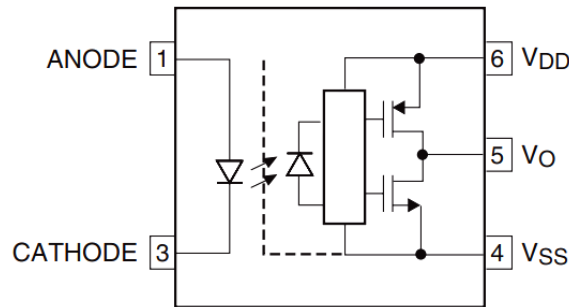


Fig. 8 Internal diagramme of a gate drive optocoupler

2.3.1.3 Magnetic or capacitive IC

The last type uses a modulation of the command signal that is carried throught a capacitive or magnetic coupling. These drivers are more modern and are the most used solution for small gate current (generally lower than 5A peak). They only need a few components and a power supply. They provide the fastest, most compact and simplest solution for a low cost. Some additional features can be found such as driving two Mosfets with one IC, hardware deadtime limit and various protection.

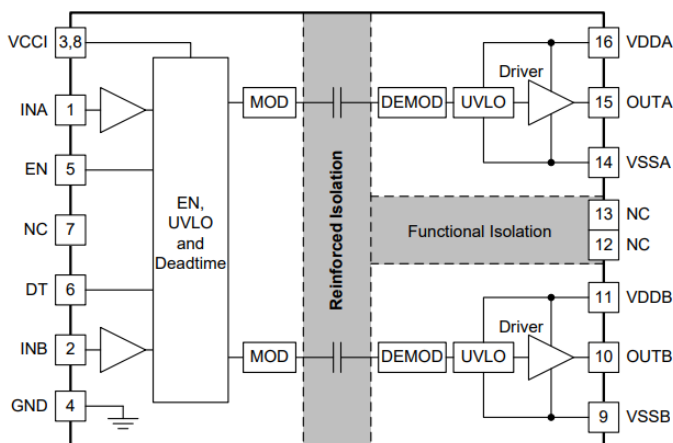


Fig. 9 Internal diagram of the UCC21521

2.3.2 Driver

We need the driver to match the requirements of the Mosfet.

Important information from the Datasheet of the C3M0065090D:

- Recommended gate voltage: $V_G = 15V$
- Internal gate resistor: $R_{Gin} = 4,7\Omega$
- Total gate charges: $Q_{Gtot} = 30,4nC$

We can calculate the maximum gate current: $I_{Gmax} = V_G \div R_{Gin}$

From this equation, we know that we need a driver with a current capability of at least 3,2A and a voltage capability of at least 15V. In practice, an external gate resistor will be added to further reduce the current and thus the switching speed. However, during the testing we may need to switch the mosfets as fast as possible to minimize the losses.

The second feature we need is the isolation. We want to keep the signal side isolated from the power side and the two high side drive circuits use a floating ground. However we don't need a high voltage rating as the routing of the PCB will be the limiting factor. We can calculate the voltage transient as follow: $V_{trans} = V_{out} \div DT$

Which gives us a requirement of 10kV/us.

We used these criterions to find the adequate references of drivers. Then to save some space on the board, we selected drivers that can drive 2 mosfets each. We eliminated the slowest ones as they would add an important delay. This leaves only a few drivers possible, all from the UCC21xxx family of Texas Instrument. To simplify the power supply circuit on the low power side, we kept only the drivers with a 3,3V supply voltage. The choice between the last models is based on the presence of an additional hardware Dead Time on the UCC21521. This feature may help prevent destroying the *Mosfets* in case of malfunction during the testing.

2.3.3 Gate voltage supply

For the driver to operate, we need a voltage supply of 15V. The current necessary can be calculated by the formula: $I = Q_{Gtot} * F_{sw}$

Which gives us a current of 15,2mA. This current is very small but the main difficulty is to provide the isolation for the same reason as the drivers.

There are two main ways of providing this supply, having an isolated converter or a bootstrap circuit. We could make the converter circuit can but it would take too much time and too much space on the board. It can also be bought in the form of a complete component to solder. The bootstrap is cheaper but it is slightly more complicated and it needs the presence of at least one converter that will supply all the bootstrap circuit of all the drivers. The bootstrap circuit could be a good solution as it is much smaller than to have 4 converters. However, for the testing and experimenting it is simpler and safer to use off the shelf converters.

2.4 MCU

We knew we would face an obvious lack of space. Fitting all the components on a board of 67x115mm seem difficult. The first solution to this problem would be to solder components on both sides of the board. However, with the different isolated part, this is a limited improvement. The second solution that is very common is to use a pcb for the power part and a second one for the signal part. This simplifies the isolation and the overall routing while doubling the surface. It also allow to test and debug the software without being connected to the power side. On the signal side we only have the MCU and a led driver and the programming interface. In the university, some launchpad from TexasInstruments are used. They are develloppement board that integrate a similar MCU and the necessary interface. This seem to be an ideal choice for our purpose. However, as we will see during the routing, the main drawback is the imposed formfactor.

The launchpad that we used for this project is fitted with a TMS320F28027 MCU, it runs at 60MHz with 64KB of memory, 13 ADCs on 12bits and 8 PWM channels. It can be replaced with most other launchpad models with only changes in the software.



Fig. 10 Launchpad F28027

2.5 Measurement Circuit

We added two measurement to be able to protect the inverter against an overload and to implement some control algorithm.

2.5.1 Input voltage measurement

The voltage measurement circuit is sending a low voltage to the MCU that is proportional to the input voltage. The circuit needs to provide an isolation between the two sides and to stay linear with an input voltage up to 150V.

Different techniques are available, with an optocoupler, with a hall effect sensor, or with a specialised IC. We choose the AMC1211 from Texas instrument as it comply with the above constraints and it also has the advantage of being powered in 3,3V like our MCU and of being faster and more precise than most other solutions.

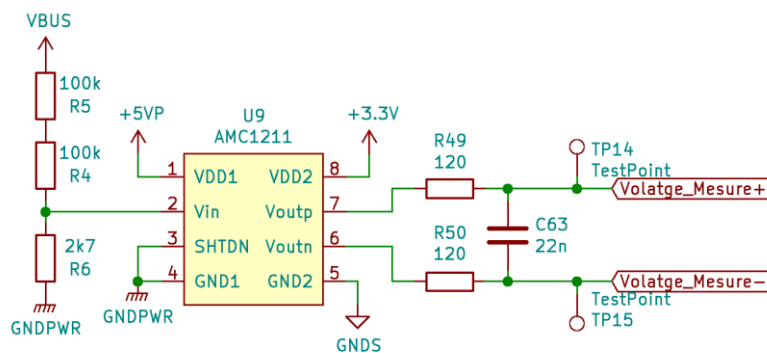


Fig. 11 Voltage measurement in the schematic

2.5.2 Current measurement

The current sensing circuit has to be capable of measuring up to 10A but support 15A and provide isolation. To keep a smaller number of components, we choose one that also works on 3,3V like the voltage sensor and the MCU. We choose the ACS722LLCTR-xxAU family of hall effect sensors from allegro. They comply with our requirements and provide a high bandwidth, good noise immunity and small form factor. The sensor that is fitted on the board is the ACS722LLCTR-10AU which saturate at 10A but it is pin to pin compatible with all the rest of the family. Compared to a circuit based on a shunt resistor this offer smaller footprint and better efficiency.

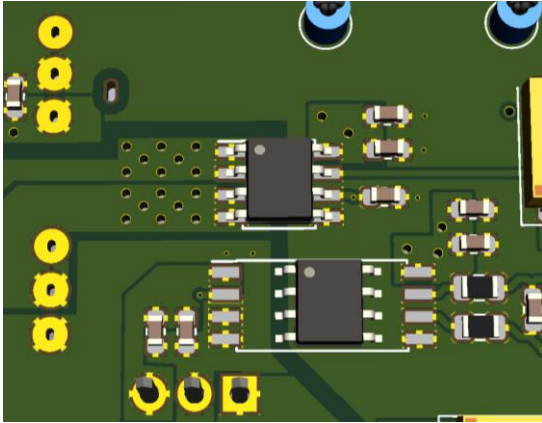


Fig. 12 Current (top) and Voltage (bottom) sensors in Kicad 3D view after routing

2.6 Power supply circuit

The board is powered via an input of 100V on its main connector. The power needs to be distributed and adapted to get every parts of the board to work properly

2.6.1 Input filter

To avoid having EMC issues, we added an input filter. Its goal is to avoid voltage ripple from the board to pollute the source of voltage and to keep a stable supply voltage for the *Mosfets*

To provide the energy storage, we used two polymer capacitors of $22\mu\text{F}$. However, the lack of space doesn't allow to get a proper capacitor bank to cope with important voltage drop of the input. The converter for the low power side works with an input voltage between 43 and 160V which should allow to program an under-voltage protection in the MCU.

For the voltage ripple we use ceramic capacitors of 100nF and 10nF and an inductor of $5,6\mu\text{H}$ to provide a cutting frequency at 14kHz.

2.6.2 Converter for signal side

To provide the voltage for the low power side, we selected an isolated converter that adapt the 100V input to 12V. However, there isn't many models capable of handling 150V. We choose the TMR3WIR from Traco Power as 3W was supposed to be enough.

During the testing we observed a consumption of about 5W which force the converter to shutdown and we had to do the testing with an external 12V power supply. As mentionned in the next part, this is due to the converters for the gate drive being powered from the 12V.

2.6.3 Converter for gate drive

We choose to use off the shelf converters for simplicity. They have to provide 15V and 18mA for the gate drive. They also need to provide an isolation as the gate driving circuit of the high mosfets use a floating ground that is connected to the source of the mosfet.

Even if the power is very limited, there are only a very few references that comply with those constraints and their prices are relatively high. By selecting converter with an input of 12V instead of 150V, we greatly reduced the price. However, this resulted in an issue as they are now loading the 12V converter that we use for the low power side. As I forgot to upgrade this converter, it was not capable of delivering enough power. During the testing it was entering shut down mode and we had to use an external power supply for the 12V.

2.6.4 Close decoupling

We added similar decoupling to the voltage supply of every IC. It was composed of an electrolytic capacitor and two ceramics, one of 220nf and one of 22nf. The electrolytic allow to provide a large enough value while the ceramics provide better decoupling at high frequency. Because of the high frequency noise that may result from the switching and the proximity of the transformer, we give special care to EMI. To get better frequency response, the capacitors were choosen in a small package 0603. Smaller may improve even more the performances but hand soldering would be to difficult.

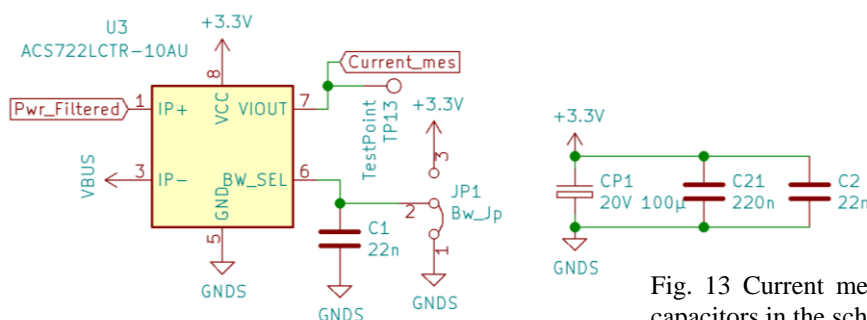


Fig. 13 Current measure and its decoupling capacitors in the schematic

2.7 Heat dissipation

As seen in the mosfet comparison, we already have an estimation of the power to dissipate from the mosfets. SMD mosfet had the best efficiency and lowest price. In normal use *Mosfets* will be soft-switched thanks to the resonant load which will greatly improve the efficiency. But because this project is part of an experimentation, the inverter has to be rugged and capable of handling severe fault conditions. Under those conditions, the dissipation of heat could be handled by using thermal vias, special SMD heatsink or even by using an aluminium PCB. However, the constraint in space makes it impossible. Thus, we choose a through holes mosfet with higher losses but that we can be cool with an extruded heatsink.

In the next step we will calculate the performance that we need from the heatsink and we will see which type we can fit.

