Vishay Application Note: 800 VDC 50 A bidirectional eFuse

By Mustafa Dinc, Eckard Eikelmann, Manfred Kopp and Leonard von Hagen

1. System Description

With the steady increase in high voltage eMobility applications semiconductor-based resettable fuses are quickly replacing mechanical relays and contactors as well as traditional non-resettable fuses. The eFuse concept is an innovative new trend for protecting both the user and the hardware in high power applications. In a new reference design by Vishay, an eFuse featuring SiC MOSFETs and a VOA300 optocoupler was designed to handle continuous power up to 40 kW. It has been designed to operate continuously at full power with less than 25 W of losses without requiring active cooling. The design features a preload function, continuous current monitoring and overcurrent protection. Shutting down after a fault only takes 2.5 µs.

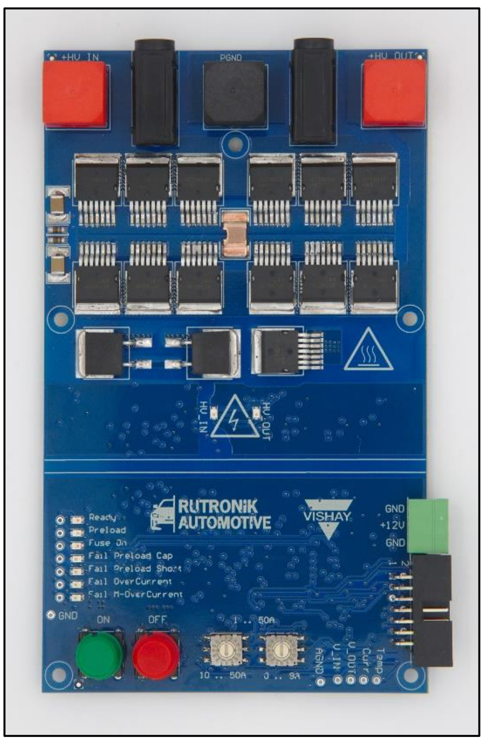

Figure 1: Vishay eFuse 800 VDC 50 A (Top View)

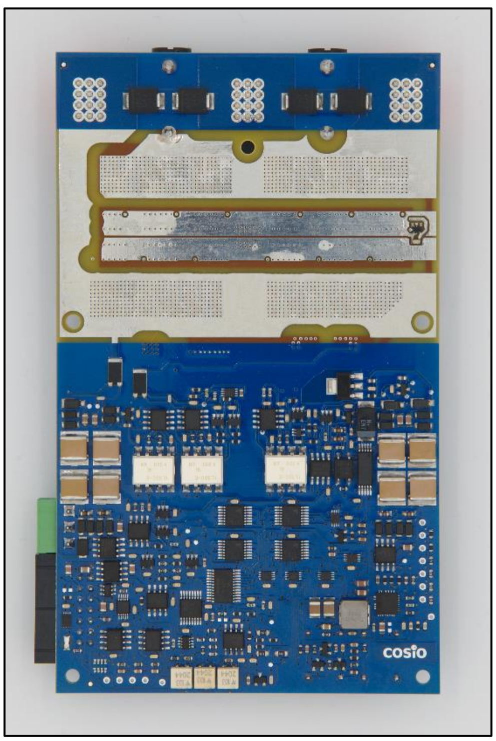

Figure 2: Vishay eFuse 800 VDC 50 A (Bottom View)

The Vishay eFuse has been designed to safely connect and disconnect a high voltage power source (typically a high energy battery pack) to any type of vehicle load using SiC MOSFETs as the primary switches, which can operate up to 50 A continuously.

If the current exceeds a pre-determined limit the load is quickly disconnected from the battery pack to protect both the battery pack and the user. The eFuse can also detect excessive load capacitance or a short circuit during power-up and immediately shutdown.

The eFuse is constructed using a standard double-sided four-layer PCB (FR4) with 70 µm thick copper for each layer. The overall dimensions of the PCB are 150 mm × 90 mm with some extension of the connectors beyond the edges.

The high voltage circuitry (12 × SCT4020 SiC MOSFETs) is in the upper part of the PCB. The low voltage control circuitry with the connectors, control buttons, status LEDs and multiple test points is in the lower part of the PCB. In addition, the eFuse can be controlled remotely using a web browser that will described in more detail later in this application note.

The heat generated by the SiC MOSFETs is transferred to the bottom using thermal vias to a solid layer of copper and then to a heat sink which is electrically isolated from the high voltage.

The three sockets for the high-voltage connections are included in the demo kit and cables with a cross section of 16 mm^2 must be crimped into a suitable connector. If needed, connectors for wires with a cross section of 4 mm^2, 6 mm^2 or 10 mm^2 are available.

The high voltage power source must be connected to the <+HV_IN> socket and the load to the <+HV_OUT> socket. The <PGND> terminal serves as a reference point for the voltage measurement as well as a discharge path for voltages exceeding the specification.

The control section of the PCB must be supplied with an external voltage source between 10 V – 16 V and requires approximately 60 mA of current (170 mA – 210 mA if an external controller is connected). The power supply on the PCB is protected against a reverse polarity connection.

The low voltage power supply must always be enabled first and then the high voltage power supply on the input. For safety reasons an LED will illuminate as soon as the voltage at the input terminal exceeds 50 V.

