RABID MANTIS

Braking Resistor

Flexible braking resistor with configurable hysteresis and minimum on-time.

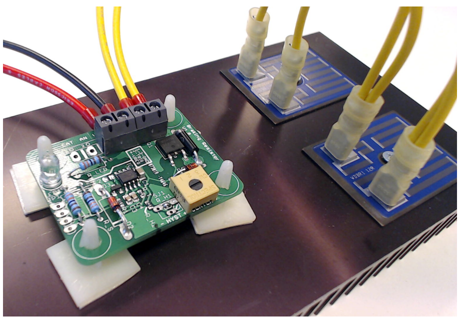
Features

As few as 16 components.
Adjustable trigger voltage from 12 V to 300 V.
Arbitrary voltage hysteresis and minimum on-time.
Can sustain an average of 8 A, or 35 A pulsed, with default transistor.
LED / Optocoupler output for diagnostics.

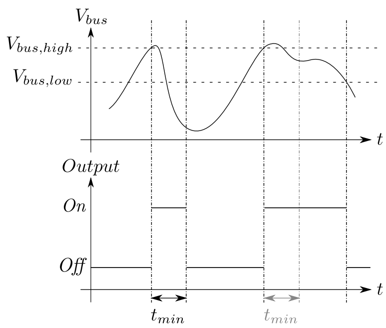
Description

Braking Resistor is, as it's name suggests, a general-purpose braking resistor primarily intended for handling regenerative power from low to mid-power servo and stepper-motor drives.
An external high-power shunt resistor is switched on, drainging power from the bus when the bus voltage exceeds some limit $V_{bus,high}$, and kept on for at least t_{min} and until the bus voltage falls below $V_{bus,low}$.
Braking Resistor can be used with bus voltages ranging from 12 V to 75 V, and can sustain an average load of 8 A, or 35 A at a 5% duty cycle with 1 ms pulses, with the default pass transistor. Other transistor choices allow operation at up to 300 V and significantly higher currents.

Overview



Braking Resistor connected to two power resistors and a heatsink.



System behavior showing hysteresis and minimum on-time.

Contents

Copyright Notice

Hardware Revision History

1.0.0 Initial version.

Documentation Revision History

1.0.0 Initial version, applies to hardware revision 1.0.0.

Absolute Maximum Ratings

PARAMETER	SYMBOL	RATING
Input bus voltage	V_{bus}	+75 V to -0.5 V
Average shunt current	$I_{shunt,avg}$	8 A
Repetitive pulsed shunt current, 5% duty cycle, 1 ms pulse length	$I_{shunt,5\%,1\text{ms}}$	35 A
Externally supplied logic supply voltage	V_{logic}	+15 V to -0.5 V

Assembly

Braking Resistor is relatively simple to assemble, constsiting of through-hole components and large- to medium-sized surface mount components that are easily soldered with a fine-point soldering iron.

See the section Bill of materials for the default components used, figure 6 for the component placement, and the section Pin Description for the connector pin usage. The section Operation describes how Braking Resistor functions internally and derives some of the equations presented in this section.

Determining component values

In order to configure Braking Resistor to the desired voltage levels and minimum on-time some component values must be determined. The typical behavior of Braking Resistoris shown in figure 1, where the output shunt resistor is activated when the bus voltage exceeds $V_{bus,high}$ and is kept on for at least t_{min} and until the bus voltage sinks below

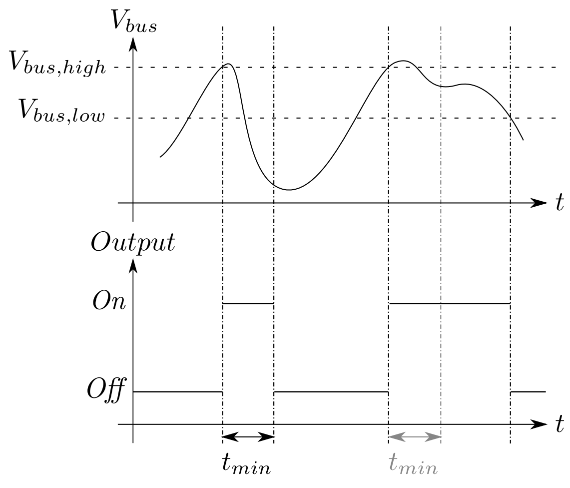


Figure 1: Braking Resistor parameter definitions.

$V_{bus,low}$. The calculations for determining values for the eight components to determine follows;

$V_{bus,high}$ and $V_{bus,low}$ control the turn-on and turn-off voltages for the device, and must be chosen with some care. Be sure that $V_{bus,low}$ is sufficiently far above the nominal bus voltage $V_{bus,nom}$ so that the output is switched off after all regenerative power has been dissipated. Choose a value for $V_{bus,high}$ that gives a moderate level of hysteresis. A general rule of thumb is to select $V_{bus,low} = 1.1 \cdot V_{bus,nom}$ and $V_{bus,high} = 1.1 \cdot V_{bus,low}$. Keep in mind that $V_{bus,high}$ must be within the permissible operating range for all the other devices on the bus.