2.7.1 Calculation

The calculations of the losses are explained in the mosfet comparison. We expect up to 22W of dissipation. From the datasheet of the mosfets we can find the following data:

- Maximum junction temperature: $T_{jmax} = 150^{\circ}\text{C}$
- Thermal resistance from junction to case: $R_{thJC} = 1^{\circ}\text{C/W}$

We assumed the following values:

- Ambient temperature: $T_{amb} = 25^{\circ}\text{C}$
- Thermal resistance of a silicon pad: $R_{thPad} = 1^{\circ}\text{C/W}$

We can calculate the maximum thermal resistance of the heatsink as:

$$R_{thHeatsink} = \frac{T_{max} - T_{ambient} - P_{mosfet} \times (R_{thJC} + R_{thPad})}{4 \times P_{mos}}$$

We obtain a maximum thermal resistance of $1,28^{\circ}\text{C/W}$.

2.7.2 Heatsink

For this project, there was Two types of heatsink with an acceptable form factor. A tunnel type that would be placed on the side off the board or a flat extruded one that would be placed under the board.

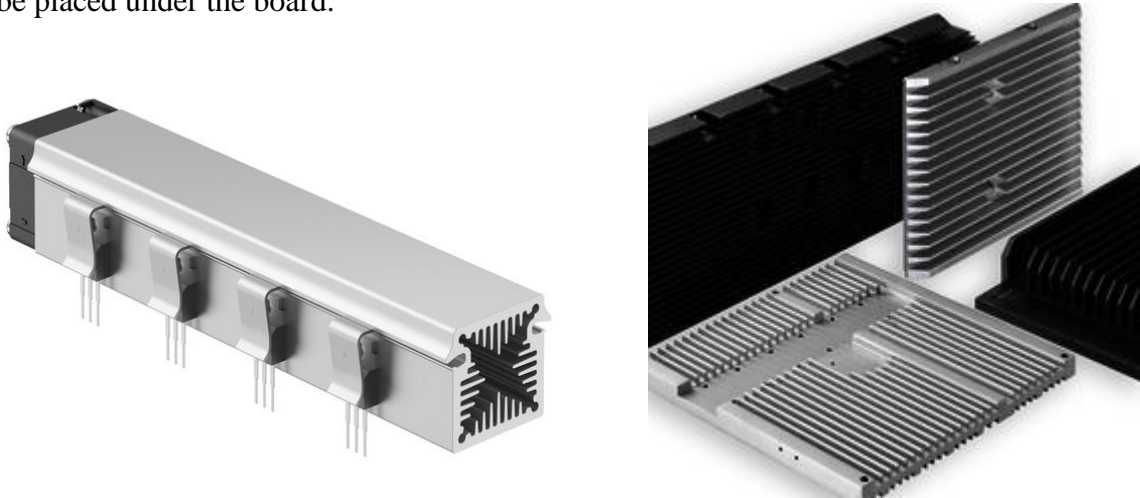


Fig. 15 & 15 Pictures of heatsink from the supplier Fischer elektronik

To select the exact model, we needed to know how the *Mosfets* would be placed. To visualize the possibilities of placement, we made a modelisation on a CAD software called Solidworks.

2.7.3 Solidworks

To find what heatsink we can fit, we made a 3D model of the board. This model is approximative as all the components were not decided yet but it will help anticipate the lack of space and decide which type of heatsink to get.

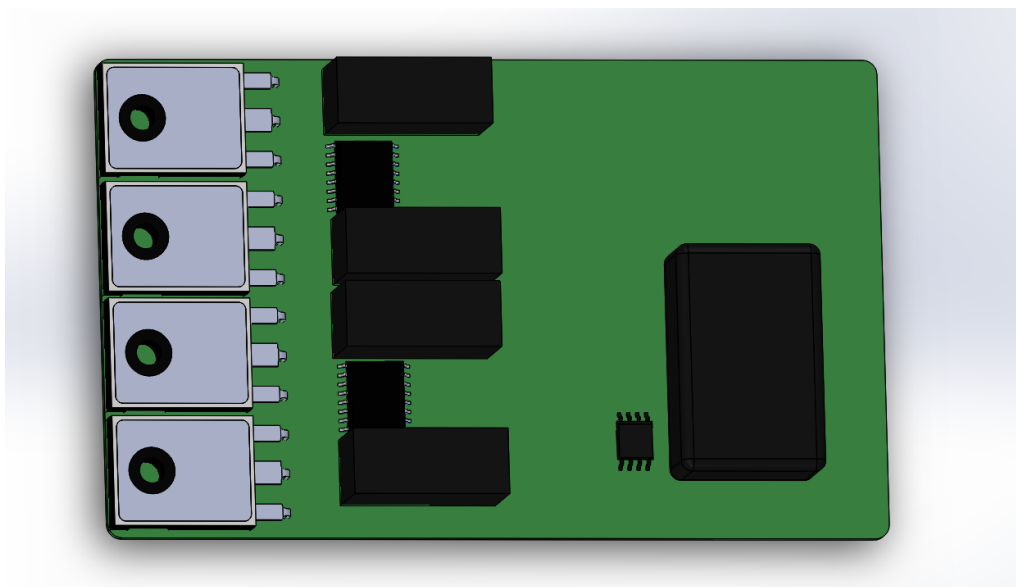


Fig. 16 First layout in CAD

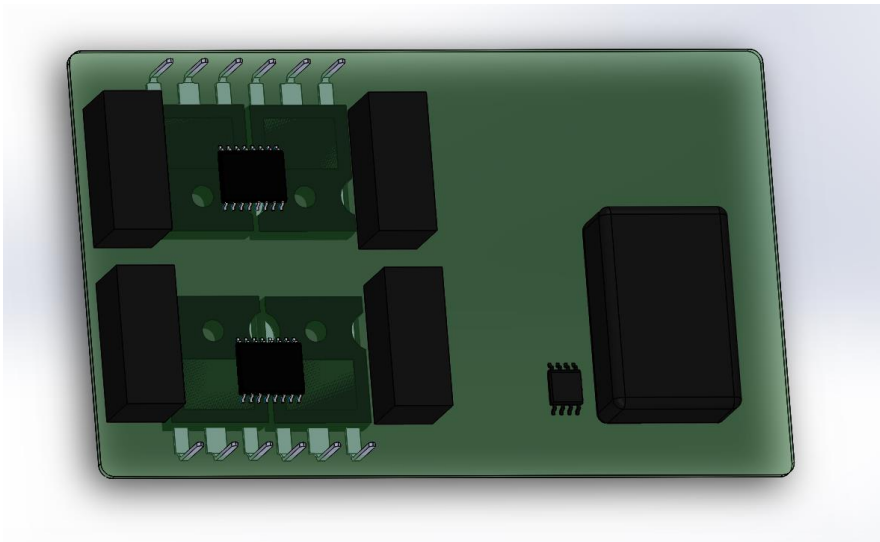


Fig. 17 Second Layout in CAD

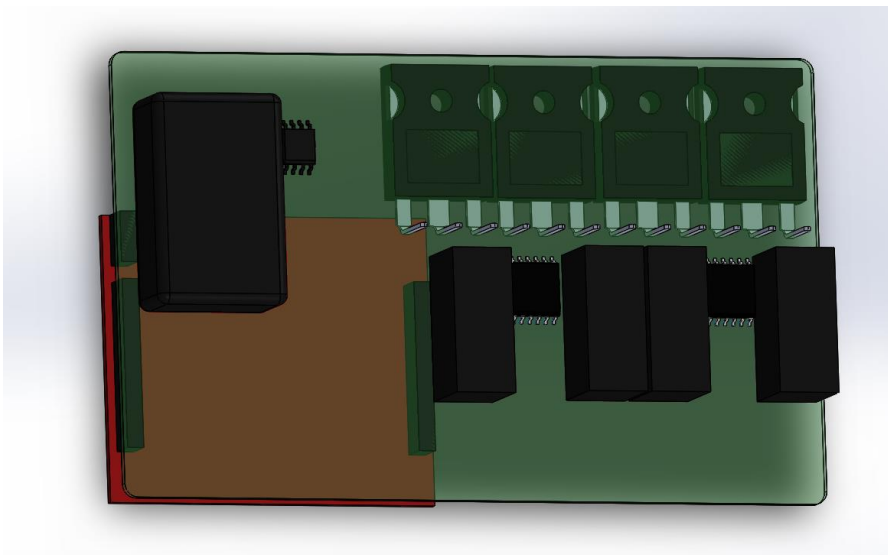


Fig. 18 Third Layout in CAD

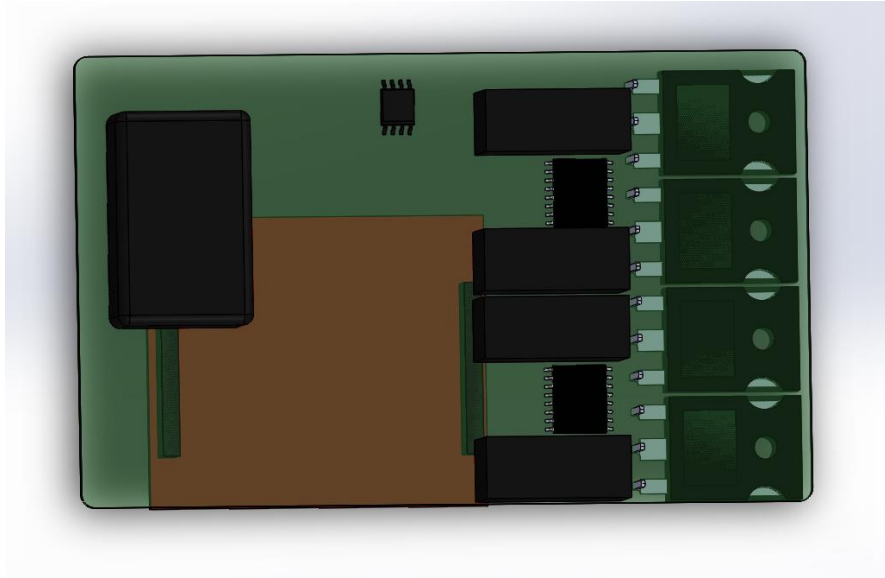


Fig. 19 Fourth Layout in CAD

2.8 Finishing the schematic

The last step to finish the schematic is to link the symbols of the component with the footprint of the component on the board. Some components have very standard package and thus the footprint is built in the software. For some others, the manufacturers supply the file of the footprint. For the rest, footprints need to be designed based on recommendations from the datasheet.

3 Designing the PCB

The PCB is a board generally made of alternating layers of glass fibre reinforced plastic and copper. It act as a support to hold the components and connect them together. The size of the PCB has to be 115x67mm and will be done using Kicad as described in the next parts.

3.1 PCB in Kicad

Kicad allows to design PCBs based on a schematic. It replaces the symbols of the schematic with footprints:

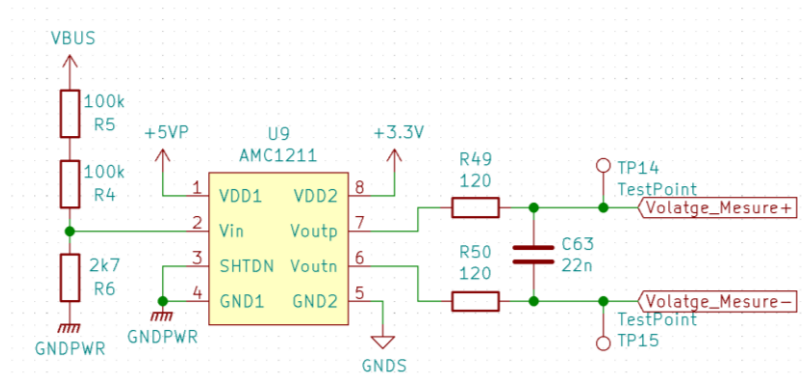


Fig. 20 Voltage sensor in the schematic

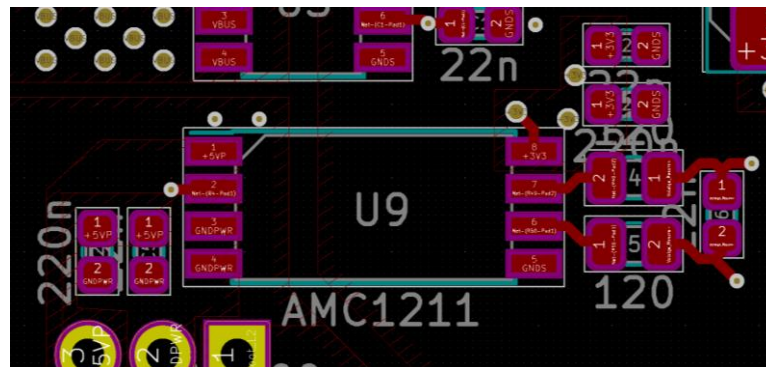


Fig. 21 Voltage sensor in the routing

The pads of the footprint are where the leg of the component will be soldered to the copper of the PCB. The pads need to be connected to other pads of some components to create the same circuit as in the schematic. To connect the pads, we can use a combination of traces, vias and copper planes. Thanks to the schematic, the pads that needs to be connected together are displayed during the PCB routing.