2. Principle Diagram

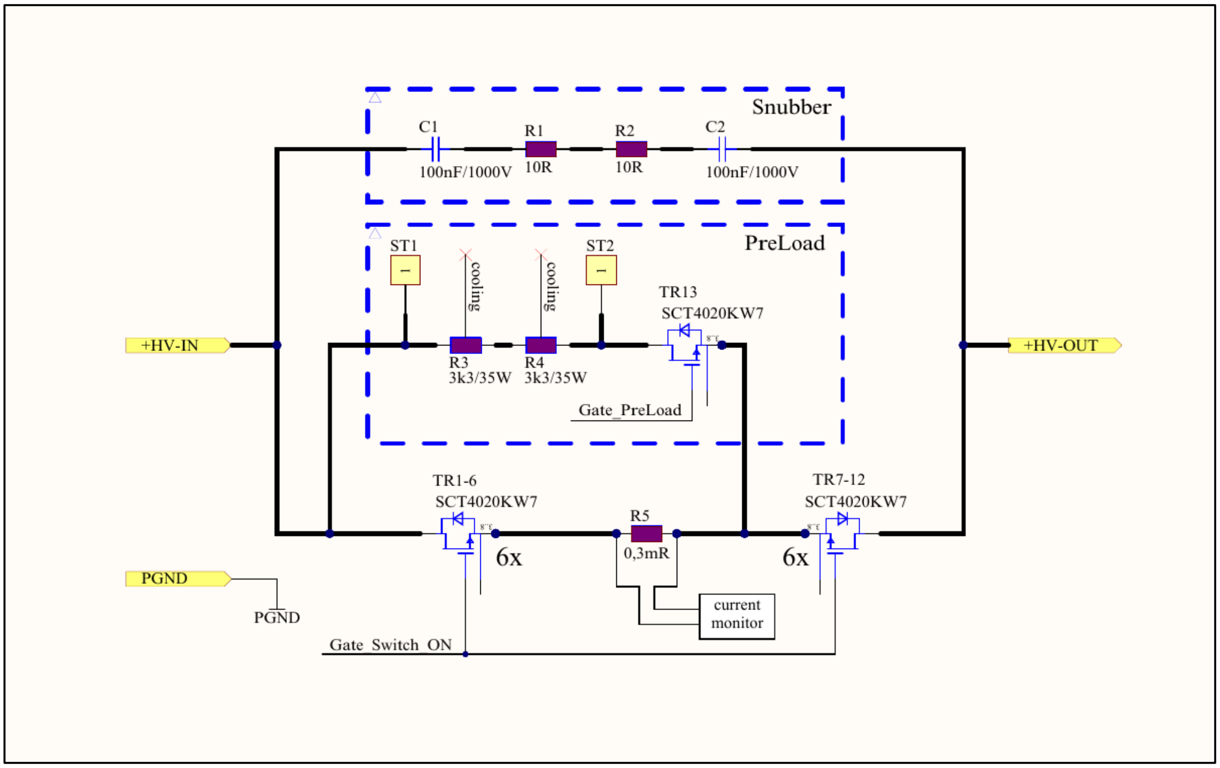

Figure 3: Overview of the High Voltage Side

The eFuse must be able to switch currents that are flowing in either direction. Therefore, two sets of six parallel-connected SiC MOSFETs (TR1-6 and TR7-12) are connected in a back-to-back configuration. The load current is measured using a Vishay WSLP3921 Current Sensing Shunt Resistor that is located between the two sets of MOSFETs.

The preload function is carried out by a single MOSFET (TR13) and two thick film resistors (R3,4) in a D^2PAK package (see section 3.1 for more details). Note, that there is no preload function for currents flowing from <+HV_OUT> to <+HV_IN>.

To prevent high voltage transients during switching the MOSFETs are bypassed with a double RC snubber (see Figure 3). Vishay VJ OMD ceramic capacitors and Vishay MMB 0207 power resistors are used for this purpose.

3. Voltage isolation

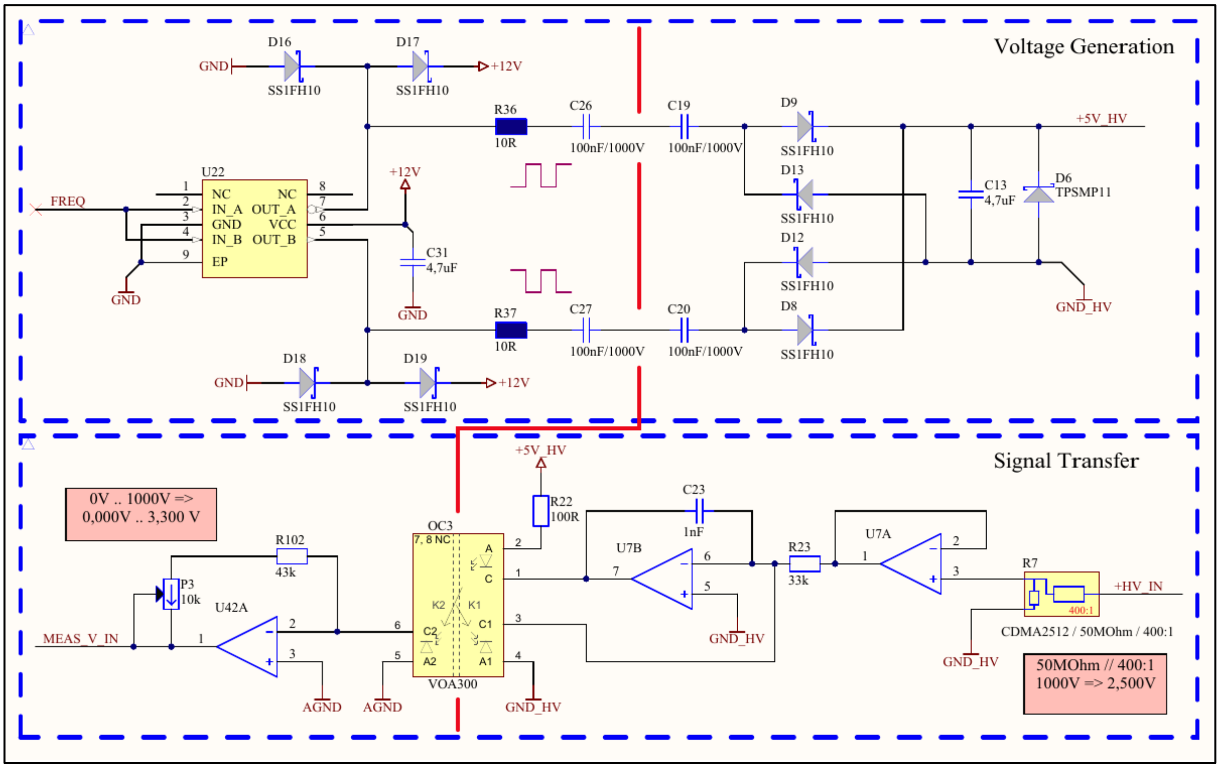

Figure 4: Connections between High Voltage and Control Side

The components on the high voltage side must receive voltage from the low voltage control side and they must be galvanically isolated from each other for safety purposes. Therefore, two AC voltages of 0 V – 12 V are created on the control side using a 200 kHz switching frequency. This energy is transferred capacitively via two capacitors across the isolation barrier to the high voltage side where it is rectified back to the original supply voltage level. Vishay VJ OMD ceramic capacitors were used for this purpose, as they have optimal properties for this application (see section 3.4 for more details).