R_{shunt} must be selected so that enough current is drawn from the bus. This depends on the amount of current generated by the servo or stepper motor drive when in the regenerative state and is highly application dependent. A conservative guideline is to choose

$$R_{shunt} = \frac{V_{bus,high}}{2 \cdot I_{regen}} \tag{1}$$

where I_{regen} is the regenerative current from the servo or stepper motor drive. For high regenerative currents be sure to respect Braking Resistor's absolute maximum ratings!

t_{min} A guidline for choosing t_{min} is to use

$$t_{min} = R_{shunt} \cdot C_{bus} \cdot \ln\left(\frac{V_{bus,high}}{V_{bus,low}}\right) \tag{2}$$

where R_{shunt} is the chosen shunt resistor resistance and C_{bus} is the total bus capacitance. See section Operation for the derivation of this equation. Be sure that $t_{min} > 50\,\mu$S, especially for high shunt currents, by increasing C_{bus} or $V_{bus,high} - V_{bus,low}$, as this will reduce the switching losses in the pass transistor Q1.

R_T can be determined given a value of t_{min} by the relation;

$$\begin{aligned} R\_T &= \frac{t_{min}}{1.1 \cdot C4} \\ &\approx \frac{t_{min}}{110 \cdot 10^{-9}} \end{aligned} \tag{3}$$

R_S must be chosen to ensure that enough current is suppled to the active components. This gives a maximum value of

$$\begin{aligned} R\_S_{max} &= \frac{V_{bus,nom} - V_{logic}}{I_{logic,min}} = \frac{V_{bus,nom} - V_{logic}}{I_{D2,min} + \frac{V_{logic}}{R1} + IC1_{IQ} + \frac{Q1_{Qtot}}{t_{on,min}}} \\ &\approx \frac{V_{bus,nom} - 12}{3 \cdot 10^{-3}}, \text{ for } t_{on,min} \geq 100\,\mu S \end{aligned} \tag{4}$$

where $V_{bus,nom}$ is the nominal bus voltage (which is $< V_{bus,low}$). Generally, choose a value of R_S that is at least 20% smaller to give some margin. The maximum power dissipation in R_S can be calculated by

$$\begin{aligned} P_{R\_S} &= \frac{(V_{bus,high} - V_{logic})^2}{R\_S} \\ &= \frac{(V_{bus,high} - 12)^2}{R\_S} \end{aligned} \tag{5}$$

For high bus voltages the power dissipation starts becoming difficult to handle (>1W). For these applications there is a connection for supplying an external logic supply voltage and is described in more detail later in this section.

R_LED should be chosen to give a reasonable current through the diagnostic LED (LED1) or optocoupler input connected to the terminal block. Choose a value

$$R\_LED = \frac{V_{bus,high} - V_{LED}}{I_{LED}} \tag{6}$$

where V_{LED} is the LED forward voltage (typically in the range of 1.5 to 3 V) and I_{LED} is the desired LED current. Keep the maxmim power dissipation

$$P_{R\_LED} = \frac{(V_{bus,high} - V_{LED})^2}{R\_LED} \tag{7}$$

in mind and choose a resistor with a suitable power rating.

R_B1, R_B2, and R_B3 determine the center voltage $V_{ctr} = \frac{V_{bus,high}+V_{bus,low}}{2}$ (which lies in the middle of $V_{bus,low}$ and $V_{bus,high}$). For a given value of R_B2 and R_B3 (typically in the range of 100 Ω to 1000 Ω)

$$\begin{aligned} R\_B1 &= (R\_B2 + R\_B3)\left(\frac{V_{ctr}}{V_{ref}} - 1\right) \\ &= (R\_B2 + R\_B3)\left(\frac{V_{bus,high} + V_{bus,low}}{2 \cdot 2.5} - 1\right) \end{aligned} \tag{8}$$

Ensure that the current in R_B1 is at least 500 µA in order to maintain accuracy, giving a maximum value of

$$\begin{aligned} R\_B1_{max} &= \frac{V_{bus,low} - V_{ref}}{500 \cdot 10^{-6}} \\ &= \frac{V_{bus,low} - 2.5}{500 \cdot 10^{-6}} \end{aligned} \tag{9}$$

For high bus voltages, keep the power dissipation of R_B1 in mind, which is

$$\begin{aligned} P_{R\_B1} &= \frac{(V_{bus,high} - V_{ref})^2}{R\_B1} \\ &= \frac{(V_{bus,high} - 2.5)^2}{R\_B1} \end{aligned} \tag{10}$$

If an adjustable range of $V_{bus,high}$ and $V_{bus,low}$ is desired, calculate a value for R_B1 using (8) with R_B2 set to zero and $V_{bus,high}$ and $V_{bus,low}$ set to their lowest desired adjustable values ($V_{bus,high,min}$ and $V_{bus,low,min}$). R_B2 can then be determined by the relation

$$R\_B2 = R\_B3 \left(\frac{V_{bus,high,max}}{V_{bus,high,min}} - 1 \right) \tag{11}$$

where $V_{bus,high,max}$ is the maximum value $V_{bus,high}$ can be adjusted to and $V_{bus,high,min}$ is the lowest value $V_{bus,high}$ can be adjusted to.