3.2 Components placement

We started with setting the edge of the board and then place the components by groups. The problem was that right after importing the footprints it was visible that they wouldn't fit on the board.

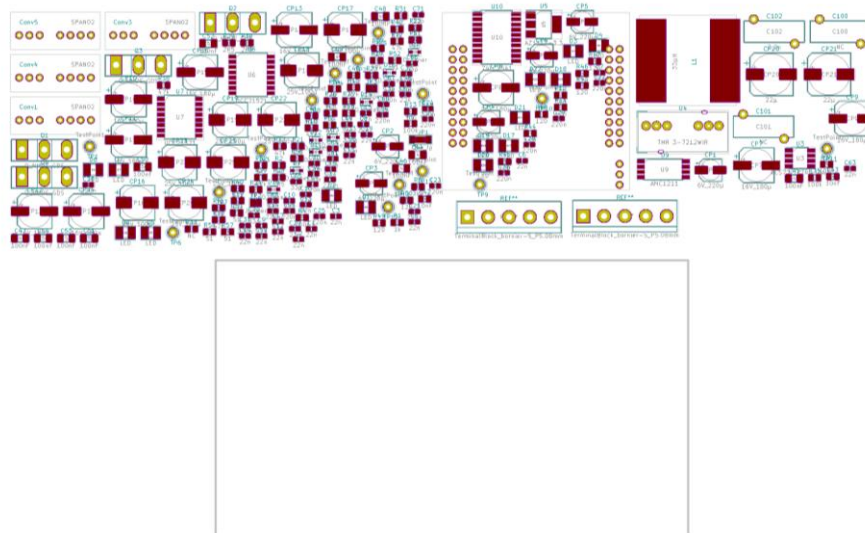


Fig. 22 Footprints as imported (top) Area available to place them (bottom)

To reduce the space taken by the components, we changed the low voltage electrolytic capacitors to smaller tantalum. We replaced the linear regulator from SMD to through holes and changed the inductor. We also placed components on both sides of the board to maximise the available surface.

The major difficulty is to fit the large launchpad over the rest of the board as its headers shouldn't overlap with the power side. To save some space, we changed the headers on which the launchpad is connected from through holes to SMD. This makes it easier to fit components under the launchpad. To save even more space, we also tried to fit only one header. However, we couldn't get the right pins from one header and by changing the footprint so many times, we ended up with an error of placement that had to be corrected during prototyping.

3.2.1 Final fitment

We had to try different placement to find one where almost every component can be placed. Only a few capacitors were not fitted.

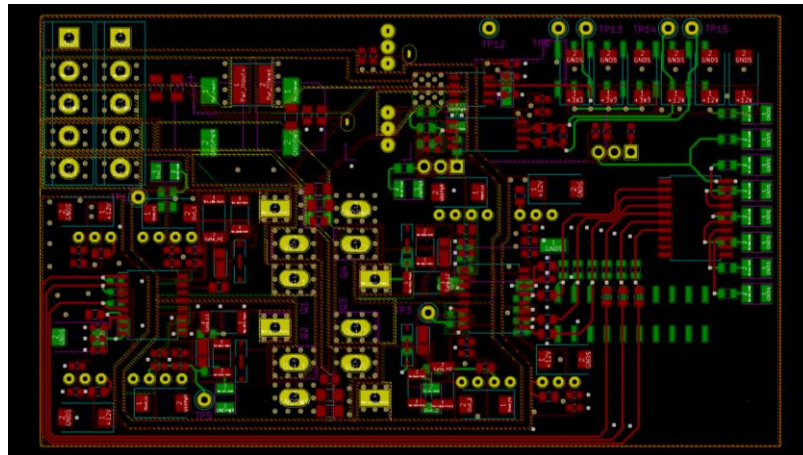


Fig. 23 Final routing

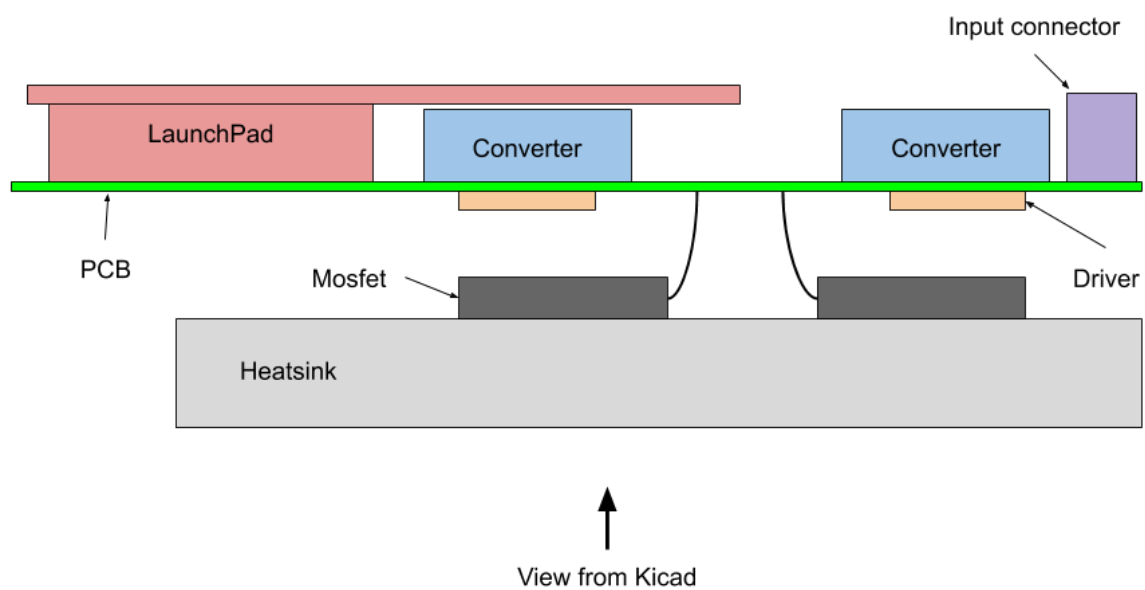


Fig. 24 Components placement and view during routing

3.3 Routing

To connect the components together, we generally use traces. In our circuit, we don't have very high frequency that would require a specific size of trace or any very small SMD chip with very high density of pins. Consequently, we choose to do all the traces at a relatively large 0,3mm. To connect components that are on different sides, we used vias of 0,5mm.

To connect the ground and the supply voltage, we use power planes. They have a much higher surface area which provide cooling and help keeping the ground and supply potential constant by having very low impedance.

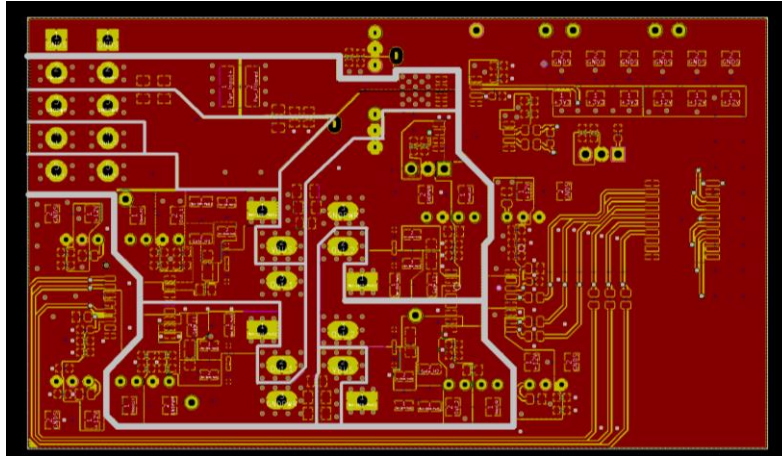


Fig. 25 View of power plans and isolations

On the above picture, you can see the traces as red lines, planes as large red areas and the main isolations are shown in white.

The isolation distances were calculated using the IPC2221 recommendations. The isolation between the power plane and the input power needs to be at least 0,4mm. We kept a small margin and made it at 0,5mm. For the isolation between the high and the low power sides, we made an isolation of 1mm which should withstand more than 575V safely following the recommendation.

Because of the tight placement of the components and the numerous isolations, the top and bottom copper sides were not enough to place all the traces and power planes needed. We had to use a 4 layers PCB.

To improve the quality of the PCB, we used some additional techniques:

For thermal dissipation, we added vias of 0,75mm around the heat generating components.

For the reliability of the connectors, a second footprint has been placed next to the first one. If the connector is sheared off of the board, a new one can be soldered on the second footprint.

For decoupling of power inputs of IC, we used 220nF and 22nF ceramic capacitors in 0603 package in addition to the tantalum ones. The smaller value and the small package

allow for higher frequency decoupling. They are connected to the IC using a small copper plane instead of a trace as it exhibits better high frequency behaviour. Moreover, we placed them so that the closest capacitor to the IC are the one capable of higher frequency.

To improve the consistency of the ground potential on the entire board and to improve EMC, the ground plans of the different layers are regularly connected together by some vias. However, the files that I sent for manufacturing didn't have these "stitching" vias and a small ground plane was not connected which was corrected during the testing.

4 Realisation of prototype

Once the PCB design sent and manufactured into a complete PCB, we started the realisation of the prototype

4.1 Soldering

The first step of the realisation of the prototype was to solder the components on the PCB. They were all soldered by hand. Some SMD chips were not perfectly soldered and during the testing, we had to resolder them. Some components were not received such as the tantalum capacitors so we replaced them with electrolytic. Some ceramics ran out of stock during the routing and the replacement capacitors that were ordered are not in the right package which created additional difficulties during soldering. As the tantalum capacitors were not received, we used some electrolytic that were available. However, they are higher which resulted in the *Mosfets* having very long leads to fit the capacitors.



Fig. 26 Prototype soldered and rectified

4.2 Programming

To operate the board for the testing we made a simple program for the MCU CodeComposer. We used the built-in examples for this MCU to set the sampling of the measurement through the ADC and we set and synchronized the PWM modules to operate the *Mosfets*. The entire program is available in the attachements.

5 Testing

5.1 Power supply testing

The power supplies are all working. However, in normal use, the power consumption on the 12V is much higher than planned which resulted in the 12V converter to shut down. For the rest of the testing we had to attach an external power supply to the board.

5.2 Sensor testing

We measured the output of the sensors with different input voltage and different currents. We stop the measurement before the end of the sensors range as the results were linear and higher current or voltage needed an stronger equipment.

