DC/DC Power Supply Module Six

Dual Mosfet On-Off Switch

Application Report

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Contents

Abstract

On April 2023 I finish the design of this module. As you will notice while you advance in the document, there are many equations regarding to different topics with the purpose of showing the importance of design simulation and verification prior to manufacture.

This circuit will have the responsibility of isolate or connect the power supply to the input voltage among providing some extra protections. I take extra considerations on environment and temperature aspects in order to encompass as much extra variables as design stability I want to provide.

What is a Dual Mosfet On-Off Switch?

This type of circuit uses a specific configuration in its components to achieve similar characteristics of a Bidirectional Power Switch (BPS) [1].
A BPS has bidirectional current flow in the ON-state and bidirectional voltage block in the OFF-state as shown in Figure 1 and Figure 2.

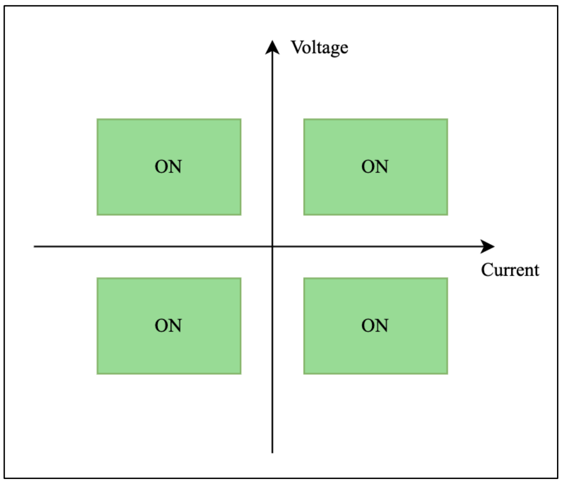

Figure 1. Characteristics in the ON State

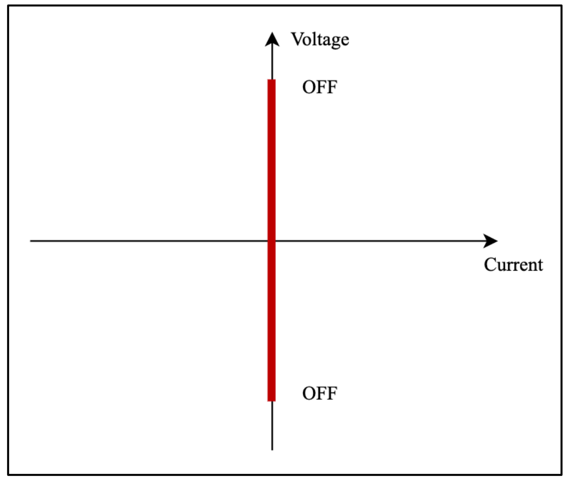

Figure 2. Characteristics in the OFF State

With the use of two P-Mosfets in a back-to-back configuration with common source connected together we can achieve symmetrical OFF-state blocking characteristics similar to BPS.
Figure 3 shows mosfet configuration.