When transmitting the voltage and current measurements between the high voltage and low voltage side the galvanic isolation must also be maintained. For this purpose, the high voltages are first scaled down using a Vishay CDMA 2512 integrated voltage divider by a factor of 400:1 and transmitted with minimal delay to the control side using the Vishay VOA300 high speed optocoupler.

3.1. Linear Optocoupler: Vishay VOA300

The VOA300 is a linear optocoupler designed for automotive applications. Due to the bifurcated arrangement of the two photodiodes, the non-linear behavior of the internal LED can be optimally compensated. Therefore, the signal typically drifts during operation by only ± 0,005 %/°C. The optocoupler is particularly suited for measurement applications (e. g. voltage and current sensing), as the signals can be transmitted directly across the isolation barrier.

In addition, because of the low capacitance at the inputs and outputs, the optocoupler is also capable of transmitting digital signals up to 200 kHz.

The VOA300 is available in DIP-8 and SMD-8 packages. The internal isolation distance is 0.4 mm and the package allows for an external track clearance of 7 mm, which results in a continuous voltage isolation rating of 5300 V.

Figure 5: VOA300

3.2. Current Sense Shunt Resistor: Vishay WSLP3921

Since the eFuse must accurately measure the current in steady-state operation, a Vishay WSLP3921 Current Sensing Shunt Resistor was selected for this design. These resistors are fabricated from a single metal strip and are available in very low resistance values (down to 0.1 mΩ). This package allows for continuous high power dissipation (up to 9 W). The resistor is also available in the larger WSLP5931 package which can dissipate up to 15 W.

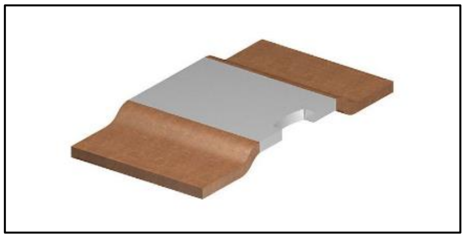

Figure 6: WSLP3921

3.3. Integrated Voltage Divider: Vishay CDMA 2512

A voltage divider is required to scale both the input and output voltages of the eFuse for measurement purposes. The Vishay CDMA 2512 Integrated Voltage Divider greatly simplifies this task. The chip is constructed from two thick film resistors and is available in the common 2512 package.

Because the two resistor elements are located in the same package, the ratio of the two values exhibits very little drift due to temperature changes (+ 50 ppm/°C) so that the measured value accurately represents the actual value. The divider is designed for voltages up to 1415 V and is available in several ratios (eight options ranging from 25:1 to 700:1).

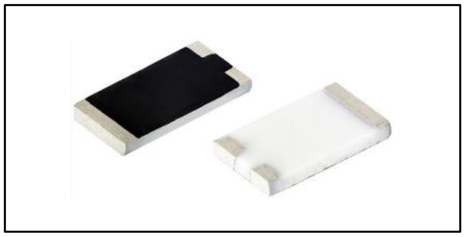

Figure 7: CDMA 2512

3.4. Ceramic Capacitor: Vishay VJ OMD X7R

The Vishay VJ OMD Ceramic Capacitors were used in the eFuse on both the high voltage side as well as between the isolation barrier for power transmission. These capacitors are specified for voltages up to 3000 V, can conduct AC with up to 1.2 A for short periods of time, and are available with values ranging from 10 pF through 1.8 µF.

Due to the capacitor's Open Mode Design (OMD), unlike conventional capacitors, the two terminals remain isolated from each other even in the event of a mechanical break in the package.

Figure 8: VJ OMD

3.5. Preload Resistor: Vishay D2TO35

During the preload operation, the eFuse momentarily connects a resistor between the high voltage input supply and the load. This resistor limits the power for the duration of the preload period to protect the power supply from either an excessive capacitive load or a short circuit condition. In this design, two Vishay D2TO35 Thick Film Resistors were used.

These resistors are available in many values between 10 mΩ and 550 kΩ and can continuously dissipate up to 35 W at operating voltages up to 500 V.

Due to the large metal pad on the back of the package, even more power can be absorbed for a short period of time. For the duration of the preload period (approximately 250 ms) the resistors are capable of handling up to 100 W.

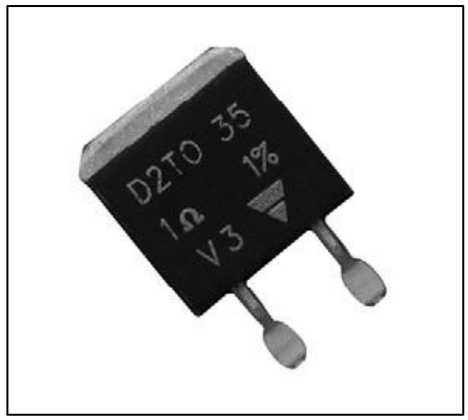

Figure 9: D2TO35

3.6. Pulse-Resistant Resistor: Vishay MMB 0207

In order to suppress transient voltage spikes which may occur due to the inductance of any high voltage cables that are connected to the eFuse, a dual snubber configuration using Vishay MMB 0207 Professional MELF Resistors was implemented.

The cylindrical construction of these MELF resistors provides excellent pulse load capability. Therefore, since it only takes a few microseconds for the snubber capacitors to charge through the resistors, and very little energy is absorbed during this time, the small 0207 package is suitable for this design.

Figure 10: MMB 0207

4. User Interface

The Vishay eFuse can be enabled/disabled using either the ON/OFF push buttons on the PCB or by an external controller. The current limit is manually adjustable within a range of approximately 1 – 50 A using either the two potentiometers on the PCB or the external controller.

The status of the system is displayed using seven LEDs on the PCB. As soon as the eFuse is supplied with power, the “Ready” LED indicates the unit is in a standby condition, and when the load is energized, the “Fuse On” LED illuminates.