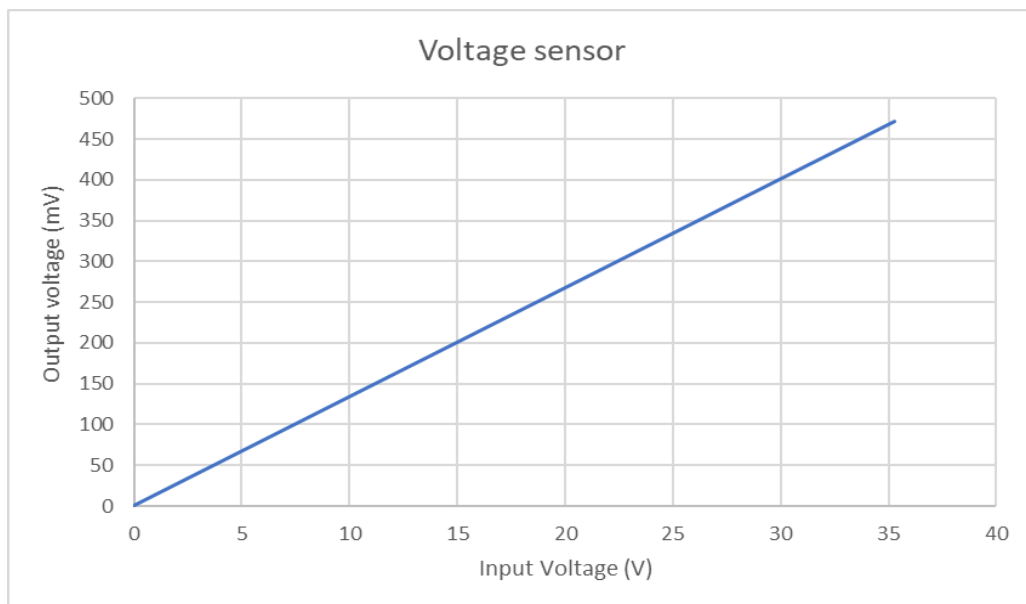


Fig. 27 Voltage sensor output as function of input voltage

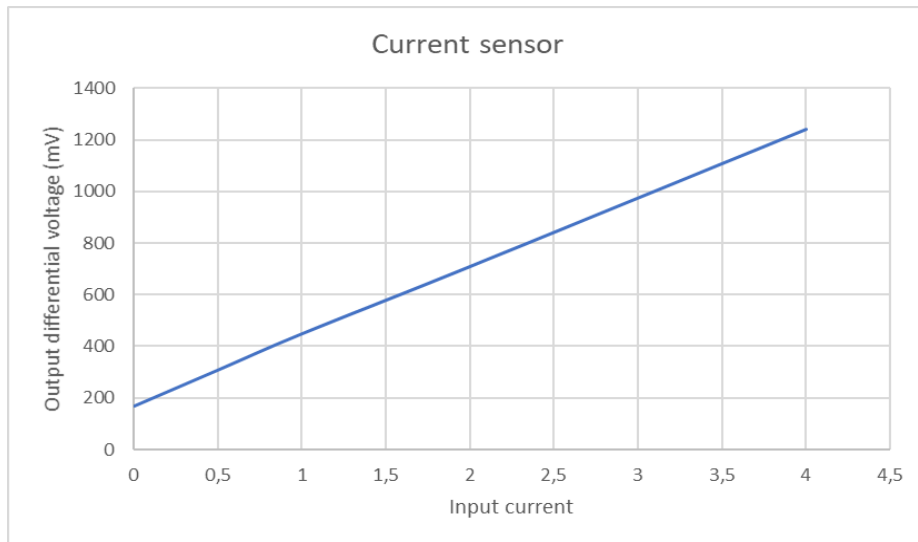


Fig. 28 Output of current sensor as function of current consumption

5.3 Gate signal

We observed the gate signal from the launchpad to ensure having the right frequency and the right synchronisation.

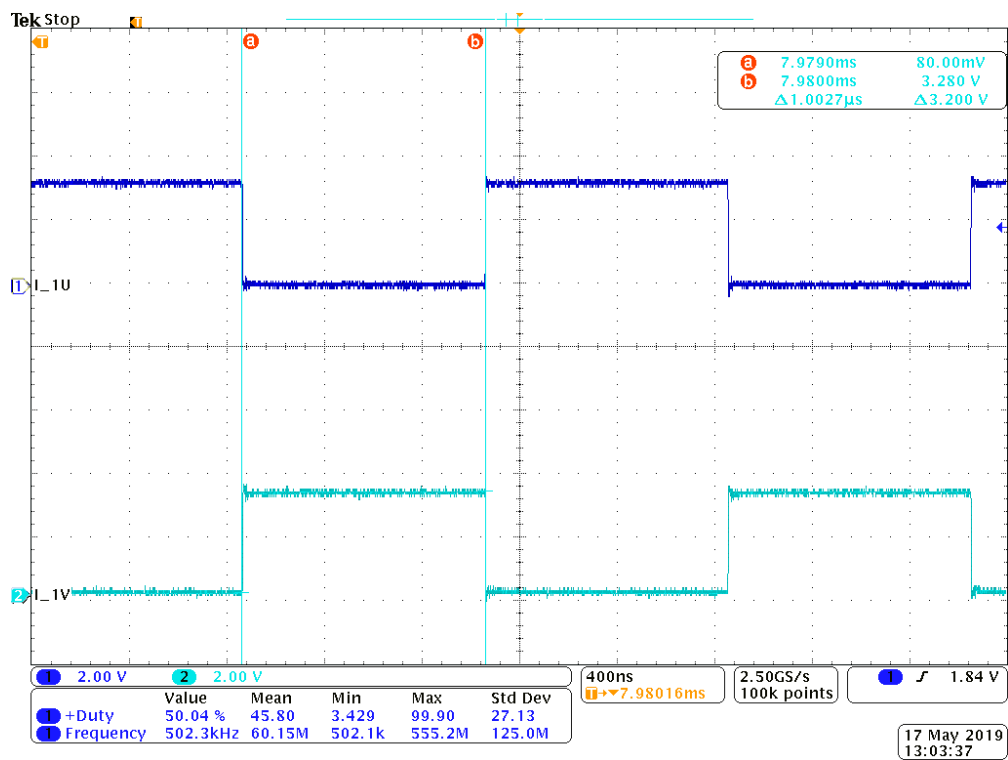


Fig. 29 Launchpad gate command with frequency and dutycycle measure

Then we added Dead Time:

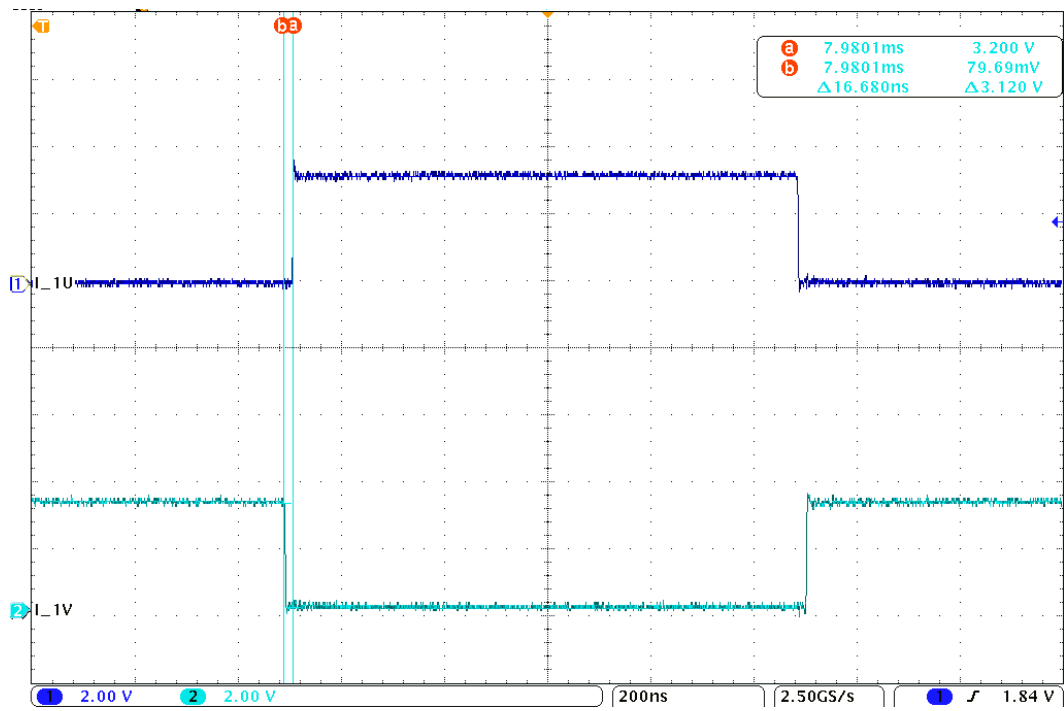


Fig. 30 Dead time measurement

We observed the gates of high and low mosfets without voltage on the power side to check the gate driving circuit.

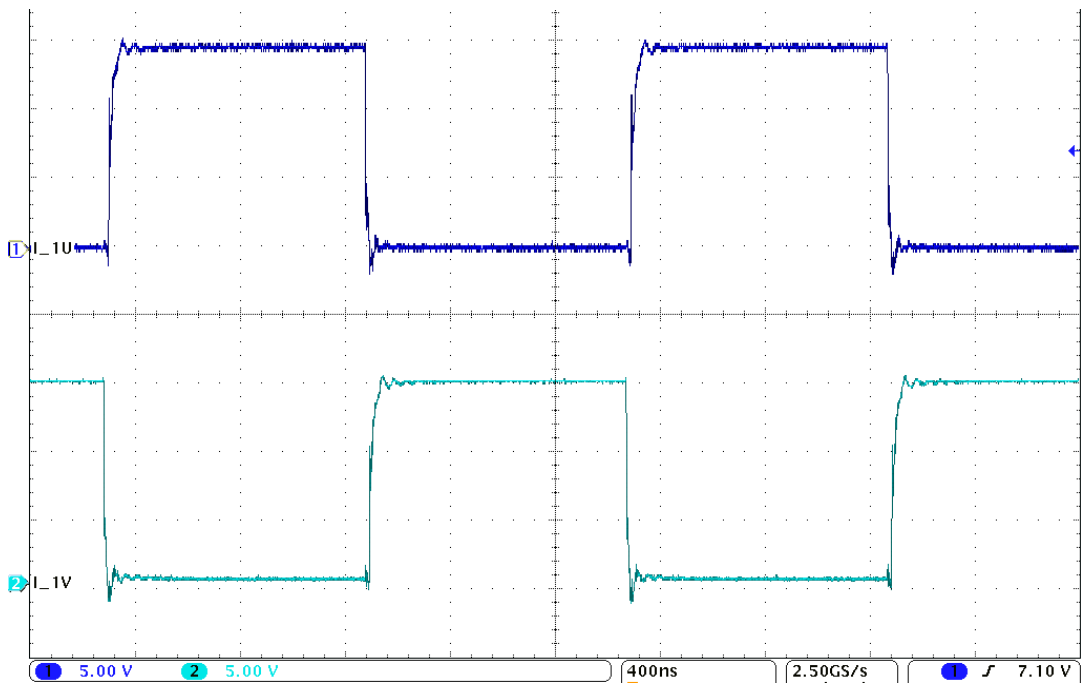


Fig. 31 Gate voltages without input voltage on powerside

We measured the delay between the launchpad and gate at 40,7ns:

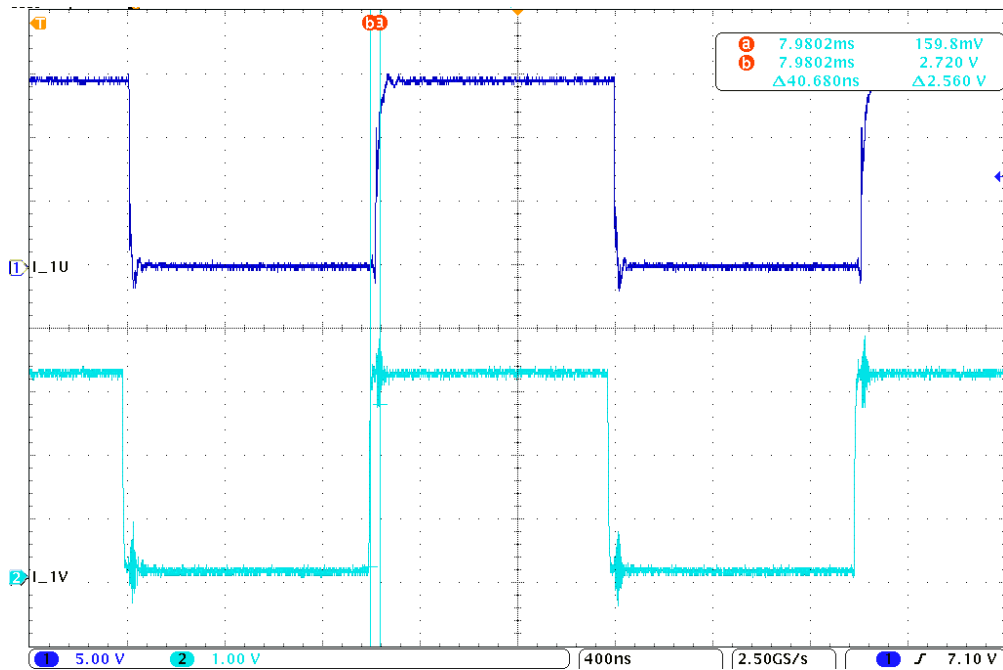


Fig. 32 Propagation delay measurement

This is exactly the expected result expected as there is 19ns of propagation from the driver, 10ns of hardware dead time and the filter at the input of the driver as a time constant of 10ns

We measured the effective dead time with a setting of 16ns in the program:

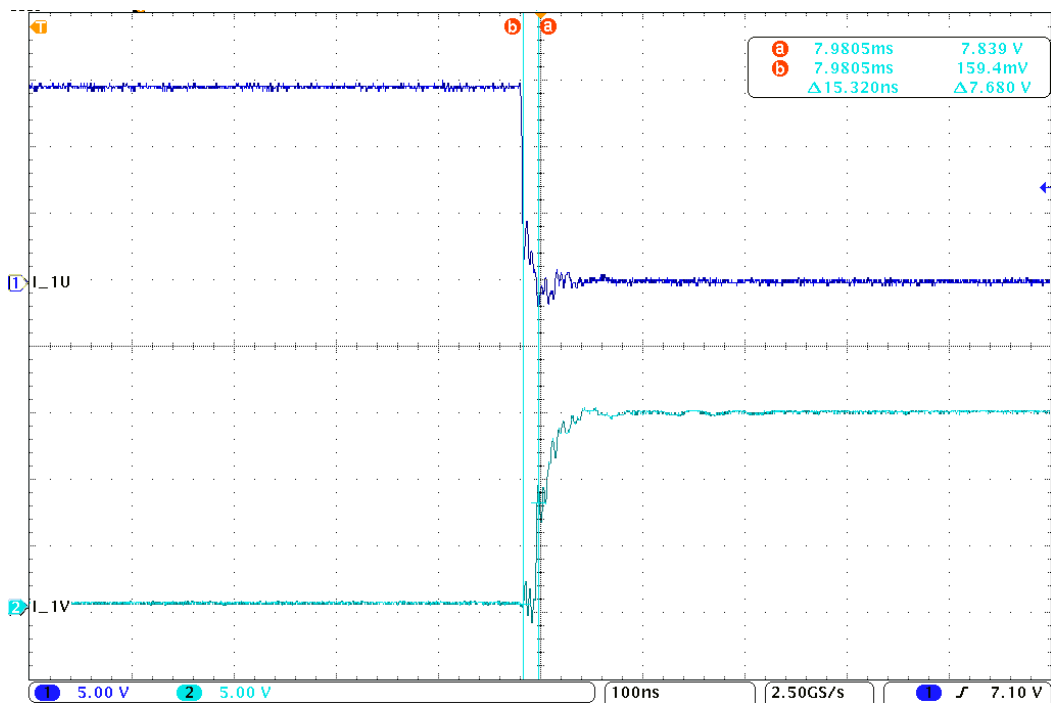


Fig. 33 Software dead time measurement

Then we added some voltage on the power side which resulted in an important perturbation

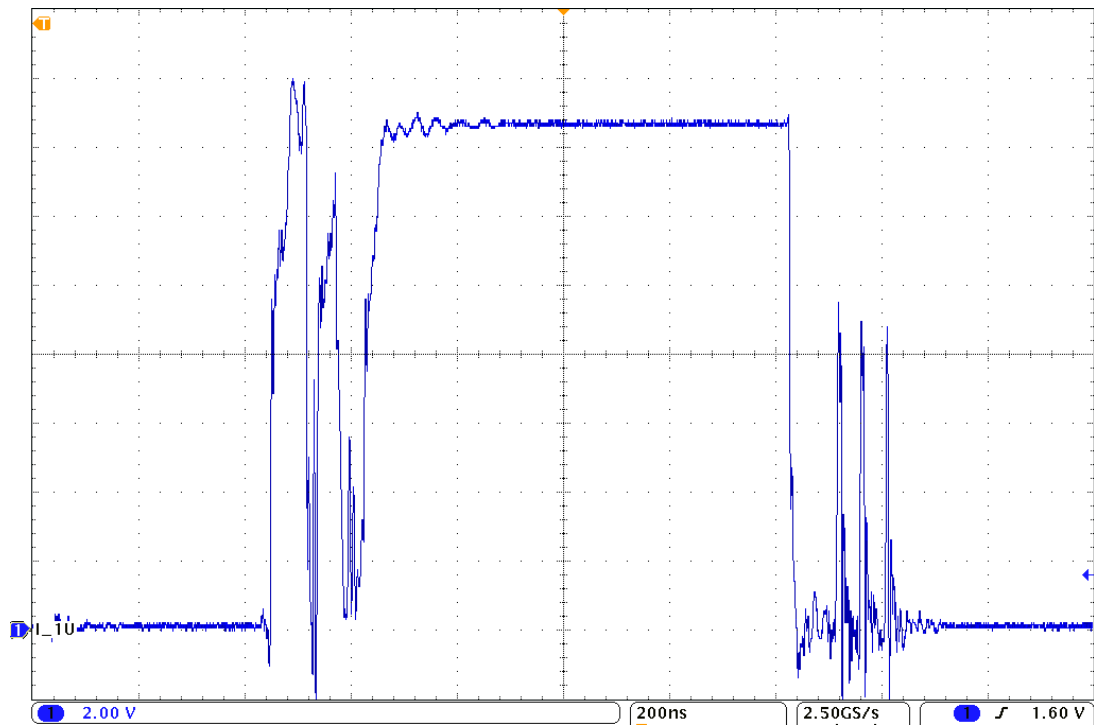


Fig. 34 Gate voltage with perturbation

We found that it was caused by a ground plane not being correctly connected. Once corrected we could observe the correct gate signal:

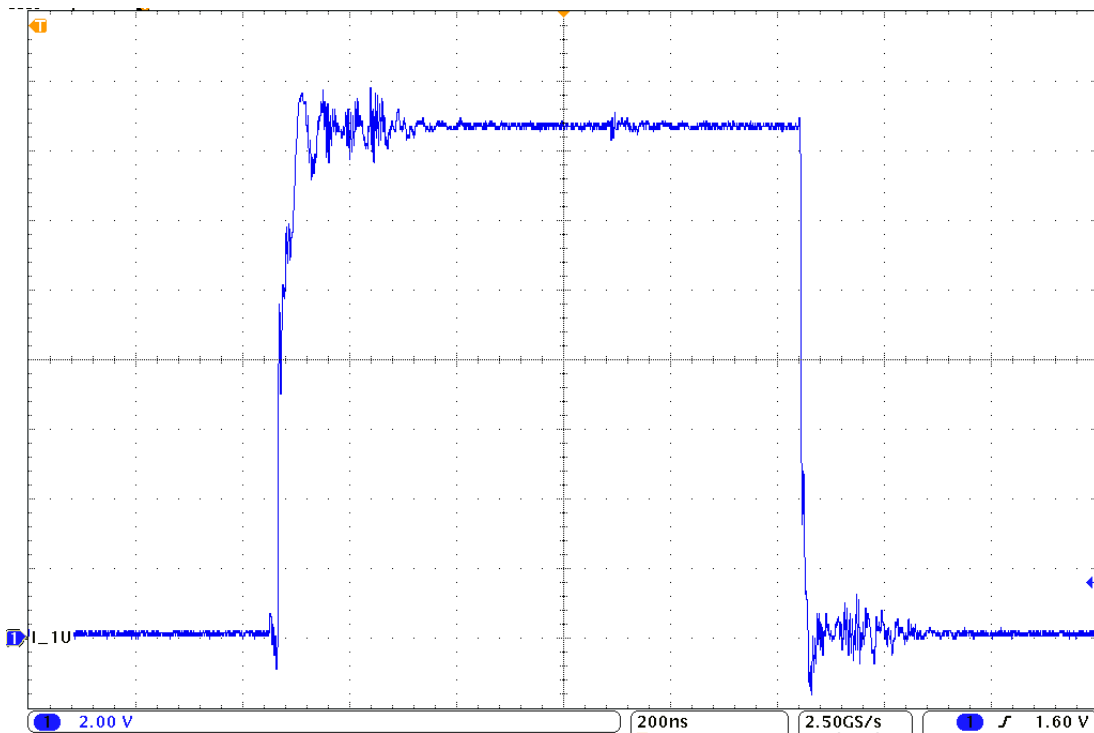


Fig. 35 Gate voltage after rectification

5.4 Switching behaviour

We applied 30V on the power side but no load to observe the behaviour of the mosfets. The voltages displayed below are the drain to source voltage of both low mosfets. This is equivalent to the output1 to ground and output2 to ground.

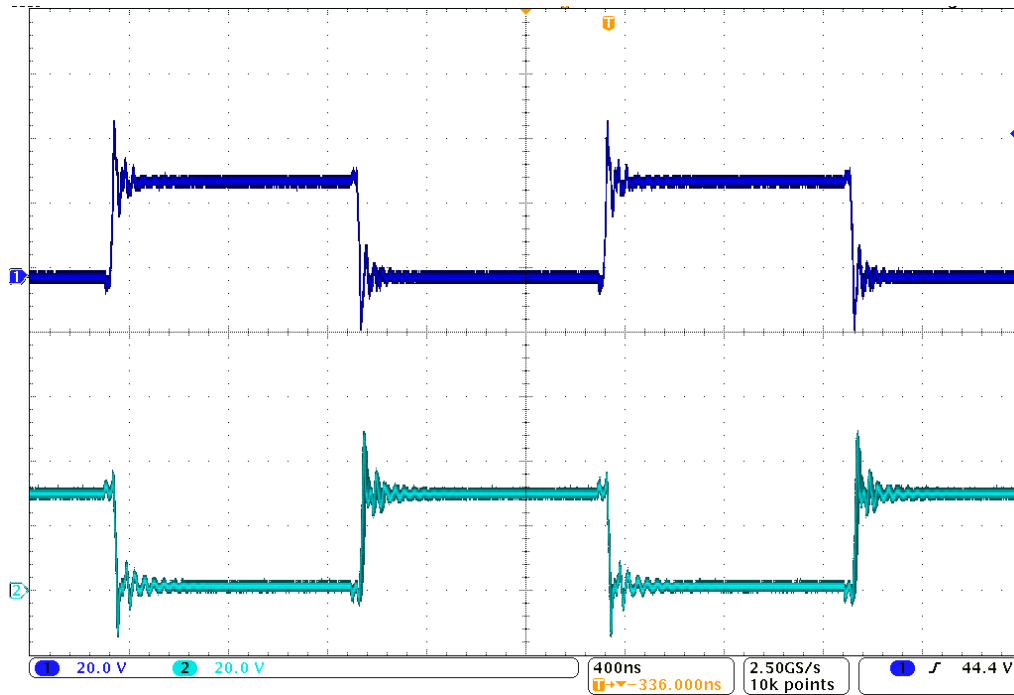


Fig. 36 Drain Source voltage of Mosfets with 30V input

We can observe an important overshoot due to the fast edge and the particularly long lead of the mosfet on this prototype. But this was expected, then we applied 50V:

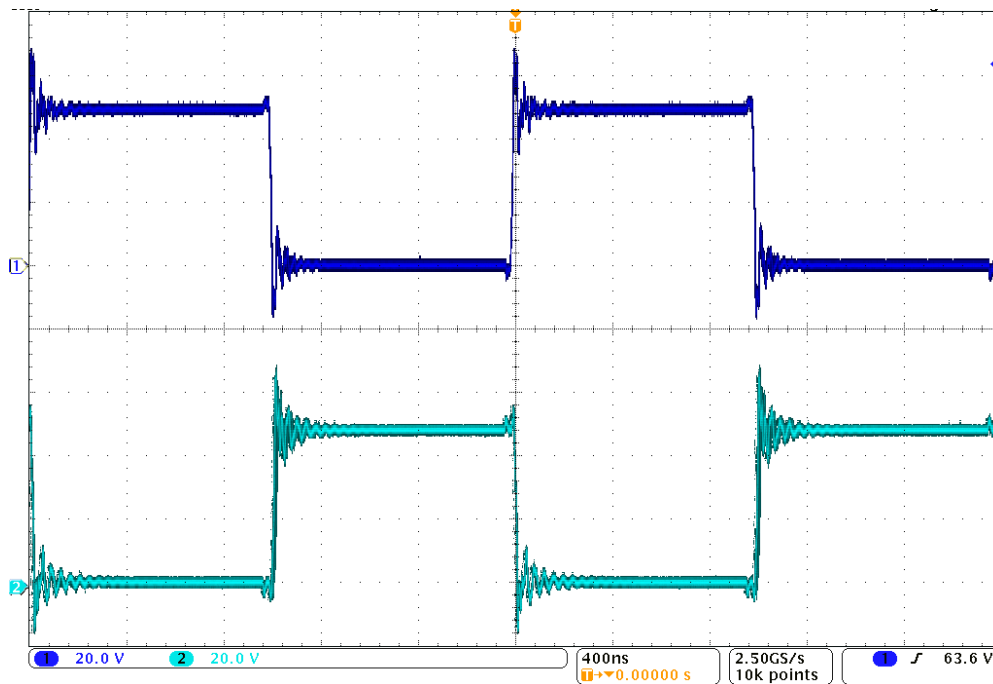


Fig. 37 Drain Source voltage of Mosfets with 50V input

With 80V and 100V input:

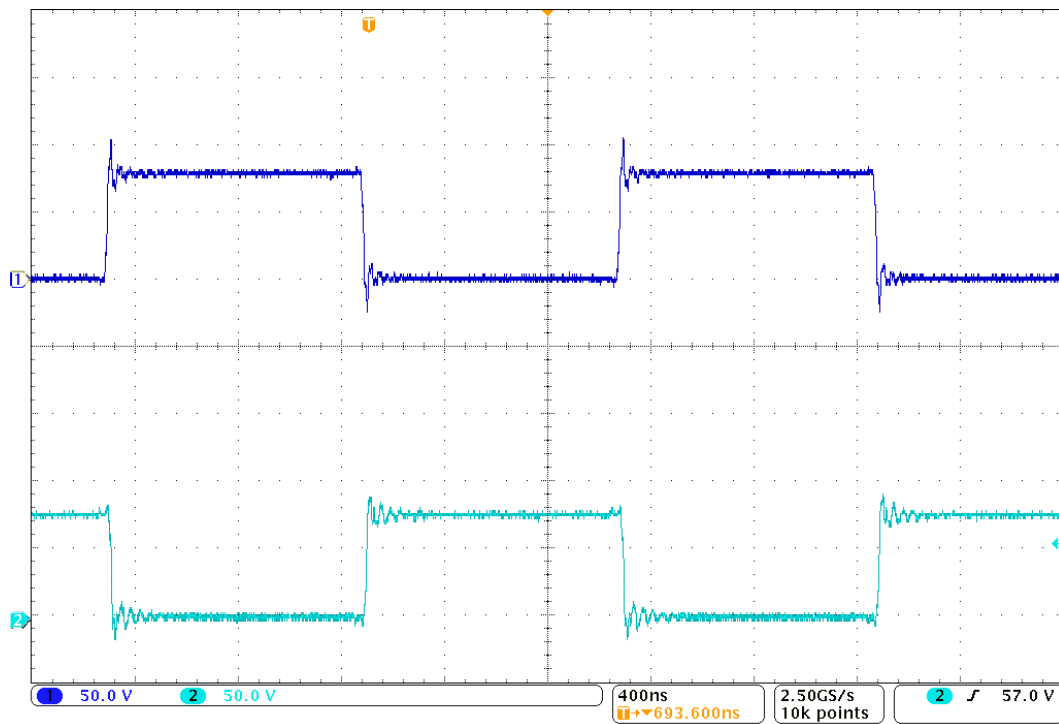


Fig. 38 Drain Source voltage of Mosfets with 80V input

We can see an important improvement. It seem that the change actually came from the oscilloscope used that had issues with its inputs and with the triggering.

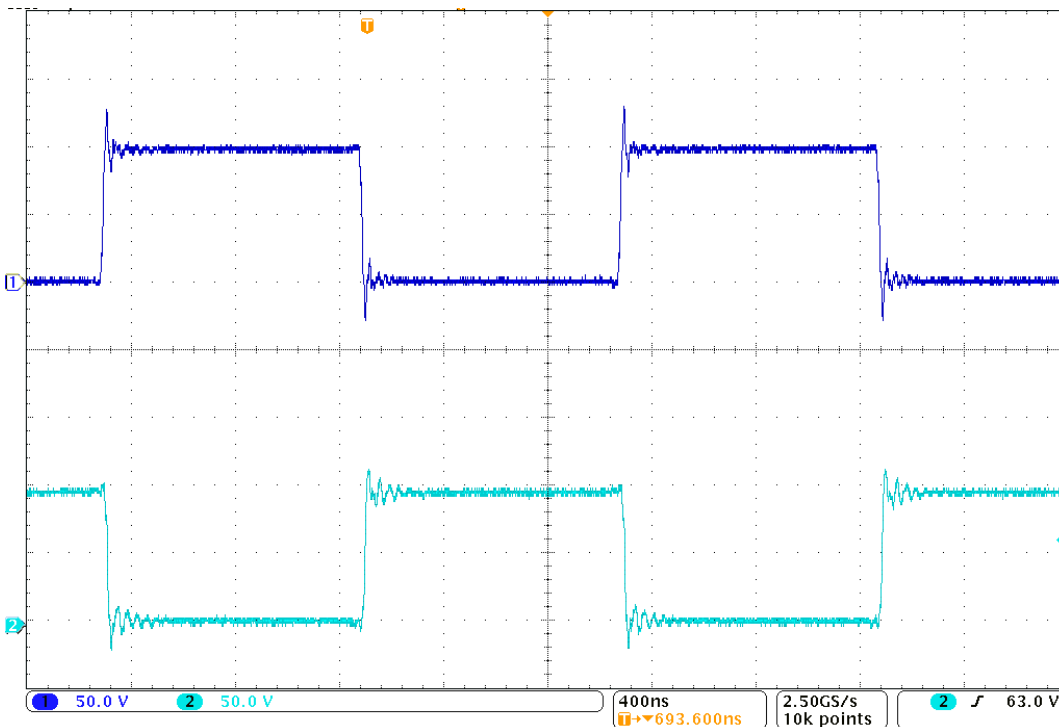


Fig. 39 Drain Source voltage of Mosfets with 100V input

At 130V:

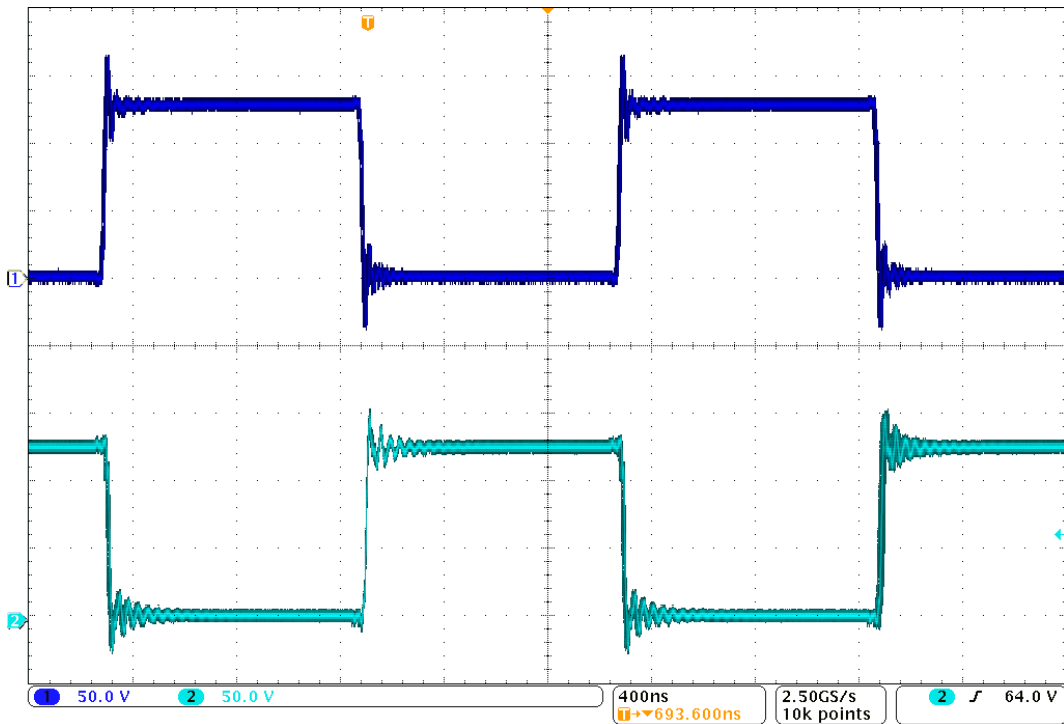


Fig. 40 Drain Source voltage of Mosfets with 130V input

At 150V

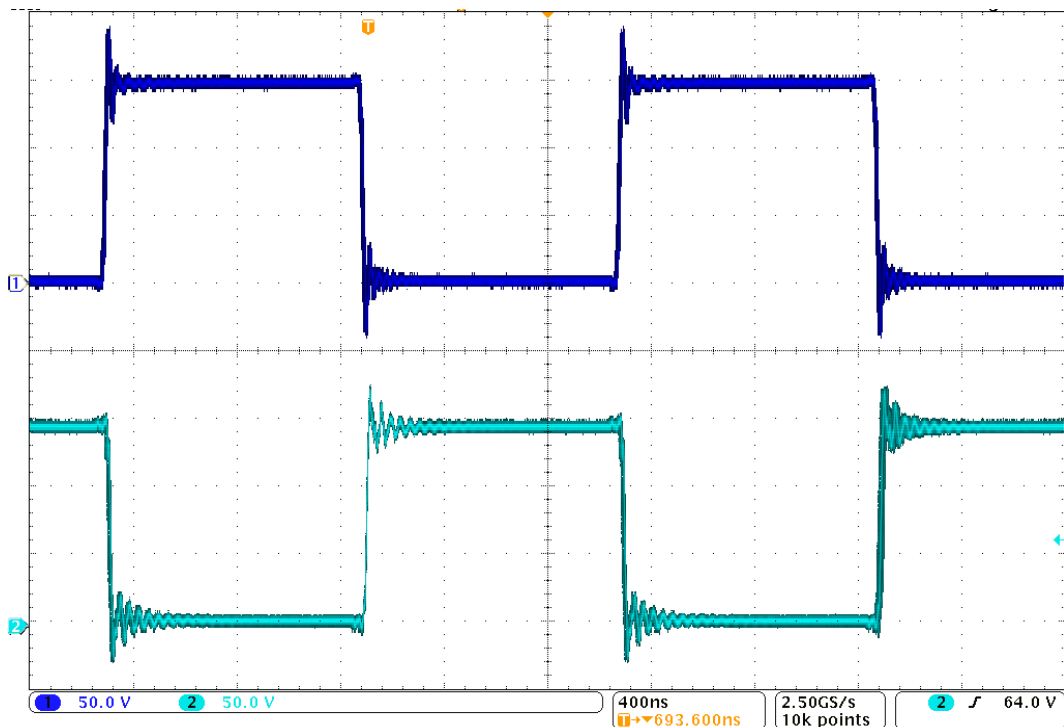


Fig. 41 Drain Source voltage of Mosfets with 150V input

This is the maximum voltage that the board should have to withstand. We measured the value of overshoot to be 28V:

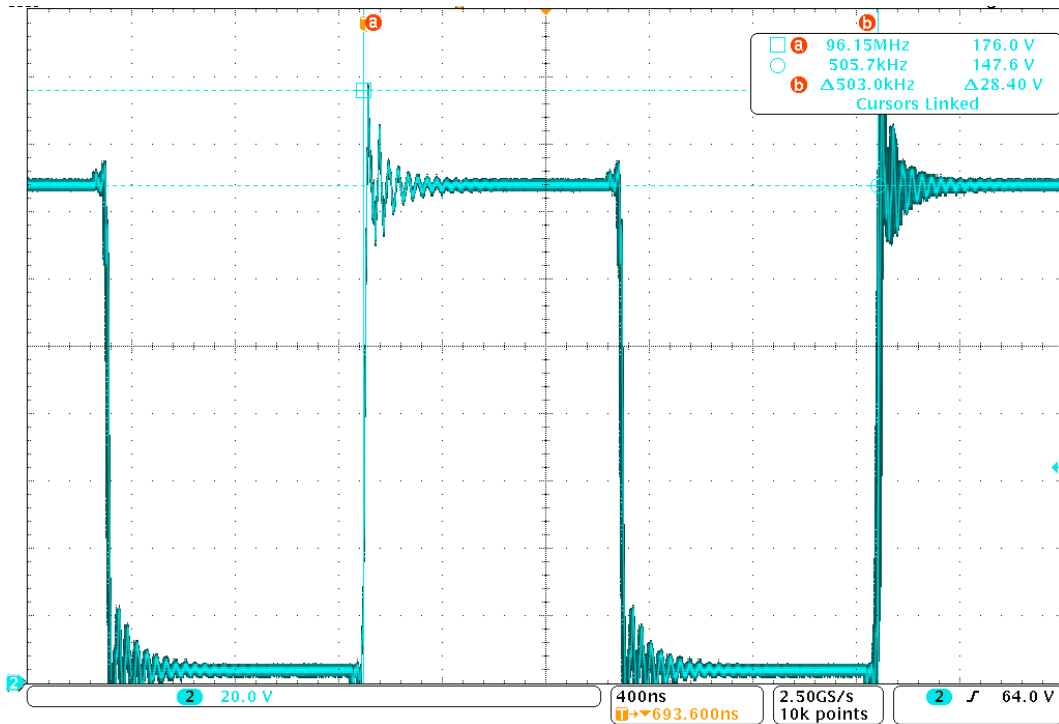


Fig. 42 Overshoot measure

To continue the testing, we added the primary coil of the induction charger. Because of the absence of secondary coil, there was a consumption of 5A with only 3,5V on the input.