R_H1 and R_H2 set the total hysteresis, their values can be determined by the relations

$$R\_H1 + R\_H2 = \frac{V_{logic} \cdot R\_B1}{V_{bus,high} - V_{bus,low}} \tag{12}$$

(see section Operation for the derivation of this equation).
If an adjustable hysteresis is desired, calculate a value for R_H2 using (12) with R_H1 set to zero and $V_{bus,high} - V_{bus,low}$ set to its smallest desired value. R_H1 can then be determined by the relation

$$R\_H1 = R\_H2 \left(\frac{V_{hyst,max}}{V_{hyst,min}} - 1 \right) \tag{13}$$

where $V_{hyst,max}$ is the maximum level of hysteresis ($V_{hyst} = V_{bus,high} - V_{bus,low}$) and $V_{hyst,min}$ is the minimum level of hysteresis. Additionally, note that the hysteresis level is dependent on $V_{bus,high}$ and $V_{bus,low}$, meaning that if $V_{bus,high}$ and $V_{bus,low}$ are adjusted with R_B2 the hysteresis level will also be affected!

Example

Example calculations follow for a system with a nominal bus voltage of $V_{bus,nom} = 32\,\text{V}$, a fixed output turn-off voltage of $V_{bus,low} = 35\,\text{V}$, a fixed output turn-on voltage of $V_{bus,high} = 38\,\text{V}$, with an external current source (servo drive or stepper motor driver) generating $I_{regen} = 6\,\text{A}$ when braking, with a total bus capacitance of $C_{bus} = 4700\,\mu\text{F}$, and an LED with current of $I_{LED} = 10\,\text{mA}$ and forward voltage of $V_{LED} = 2\,\text{V}$.

First, R_{shunt} is determined by using equation (1), giving

$$R_{shunt} = \frac{V_{bus,high}}{2 \cdot I_{regen}} = \frac{35}{2 \cdot 6} \approx 2.91\,\Omega$$

Note that this resistor value gives a peak shunt current of 12 A, which is above the maximum average current that can be sustained. Braking Resistor can most likely sustain this current for short intervals — which is often the case for a dynamic braking — making an evaluation of the shunt transistor's (Q1) temperature prudent during initial runs.

R_T can be determined by using equation (2) and equation (3), giving

$$\begin{aligned} t_{min} &= R_{shunt} \cdot C_{bus} \cdot \ln\left(\frac{V_{bus,high}}{V_{bus,low}}\right) \\ &= 2.91 \cdot 4700 \cdot 10^{-6} \cdot \ln\left(\frac{38}{35}\right) \approx 1.12\,\mathrm{ms} \end{aligned}$$

and

$$R\_T = \frac{t_{min}}{110 \cdot 10^{-9}} = \frac{1.12 \cdot 10^{-3}}{110 \cdot 10^{-9}} \approx 10.181 \cdot 10^3\,\Omega$$

R_S is given by equation (4) (as $t_{min} > 50\mu$S)

$$\begin{aligned} R\_S_{max} &= \frac{V_{bus,nom} - 12}{3 \cdot 10^{-3}} = \frac{32 - 12}{3 \cdot 10^{-3}} \approx 6666\,\Omega \\ \implies R\_S &\approx \frac{R\_S_{max}}{1.2} \approx 5800\,\Omega \end{aligned}$$

and will experience a maximum power dissipation given byequation (5)

$$P_{R\_S} = \frac{(V_{bus,high} - 12)^2}{R\_S} = \frac{(38 - 12)^2}{5800} \approx 110\,\mathrm{mW}$$

meaning that a standard 1/4 W resistor will suffice.

R_LED is chosen with equation (6)

$$R\_LED = \frac{V_{bus,high} - V_{LED}}{I_{LED}} = \frac{38 - 2}{10 \cdot 10^{-3}} \approx 3600\,\Omega$$

and will at most dissipate (as per equation (7))

$$P_{R\_LED} = \frac{(V_{bus,high} - V_{LED})^2}{R\_LED} = \frac{(38 - 2)^2}{3600} \approx 360\,\mathrm{mW}$$

meaning that a 1/2 W resistor should be chosen.

Assuming a R_B3 is chosen to be $1000\,\Omega$ (selected somewhat arbitrarily) and R_B2 is not mounted (giving fixed voltage levels) equation (8) gives

$$R\_B1 = (R\_B2 + R\_B3)\left(\frac{V_{bus,high} + V_{bus,low}}{2 \cdot 2.5} - 1\right) = 1000\left(\frac{38 + 35}{5} - 1\right) \approx 13.6 \cdot 10^3\,\Omega$$

and will dissipate an average (given by equation (10))

$$P_{R\_B1} = \frac{(V_{bus,high} - 2.5)^2}{R\_B1} = \frac{(38 - 2.5)^2}{13.6 \cdot 10^3} \approx 92\,\mathrm{mW}$$

meaning that a standard 1/4 W resistor will suffice. Checking (9);

$$R\_B1_{max} = \frac{V_{bus,low} - 2.5}{500 \cdot 10^{-6}} \approx 71 \cdot 10^3\,\Omega$$

shows that the selected value of $R\_B1 = 13.6 \cdot 10^3\,\Omega$ is sufficiently small. Had the desired R_B1 been too large then R_B2+R_B3 could be reduced, which also gives a smaller value for R_B1.