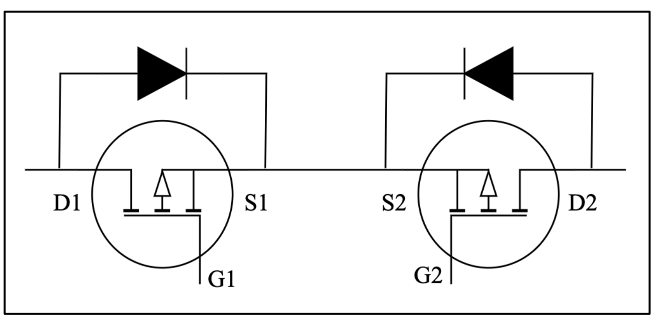

Figure 3 Mosfet Configuration

Module Characteristics

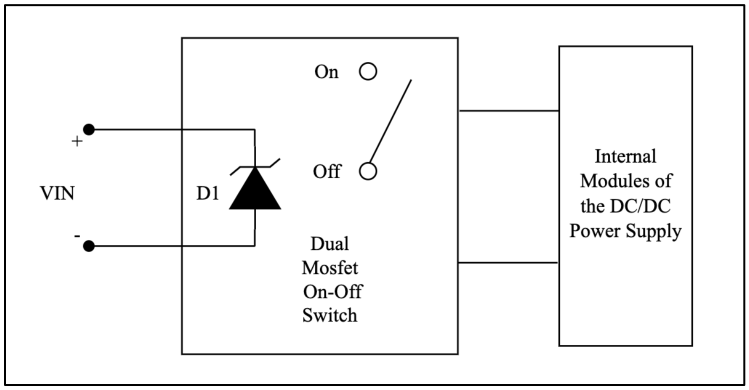

Figure 4 Module Function

VIN has a rated voltage of 12V and cannot be above 25V. Module is able to work with currents up to 6.5A. Figure 4 shows a diagram of his function.
In order to avoid reverse polarity protection, I've use two 4-pin male atx connectors (J1-J2).
A small SPST switch (S1) connects mosfet gates to GND allowing the power supply to be turned-on or off manually.

Overvoltage Protection

To protect internal modules from transient voltages, there is a unidirectional tvs diode (D1) LCE14A [2] connected across VIN and GND. This diode has the ability to provide a specific voltage level if a voltage spike occurs at the input of the circuit. I choose a unidirectional one instead of a bidirectional because VIN in the circuit is always positive.

The design contemplates the exposure to random non-repetitive exponential overvoltages with an amplitude of 100V (V_P) and a duration of 8ms (td) at 10% of peak voltage (standard wave - see Figure 6).

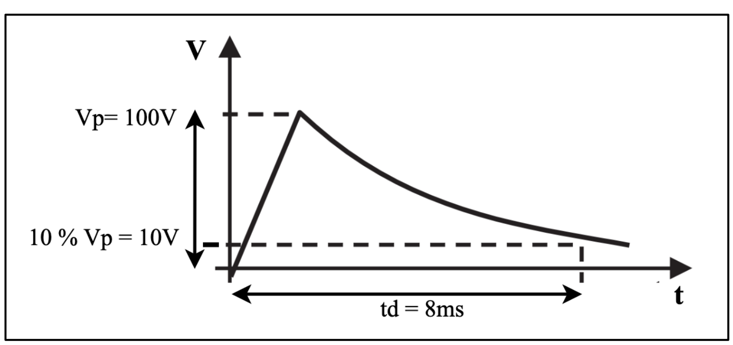

Figure 6 Surge

Now let's see all the math involved to show that the selected tvs can withstand those non repetitive overvoltages and protect the module from damage [3].
D1 characteristics are:
. V_R = 14V
. V_{BR} min = 15.60V
. V_{BR} max = 17.20V
. V_C max = 23.2V for I_{PP} = 65A at 10/1000 μs exponential waveform
. I_{PPM} = 65A
. Power capability: 1500W at 10/1000 μs exponential waveform

The equivalent internal impedance (Z) of the surge source is 5.5Ω and the maximum working temperature is 125°C. VIN cannot exceed 25V.

Tvs peak pulse power can be calculated using this formula:
$P_{PP} = V_C \times I_P$
$I_P = V_P - V_C / Z$ = 100V -23.2V / 5.5Ω = 76.8V / 5.5Ω = 13.96A
P_{PP} = 23.2V x 13.96A = 323.87W

We need to extrapolate the power to 125°C because diode datasheet specifies it at 25°C.
At 125°C power capability is around 68%, approximately 1020W according to diode datasheet graphic (see Figure 7) so ratio is 1020W/1500W = 0.68