There are several test points located on the top of the PCB to monitor the operation:

Table 1 – External Test Points

Test Point	Name	Function
TP1	+ 5.0 V	Internal Voltage + 5.0 V
TP2	E_PreLoad	Preload SiC MOSFET switched on
TP3	E_Switch_ON	Main SiC MOSFETs switched on
TP4	E_Fail_Pre_Cap	Error: Capacitance at the output too large
TP5	E_Fail_Pre_Short	Error: Short circuit at the output
TP6	E_Fail_OC	Error: Current exceeded the configured limit for an extended duration
TP7	E_Fail_MOC	Error: Current greatly exceeded the configured limit
TP8	DGND	Ground reference for TP2 through TP7
TP9	Meas_V_In	Voltage at <+HV_IN>, scaled to 0 V – 3.3 V: $<+HV\_IN> = <U\_TP9> \cdot \frac{1000\ V}{2.5\ V}$
TP10	Meas_V_Out	Voltage at <+HV_OUT>, scaled to 0 V – 3.3 V: $<+HV\_OUT> = <U\_TP10> \cdot \frac{1000\ V}{2.5\ V}$
TP11	Meas_Current	Measured current, scaled to 0.900 V – 2.400 V: $I = (<U\_TP11> - 1.650\ V) \cdot \frac{50\ A}{0.75\ V}$ Positive currents flow from <+HV_IN> to <+HV_OUT>, Negative currents flow from <+HV_OUT> to <+HV_IN>.
TP12	Meas_Temp	Temperature Measurement on the high-power side, the temperature can be calculated using $T\ [°C] = 421 - (751 \cdot T_H/T_L)$.
TP13	AGND	Ground reference for TP9 through TP12

The TP2 through TP7 are logic signals and active when in the high state. The names in the table refer to the names used in the schematics.

As mentioned, an external controller (for example the "Vishay MessWEB") can be connected to the eFuse via the 14-pin shrouded connector and can be used to control the eFuse and display additional information. When the external controller is connected, the current settings from the two potentiometers on the PCB are ignored.

5. Mode of Operation

The 12 MOSFETs are controlled by a gate driver to keep the switching times low, and the resulting current in the gate will be + 5 A maximum for a brief period of time during turn-on.

If an error occurs during operation of the eFuse, the load is disabled and the corresponding LED on the PCB is illuminated. The error is also indicated in the web interface when the MessWEB is being used, and the error must first be acknowledged using the red button (OFF) before the eFuse can be switched on again by the user.

5.1. Turn-On Procedure

The user can enable the eFuse by using either the green button (ON) or the web interface. To prevent high inrush currents during turn-on, the eFuse employs a two-stage preload function:

1. The eFuse is enabled.
2. The eFuse checks for excessive current in the load circuit (short circuit condition).
3. The eFuse checks for excessive capacitance in the load circuit to prevent a high in-rush current from the battery.
4. If both stages of the preload have been completed successfully, the load is energized by switching-on the main MOSFETs.

5.1.1. First Stage of the Preload

In the first stage of the preload, a resistor (6.6 kΩ, 70 W) is connected in series between <+HV_IN> and <+HV_OUT>. After 25 ms, the output voltage is measured to see if it is greater than 10 % of the input voltage. If the output voltage remains close to 0 V a short circuit condition exists in the load, the preload stage is terminated, and the error “Fail Preload Short” is displayed. During this first stage of the preload the power dissipation in the resistor is 152 W maximum, which is permissible for the short period of time.

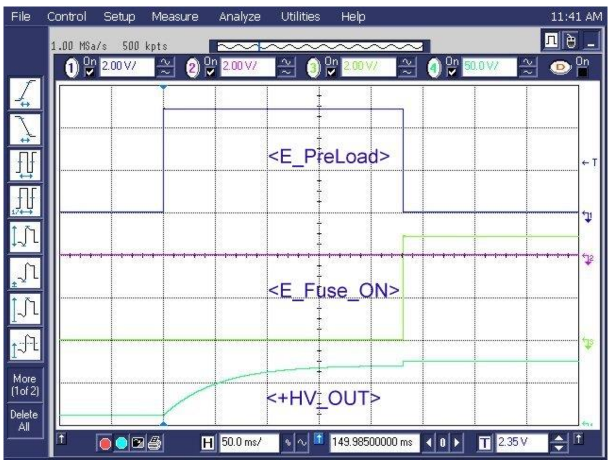

Figure 11: Successful Switch-On Procedure, First Preload Stage

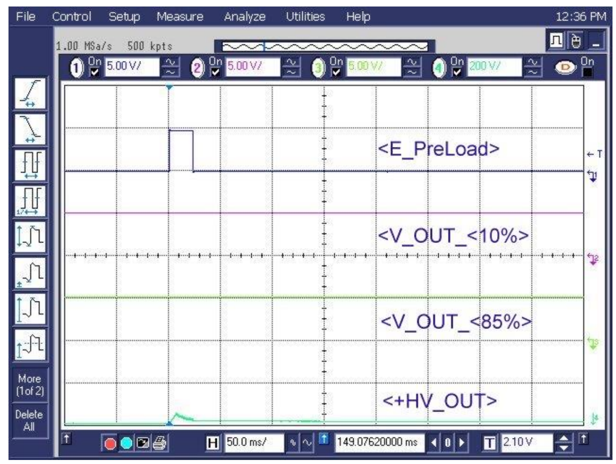

Figure 12: Switch-On Procedure Terminates During the First Preload Stage

In Figure 11, the eFuse was operated without any significant load connected. Before the system is enabled, the logic signal <V_OUT_<10%> indicates that the output voltage is still less than 10 % of the input voltage. After the system is enabled the output voltage <+HV_OUT> immediately reaches full voltage, and the logic signal <V_OUT_<10%> goes low to indicate the threshold being successfully reached and the load is energized.

In Figure 12, the output of the eFuse was shorted. The output voltage <+HV_OUT> increases only marginally after the system is enabled so the logic signal <V_OUT_<10%> stays high for the entire 25 ms period, and therefore, the preload is terminated.

5.1.2. Second Stage of the Preload

If the first stage is successful, the preload will be extended. During the second stage, the output voltage is measured after approximately 250 ms to see if it has risen to at least 85 % of the input voltage. If the total capacitance of the load is excessive the output voltage will not rise sufficiently, the preload will be terminated, and the error “Fail Preload Cap” is displayed.