Finally, R_H2 can be determined (as R_H1 is not mounted in this fixed-hysteresis application) by (12) giving

$$\begin{aligned} R\_H1 + R\_H2 &= \frac{V_{logic} \cdot R\_B1}{V_{bus,high} - V_{bus,low}} \\ \therefore R\_H1 &= \frac{12 \cdot 13.6 \cdot 10^3}{38 - 35} \\ &\approx 54.4 \cdot 10^3\,\Omega \end{aligned}$$

Optional components and component variations

The chosen shunt transistor (Q1) can be replaced with nearly any other N-channel TO-252-3 (D-PAK) transistor (more on this in the section Operation), allowing for operation at higher currents and/or higher bus voltages. If choosing a different transistor, be sure to stay within it's safe operating area as specified in the datasheet!

When operating at high bus voltages the power dissipation in R_S may become impractically large (>1 W). In these applications, there is an optional logic supply input available, allowing for supplying V_{logic} from an external source. To use this input, leave R_S and D2 unmounted and externally supply V_{logic} through JP1 (see section Pin Description for the pins used). Be sure the externally supplied V_{logic} meets the voltage specifications specified in section Electrical Characteristics.

If R_B2 is not mounted (giving fixed levels for $V_{bus,high}$ and $V_{bus,low}$) be sure to short SJ2. Similarly, if R_H1 is not mounted (giving a fixed level of hysteresis), be sure to short SJ1.

If there is no need for the LED status indicator or optocoupler output then LED1 and R_LED may be left unmounted. **Note that LED1 must not be mounted in order to use the LED / optocoupler output terminals on X1!**

Pin Description

Connections are as follows;

HEADER	PIN	DESCRIPTION
X1	CAT	Cathode terminal for external shunt-active LED or optocoupler.
	AN	Anode terminal for external shunt-active LED or optocoupler.
	VBUS	Bus positive voltage input.
	GND	Bus ground input.
	R+	Shunt resistor positive terminal
	R-	Shunt resistor negative terminal
JP1	1	Ground connection.
	2	External trigger input, see section Operation for use.
	3	Ground connection.
	4	External logic supply input, see section Assembly for use.

Usage

In order to use Braking Resistor, assemble the device as per Assembly and, at a bare minimum, connect Braking Resistor to the voltage bus and shunt resistor as defined in section Pin Description. The terminal block (X1) has an optional output for an external status LED or optocoupler that allows for monitoring the output state, lighting the LED or activating a connected optocoupler when the ouptut is active.

Be sure to use cabling that is of sufficient size to handle the current passed through the shunt resistor. Depending on the application this requirement varies greatly, to a large extent due to the pulsed nature of the shunt resistor. If using the default shunt transistor (Q1), generally a cable with a conductor area of $\geq 1\,\mathrm{mm}^2$ should be sufficient for connections to the bus as well as an external shunt resistor. **In particular, keep the distance between the device raising the bus voltage (such as a servo or stepper motor drive) and Braking Resistor as short as possible!** Generaly, the total impedance between the devices should be kept to below $0.2\,\Omega$ (preferably below $0.05\,\Omega$) in order to avoid excessive voltage drop in the cabling. For example, a seperation distance of 0.5 meters (giving a cable length of 1 meter) and a cable with a $1\,\mathrm{mm}^2$ conductor will give a cable impedance of approximately $0.2\,\Omega$; giving a voltage drop of 4 V at a load of 20 A — which may be more than the set hysteresis!

There are no components on Braking Resistor that require heatsinking, though be sure to monitor the temperature of the shunt transistor (Q1) for applications approaching the maxmimum current capability of the device. Do keep in mind the external shunt resistor(s) will generally require some form of cooling!

Bill of materials

Note; A value of 4n7 corresponds to a value of 4.7n, and in the case of a capacitor corresponds to 4.7nF. The suggested part number is only that — a suggestion — and may be replaced with any other equivalent matching the specifications listed under value, rating, and type.