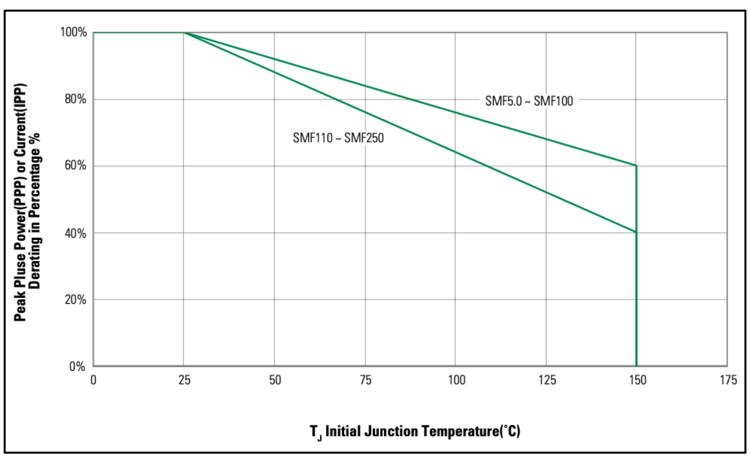

Figure 7 Peak Pulse Power Derating Curve

In order to estimate t_p value, we need to define pulse duration. This type of pulse match most of the standards used for the protection device. Duration time is defined at 50% of exponential peak current through tvs diode when surge is applied (see Figure 8).

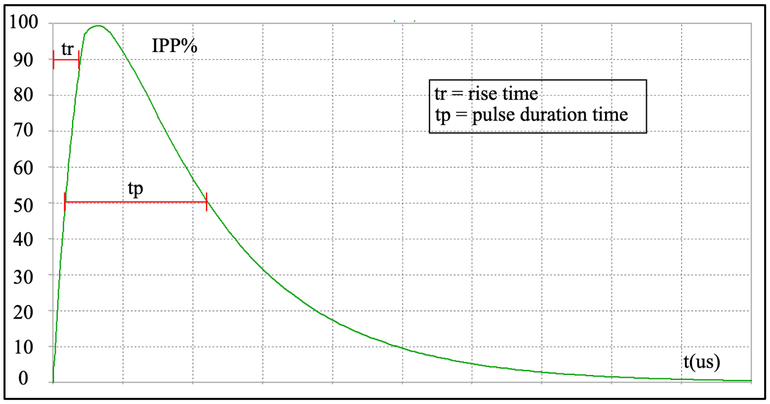

Figure 8 Pulse Definition for Electrical Characteristics

Based on td definition on Figure 6, for terms of simplification we are going to consider only exponential decreasing voltage using this equation: $v(t) = V_p \times e^{-t/\tau}$

Now we can calculate the constant time Tau (τ) using these equations:
$v(td) = 10\% \times V_p = V_p \times e^{-td/\tau}$
$\tau = -\ td / \ln 0.1$
$\tau = -\ 8ms / \ln 0.1 = 3.47ms$

When surge is applied to tvs diode the current flow through it only when v(t) is higher than his voltage breakdown V_{BR}. Current formula is given by this equation:
$i(t) = (v(t) - V_{BR}) / Z = (V_p \times e^{-t/\tau} - V_{BR}) / Z$

Next, tp value can be obtained using these equations:
$i(tp) = (V_p \times e^{-tp/\tau} - V_{BR}) / Z$
For tp value, $i(tp) = I_p / 2$ so, $i(tp) = I_p / 2 = (V_p \times e^{-tp/\tau} - V_{BR}) / Z$
$tp = -\ \tau \times \ln(((Z \times (I_p / 2)) + V_{BR}) / V_p) = -3{,}47ms \times \ln(((5.5\Omega \times (13.96A / 2)) + 17.2V) / 100V) = -3{,}47ms \times \ln(0.555) = 2.04ms$

Last step is calculating the clamping voltage at 2.04ms using this equation [4]:
$V_C = (I_P / I_{PP}) \times (V_C \max - V_{BR} \max) + V_{BR} \max = (6.98A / 65A) \times (23.2V - 17.2V) + 17.20V = 0.107 \times 6V + 17.2V = 17.84V$.

Finally, is necessary to adjust this value at maximum working temperature (125°C) using this equation: $V_C(T_j) = V_C(25°C) \times (1 + \alpha T \times (T_j - 25°C))$ with αT = temperature coefficient. For Littlefuse 1.5KE series typical value is 0.1%.
$V_C(125°C) = 17.84V \times (1 + (0.1 / 100) \times (125°C - 25°C)) = 17.84V \times 1.1 = 19.62V$

Using this equation, we can get peak pulse power of the diode at 2.04ms:
$P_{PP} = V_C \times I_P = 17.84V \times 6.98A = 124.52W$

This value is obtained at 25°C, we have to consider maximum working temperature (125°C), so applying the derating for the temperature $P_{PP} = 124.52W \times 0.68 = 84.67W$.