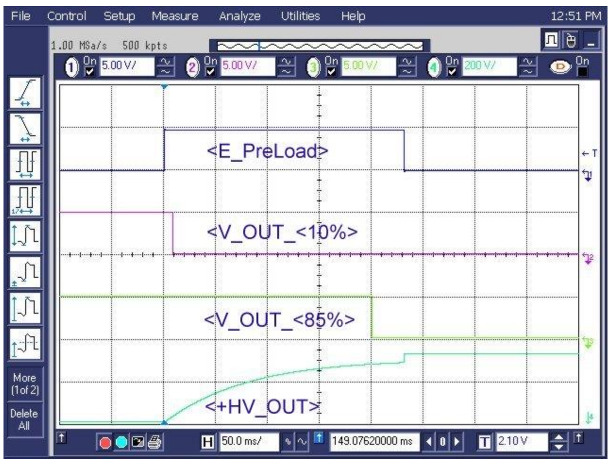

Figure 13: Successful Switch-On Procedure, Second Preload

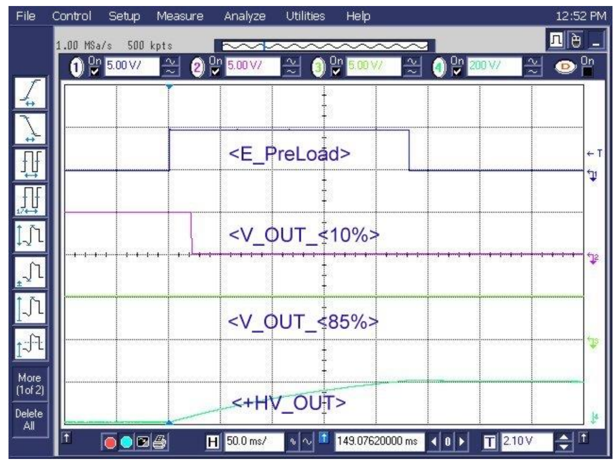

Figure 14: Switch-On Procedure Aborts During the Second Preload

In Figure 13, the eFuse was operated with a 4.4 µF capacitor connected to the output. The 85 % threshold of the input voltage is reached after a brief time, and the logic signal <V_OUT<85%> goes low to indicate the preload is successful.

In Figure 14, the eFuse was operated with a 47 µF connected to the output. The output voltage <+HV_OUT> rises very slowly and does not reach the 85 % threshold after 250 ms. Therefore, the logic signal <V_OUT_<85%> stays high for the entire duration, and the preload is terminated after approximately 250 ms.

The threshold for the maximum capacitance allowed is approximately 20 µF and is set by the series resistor. Another resistor can be connected between <ST1> and <ST2> (blade connections with a 4 mm diameter) to raise the threshold as follows: $1 - \exp(-\frac{250\ \text{ms}}{R \cdot C}) \geq 85\ \%$. When using an external preload resistor, it must have a similar power rating to the one used on the PCB.

WHITE PAPER

5.1.3. Turn-On after Successful Preload

If the preload stages have both been completed successfully, the 12 main MOSFETs will be switched-on. The MOSFET driver charges the gates of all the MOSFETs in parallel, and the time required for switching is approximately 1 µs.

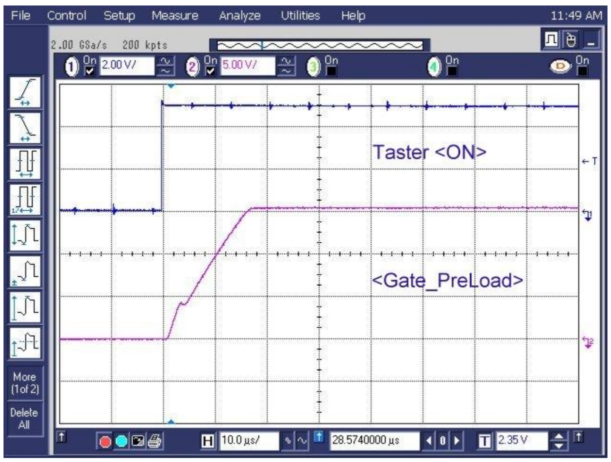

Figure 15: Switching on the Preload MOSFET

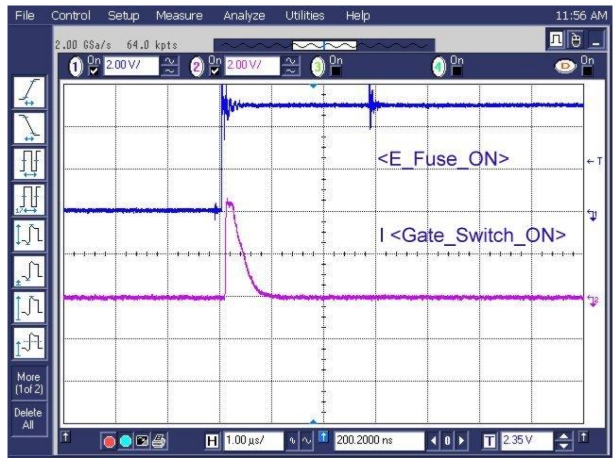

Figure 16: Switching on the Main MOSFETs

The turn-on procedure of the preload MOSFET is shown in Figure 15 which occurs immediately after pressing the <ON> button.

Once the preload has been completed, the logic signal <E_Fuse_ON> goes high and the main MOSFETs are switched-on (see Figure 16). The MOSFET driver current supplied to the gates is equal to the voltage across the 1 Ω series resistor (R19) of the gate driver and fully charges the gates within 1 µs to energize the load.

5.2. Turn-Off Procedure

The eFuse can be turned-off for various reasons:

- The user presses the red OFF button.
- The user uses the OFF button on the web interface.
- The adjustable current limit threshold is exceeded for over 300 µs, and a “Fail OverCurrent” error is displayed.
- The adjustable current limit threshold is substantially exceeded, and the load is assumed to have a short circuit.

5.2.1. Standard Turn-Off Procedure

When the eFuse is disabled (either by the user or due to an overcurrent situation) the MOSFET driver discharges the gates within 0.5 µs:

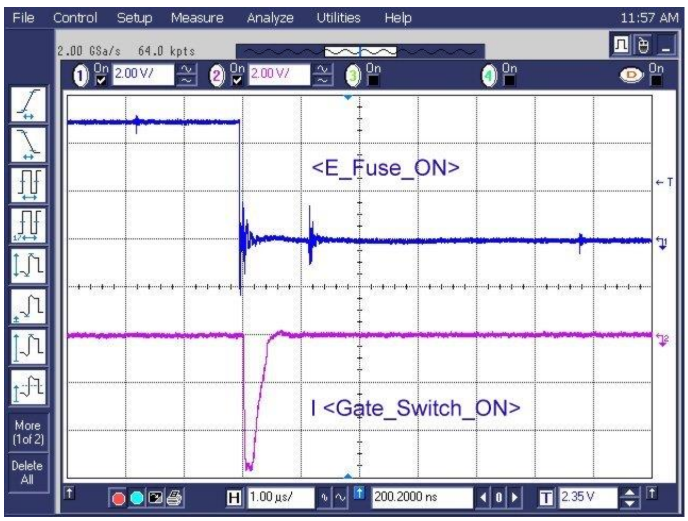

Figure 17: Switch-Off Procedure of the eFuse

In Figure 17, the eFuse was turned-off manually. The logic signal <E_Fuse_ON> goes low, and the MOSFET gates are discharged into the driver (as indicated by the negative current).