Component name	Value	Rating	Type	Suggested Part No.
C1	10uF	25V	X7R ceramic, SMD 1206	12063D106KAT2A
C2	Do not mount[1]	6v3	X7R ceramic, SMD 0805	-
C3	10n	25v	X7R ceramic, SMD 0805	MCCA000368
C4	100n	25v	X7R ceramic, SMD 0805	MCCA000295
D1	82V	5W	Through-hole zener diode, 12.7mm grid	1N5375BG
D2	12V	1W	Through-hole zener diode, 15.24mm grid	BZV85-C12
D3	LM431/TL431	-	SOT-23 package	LM431ACM3
D4	15V	1W	Through-hole zener diode, 10.16 mm grid	BZV85-C15
IC1	CMOS 555-timer	-	SO8 CMOS 555-timer equivalent	LMC555CMX
JP1	-	-	2.54mm x 4-way jumper	-
LED1	-	-	Generic 5mm, 20mA LED	L-53LGD
R1	10k	5%, 100mW	SMD 0603 resistor	CRCW060310K0FKEA
R_LED, R_B1, R_S	See section Assemblyfor application-specific value		Through-hole resistor, 12.7mm grid	-
R_T, R_H2, R_B3			SMD 0603 resistor	-
R_H1, R_B2			Vertical through-hole potentiometer, 2.54mm grid	-
SJ1	-	2-way jumper	Short if R_H1 not mounted	-
SJ2	-	2-way jumper	Short if R_H2 not mounted	-
Q1	N-MOS, $I_{Q,TOT} \leq 50$nC	-	TO-252-3 (D-PAK) transistor	IPD16CN10N G
X1	-	-	5mm x 6-way terminal	CTB5202/6

[1] Not used in normal operation, see section Operation for usage.

Mechanical Description

Braking Resistor consists of a PCB and associeated components, with a finished size of 40 mm by 50 mm, with a build height of 14 mm, limited by the terminal block X1. Mounting holes are listed in table 4 following the coordinate system shown in figure 2. PCB manufacturing requirements are shown in table 3 and should be generally achievable at any PCB house.

Table 3: PCB manufacturing requirements.

PARAMETER	REQUIREMENT	UNIT
PCB thickness	Any (nominal 1.6)	mm
PCB layers	2	-
Copper fill thickness/density (tested)	35/1	µm / oz/ft^2
Trace isolation (minimum)	0.6096/24	mm/mil
Trace width (minimum)	0.4064/16	mm/mil
Trace to board edge (minimum)	0.25	mm
Drill to board edge (minimum)	0.4532	mm
Drill diameter (minimum)	0.3	mm
Via annular ring (minimum)	0.2032/8	mm/mil

Table 4: Mounting hole locations.

HOLE DIAMETER [mm]	POSITION X [mm]	POSITION Y [mm]
4.1	5	5
4.1	5	45
4.1	35	5
4.1	35	45

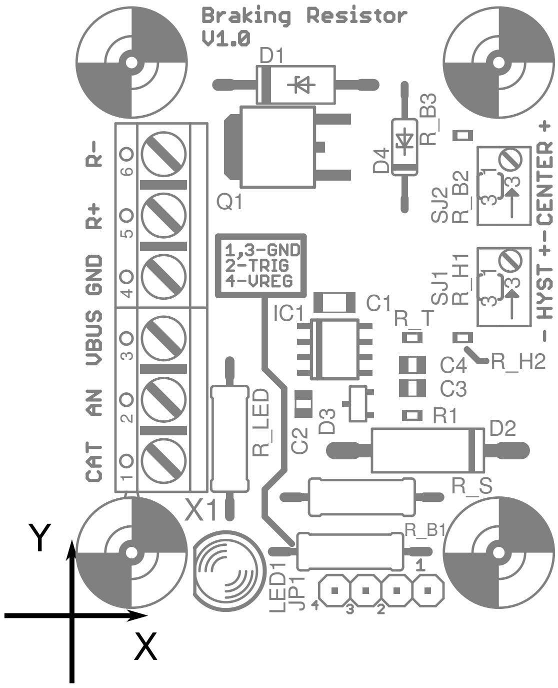


Figure 2: Coordinate system for mounting holes.

Electrical Characteristics

PARAMETER	SYMBOL	TEST CONDITIONS/COMMENTS	MIN	TYP	MAX	UNIT
Input Characteristics						
Bus input voltage	V_{in}	Using default components	10		75	V
Quiescent supply current		Dependent on value of R_S	3	≥ 3.5		mA
Output Characteristics						
Average shunt current	$I_{shunt,avg}$	Largely dependent on choice of Q1			8	A
Dynamic behavior						
Propogation delay	t_{prop}	Time from V_{bus} exceeding $V_{bus,high}$ to shunt transistor (Q1) fully on ($V_{gs} \geq 0.8 \cdot V_{logic}$)		10		us
On-time		Determined by R_T and C4	50			us
Shunt transistor temperature increase	ΔT_{Q1}	With an RMS load of 8A, PCB placed horizontally, and no active cooling (See figure 3).		65		°C
Internal characateristics						
Logic voltage	V_{logic}	Regulated or externally supplied	9	12	14	V

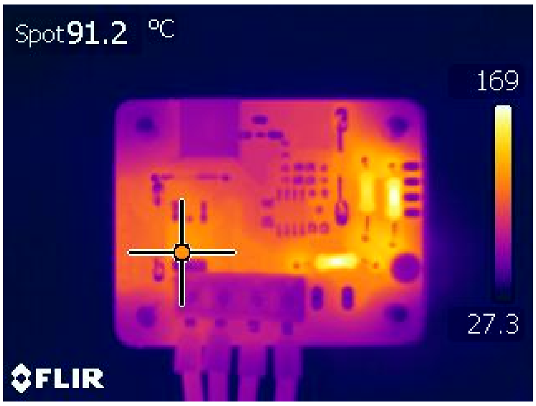


Figure 3: Braking Resistor steady-state temperature, with cursor indicating the peak temperature of Q1. Test conditions are an RMS load of 8 A, with device placed horizontally, with no active cooling, and at an ambient temperature of 27 °C. In this application R_LED and R_B1 are somewhat undersized, leading to high temperatures.