After getting these results we can see that selected tvs diode LCE14A is appropriate for this scenario in terms of power capability and, during surges the clamping voltage will be below 25V.

Voltage and Thermal Considerations

Let focus first on Vgs voltage of the mosfets (Q1-Q2) IRF5305PBF. Based on their datasheet [5], maximum value cannot exceed +/- 20V. To ensure it doesn't go beyond these limits, there is a Zener diode (Z1) connected across the source and the gates. I've decided to use a 10V 1W 1N4740A [6].

There are two resistors R2 and R3 (CMF55 model) [7] connected in series at the gate of the mosfets, so current across them will be the same. By having the clamping voltage (V_C) of the tvs diode in an overvoltage scenario, we can calculate the maximum current across them and on the zener diode.
We know that the clamping voltage will be 17.84V. Using this equation, we have:
$I_{R2} = I_{R3} = I_{R2/3} = ((V_C - V_{Z1}) / 2) / R_{2/3} = ((17.84V - 10V) / 2) / 200\Omega = 0.02A$ with V_{Z1} the voltage of the zener diode.
The power dissipated by the resistors will be $P_{R2/3} = I_{R2/3}^2 \times R_{2/3} = 0.02^2A \times 200\Omega = 0.08W$. We are using 0.5W resistors so in case of an overvoltage they will tolerate it without damage.

Note that this applies up to 70°C. Based on resistors datasheet, at 125°C wattage specified down to 0.25W. At this temperature current across the resistors will be 0.049A ((19.62V / 2) / 200Ω) and power equals to 0.48W exceeding resistor maximum specifications.

A resistor (R1) connected in parallel with the zener diode, it's used to shut-down the mosfets if the gates are left floating.
Current across the resistor will be: $I_{R1} = V_{Z1} / R_1 = 10V / 2000\Omega = 0.005A$ with V_{Z1} voltage of the zener diode.

Maximum zener current is given by the equation: $I_{Z1\ max} = P_{Z1\ max} / V_{Z1} = 1W / 10V = 0.1A$, with $P_{Z1\ max}$ the maximum power the diode can dissipate.
In an overvoltage scenario, using this equation we can get diode current: $I_{Z1} = I_{R2/3} - I_{R1}$. We already calculate $I_{R2/3}$ and I_{R1}, so $I_{Z1} = 0.02A - 0.005A = 0.015A$. Power dissipation on Z1 will be: $P_{Z1} = V_{Z1} \times I_{Z1} = 10V \times 0.015A = 0.15W$.
With this value we can confirm that power on zener diode will be below its maximum specification according to datasheet derating temperature curve on Figure 9.

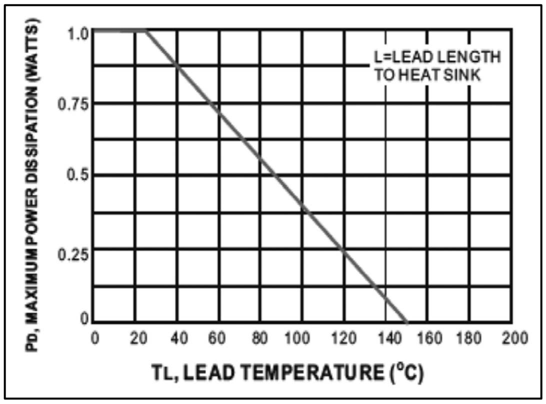

Figure 9 Temperature Derating Curve

Mosfets, uses each one a heatsink in order to provide an efficient path for heat to be transferred into ambient air. The heatsinks I decided to use are 530714B00000G with a thermal resistance of 20.3°C/W [8].

Between each mosfet and the heatsink there's a thermal pad in order to provide a better interface for the heat to transfer into the heatsink. I use 53-78-1ACG pads [9].