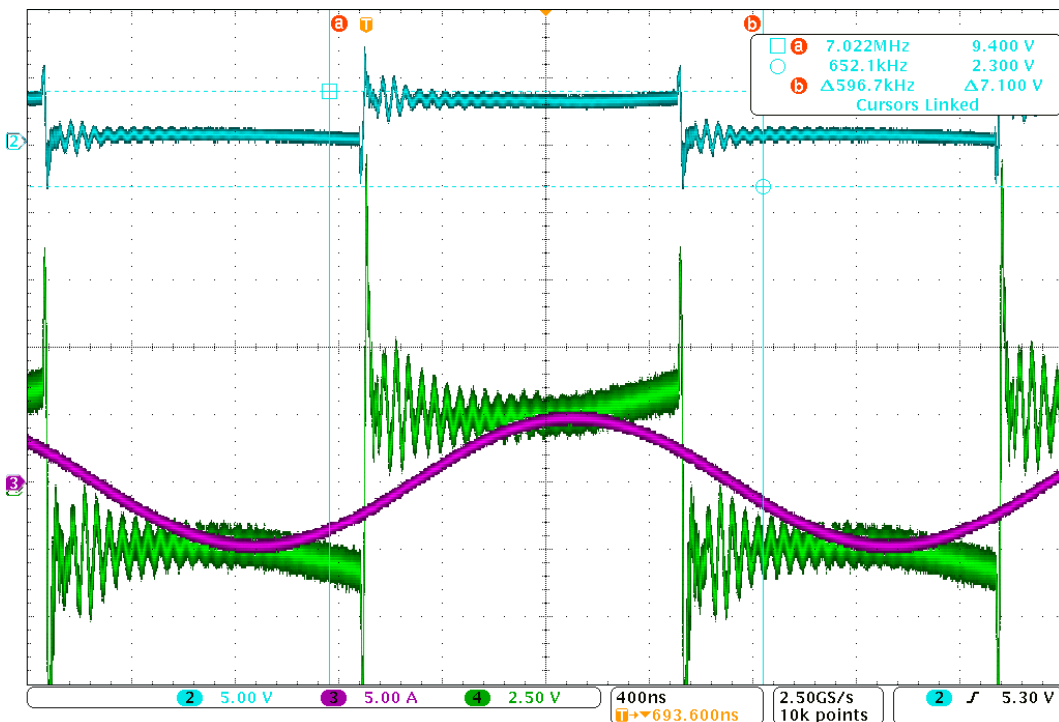


Fig. 43 Output voltage and current with primary of transformer

We observed that the voltage input was not constant as there wasn't enough fast capacitors. We added more ceramic capacitors close to the mosfets, doubling the capacity of the decoupling.

Then we ran the test again with a secondary coil to charge the system. With an 50V input the system was drawing 3,23A:

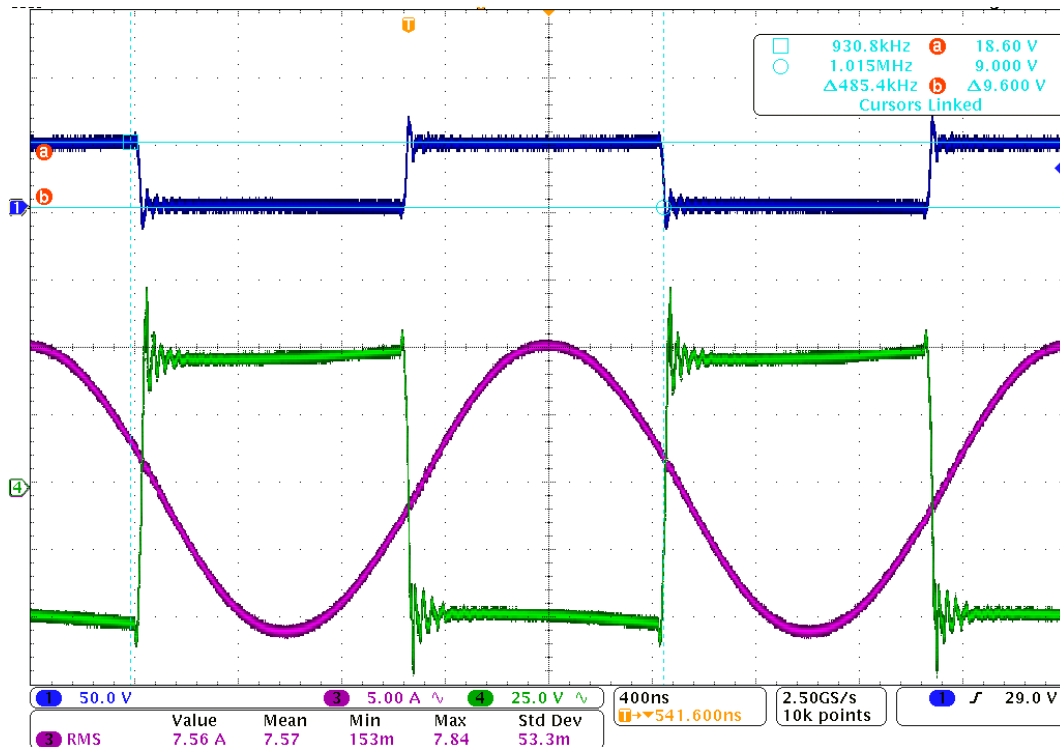


Fig. 44 Output voltage and current with load, added capacitors and 50V input

As we can see, the problem of decoupling is relatively well sorted. However, as we had to set the switching frequency to be at resonance, we found out that the resolution available is not good enough. The launchpad the we used has a clock of 60MHz which gives a resolution of 16.7ns on the period. At the frequency of 483,9kHz that we used, adding one cycle leads to a frequency of 480kHz. It may seems very precise as the change is of only 0,8% but the very high quality factor of the coil lead to high variation of impedance over a very short frequency range.

We continue by setting the input at 50V which draw a current of 8,39A:

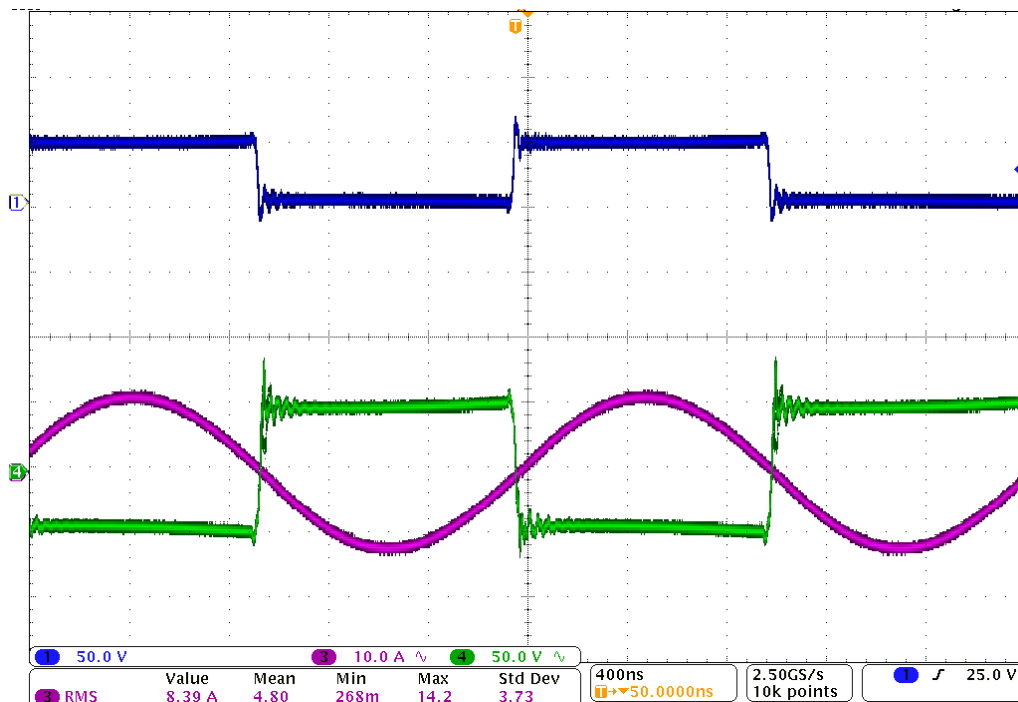


Fig. 45 Output voltage and current with load and 50V input

At this point, the rectifier on the secondary side blow up. So we replaced it with a *SiC* rectifier. After that, we measured the input power at 380,5W and the output power at 362,9W. We calculated an efficiency of 95,4%. However, if we take in account the 4,9W consumed by the low power side on an external 12V power supply, we get 94,2% efficiency.

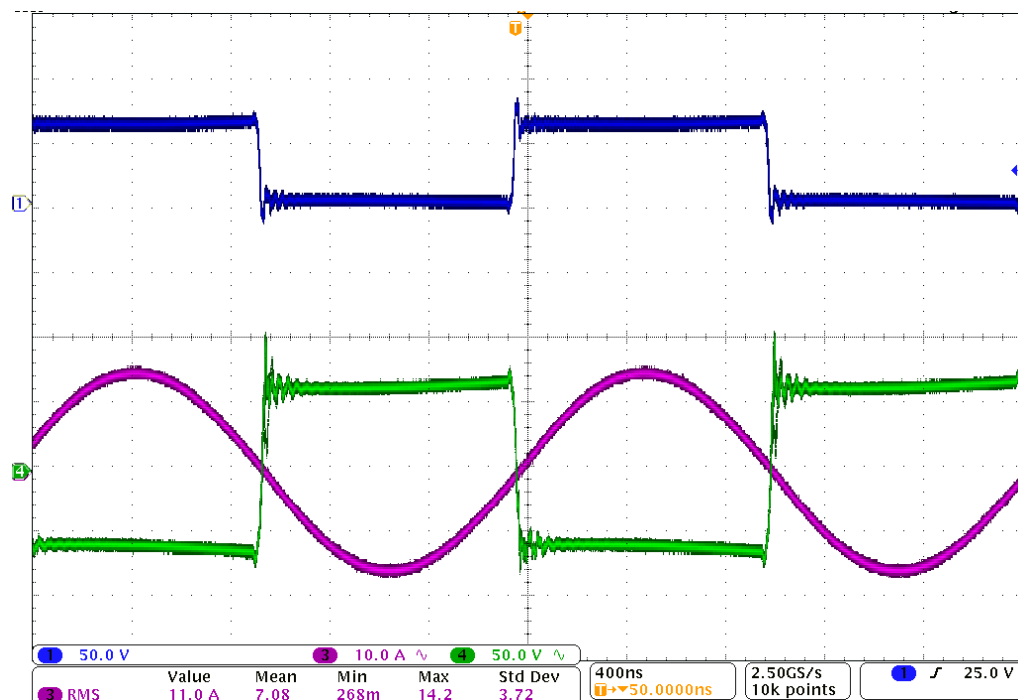


Fig. 46 Output voltage and current with load and 60V input

We couldn't push the power higher as the capacitors mounted on the induction coil were failing. However, the inverter remained cool and no issues were found

After replacing the capacitors of the transformer, we measured the turn on and turn off speed of the mosfets.