Operation

Braking Resistor is at its core a device that shunts power through a dump resistor when the input bus voltage is too high. Adding hysteresis and a minimum on-time reduces the risk of high-speed oscillation, reducing the performance requirements of the power transistor.

The entire schematic for Braking Resistor is shown in figure 4, and consists of two integrated circuits (D3 and IC1) along with supporting passive components and a power shunt transistor.

The bus voltage V_{bus} is supplied through the terminal block X1 and is connected to one terminal of the external shunt resistor as well as internal nodes. R_S, D2, and C1 form a simple decoupled linear regulator that generates V_{logic}, which is used for the integrated circuits. R_B1, R_B2, and R_B3 form a voltage divider whose resulting voltage V_{div} is fed to the reference of D3, which in this application is used as a comparator. When V_{div}, the voltage at the reference terminal of D3, exceeds D3's internal reference voltage (typically 2.5 V) the cathode transitions from a high-impedance state (which is kept at V_{logic} by the pullup resistor R1) to a low impedance state, bringing the trigger input of IC1 (a CMOS 555 timer) low.

IC1 is configured as a monostable multivibrator (configured with R_T and C4) and brings its output to V_{logic} for a minimum time $t_{on,min}$ when triggered by a logic low level on its trigger input. This is directly connected to the gate of the shunt transistor Q1, activating the load and (hopefully) bringing the bus voltage to a lower level. As long V_{div} is above D3's internal reference level the trigger input to the 555-timer will be kept low, thereby keeping the output active. Only when both the minimum on-time has elapsed and V_{div} is below D3's internal reference voltage will the output turn off.

D4 and D1 act as safety protection diodes; D4 protects the gate from excessive voltage transients while D1 absorbs any parasitic inductive current. C2 is an optional low-pass capacitor that is not normally used; in some applications there may be a need to increase the propogation delay or otherwise act more slowly, which can be added by mounting a capacitor here.

R_H1 and R_H2 adds hysteresis to the output transition levels by injecting current into the measurement node. When IC1's output is low some of the current through R_B1 is sinked by the output of IC1, reducing V_{div}, and (more significantly) when IC1's output is high additional current is sourced by IC1 and fed over RB_2 and RB_3, increasing V_{div}.

The hysteresis and minimum on-time together create a relatively robust control system which minimizes the switching frequency of Q1, which is important for multiple reasons; IC1's output is relatively weak and can only sink and source on the order of 50 mA (giving slow gate transitions, causing much of the losses in the Q1); Q1's large gate capacitance would cause a relatively large average current to be drawn if switched rapidly, which would cause large losses in the regulation resistor R_S; and a high switching frequency will generate needless EMI (electromagnetic interference).

For higher shunt currents the default shunt transistor Q1 can be replaced with nearly any TO-252-3 (DPAK) transistor, which have the potential to have a significantly lower $R_{DS,on}$ impedance. If a transistor with a significantly greater gate charge is chosen (above 50 nC) be sure to increase the minimum on-time as well in order to reduce the total switching loss. When very heavily loaded (average currents over 10-15 A) resistive losses in Braking Resistor's PCB traces may become problematic and should be verified.

For high bus voltages the power dissipation in R_S may be impractically large (>1 W), and for these applications the is the ability to externally supply V_{logic}. This voltage is relatively uncritical, but care should be taken not to allow V_{logic} to fall too low, as the voltage supplied to the gate of Q1 is based on this voltage, and for too small values Q1 will not fully turn on, creating large losses and potentially destroying the transistor.

There is also an additional trigger input, which is directly connected to the reference input of D3. This allows for controlling the output state from an external device, and can be used with or without R_B1, R_B2, R_B3, R_H1, and R_h2 mounted. The trigger voltage is equal to the reference voltage in D3, which is typically 2.5 V, effectively making the trigger input both 3.3 V and 5 V compatible.