Let's make all the calculations to show mosfets junction temperature is below its maximum value when working up to 6.5A.

According to mosfet datasheet we have:
. I_D = -31A (continuous drain current at 25°C)
. $R_{DS(on)}$ = 0.06Ω (Static Drain-to-Source On-Resistance)
. P_D = 110W (power dissipation at 25°C)
. T_J = 175°C (maximum junction temperature)

Effective temperature differential [10] is given by $\Delta T = P \times \theta$ with:
. P = total device power dissipation (W)
. θ = total thermal resistance (°C/W)

Junction temperature is given by: $T_J = T_A + (P \times \theta_{JA})$ with:
. T_A = ambient temperature
. θ_{JA} junction-ambient thermal resistance.

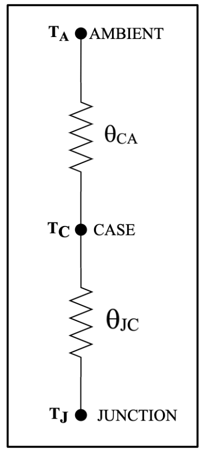

Figure 10 Thermal Relationships

$\theta_{JA} = \theta_{JC} + \theta_{CA}$ as we show in Figure 10 with:
. θ_{JC} = junction-case thermal resistance
. θ_{CA} = case-ambient thermal resistance

As we are using heatsinks $\theta_{CA} = \theta_{CS} + \theta_{SA}$ with:
. θ_{CS} = case-sink thermal resistance
. θ_{SA} = sink-ambient thermal resistance

So, $\theta_{JA} = \theta_{JC} + \theta_{CS} + \theta_{SA}$

Replacing θ_{JA} gives us $T_J = T_A + (P \times (\theta_{JC} + \theta_{CS} + \theta_{SA}))$

On mosfet datasheet θ_{JC} is given, θ_{CS} is the thermal resistance of thermal compound/pad and θ_{SA} is thermal resistance of the heatsink given by manufacturer datasheet.
Looking in thermal pad datasheet I realize thermal resistance is not given but thermal conductivity. Having the thickness and the dimensions of the pad we can get the thermal resistance (R) using this equation: $R = L / k$ with:
. k = thermal conductivity (W/m°C)
. L = thickness (m)

In datasheet we have:
. thermal conductivity = 0.92W/(m°C)
. thickness = 0.15mm
. dimensions = 22.098mm x 15.748mm

Introducing all the thermal pad information in the equation give R = 0.00015m / 0.92 W/(m°C) = 0.00016 m^2 °C/W.

If we have 1cm^2 of thermal pad it's thermal resistance will be 1.6°C/W, so translating to our pad dimensions, thermal resistance is 0.46°C/W.

Mosfet power dissipation will be $P = I^2_{DS} \times R_{DS(on)} = 6.5^2 A \times 0.06\Omega = 2.535W$ up to 35°C.

On datasheet θ_{JC} = 1.4°C/W and ambient temperature inside the enclosure will go up to 35°C, so with all thermal's resistance information we have:
T_J = 35°C + (2.535W x (1.4°C/W + 0.46°C/W + 20.3°C/W)) = 35°C + (2.535W x 22.16°C/W) = 91.18°C.

With this result we can see that mosfet junction temperature will not be exceeded when working up to 6.5A. Ambient temperature inside the case will rise up to 35°C due to a dc fan always turned on. If the fan fails, the temperature control module will set off an alarm to warn there's an error with the fan.

Circuit Simulation

For simulation I decided to use a step voltage from 9V to 14V having in mind that VIN is rated 12V. This allows to see interesting characteristics in certain voltages that other way we weren't able to see.