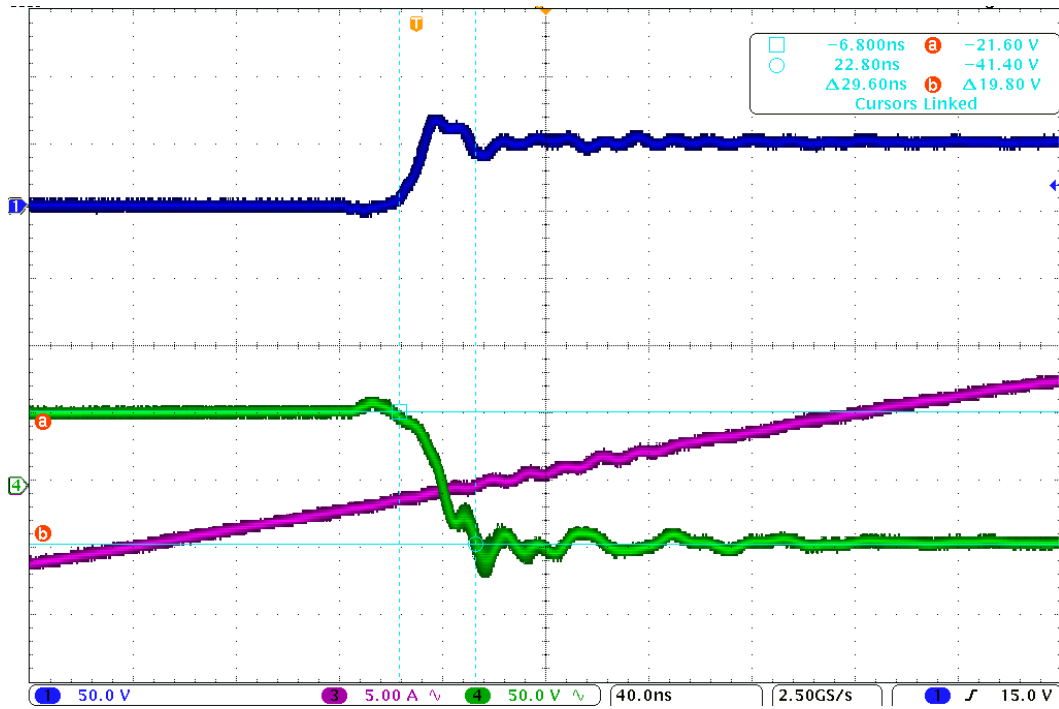


Fig. 47 Turn on time of the mosfet

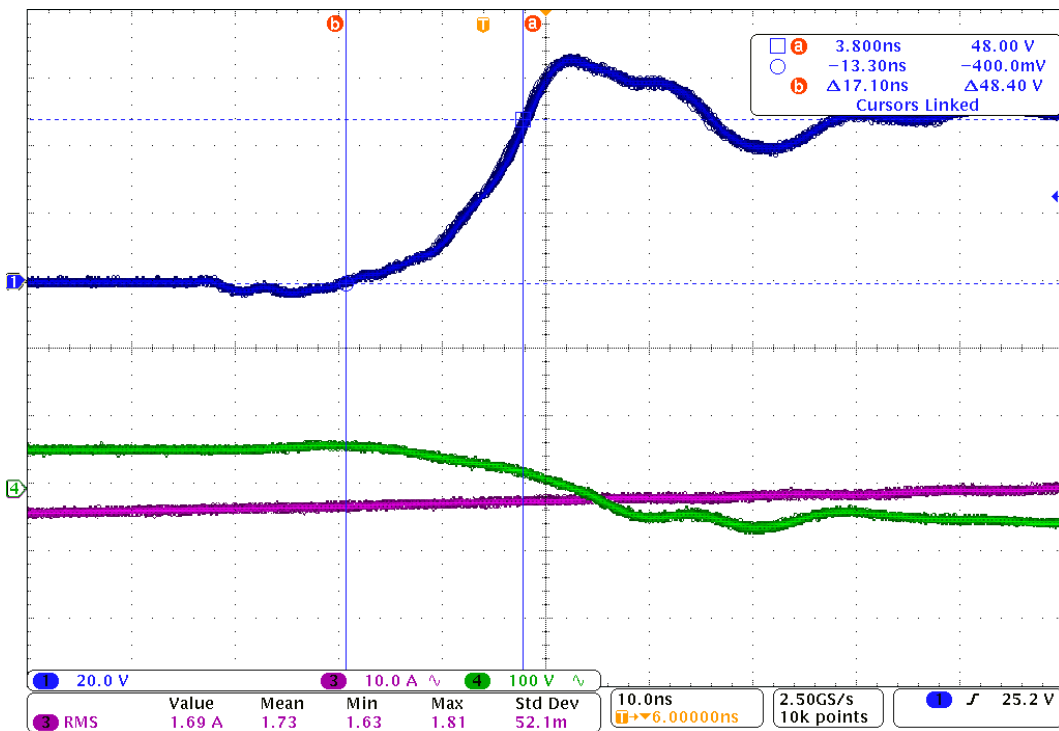


Fig. 48 Turn off time of a mosfet

The turn off time is measured at 17,1ns which is much slower than the 6ns advertised by the manufacturer.

5.5 Thermal behaviour

We couldn't get the heatsink that we planned to use. Instead we used a smaller heatsink in combination with a fan. The temperature of the inverter stayed cold and the induction transformer systematically failed first.

Conclusion

A presentation of nowadays technologies of wireless chargers and inverters. Followed by an overview of the possibilities of control. In the second, part we choosed the components to make the schematic. In the third part, we routed the *PCB* and soldered the components in the fourth. We finished with the observation and measurement of the inverter in operation.

The prototype is working is capable of delivering the specified maximum current and maximum voltage. The PCB is contained is the disered dimension while maintaining 94,2% efficiency at the power that was achieved during testing.

Some error were noticed and corrected on the prototype and on the design files. Because of those errors and the missing components, a corrected board needs to be manufatcured. However, it will provide a robust and practical platform for the continuation of the project.

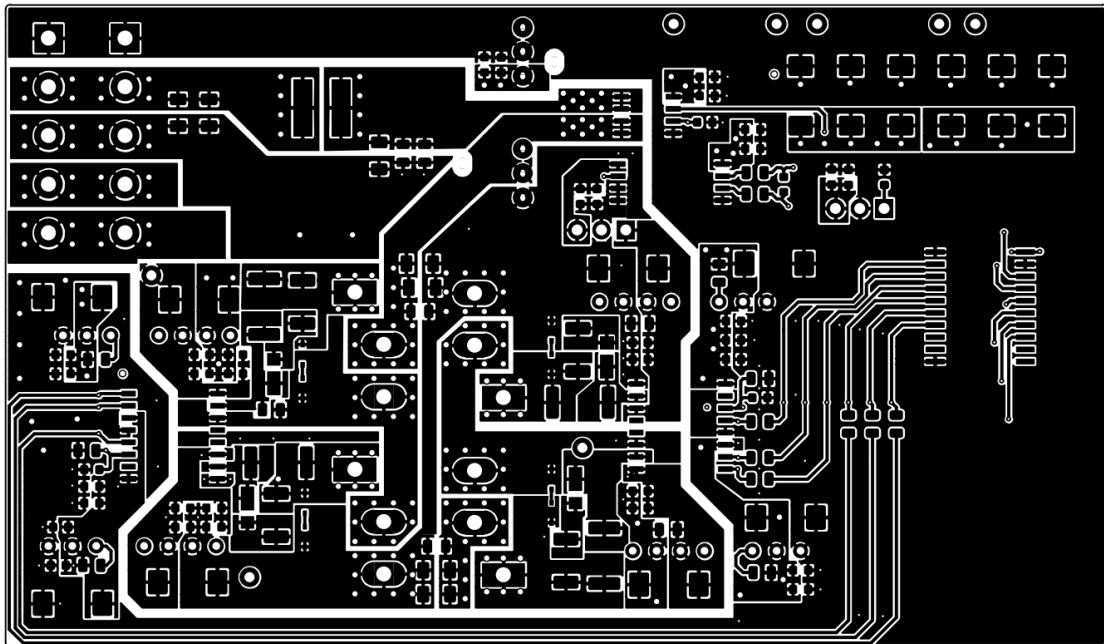
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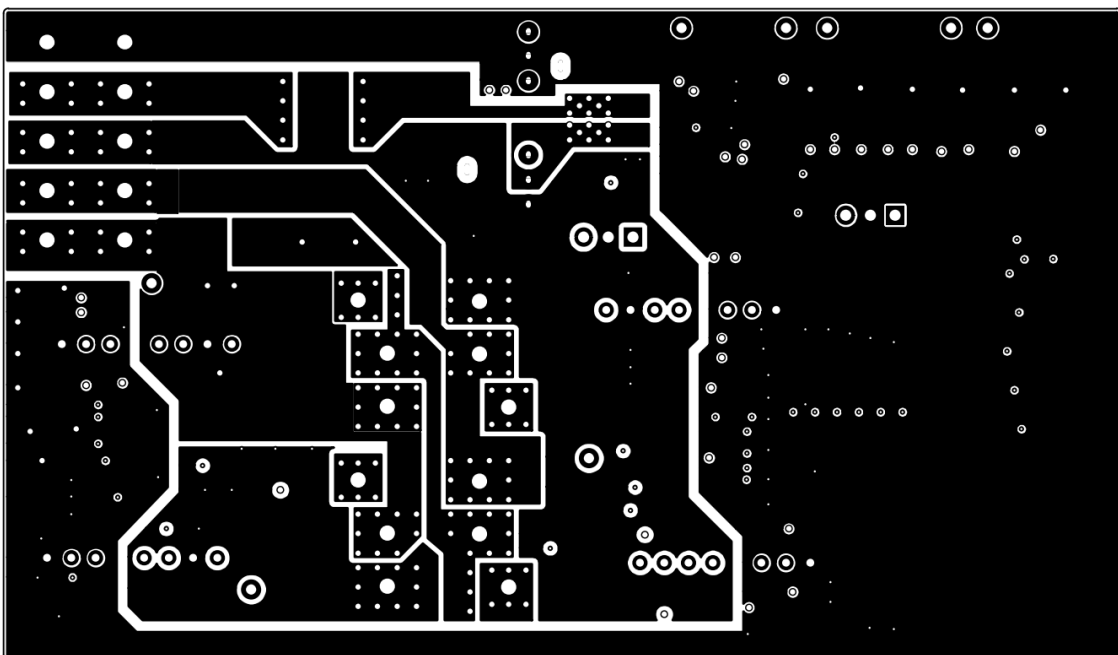
attachments

Attachment A – PCB.

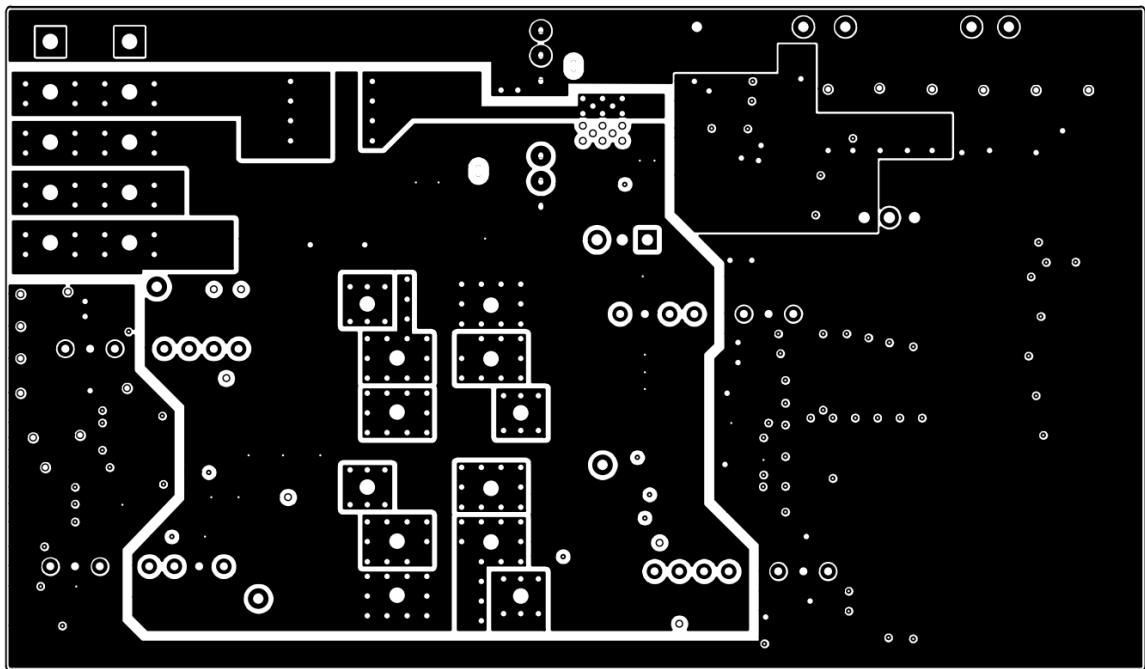
Top layer (close to heatsink)



Inner Layer 1



Inner Layer 2



Bottom Layer (close to Launchpad)