Generally, t_{min} should be no less than $50\,\mu s$, but can otherwise be chosen relatively freely[2]. One method is to set t_{min} to be the time required for the bus voltage to sink from $V_{bus,high}$ to $V_{bus,low}$ assuming no additional power is sent into the bus. This conservative estimate ensures the bus voltage will not normally sink below $V_{bus,low}$, while still being as long as possible, and is what is used in equation (2). Recall that the voltage on the capacitor and resistor for an "ordinary" parallel RC circuit can be expressed as

$$V_c\left(t\right) \quad = \quad V e^{\frac{-t}{RC}}$$

where $V_c\left(t\right)$ is the voltage over the capacitor (and resistor), and V is the initial voltage over the capacitor. Setting $V_c\left(t_{min}\right) = V_{bus,low}$ and $V = V_{bus,high}$ and then solving for t_{min} gives

$$\begin{aligned} V_{bus,low} &= V_{bus,high} e^{\frac{-t_{min}}{RC}} \\ \ln\left(\frac{V_{bus,low}}{V_{bus,high}}\right) &= \frac{-t_{min}}{RC} \\ t_{min} &= -RC \ln\left(\frac{V_{bus,low}}{V_{bus,high}}\right) \end{aligned}$$

This estimate tends to give values that are shorter than strictly required, due to the assumption that no additional current is pushed into the capacitor during the entire discharge period, however for most applications this minimum on-time is still sufficiently long to not be problematically short.

Equation (12) is derived by applying kirchoff's current law to the node connected to the reference input of D3. When precisely at the tripping points $V_{bus,high}$ and $V_{bus,low}$ the voltage at the reference input of D3, referred to as V_r below, are exactly equal. If

[2] At very small values of t_{min}, switching losses in the pass transistor become increasingly significant and will detrimentally affect the performance of the device.

neglecting the bias current into the refernce input[3] Kirchoff's current law gives;

$$\frac{V_r - V_h}{R\_B1} + \frac{V_r}{R\_B2 + R\_B3} + \frac{V_r}{R\_H1 + R\_H2} = 0$$

when approaching $V_{bus,high}$ from below (when the output from IC1 is off) and

$$\frac{V_r - V_l}{R\_B1} + \frac{V_r}{R\_B2 + R\_B3} + \frac{V_r - V_{logic}}{R\_H1 + R\_H2} = 0$$

when approacing $V_{bus,low}$ from above (when the output from IC1 is on). Combining these equations gives (replacing $V_{bus,high}$ with V_h and $V_{bus,low}$ with V_l for compactness);

$$\begin{aligned}
\frac{V_r - V_h}{R_B1} + \frac{V_r}{R_B2 + R_B3} + \frac{V_r}{R_H1 + R_H2} &= \frac{V_r - V_l}{R_B1} + \frac{V_r}{R_B2 + R_B3} + \frac{V_r - V_{logic}}{R_H1 + R_H2} \\
\frac{V_r - V_l}{R_B1} - \frac{V_r - V_h}{R_B1} &= \frac{V_r}{R_H1 + R_H2} - \frac{V_r - V_{logic}}{R_H1 + R_H2} \\
\frac{V_h - V_l}{R_B1} &= \frac{V_{logic}}{R_H1 + R_H2} \\
\implies R_H1 + R_H2 &= \frac{V_{logic} \cdot R_B1}{V_h - V_l}
\end{aligned}$$

[3] With a typical value of 2 µA this is equivalent to 1.25 MΩ at 2.5 V (the typical reference voltage of the LM431) and far larger than the 1000-odd ohms presented by R_B2 and R_B3, making this term insignificant.