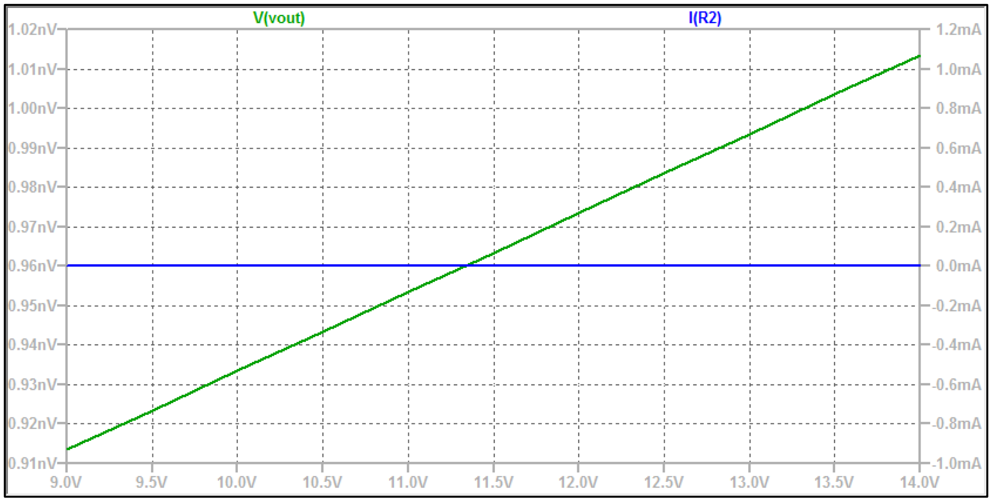

Figure 11 Circuit in OFF State

Figure 11 shows voltage output (green line) and R2 gate resistor current (blue) when circuit is in the off state (switch S1 is open). As you can see, there's no voltage at the output considering that 1nV is practically negligible in our context. Same happens with current on R2, graphic shows there's no current when switch is open.

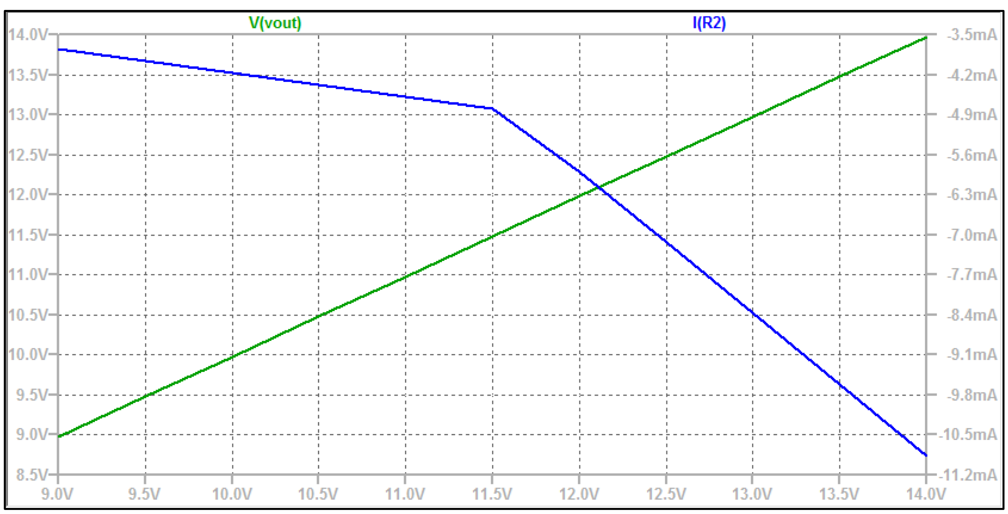

Figure 12 Circuit in ON State

Now, when switch S1 is closed, we have voltage at our output (green line) as it shown in Figure 12. When gate voltage of the mosfets are above its minimum threshold, current start to flow and

the resistance between drain and source has a very low value, that's why relationship between VIN and VOUT is almost linear.
Gate resistors current (blue line) at VIN = 12V is given by the equation: $((VIN - V_{Z1}) / 2) / R$ with V_{Z1} voltage of the zener diode and R the value of gate resistors.
It's important to notice that V_{Z1} is not exactly 10V as you were expecting, instead based on diode datasheet we can see that at 10V the diode has an impedance $Z_{ZT1} = 7\Omega$ and $I_{ZT1} = 0.25A$. Voltage is given using this equation: $V_{Z1} = V_{Z0} + I_{ZT1} \times Z_{ZT1} = 9.5V + 0.25A \times 7\Omega = 9.675V$ with V_{Z0} = min V_{Z1}.
Now having V_{Z1}, gate resistors current is: $((12V - 9.675V) / 2) / 200\Omega = 0.0058A$.