5.2.2. Turn-Off Procedure After a Short Circuit Condition

In addition to the adjustable current limit, another limit of 120 A has been hardcoded into the eFuse. If the load current exceeds this limit, the eFuse is immediately turned-off to protect the power supply. Afterwards, an error “Fail Massive OverCurrent“ is displayed.

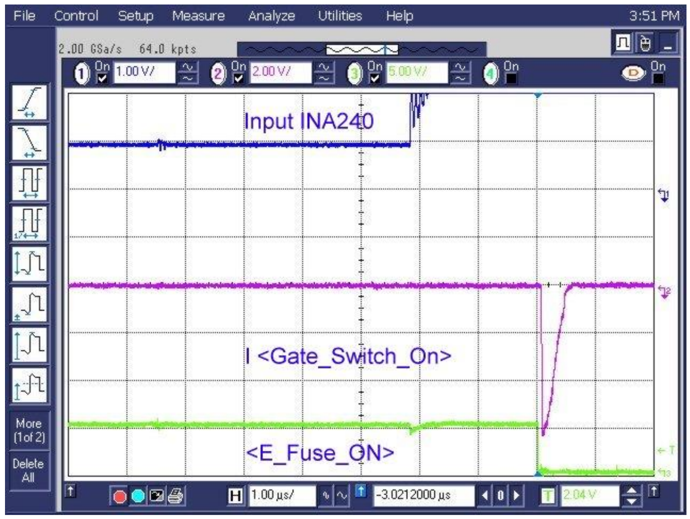

Figure 18: Switching Off after a Short Circuit Event

In Figure 18, a short circuit condition has been manually induced. When the current exceeds the 120 A limit, the voltage across the two inputs of the INA240 precision current sense amplifier exceeds the preset threshold (approximately 2 µs to detect this event) and the MOSFET gates are discharged within 0.5 µs.

The VOA300 high speed optocoupler, in conjunction with a precision current sense amplifier, allows for particularly fast detection and reaction to a short circuit condition and can disable the load within 2.5 µs.

5.3. Power Dissipation

The total resistance of the eFuse at 25 °C is composed of several components:

- The on-resistance of the MOSFETs: 2× 18 mΩ / 6 = 6 mΩ
- The shunt resistor for measuring the current: 0.3 mΩ
- The parasitic resistances of copper traces and connectors: 0.2 mΩ

Therefore, the total on-resistance is approximately 6.5 mΩ. With a continuous load current of 50 A the total power loss is approximately 18 W.

During continuous operation at a 25 °C ambient condition the temperature of the eFuse will increase to approximately 80 °C due to the internal power losses. As a result, the on-resistance of the MOSFETs increases to approximately 2× 24 mΩ / 6 = 8 mΩ, combined with similar increases in the copper traces and connectors due to the positive temperature coefficient, which causes the total power loss to increase to approximately 24 W.

To verify the calculations detailed above, the eFuse was operated with a continuous load current of 50 A, which resulted in the MOSFETs reaching a final temperature of 79.1 °C after 60 minutes. Therefore, the on-resistance increased by 33 % to 24 mΩ for each MOSFET.

Figure 19: eFuse including Heat Sink and Case

The power components on the PCB are passively cooled using a heat sink which measures 160 mm × 100 mm × 15 mm.

6. Thermal Operation

The integrated temperature sensor can be monitored at any time using the TP12 test point. The sensor is located at the center of the MOSFETs so it may display a lower temperature than the actual highest temperature on the PCB.

The actual temperatures on the PCB were captured using a thermal imaging camera (see section 6.2).

6.1. Temperature Measurement

The temperature measurement on the high-voltage side is transmitted as a PWM signal, and can be monitored at test point TP12:

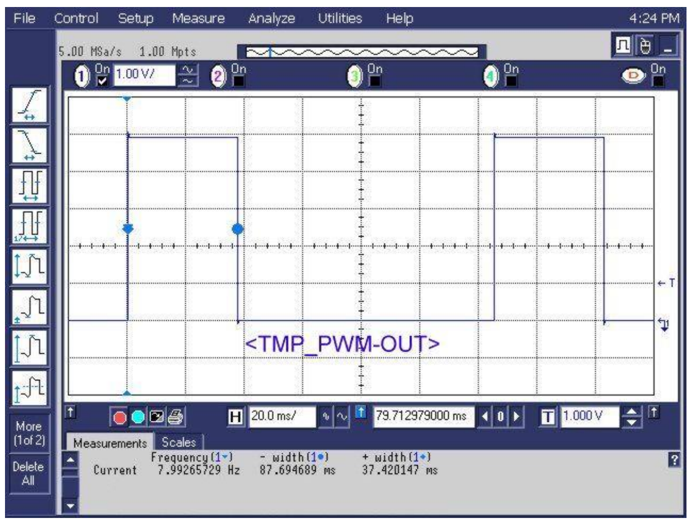

Figure 20: Temperature Measurement as seen at TP12

The temperature can be calculated from the duty cycle of the signal using the following formula:

$$T\ [°C] = 421 - (751 \cdot T_H/T_L)$$

In the example shown in Figure 20, the temperature measures 100 °C.

6.2. Thermographic Images

The eFuse was operated with various continuous load currents up to 50 A for 60 minutes using only the attached heat sink for passive cooling. The resulting temperature increase was monitored using a thermal imaging camera and the results are shown below. Even with a 50 A load current the maximum temperature never exceeded 80 °C.