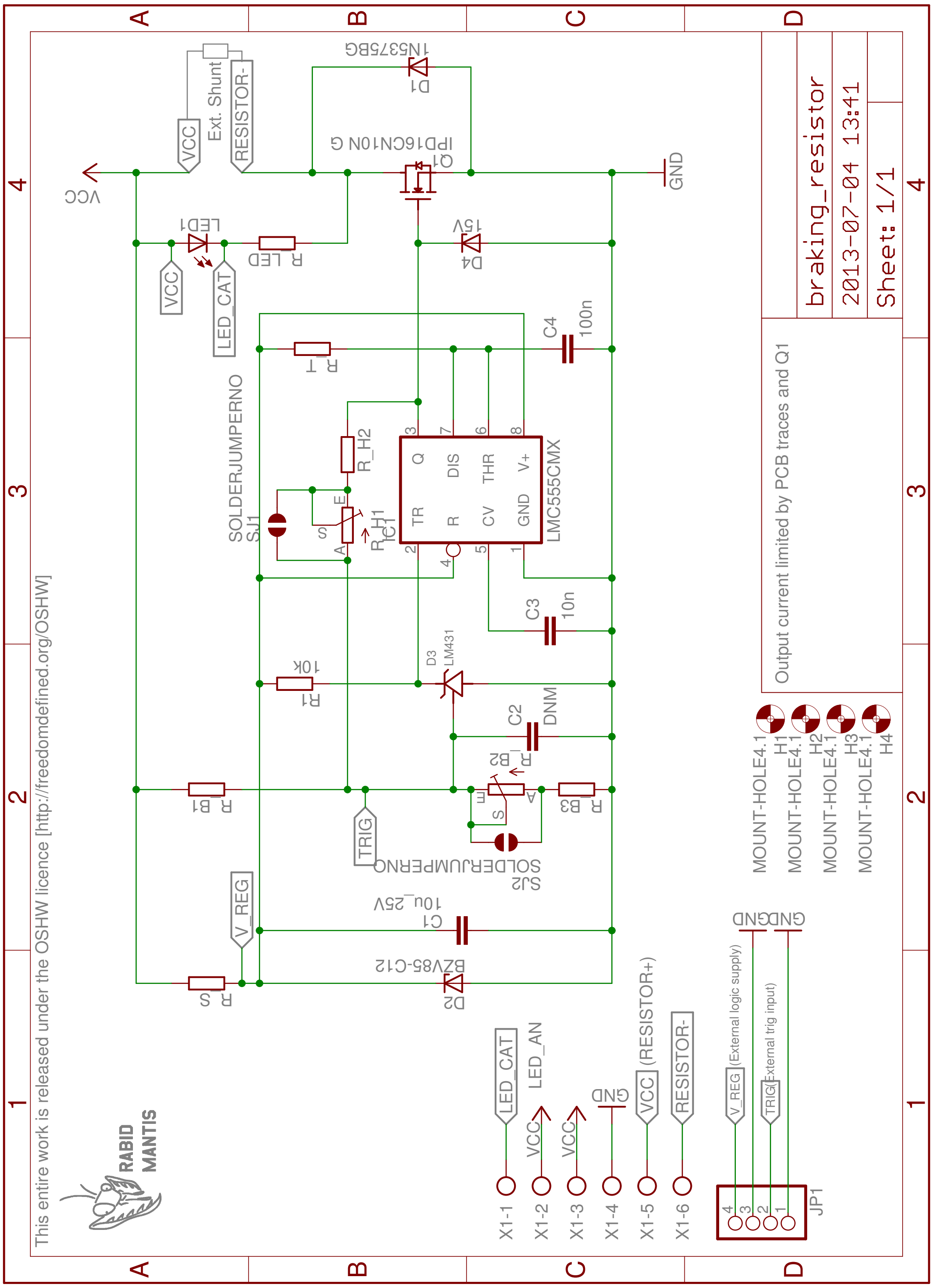
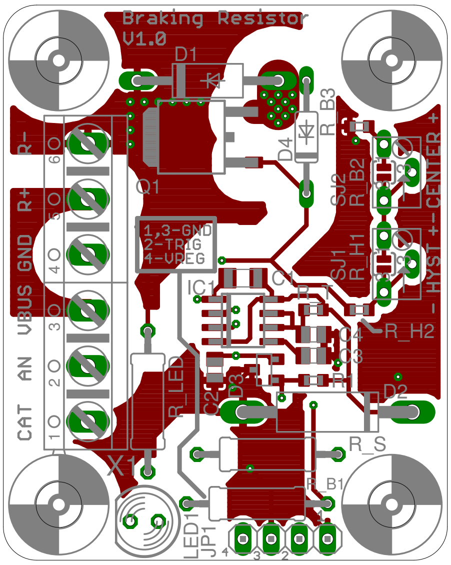
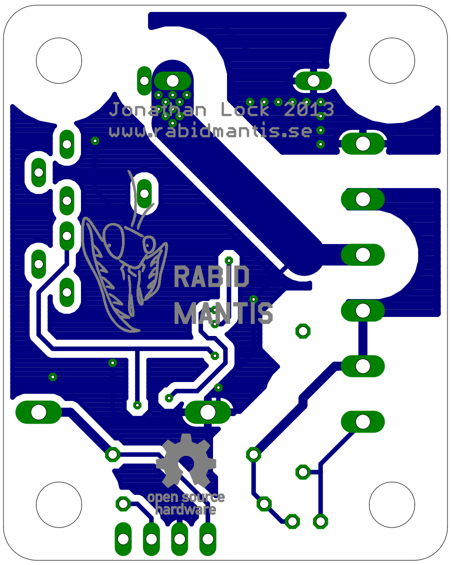


Figure 4: Braking Resistor schematic.

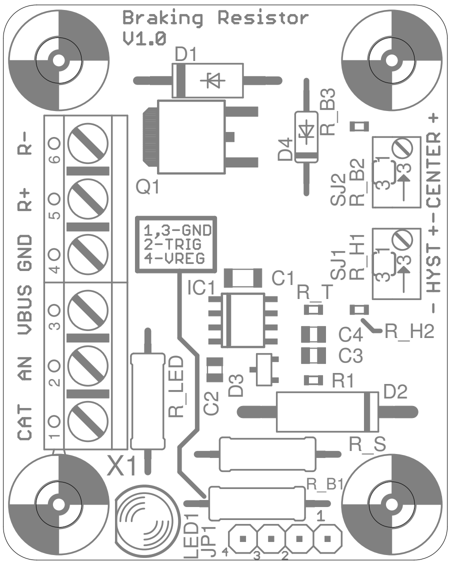


(a) Complete top layer as seen from above.



(b) Complete bottom layer as seen from below.

Figure 5: PCB details.



(a) Top layer component outline as seen from above.

(b) Bottom layer component outline as seen from below.

Figure 6: Component placement details.