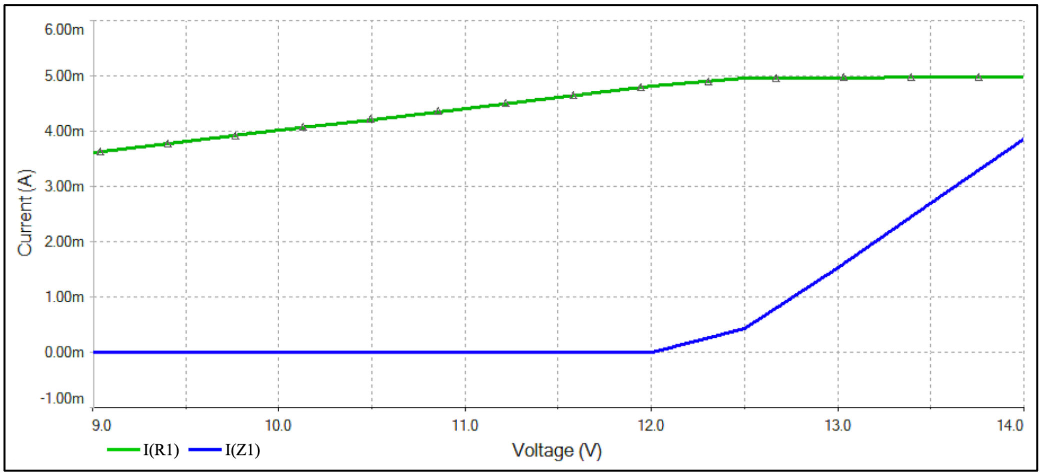

Figure 13 Resistor and Zener Diode Current

Figure 13 shows a graphic with R1 (green line) and Z1 (blue line) current according to VIN. You may ask why zener current up to 12V remains close to 0A. Same as we calculate on section (see Voltage and Thermal Considerations) current on Z1 can be obtained by: $I_{Z1} = I_{R2/3} - I_{R1}$.
At 12V current on R1 is: $I_{R1} = V_{Z1} / R_1$. Voltage on Z1 as we explain in the last point has a value of: $V_{Z1} = 9.675V$ so $I_{R1} = 9.675V / 2000\Omega = 0.0048A$.
$I_{R2/3} = ((VIN - V_{Z1}) / 2) / R_{2/3} = ((12V - 9.675V) / 2) / 200\Omega = 0.005A$.
Finally, we can see that $I_{Z1} = 0.005A - 0.0048A = 0.0002A$.
You may notice also that above 12V current on Z1 increases and current on R1 remain constant. That's because as VIN increases, zener current start to increase also as a consequence of lowering its resistance Z_{ZT1} in the same extent, leading to V_{Z1} remaining constant.