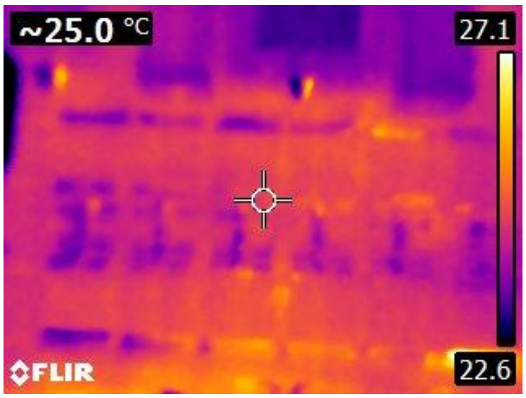

Figure 21: Stress Test with 10 A

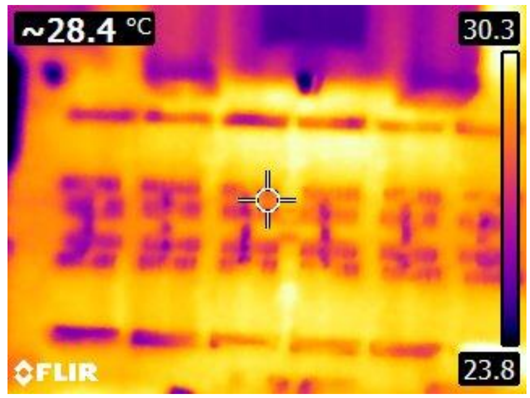

Figure 22: Stress Test with 20 A

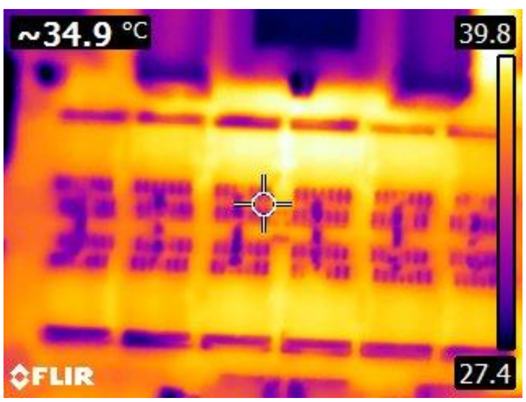

Figure 23: Stress Test with 30 A

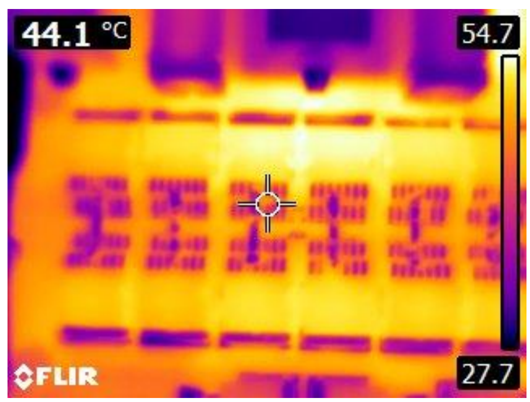

Figure 24: Stress Test with 40 A (20min)

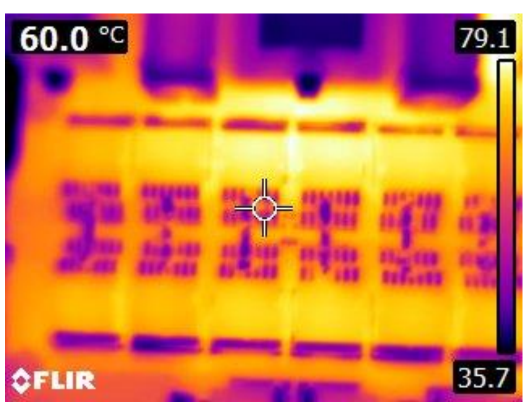

Figure 25: Stress Test with 50 A (60min)

7. Web-Interface

7.1. Overview of the MessWEB Hardware

The housing of the MessWEB measures 60 mm × 70 mm and weighs 80 g. Using the MessWEB for external control of the eFuse results in an increase of the current draw from the external power supply to 210 mA.

The MessWEB can be used to control other Vishay reference designs as well. It reads the design’s version number from its EEPROM and then provides the corresponding web interface.

The MessWEB is connected to the eFuse using the 14-pin shrouded connector, and the RJ45 connector is used to make the connection to the computer. The SD card, which is accessible from the side, contains the MessWEB’s firmware and is used for any necessary updates.

The MessWEB can also be equipped with a CAN bus compatible chip and programmed according to the customer’s specifications. The connection to the CAN bus is made using the D-Sub-9 socket.

To use the web interface the eFuse must be connected to an external power supply as described in section 1, the MessWEB connected to the 14-pin connector of the eFuse, and a LAN cable connected between the MessWEB and a computer.

Figure 26: Top View of the MessWEB

Figure 28: Shrouded Connector and Slot for the SD Card

Figure 27: CAN Bus and RJ45

WHITE PAPER

7.2. Overview of the MessWEB Software

The web browser interface of the external controller “Vishay MessWEB” can be used to control the eFuse with a computer and initialized using the address “http://192.168.0.1” (accessing the web interface using the https protocol is not possible).

With the “MessWEB”, the current status of the eFuse can be displayed on a computer, and all the parameters can be set:

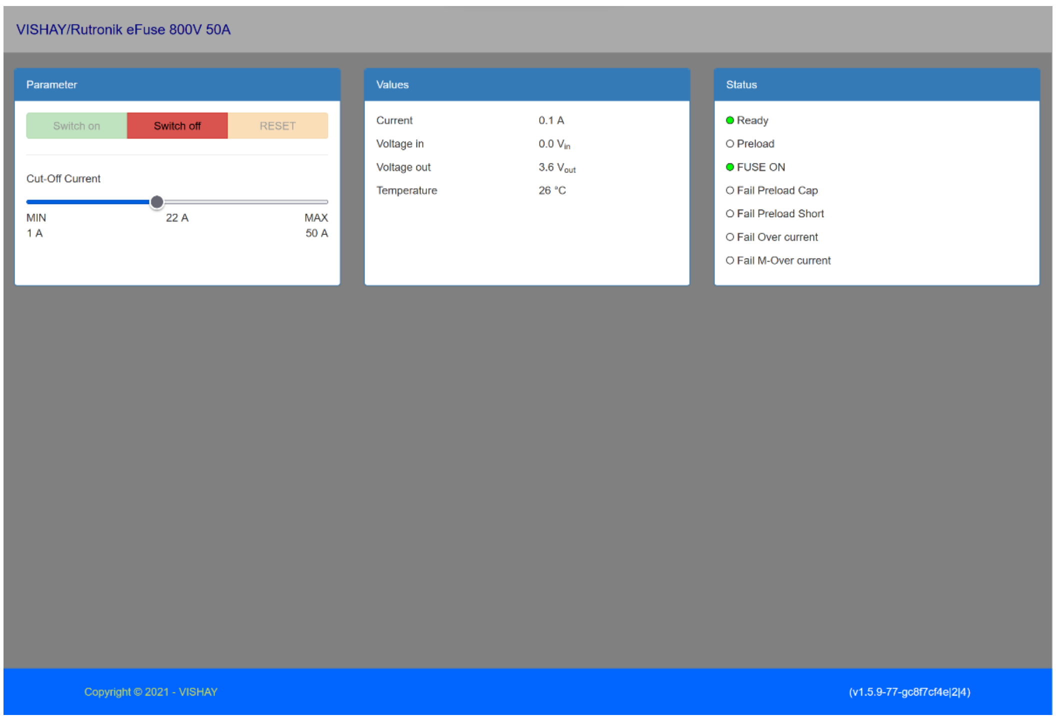

Figure 29: Overview of the Web Interface of the Vishay MessWEB

The web interface is divided into three sections. In the left column the eFuse can be switched on and off, errors can be acknowledged, and the maximum current can be set. In the middle column the currently measured values of the eFuse are displayed: input voltage, output voltage, load current, and ambient temperature. The right column displays the same status indicators as the LEDs on the PCB.

Even with the web interface in use, the eFuse can still be turned on or off at any time using the <ON/OFF> buttons on the PCB.

If an error occurs during operation and causes the eFuse to turn off, it must first be acknowledged using the <RE-SET> button on the web interface before it can be turned on again:

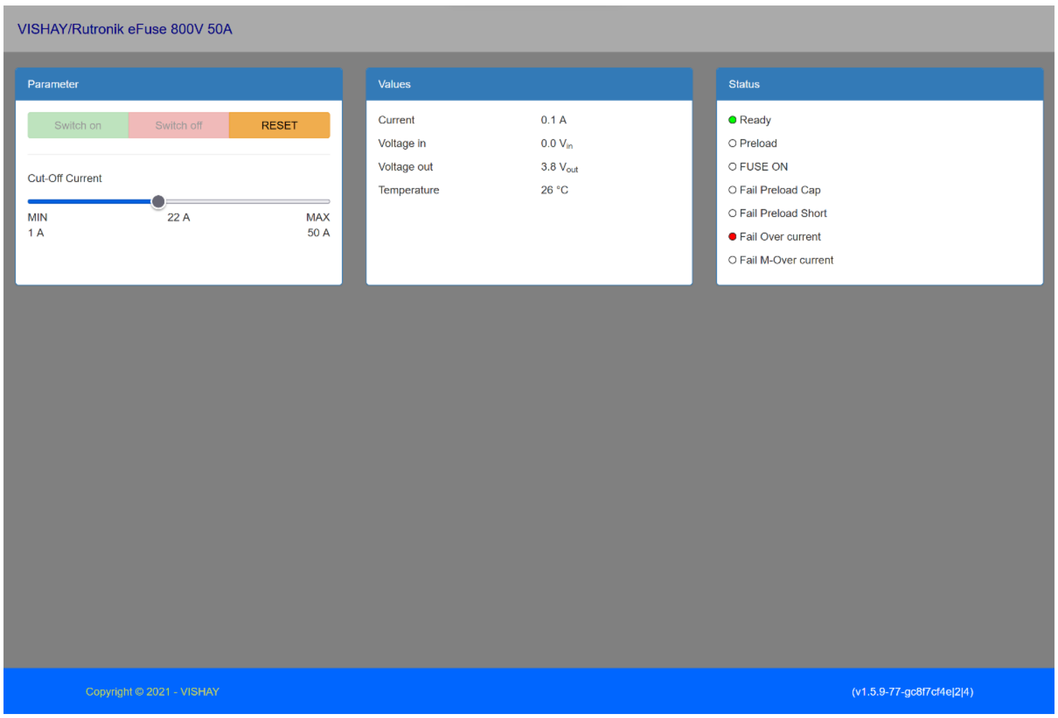

Figure 30: Web Interface after an error occurred

8. Conclusion

A high voltage resettable eFuse has been developed by Vishay for the safe operation of currents up to 50 A at a maximum voltage of 800 V using a variety of key Vishay components for the implementation.

Various safety measures have been incorporated into the design to ensure that the user is always protected from the high voltage even during overvoltage or fault conditions, and that the power source is protected from either overcurrent or short circuit conditions.

Furthermore, the eFuse can be easily controlled either with the buttons on the PCB or with the Vishay MessWEB external controller, which allows for access to even more features. The eFuse can also be integrated into a CAN bus-based system using the MessWEB with an additional chip set.

A. List of Figures

B. References

1. **Vishay Semiconductors.** VOA300: Linear Optocoupler, High Gain Stability, Wide Bandwidth. [Online] Mar 17, 2021. https://www.vishay.com/docs/80180/voa300.pdf. Vishay Document Number 80180.

2. **Vishay Dale.** WSLP3921: Power Metal Strip Resistors, Very High Power, Low Value, Surface-Mount. [Online] Nov 24, 2021. https://www.vishay.com/docs/30176/wslp3921-wslp5931.pdf. Vishay Document Number 30176.

3. **Vishay Beyschlag.** MMB 0207: Professional Thin Film MELF Resistors. [Online] Nov 11, 2021. https://www.vishay.com/docs/28713/melfprof.pdf. Vishay Document Number 28713.

4. **Vishay Vitramon.** VJ OMD: Surface Mount Multilayer Ceramic Chip Capacitor Solutions for Boardflex Sensitive Applications. [Online] Jan 29, 2021. https://www.vishay.com/docs/45198/vjomd.pdf. Vishay Document Number 45198.

5. **Vishay Techno.** CDMA: Thick Film Chip Dividers, Medium Voltage. [Online] May 19, 2021. https://www.vishay.com/docs/68040/cdmv.pdf. Vishay Document Number 68040.

6. **Vishay Sfernice.** D2TO35: Surface Mount Power Resistor Thick Film Technology. [Online] Nov 10, 2021. https://www.vishay.com/docs/51058/d2to35.pdf. Vishay Document Number 51058.