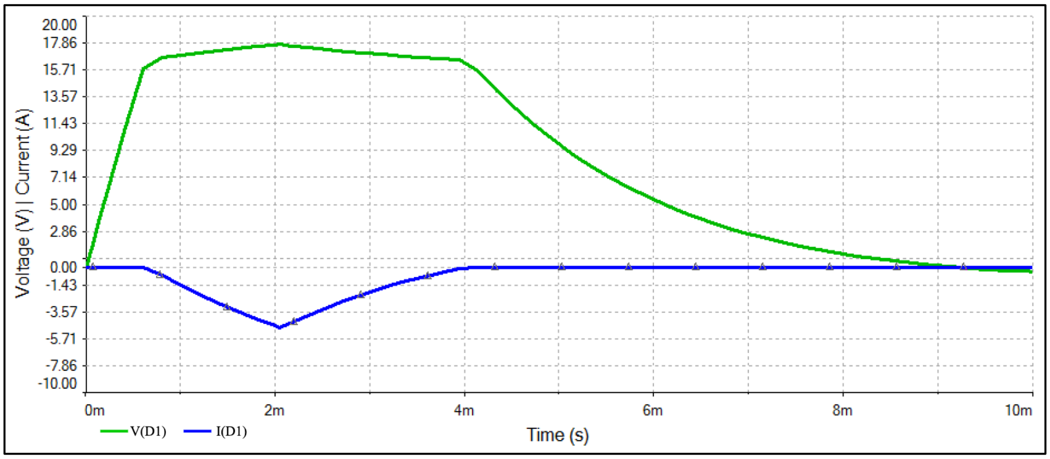

Figure 14 Diode Voltage Response to Surge

In the first part of the document, we analyze and verify the transient response of the tvs diode D1 against a surge (see Overvoltage Protection). Figure 14 shows a graphic with voltage clamp of the diode (green line) when the surge is applied. Notice that the peak voltage at 2.04ms has the same value as the one calculated at 25°C (17.84V).

You may realize that the peak current value (blue line) has not the same value as the one we use to calculate the clamping voltage of the diode at 2.04ms (6.98A). This happened for using an average diode resistance because datasheet doesn't include it, leading to have a difference in peak current value.

In summary, the voltage clamp obtained is under 25V and the peak current value is bigger than the simulation output. This brings confidence that the circuit will behave as expected in the case of an overvoltage.

Conclusions

After finishing the assembly and testing of the module, I consider this design will offer all the basic capabilities and protections that are needed to turn on and off the power supply.

Encompassing different scenarios let me include additional protections to make a more stable design against unwanted changes that could happen in the environment.

References

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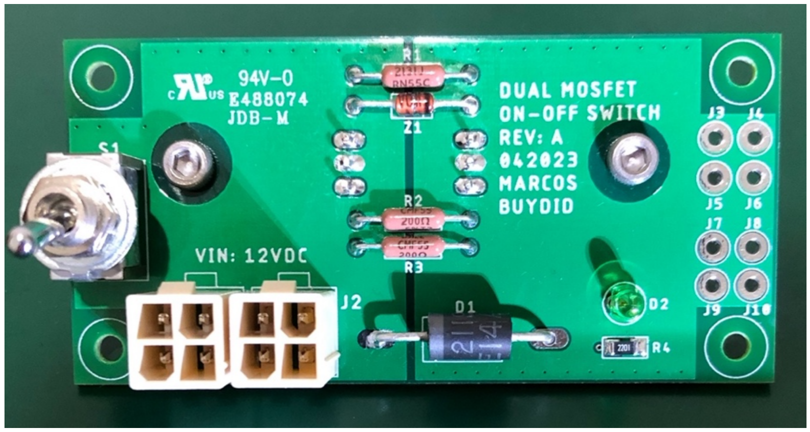
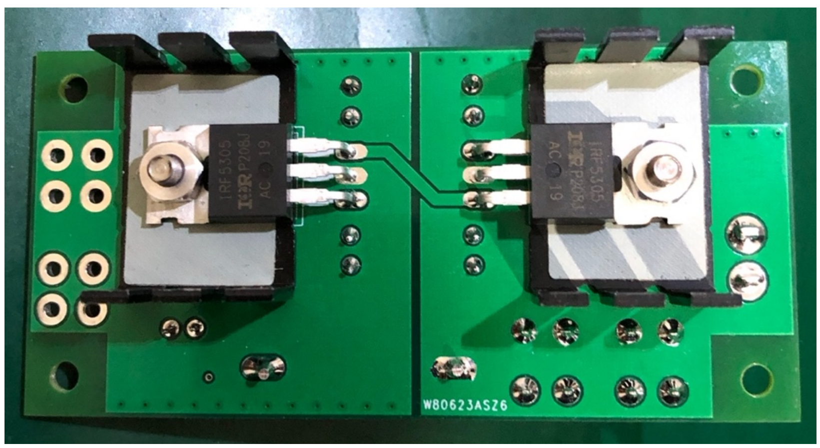
Annexes

Finish Assembly Photos



Module Front View



Module Back View

Revision History

Date	Version	Changes
Nov-2023	1	First version